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JUN 77 B R CHISHOLM, R M BURLEY  
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**TEST AND EVALUATION OF NIGHT VISION OPTICAL SYSTEMS**

**Third Generation Goggle Objective Lens**

Baird-Atomic, Inc.  
125 Middlesex Turnpike  
Bedford, Ma. 01730

June 1977

**AD No.**  
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Prepared for

DEPARTMENT OF THE ARMY  
UNITED STATES ARMY ELECTRONICS COMMAND  
NIGHT VISION LABORATORY  
ATTN: DRSEL-NV-VI  
Fort Belvoir, Virginia 22060

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## 1. INTRODUCTION

### 1.1 GENERAL

Third generation (GEN III) image intensifier tubes operate in a narrow spectral region and use a thick, low index glass faceplate (Corning 7056), rather than the conventional fiber optic faceplate of first and second generation tubes. This report analyzes the impact of this design in the area of goggle objective lens systems.

Evaluation proceeds on two levels. The first task examines the possibility of using the AN/PVS-5 goggle objective lens both "as is" and in a modified state with GEN III tubes. The second task looks at two alternate designs. One design is similar to the current objective lens configuration, while the other is an all new approach with lower cost and weight heavily favored. Based upon the results, conclusions are drawn and comparisons made, leading to recommendations for use as guidelines in the development of GEN III goggle systems.

### 1.2 APPROACH TO COLLECTION OF EVALUATION DATA

#### 1.2.1 AN/PVS-5 Evaluation

To provide a reference for comparison, the AN/PVS-5 18-mm goggle objective is evaluated as it presently operates with GEN II image intensifier tubes. This evaluation is performed in the wavelength range from  $0.5\mu$  to  $0.8\mu$ .

#### 1.2.2 Task 1 Evaluation

The aberration and color characteristics of the 0.225-inch image intensifier tube faceplate are examined in relation to the original objective's performance. A full examination, involving fan plots and MTF runs, is not performed. Calculations are given which provide the information necessary to evaluate the coupling of the lens to the faceplate.

A partial modification of the AN/PVS-5 goggle objective lens is also carried out, paying close attention to restrictions on dimensions, weight, and manufacturing costs. To minimize changes from the current system, the image intensifier tube faceplate is considered to be variable. Glass substitutions are made only where optically necessary. The intent is to optimize the lens performance with a minimum of changes. Evaluation of the system is in the spectral region from  $0.7\mu$  to  $0.9\mu$ , in accordance with the GEN III tube response.

#### 1.2.3 Task 2 Evaluation

Full modification of the AN/PVS-5 objective is performed with all curvatures and spacings variable. Curvature of the intensifier tube faceplate is avoided, and more freedom is taken in glass choice. The goal is to modify the existing objective into an alternative configuration which optimizes performance where a partial modification falls short.

A new objective lens for use with the GEN III tubes is analyzed. A Baird-Atomic objective lens which is lightweight, short, simple in configuration, and inexpensive--yet suitable in optical quality--is used. This is a demonstration of the feasibility of designing a lens which meets the above criteria.

All evaluation data for this task are prepared in the GEN III response region from  $0.7\mu$  to  $0.9\mu$ .

## 2. EVALUATION

### 2.1 GENERAL

For each of the systems, 1:1 and 2:1 scale lens plots are provided to show on-axis and full field ray traces. In addition, ray trace fan plots (aberration curves) in primary (P), secondary (S), and tertiary (T) light, and geometric MTF plots and system calculations are presented. Appendix B contains a list of the abbreviations which apply to the calculations pages. Lens prescriptions for the AN/PVS-5 goggle objective--in its present design, as well as under partial and full modification--are provided in Appendix A.

A left-handed coordinate system (Figure 1) is the convention for all the plots, calculations, and discussions in this report.

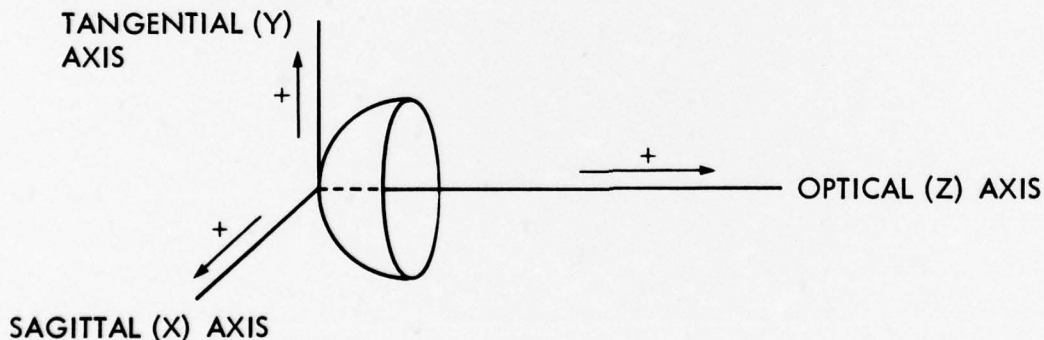


Figure 1. Left-handed coordinate system

Light rays originate from an object to the left and travel in the positive Z direction. Optical surfaces are numbered increasingly from left to right with the first surface numbered one (1). Optical elements are similarly numbered, with compound elements having alphabetic subscripts (example: AN/PVS-5 triplet is compound element 4 with individual elements 4A, 4B, and 4C).

The ray trace fan plots express the change in ray intercept height as a function of fractional ray height on the entrance pupil. The intercept height of the chief ray (ray through the center of the entrance pupil) is used as a reference (Figure 2).

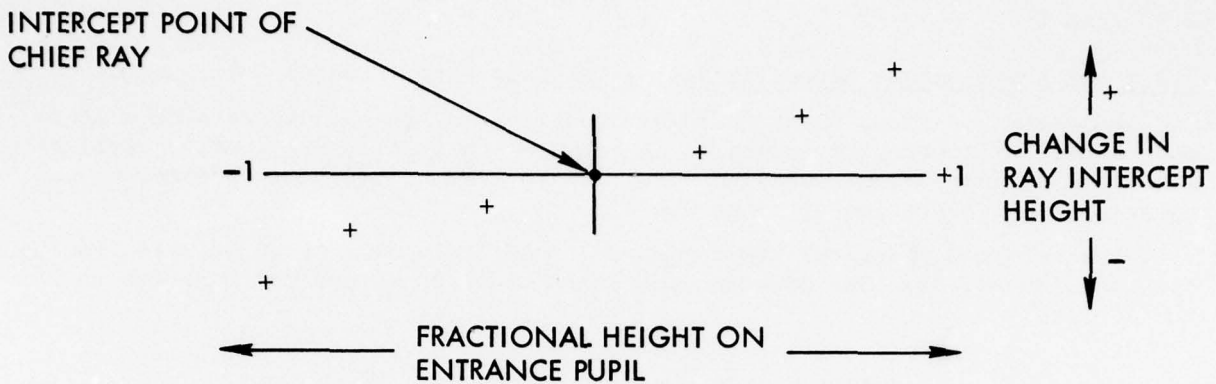


Figure 2. Ray trace fan plots

These plots may be related to the aberration coefficients given on the system calculations pages (Figures 8, 14, 20, and 26) by fifth order expansion equations. The height,  $y'$  (tangential plane), of a meridional ray at the image surface is given by:

$$y' = h'\bar{H} + (\text{SPHR}) Y^3 + (\text{COMA}) \bar{H}Y^2 + (\text{TANG}) \bar{H}^2Y + (\text{DIST}) h'\bar{H}^3 + (\text{SPHR5}) Y^5 + (\text{COMA5}) \bar{H}Y^4 + (\text{TOBSA}) \bar{H}^2Y^3 + (\text{ECOMA}) \bar{H}^3Y^2 + (\text{TANG5}) \bar{H}^4 + (\text{DIST5}) \bar{H}^5,$$

where  $\bar{H}$  is the fractional object height,  $Y$  the fractional pupil height, and  $h'$  the gaussian or first order image height. Similarly, the coordinate of a sagittal ray at the image surface,  $x'$ , is

$$x' = (\text{SPHR}) X^3 + (\text{SAGT}) X^3 + (\text{SAGT}) \bar{H}^2X + (\text{SPHR5}) X^5 + (\text{SOBSA}) \bar{H}^2X^3 + (\text{SAGT5}) \bar{H}^4X,$$

where  $X$  is the fractional pupil coordinate in the sagittal dimension.

The MTF results are calculated by tracing a number of rays through the lens system and analyzing the spatial distribution of their intercepts in the image plane. Weightings refer to the number of rays traced through half of the entrance pupil for a particular wavelength of light. For the AN/PVS-5 evaluation, a weighting of 40, 20, 20 is used for wavelengths of 706.5 nm, 546.1 nm, and 852.1 nm respectively. This is representative of the relative response of second generation tubes. GEN III tubes have a peaked red response; therefore, all MTF's for GEN III applications are given a weighting of 40 at 800 nm, 8 at 700 nm, and 8 at 900 nm.

The total lens weights given are not to be considered exact. Ground flats on negative elements, exact outer diameters, and other engineering considerations are not incorporated into the calculations. The weights are provided for comparison purposes, to analyze the benefits of one system versus another.

## 2.2 TASK 1

### 2.2.1 AN/PVS-5 Goggle Objective With Thick Faceplate (Figures 3 Through 8)

In general, a flat, thick faceplate inserted in the optical path of a lens contributes overcorrected spherical and axial-chromatic aberrations, as well as positive astigmatism and negative coma. These lead to residual aberrations and consequent deterioration of image quality.

Overcorrected spherical aberration is immediately evident in on-axis resolution considerations. The equation for third order spherical semiblur due to a thick plate is:

$$\text{SPHR} = + \frac{1}{2} \left( \frac{n^2 - 1}{n^3} \right) \times d \times (\text{N.A.})^3$$

Here,  $n$  is the refractive index of the material,  $t$ , the thickness, and N.A., the numerical aperture of the cone of light incident on the plate. The plus (+) sign indicates overcorrection. For an  $f/1.35$  light cone, 1.481 index of refraction (Corning 7056,  $\lambda = 852.1$  nm), and 5.7-mm thickness, the third order transverse semiblur is 0.05 to 0.06 mm. Referring to the aberration coefficients of Figure 8, SPHR (third order spherical semiblur) becomes approximately 0.03 to 0.04, while SPHR5 and SPHR7 have smaller positive changes. The balance achieved during the design of the AN/PVS-5 objective for GEN II use is thus lost and severe on-axis blurring occurs. The blur circle radius can be reduced by a factor of 4 if pure third order exists, but the higher order aberrations of this problem prevent such an improvement.

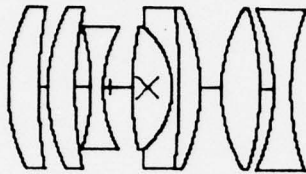
As stated, the off-axis imaging is afflicted with negative coma (negative, because the chief ray angle for off-axis points is diverging from the optical axis). The third order formula for total coma transverse blur is:

$$\text{COMA} = - \frac{3}{2} \left( \frac{n^2 - 1}{n^3} \right) \times d \times (\text{N.A.})^2 \times \bar{\mu},$$

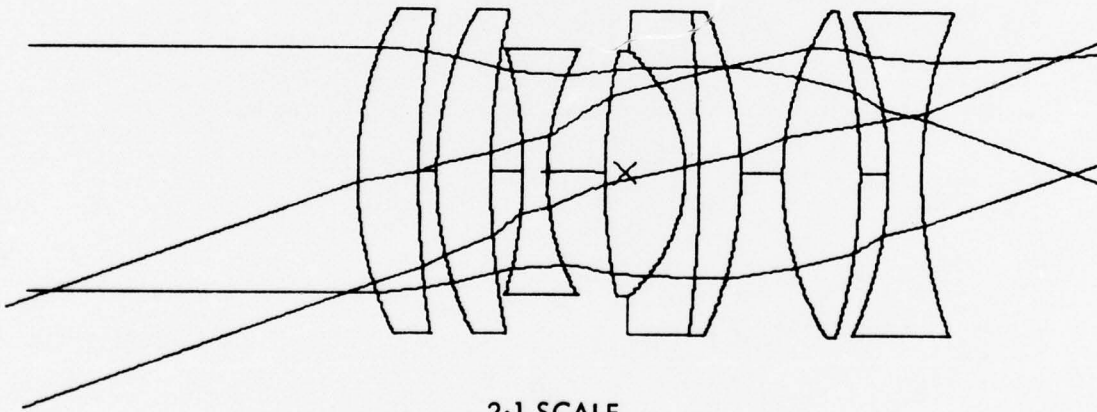
where  $\bar{\mu}$  is the tangent of the full field chief ray. At 20 degrees, this amounts to -0.16 mm. The approximate effect of this on the AN/PVS-5 is visualized by adding a negative parabola having a value of -0.16 mm at 1.0 fractional pupil height to the full field fan of Figure 6. (Figure 6 is used because it is most representative of the aberrations at long wavelengths.) This coma causes the image of off-axis points to flare toward the optical axis. Add to this positive astigmatism, and the result is extreme off-axis blurring.

### 2.2.2 Partial Modification of AN/PVS-5 Objective With Thick Faceplate (Figures 9 Through 14)

The AN/PVS-5 GEN II goggle objective performance depends upon a sensitive aberration balance of the adjacent surfaces of elements 5 and 6. Surface 12 (element 5) contributes a large amount of undercorrected spherical aberration and negative coma, while surface 13 (element 6) counters with appropriate amounts for balance. The partial modification utilizes this in minimizing the changes necessary to establish optical quality.



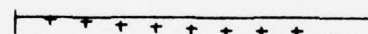
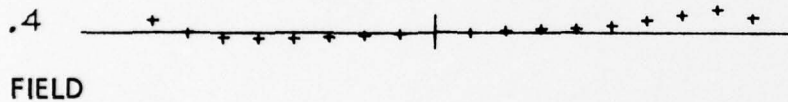
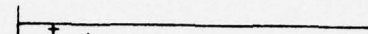
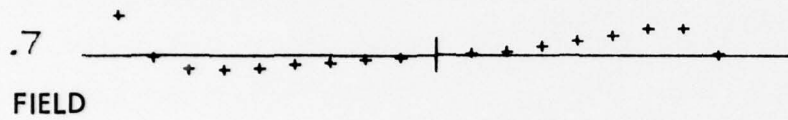
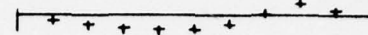
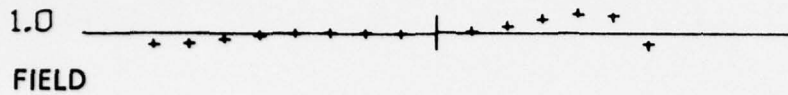
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2:1 SCALE

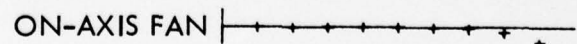
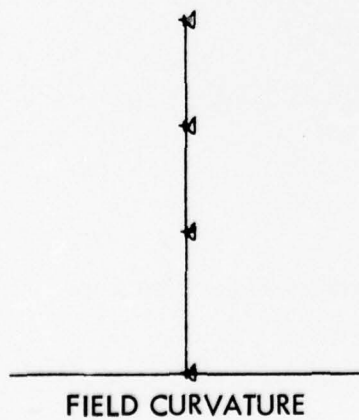
Focal length	26.64 mm	( $\lambda = 852.1$ nm)
F/no.	1.33	
Field of view	40°	

Figure 3. 18-mm AN/PVS-5 goggle objective lens



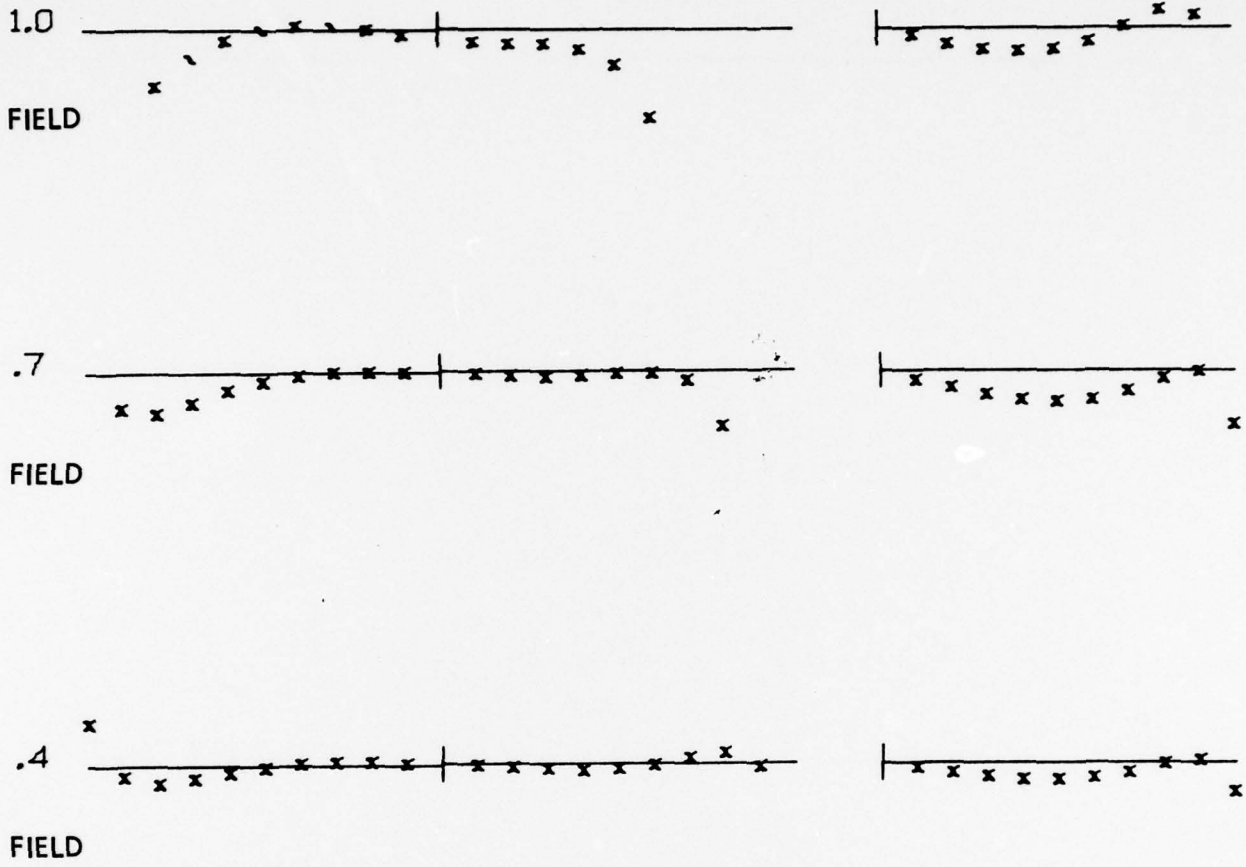
TANGENTIAL FANS

SAGITTAL FANS



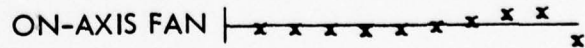
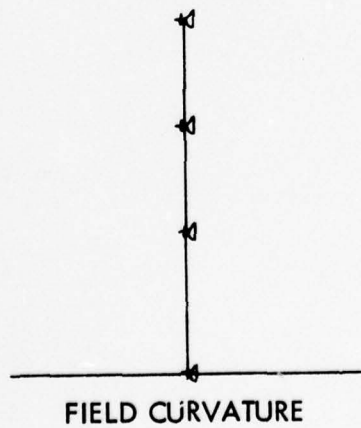
PLOT SCALE = 0.1 MM/IN.

Figure 4. 18-mm AN/PVS-5 goggle objective lens--ray trace fan plots for P light (706.5 nm)



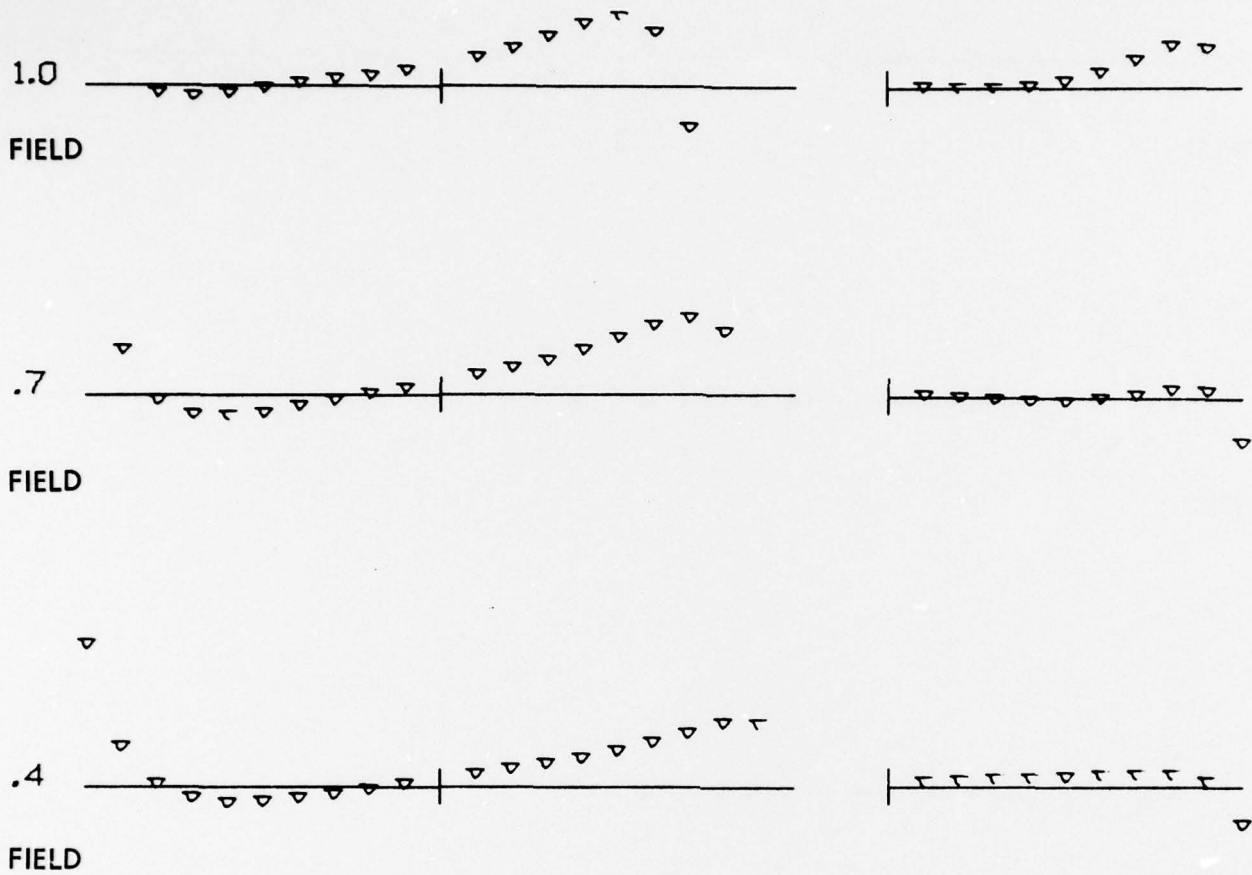
TANGENTIAL FANS

SAGITTAL FANS



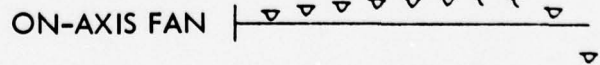
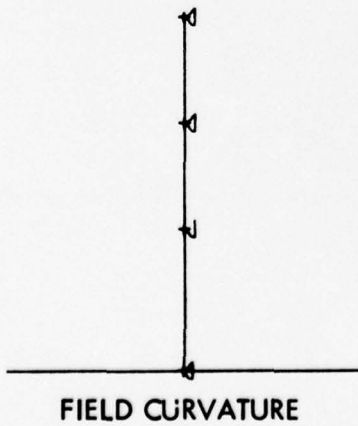
PLOT SCALE = 0.1 MM/IN.

Figure 5. 18-mm AN/PVS-5 goggle objective lens--ray trace fan plots for S light (546.1 nm)



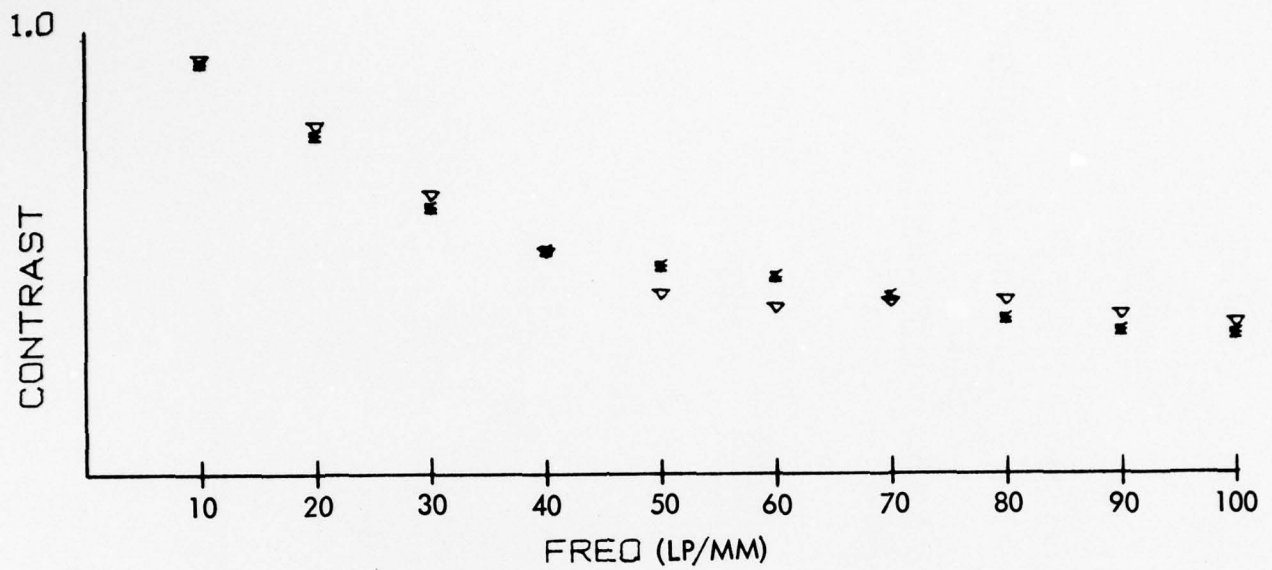
TANGENTIAL FANS

SAGITTAL FANS



PLOT SCALE = 0.1 MM/IN.

Figure 6. 18-mm AN/PVS-5 goggle objective lens--ray trace fan plots for T light (852.1 nm)



	<u>WAVELENGTH (NM)</u>	<u>MTF WEIGHTING</u>
x TANGENTIAL RESPONSE	706.5	40
+ SAGITTAL RESPONSE	546.1	20
∇ 45° RESPONSE	852.1	20

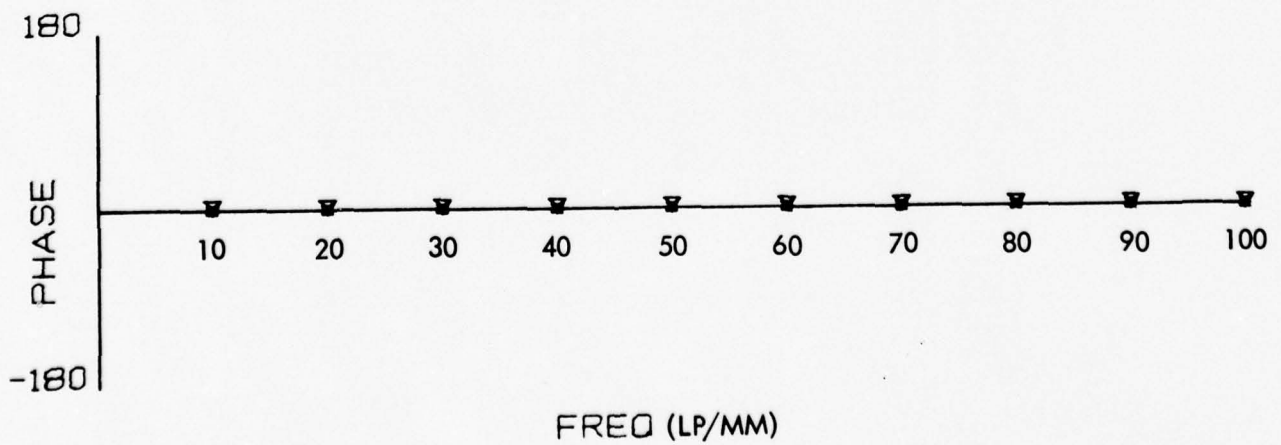


Figure 7. 18-mm AN/PVS-5 goggle objective lens--on-axis MTF plot

SYSTEM DATA

P LIGHT = 706.5 NM S LIGHT = 546.1 NM T LIGHT = 862.1 NM

RFLC = 11.911810 H WAG = -0.36000000E-09 RFLM = 10.000000 UK = -1.375493 Y1R = 10.000000  
 FCLM = 25.6316590 WAG = -0.000000 RFLV = 12.419347 UKR = 0.289470 Y1R = -4.685816  
 FOLM = 1.331934 CRJD = 0.1000000E+10 RFLU = 13.016156 UKR = 0.000000 Y1R = 0.000000  
 SCMT = 9.596469 OVLN = 51.511810 RFLV = -23.159770 UKR = 0.360000 Y1R = 0.000000  
 SCHR = -0.0190762 COWA = -0.0219797 TANG = 0.0190152 SAGI = -0.1253263 PFTZ = -0.1978374 DIST = -0.0691872  
 SCHR = -0.0208491 COWA = 0.0827456 TANG = 0.0000364 SAGI = 0.0858284 PFTZ = 0.1072765 DIST = -0.0000745  
 SCHR = -0.0151919 COWA = 0.0027446 TANG = 0.0000000 SAGI = 0.0087384 PFTZ = 0.0000000 Y1R = 0.0000000  
 SCHR = -0.0151919 COWA = 0.0046637 SA = -0.0141269 SL = 0.0013041

FULL FIELD CHIEF RAY DATA

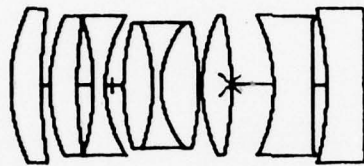
-- CHIEF RAY DATA IN P-LIGHT -- FAN IN AT 1.00 FIELD, OBJECT HEIGHT IS -0.3600000E 09  
 YEA YFX YFM Y-IMAGE L/M-IMAGE  
 0.000000 1.192381 A.887465 0.232679

S-T COLOR S-P COLOR X(S) X(T)  
 -0.018171 -0.0089523 -0.089523 0.026399

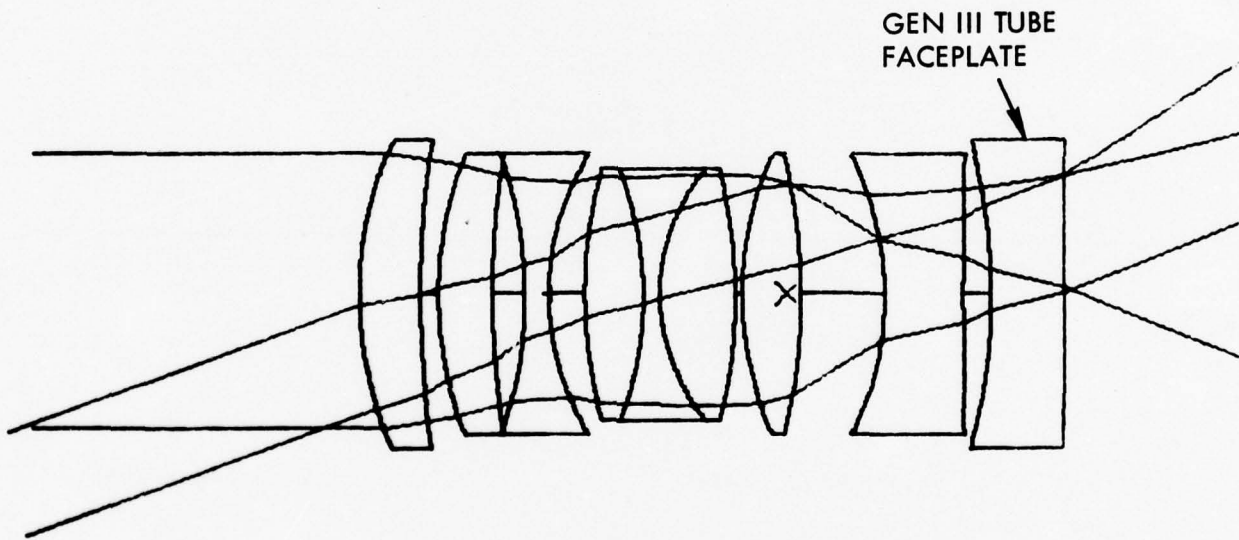
ON-AXIS MTF DATA

CODE	SPOTS	FAILURES	FIELD POSITION	Y0/M	X0/M	CHIEF RAY (T,AGE)	XK	(X,Y)K FOCUS-SHIFTED	PHASE
P	S	P	S	Y	T	Y	YK		45 DEGREE
1:	10.000000			0.000000	0.000000	0.000000	0.000000		0.931337
2:	20.000000			0.000000	0.000000	0.000000	0.000000		0.779825
3:	30.000000			0.000000	0.000000	0.000000	0.000000		0.623020
4:	40.000000			0.000000	0.000000	0.000000	0.000000		0.493094
5:	50.000000			0.000000	0.000000	0.000000	0.000000		0.398001
6:	60.000000			0.000000	0.000000	0.000000	0.000000		0.326801
7:	70.000000			0.000000	0.000000	0.000000	0.000000		0.278593
8:	80.000000			0.000000	0.000000	0.000000	0.000000		0.248377
9:	90.000000			0.000000	0.000000	0.000000	0.000000		0.235084
10:	100.000000			0.000000	0.000000	0.000000	0.000000		0.231260

Figure 8. 18-mm AN/PVS-5 goggle objective lens--system calculations



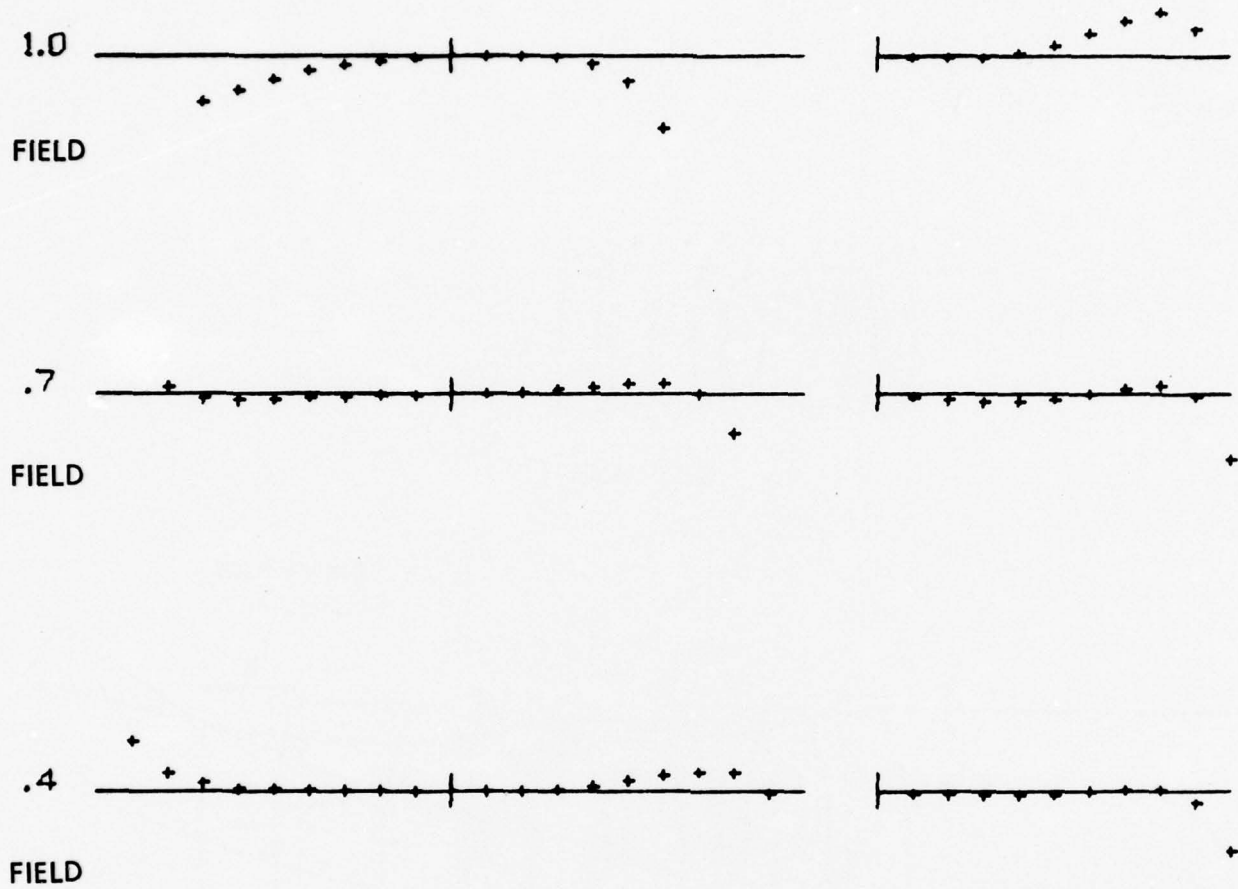
1:1 SCALE



2:1 SCALE

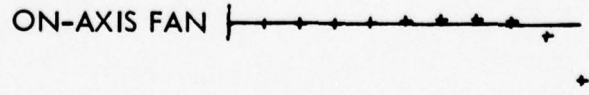
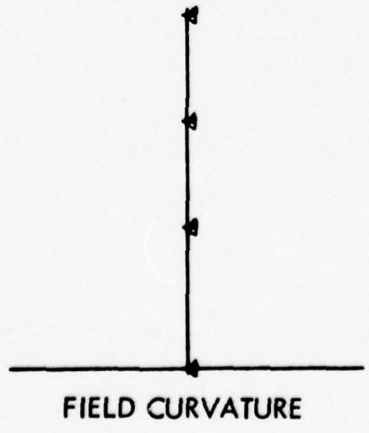
Focal length	26.58 mm ( $\lambda = 800$ nm)
F/no.	1.35
Field of view	40°

Figure 9. Partial modification of AN/PVS-5 with GEN III tube faceplate



TANGENTIAL FANS

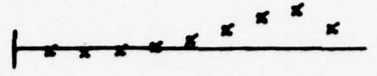
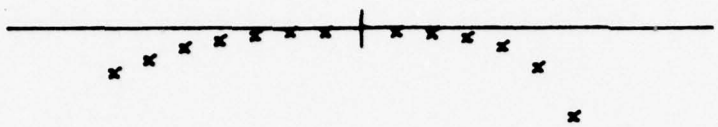
SAGITTAL FANS



PLOT SCALE = 0.1 MM/IN.

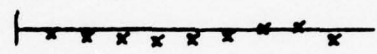
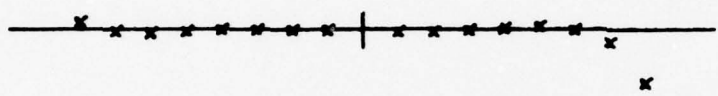
Figure 10. Partial modification of AN/PVS-5 with GEN III tube faceplate-- ray trace fan plots in P light (800 nm)

1.0



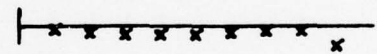
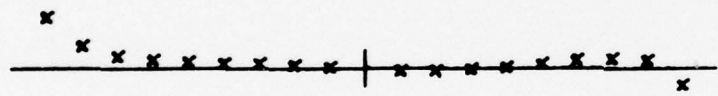
FIELD

.7



FIELD

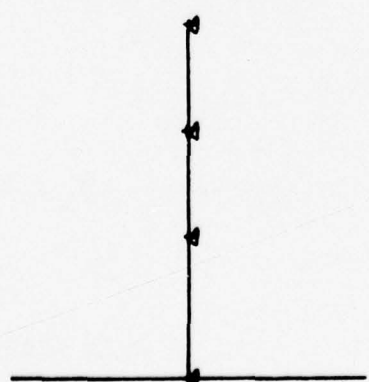
.4



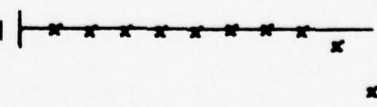
FIELD

TANGENTIAL FANS

SAGITTAL FANS



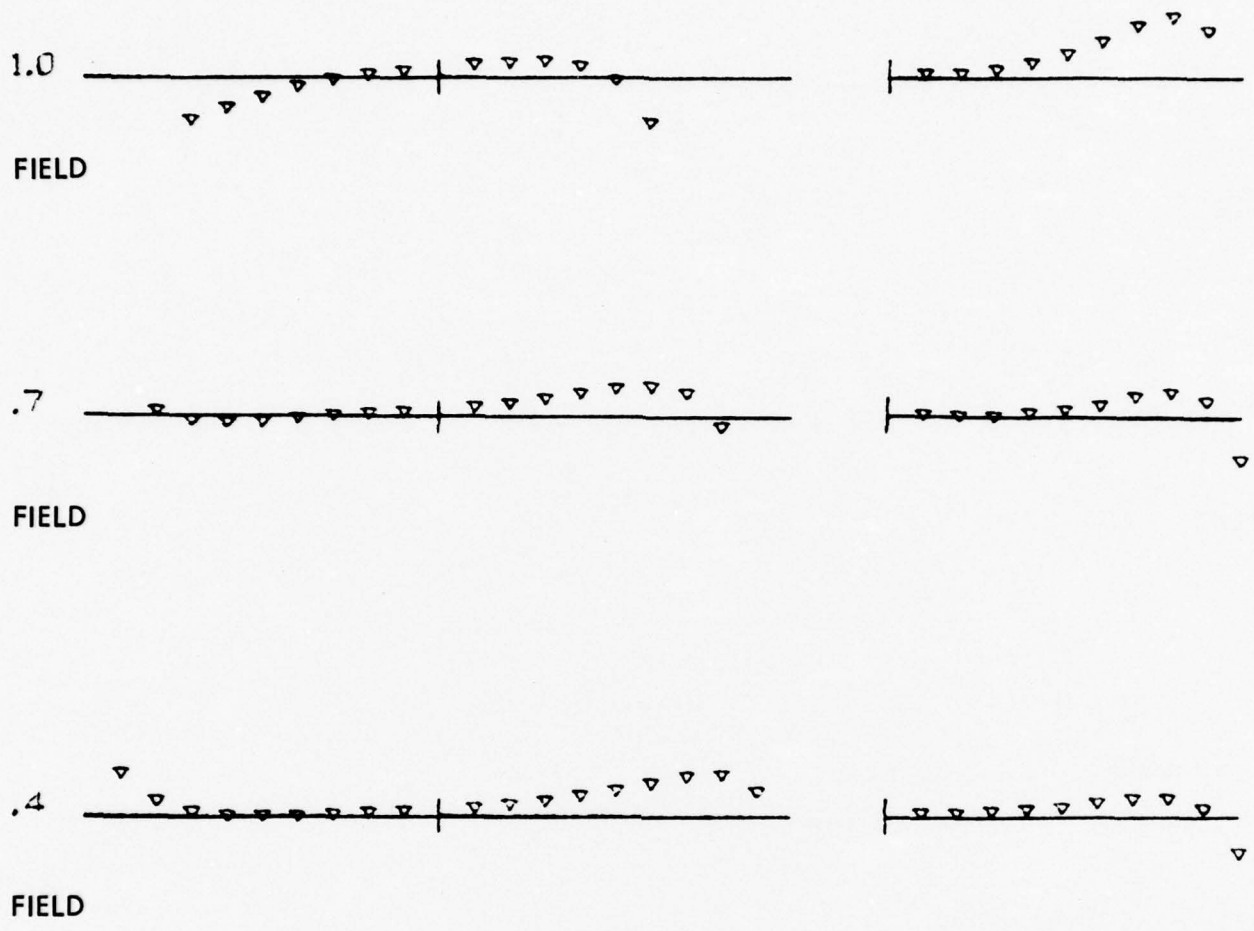
ON-AXIS FAN



FIELD CURVATURE

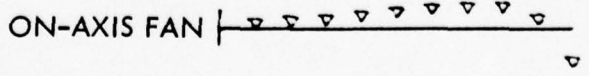
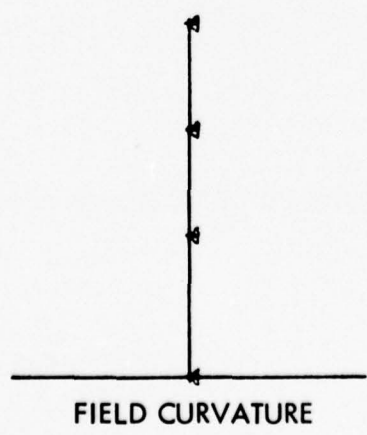
PLOT SCALE = 0.1 MM/IN.

Figure 11. Partial modification of AN/PVS-5 with GEN III tube faceplate-- ray trace fan plots in S light (700 nm)



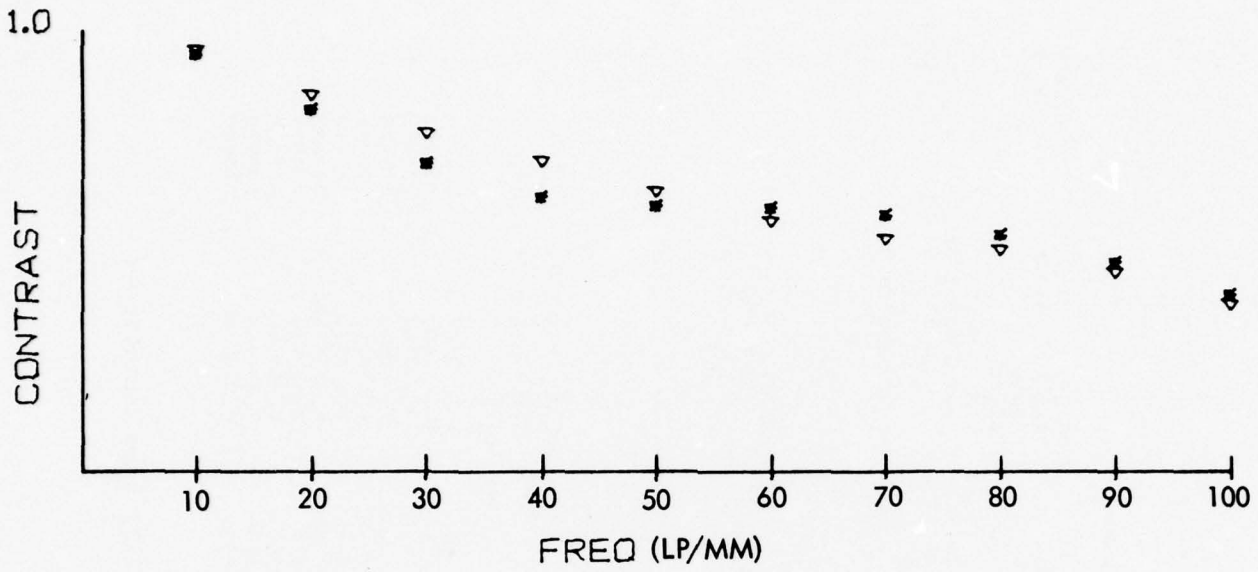
TANGENTIAL FANS

SAGITTAL FANS



PLOT SCALE = 0.1 MM/IN.

Figure 12. Partial modification of AN/PVS-5 with GEN III tube faceplate-- ray trace fan plots in T light (900 nm)



	<u>WAVELENGTH (NM)</u>	<u>MTF WEIGHTING</u>
x TANGENTIAL RESPONSE	800	40
+ SAGITTAL RESPONSE	700	8
∇ 45° RESPONSE	900	8

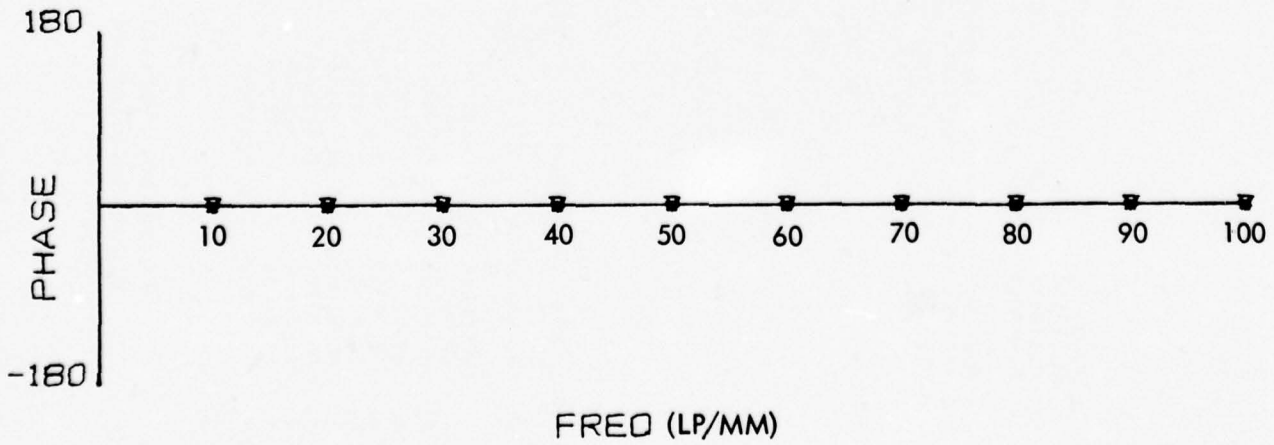


Figure 13. Partial modification of AN/PVS-5 with GEN III tube faceplate--on-axis MTF plots

SYSTEM DATA

P LIGHT=800 NM S LIGHT=700 NM T LIGHT=900 NM

BKFC = 0.000001 H = -0.9611038E 10 <F> = 9.379012 UK = -0.371659 Y1 = 9.878012  
 FCLN = 26.578100 MAG = -0.000000 <X> = 7.729409 UKRAR = 0.460048 Y19AR = -4.685411  
 FNIM = 1.345316 ORJD = 0.2669733E 11 TFF = 14.017809 UO = 0.000000  
 GSHT = 9.567968 OVLN = 50.872159 TFX = -20.747754 UOHAR = 0.360000  
 SPHR = 0.0167751 COMA = 0.0405832 TANG = -0.0044449 SAGT = -0.0688470 PLTZ = -0.1010281 DIST = -0.0697800  
 SPHR5 = -0.0000017 COMA5 = 0.0249715 TANG5 = 0.0407697 SAGT5 = 0.0552853 PFTZ5 = 0.0714143 DIST5 = -0.0010920  
 SPHR7 = -0.0162611 COMA7 = -0.0439639 TANG7 = 0.0469938 SAGT7 = 0.0792641  
 PA = -0.0179905 PL = -0.0035152 SA = -0.0073476 SL = -0.0010104

FULL FIELD CHIEF RAY DATA

FAM IS AT 1.00 FIELD, CHIEF RAY IS -0.9411029E 10  
 -- CHIEF RAY DATA IN P-LIGHT -- YES YEX Y-IMAGE L/W-IMAGE  
 0.000000 0.200236 9.943170 0.417072

S-T COLOR S-P COLOR X(S) X(T)  
 -0.005728 -0.002144 -0.019552 0.015991

ON-AXIS MTF DATA

GOOD SPOTS	FAILURES	FIELD POSITION	Y0/Y1	Y0/Y1	CHIEF RAY (IMAGE)	YK	YK	(XK, YK FOCUS-SHIFTED)	PHASE
P	S	T	P	S	T	P	S	T	PHASE
40	8	0	0	0	0	0.000000	0.000000	0.000000	45 DEGREE
1.	10.00000	0.949242	0.000000	0.000000	TANGENTIAL	0.949242	-0.000000	0.951127	-0.000002
2.	20.00000	0.827352	0.000000	0.000000	0.827352	-0.000000	0.849147	-0.000005	
3.	30.00000	0.701560	0.000000	0.000000	0.701579	-0.000016	0.762940	-0.000009	
4.	40.00000	0.625331	0.000000	0.000000	0.625331	-0.000023	0.699262	-0.000014	
5.	50.00000	0.604036	0.000000	0.000000	0.604036	-0.000025	0.629235	-0.000018	
6.	60.00000	0.603332	0.000000	0.000000	0.603332	-0.000023	0.561036	-0.000022	
7.	70.00000	0.525896	0.000000	0.000000	0.525896	-0.000017	0.522623	-0.000024	
8.	80.00000	0.540055	0.000000	0.000000	0.540055	-0.000004	0.498040	-0.000025	
9.	90.00000	0.476977	0.000000	0.000000	0.476977	-0.000003	0.446446	-0.000026	
10.	100.00000	0.407408	0.000000	0.000000	0.407407	-0.000001	0.373158	-0.000029	

Figure 14. Partial modification of AN/PVS-5 with GEN III tube faceplate-- system calculations

The triplet elements (4A, 4B, and 4C), plus the last two elements (5 and 6), are modified in position, shape, and thickness to control the aberration balance between surfaces 12 and 13 for correction of the faceplate aberrations. Elements 1, 2, and 3, and their intermediate spacings are held unchanged. The image intensifier tube faceplate has a spherical curvature with a radius of 44.3 mm. One glass change is present in element 6. The replacement is a flint glass of higher index and dispersion than the original.

The on-axis results show some improvement over the GEN II objective. Though higher order spherical aberrations are apparent in the outermost rays (note negative curl of the on-axis fan plots), MTF calculations show a 6 percent gain in contrast at both 20 and 40 line pairs per millimeter. The presence of the higher order effects impose the f/1.35 speed of this system as a maximum. If the aperture is opened, the minimum attainable on-axis spot size increases and a consequent reduction in contrast occurs.

Imaging off-axis is nearly equivalent to that of the GEN II objective. A different type of aberration balance exists with some residual negative higher order coma at full field. The resolution at these field angles can be improved by vignetting. This is an area for trade-off analysis. In many available binocular systems, high relative illuminance levels are not provided at full field and have proven not to be necessary. Since an observer tends to concentrate on the center of the field of view, and the option of adjusting the subject matter in this field exists, vignetting is not detrimental when the outer parts are visible for reference. The amount of vignetting necessary to improve the off-axis imaging will reduce the percent relative illuminance to approximately 50 percent from an initial 70 percent. Such a reduction is not significant.

Distortion is determined from the equation:

$$\% \text{ distortion} = \frac{\text{GSHT} - \text{Y-image}}{\text{GSHT}} \times 100\%$$

Y-image, the exact image height calculated by ray tracing, is provided under the heading "Full Field Chief Ray Results" on the system calculations page (Figure 14). GSHT, located under "System Data" on the same page, is the gaussian or first order approximation of the image height. This system's distortion of -7.1 percent closely matches the -7.3 percent of the original objective, providing compatibility with the current goggle eyepiece.

The length of the barrel assembly for this lens will be approximately 46 mm and have a glass weight close to 49 grams. (Note: GEN III lens lengths do not include the faceplate thickness.) Installation of a diaphragm iris, for reduction of aperture at higher than normal light levels and for increased depth of field, should be positioned behind the third lens element. The lens spacing is not, however, sufficient to easily retain the adjacent lenses and simultaneously mount the adjustable iris.

All surface curvatures and element combinations result in a manufacturing cost comparable to that of the AN/PVS-5 system. The edge on element 5 (1 mm at 20.2-mm diameter) indicates that a special lens cell must be used to mount this element if a single bore lens barrel is to be used. Further study and greater modification could alleviate this problem. Tube manufacturing costs may increase due to the curved surface required on the intensifier tube faceplate. This surface must be controlled in figure, centering, and sag to the same tight tolerances imposed on high quality lens elements.

## 2.3 TASK 2

### 2.3.1 Full Modification of AN/PVS-5 Goggle Objective With Thick Faceplate (Figures 15 Through 20)

The lens configuration of the AN/PVS-5 does not lend itself to extensive changes in element glass types without significant changes in the total lens configuration. Two advantageous material changes, plus controlled adjustment of the aberration balance, permit a reasonable performance result while maintaining a flat faceplate.

All curvatures, thicknesses, and airspaces are changed from the GEN II configuration. Element 4B (center of the triplet) is now a recently developed lightweight flint of higher index and dispersion than the original glass. Because element 6 contributes the same overcorrected spherical and axial color as the faceplate, this element's effect in these areas is reduced by using a lower index flint with less dispersion.

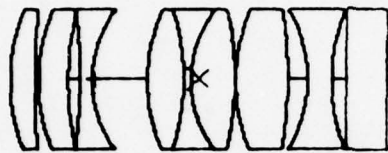
A better balance of higher order spherical aberrations with the third order contribution establishes an on-axis MTF higher than that of both the GEN II objective and the previously discussed partial modification. Gains of 14 percent for 20 lp/mm and 20 percent for 40 lp/mm at  $f/1.3$  are achieved over the AN/PVS-5. This speed is a maximum, as the dominance of higher order aberrations is already evident (see on-axis fan plots, Figures 16 through 18).

Similar improvements are present off-axis as the negative coma of the faceplate is neutralized. Calculation of distortion from the full field chief ray results gives -7.1 percent, again compatible with the current eyepiece. The sagittal full field fan does demonstrate some residual oblique spherical aberration, but, in general, the performance is equal to or better than that of the AN/PVS-5.

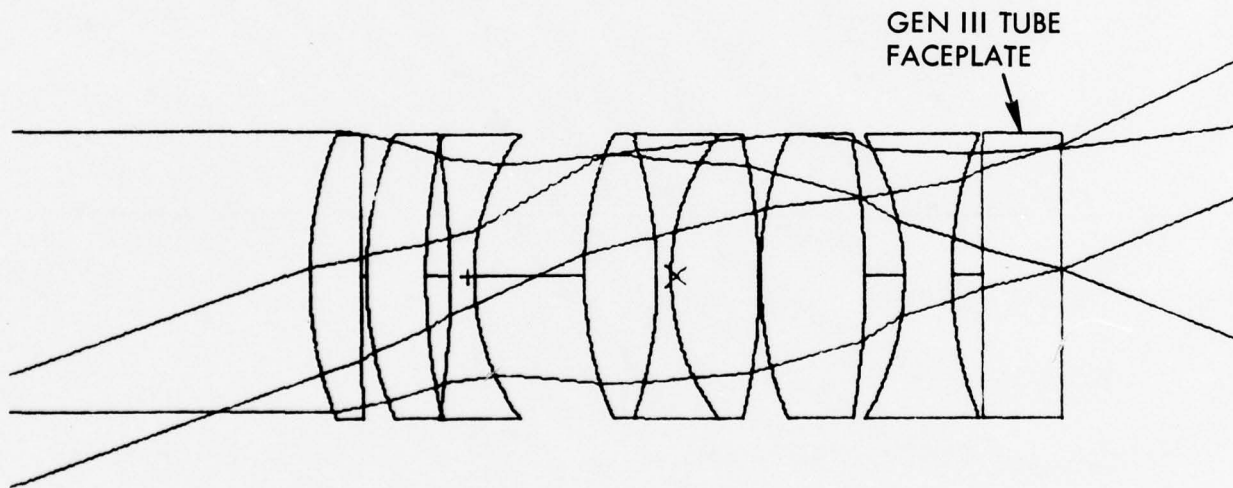
Figure 15 demonstrates that a single barrel inner diameter may be used for mounting the lens. The length of the barrel will be approximately 49 mm, which is longer than the partial modification, but not excessive. The natural stop is at element 3. The airspace between this element and the next is better suited for mounting an iris diaphragm than that afforded by the partial modification. An estimated glass weight for this system is 51 grams.

The MTF and aberration data show that when scaled for a 12-mm format, this design might be opened up to  $f/1.2$ . If further study allows modification of the higher order spherical aberration, a speed of  $f/1.1$  might be possible. The 51 grams listed above would scale to approximately 16 grams, but this number would increase if the  $f$ /number is opened up.

Several inherent characteristics of the AN/PVS-5 goggle objective still present in this system prevent significant reduction of weight and manufacturing costs. Several glass types are premium in quality with excellent resistance to environment, high transformation temperatures (desirable in obtaining hard coatings), and reasonable staining resistance. Unfortunately, weight and cost suffer. Over 50 percent of the glass types in the AN/PVS-5 have densities exceeding  $4.00 \text{ g/cm}^3$ . In addition, four of the elements have glass prices over \$50.00 per pound (grade A slab price). The lightweight, inexpensive replacement glasses used in this full modification cannot produce a noticeable reduction in weight and cost with these factors--plus the complex lens configuration--to overcome.



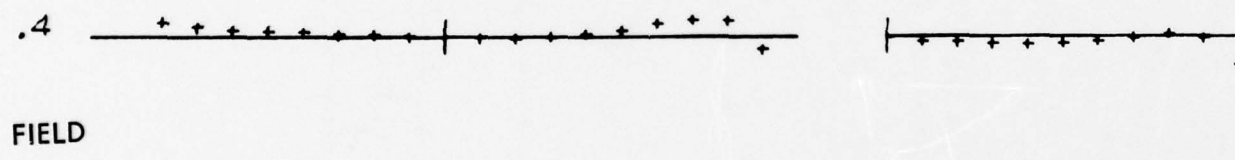
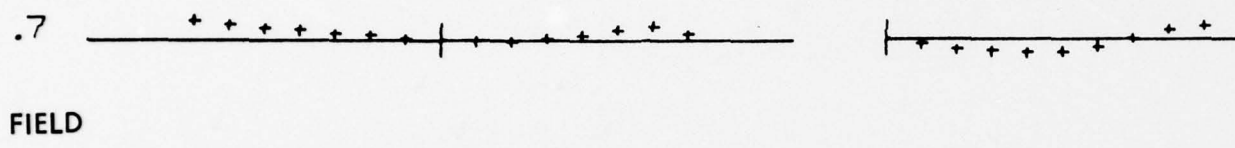
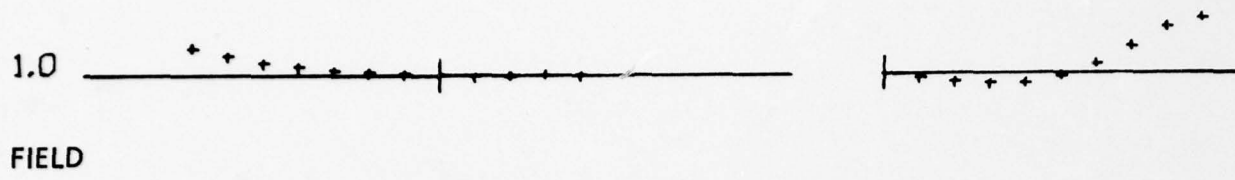
1:1 SCALE



2:1 SCALE

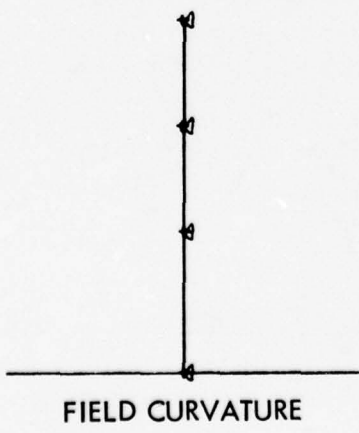
Focal length	26.55 mm ( $\lambda = 800$ nm)
F/no.	1.30
Field of view	40°

Figure 15. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate



TANGENTIAL FANS

SAGITTAL FANS



PLOT SCALE = 0.1 MM/IN.

Figure 16. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--ray trace fan plots for P light (800 nm)

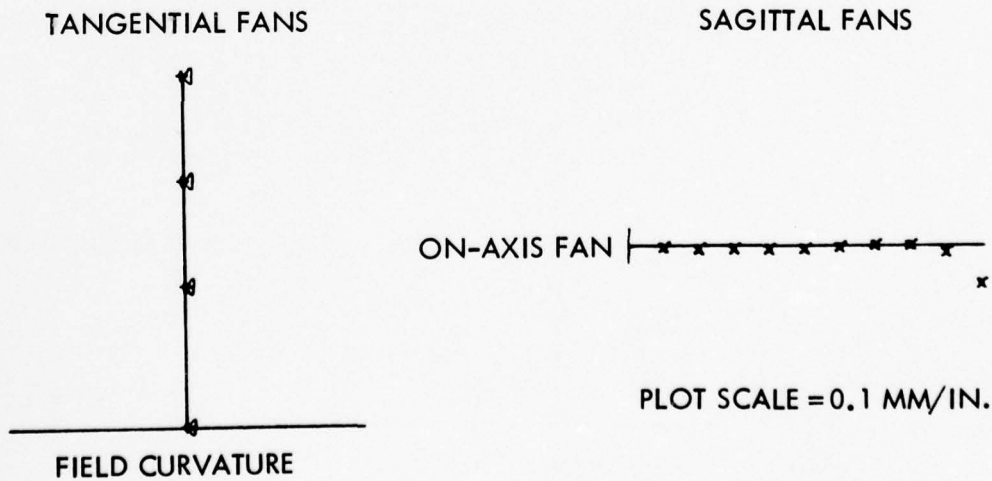
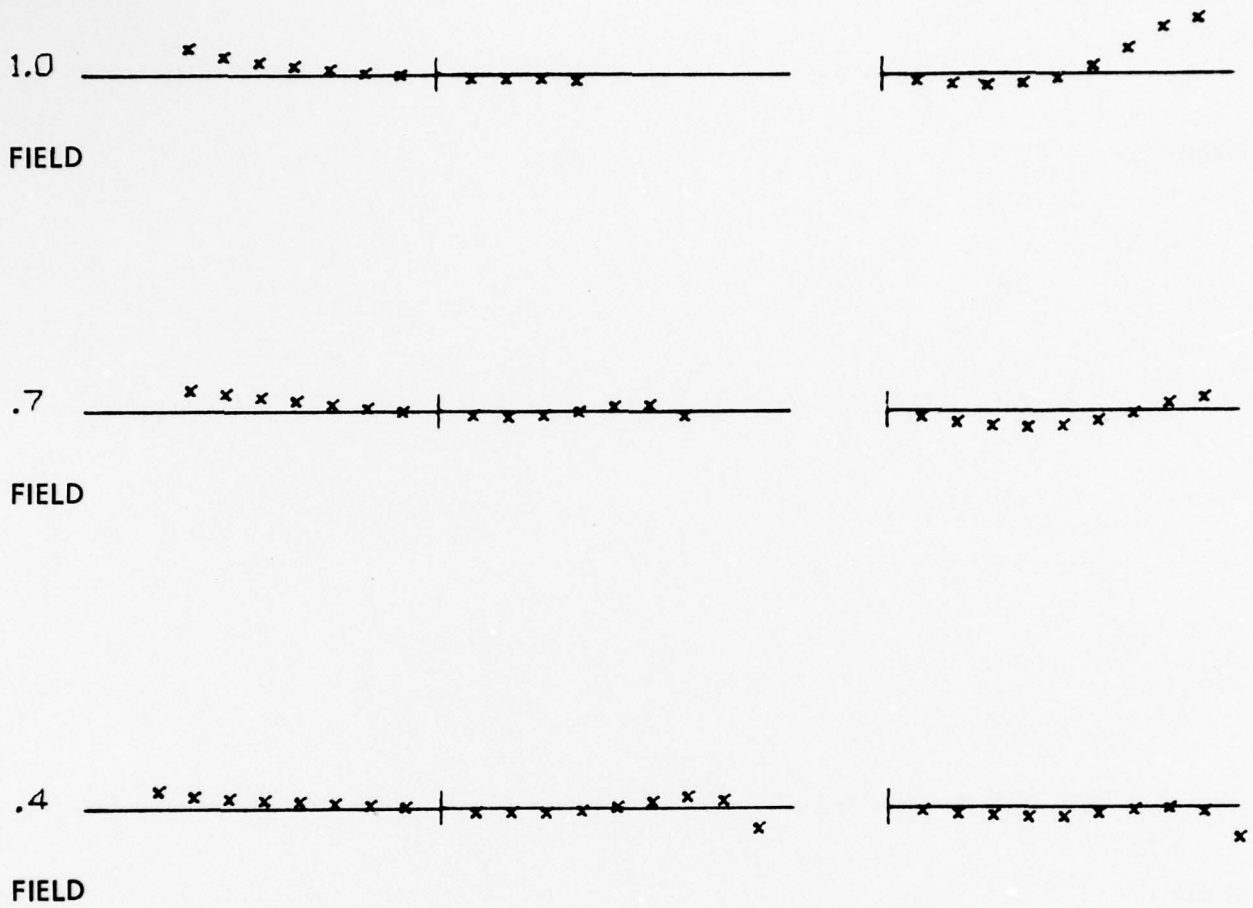
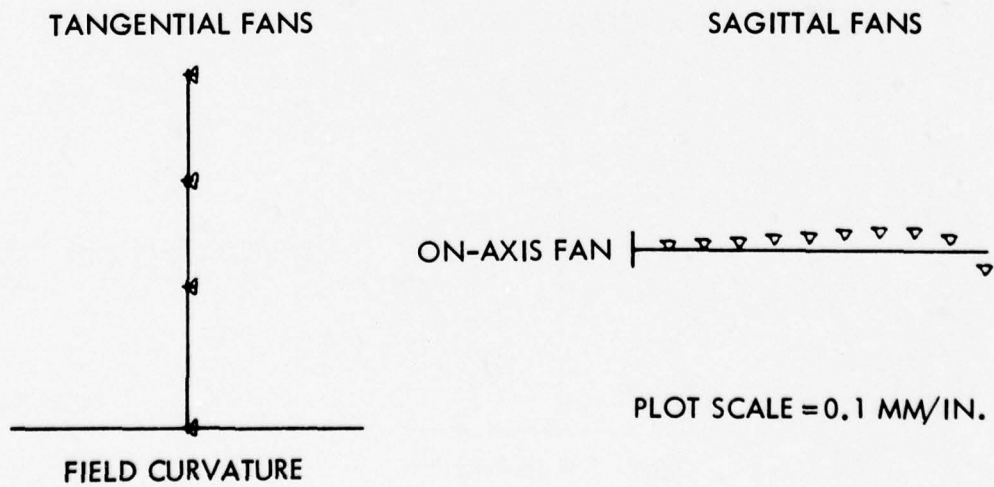
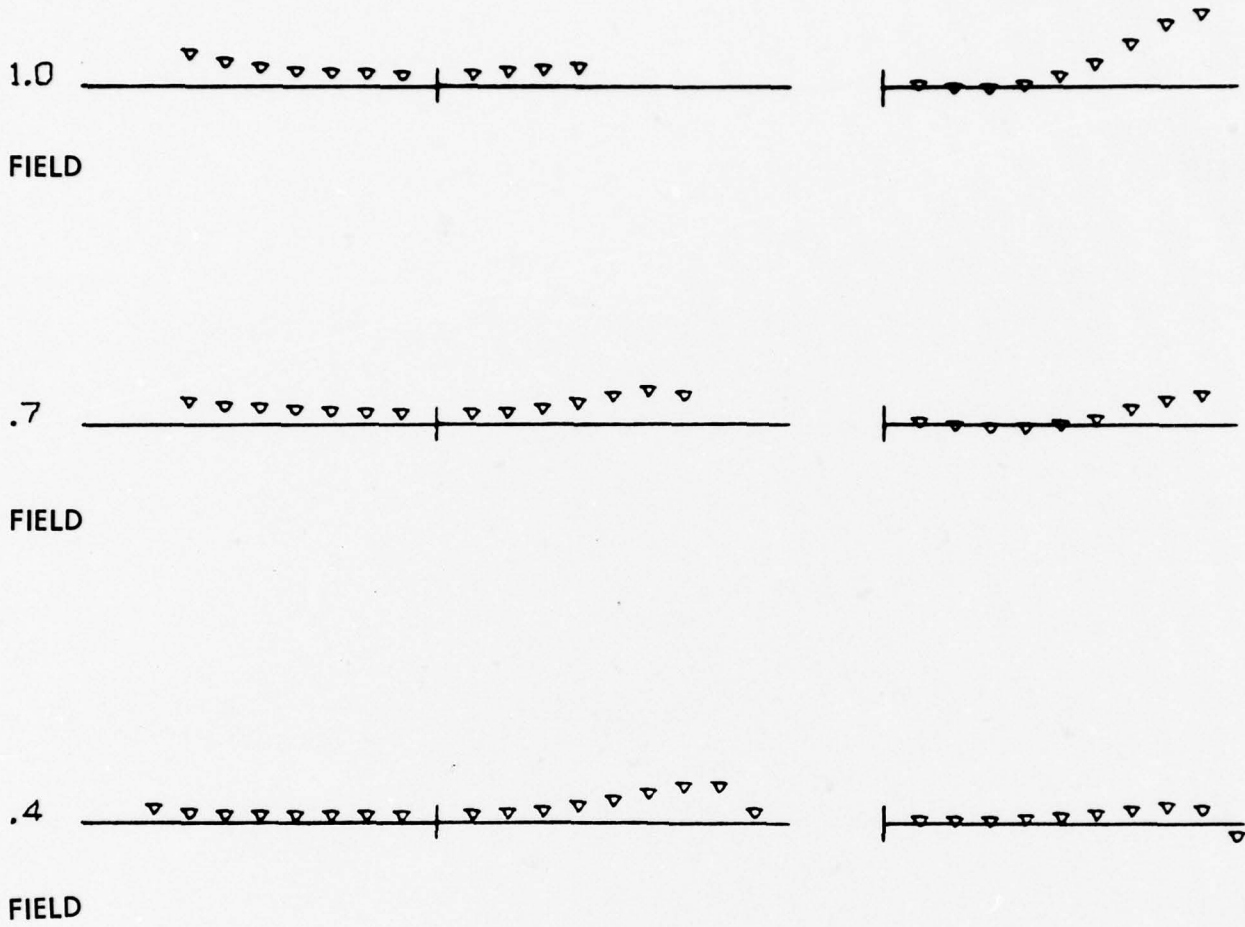
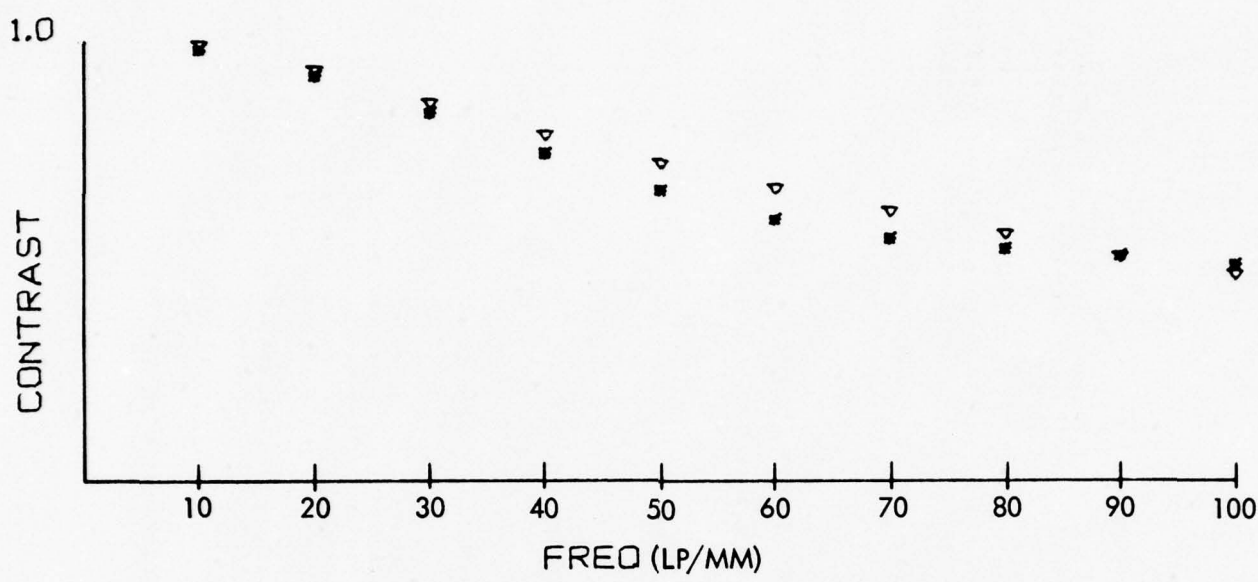


Figure 17. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--ray trace fan plots for S light (700 nm)



PLOT SCALE = 0.1 MM/IN.

Figure 18. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--ray trace fan plots for T light (900 nm)



	<u>WAVELENGTH (NM)</u>	<u>MTF WEIGHTING</u>
x TANGENTIAL RESPONSE	800	40
+ SAGITTAL RESPONSE	700	8
∇ 45° RESPONSE	900	8

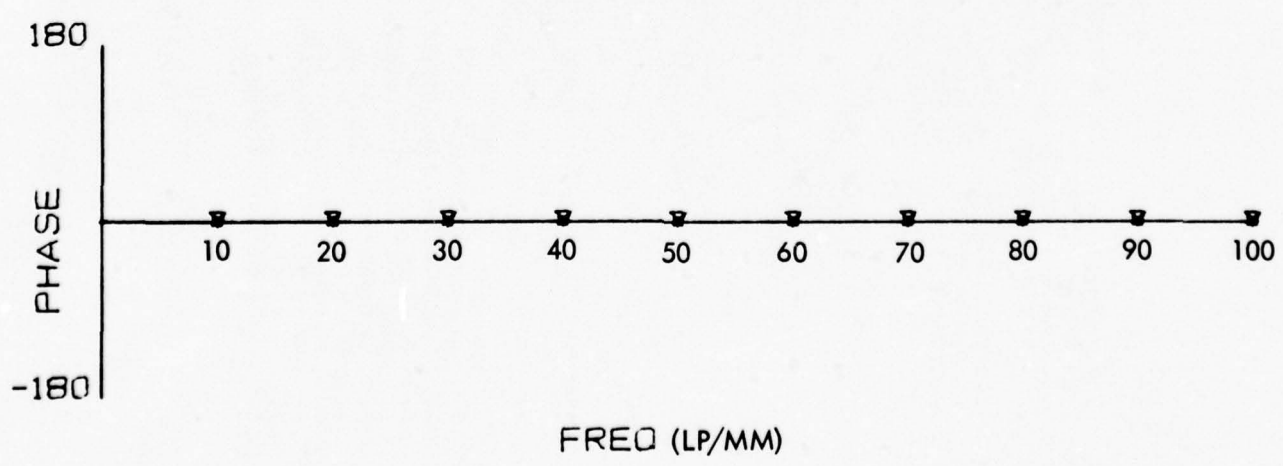


Figure 19. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--on-axis MTF plots

SYSTEM DATA

P LIGHT = 800 NM S LIGHT = 700 NM T LIGHT = 900 NM

BKFC = 0.000001 H = -0.9499017E 10 REH = 10.211440 UK = -0.384600 Y1 = 10.211440  
 FC1N = 26.550750 MAG = -0.000000 REF = 10.963174 UKRAA = 0.33531F Y1PAR = -3.802594  
 FNUN = 1.300049 OBJD = 0.2638616E 11 TEN = 10.562763 UO = 0.000000 UORAR = 0.360000  
 GSHT = 9.458936 OVLN = 54.114535 TFX = -28.507319 UORAR = 0.360000  
 SPHR = 0.0169527 COMA = 0.0250730 TANG = -0.0292960 SAGT = -0.0958941 PETZ = -0.1141932 DIST = -0.0703887  
 SPHR5 = 0.0000308 COMA5 = 0.0485097 TANG5 = 0.0330911 SAGT5 = 0.0607788 PETZ5 = 0.0577008 DIST5 = -0.00006153  
 SPHR7 = -0.0122014 ECOMA = 0.0222658 TORSA = 0.0775452 SORSA = 0.0949517  
 PA = -0.0152737 PL = -0.0071754 SA = -0.0065146 SL = -0.0027252

FULL FIELD CHIEF RAY DATA

FAN IS AT 1.00 FIELD, OBJECT HEIGHT IS -0.9499017E 10  
 -- CHIEF RAY DATA IN P-LIGHT -- YES YEN Y-IMAGE L/M-IMAGE  
 0.000000 0.789913 0.895508 0.28399E

S-T COLOR S-P COLOR X(S) X(T)  
 -0.005901 -0.001871 -0.068009 -0.007477

ON-AXIS MTF DATA

GOOD SPOTS P S T P S T	FAILURES P S T P S T	FIELD POSITION		CHIEF RAY (IMAGE)		45 DEGREE	PHASE
		YO/H	XO/H	YK	XK		
1.	10.00000	0.000000	0.000000	0.000000	0.000000	0.978606	-0.000005
2.	20.00000	0.978367	0.000000	-0.000007	0.000000	0.921774	-0.000010
3.	30.00000	0.918399	0.000000	-0.000015	0.000000	0.847203	-0.000016
4.	40.00000	0.833339	0.000000	-0.000022	0.000000	0.772931	-0.000022
5.	50.00000	0.740659	0.000000	-0.000030	0.000000	0.708511	-0.000028
6.	60.00000	0.656825	0.000000	-0.000036	0.000000	0.653066	-0.000035
7.	70.00000	0.592681	0.000000	-0.000041	0.000000	0.600659	-0.000043
8.	80.00000	0.550960	0.000000	-0.000045	0.000000	0.548085	-0.000052
9.	90.00000	0.526618	0.000000	-0.000048	0.000000	0.498741	-0.000062
10.	100.00000	0.509710	0.000000	-0.000050	0.000000	0.459677	-0.000072

Figure 20. Full modification of AN/PVS-5 goggle objective with GEN III tube faceplate--system calculations

### 2.3.2 Coupling of Baird-Atomic Lens No. MT/RR-001 to Thick Faceplate (Figures 21 Through 26)

As stated in the discussion of Task 1, the thick faceplate introduces over-corrected spherical and axial color, with off-axis positive astigmatism and negative coma. The new design reported in this section compensates for several of these problems and demonstrates the potential for modification toward an overall high quality performance.

The Baird-Atomic objective lens (No. MT/RR-001) consists of four simple singlets plus a doublet, and contains only two optical materials. Elements 1, 3, and 4B are of readily available, inexpensive, low dispersion crown glass. A styrene plastic is used in the remainder of the elements as a flint. Aspheric surfaces are not used on the plastic elements, but can be introduced to obtain increased performance levels.

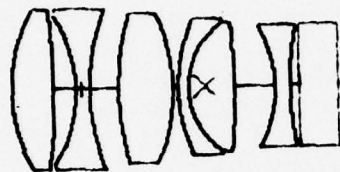
The length of the barrel assembly for this lens is 42 mm, a substantial improvement over that of the AN/PVS-5 by virtue of a 10-mm reduction. With no thin edge problems, a uniform barrel inner diameter is easily accommodated. However, the natural stop position, located after element 2, implies some difficulty in mounting an iris diaphragm. The glass/plastic weight is 28.3 grams, far lower than in any of the other systems considered, with the density of styrene (1.04 grams/cm<sup>3</sup>) accounting for much of this weight-saving.

The on-axis fan plots and MTF demonstrate excellent balancing of axial aberrations. Contrast is held to greater than 58 percent as far as 100 lp/mm, with values of 94 percent at 20 lp/mm, and 83 percent at 40 lp/mm. Because of the resolution limit of image intensifier tubes, this MTF is excessive and should be reduced to permit improvement in the off-axis behavior. Such a reduction will not result in a significant decrease in the f/1.25 speed, as trade-off can be accomplished without decreasing the system aperture.

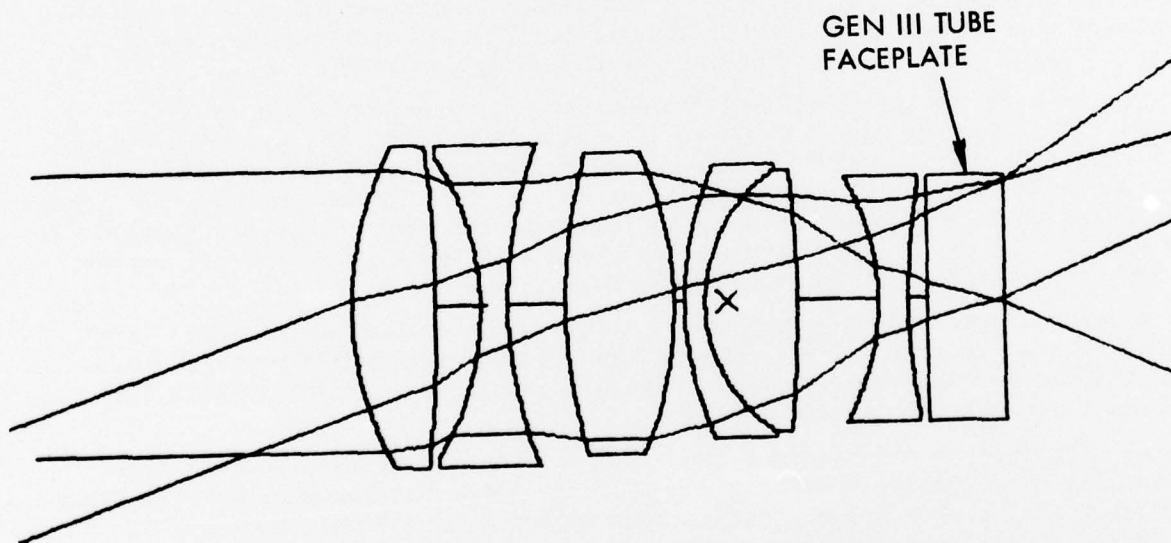
A final version of this lens could attain a speed approaching f/1.0 when scaled to a 12-mm format. In addition, the glass weight would most likely be less than 10 grams. Optimization of overall image quality for an 18-mm format ensures a similar result when scaled.

As presented, the design does not fully compensate at intermediate field angles for the negative coma introduced by the thick faceplate of GEN III tubes. At full field, higher order positive aberrations overcome the coma, but residual oblique spherical aberration remains. In optimizing the off-axis resolution, the distortion will also have to be modified as it is currently -4.9 percent.

Because of the small size of goggle objective elements, the material cost of the glasses is not as significant as their workability. This lens design is extremely simple in this respect. The glass elements are easily manufactured lens shapes, and the plastic elements, on a production basis, could be from 1/2 to as little as 1/20th the cost of equivalent glass elements. The exact cost of the plastics is a function of the production quantity, precision requirements, and optical coating complications. Due to the simplicity of this lens configuration, cost savings will still be evident even if replacement glass elements are used. If the benefits of plastics in cost and weight are to be realized, the current goggle standards may have to be relaxed. Plastics are not as stable as desired, which limits their use in systems containing critical balancing of surface aberrations.



1:1 SCALE

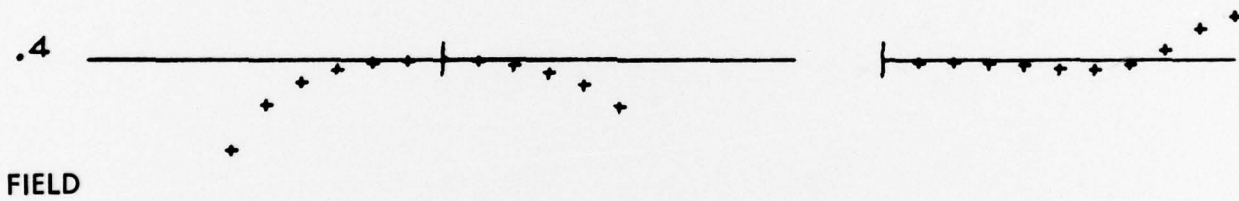
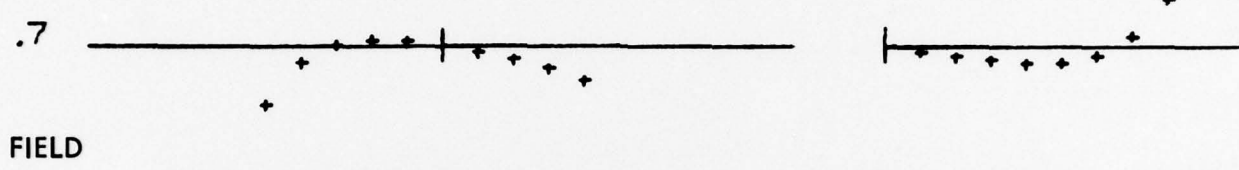
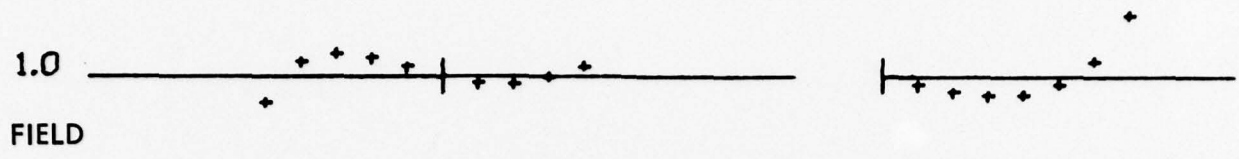


GEN III TUBE  
FACEPLATE

2:1 SCALE

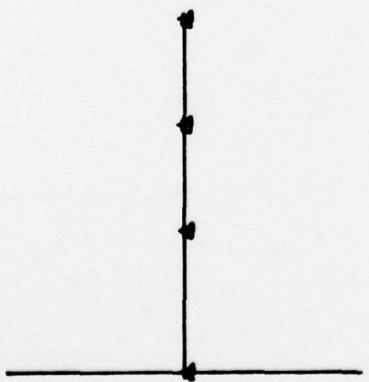
Focal length	26.24 mm ( $\lambda = 800$ nm)
F/no.	1.25
Field of view	40°

Figure 21. MT/RR-001 objective lens with GEN III tube faceplate

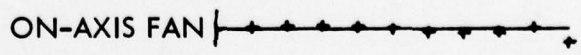


TANGENTIAL FANS

SAGITTAL FANS

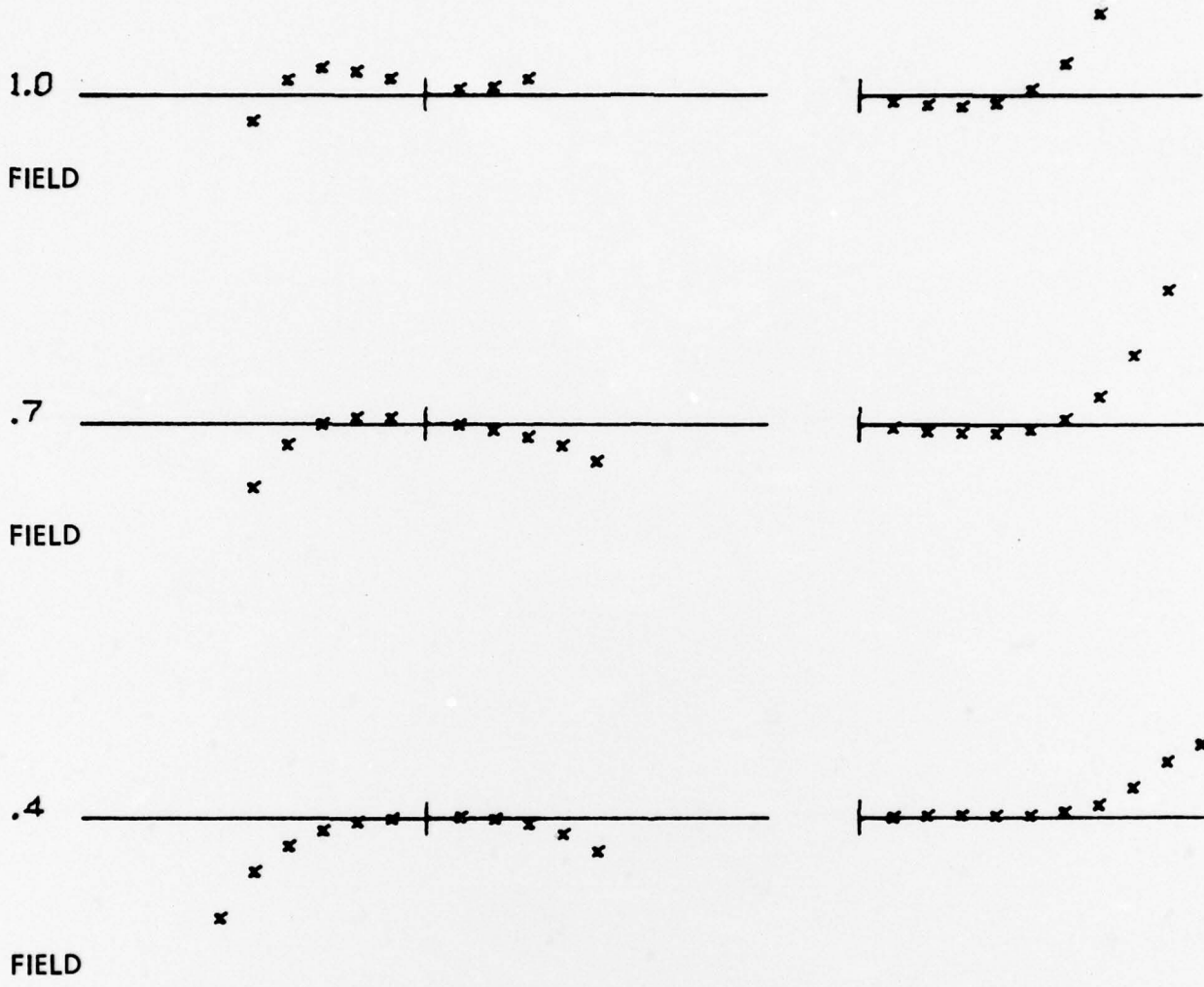


FIELD CURVATURE



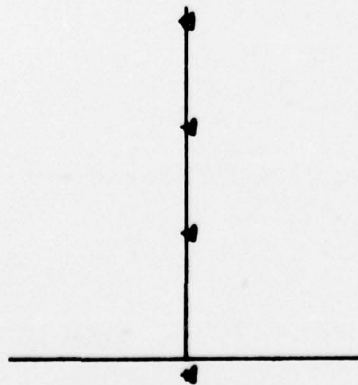
PLOT SCALE = 0.1 MM/IN.

Figure 22. MT/RR-001 objective lens with GEN III tube faceplate-- ray trace fan plots for P light (800 nm)

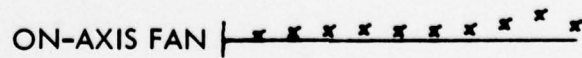


TANGENTIAL FANS

SAGITTAL FANS

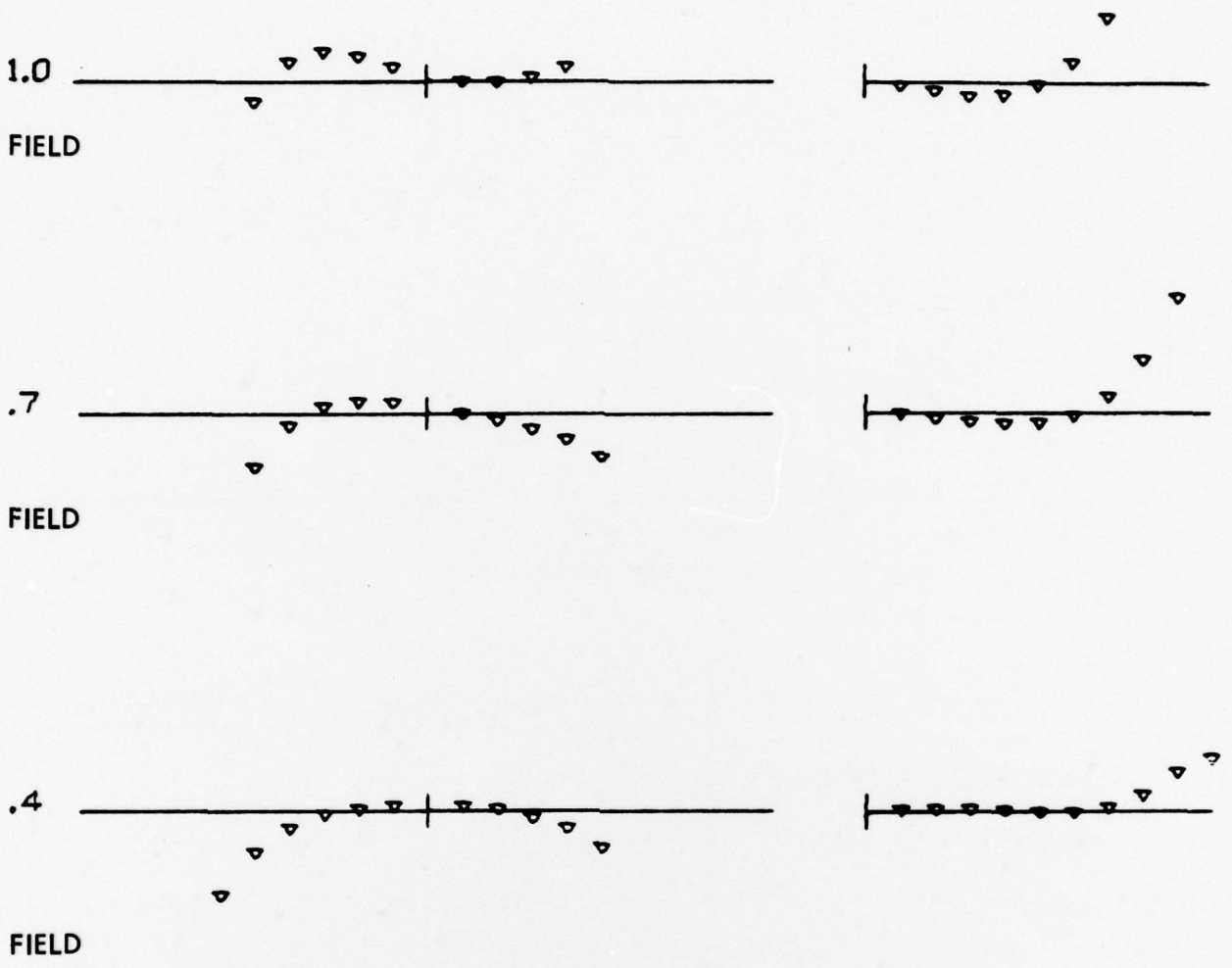


FIELD CURVATURE



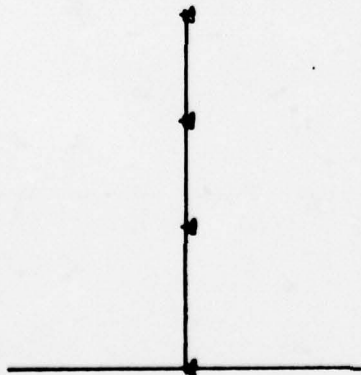
PLOT SCALE = 0.1 MM/IN.

Figure 23. MT/RR-001 objective lens with GEN III tube faceplate-- ray trace fan plots for S light (700 nm)

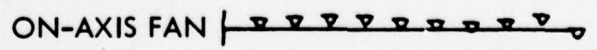


TANGENTIAL FANS

SAGITTAL FANS



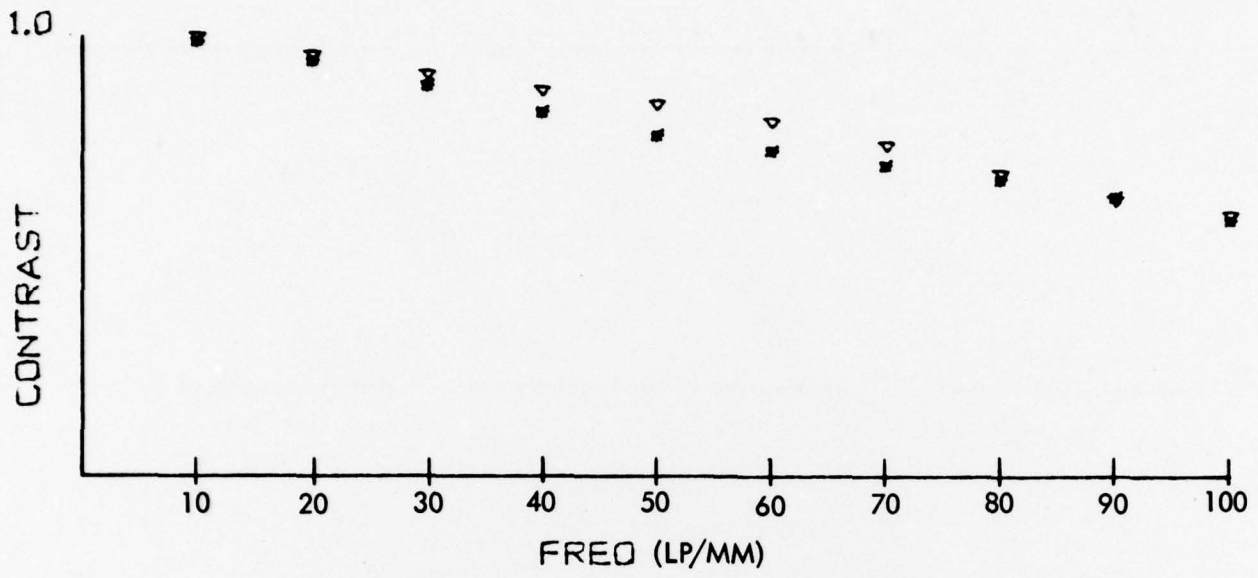
FIELD CURVATURE



ON-AXIS FAN

PLOT SCALE = 0.1 MM/IN.

Figure 24. MT/RR-001 objective lens with GEN III tube faceplate-- ray trace fan plots for T light (900 nm)



	<u>WAVELENGTH (NM)</u>	<u>MTF WEIGHTING</u>
x TANGENTIAL RESPONSE	800	40
+ SAGITTAL RESPONSE	700	8
∇ 45° RESPONSE	900	8

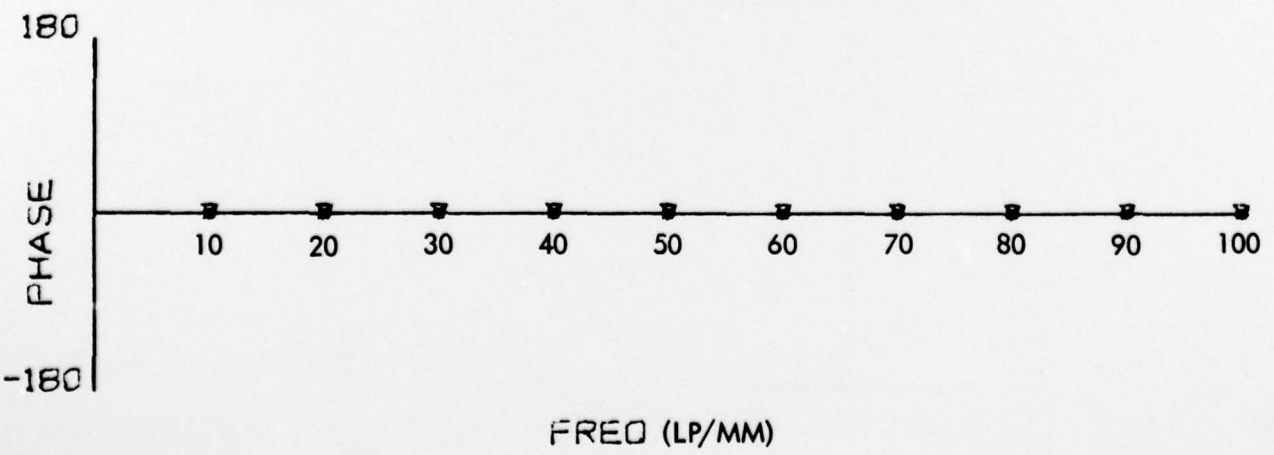


Figure 25. MT/RR-001 objective lens with GEN III tube faceplate-- on-axis MTF plots

SYSTEM DATA

P LIGHT = 800 NM S LIGHT = 700 NM T LIGHT = 900 NM

BKFC = 0.000010 H = -0.7055943E 10 REF = 10.500000 UK = -0.400140 Y1 = 10.500000  
 FCLN = 26.240767 MAG = -0.000000 REF = 0.351932 UKBAR = 0.4525A9 Y1RARE = -3.105631  
 FNUM = 1.249560 OBJD = 0.195994E 11 TFI = 0.626753 UO = 0.000000 UORAR = 0.360000  
 GSHT = 9.429872 OVLN = 47.173119 TFX = -20.835348 UORAR = 0.0096032 SL = 0.0013591  
 SPHR = -0.0747364 COMA = -0.1678585 TANG = -0.1305013 SAGT = -0.1172795 PETZ = -0.1106686 DIST = -0.0481948  
 SPHR5 = 0.0658596 COMA5 = -0.4135599 TANG5 = 0.6571687 SAGT5 = 0.0541446 PETZ5 = 0.0533886 DIST5 = -0.0007145  
 SPHR7 = 0.0231982 COMA7 = 0.1903245 TORSA = 0.3771697 SORSA = 0.1784069  
 PA = 0.0066364 PL = -0.0013214 SA = 0.0096032 SL = 0.0013591

FULL FIELD CHIEF RAY DATA

FAN IS AT 1.00 FIELD OBJECT HEIGHT IS -0.7055944E 10  
 -- CHIEF RAY DATA IN P-LIGHT --  
 YEN 0.000000 YFX -0.221367 Y-IMAGE 0.970542 L/M-IMAGE 0.441160  
 X(S) -0.102570 X(T) -0.006376

S-T COLOR S-P COLOR X(S) X(T)  
 0.004523 0.005050 -0.102570 -0.006376

ON-AXIS MTF DATA

GOOD P	SPOTS S	FAILURES T	FIELD POSITION YC/ZH	CHIEF RAY (IMAGE) YK	PHASE	TANGENTIAL	PHASE	45 DEGREE	PHASE
40	A	0	0	0.000000	0.000000	0.000000	-0.000000	0.000000	-0.000000
1.	10.00000	0.984510	0.000000	0.944510	0.000002	0.944510	-0.000002	0.944840	-0.000001
2.	20.00000	0.942415	0.000000	0.942415	-0.000005	0.942415	-0.000005	0.946907	-0.000003
3.	30.00000	0.885007	0.000000	0.885007	-0.000007	0.885007	-0.000007	0.903007	-0.000005
4.	40.00000	0.825818	0.000000	0.825818	-0.000010	0.825818	-0.000010	0.965026	-0.000007
5.	50.00000	0.775196	0.000000	0.775196	-0.000014	0.775196	-0.000014	0.932001	-0.000008
6.	60.00000	0.736544	0.000000	0.736544	-0.000016	0.736544	-0.000016	0.903146	-0.000010
7.	70.00000	0.705832	0.000000	0.705832	-0.000019	0.705832	-0.000019	0.874014	-0.000011
8.	80.00000	0.674509	0.000000	0.674509	-0.000021	0.674509	-0.000021	0.847735	-0.000013
9.	90.00000	0.634333	0.000000	0.634333	-0.000023	0.634333	-0.000023	0.819892	-0.000016
10.	100.00000	0.581845	0.000000	0.581845	-0.000026	0.581845	-0.000026	0.7861522	-0.000018

Figure 26. MT/RR-001 objective lens with GEN III tube faceplate-- system calculations

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### 3. CONCLUSIONS

A summary of the evaluation results is presented in Table 1 for reference. The conclusions given below are based upon the collected data and the results obtained for this report.

- The standard 40-degree GEN II goggle objective lens will not provide an adequate image through the flat faceplate of the GEN III image tube.
- A standard 40-degree GEN II goggle objective lens, with 75 percent of its elements modified, will give an adequate image on a curved faceplate GEN III tube, but is not a reasonable solution due to the high cost associated with this special curved image tube faceplate.
- A lens using the general form factor of a GEN II lens, but with new curvatures and some low-cost glass, will offer good image quality on a flat faceplate GEN III lens.
- A lens designed solely for the narrow spectral response of a flat faceplate GEN III tube is the best solution.
- No substantial gain in optical aberration correction is achieved by curving the thick faceplate of the GEN III tube.
- The stability of plastic lens elements limits the useful operational temperature range for total aberration correction.
- The length, weight, and cost of goggle objective lens systems can only be reduced in a lens with form factors different from those of the GEN II lens design.
- A multilayer, antireflection coating on the tube may improve the contrast transfer of a GEN III tube. Because of the low index glass faceplate, single layer magnesium fluoride does not offer much improvement over uncoated glass for its cost.
- Any rejection filters needed should be built into the objective lens glass to save system weight.

Table 1. Summary of Results

	18-mm AN/PVS-5 Goggle Objective Lens Without Glass Faceplate	Partial Modification of AN/PVS-5 With GEN III Faceplate (Curved)	Full Modification of AN/PVS-5 With GEN III Faceplate (Flat)	MT/RR-001 Objective Lens With GEN III Faceplate (Flat)
Spectral region, $\mu$	0.55-0.85	0.7-0.9	0.7-0.9	0.7-0.9
Field of view, degrees	40	40	40	40
EFL, mm	26.64	26.58	26.55	26.24
F/no.	1.33	1.35	1.30	1.25
T-no.	1.46	1.48	1.43	1.42
Full field rel. illum., percent	70	65	60	50
MTF at 30 lp/mm, percent	60	68	81	89
Distortion, percent	-7.29	-7.05	-7.05	-4.87
Glass weight, grams	57.19	48.90	50.75	28.28
Length, mm	51.51	45.59	48.44	40.02

#### 4. RECOMMENDATIONS

1. Develop and build a glass prototype goggle objective lens system specifically designed for use with flat faceplate, third generation image intensifier tubes.
2. Develop and build a glass/plastic prototype goggle objective system for the same application as 1.
3. Require 1 and 2 to have equivalent laboratory performance.
4. Specify 1 and 2 to have length, weight, and projected manufacturing costs less than for current goggle objective systems.
5. Carry out environmental field test of both 1 and 2 incorporated into a GEN III goggle system or equivalent.
6. Examine the effects of 5 on a glass/plastic prototype objective with human response and laboratory tests.

In the course of developing the prototypes of 1 and 2, focal length, field of view, and distortion results may not be compatible with existing goggle eyepiece systems. The concurrent development of less costly, lightweight eyepieces compatible with the prototype objective lenses should be considered. This will permit advantageous changes in focal length and field of view while ensuring the maintenance of a distortionless system.

Appendix A  
LENS PRESCRIPTIONS

Table A-1. Lens Prescription, AN/PVS-5 Goggle Objective

	<u>Radius of Curvature, mm</u>	<u>Thickness, mm</u>	<u>N<sub>d</sub></u>	<u>V<sub>d</sub></u>
Element 1	26.82	4.40	1.728	28.7
	72.61	1.29		
Element 2	26.82	3.90	1.734	51.7
	58.74	2.34		
Element 3	-32.17	1.70	1.785	26.1
	18.93	4.17		
Element 4A	43.00	5.80	1.734	51.7
Element 4B	-11.83	1.00	1.698	38.6
Element 4C	-101.54	3.00	1.697	55.4
	-27.73	3.00		
Element 5	22.99	5.60	1.788	47.4
	-41.45	2.00		
Element 6	-28.14	2.40	1.654	33.7
	33.7			

Table A-2. Lens Prescription, Partial Modification of AN/PVS-5 With GEN III Tube Faceplate

	<u>Radius of Curvature, mm</u>	<u>Thickness, mm</u>	<u>N<sub>d</sub></u>	<u>V<sub>d</sub></u>
Element 1	26.886	4.405	1.728	28.7
	72.745	1.281		
Element 2	26.886	3.898	1.734	51.7
	58.870	2.349		
Element 3	-32.243	1.709	1.785	26.1
	18.975	2.606		
Element 4A	33.082	4.234	1.734	51.7
Element 4B	-26.046	1.175	1.698	38.6
Element 4C	14.066	5.446	1.697	55.4
	-39.203	0.507		
Element 5	24.303	4.232	1.788	47.4
	-46.189	6.060		
Element 6	-23.357	5.657	1.785	25.8
	366.722	2.032		
Faceplate	-44.274 ∞	5.281	1.487	65.2

Table A-3. Lens Prescription, Full Modification of AN/PVS-5 Goggle Objective  
With GEN III Tube Faceplate

	<u>Radius of Curvature, mm</u>	<u>Thickness, mm</u>	<u>N<sub>d</sub></u>	<u>V<sub>d</sub></u>
Element 1	28.043	3.689	1.728	28.7
	258.664	0.391		
Element 2	26.692	4.275	1.734	51.7
	43.659	1.773		
Element 3	-67.591	1.683	1.785	26.1
	17.539	7.924		
Element 4A	25.998	5.280	1.734	51.7
Element 4B	-32.336	0.979	1.706	30.8
Element 4C	17.059	6.364	1.697	55.4
	-45.585	0.082		
Element 5	27.576	7.533	1.788	47.4
	-60.778	2.861		
Element 6	-20.048	3.404	1.549	45.4
	27.824	2.199		
Faceplate	$\infty$ $\infty$	5.678	1.487	65.2

## Appendix B

### ABBREVIATIONS, ACRONYMS

BKFC	Paraxial system backfocus
COMA	Transverse tangential coma--3rd order
COMA5	Transverse tangential coma--5th order
DIST	Fractional distortion--3rd order
DIST5	Fractional distortion--5th order
ECOMA	Transverse elliptical coma
FCLN	Equivalent focal length
FNUM	F/number
GSHT	Gaussian image height
H	Object height
L/M-IMAGE	Slope of chief ray at image
OBJD	Object distance
OVLN	System length (first surface to paraxial image plane)
P	Primary light
PA	Transverse primary axial color--1st order
PETZ	Transverse Petzval blur--3rd order
PETZ5	Transverse Petzval blur--5th order
PL	Transverse primary lateral color--1st order
REN	Radius of entrance pupil
REX	Radius of exit pupil
S	Secondary light
SA	Transverse secondary axial color--1st order
SAGT	Transverse sagittal blur--3rd order
SAGT5	Transverse sagittal blur--5th order
SL	Transverse secondary lateral color--1st order
SOBSA	Transverse sagittal oblique spherical
S-P COLOR	Transverse secondary lateral color
SPHR	Transverse spherical--3rd order
SPHR5	Transverse spherical--5th order
SPHR7	Transverse spherical--7th order
S-T COLOR	Transverse primary lateral color
T	Tertiary light
TANG	Transverse tangential blur--3rd order
TANG5	Transverse tangential oblique spherical
TEN	Distance from first surface to entrance pupil
TEX	Distance from last surface to exit pupil
UK	Slope angle of axial ray at last surface
UKBAR	Slope angle of chief ray (full field) at last surface
UO	Slope angle of axial ray at object
UOBAR	Slope angle of chief ray (full field) at object

ABBREVIATIONS, ACRONYMS (Cont.)

XK	Sagittal ray height at last surface
XO	Sagittal ray height at object
YEN	Tangential height of ray at entrance pupil
YEX	Tangential height of ray at exit pupil
Y-IMAGE	Tangential ray height at image
YK	Tangential ray height at last surface
YO	Tangential ray height at object
Y1	Tangential height of axial paraxial ray at first surface
Y1BAR	Tangential height of chief paraxial ray at first surface