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VARIABLE FOCAL LENGTH HIGH SPEED LENS

A. Lee Shawcross
Bausch and Lomb, Inc.

TECHNICAL REPORT AFAL-TR-72-42

March 1972

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Air Force Avionics Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

VARIABLE FOCAL LENGTH
HIGH SPEED LENS

A. Lee Shawcross

Bausch and Lomb, Incorporated

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Test and Evaluation; 18 MAY 1972 . Other requests
for this document must be referred to
[redacted] approval
of AFAL/RSP, Wright-Patterson AFB, Ohio.

FOREWORD

This report was prepared by Bausch and Lomb, Inc., Rochester, New York under Air Force Contract F33615-68-C-1295. The work was administered under the direction of the Air Force Avionics Laboratory, Air Force Systems Command, Mr. Lewis Bruckner, task scientist. This effort is documented under Project 7646, Task 7646 01.

The work began in February 1968 and was completed in January 1972.

This technical report has been reviewed and is approved for publication.

Albert W. Berg

ALBERT W. BERG, Chief
Recon Sensor Development Branch
Recon & Surveillance Division

ABSTRACT

This report describes the development and prototype manufacture of a high speed (f/2.4) zoom lens to work in the near infra-red (0.7 to 0.9mm) in conjunction with an image tube night viewing system. The development or design effort covered a period of 32 months and proved to be a very difficult design problem which required the performance objectives (specs) to be modified somewhat in order to permit the realization of a successful design. The completed design was fabricated (in 17 months) as a bench model prototype and found to meet the expected performance values. This unit was delivered for final testing in December 1971.

A

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LIST OF ILLUSTRATIONS

FIGURE 1

Variable Focal Length High Speed Lens

Section 1.0 INTRODUCTION

This document contains the final summary and technical report covering the work done under contract #F33615-68-C-1295 between Bausch and Lomb Inc. and Wright-Patterson Air Force Base. This contract covered design, development and manufacture of a Variable Focal Length High Speed Lens. The first section of the report is a review of the program as it progressed from the date of contract to completion. Ensuing sections describe the unit produced.

Section 2.0 DEVELOPMENT

2.1 Pre-award

The Air Force Avionics Laboratory, WPAFB, issued a purchase request #8-32383 of August 22, 1967 which was forwarded to Bausch and Lomb as part of RFP #33615-68R-1579 dated September 27, 1967. This request contained the following problem statement.

"For the purpose of performing visual surveillance utilizing an image amplifier under very low light level conditions, an efficient high speed zoom lens is required. To detect an area of interest requires a short focal length giving a wide angle of view, while closer scrutiny of details demands the use of a longer focal length. It is the purpose of this effort to achieve an optical system which fulfills these requirements."

The lens desired would have the following characteristics.

a. Focal length range of 3" to 12".

b. Aperture of f/2.0 or faster, constant throughout.

c. Format diameter of 3".

d. Color correction in 700m to 900m range

e. Resolution on the order of 100 l/mm throughout.

f. Overall length of 18".

g. Cover EFL range within 5 seconds.

Bausch and Lomb responded to the RFP in October 1967 with proposal #7-1335. This proposal stated in part:
"The difficult characteristics of this request (RFP) are the simultaneous attainment of wide field coverage at high numerical aperture in a relatively long focal length zoom lens constrained within a short mechanical length. The four to one zoom range at a constant speed of f/2.0 with high resolution is a difficult requirement but is within the state of the art. Color correction in the range 700 to 900m presents some difficulties in materials selection. Glasses must be chosen which have properties permitting adequate color correction through this wavelength range."

The proposal accepted the values listed in the RFP as design goals. The design process, optical and mechanical, was discussed and the proposed approach was closely followed. As a result of this proposal, a CPFF contract (#F33615-68-C-295) for a maximum value of $75,900 was awarded in February 1968.

2.2 Design Program

Work commenced immediately upon award of the contract with the first progress report being submitted March 1, 1968. A milestone/cost chart for the entire contract period is included as figure 2.

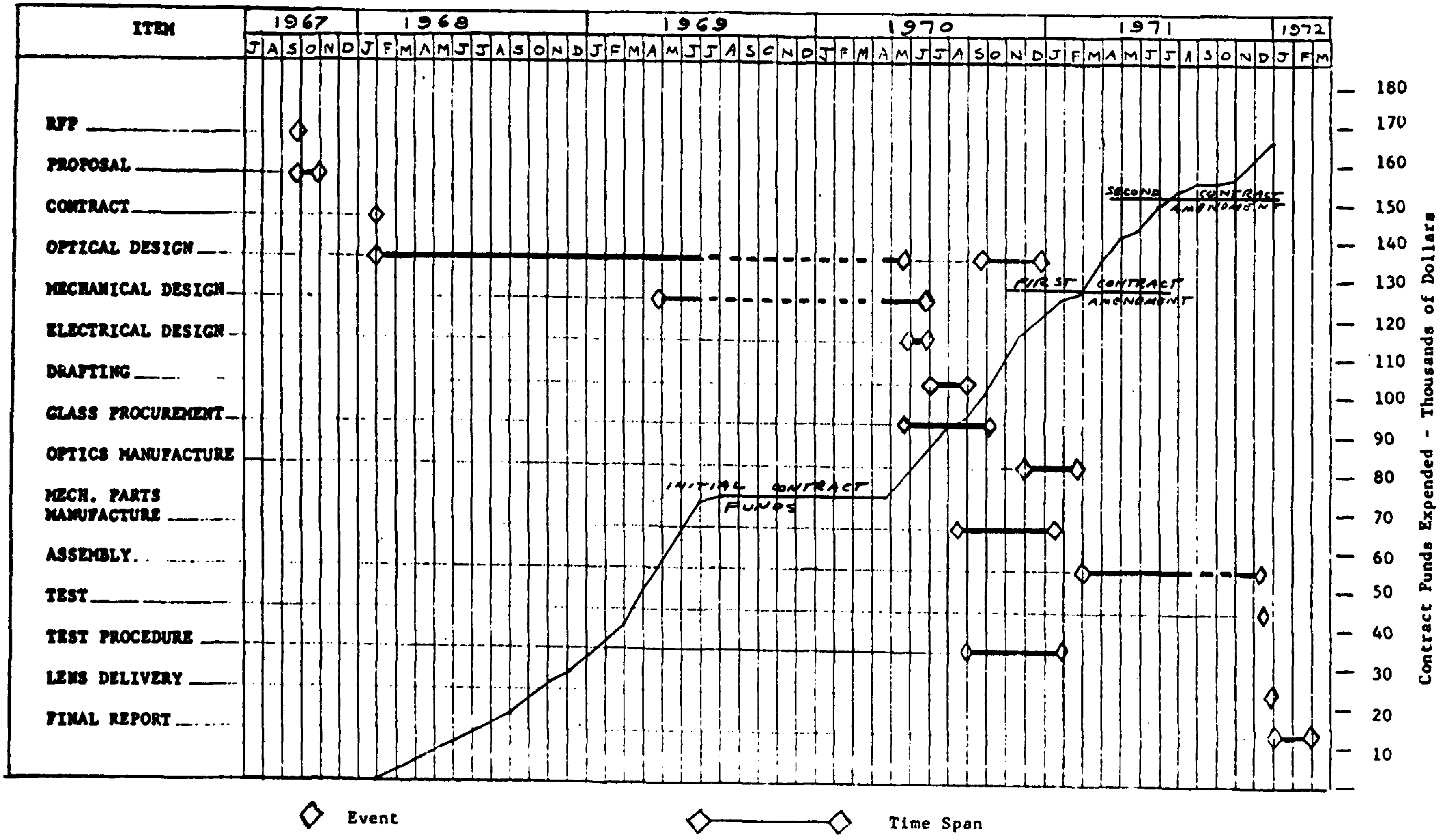
Initial efforts involved the selection of an appropriate "prototype" system to design around. It has been found that in any optical design task, it is more efficient and effective a practice to search existing

FIG. 2

BAUSCH & LOMB INCORPORATED

MILESTONE/COST ACCOMPLISHMENT CHART

F33615-68-C-1295



designs for one that matches your specific requirements as closely as possible and then modify the system to suit your needs. To this end, Bausch and Lomb maintains extensive design and patent files of all kinds of optical systems which are carefully catalogued and cross-referenced. A significant amount of time is spent at the outset of any design program carefully selecting the best possible candidate system (s) for subsequent modification.

In this case, Bausch and Lomb's reference books of Zoom Systems is a four-volume set consisting of hundreds of possible systems. The search concentrated on the mechanically compensated type of system and took the better part of three months. During this time, four basic prototypes had been selected for initial analysis in the Beta-Gamma program (described in Appendix I). This effort led to selection of two of these for further analysis on the Zoom Father program (Appendix I).

The design effort proved rather more difficult than first anticipated and, after approximately two months design effort, it became apparent that the prototypes would not work as they were and would require modification before being reintroduced into the automatic zoom design programs. At this point, the primary problem seemed to be the level of distortion at the short focal lengths. Progress report #5 (7/1/68) detailed the problem and established a modified schedule for the design program.

By mid-August of 1968 the rework of the prototypes was completed and work began on analysis of third order aberration. This effort again failed to develop the required lens and it was judged that there was little chance of meeting the goals for performance with any reasonable effort - if indeed it was possible at all. On 11/18/68, a meeting was held at which it was agreed to change the following values:

a. Format to be 70mm instead of 3" (≈ 76mm)
b. EFL range to be 4½" to 12" instead of 3" to 12"
c. Aperture to be f/2.8 instead of f/2.0
d. Overall length to be 18½" instead of 18"

Using these revised parameters, the prototypes were again reworked and this time a promising one appeared based on the "quality factors" being less than 14-16. (The quality factor is the square of the lens semi-aperture over its focal length and gives an indication of designability - anything over 16 being close to undesignable). At a meeting between WPAFB and Bausch and Lomb on 1/9/69, it was decided to pursue this prototype design through the optimization process based on findings to date.

Thick lens design of this prototype began in February 1968 with final optimization begun in April. With the lens now this close to realization, the mechanical design plan was initiated in April and the process of amassing the necessary interface data undertaken.

At this point, a progress review meeting was convened to evaluate the prospects of successful program completion. The two main items brought up were (1) that a very high level of confidence in the design existed and (2) that contract funds would run out sometime in July 1969. Bausch and Lomb was advised to continue working until remaining funds were exhausted and to submit a request for the additional funds required immediately as more funds would be difficult to get.

Bausch and Lomb complied by submitting a request on 5/15/69 for an additional $52,328 (total of $128,228) and continued work through July, at which point the optical design was complete except for tolerancing and the mechanical design was 25% completed.

2.2 First Contract Extension

In April 1970, Bausch and Lomb received authorization to proceed with the program under the contract which was now extended to cover $128,228 of effort as requested. Optical tolerancing began immediately and advance orders for glass were placed. The mechanical design concepts were reviewed for compatibility with optical tolerances and then designing recommenced.

By July 1970, optical tolerancing and mechanical design were completed and detailing began. Glass blanks were being received and the design rechecked using actual index and dispersion values. By September, the optical rechecking was completed and the design found to be in trouble due to out-of-tolerance values on those glasses at the extreme ends of the index range. Having little confidence that in-tolerance glass could be obtained, it was decided to modify the design to suit the glass in hand.

While it was felt that the design modification could be successfully accomplished, it would delay the program further and use up the funds allocated for the final assembly and testing of the unit. WPAFB agreed to entertain a request for an additional $22,815 and Bausch and Lomb would continue to work - on its own funds if necessary - to the point of assembling an imaging unit for review and evaluation.

This unit was assembled and reviewed by August 1971 and WPAFB agreed to authorize the additional funding, which authorization was received in November 1971. Although the entire $22,815 was expended in assembling the imaging unit, Bausch and Lomb agreed to complete assembly and testing using its own funds with no further expense to WPAFB. This assembly and testing was completed in December 1971 with the unit delivered to WPABF on 12/29/71. As tested at Bausch and Lomb, this unit met or exceeded the revised specification values as is shown in Appendix II of this report.

3.0 HARDWARE

3.1 Optical System Description

The optical system as developed is detailed in figure 3 which shows the lens data in terms of radii, diameter, thickness, spacings and glass types. The relationship between the optics and their mounts is shown in figure 4.

The lens is a mechanically compensated zoom system consisting of 13 elements separated into four groups - two fixed and two moving. As with most zoom lenses, the unit goes from telephoto at the long focal length position to inverse telephoto at the short focal position.

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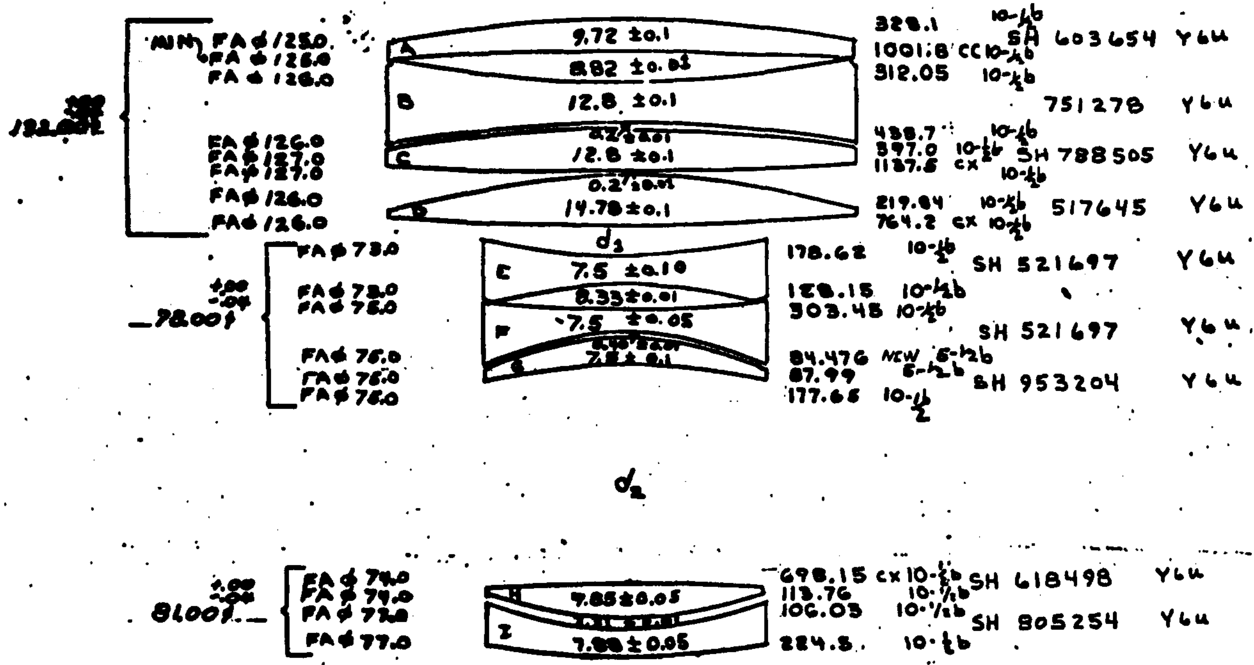
FIG 3 - OPTICAL DATA

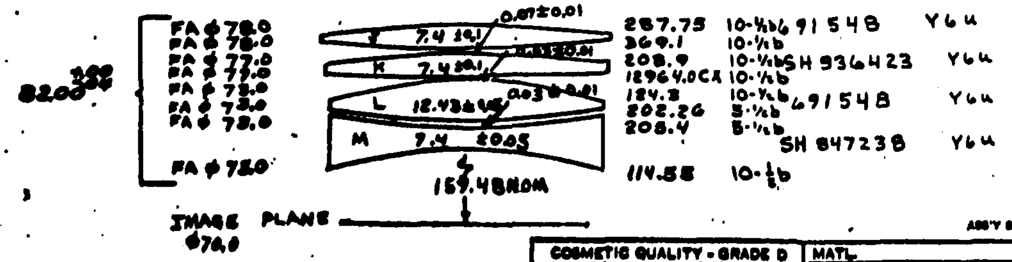
VARIABLE FOCAL LENGTH HIGH SPEED LENS

EF 4.5 INCHES TO 12 INCHES
f/2.4
BF - 6 INCHES



ZOOM SYSTEM TABLE (REF)			
EF	d_1	d_2	d_3
112.46	8.29	61.44	84.38
149.68	55.96	56.30	41.84
224.34	110.80	34.07	9.84
300.09	132.89	3.41	10.82

d_3



Ⓒ ALL SURFACES 5-6-1
COAT Ⓑ ALL SURFACES FOR MAXIMUM TRANSMISSION AT λ = 800 mμ

ASS'Y SHOWN ON

CHANGES		
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Y		
X		
W		
U		
T		
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R		
P		
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M		
L		
K		
H		
G		
F		
E	B.F., BF, EE DATA FILLED IN	PKJ 11-8-71
D	UP GRADED	DG 12-29-70
C	ADDED	JWS 10-7-70
B	ADDED Dwg # & LENGTHS	AJC 7-31-70
A	ADDED	JWS 5-12-70

DO NOT SCALE - WORK TO FIGURES
REPORT ERRORS - UNLESS OTHERWISE SPECIFIED TOLERANCES ARE AS NOTED

TYPE	FRAC.	DEC.	ANG.
MACHINED			
CAST-MOLDED			

THREADS—UNIFIED CL-2A OR 2B
DR'D HOLE & B&L STANDARDS

BAUSCH & LOMB INCORPORATED
ROCHESTER, N. Y., U. S. A.

MATERIALS REVIEW

APPROVALS	DEPT. HEAD
APPROVED FOR PROTOTYPE MANUFACTURING	
APPROVED FOR PRE-AUTHORIZATION TOOLING AND PARTS	
AUTHORIZED FOR PRODUCTION	

COSMETIC QUALITY - GRADE D UNLESS OTHERWISE SPECIFIED

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FINISH

UNIT
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APPD.
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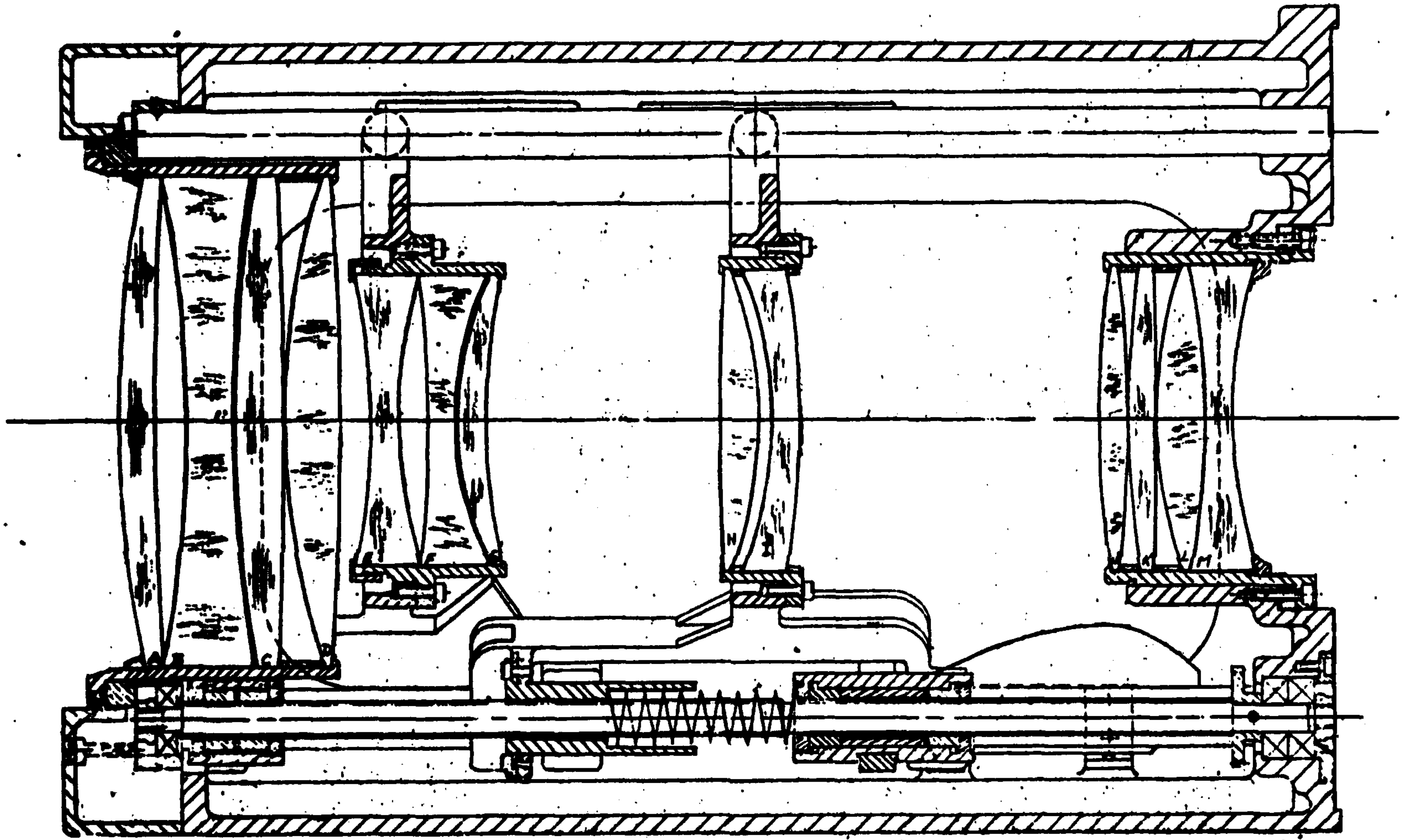


FIGURE 4. VFLHSL

GENERAL ARRANGEMENT

(Shown in 4½" EFL Position)

The range of correction for the lens-being in the 700 to 500mm range - requires glasses at extreme ends of the dispersion range. The 18½" TCL for a 12" EFL zoom lens is very short in that most designs would require on the order of 24" TCL. This is especially notable in that the lens features a large back focus in order to meet the high voltage clearance requirements. The fronting lens consists of four elements approximately five inches in diameter and having an overall EFL of 351mm. The first zooming lens is a negative lens group consisting of three elements about three inches in diameter and has an EFL of (-) 104mm. This group zooms from a position approximately eight mm from the fronting lens (at the 4½" EFL setting) to about 140mm at the 12" EFL setting.

The second moving group has two elements and a focal length of 416mm. This group moves to within about five mm of the backing lens at approximately the 10" EFL setting and then comes forward to a distance of about 11mm at the 12" EFL position. At this 12" setting, the two zooming elements come within three mm of each other. The backing lens is a four element group also about three inches in diameter and had a focal length (EFL) of 142mm. The pupil of the overall lens is not fixed at any one spot but at different EFL positions is defined by various lens mounts. This allows the lens to operate throughout to range with a constant f/#.

The distortion of the lens is seen to vary from 3% to 8% (barrel) and was selected to best off-set the 5% pin cushion distortion in the image intensifier. The lens is designed for maximum contrast at a resolution of 50 cycles per millimeter.

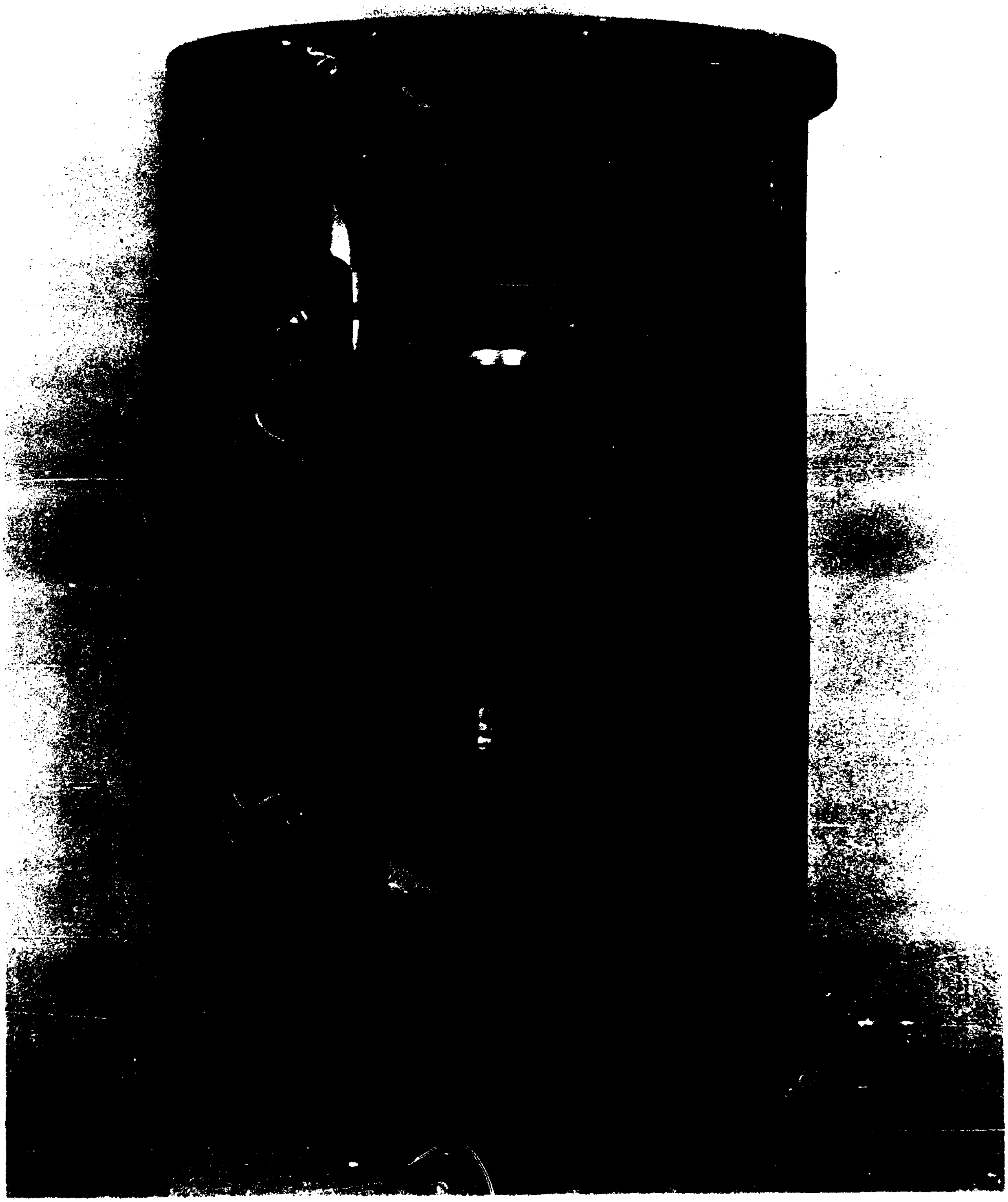
3.2 Mechanical Description

The lens assembly is shown in Figure 4 and photographs of the assembled unit in figure 5, 6, & 7. The main body of the lens assembly is a unitized aluminum casting which directly supports the fixed fronting and backing lens components as well as providing mounting points for the zoom actuating mechanism for the moving elements. Integral with the casting is a simple flange interface for attaching the lens to the rest of the system. The moving lens components are supported in cells which are carried on a ½-inch stainless steel precision shaft and steadied by pads which ride on a similar shaft diametrically across the lens. These component cells are driven by a multiple-lead precision lead screw and compensating cam mechanism. The motor driven lead screw drives the front zoom component directly through a pre-loaded nut and this imparts an essentially linear change of position with time. The lead screw also drives another pre-loaded nut which is connected to the rear zoom component through a compensating cam mechanism which imparts the necessary non-linear motion.

The drive motor is a DC - operated reversible gear motor which is coupled to the lead screw with gear and pinion. The motor drives the lead screw at approximately 600 RPM for a zoom range coverage in 3½ seconds. Travel is defined by limit switches at each end of the range (4½" EFL and 12" EFL) and is remotely controlled through a spring-loaded multipole switch. Details of the electrical connections are shown in Figure 8.

3.3 Assembly

The first step in assembly of the VFLESL is mounting of the elements into the individual cells. Each group of lenses is contained in its own precision cell which is in turn mounted either into the body casting or the moving carrier. Each cell is mounted on a lathe and bored to precisely fit the element to be installed Since one lathe set-up is used, the all diameters are completely concentric. As the lenses are fitted to the cells, each spacer is machined to give



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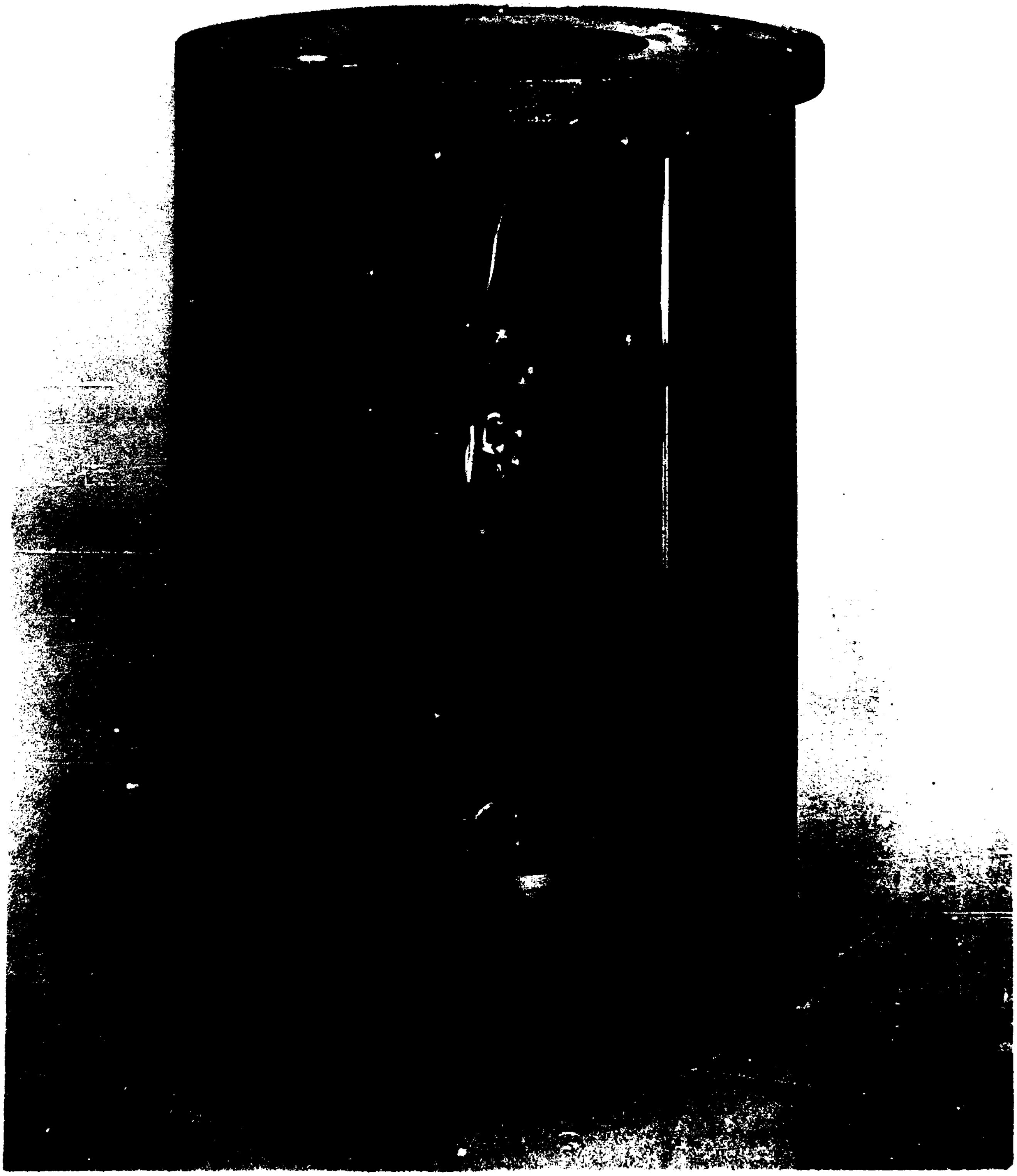

FIGURE 6

Variable Focal Length High Speed Lens
Internal View (Upper Right)

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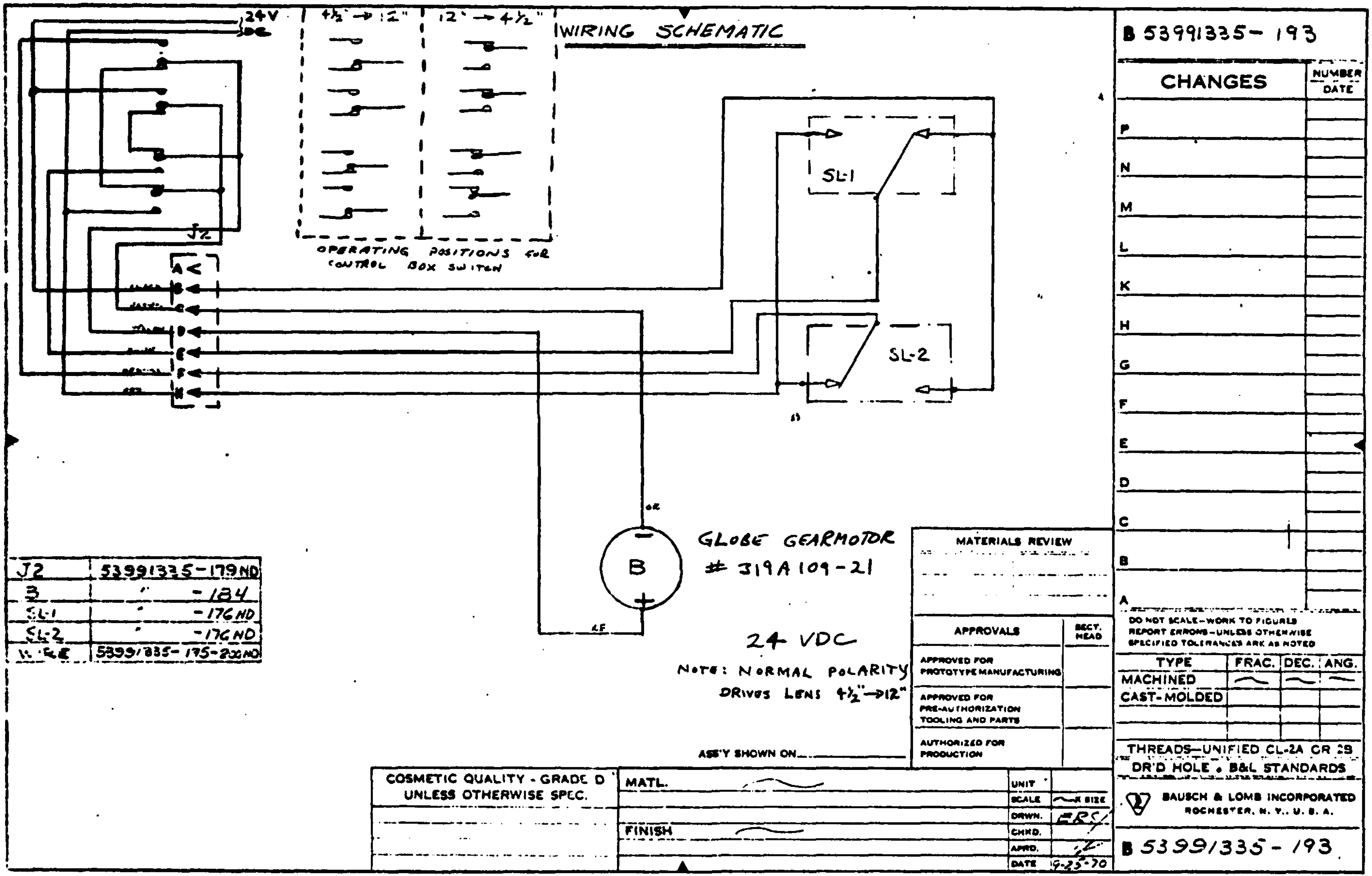


FIGURE 8 Wiring Schematic

the precise space required by the design. The cells are then mounted on an optical bench (infinity bench) and checked for such characteristics as tip and decentration and the focal length is measured. If necessary, the individual elements are oriented with respect to each other for the best possible star image.

Simultaneously, the mechanical assembly has been carried to the point of introducing the cells. Using alignment tools, the moving carriers are centered to the bores for the fronting and backing lens cells in the casting. Working with a surface plate and height gage, the relative position of the pre-loaded nuts on the lead screw is set to agree with the optical design requirements. This setting is approximate or nominal and requires touch-up as detailed below.

At this point, the lens assembly is mounted on the fixture which is aligned to the 147.5" EFL collimator. This set-up is shown in figure 9 . An alignment telescope is centered to the lens cell bores and aligned to the collimator. This telescope is used to assure the alignment of the fixture to the collimator through auto collimation off the lens assembly mounting surface.

With the rear cell bore centered to the telescope axis and squared to the collimator axis, the front cell bore is adjusted for centration and squareness as are then the moving cell carriers. As the cells are introduced starting from the front, squareness is checked by auto collimation and the cells shimmed as required. When the cells are in place, the microscope is used to examine the star image and cell rotation or orientation accomplished or required for the best possible image.

The final step is to touch-up the compensating cam to cause the image plane to remain in one position. The cam is adjustable in tip and position and can generally be worked into the necessary position without dressing the cam surface itself. The method used to bring the cam into position was to zoom to each of the four EFL's (4.5", 6", 9", and 12") and find the position of best focus on a ground glass of an imaged resolution target. From a focal plane runout or position curve, the appropriate adjustment can be judged and then rechecked. In this case, about 15 curves were evaluated before enough "feel" for the proper adjustment motions was achieved to bring it into position.

Once visual observation of the image on ground glass and aerial indicated the proper alignment was achieved, the results were checked photographically using film responsive to the 700-900m range.

3.4 Problems (in Assembly)

A completely "perfect" star was not achievable in that some astigmatic flare was seen. This defect was located entirely in the rear group but does not seem to have introduced systematic astigmatism in the image. Also some "hysterisis" was noted in the zoom mechanism in the corrector cam area. Whereas the lens zooms "flat" in the 12" EFL to 4½" EFL direction, upon reversal the 5" - 6" EFL position goes slightly out of focus. By 7" EFL in this direction, the focal plane returns to nominal position and remains there throughout the rest of the range. The reason for this is known and a modest design change can eliminate it entirely. However, delivery considerations decreed that it not be done on this unit.

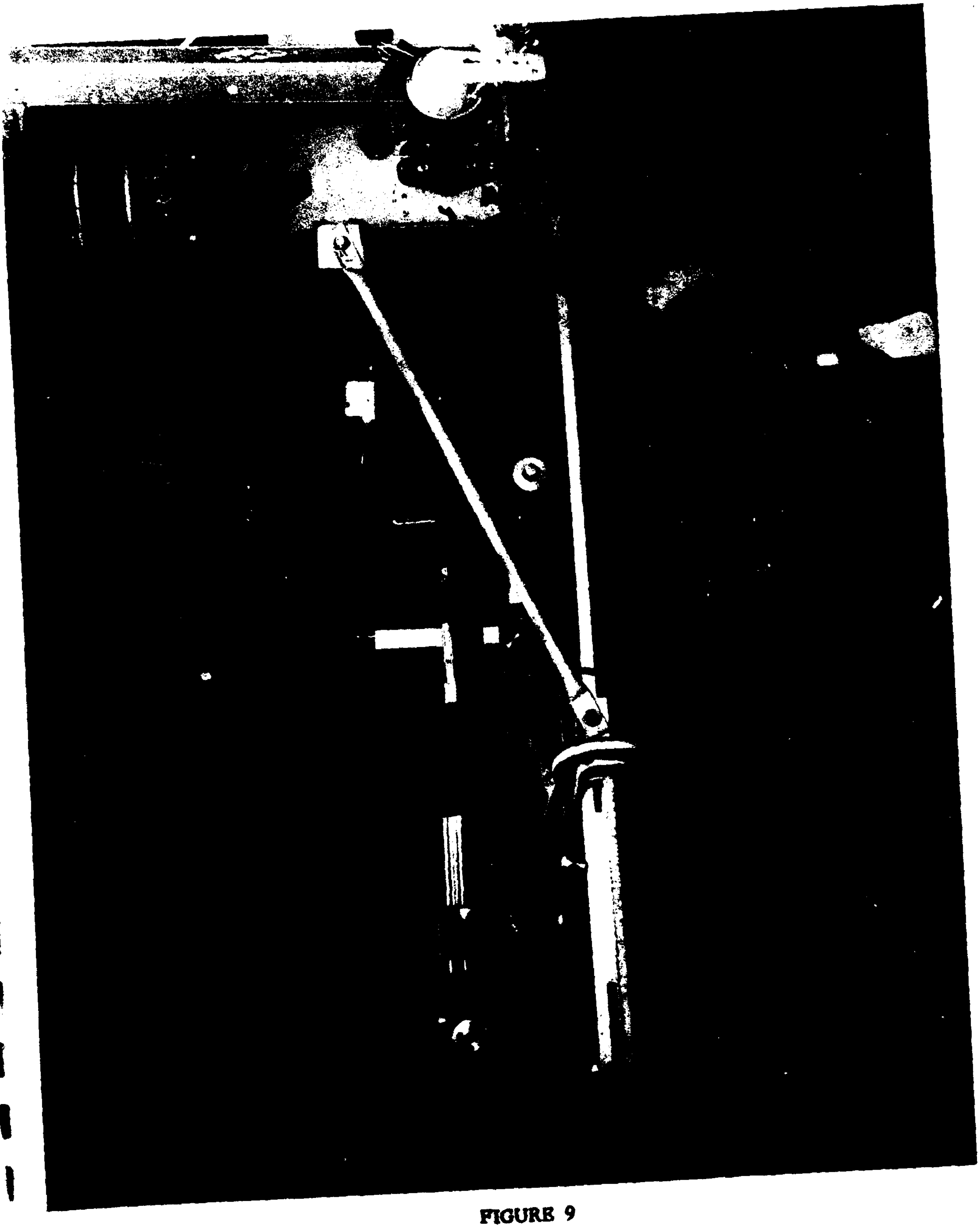


FIGURE 9

Alignment Set-Up

For mechanical reasons, the unit as delivered will not cover the 4½" to 12" EFL range, This is primarily due to physical interferences related to the finalized cam position. In some positions of the cam, the range was seen to exceed the required range in that it would zoom from 4¼" EFL to 12½" EFL. However, at the position of the cam where the focal plane stabilized, the range was offset and seen to run from 4¼" EFL to 11 3/4" EFL. Therefore, the lens is seen to be able to cover the range optically with only some minor redesign necessary to achieve it in practice.

3.5 To Use

The lens assembly is very simple to use. It is attached to the interfacing equipment in such a manner as to be parallel to and the specified distance from the sensor surface. Zoom control is excerised through the control box which is supplied with 110 VAC. An indicator on the body of the lens gives an approximate EFL readout. While a bench model only, the unit is constructed along the lines of a flight model and is not overly fragile.

The zoom drive can be plugged into a control system other than the box supplied but extreme caution is advised in observing that only the proper voltages are supplied and that the limit switches are hooked up to the control switch properly. If this latter is not done, the lens will drive past the stops and jam, thereby creating the chance that zoom alignment will be lost and realignment necessitated. Overdriving the stops will not cause physical damage, however, and any subsequent models of this lens will be designed such that zoom alignment would not be compromised.

3.6 Performance

The test procedure submitted by Bausch and Lomb and approved by WPAFB is attached to this report as Appendix III . The data recorded by Bausch and Lomb has been entered.

The methods outlined in the procedure were generally followed. In the case of the Relative Illumination, it was not possible to measure this quantity on the RI Analyzer as originally planned. The reason for this is that the exit lens of the Analyzer for the illumination is not large enough to allow that large a lens to be rotated through the necessary angle without vignetting. At the 4½ EFL, the maximum possible angle was about 9° or 10° and at the 12" EFL, this reduced to about 2° off axis. The RI could be measured by photographing a clear blue sky with the lens and reading the film density with a microdensitometer; however, no such conditions were experienced during the period the completed lens was available.

The performance figures are summarized below:

a) Effective Focal Length Range	4½" to 11 3/4"
b) Average Resolution (AWAR) on film	42 l/mm
c) Aperture (f/#) Range	2.29 - 2.56
d) Back focus (in air)	7.154"
e) Flange Focus (in air)	5.004"
f) Image Size (AWAR)	70mm

g) Image Size (maximum)	100mm (approx)
h) Overall Length	18.411"
i) Weight	24½ lbs.
j) Zoom coverage speed	3½ sec
k) Distortion	3%-8% (barrel)

Details of the photographic testing are contained in Appendix C.

Section 4.0 FUTURE CONSIDERATIONS

The lens design effort just executed pushed the state of the art rather severely but was successful in producing a lens that performed as expected. The result was a high quality optical system that shows great promise. In the event that production of such a unit is under consideration, the following observations are in order.

Optically, the lens is produceable but would probably not lend itself to any quantity production techniques. Each unit would be handled individually. In a lens of this calibre and quality, it is considered standard practice to tune up the design to match index and dispersion values of glass as received and-as seen during the prototype effort - is especially true in this case due to the nature of the glass used in some elements. While the work done on this lens indicates that it will be a more involved "tuning up" than most, it certainly is within reason. In any case, it is one effort per production lot and this should be taken into account.

Mechanically, the unit as designed is straight forward - if extremely precise - and certainly presents no particular production or assembly problems. The learning curve on this is a consideration but once past that, assembly is not difficult. The design itself is accomplished along the lines of a flight model and would only require minor redesign, environmental sealing and verification to be fully qualified.

Appendix I

Zoom Lens Design

Computer Programs

ZOOM LENS PROGRAMS

The Automatic Zoom Lens Program to establish, in detail, the first order parameters of a zoom lens has been designed to be used in conjunction with a Matrix program described earlier. The starting data is altered a little each cycle obtaining an improvement in each of the defined aberrations of the first order. These include lens positions, lens spacings, pupil positions, sums of lens powers and quality factors related to higher order aberrations. There are 25 different aberrations that can be controlled at 5 positions in the zooming range by a total of 12 variables. If all of these were in use at one time there would be 1500 matrix elements augmented by an additional 125 target values. Each matrix element is a finite derivative for one variable and one aberration at one zoom position, and the total matrix must be solved simultaneously. The solution is then fed back into the Zoom program for another cycle or until selected target values for selected aberrations are obtained. Here, through the use of unique "quality factors" that indicate the degree of difficulty of final correction, is the place to avoid future problems with higher order aberrations. At large stages, these higher order problems become extremely difficult to solve.

Other first order zoom lens programs permit precise determination of lens motions throughout the zoom range to determine if any mechanical interference problems exist and to assure that the focal length change is smooth and continuous. These other programs also permit a rapid roughing out of the first order prototype and can be used to determine the dependence and sensitivity of the lens motions to minor errors in zoom component focal lengths.

BETA GAMMA PROGRAM

The thin lens first order solution described in the previous section provides input lens parameters which the Beta Gamma program uses to distribute third order aberrations in the most efficient way. This distribution of aberrations in analyzed simultaneously throughout the zoom range.

The data show whether or not the lens elements are physically makeable and whether or not the aberrations will be acceptable. While this information is generated for thin lenses it nevertheless has proven to be indispensable for indicating what changes may be required in the first order solution to avoid an unacceptable buildup of aberrations. Consequently, early in the lens design, trouble areas can be evaluated and remedial action undertaken. Most of the design effort centers around these first programs. This emphasis on the initial steps assures that the following phases are straightforward.

ZOOM STEP FATHER PROGRAM

The thin lens design, resulting from the Beta Gamma program, must next be made physically realizable by adding thickness to the components. The Father program will automatically alter radii, thicknesses and separations to meet target aberrations set by the previous programs. Thus, using this program, the final thick lens form can be designed to have essentially the same aberrations as the thin lens solution. The program treats the zoom lens as a whole, correcting aberration at up to five zoom positions simultaneously. Third and fifth order aberrations, general skew ray errors, as well as physical parameters and principal ray angles may be corrected. First order parameters of the system may or may not be maintained automatically at the discretion of the designer.

RAY ANALYSIS AND MODULATION TRANSFER FUNCTION

Once the aberrations are brought into acceptable ranges, the final touching up of the lens system is accomplished on the Ray Analysis Program.

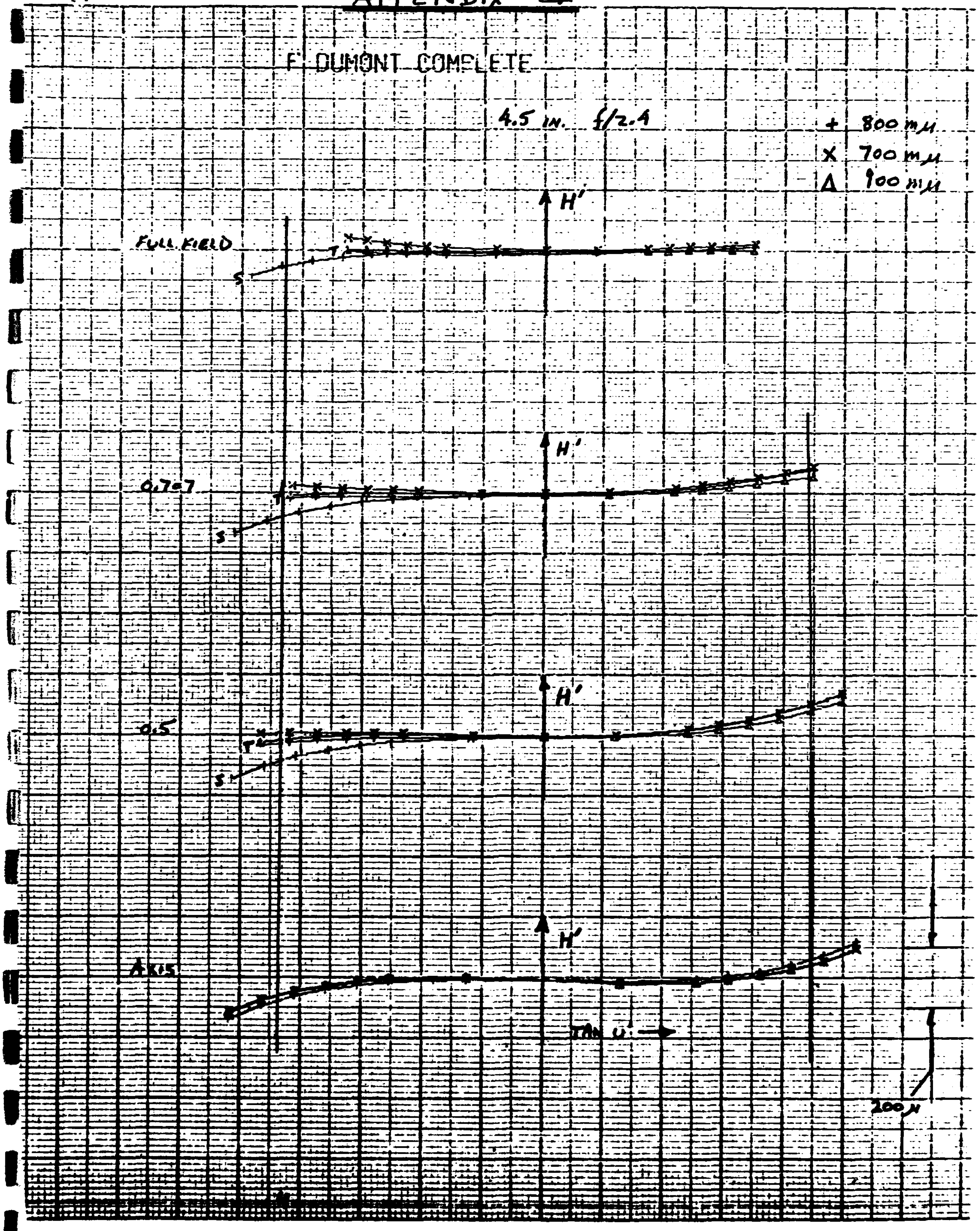
The standard aberration curves are generated for four field angles at each focal length desired in the zoom range. This analysis shows any discrepancy (resulting from higher order aberration terms) between actual performance and performance predicted from third and fifth order aberration theory. Any discrepancy is corrected by returning to the Father program and solving for new third and fifth order aberrations that compensate the higher order errors. Working back and forth between the Father and Analysis program the desired aberration curves are obtained. Final evaluation and prediction of performance is accomplished using a program that computes the modulation transfer function.

Appendix II

Lens Design Data

1. H' /Tan U' Curves
2. MTF Curves

APPENDIX II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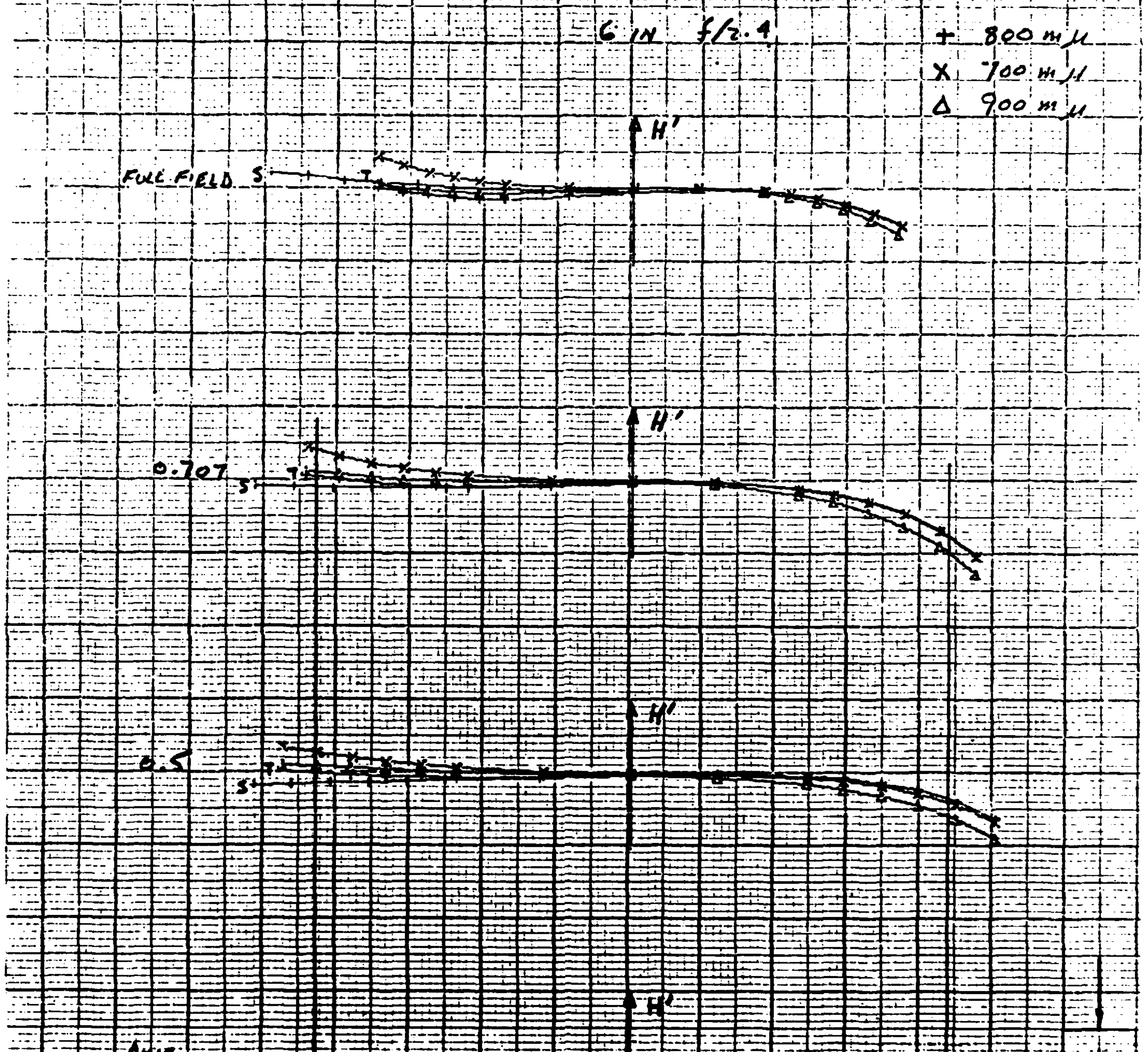
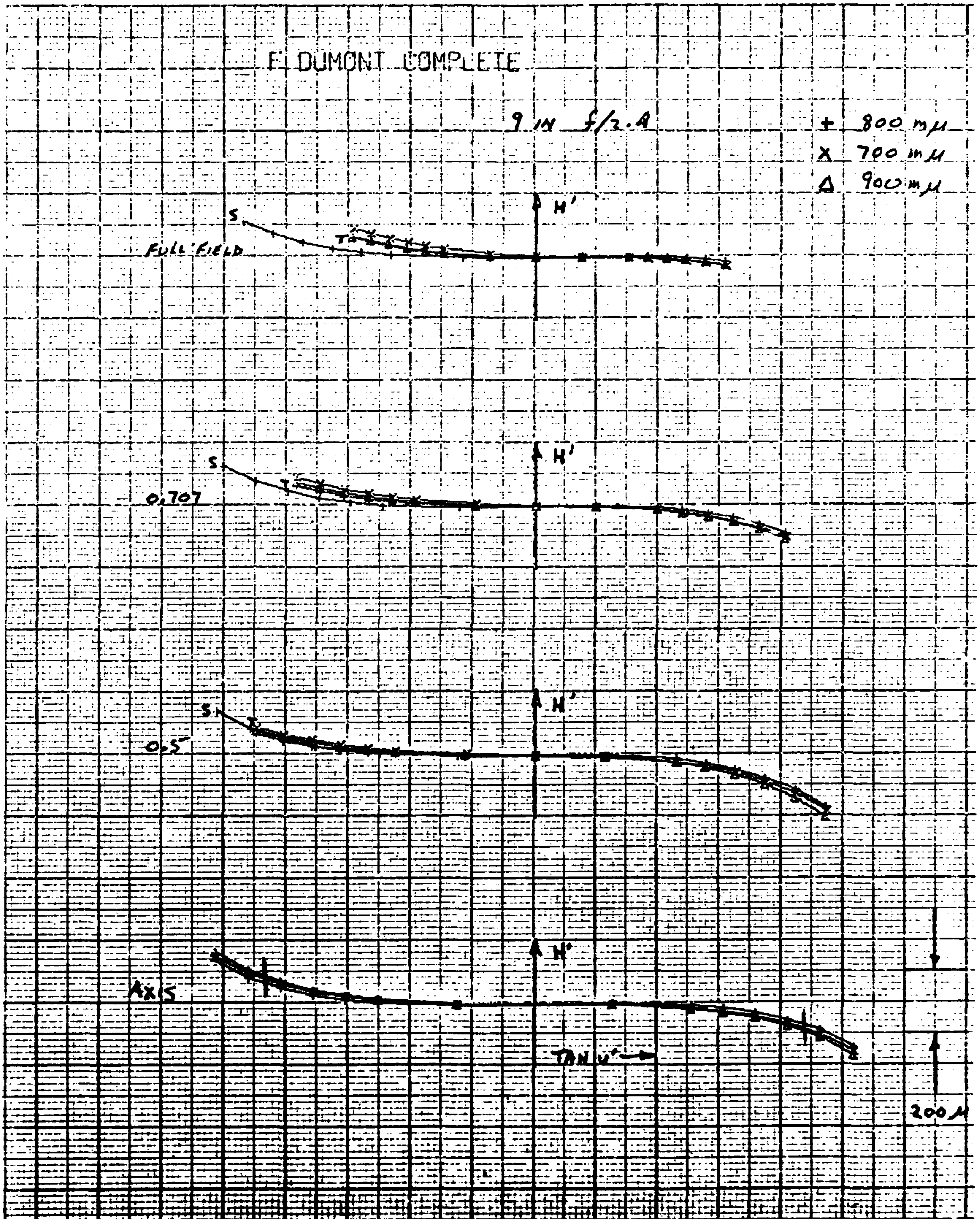
F' DUMONT COMPLETE

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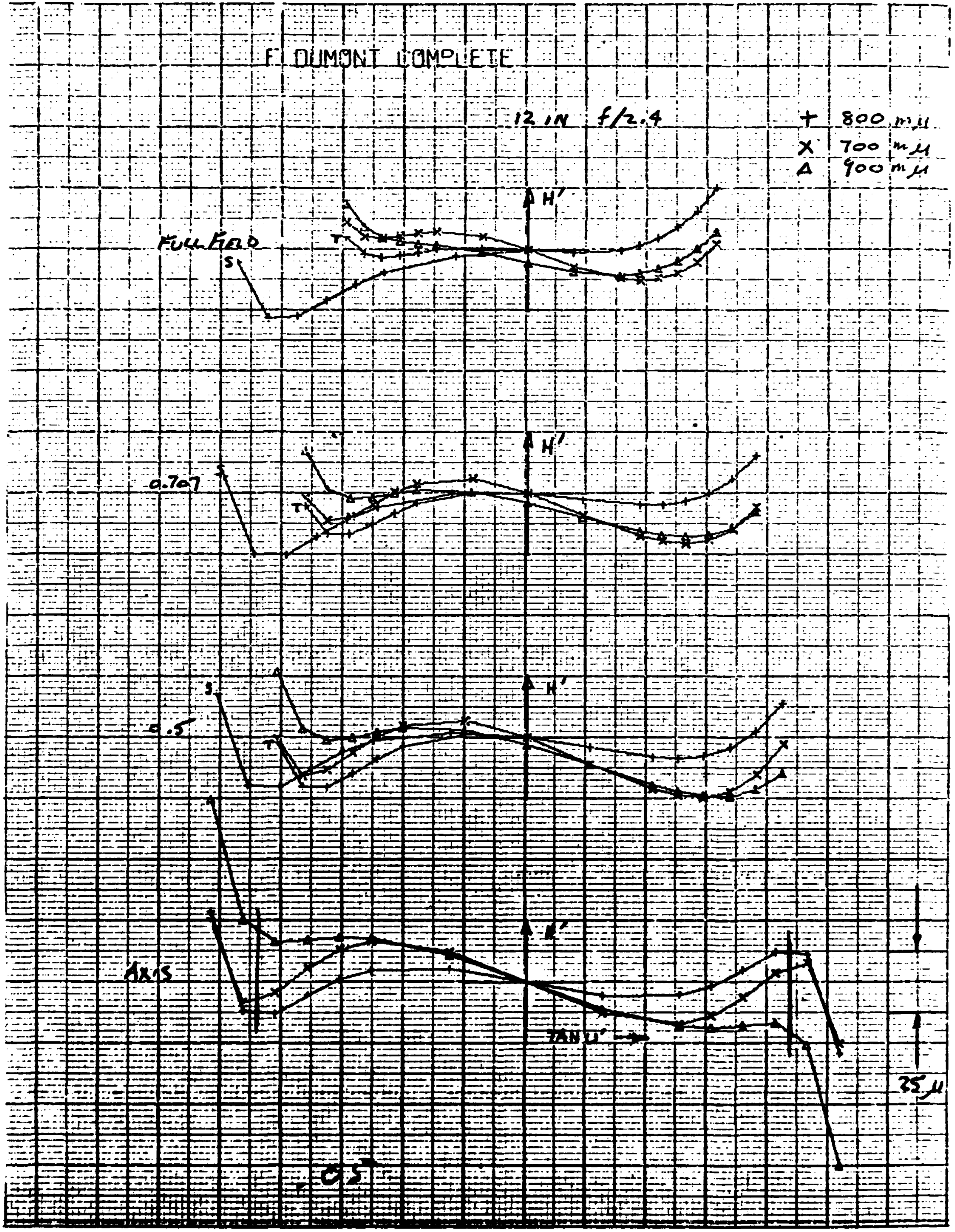
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Δ 900 mμ
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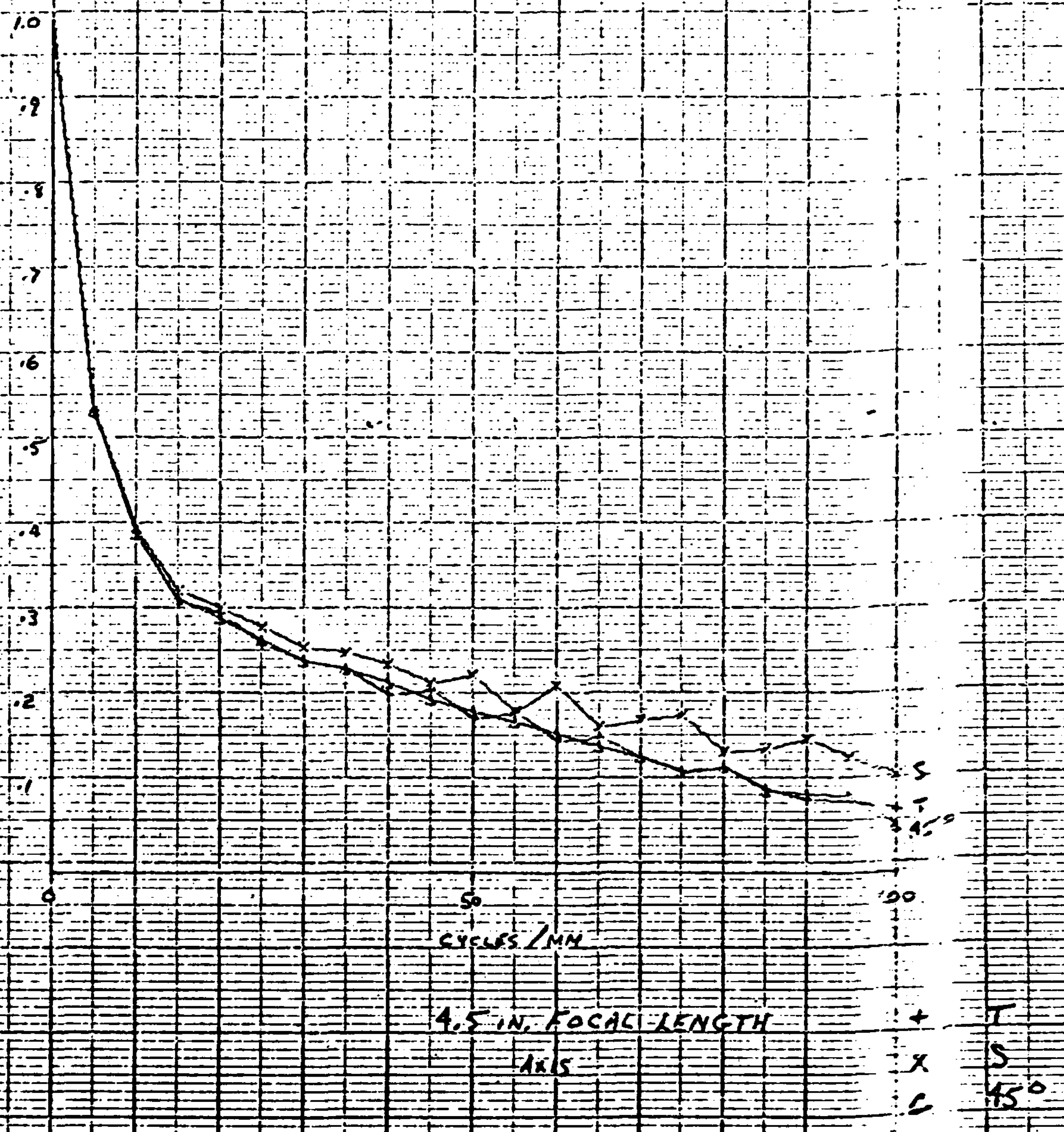
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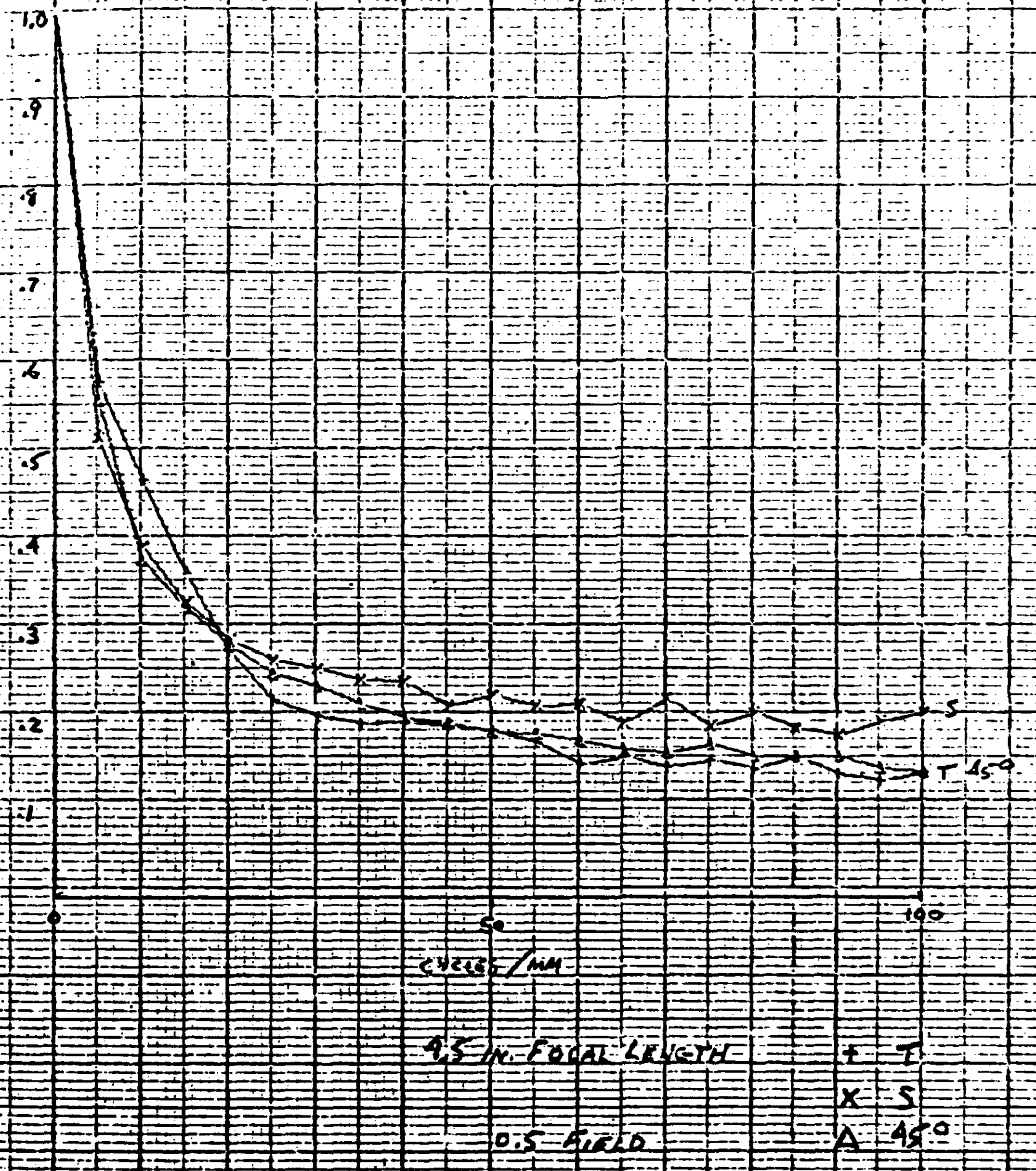

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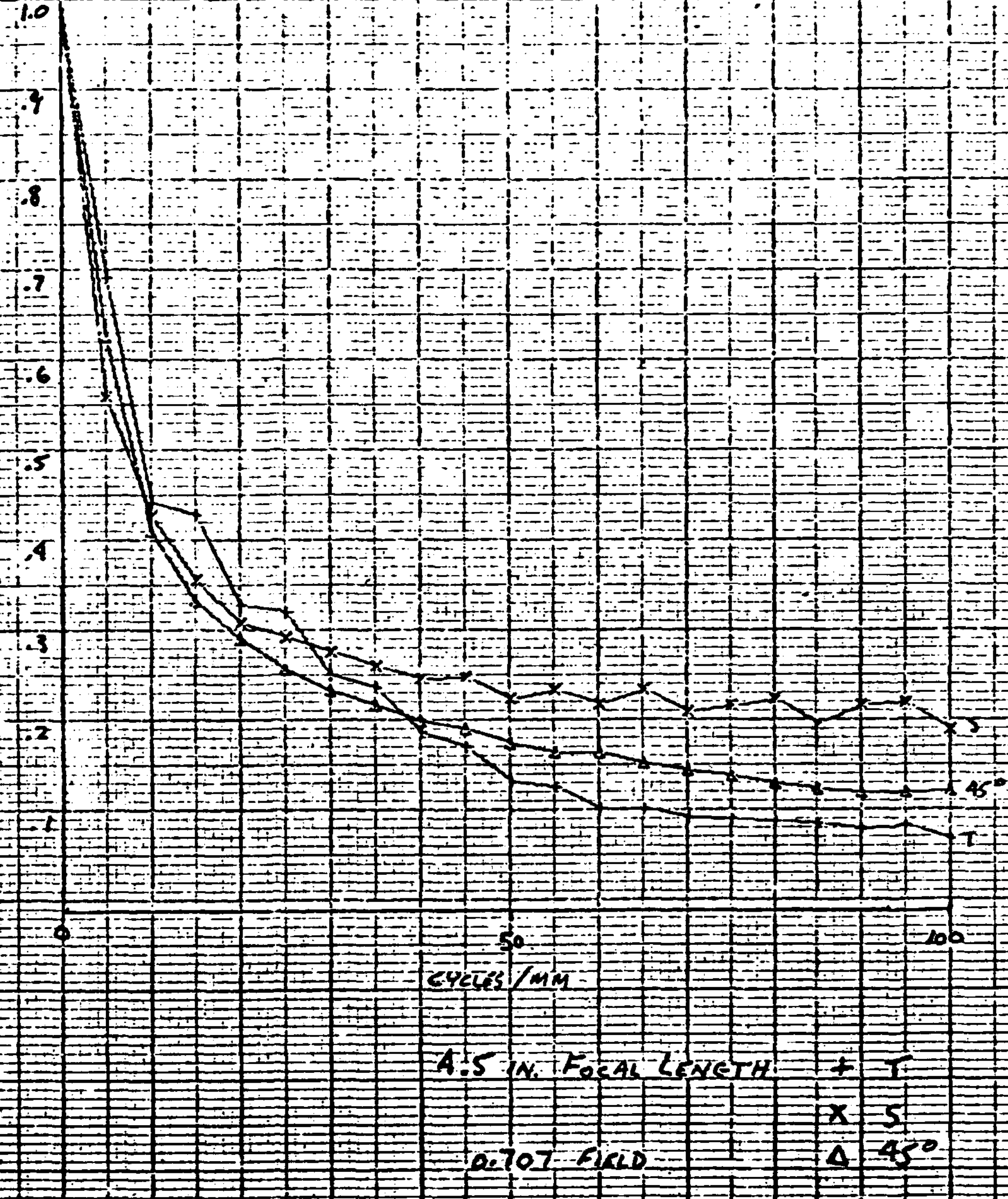
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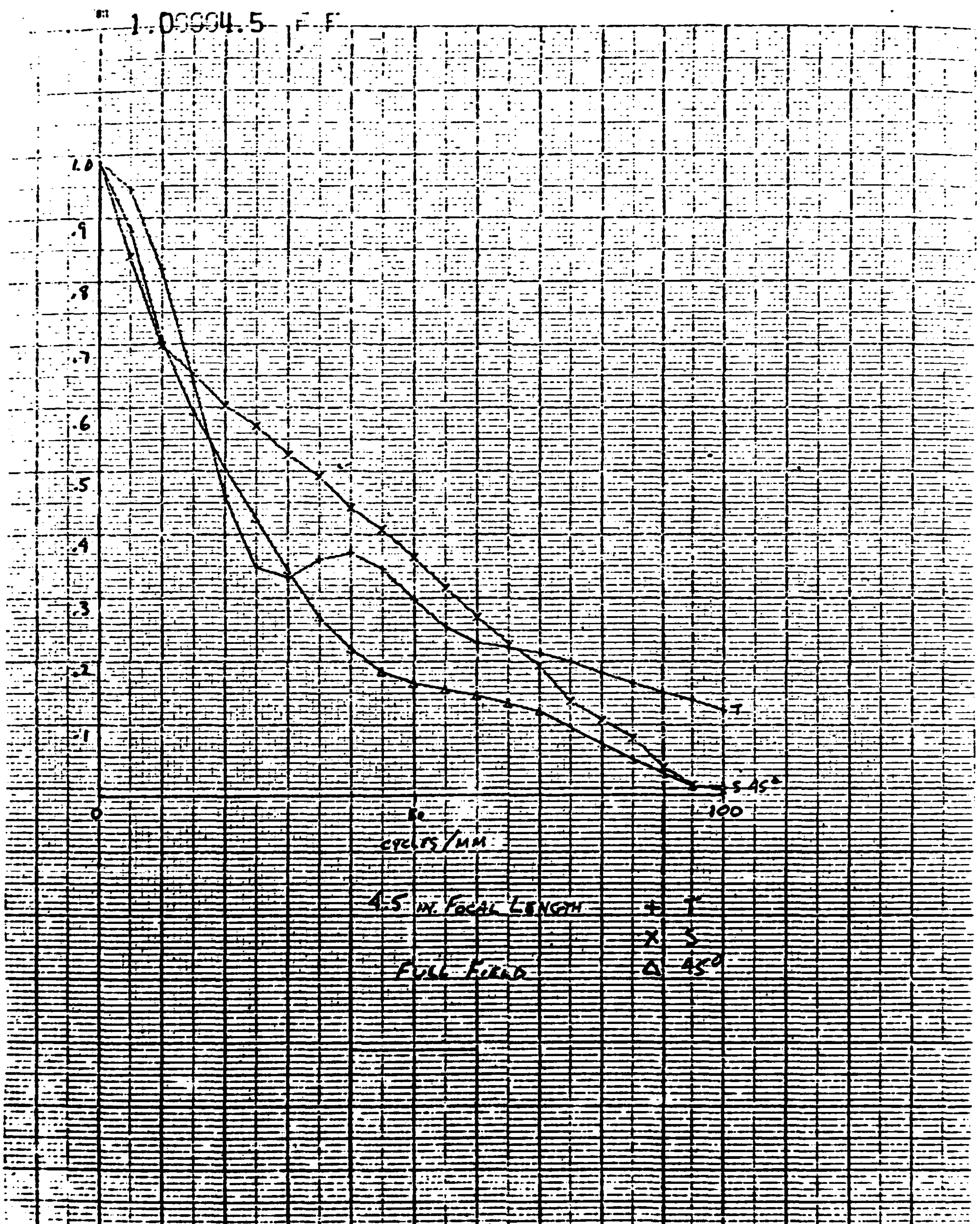
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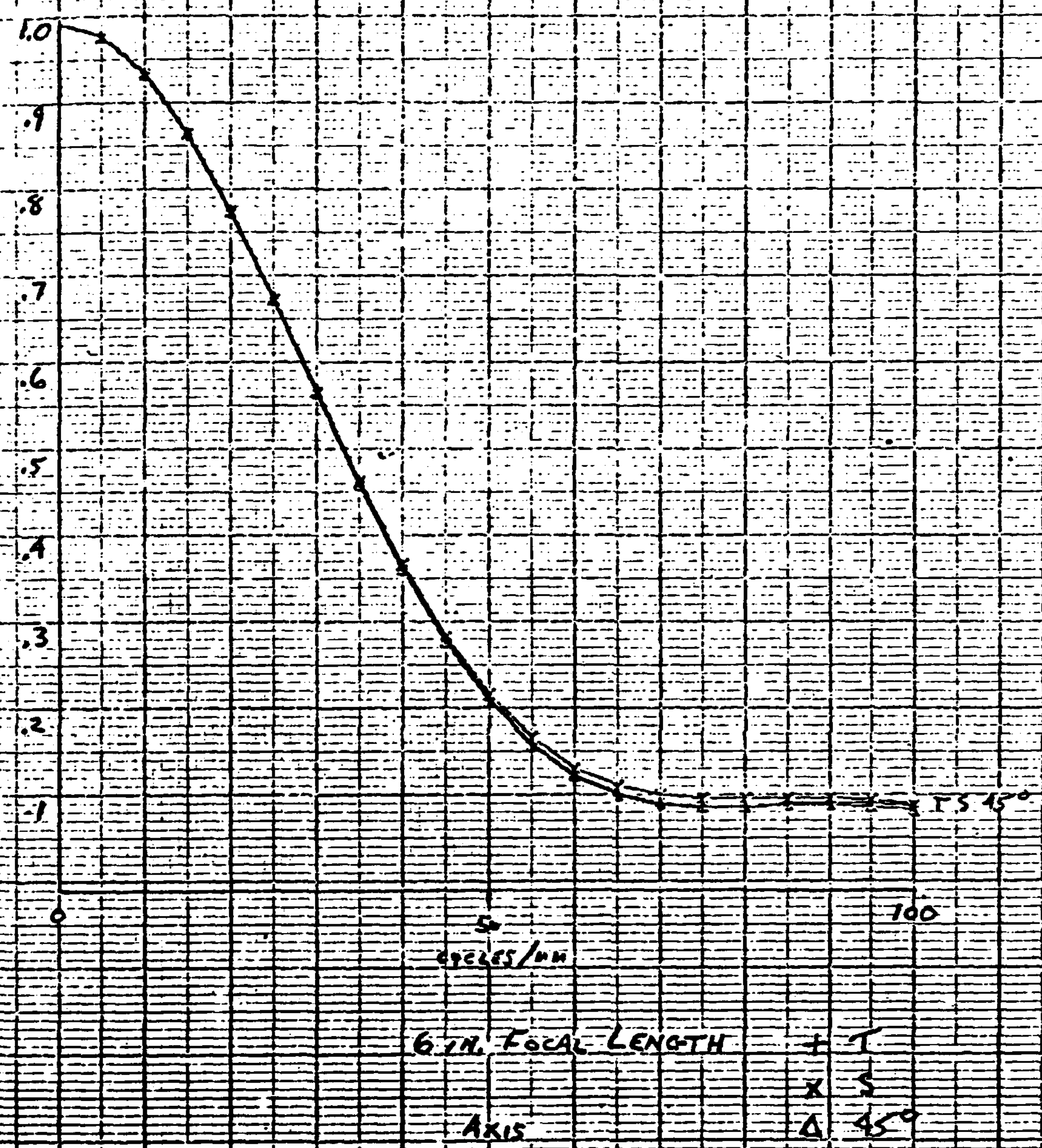
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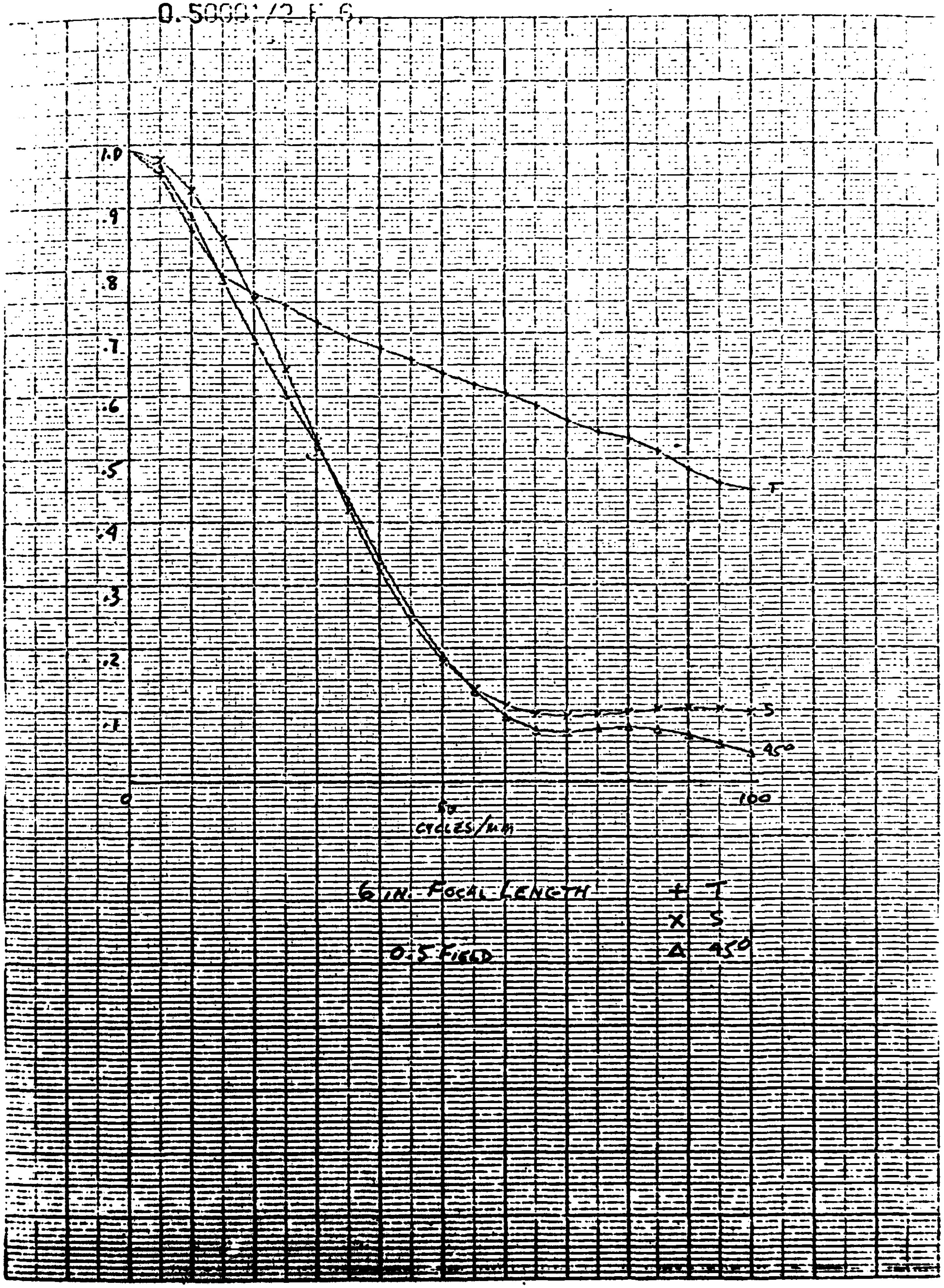

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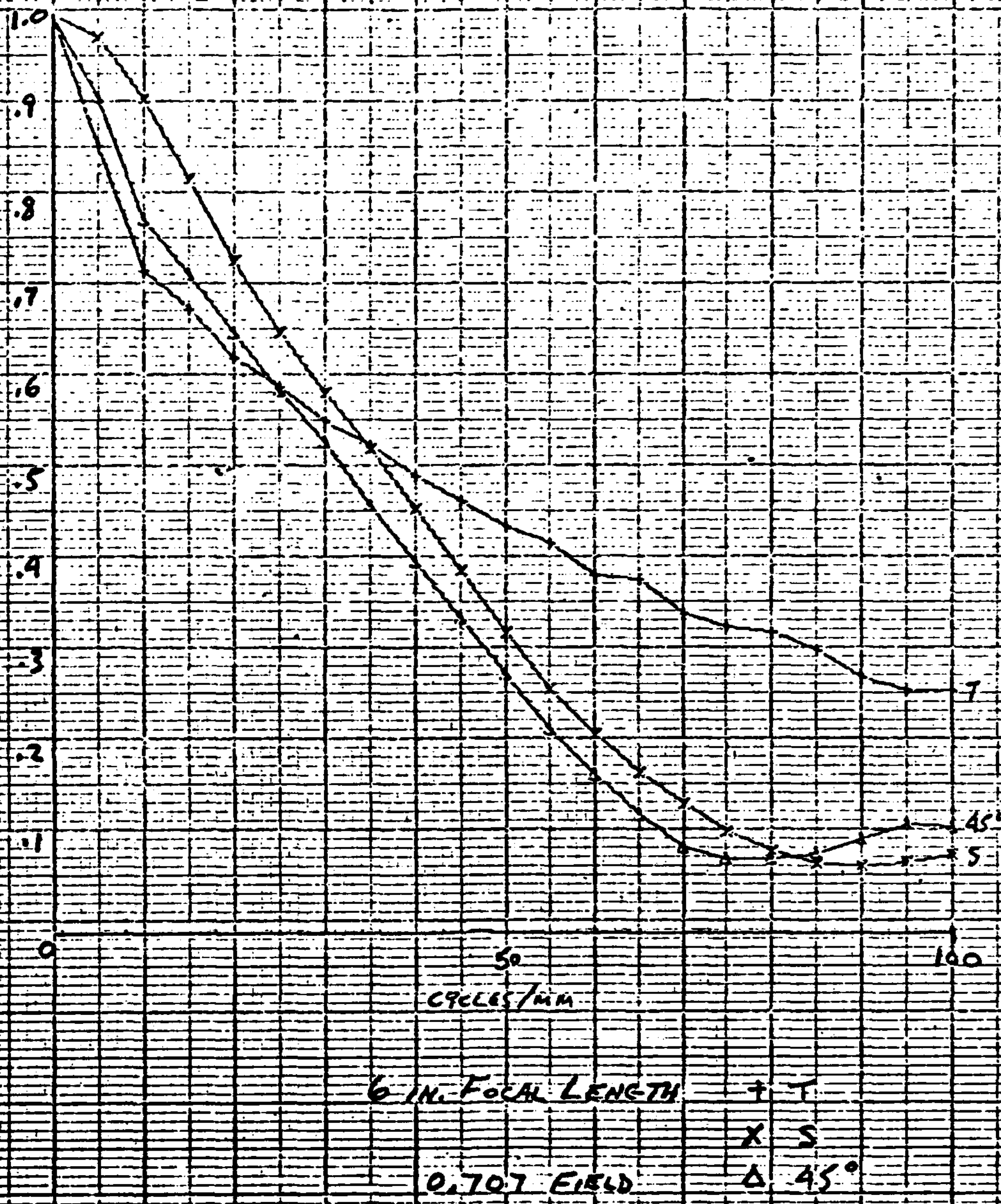

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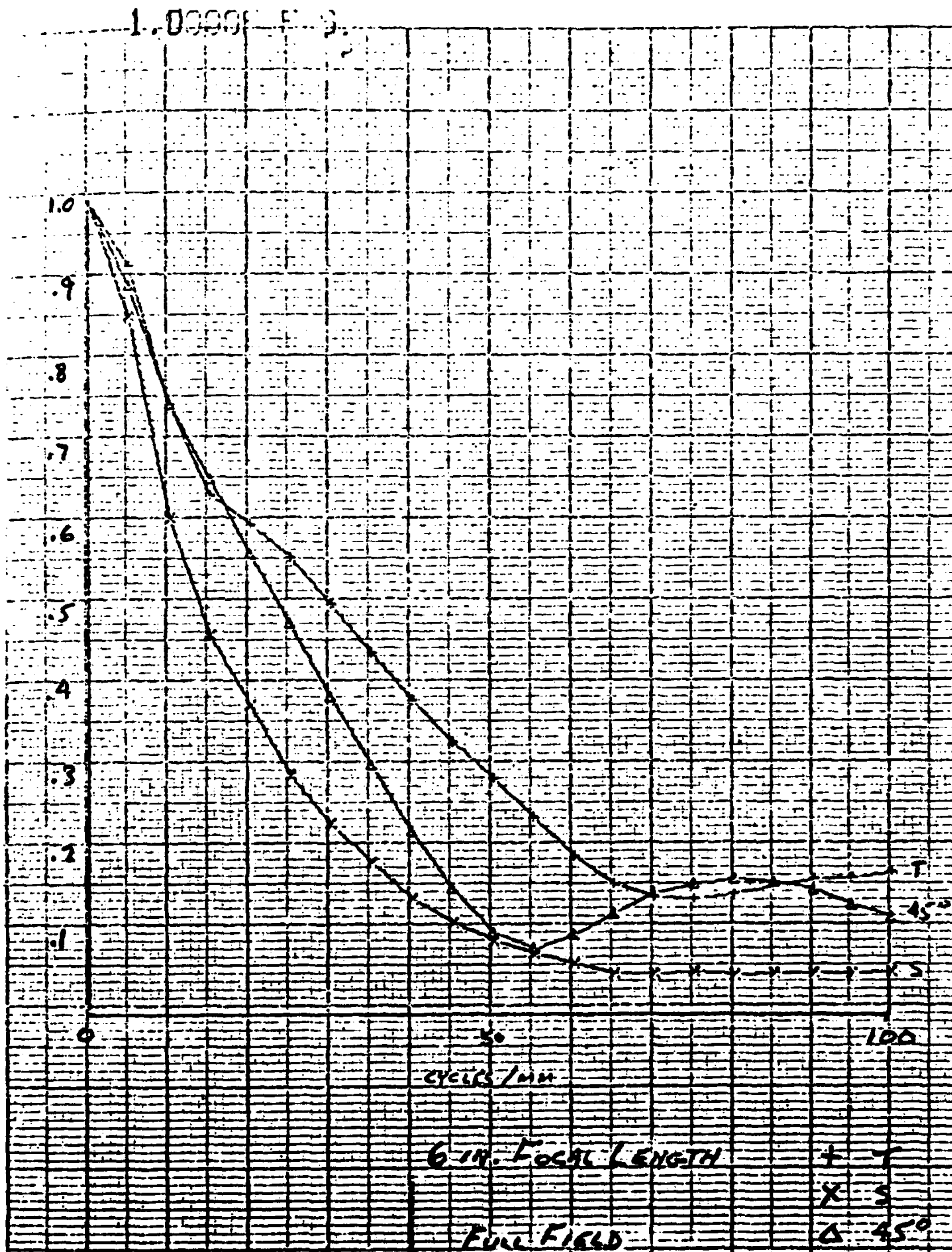
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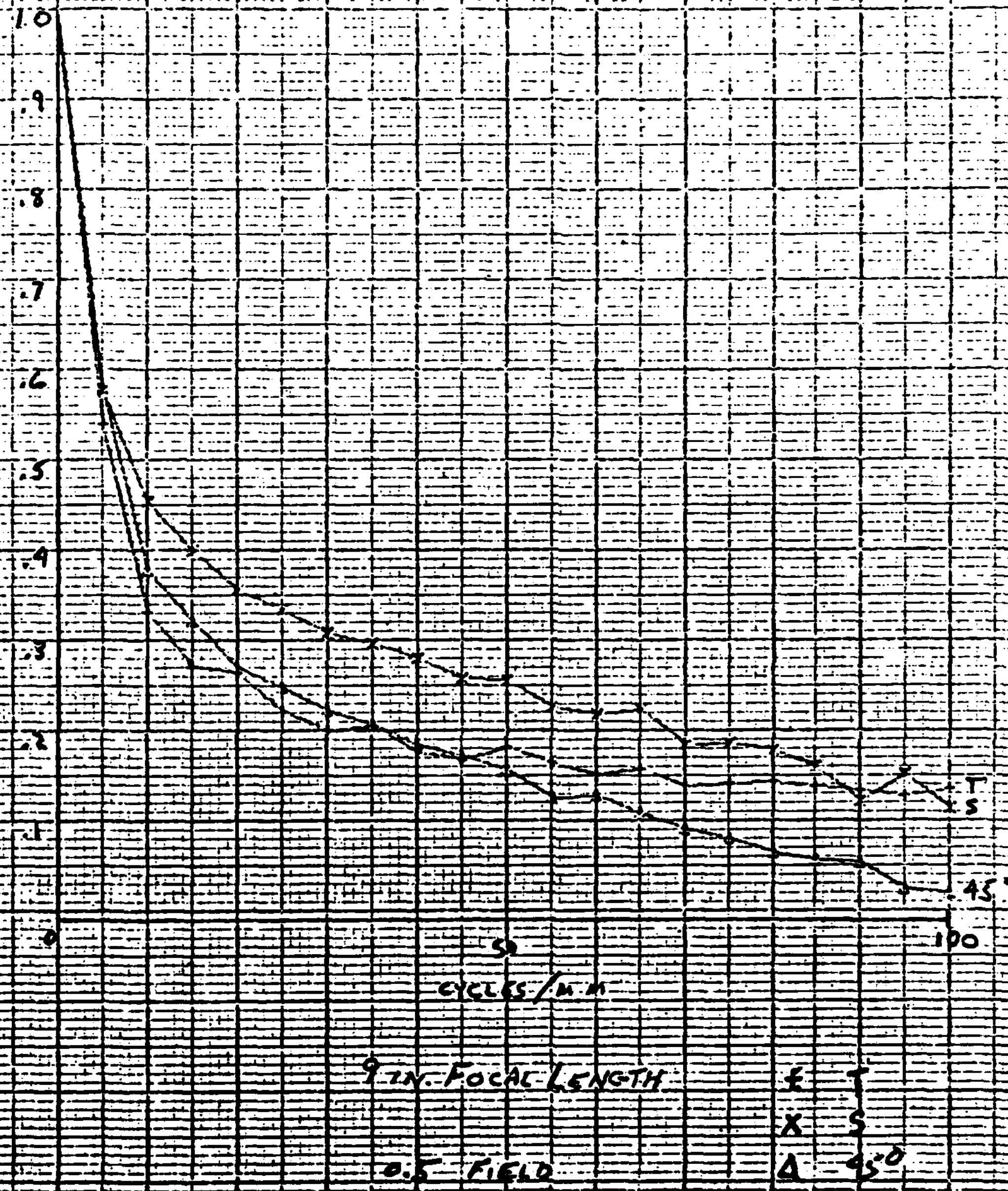
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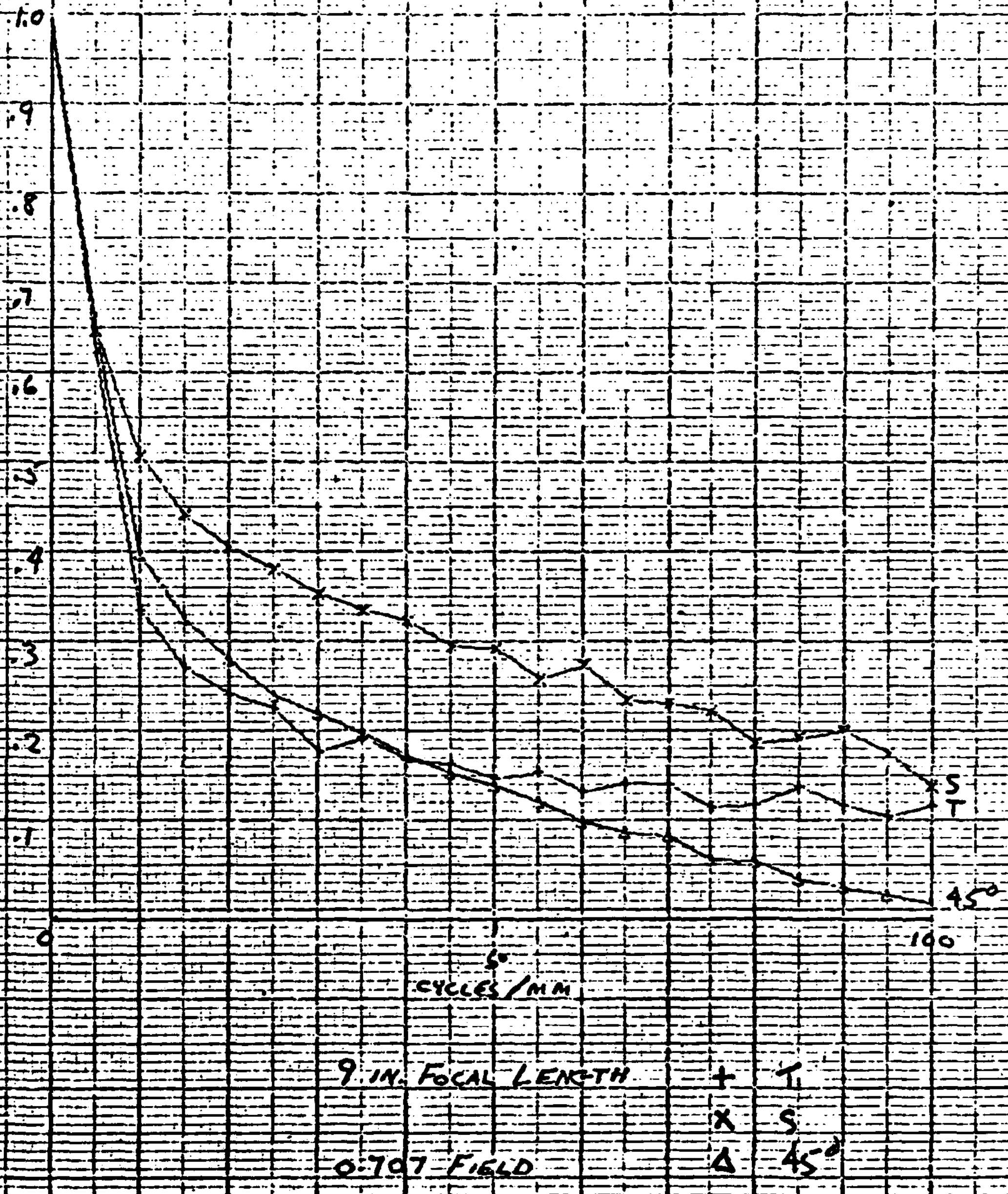

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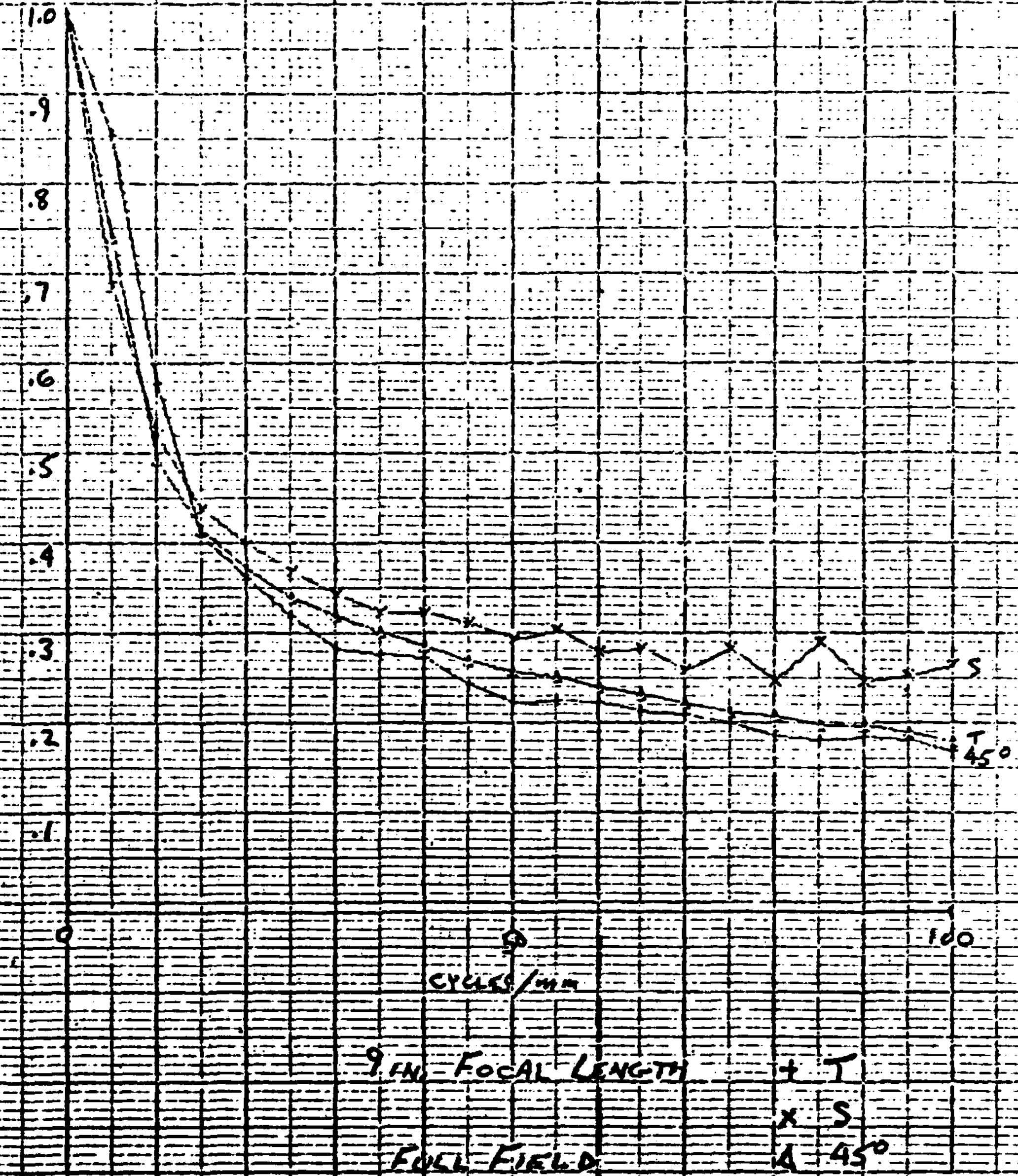
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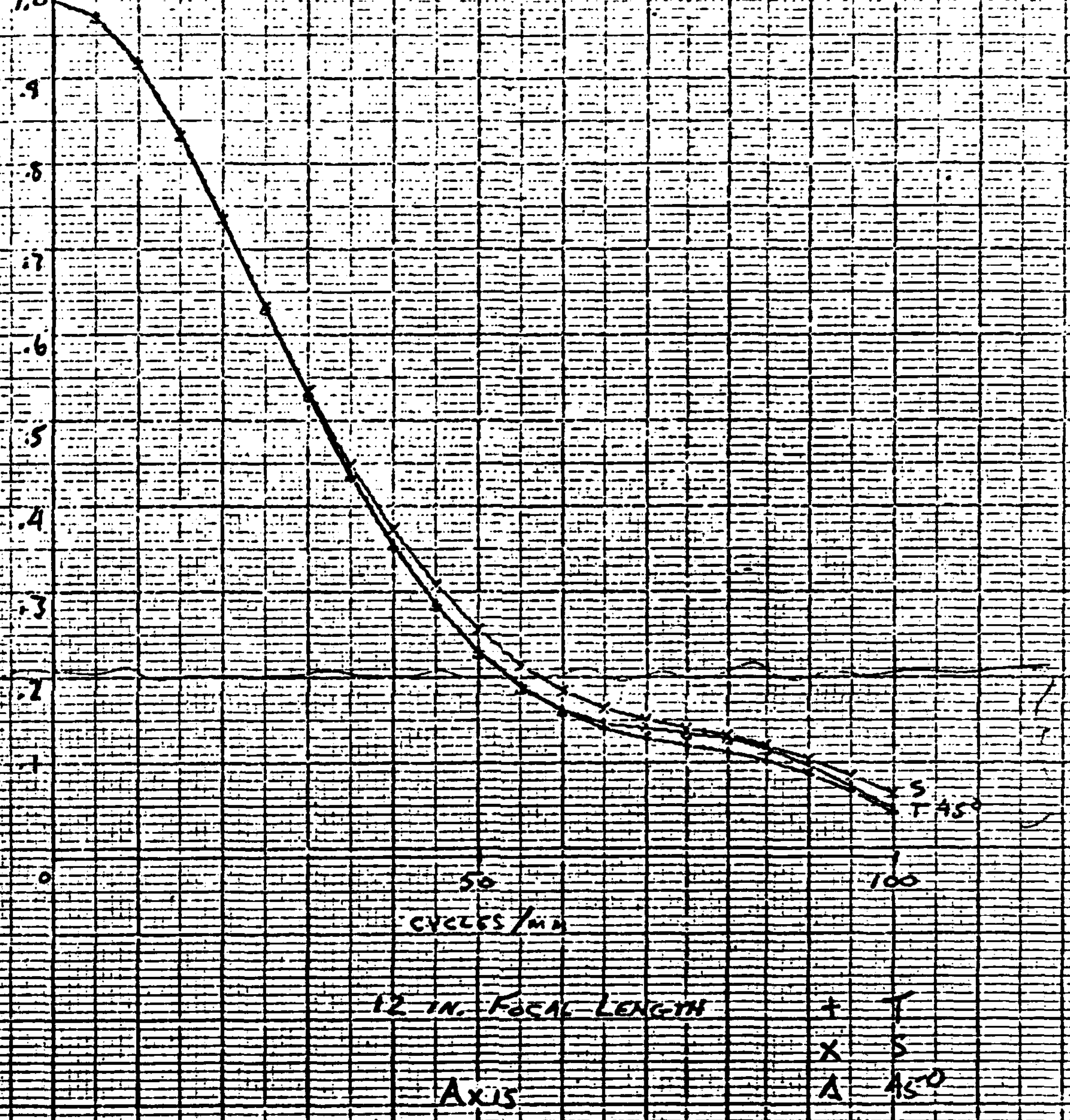
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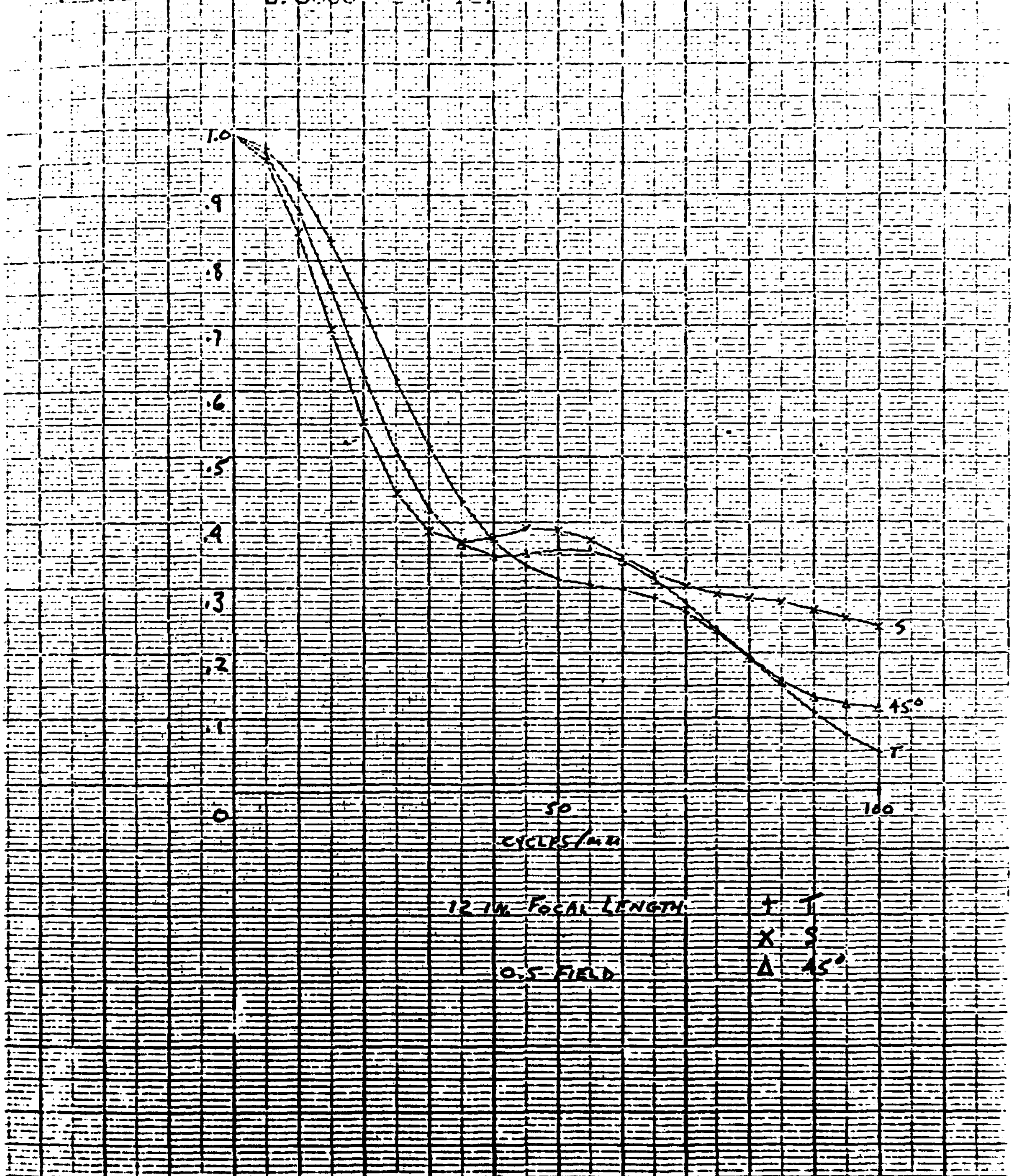

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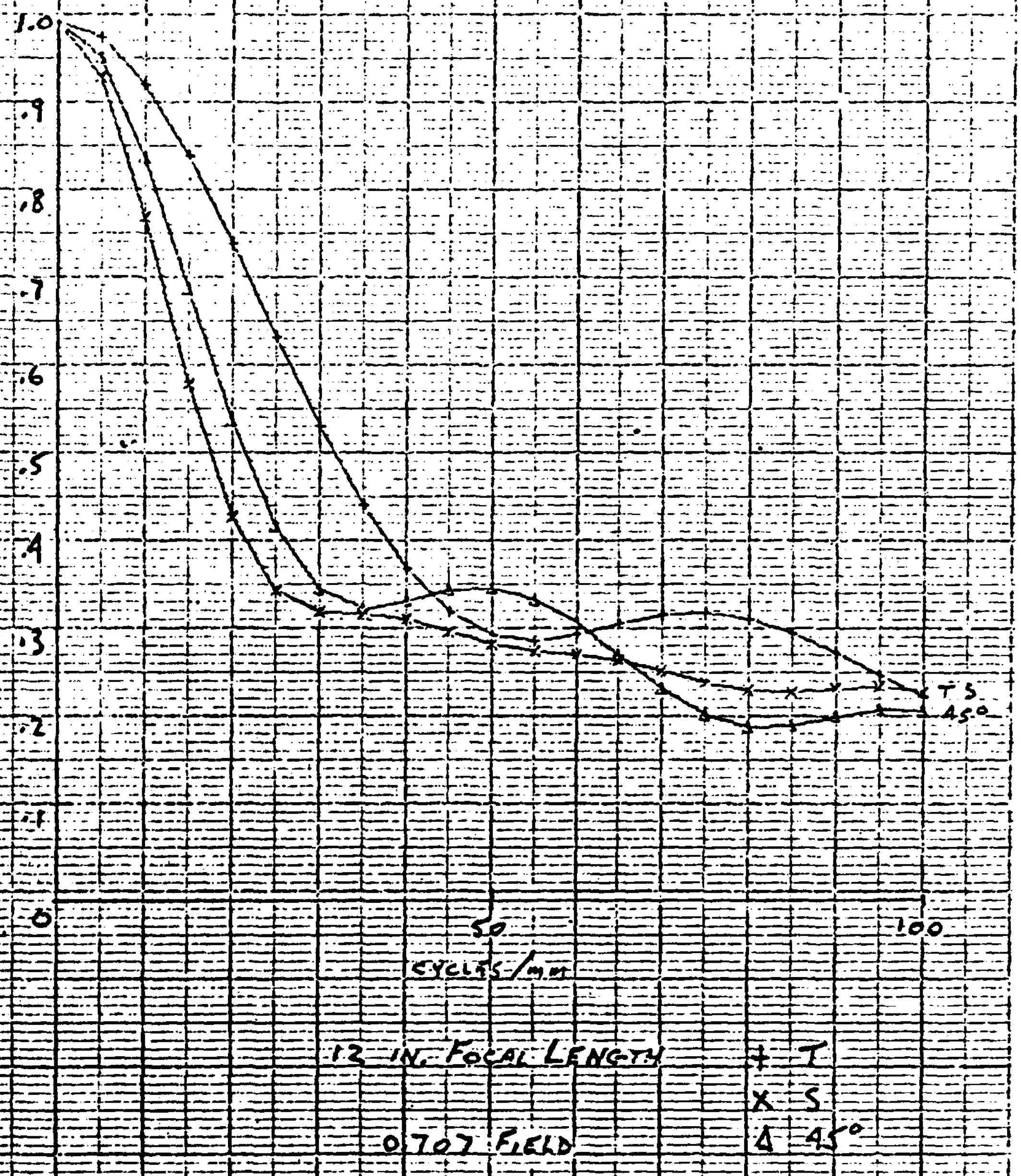
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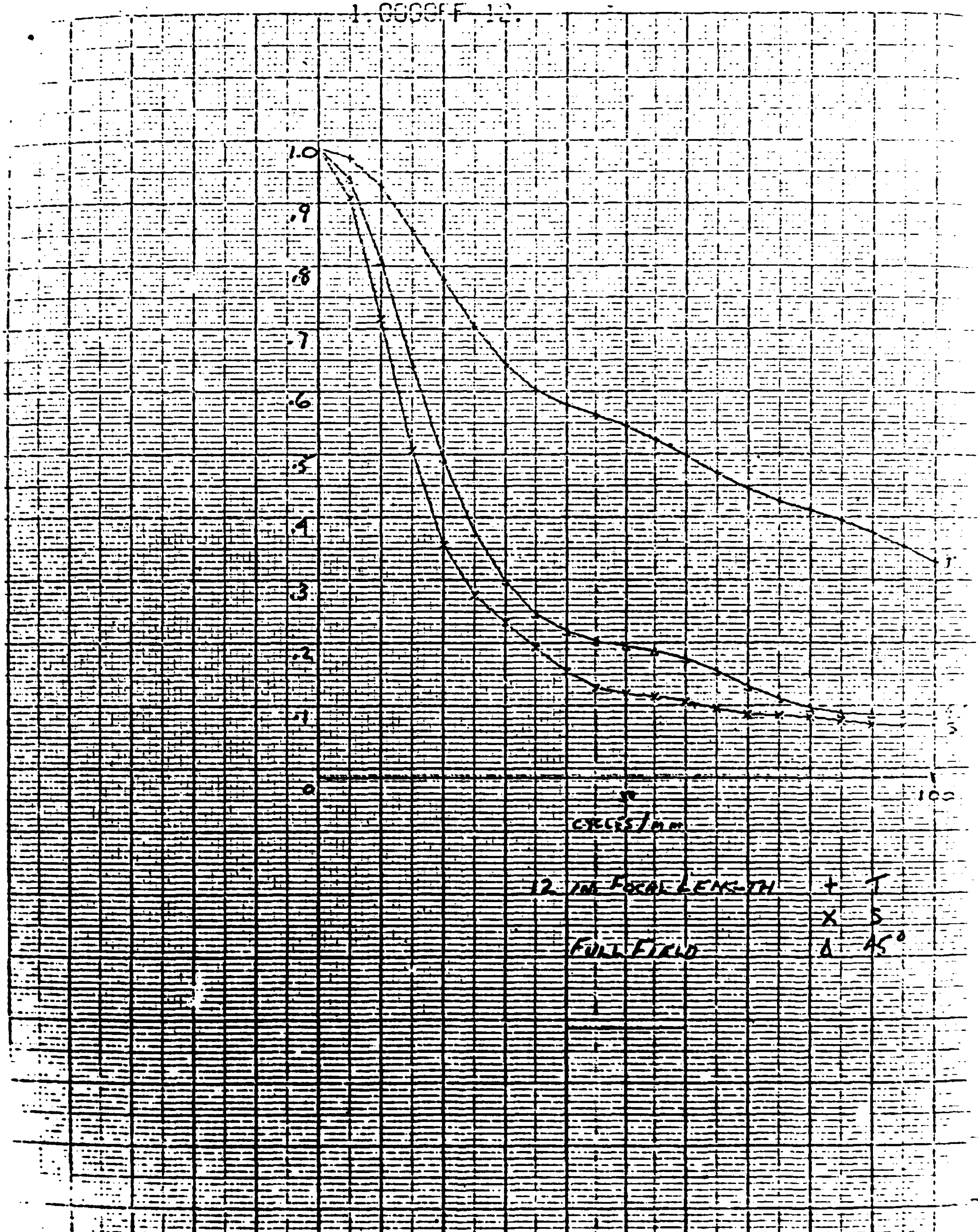
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Appendix C

Lens Test Data

1. Procedure
2. Results
3. Photography Data

Appendix C TEST PROCEDURE AND RESULTS

1.0 INTRODUCTION

This procedure determines the method and apparatus to be used for testing and evaluating the performance of the Variable Focal Length High Speed Lens being made for the U.S. Government under contract No. F33615-68-C-1295.

The focal length of the lens is continuously variable from 4.5 to 12 inches, has a speed of f/2.4 and is optically corrected for the spectral range from 700 to 900 millimicrons.

Features such as focal length, f number, image format diameter, relative illumination and back focal length will be measured in visible light and where necessary, the recorded data will be adjusted to compensate for the spectrum shift. The resolution of the lens will be evaluated photographically using infrared light and infrared film. It is understood that the photographic image will record less resolution than the lens is producing by an amount which is a function of film - lens modulation transfer functions. This difference will be taken into account in determining the true resolution of the lens.

Individual characteristics, like spherical aberration, coma, lateral and transverse color and astigmatism all tend to degrade the resolution of the lens image. Image resolution has been determined as the important performance feature for this lens so the individual aberrations will not be measured. The resolution will be determined using the Area Weighted Average Resolution method of MIL-STD-150A.

2.0 APPARATUS FOR RESOLUTION TESTING

Collimator

A reflective collimator will be used having a parabolic primary mirror 20 inches in diameter and 150 inches in focal length. The parabola's figure has been tested and found to be more than adequate for these tests. The large aperture of the collimator will allow the 5 inch aperture of the zoom lens to be unobstructed by the collimator's folding mirror or any of the mirror's support structure.

This collimator is mounted in a 24 inch diameter steel tube that is vibration isolated - a full description appeared in a paper entitled "Structural Problems in Large Lightweight Optics", by M. Dvorin and B. Welham delivered at the 1965 Spring O.S.A. conference in Dallas, Texas. The vibration-isolated steel tube will be used to support the lens and film holder, see Figure 1.

The light source for the collimator will consist of a tungsten lamp and the necessary filters. The spectral range of the lamp extends from well below 700 millimicrons to well above 900 millimicrons, see Figure II and Figure III.

The resolution target will be a USAF 1951 high contrast, three bar, clear lines on a black background target of proper range to attain 100 line paris per millimeter in the lens image. The ratio of focal lengths of the collimator and zoom lens indicates that the resolution target need have no line patterns finer than 8 line pairs per millimeter to create a lens image at 100 line pairs per millimeter.

FILM AND HOLDER

High speed infrared film will be used to record the image of the resolution target made by the zoom lens. The films used will, of necessity, impose some limitation on the image quality of an amount that will be known in advance. Well catalogued film characteristics will be used to extrapolate the recorded film image quality upwards to determine the lens performance.

Two film types are considered suitable for the test purposes. Kodak Infrared Aerographic Film 2424 (in 70mm, 5 inch, and 9½ inch rolls) and Kodak High Speed Infrared Sheet Film 4143 (in 4 x 5 cut sheets). Both of these films have the same emulsion, the only difference being in the size and shape of the available film. To use the roll film (2424) a Hasselblad camera with a 70mm film back will be used without its lens - the 4143 film would be used with a Speed Graphic 4 x 5 camera without its lens. In both cases the image from the zoom lens would fall directly on the film, a focal plane shutter being available in either camera.

3.0 PROCEDURE

3.1 Focal Lengths (effective, back and flange)

These features will be measured on an optical bench with nodal slide in accordance with the accpeted procedures for photographic lens testing in MIL-STD-150A. These measurements will be made with a light source filtered with a narrow band-pass filter in the 500-600 millimicron range - the particular filter to be selected later - and the measured lengths will then be converted mathematically to focal lengths in the 700 to 900 millimicron spectral band. The flang to film plane distance, however, will be verified and recorded photographically in the 700-900mm spectral range.

3.2 Overall Length

The overall length will be derived from the mechanical length of the lens assembly, as measured with a scale and adding to that the flange focal length as determined photographically by the method just described.

3.3 Relative Illumination

The Bausch and Lomb Illumination Analyzer, model 3, will be utilized to determine transmission and relative illumination, see Figure IV.

3.4 Focal Length Change Speed

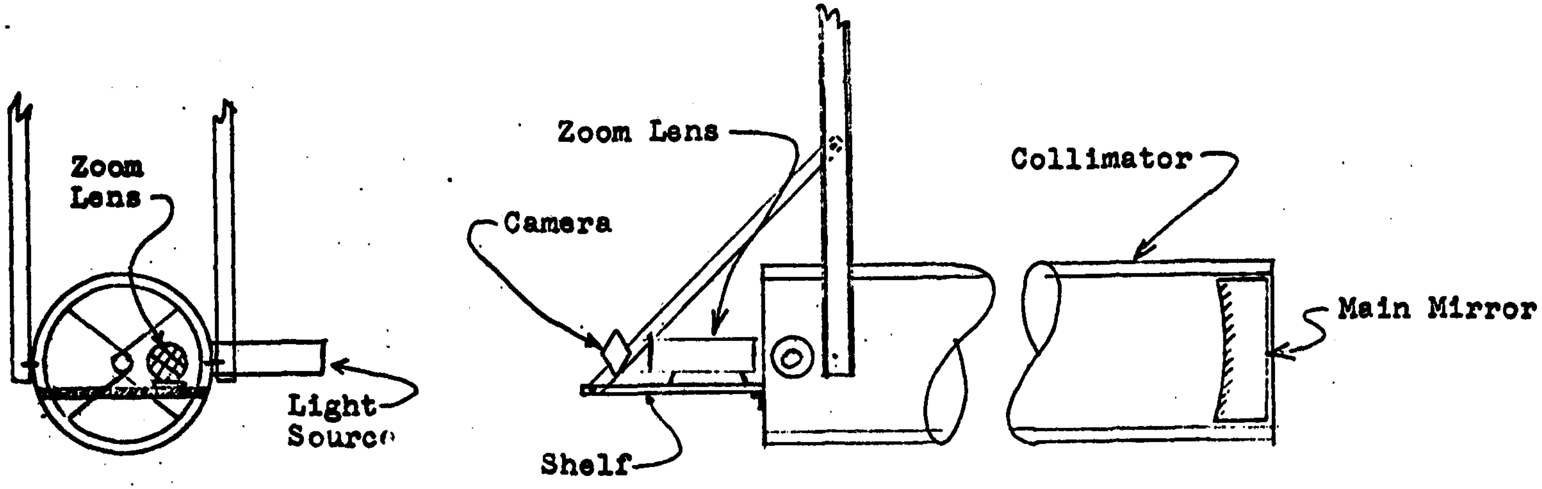
The speed of the motor drive for changing focal length will be checked by the use of a stop-watch as the lens is driven from one end of its range to the other.

3.5 Resolution

Resolution will be measured with the apparatus already described. The spatial frequency of the target pattern will be converted to spatial frequency in the lens image plane by the ratio of focal length of the collimator to the focal length of the lens.

The plane of best definition will be determined in a manner like that of section 5.1.2.1 in MIL-STD-150A. With the film then held stationary at that position the A W A R resolution will be measured as follows:

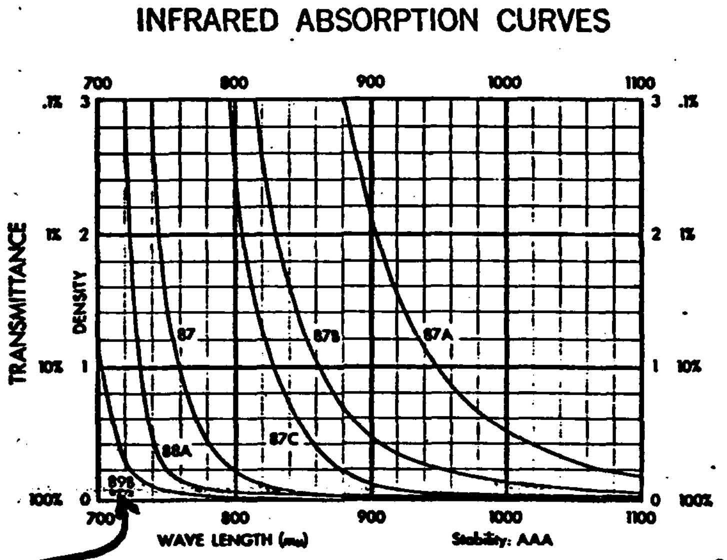
e.f.l.	# of check pts.	half field	spacing of check pts.
4.5"	7	17°1'	2½° (on axis to 15°)
6"	6	13°3'	2½° (on axis to 12½°)
9"	7	8°30'	1¼° (on axis to 7½°)
12"	6	6°33'	1¼° (on axis to 6¼°)



End View

Section View

Fig. I. -- General Arrangement



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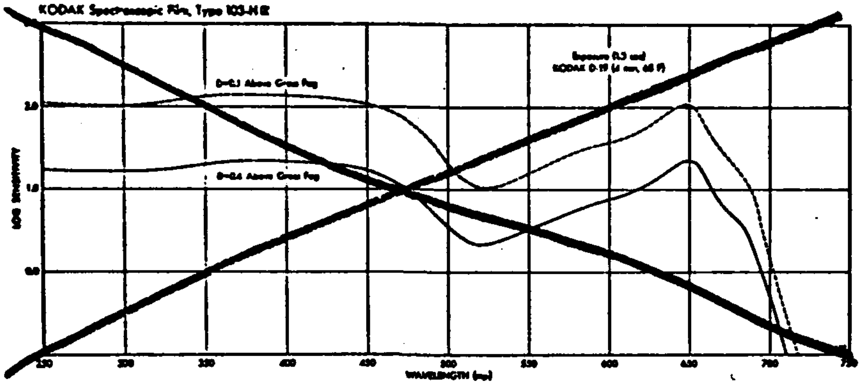
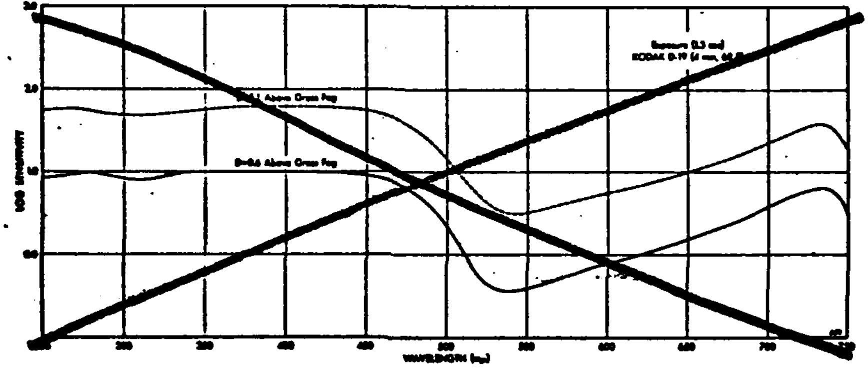
		~~No. 87~~	~~No. 87A~~	~~No. 87B~~	~~No. 87C~~	~~No. 88A~~	No. 89B
Dominant Wave Lgth.	(A)	~~757.0~~	~~None~~	~~None~~	~~None~~	~~746.0~~	718.0
Excitation Purity	(A)	~~100.0~~	~~None~~	~~None~~	~~None~~	~~100.0~~	100.0
% Luminous Transmit.	(A)	~~0.0002~~	~~None~~	~~None~~	~~None~~	~~0.005~~	0.034
x_A y_A		~~0.7347~~ ~~0.2653~~	~~None~~ ~~None~~	~~None~~ ~~None~~	~~None~~ ~~None~~	~~0.7347~~ ~~0.2653~~	0.7347 0.2653
Dominant Wave Lgth.	(C)	~~757.0~~	~~None~~	~~None~~	~~None~~	~~748.0~~	718.0
Excitation Purity	(C)	~~100.0~~	~~None~~	~~None~~	~~None~~	~~100.0~~	100.0
% Luminous Transmit.	(C)	~~0.0001~~	~~None~~	~~None~~	~~None~~	~~0.002~~	0.013
x_C y_C		~~0.7347~~ ~~0.2653~~	~~None~~ ~~None~~	~~None~~ ~~None~~	~~None~~ ~~None~~	~~0.7347~~ ~~0.2653~~	0.7347 0.2653

Fig. II.---Wratten Filter 89B Transmission

SPECTRAL SENSITIVITY


KODAK Spectroscopic Film, Type 103-H E


KODAK Spectroscopic Plate, Type 103a-U

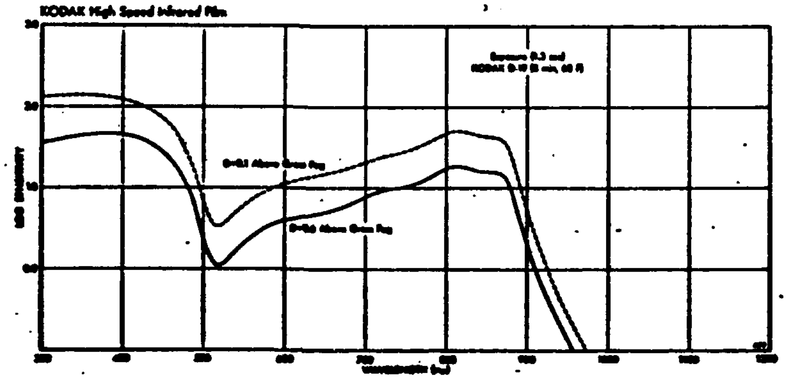

KODAK High Speed Infrared Film

Fig. III.---I-R Film Spectral Sensitivity

DATA SHEET

Feature	Design Goal	Recorded Amount
Motor Drive Speed	5 Seconds Max.	3½ max
Weight	Low as Possible	24¼
Overall Length	18½ inches	18.411

Focal Length

Approx. E. F. L.	Measured E. F. L.	Measured f/#	Back F. L.	Flange F. L.
4.5"	4.26	2.29	7.154	5.004
6"	6	2.46	7.154	5.004
9"	9	2.56	7.154	5.004
12"	11.44	2.47	7.154	5.004

Resolution 42.78 Avg.

A W A R Resolution at 4.5" E. F. L. (Design Goal = 29 lines / mm)

1 Field Pos'n.	2 Radial Resol'n	3 Tang. Resol'n	4 * Average Resol'n	5 A_z / A_t	6 Product 4 x 5
Axis	49	49	49	.0216	1.06
2½°	49	55	52	.0648	3.37
5°	49	55	52	.1079	5.61
7½°	31	31	31	.1511	4.68
10°	39	44	42	.1943	8.16
12½°	39	35	37	.2375	8.79
15°	49	39	44	.2211	9.73
			AWAR Resol'n = SUM		41.40

* Average resolution is $\frac{\text{Rad + Tang}}{2}$ if ratio of rad to tang is 2.0 or less, otherwise the average resol'n = $\sqrt{\text{rad x tang}}$.

DATA SHEET 2

A W A R Resolution at 6" E. F. L. (Design Goal = 41 lines / mm)

1 Field Pos'n	2 Radial Resol'n	3 Tang. Resol'n	4 * Average Resol'n	5 A_z / A_t	6 Product 4 x 5
Axis	44	49	47	.0367	1.72
2½°	49	49	49	.1468	7.19
5°	44	44	44	.1835	8.07
7½°	31	31	31	.2569	7.96
10°	39	25	32	.3303	10.57
12½°	39	25	32	.0825	2.64
				A W A R Resol'n = SUM	38.15

* Avg. resolution is $\frac{Rad + Tang}{2}$ if ratio of rad to tang is less than 2.0, otherwise the average resol'n = $\sqrt{rad \times tang}$.

A W A R Resolution at 9" E. F. L. (Design Goal = 27 lines / mm)

1 Field Pos'n	2 Radial Resol'n	3 Tang. Resol'n	4 * Average Resol'n	5 A_z / A_t	6 Product 4 x 5
Axis	52	47	50	.0216	1.08
1¼°	52	47	50	.0648	3.24
2½°	41	47	44	.1082	4.76
3 3/4°	47	58	53	.1515	8.03
5°	41	41	41	.1945	7.97
6¼°	41	41	41	.2379	9.75
7½°	47	41	41	.2215	9.08
				A W A R Resol'n = SUM	43.91

DATA SHEET 3

A W A R Resolution at 12" E. F. L. (Design goal = 45 lines / mm)

1 Field Pos'n	2 Radial Resol'n	3 Tang. Resol'n	4 * Average Resol'n	5 A_z / A_t	6 Product 4 x 5
Axis	32	32	32	.0364	1.16
1¼°	40	40	40	.1092	4.37
2½°	51	57	54	.1822	9.84
3 3/4°	51	51	51	.2553	13.02
5°	32	36	44	.3277	14.42
6¼°		32	32	.0896	2.87
				A W A R Resolution = SUM	45.68

* Average resolution is $\frac{\text{Rad + Tang}}{2}$ if the ratio of rad to tang is 2.0 or less, otherwise the average resolution is $\sqrt{\text{rad x tang}}$.

PHOTOGRAPHY DATA

Resolution targets from which test performance figures are listed were recorded on film and read using a microscope.

1. Target

   a - 1951 USAF target
   b - clear lines on black (negative)
   c - installed in 147.5" collimator

2. Exposure
   a - Film - Kodak Hi-Speed I.R. Film Type 4143
   b - Strobe - Ultra blitz Metero 11
   1/1300 second flash duration
   Narrow angle focus
   Fresnel type cover
   c - Filtering - 2.7 neutral density and Kodak Wratten #89B filter between strobe and target

3. Development

   a - film developed in Kodak developer type D-19
   b - 11 minutes @ 68° F

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13. ABSTRACT

This report describes the development and prototype manufacture of a high speed (f/2.4) zoom lens to work in the near infra-red (0.7 to 0.9mm) in conjunction with an image tube night viewing system. The development or design effort covered a period of 32 months and proved to be a very difficult design problem which required the performance objectives (specs) to be modified somewhat in order to permit the realization of a successful design. The completed design was fabricated (in 17 months) as a bench model prototype and found to meet the expected performance values. This unit was delivered for final testing in December 1971.

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Photographic Lens						
Reconnaissance & Surveillance						
Aerial Camera Lens						
Variable Focal Length Lens						

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