The CECOM Center for Night Vision and Electro-Optics

OPTOELECTRONIC WORKSHOPS

VI

TESTING / FABRICATION / GRADIENT INDEX OPTICS AND COMPUTER AIDED MANUFACTURE OF OPTICS

May 24, 1988

sponsored jointly by

ARO-URI Center for Opto-Electronic Systems Research
The Institute of Optics, University of Rochester

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This workshop on "Testing/Fabrication/Gradient Index Optics and Computer Aided Manufacture of Optics" represents the sixth of a series of intensive academic/ government interactions in the field of advanced electro-optics, as part of the Army sponsored University Research Initiative. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, NVEOC.

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OPTOELECTRONIC WORKSHOP

ON

TESTING / FABRICATION / GRADIENT INDEX OPTICS AND COMPUTER AIDED MANUFACTURE OF OPTICS

Organizer: ARO-URI-University of Rochester
and CECOM Center for Night Vision and Electro-Optics

1. INTRODUCTION

This workshop on "Testing/Fabrication/Gradient Index Optics and Computer Aided Manufacture of Optics" represents the sixth of a series of intensive academic/ government interactions in the field of advanced electro-optics, as part of the Army sponsored University Research Initiative. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, CCNVEO.

2. SUMMARY AND FOLLOW-UP ACTIONS

As part of the URI program, I visited Fort Belvoir to give a workshop on gradient index optics. The workshop was organized by Bob Spande (703-664-6665) and Tom Cody who works for Bob. Approximately ten to twelve people attended the workshop, although the number varied throughout the day. In addition, representatives of CVD, Incorporated, Woburn, MA were in attendance (Dr. Ray Taylor and Dr. Hemant Desai) and two people from Gradient Lens Corporation (Dr. Leland Atkinson and Mr. Robert Zinter). I gave a standard presentation of gradient index optics which created pretty lively discussion, particularly on the possibilities of using gradient index for night vision goggles, helmet mounted displays, IR rifle scopes and IR goggles. Some interesting interaction occurred with the possibility of using tin in germanium to make gradient index. This has been suggested by Charles Freeman. He also suggested the possibility of making gradient detectors, for example, to change the spectraband of various detectors. Apparently this has been done already. He also suggested it might be possible to do space processing of radial gradients and that they would help us in doing this if we were interested. Finally, he suggested it might be time to revisit the Ogive problem. (This is a problem whereby the shape of the surface is no longer spherical but is pointed, and thus the optics are complicated. This would be particularly important since high index materials may now be available and it may be possible to correct the aberrations in a better way than had been previously done. It might be worth proposing something to them.

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH

GRADIENT INDEX OPTICS

REFRACTION IN NATURE

MIRAGE -- UNUSUAL REFRACTION

MATHEMATICAL BASIS

SCORESBY	1828
BREWSTER	1835

SUN

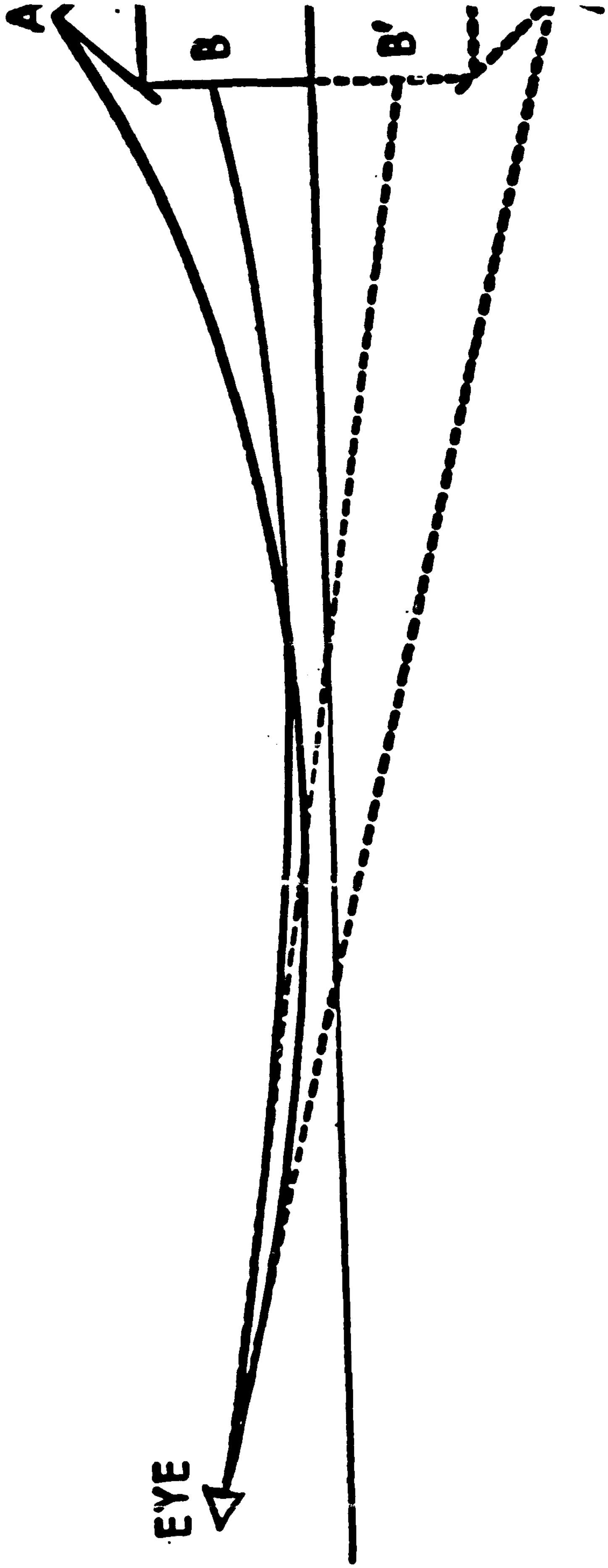
SCHMIDT

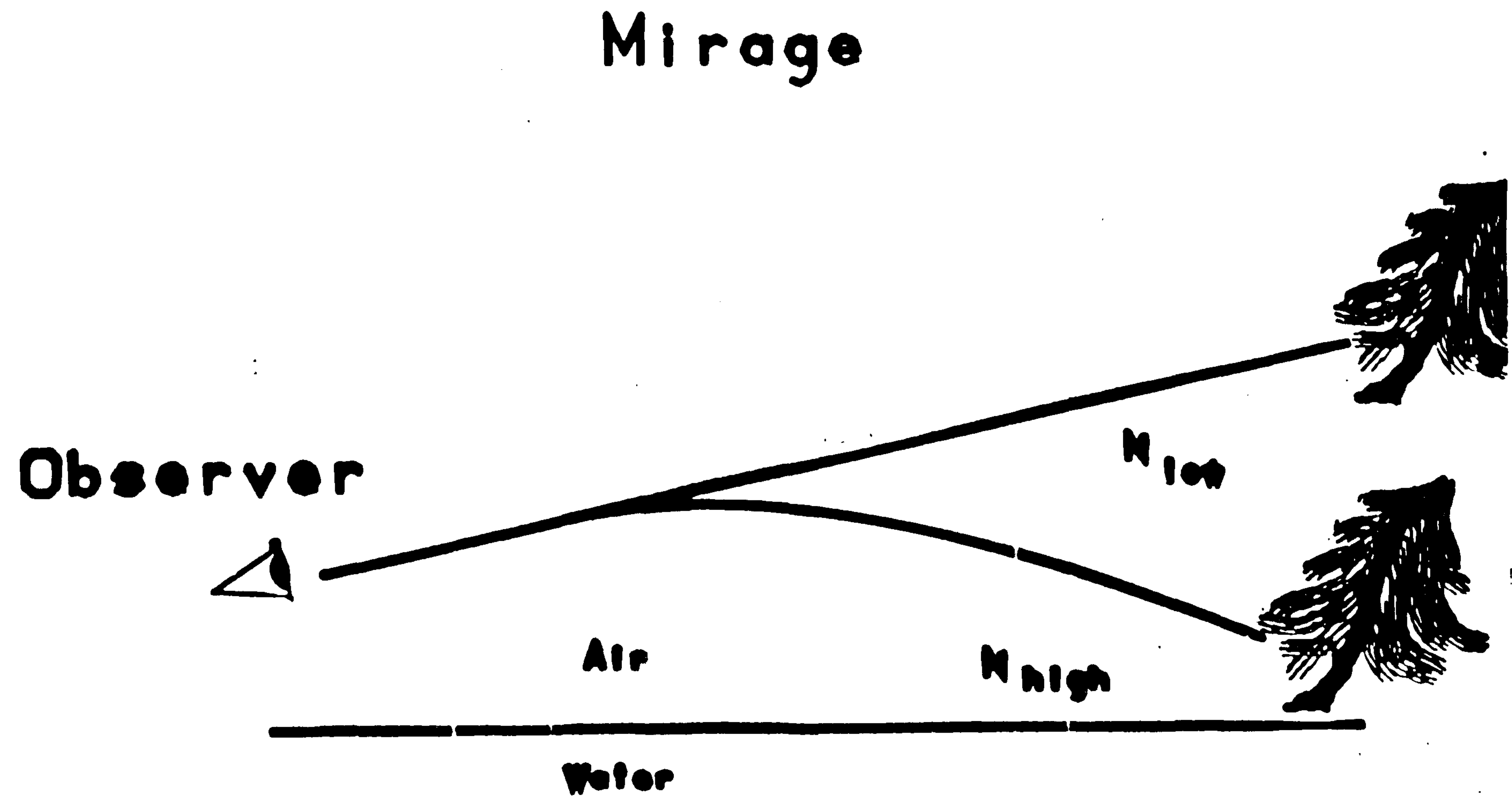
HUMAN EYE

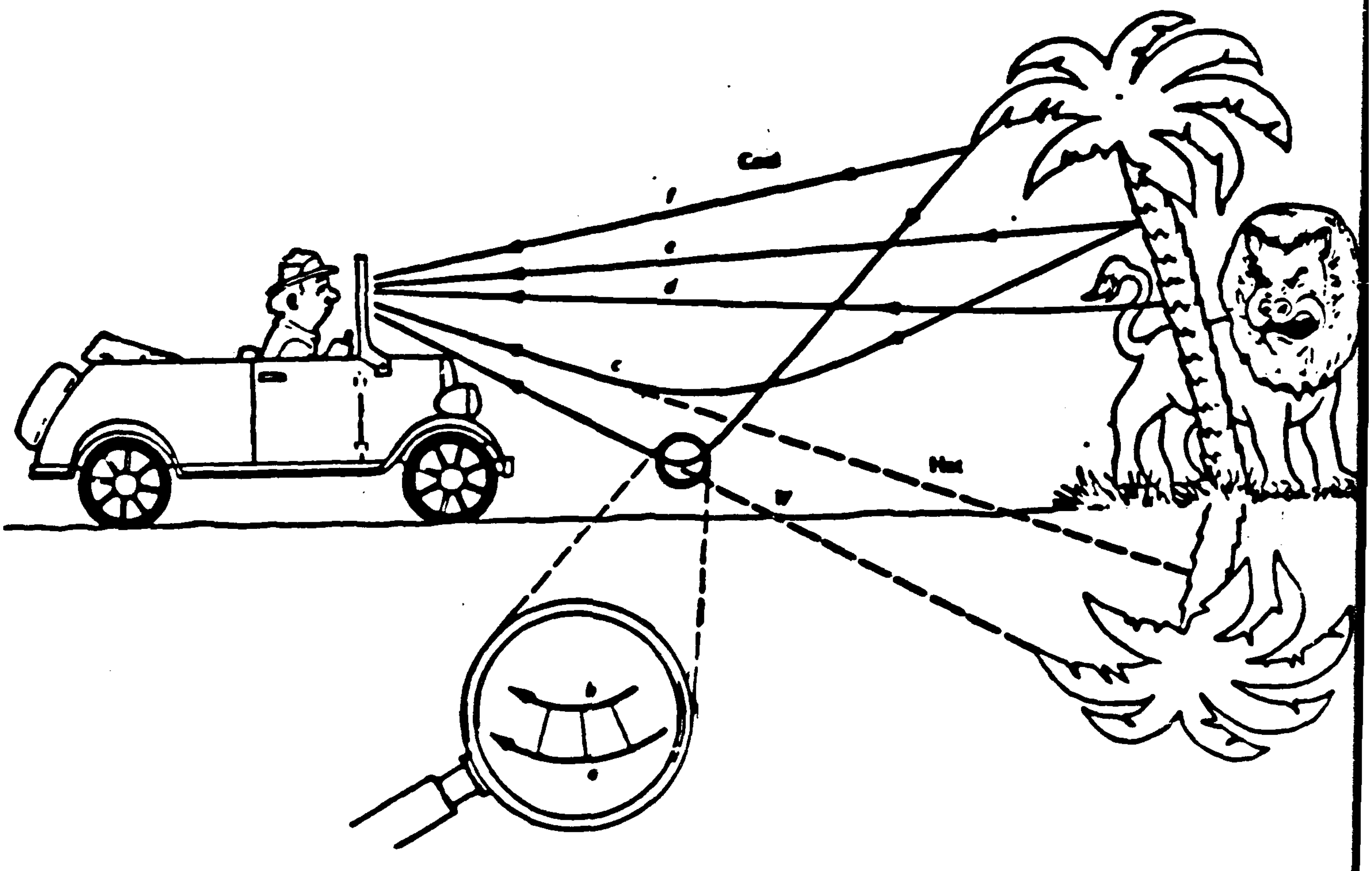
HELMHOTZ	1909

INSECT EYE

EXNER	1887


A
B
B'
EYE


Mirage
Observer
N low
Air
N high
Water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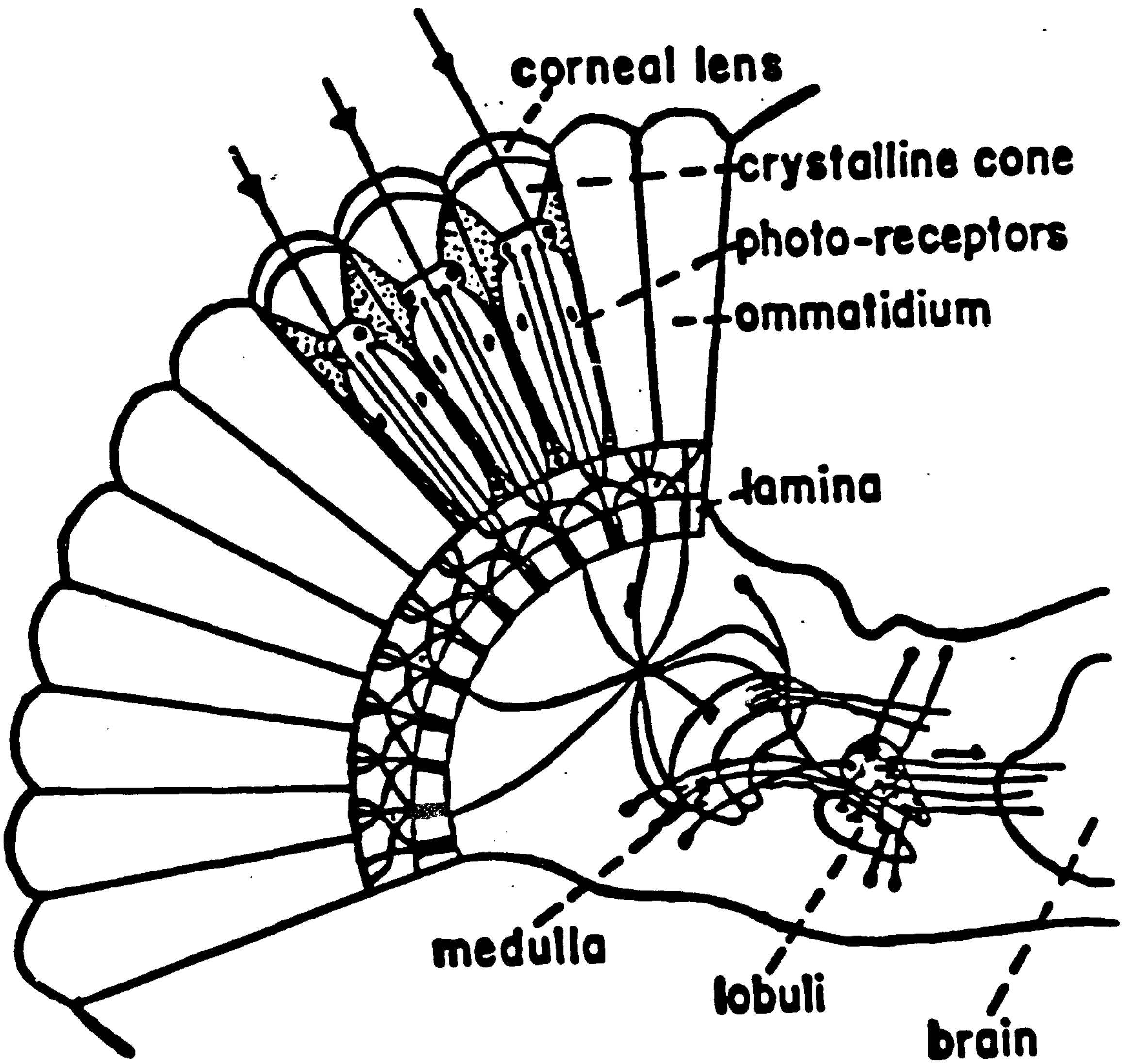
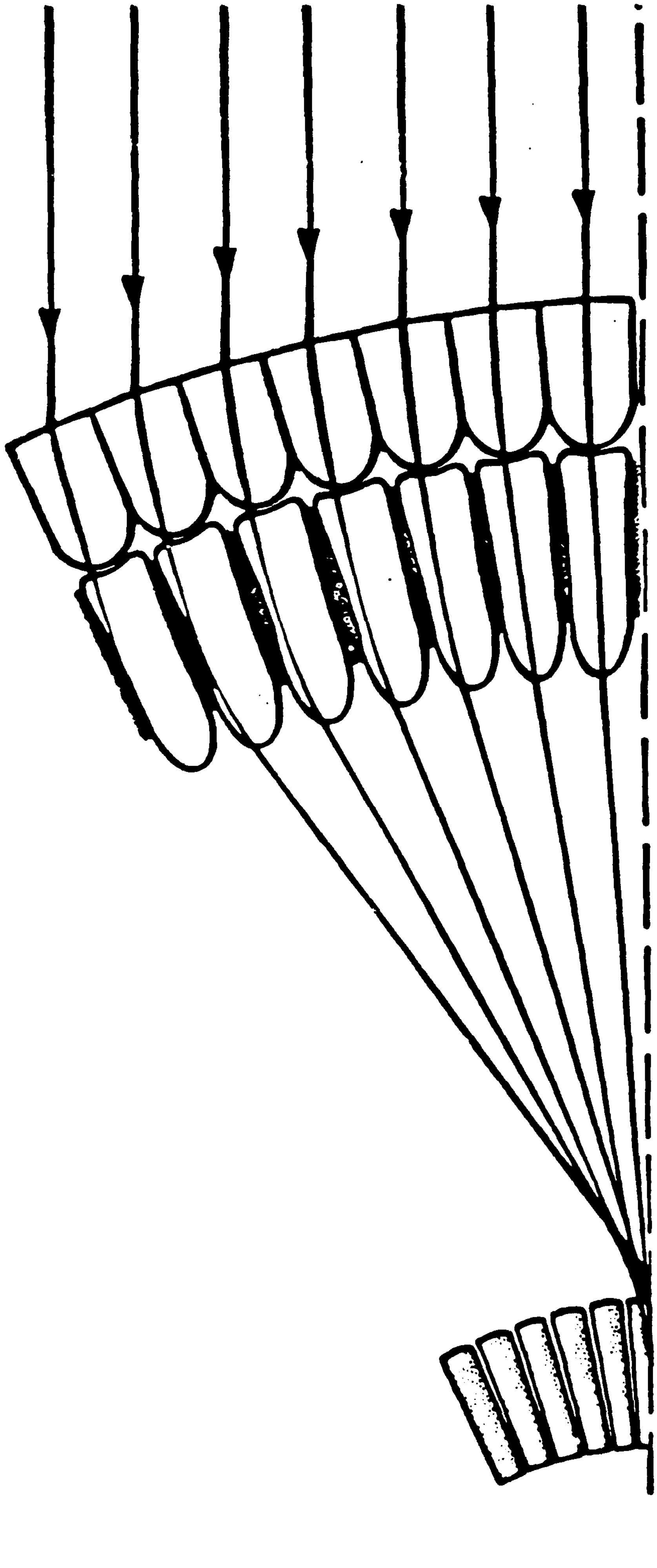
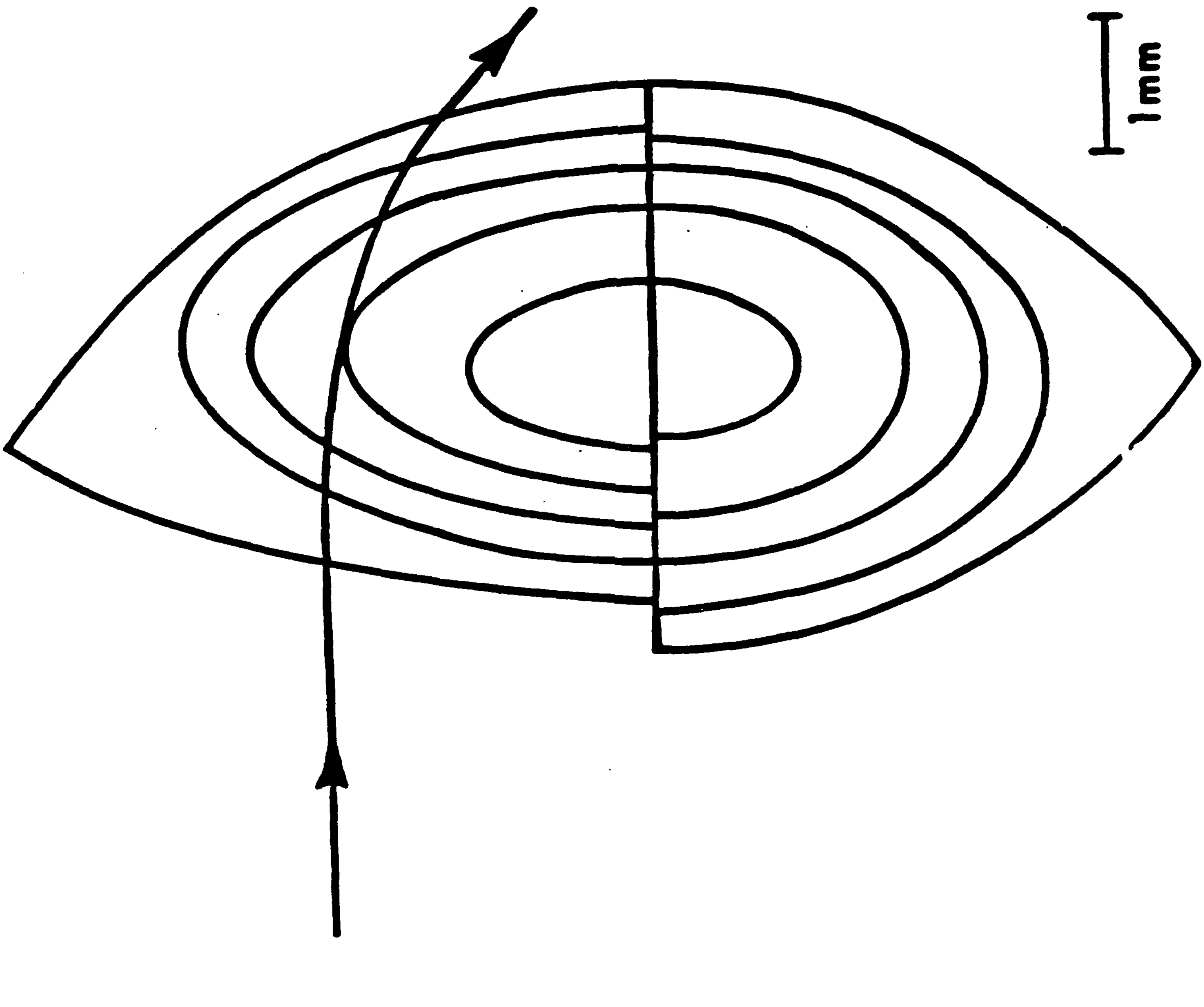


Figure 1.3
Compound Eye of the Musca Insect




1mm

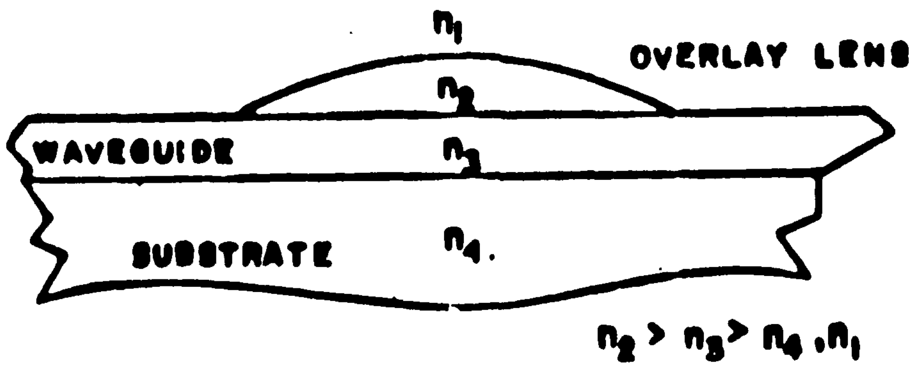
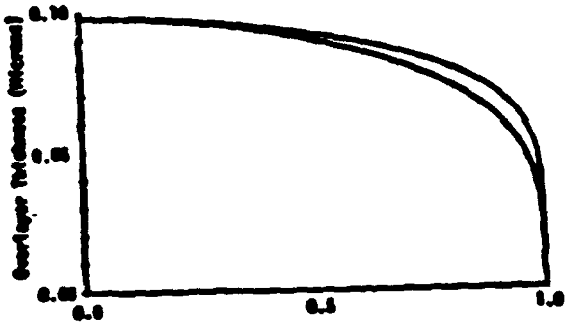


Fig. 1 Cross section of multilayer planar dielectric waveguide

OPTICAL GUIDED WAVES

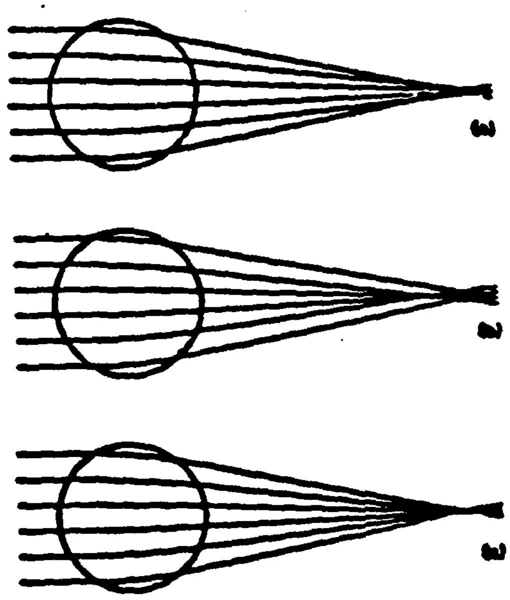
OVERLAY THICKNESS



RADIUS

A- $\cos^{0.18}$
B- $\cos^{0.25}$

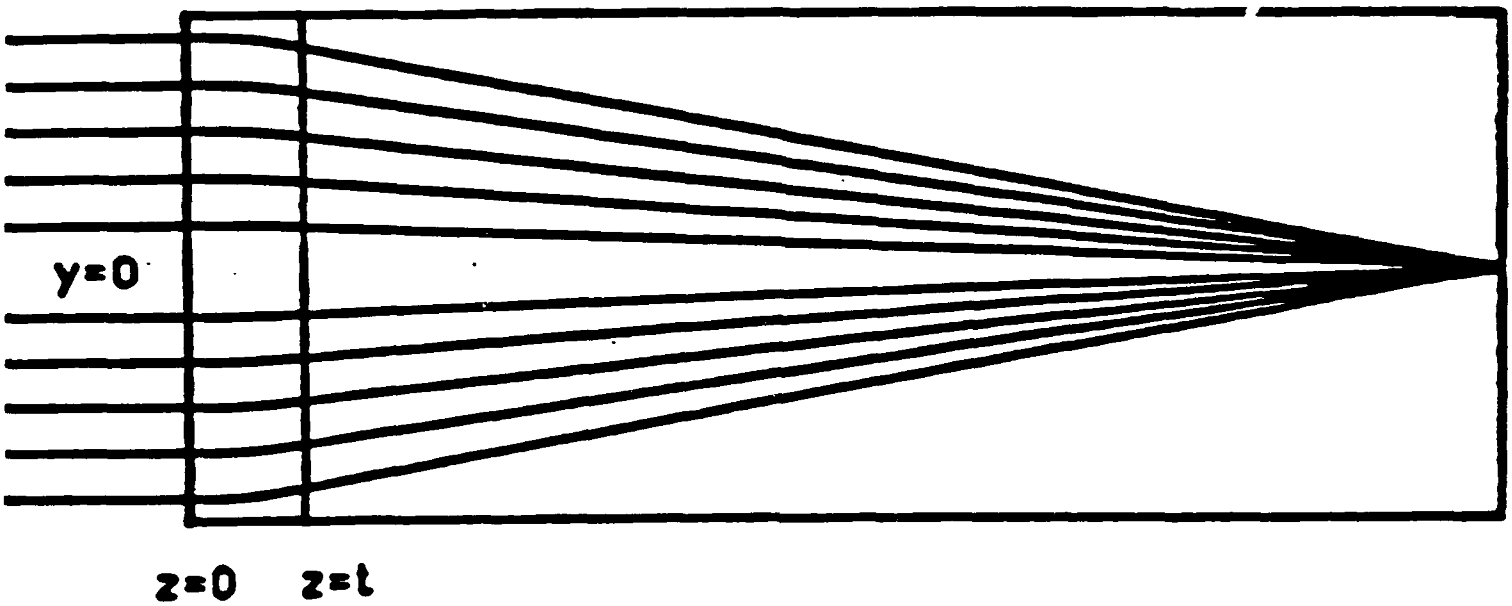
ABERRATIONS

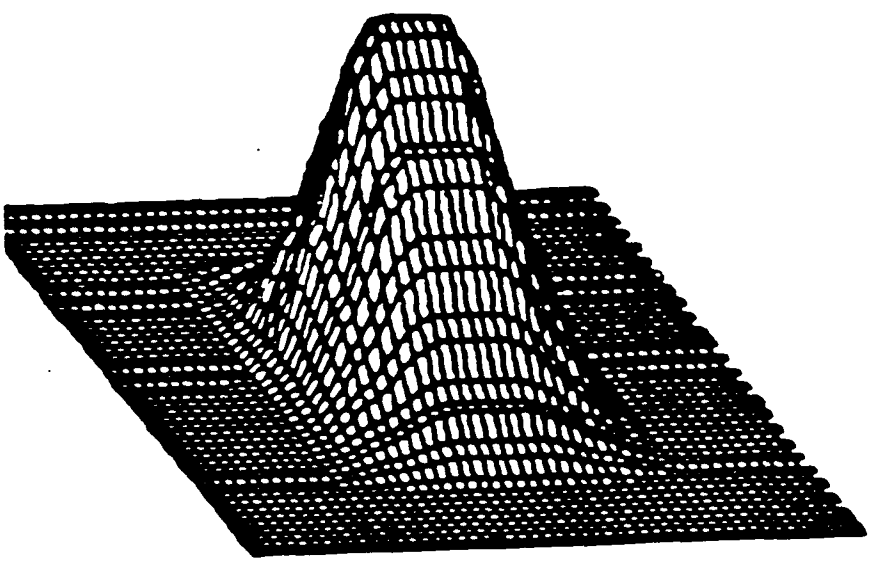


C- $\cos^{0.211}$

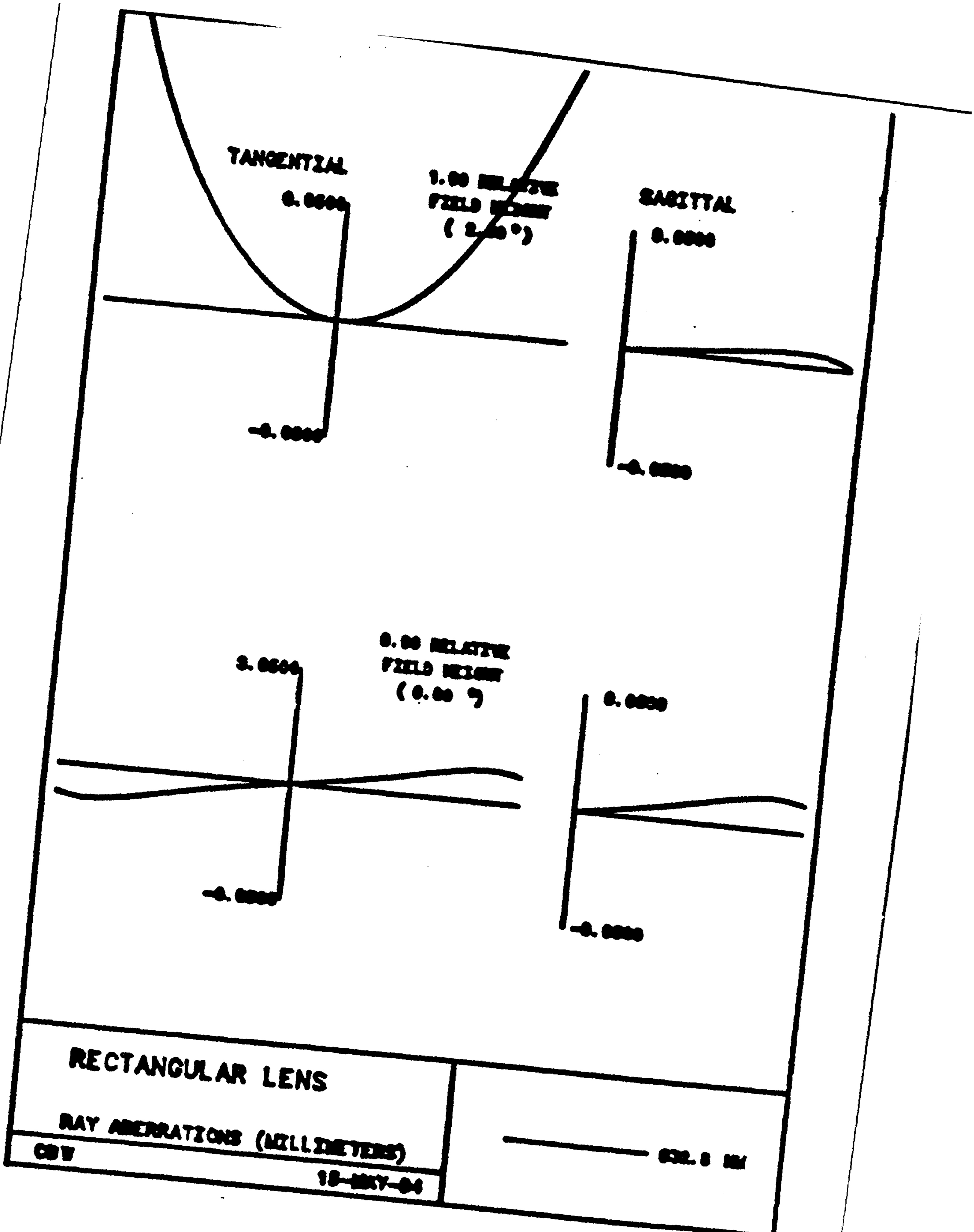
Southwell, J.Opt.Am.Soc, 67

N(y,z) = Base Index + A1 cos (pi * (z-.5*t)/t) * (1 + A2*y**2+ A3*y**4)

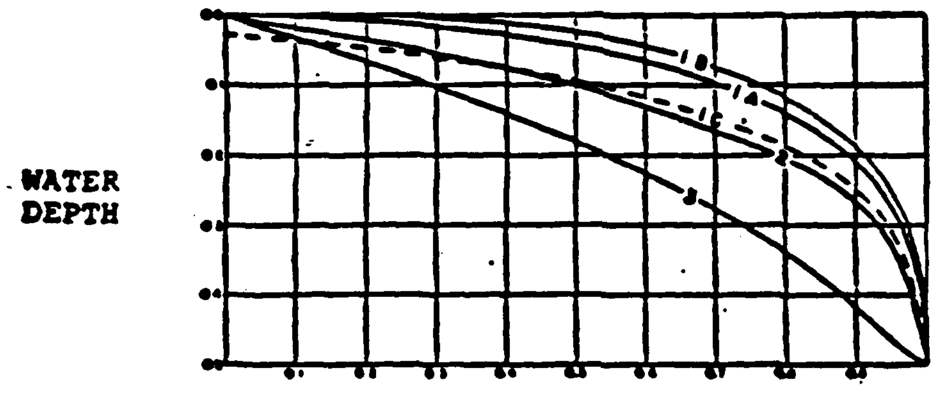


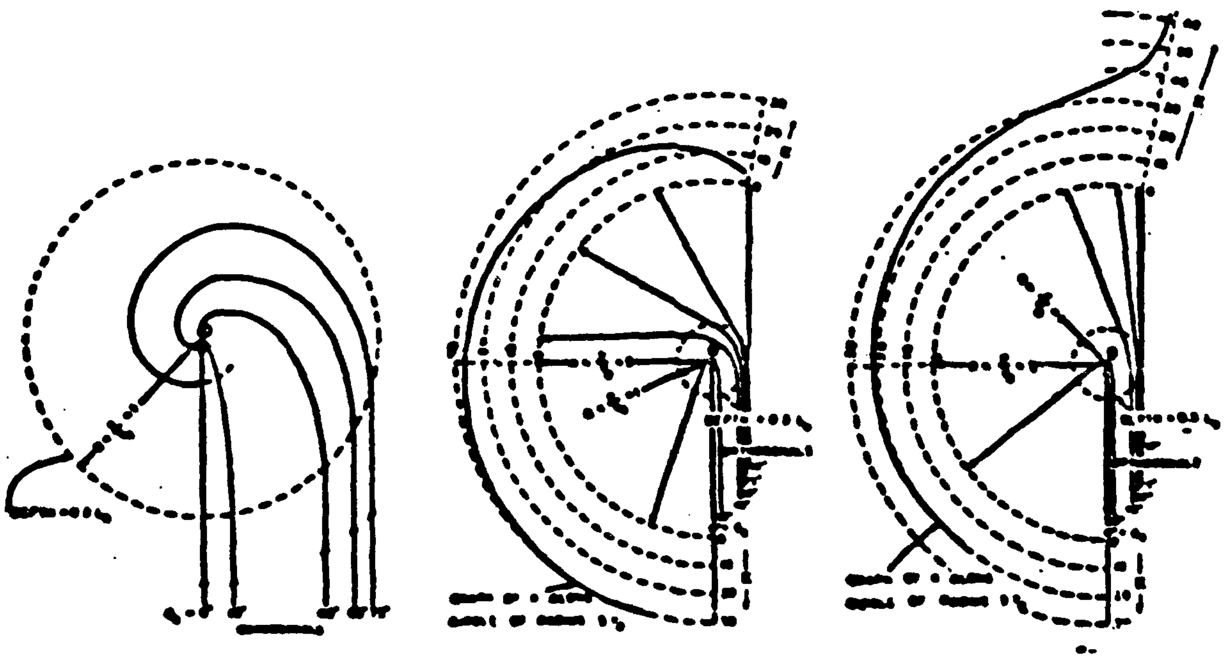


t=5 mm
A1= .7207
A2= -.7967E-2
A3= .1021E-5
BFL= 50 mm


TANGENTIAL
RELATIVE FIELD HEIGHT
SAGITTAL
RELATIVE FIELD HEIGHT
RECTANGULAR LENS
RAY ABERRATIONS (MILLIMETERS)

OCEAN WAVES

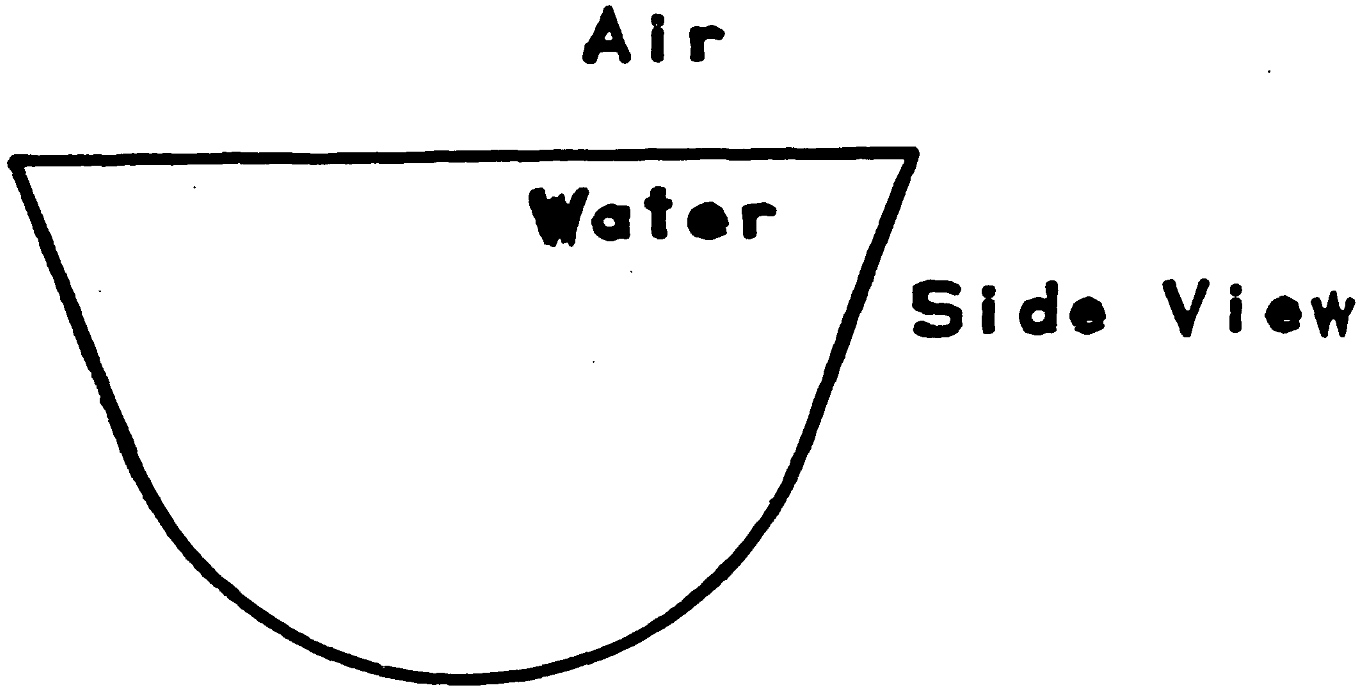


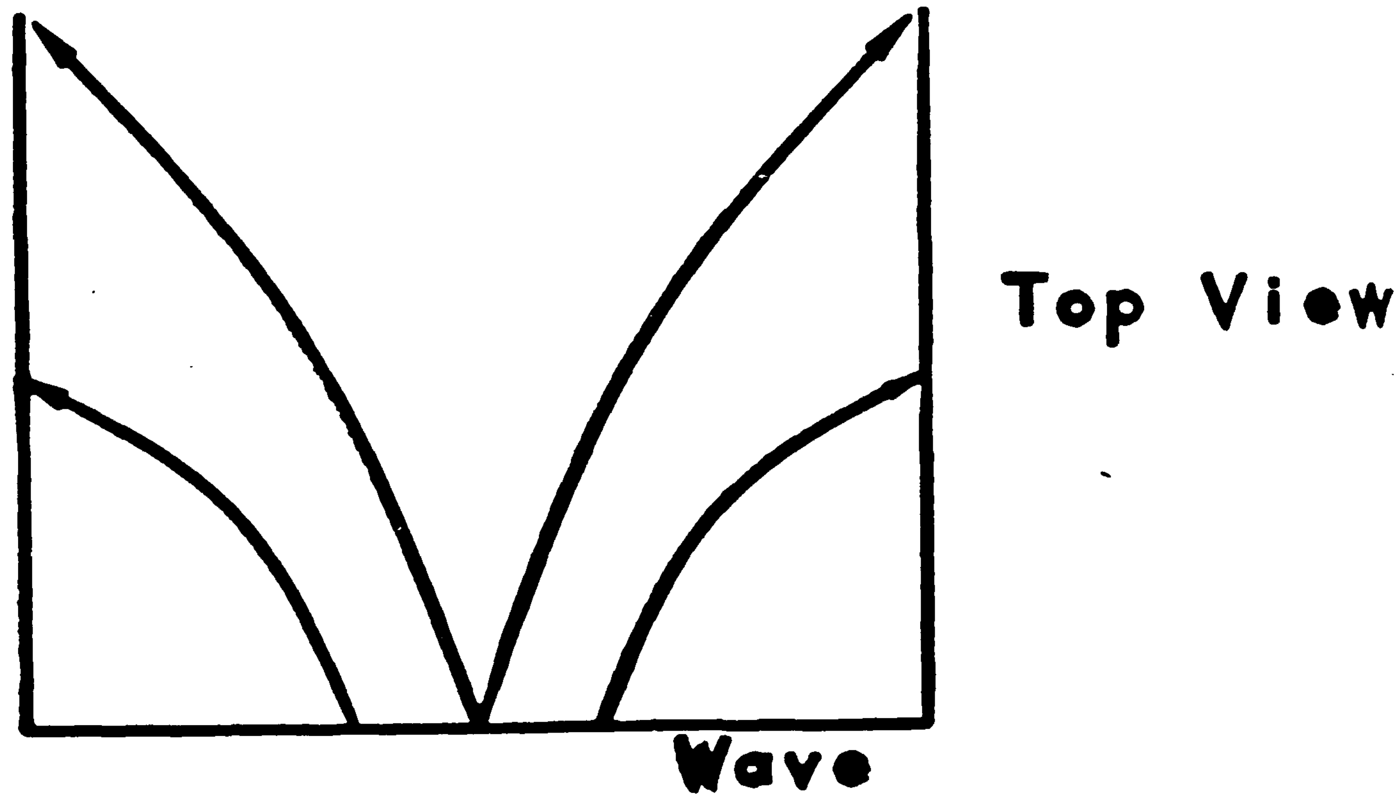


POINT ISLAND RAY PATHS

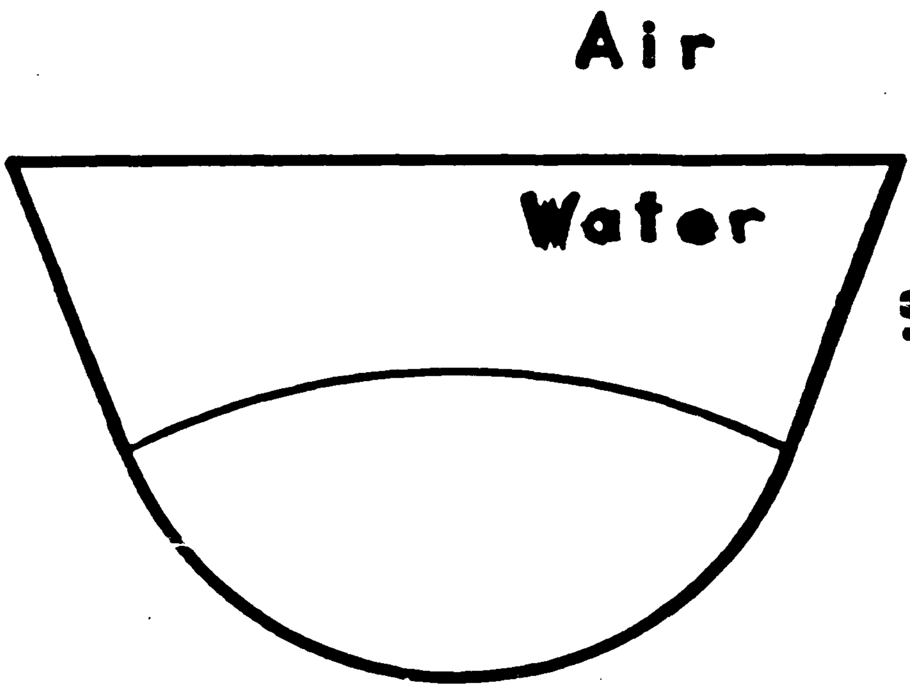
R.S.Arthur, Trans Am Geophy Union,1946

Water Wave Focusing

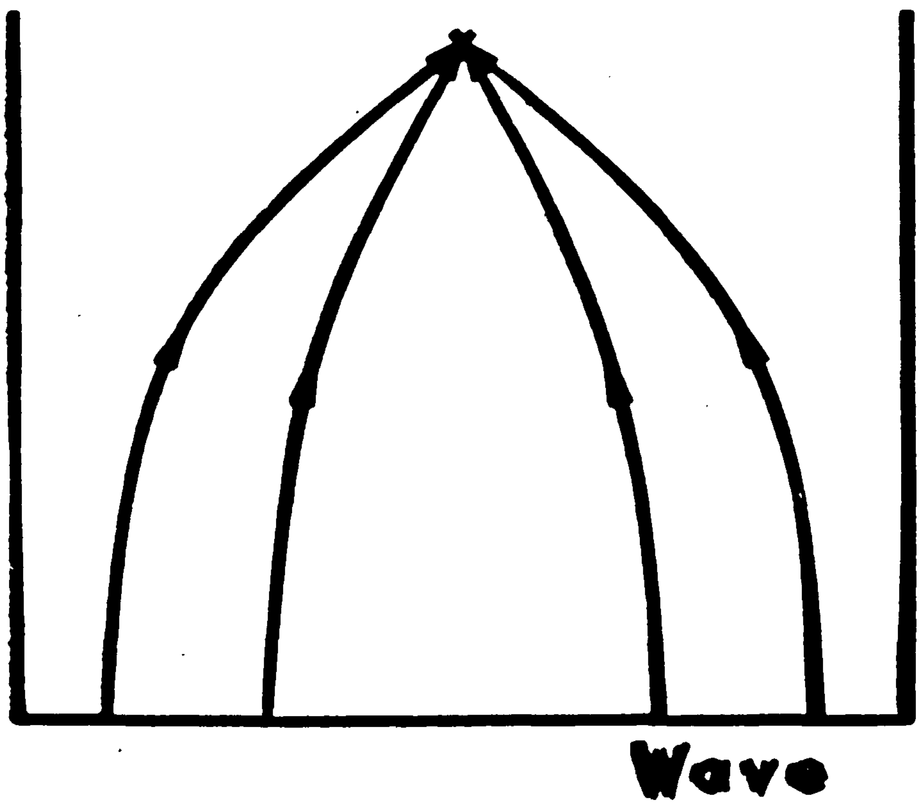




Water Wave Focusing

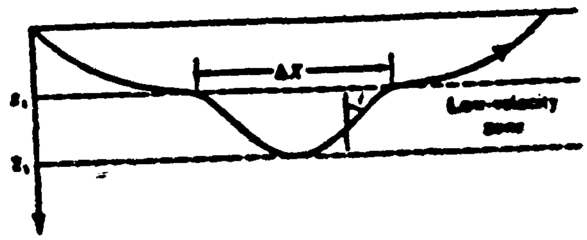


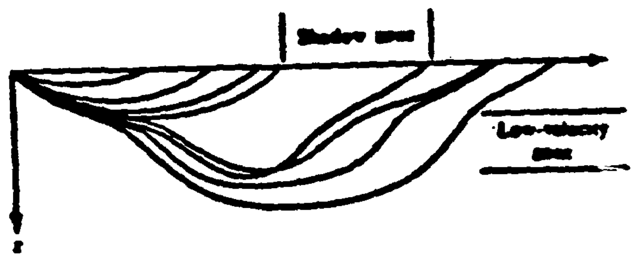
Side View



Top View

SEISMIC WAVES

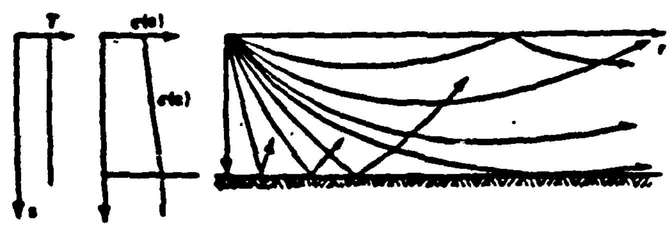




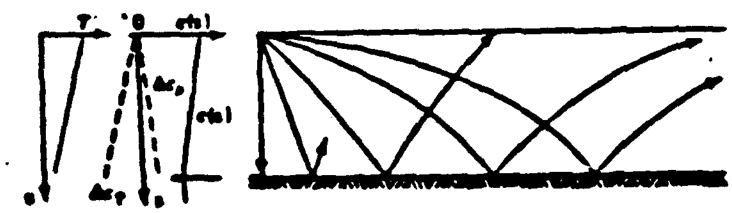
RAY PATHS

Akii, Quantitative Seismology, vol 2, p652

SOUND IN WATER



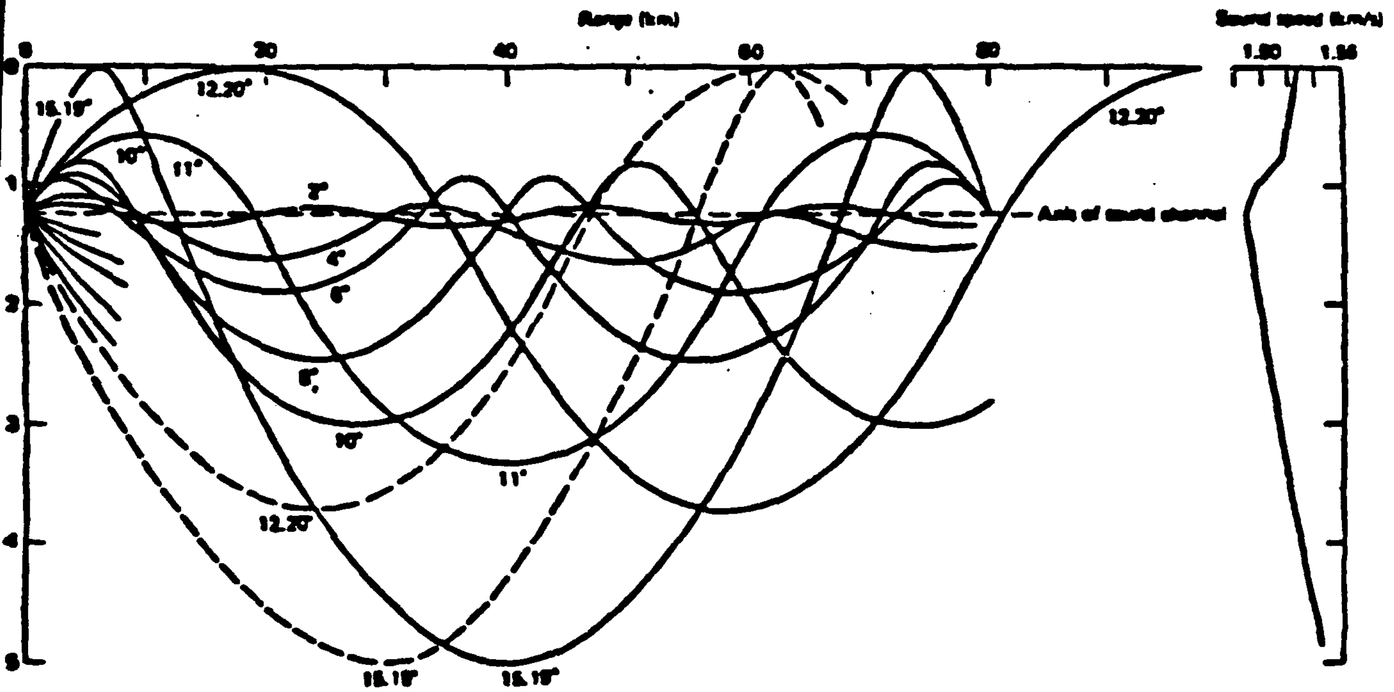
CONSTANT TEMPERATURE
PRESSURE INCREASES WITH DEPTH



TEMPERATURE DECREASES WITH DEPTH
PRESSURE INCREASES WITH DEPTH

Clay, Acoustical Oceanography p88

SOUND IN THE ATLANTIC OCEAN



Clay, Acoustical Oceanography, p89

WHAT IS GRADIENT INDEX OPTICS

In a conventional optical system, the index refraction within each optical component is homogeneous. That is, it is constant within the material. Therefore, in the design of such systems, the lens designer is allowed to vary the curvature, the thickness, and the index of refraction of each component independently to try to optimize the performance. However, it is possible to manufacture a lens element whose index refraction varies continuously within the material. Such a lens element is said to be a gradient index component. We differentiate these types of elements from elements which have random errors in their index of refraction resulting from stria or cord in the material. At this point, we can find no advantage in using materials with these random errors.

The subject of gradient index optics is subdivided into two major sections. The first is gradient index components used for telecommunications. In this example, the material is normally a very long fiber of the order of many kilometers with a diameter approximately twenty to one hundred microns. The index of refraction varies radially out from the center such that the index of refraction is higher along the center of the fiber than it is near the edge. If the gradient profile is chosen properly, the height of the ray varies sinusoidally motion down the fiber - never actually touching the walls. This differs dramatically from the step index fiber which relays on total internal reflection of the walls. In this case, the propagation velocities of the various modes differ. In the gradient index fibers, all modes propagate at the same velocity and thus, the temporal bandwidth of such a fiber can be relatively high. In this particular publication, we are not concerned with telecommunications. The interested reader is referred to the book by Midwinter entitled Optical Fibers for Transmission for more information.

The major thrust of this work will be the use of gradient index materials for imaging purposes. This does not rule out, however, the possibility of using fibers. In such a case, an image is formed on one end of the fiber and the entire image is transmitted to the opposite end of the fiber. The typical lengths for such a device are only a few meters with the diameters of approximately one millimeter.

Gradient index optical systems for imaging purposes can be divided into four distinct sections. The first is the design and analysis of such systems. This involves problems of calculating the aberrations, either by aberration theory or by using raytrace algorithms. Further, it is important to be able to evaluate complex lens systems with both inhomogeneous and homogeneous components.

The second important area is the manufacture of materials. For many years, this has been the limiting feature in implementing gradient index optics. There are now, however, many different materials in which gradients can be made. These include optical glasses, plastics, germanium, zinc selenide, and sodium chloride, to name but a few. Within this area, it is important to be able to not only make the materials but to be able to predict what the gradient will be, what its wavelength dependence will be, as well as its temperature and mechanical properties.

Once the materials have been manufactured, the optical properties must be determined. Currently, there is very little instrumentation for such metrology and the final implementation of such materials in a lens system relies heavily on being able to measure in a short time the various mechanical and optical properties.

Finally, once the other three steps have been completed, we must be able to fabricate them into finished components. It is not as straightforward as one might imagine to take a gradient index component and make it into a finished lens. Because the glass has certain symmetry properties, the axis of symmetry must be colinear with the optical axis of the lens surfaces. If it is not, then aberrations of non-rotationally symmetric lens systems become present.

Why Gradients

Cost Reduction

Weight Reduction

Length Reduction

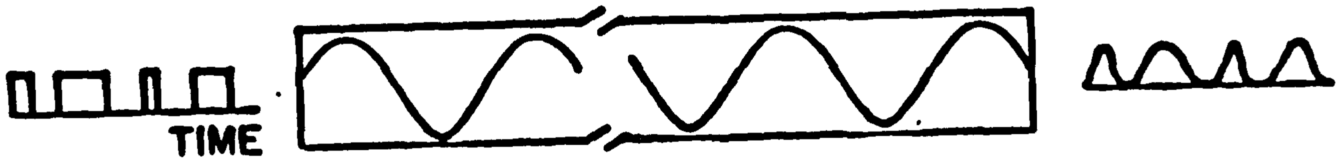
Reliability

More Performance for same number of elements

GRADIENT INDEX FIBERS

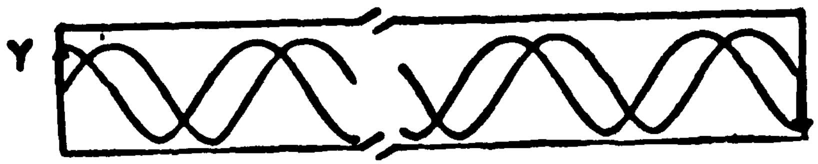
IMPORTANT
PARAMETERS

TELECOMMUNICATIONS

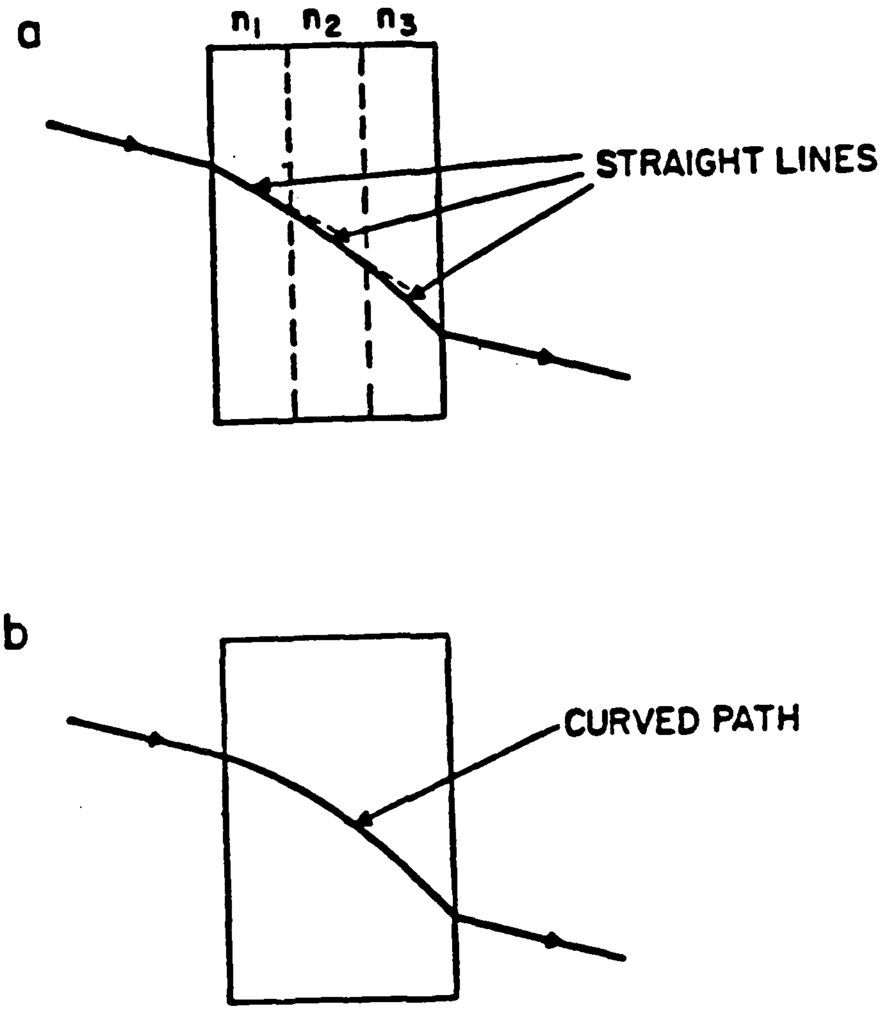


TEMPORAL DAT
RATE
LENGTH ~l km

IMAGING



SPATIAL DATA
RATE
LENGTH ~l m



5

INDEX OF REFRACTION POLYNOMIAL

$$N(x,\xi) = N_0(x) + N_1(x)\xi + N_2(x)\xi^2 + \cdots$$

where $\xi = Y^2 + Z^2$

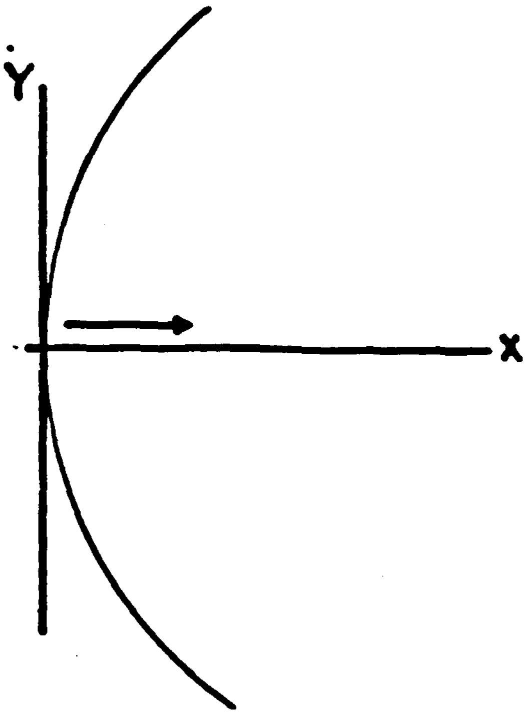
and

$$N_0(x) = N_{00} + N_{01}x + N_{02}x^2 + \cdots$$

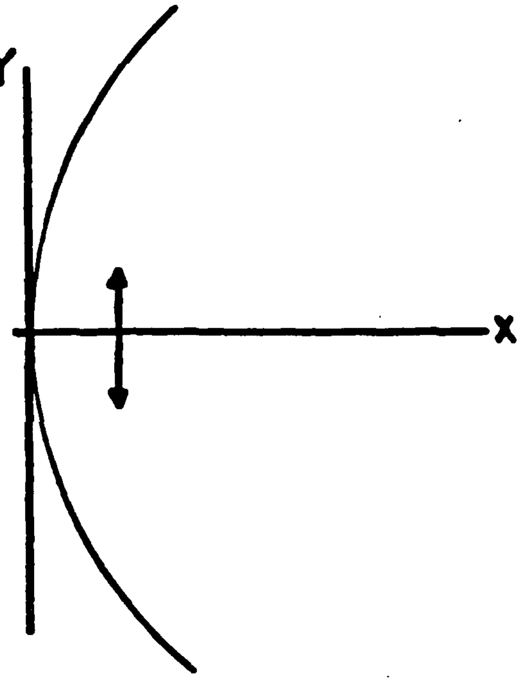
$$N_1(x) = N_{10} + N_{11}x + N_{12}x^2 + \cdots$$

$$\vdots$$

$$N_n(x) = N_{n0} + N_{n1}x + N_{n2}x^2 + \cdots$$



Axial Geometry



Radial Geometry

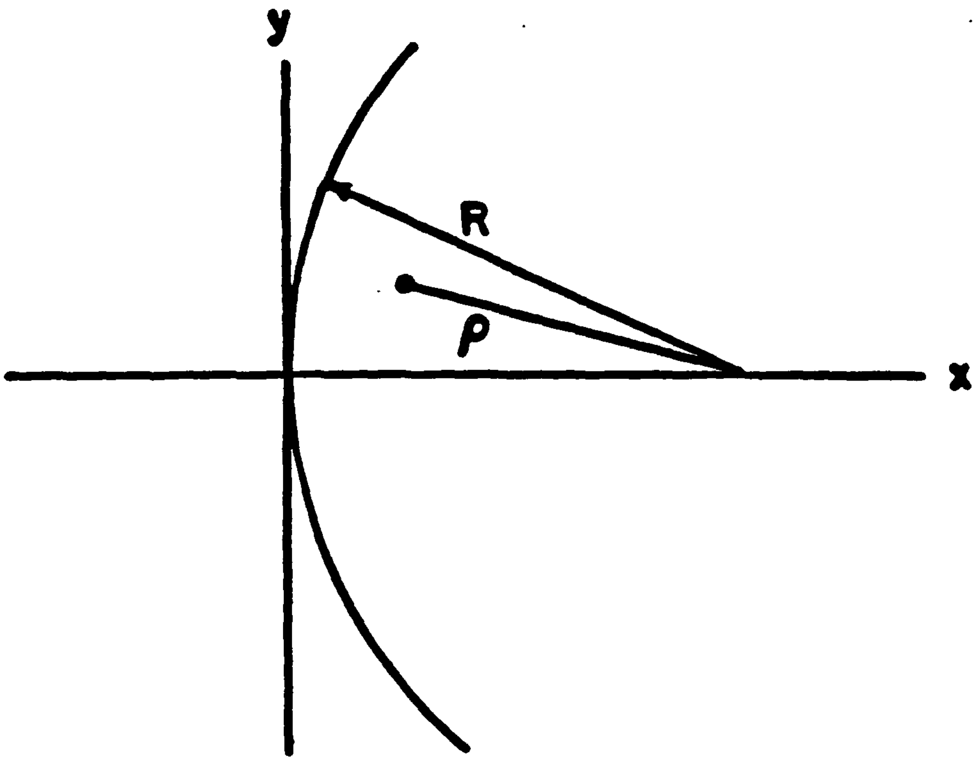
Axial Gradient

$$N_A\ (x) = N_{00} + N_{01}\,x + N_{02}\,x^2 + \cdots$$

Radial Gradient

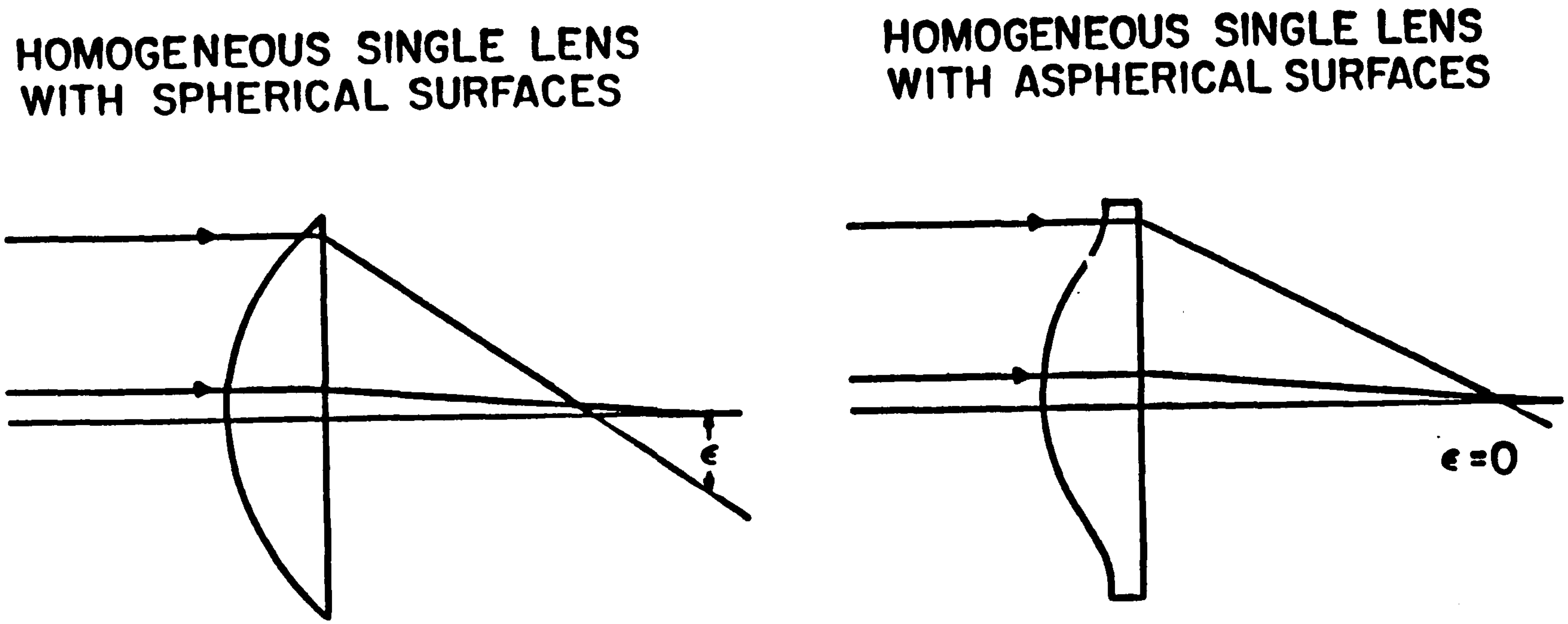
$$N_R\ (x) = N_{00} + N_{10}\,\xi + N_{20}\,\xi^2 + \cdots$$

$$\xi = Y^2 + Z^2$$



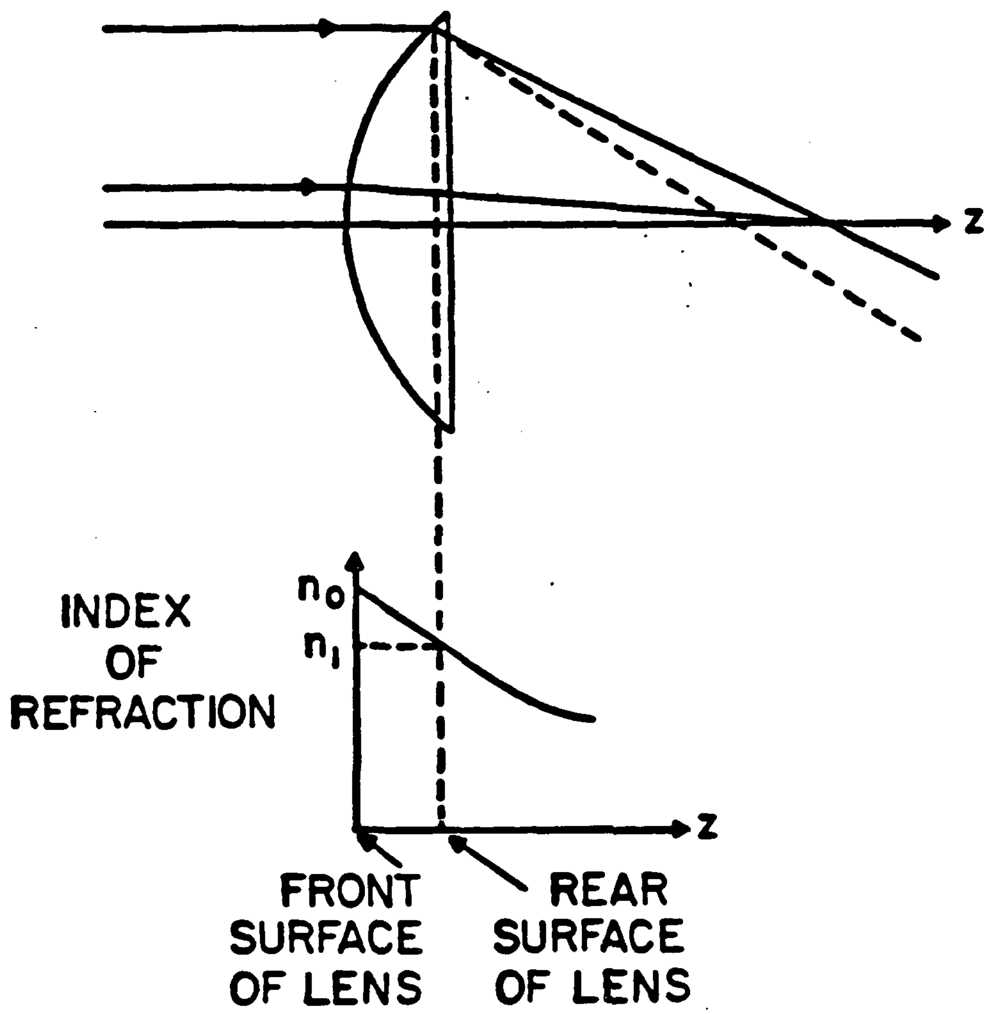
Spherical Geometry

$$N(R-\rho) = N_{00} + N_{01s}(R-\rho) + N_{02s}(R-\rho)^2 + N_{03s}(R-\rho)^3 + \cdots$$



ε = SPHERICAL ABERRATION

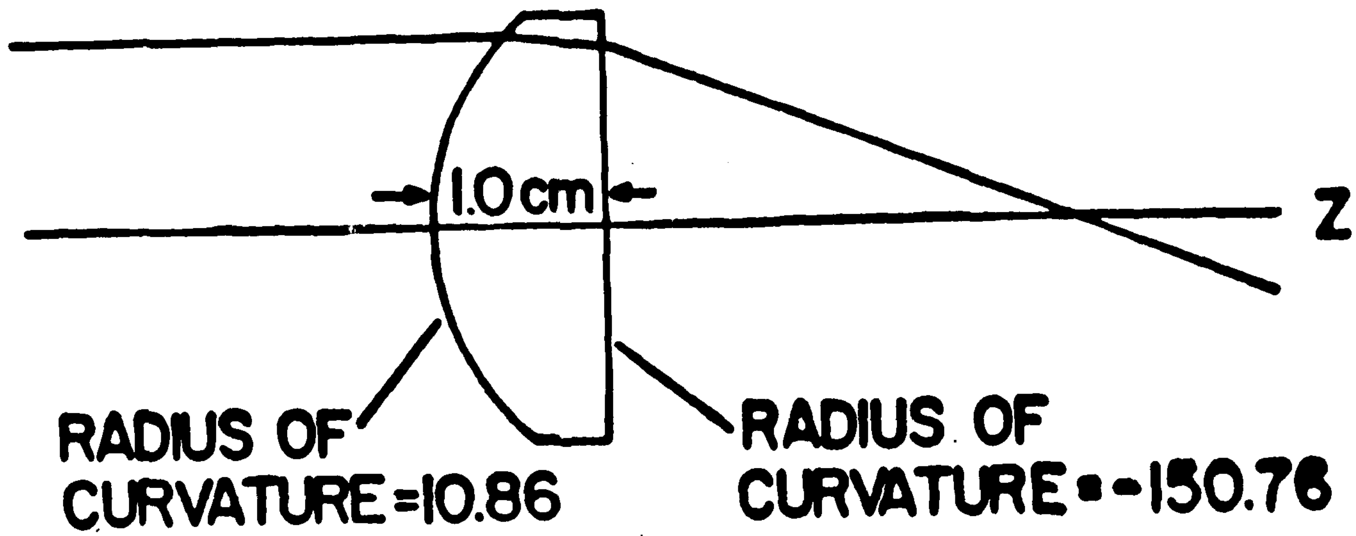
GRADIENT INDEX SINGLE LENS WITH SPHERICAL SURFACES



SINGLE ELEMENT COLLIMATOR

BL-3

f/4 focal length 20.0 cm



N = 1.5062 − 0.0355 Z

$$\epsilon_y{}' = \sigma_1 \rho^3 \cos\theta + \sigma_2 \rho^2 h'(2+\cos 2\theta) + (3\sigma_3+\sigma_4)\rho h'^2 \cos\theta +$$

$$+ \sigma_8 h'^3$$

$$\epsilon_z{}' = \sigma_1 \rho^3 \sin\theta + \sigma_2 \rho^2 h' \sin 2\theta + (\sigma_3+\sigma_4)\rho h'^2 \sin\theta$$

σ_i = Sum of ordinary surface contributions

+

Sum of inhomogeneous surface contributions

+

Sum of inhomogeneous transfer contributions

$$a^*_1 = \frac{1}{2}\nabla N_0 y_a v_a^{\,3} + \int \left[4N_2 y_a^{\,4} + 2N_1 y_a^2 v_a^{\,2} - \frac{1}{2} N_0 v_a^{\,4} \right] dx$$

$$a^*_2 = \frac{1}{2}\nabla N_0 y_a v_a^2 v_b + \int \left[4N_2 y_a^3 y_b + N_1 y_a v_a (y_a v_b + y_b v_a) - \frac{1}{2} N_0 v_a^3 v_b \right] dx$$

$$a^*_3 = \frac{1}{2}\nabla N_0 y_a v_a v_b^2 + \int \left[4N_2 y_a^2 y_b^2 + 2N_1 y_a y_b v_a v_b - \frac{1}{2} N_0 v_a^2 v_b^2 \right] dx$$

$$a^*_4 = \lambda^2 \int (N_1 / N_0^2)\, dx$$

$$a^*_5 = \frac{1}{2}\nabla N_0 y_a v_b^{\,3} + \int \left[4N_2 y_a y_b^{\,3} + N_1 y_b v_b (y_a v_b + y_b v_a) - \frac{1}{2} N_0 v_a v_b^3 \right] dx \cdot$$

AXIAL GRADIENT

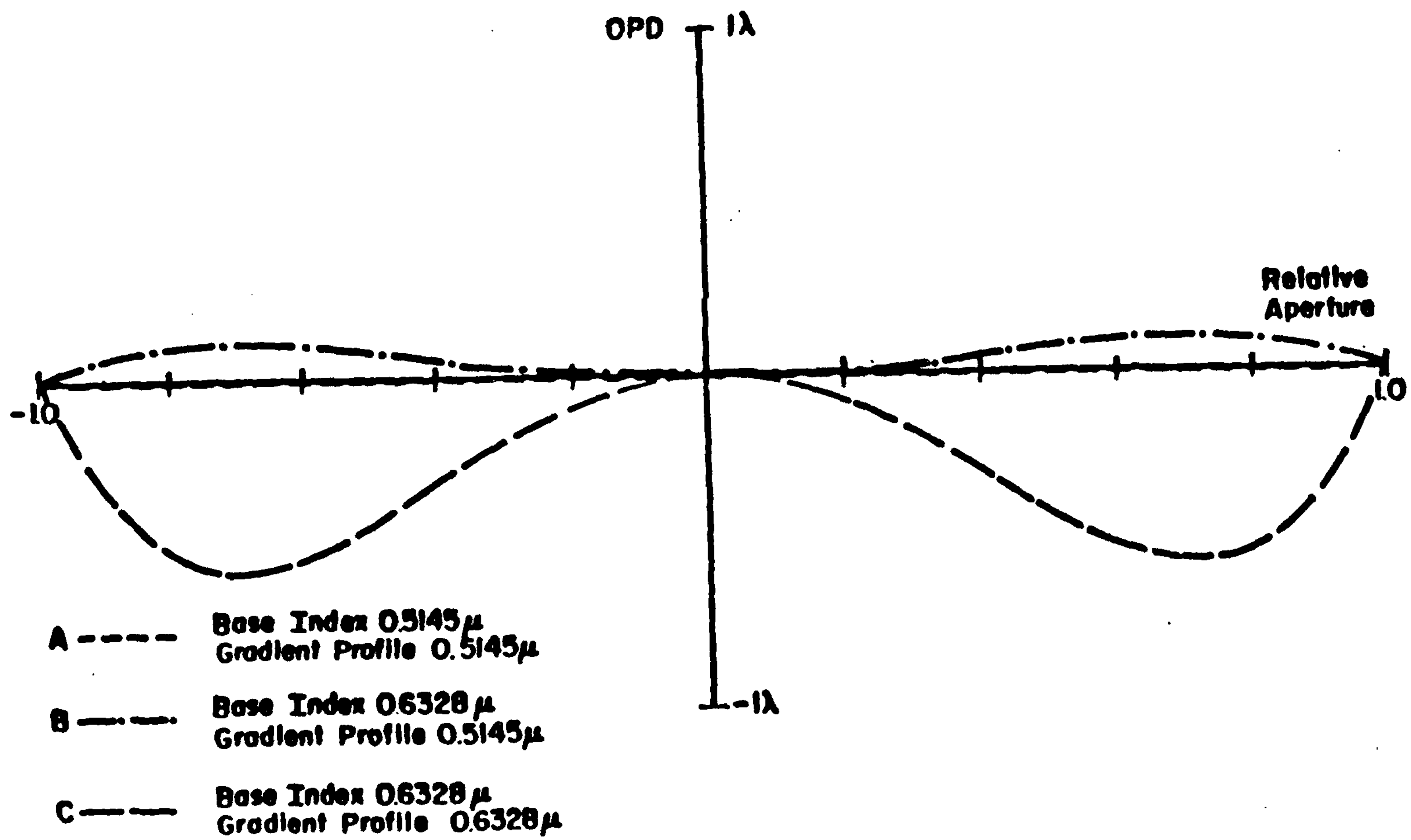
DEGREES OF FREEDOM	CORRECTION
VALUE OF N_{01}	SPHERICAL ABERRATION
FIRST CURVATURE	COMA
SECOND CURVATURE	FOCAL LENGTH
STOP POSITION	DISTORTION

Aspheric Contribution		Inhomogeneous Surface Contribution
$-4\,AD\,y_a^4\,\Delta n$	$=$	$\frac{-c^2}{2}\,y_a^4\,\Delta\dot{N}_0$

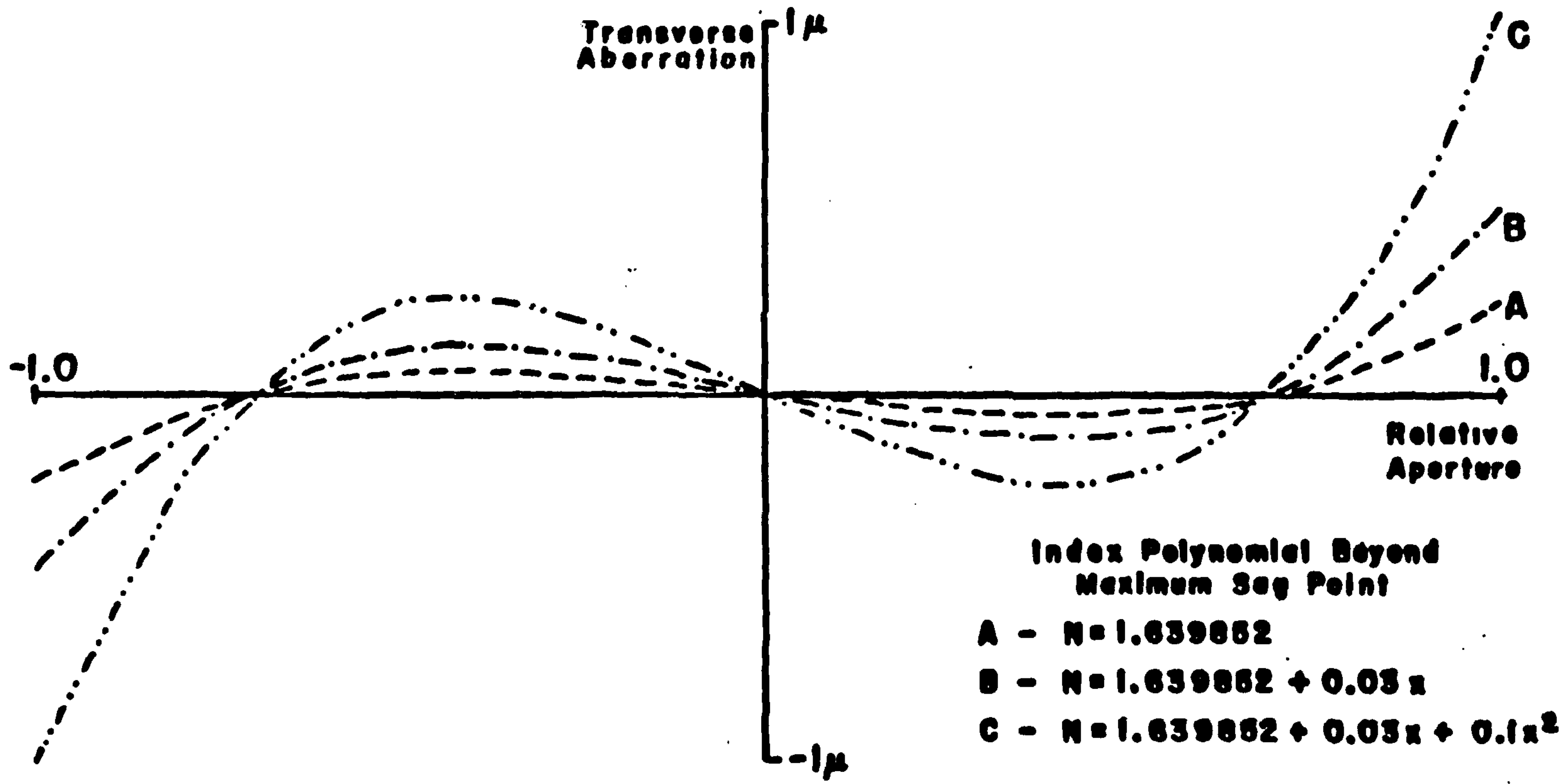
$$\Delta\dot{N}_0 = \frac{8\,AD\,\Delta n}{c^2}$$

$$N_0 = N_{00} + N_{01}x + N_{02}x^2 + \ldots$$

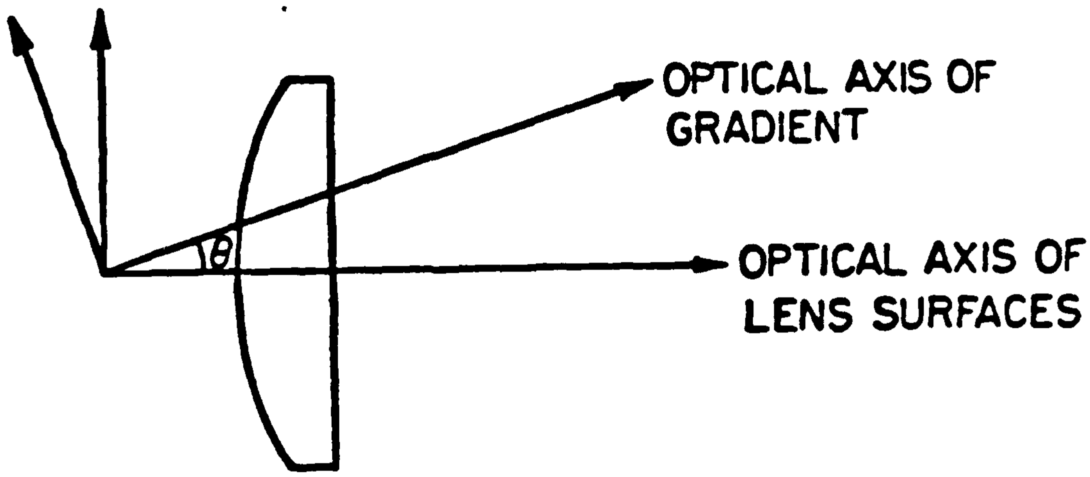
f/4 Axial Gradient Collimator
Spherochromatism
Axial Fan OPD



RAY INTERCEPT PLOTS
f/4 COLLIMATOR
AXIAL GRADIENT



TOLERANCING GRADIENT



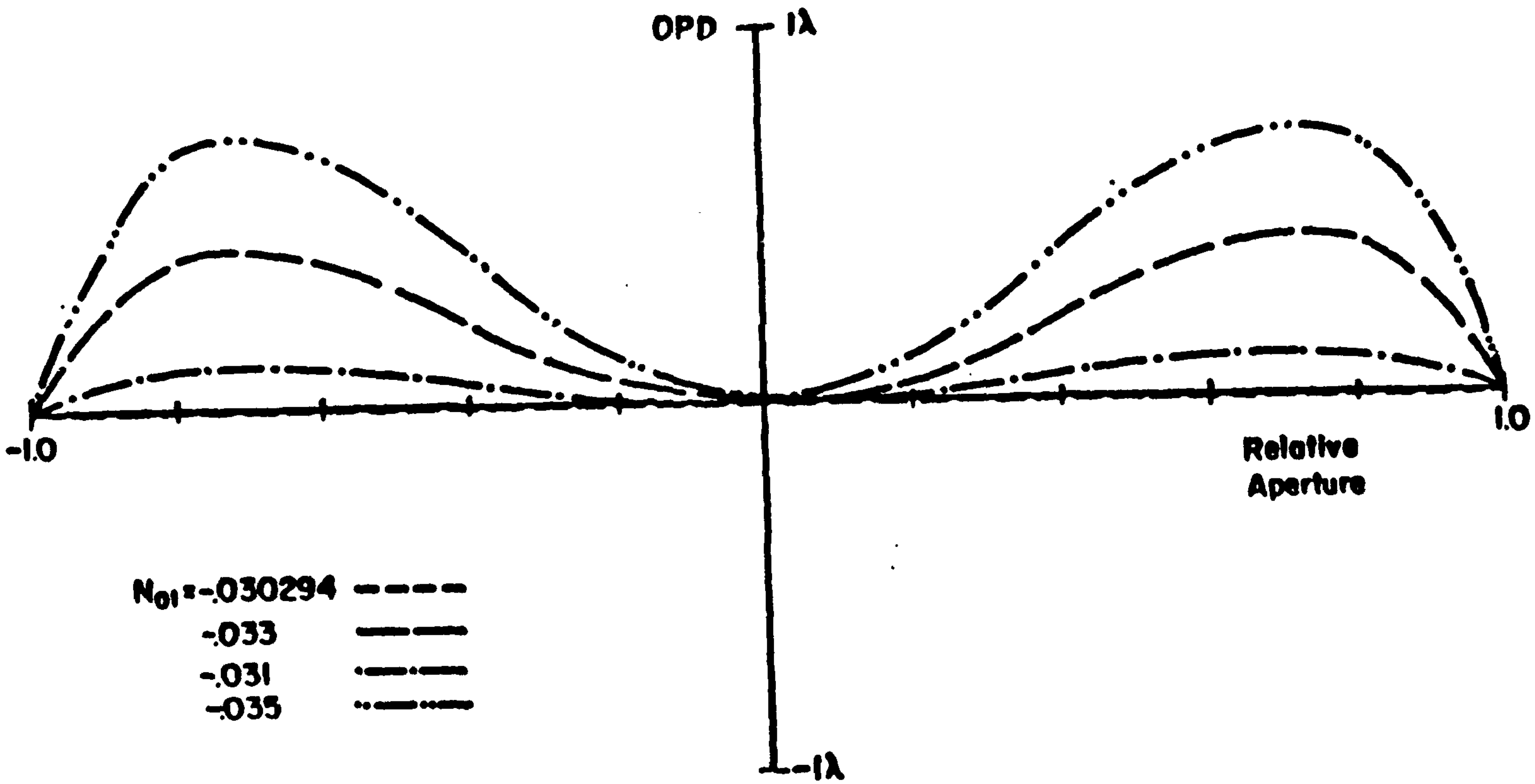
TEN PARAMETERS TO BE TOLERANCED

N_{01}, N_{02}, N_{03}, N_{04},

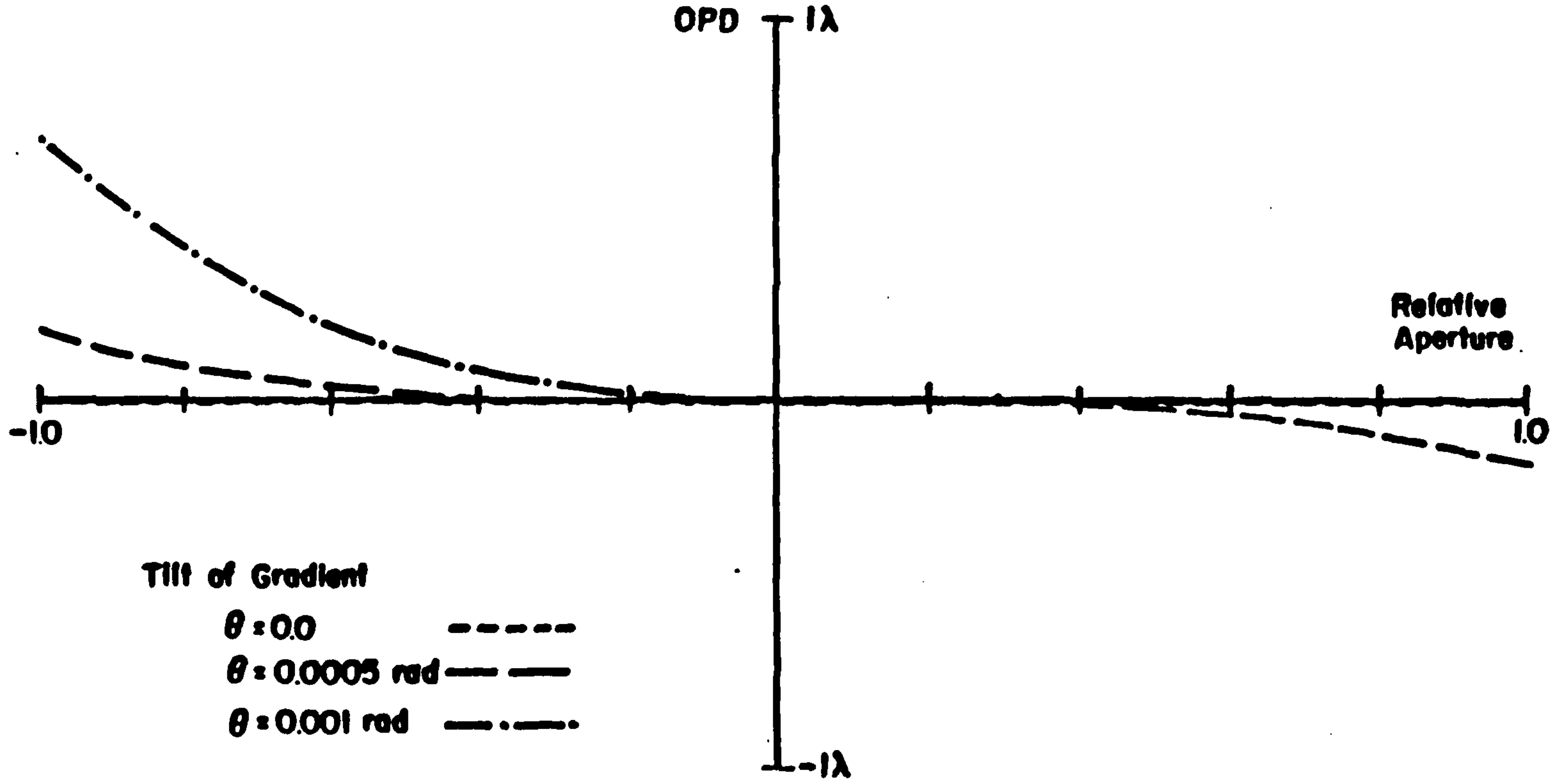
N_{10}, N_{20}, N_{30}, N_{40},

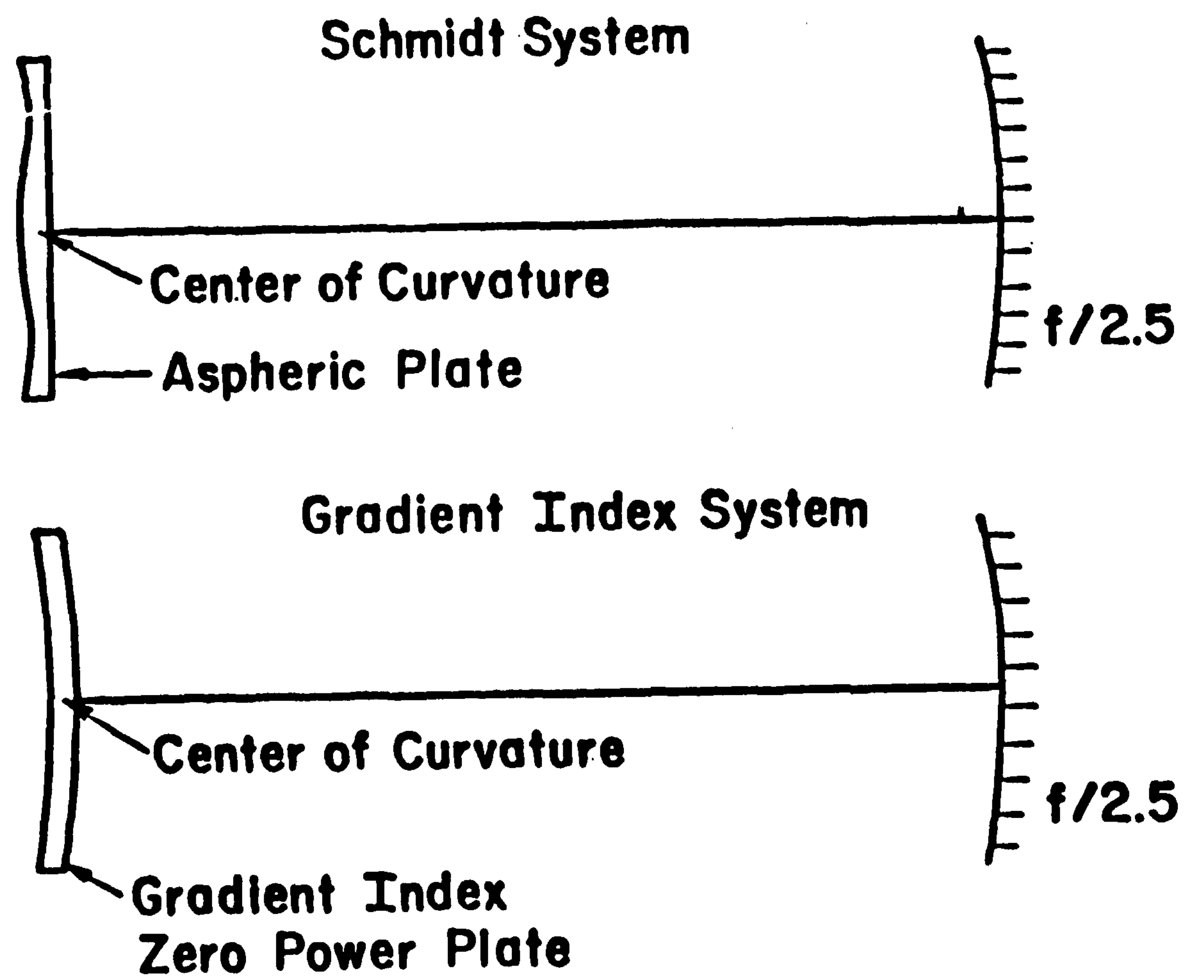
TILT, DECENTER

f/4 Axial Gradient Collimator
Effect of N_{01}
Axial Fan OPD

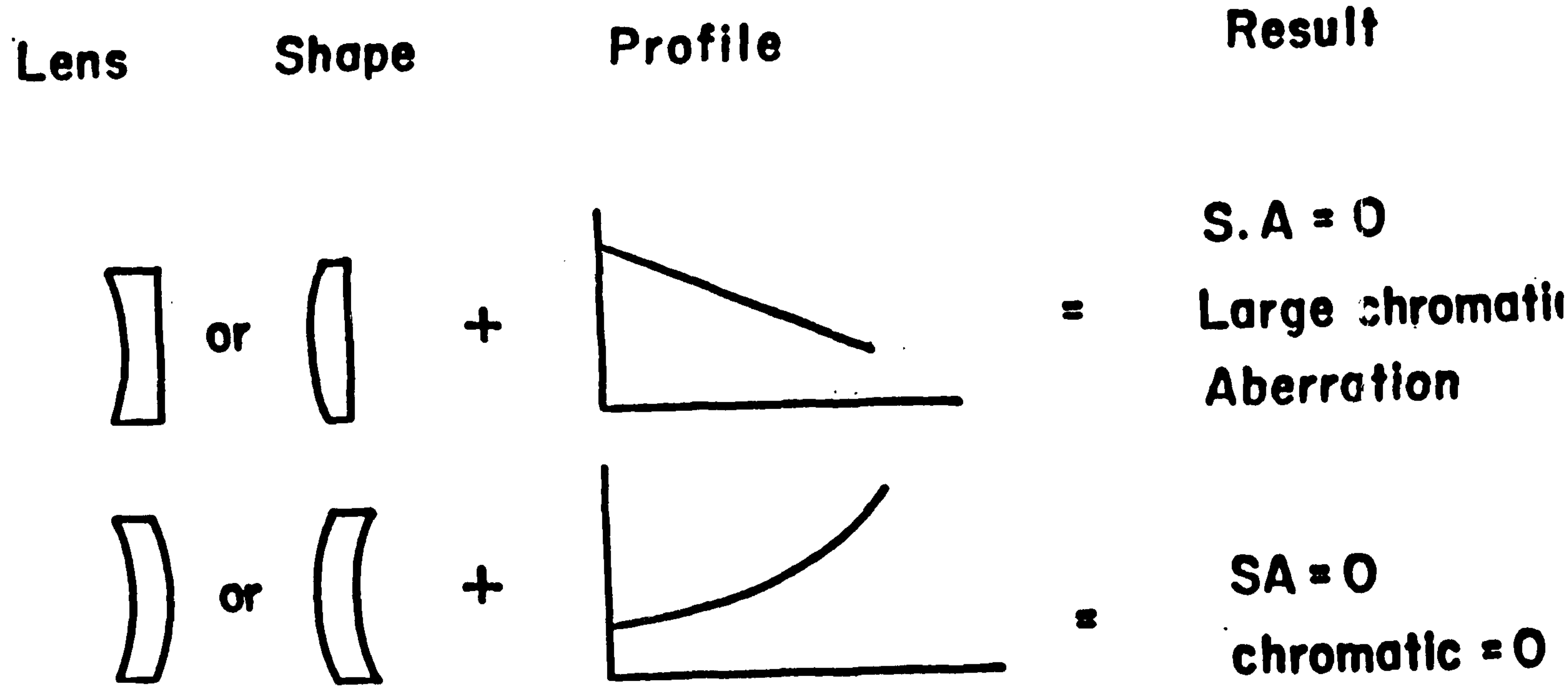


f/4 Axial Gradient Collimator
Effect of Gradient Tilt
Axial Fan OPD




Schmidt System
Center of Curvature
Aspheric Plate
f/2.5
Gradient Index System
Center of Curvature
Gradient Index
Zero Power Plate
f/2.5

Linear vs Quadratic Profiles



Spherical Aberration For Gradient Index Corrector Plate and Spherical Mirror

$$y_{a3}^4 \; c_{primary}^3 \; + \; \frac{y_{a1}^4 \, c^2}{2} \left[2 N_{02} t + 3 N_{03} t^2 \ldots \right] \sim 0$$

Let $N_{0j} = 0$ $\quad j \geq 3$ and assume $y_{a1} = y_{a3}$

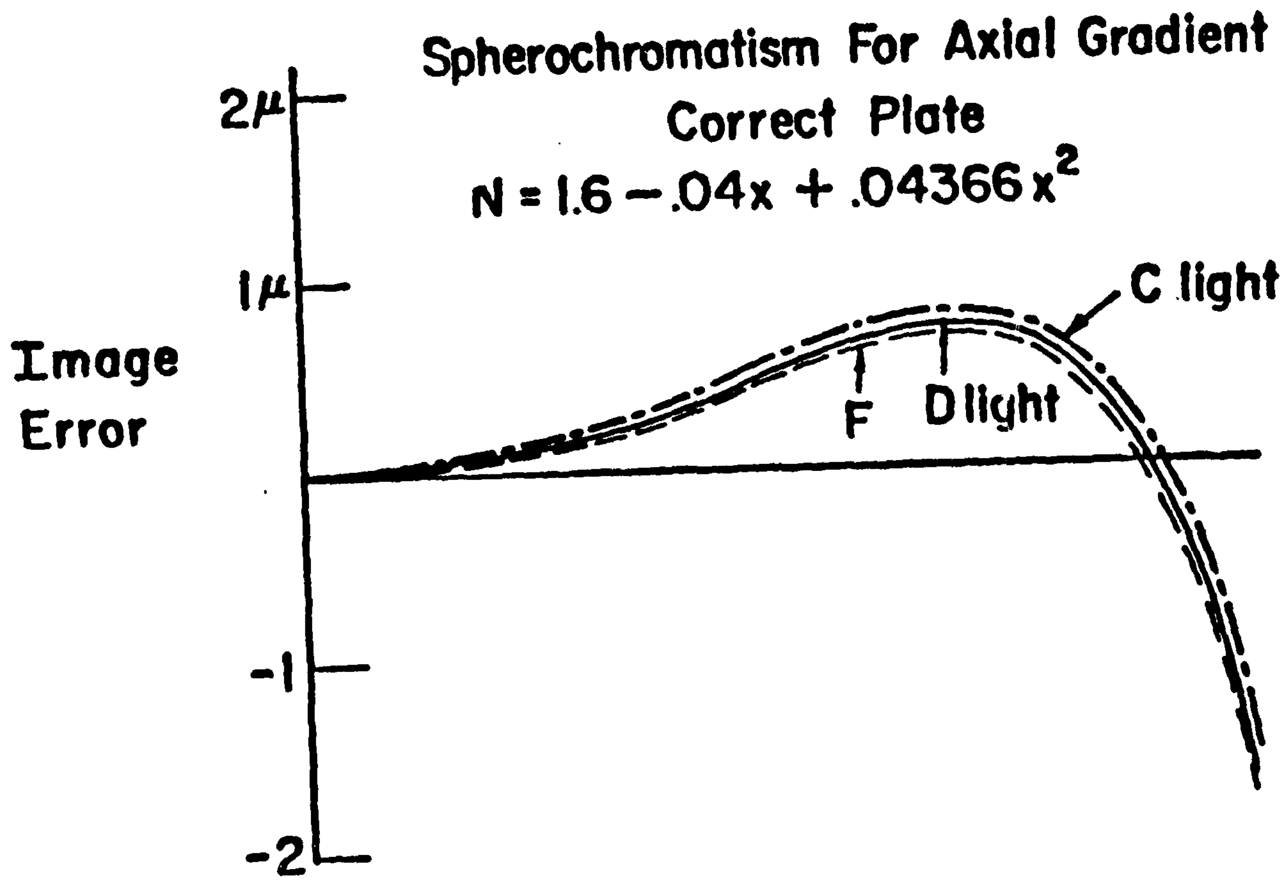
$$N_{02} = \frac{- c^3_{primary}}{c^2_{plate} \, t_{plate}}$$

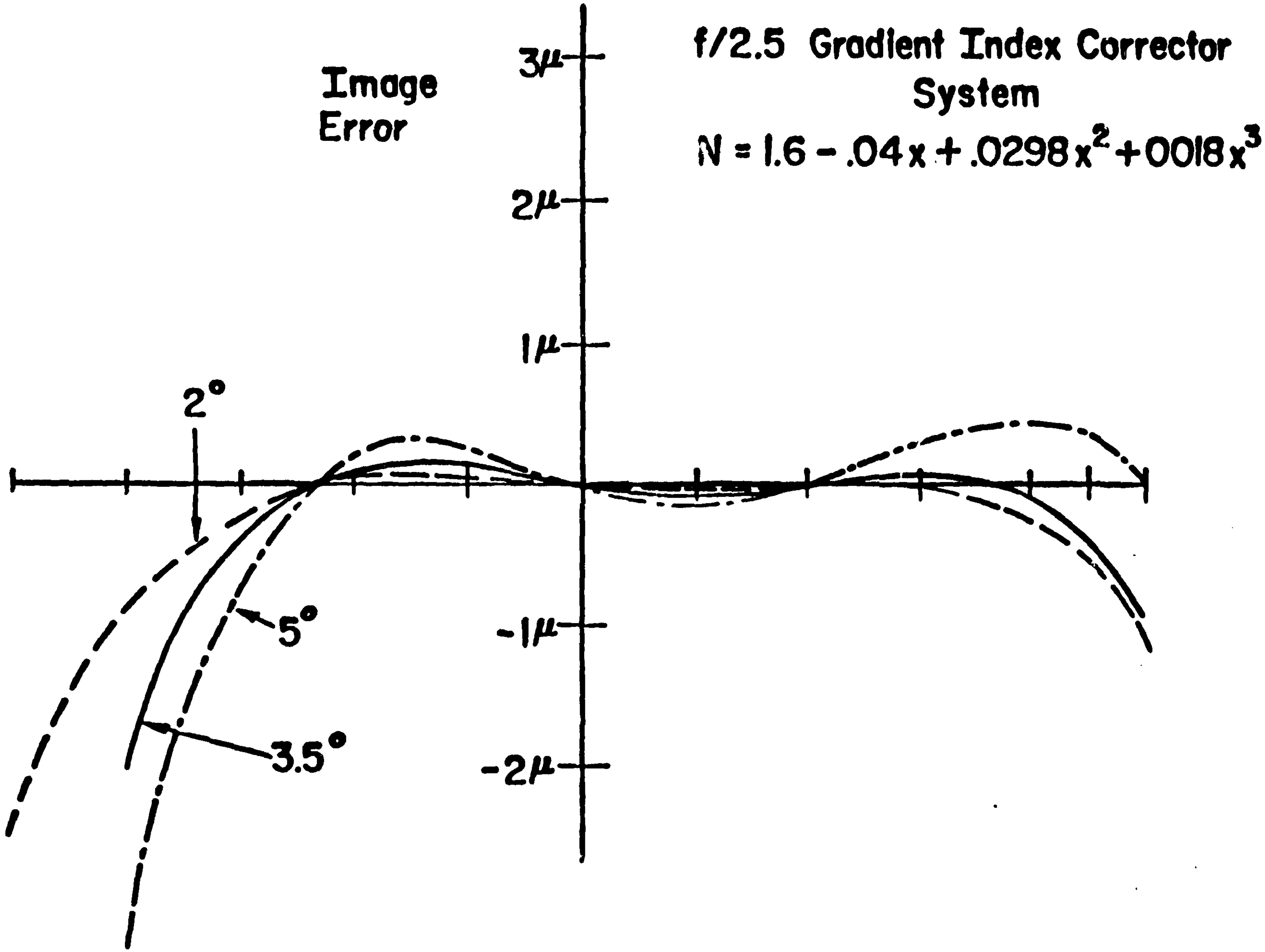
Third Order Aberration Coefficients

Spherical Aberration

	Ordinary Surface Contribution	Inhomogeneous Surface Contribution	Transfer Contribution
Plate	−.000012	+ .015006	.000000
Primary	−.014832	0.0	0.0

Total σ_1 = + .000168

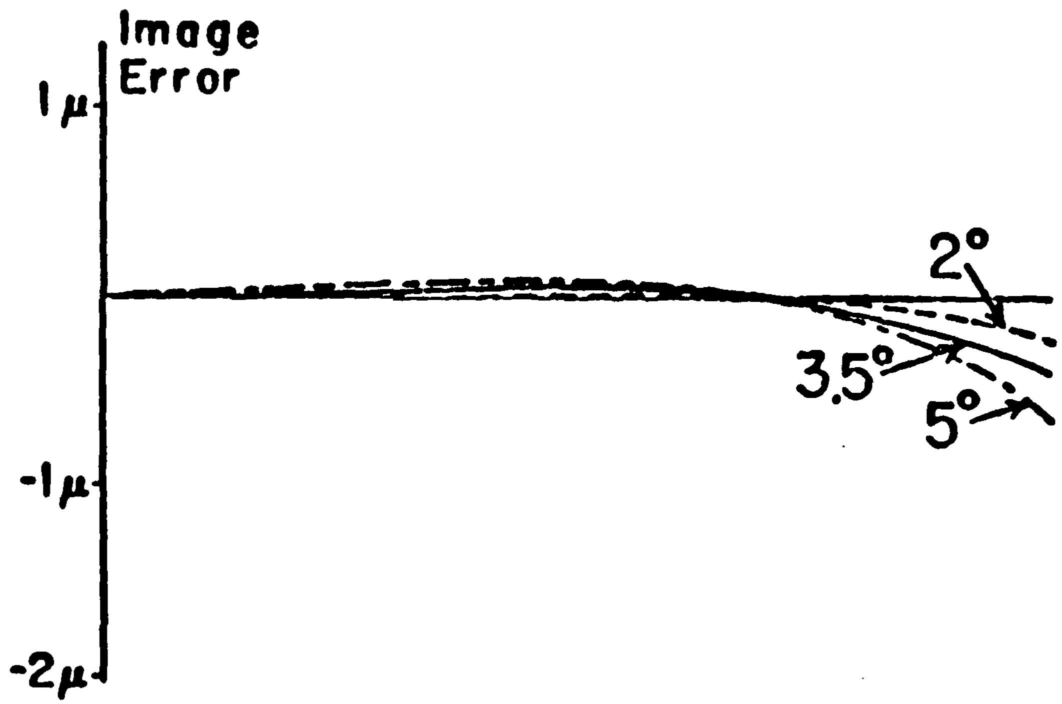

Spherochromatism For Axial Gradient
Correct Plate
N = 1.6 − .04x + .04366x²
Image
Error
2μ
1μ
-1
-2
C light
F
D light


f/2.5 Gradient Index Corrector
System
N = 1.6 - .04x + .0298x² + 0018x³
Image
Error
3μ
2μ
1μ
-1μ
-2μ
2°
5°
3.5°

RAY INTERCEPT PLOT

CORRECTOR PLATE

SAGITTAL FAN



RAY DISPLACEMENT PLOTS

GRADIENT CORRECTOR PLATE

VARIOUS GRADIENT DISPLACEMENTS

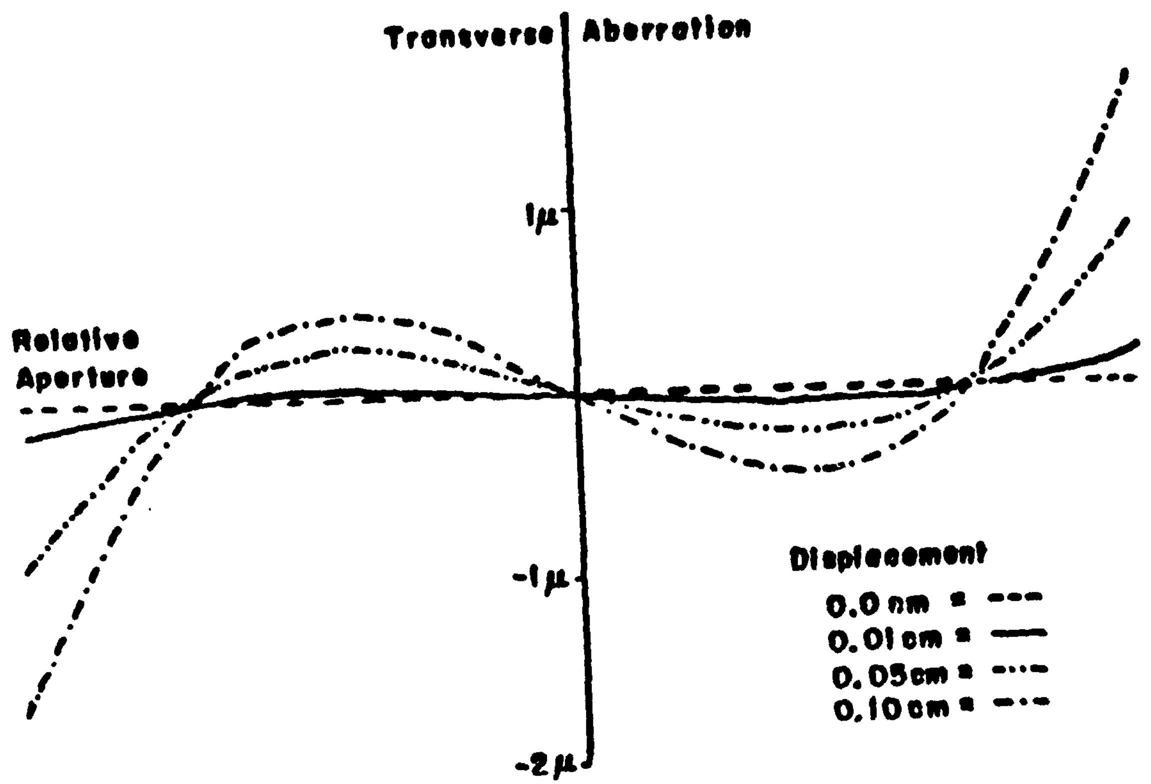


FIGURE 3-9

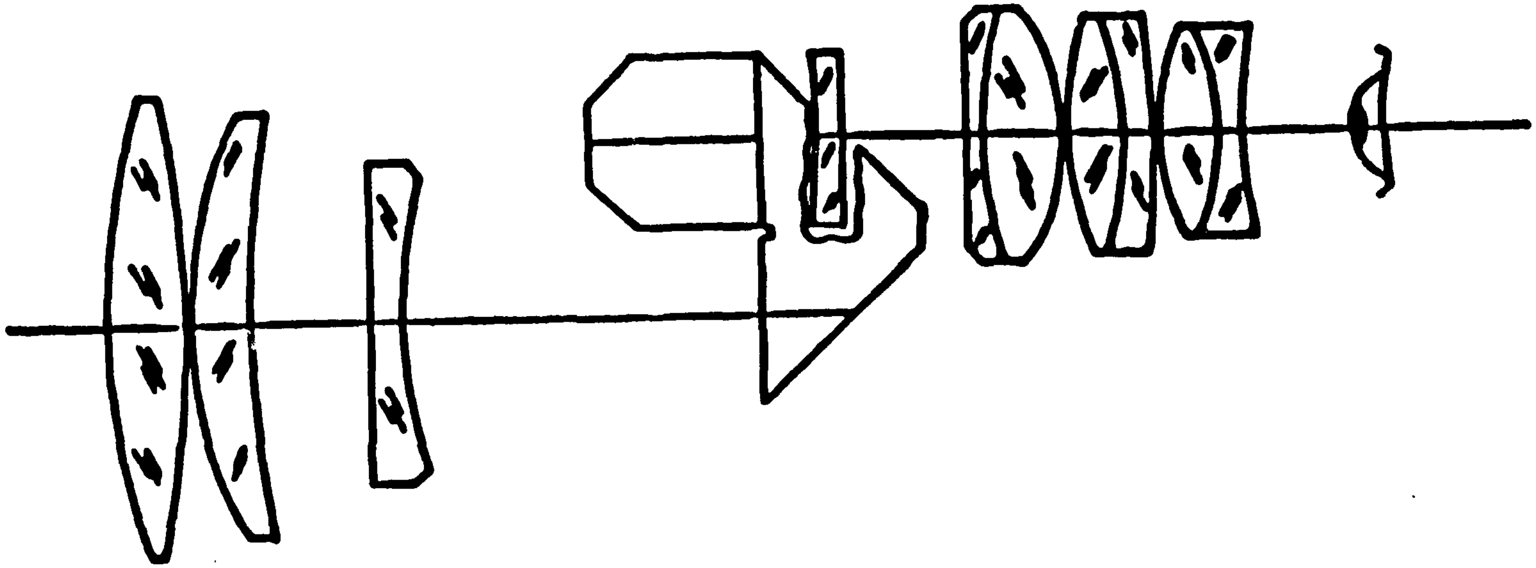
THE PROJECT

To redesign the M19 binocular objective using gradient index materials to :

1) reduce the number of elements,

2) maintain equivalent performance,and

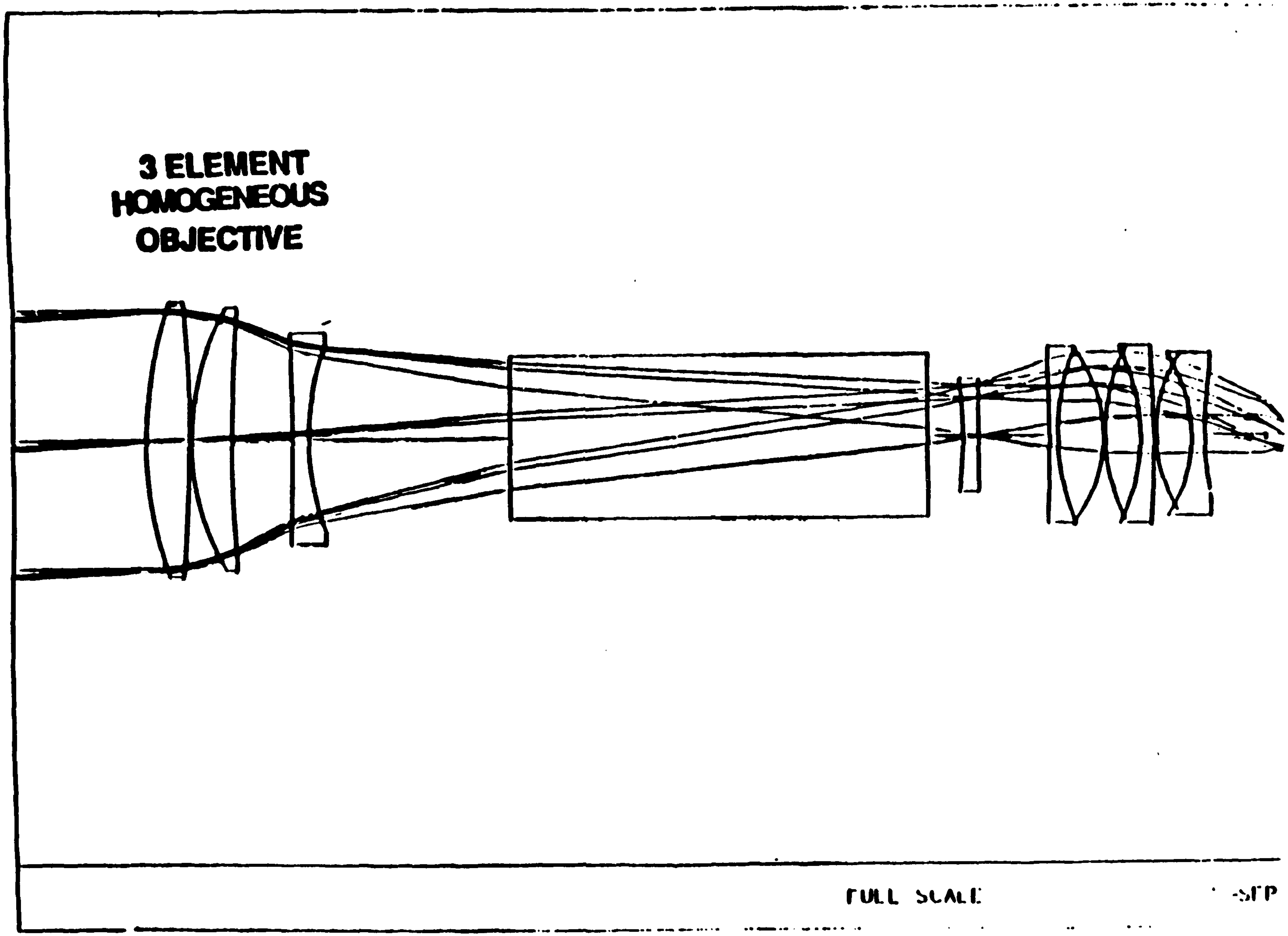
3) develop a system that can be manufactured using ion exchange techniques.



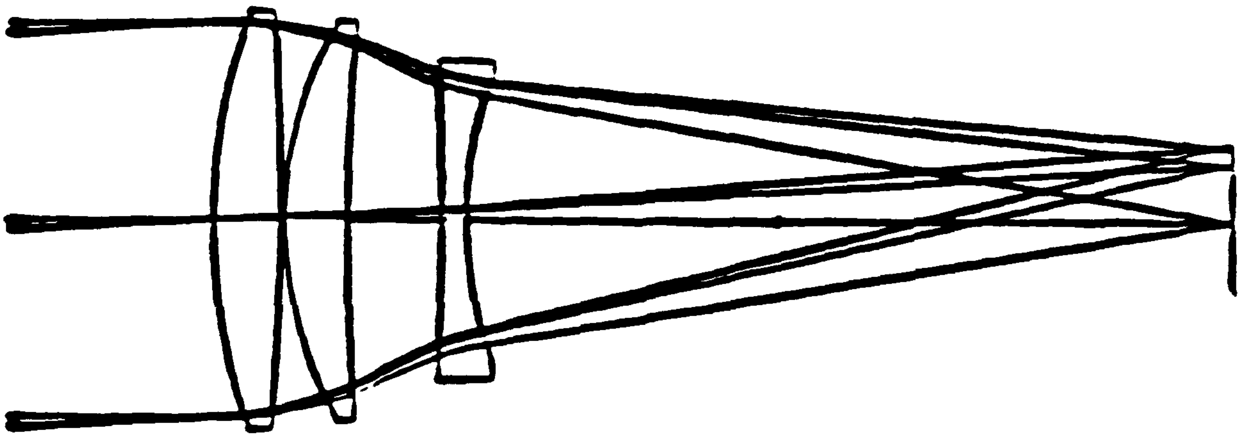
BINOCULAR SYSTEM

P.R. YODER, JR., J. OPT. SOC. AM. <u>50</u>, 491 (1960)

M19 BINOCULAR



The original M19 binocular has a three element telephoto objective.

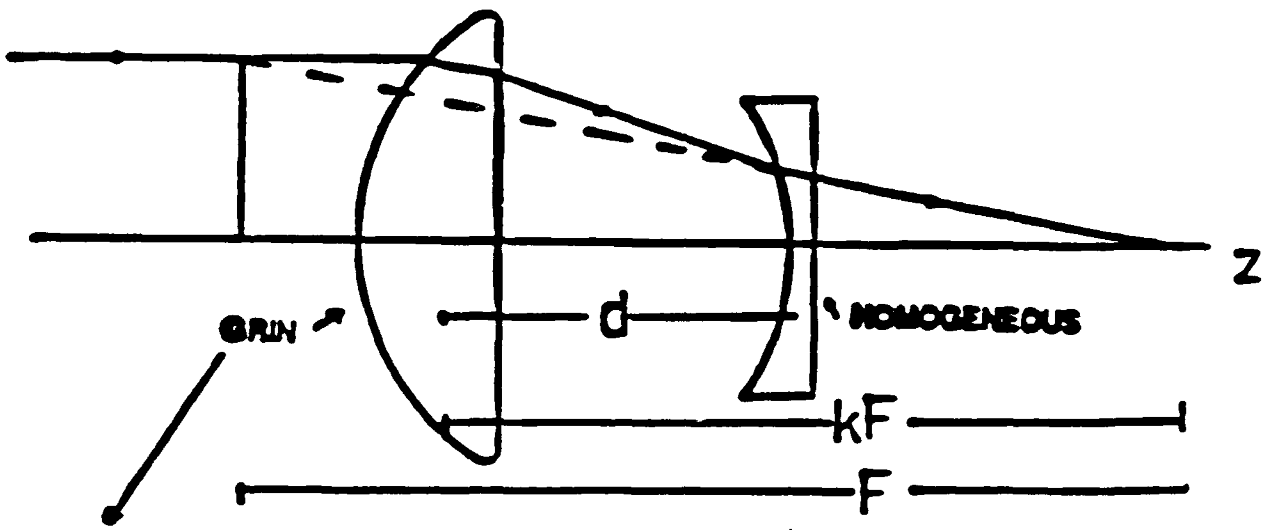


FIRST ORDER SPECIFICATIONS

Effective Focal Length	150 mm
F number	3.0
Semi-field Angle	3.66°
Entrance Pupil	50 mm
Telephoto Ratio	0.80

THE PLAN

Design a two element telephoto system using an axial gradient index positive lens and a homogeneous negative lens.



$N = N_{00} + N_{01}Z + N_{02}Z^2 + \cdots$

Comparing positive elements:

- **Original system———2 lenses**
- **GRIN system————1 lens,1 gradient**

The major function of the gradient is to control spherical aberration.

GRADIENT INDEX GLASS

The Base Glass: We used an alumina silicate crown glass, manufactured by Bausch and Lomb for ion difusion ,for the positive lens.

n_d=1.5011 $V=(n_d-1)/(n_F-n_C)$=58.0

The Gradient: A Ag^+ for Na^+ ion exchange was used as the basis for the design, having a maximum theoretical index change ,Δn=0.15.

The dispersion of the gradient is V_{01}=15, where

$V_{01}= N_{01,d} /(N_{01,F}-N_{01,C})$.

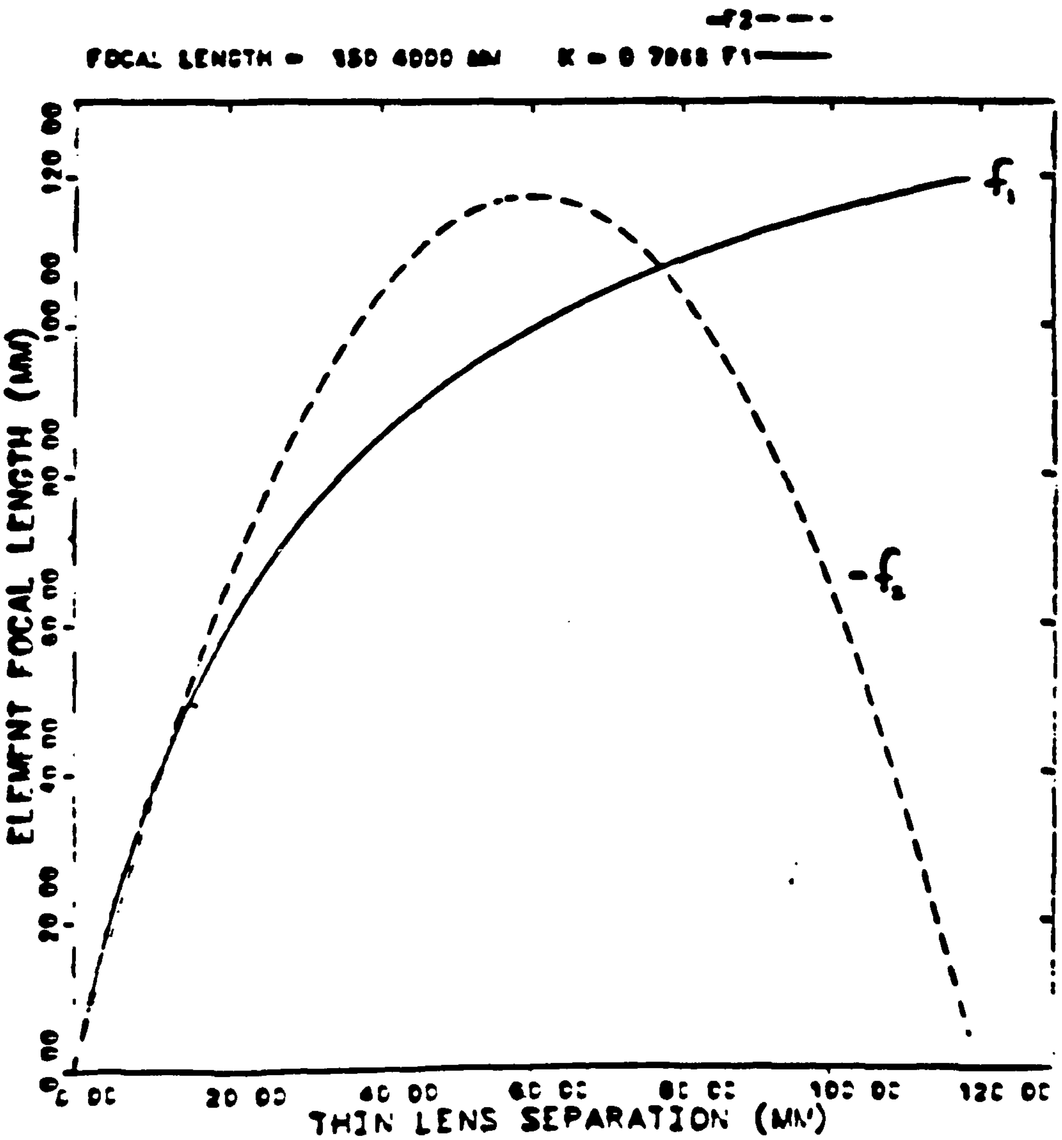
We restricted $\Delta n \leq 0.05$ for ease of fabrication and better transmission.

CONVENTIONAL TELEPHOTO DESIGN

For a focal length F, telephoto ratio k, and separation d, the focal lengths of the elements are *,

$$f_1 = F/\{F(1-k)+d\} \quad \text{and} \quad f_2 = (f_1-d)(kF-d)/(f_1-kF)$$

* Kingslake, Fundementals of Lens Design, 1978



Chromatic Aberration in Telephoto Design

Paraxial Axial Color, PAC--- the variation in focal point with wavelength

For a thin lens, $PAC \propto y_a^2/Vf$,where y_a=axial ray height

f=focal length

and $V=(n_d-1)/(n_F-n_C)$

For two thin lenses,

$$PAC \propto y_{a1}^2/V_1 f_1 + y_{a2}^2/V_2 f_2.$$

For PAC=0 ,then,

$$(y_{a1}^2 f_2)/(y_{a2}^2 f_1) = -V_1/V_2$$

We saw from the graph that as the separation increased,this ratio also increased, since f_2 increases faster than f_1.

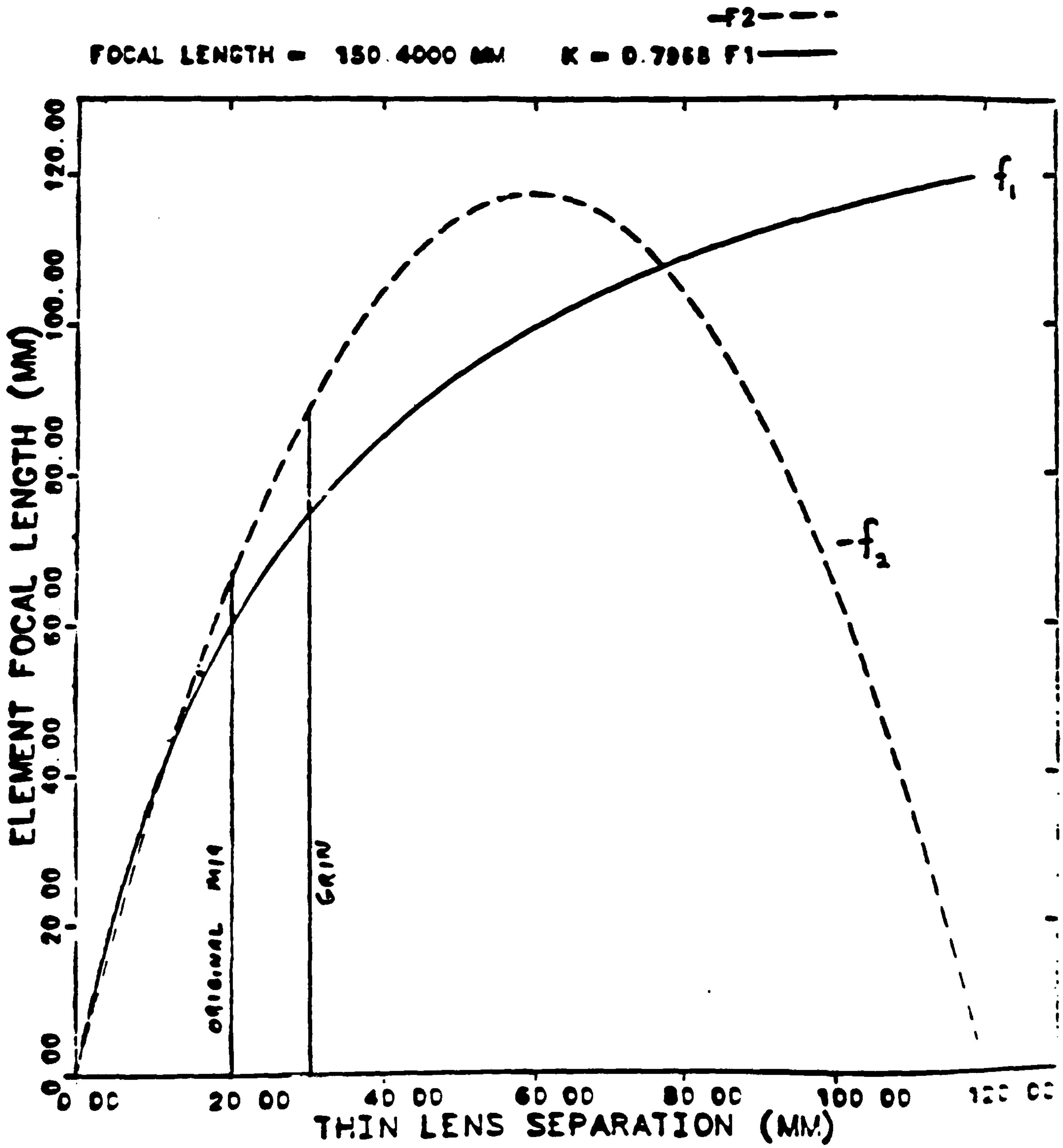
Therefore to get weak element we need a large ratio V_1/V_2.

We found that our best gradient index design had the largest value of V_1/V_2 that we could use.

SYSTEM COMPARISON

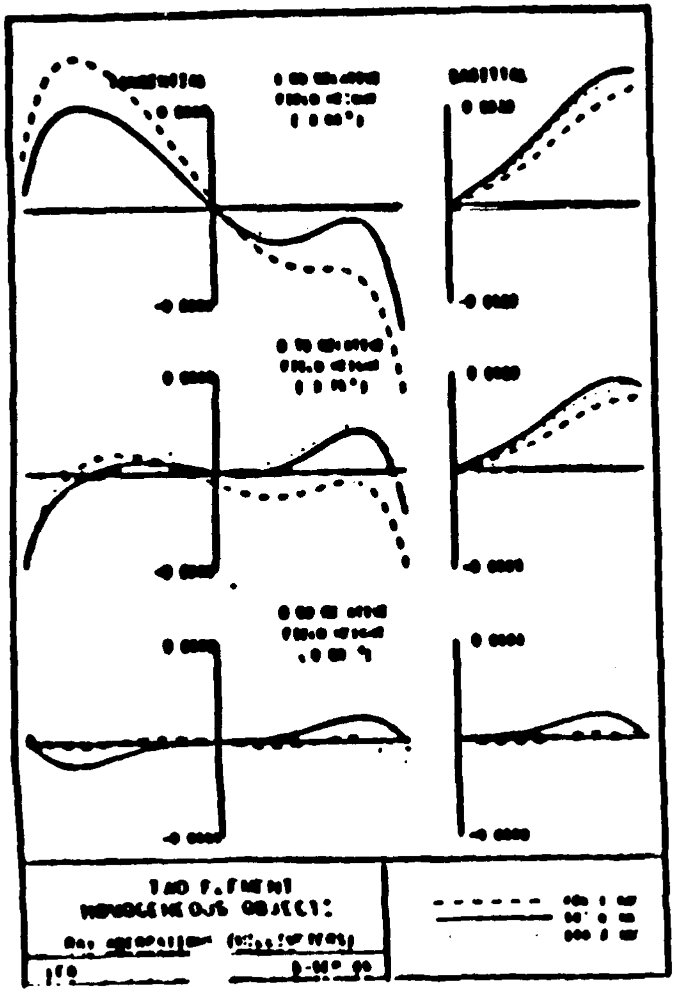
GRIN	ORIGINAL
$V_1=58.0$	$V_1=V_2=64.2$ (BK7)
$V_2=20.4$ (SF59)	$V_3=31.2$ (SF8)
$V_1/V_2=2.84$	$V_1/V_3=2.06$
d=30 mm	d=20 mm
f1=75 mm	$f_{1,2}=61$ mm
f2=-96 mm	$f_3=-66$ mm

TELEPHOTO SOLUTIONS

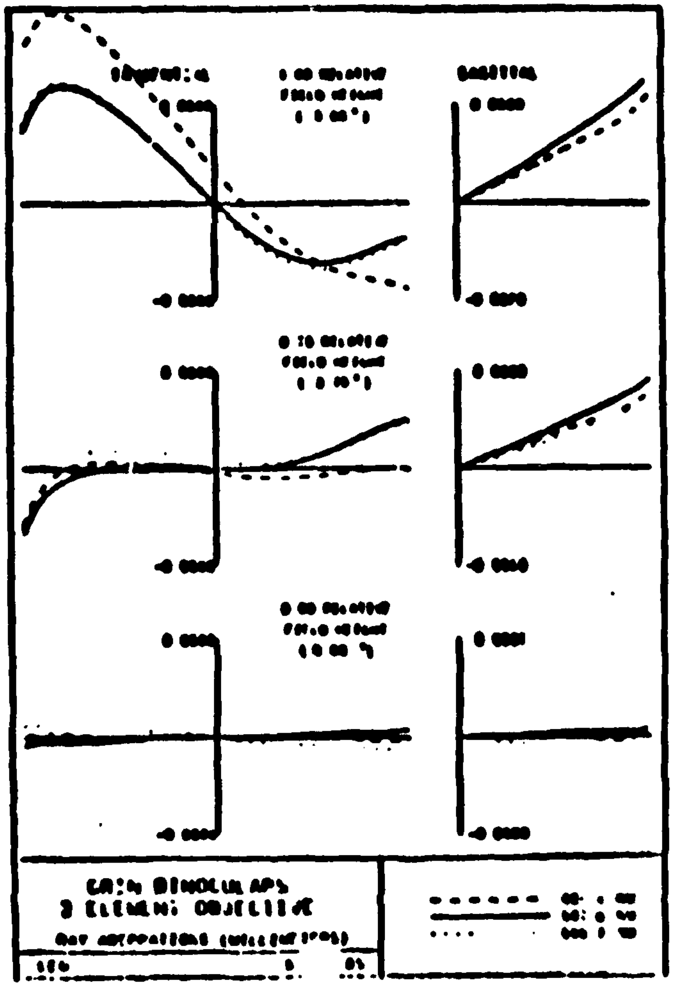


TRANSVERSE ABERRATIONS

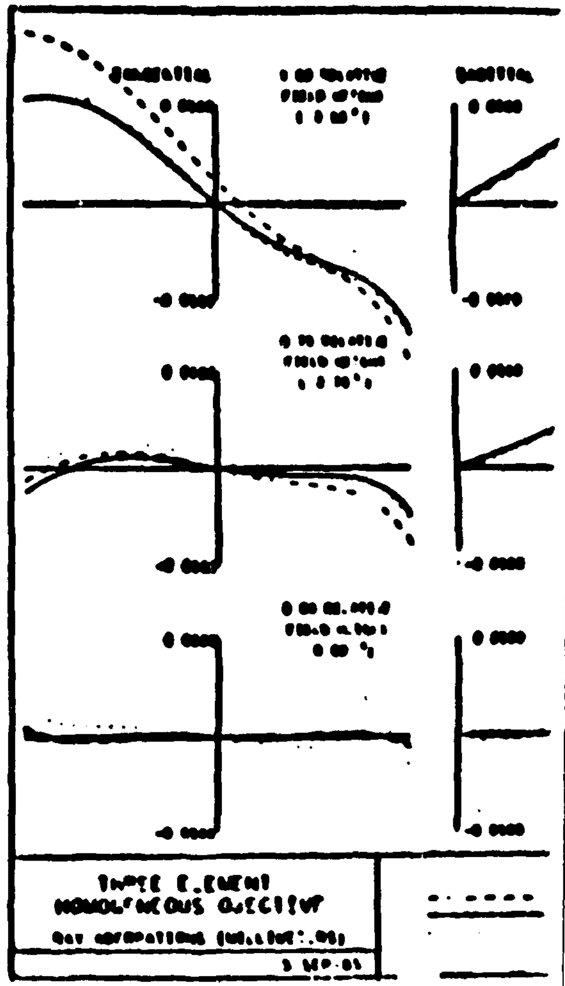
2 ELEMENT HOMOGENEOUS OBJECTIVE



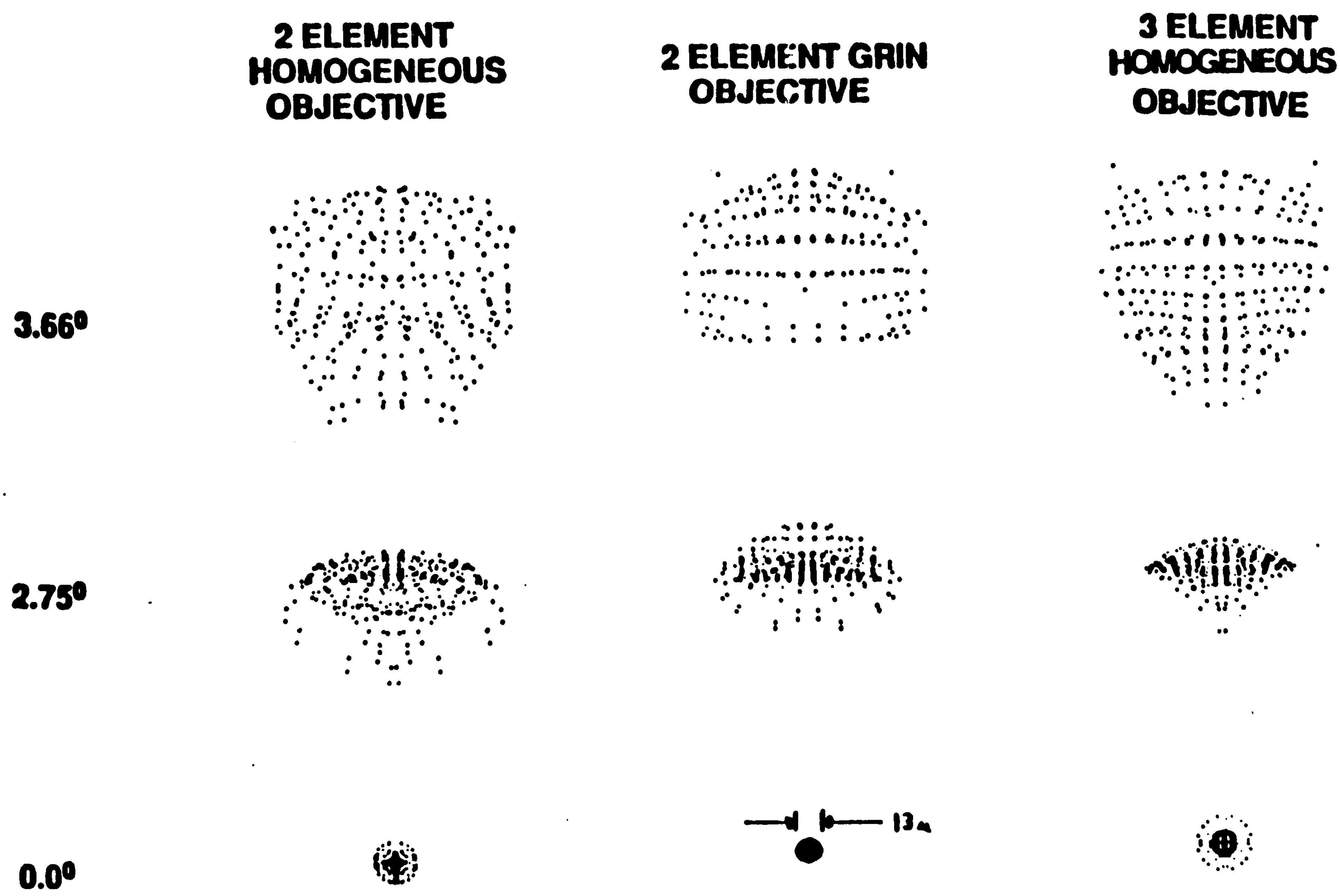
2 ELEMENT GRIN OBJECTIVE



3 ELEMENT HOMOGENEOUS OBJECTIVE



SPOT DIAGRAMS



FABRICATION OF THE GRADIENT

Glass –Bausch and Lomb 2406

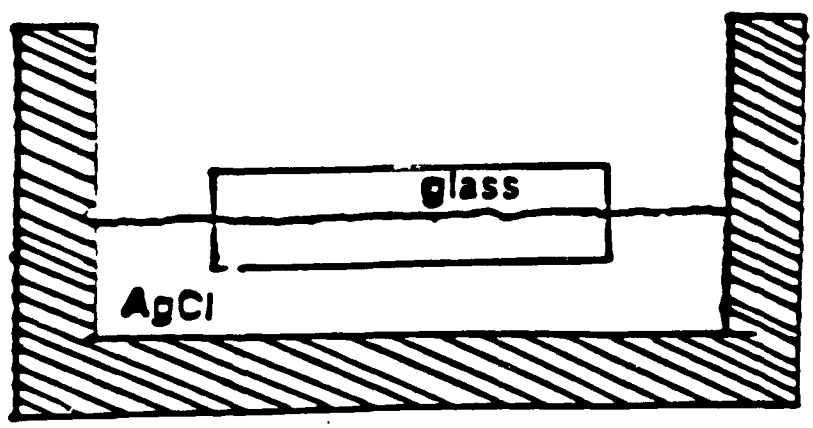
Salt —AgCl

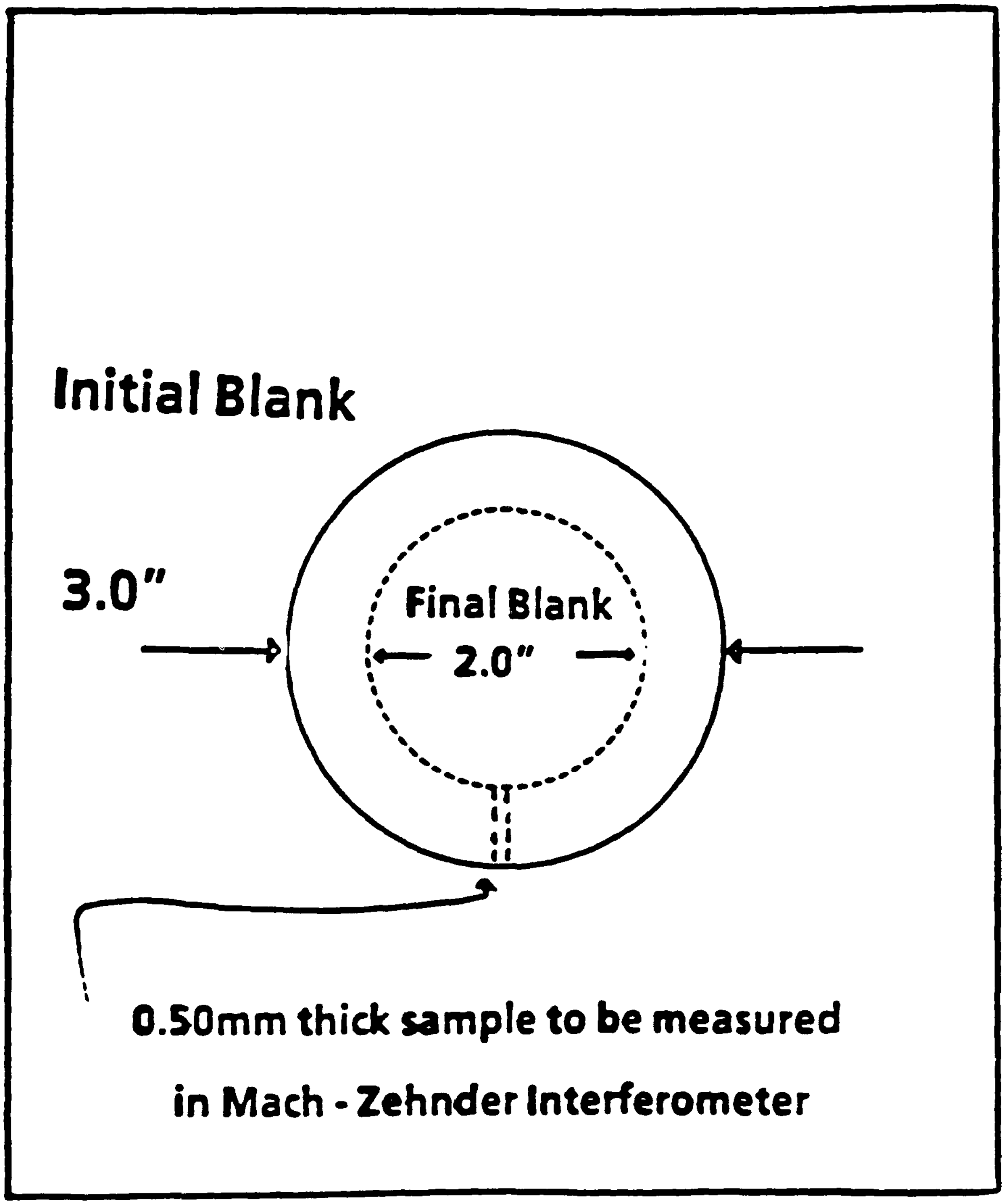
Ion Exchange— Ag^+ for Na^+

Diffusion Time— 39.5 hours

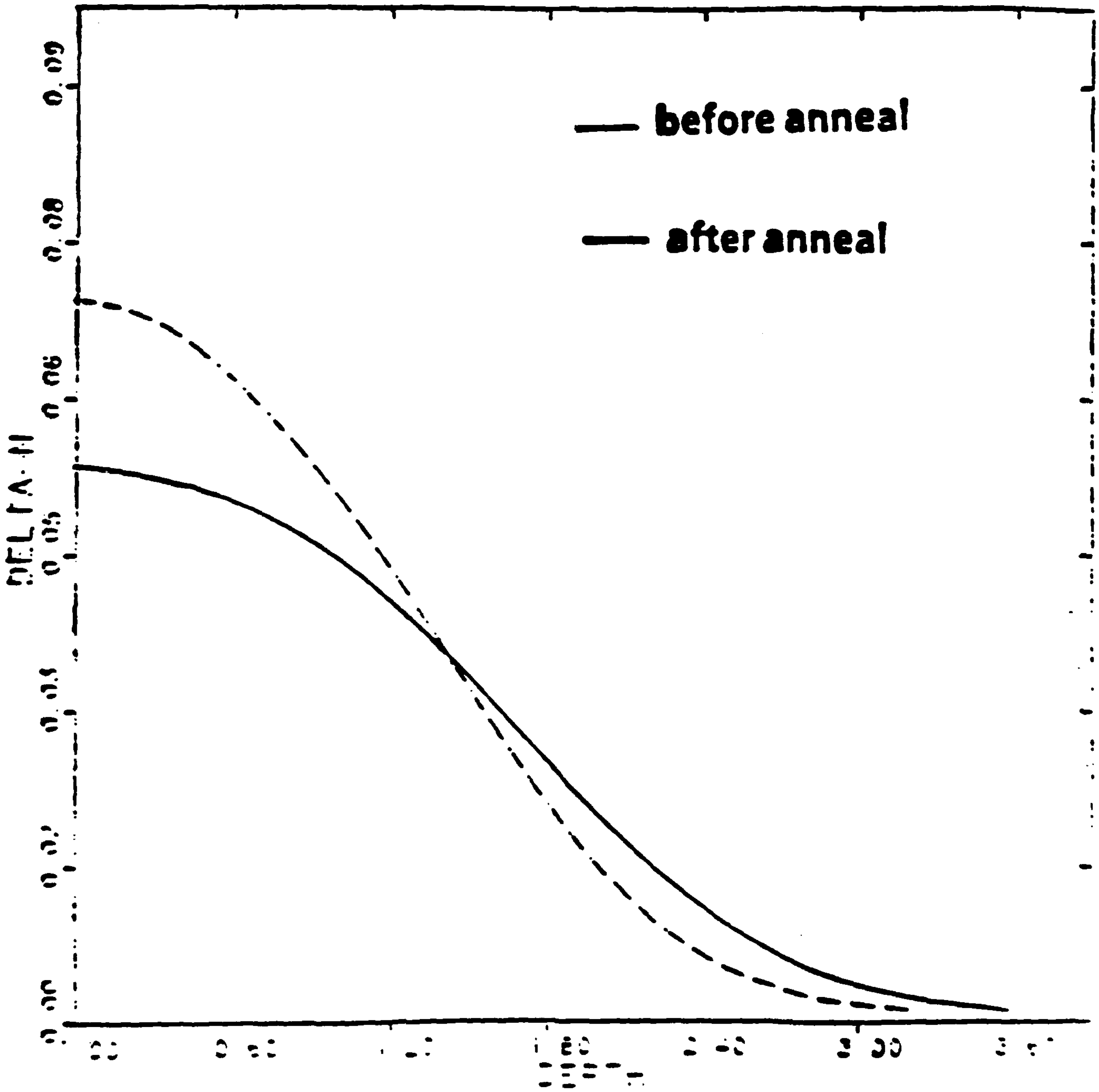
Temperature —-515^0 C

Anneal — 10 hours at 515^0 C



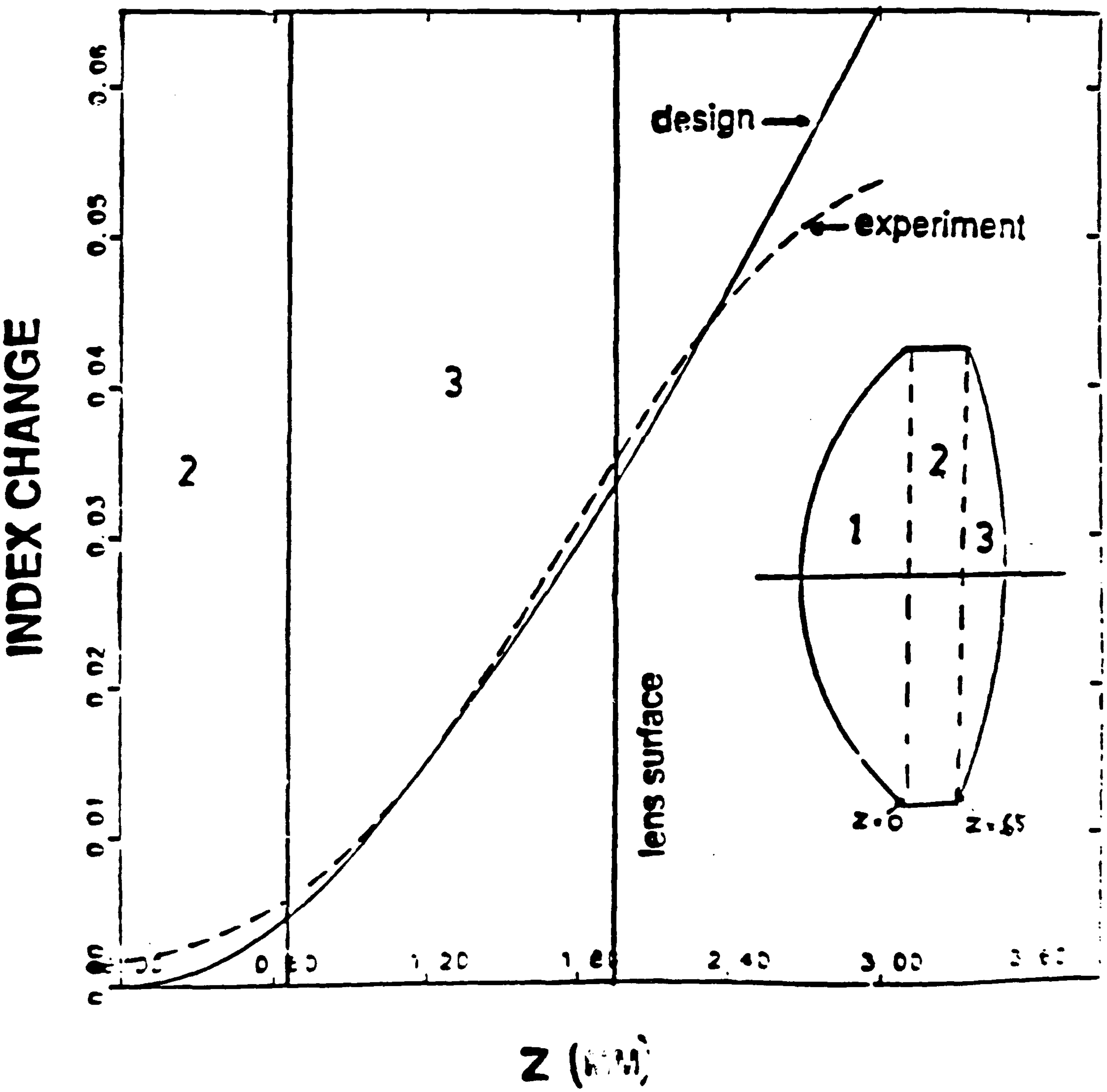

Initial Blank
3.0"
Final Blank
2.0"
0.50mm thick sample to be measured
in Mach - Zehnder Interferometer

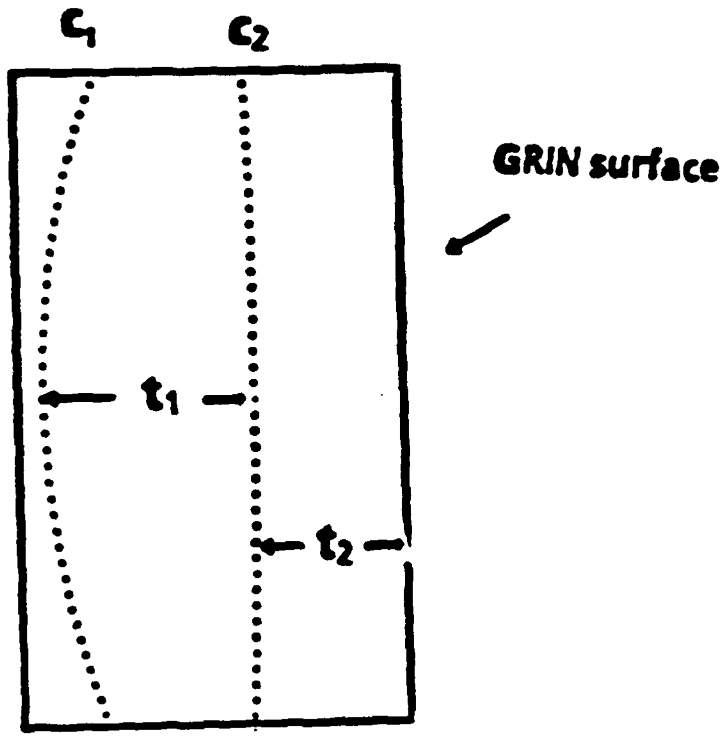
Index Profiles



INDEX PROFILE

DESIGN vs. EXPERIMENT





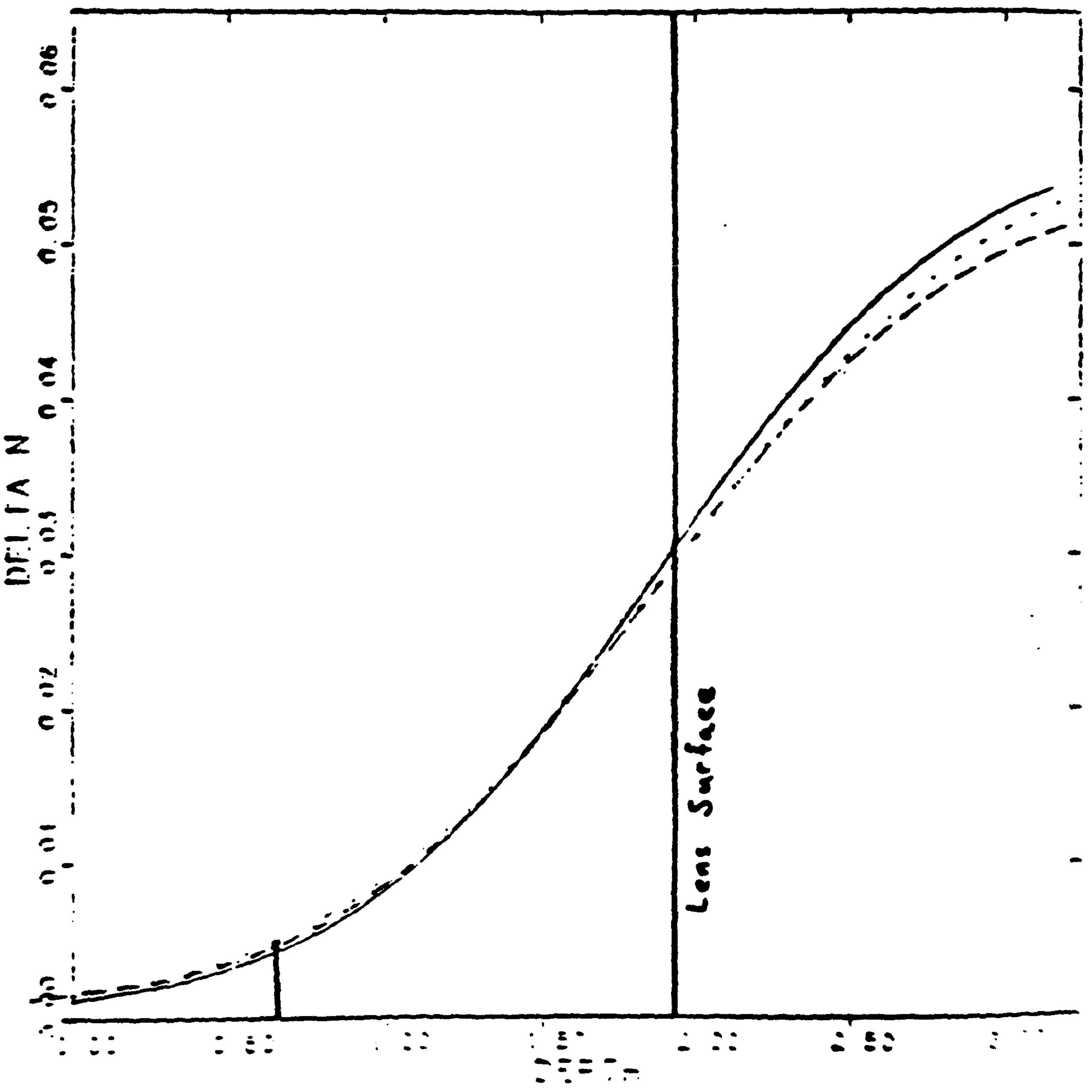
c_1 = 0.0197271 /mm.

t_1 = 14.00 mm.

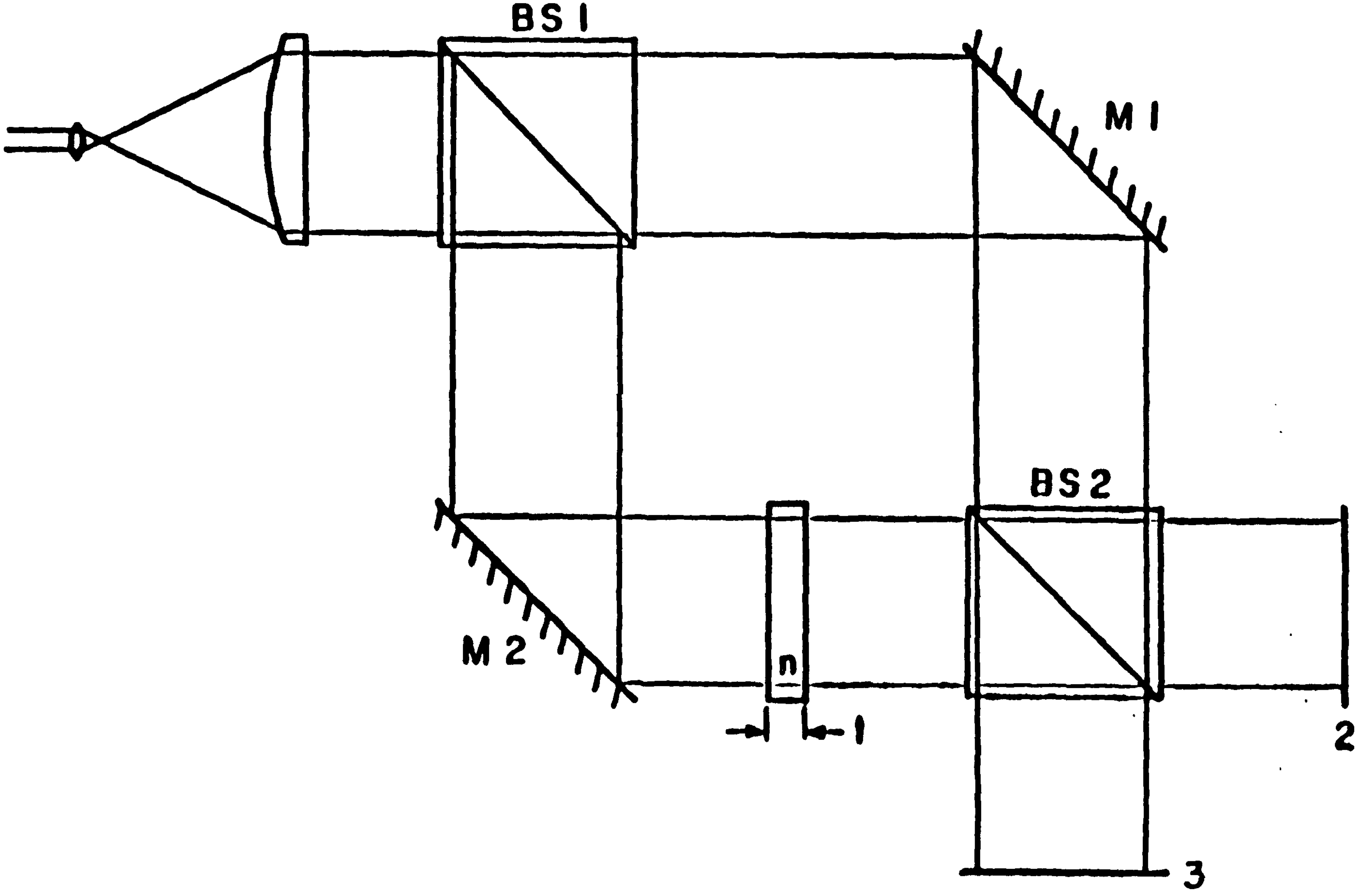
c_2 = -0.00431415 /mm.

t_2 = 1.877 mm.

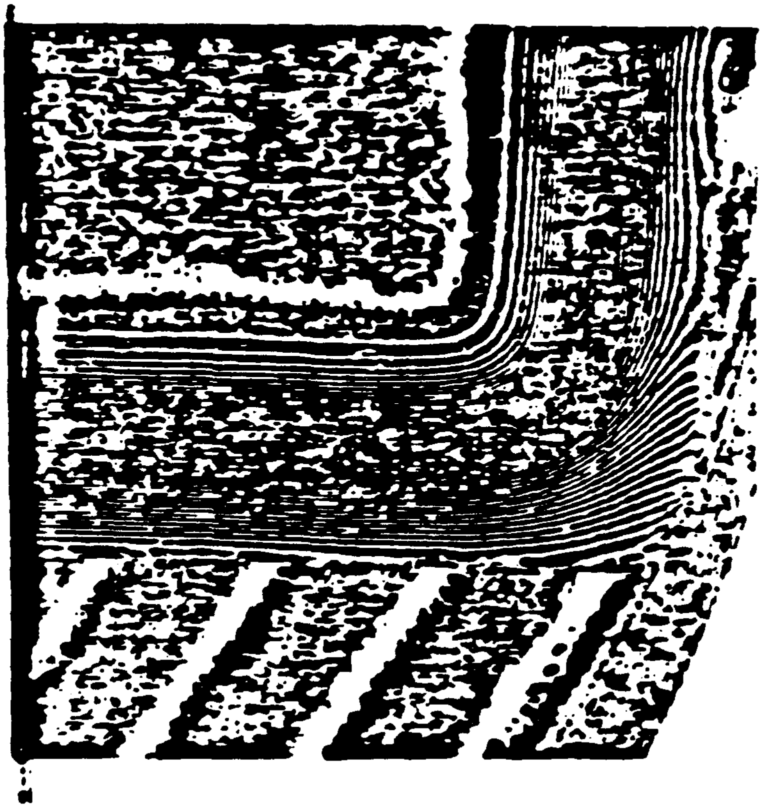
Index profiles - shifted



Mach - Zehnder Interferometer



Interference pattern Due to Index of Refraction Gradient



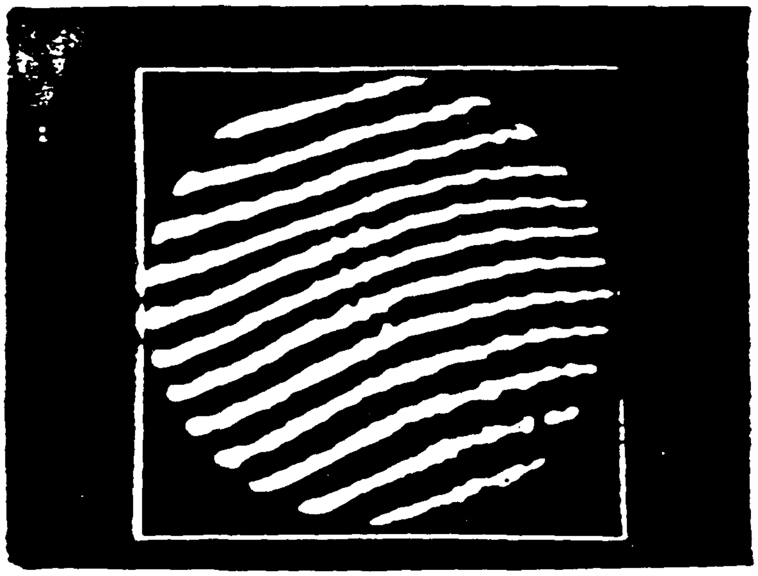
$$\Delta n = m\lambda/t$$

System Testing

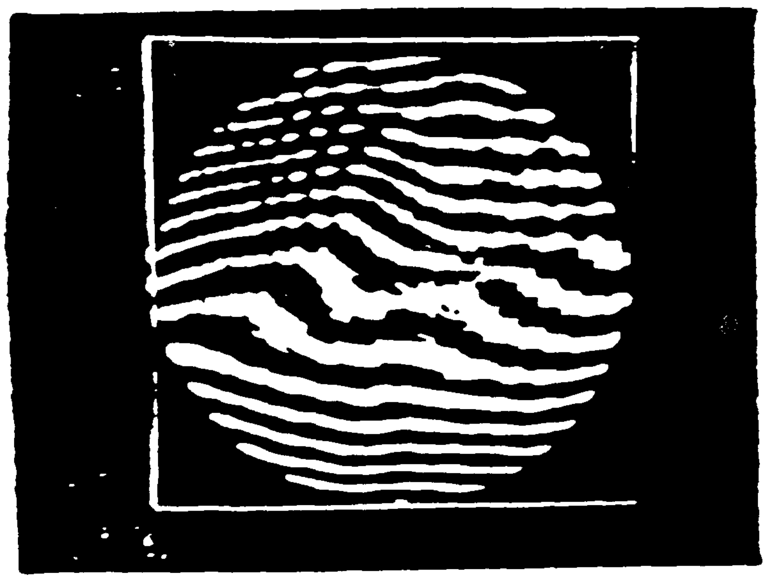
1) Wavefront measurement with Zygo Interferometer

2) MTF Measurement

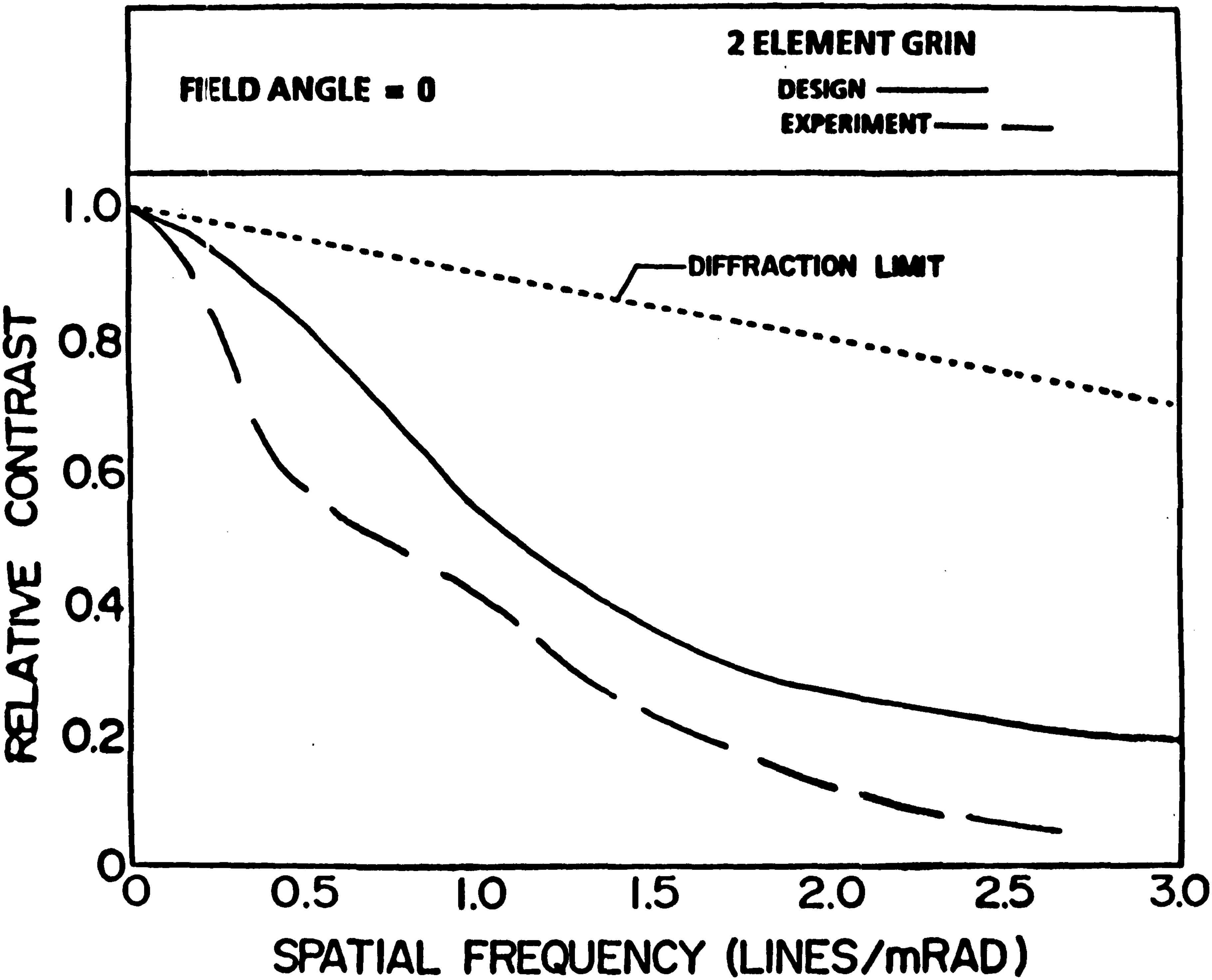
3) Visual Resolution Test with UASF - 1951 Target



Grin 1



Grin 2


FIELD ANGLE = 0
2 ELEMENT GRIN
DESIGN
EXPERIMENT
DIFFRACTION LIMIT
RELATIVE CONTRAST
1.0
0.8
0.6
0.4
0.2
0
0
0.5
1.0
1.5
2.0
2.5
3.0
SPATIAL FREQUENCY (LINES/mRAD)

SUMMARY

Key Results

1. This was the first large-scale axial gradient-index system ever fabricated.
2. The number of elements was reduced while maintaining equivilant performance.
3. The ability to alter the index profile after diffusion was demonstrated.
4. Reproducibility and the potential for mass production were also demonstrated.

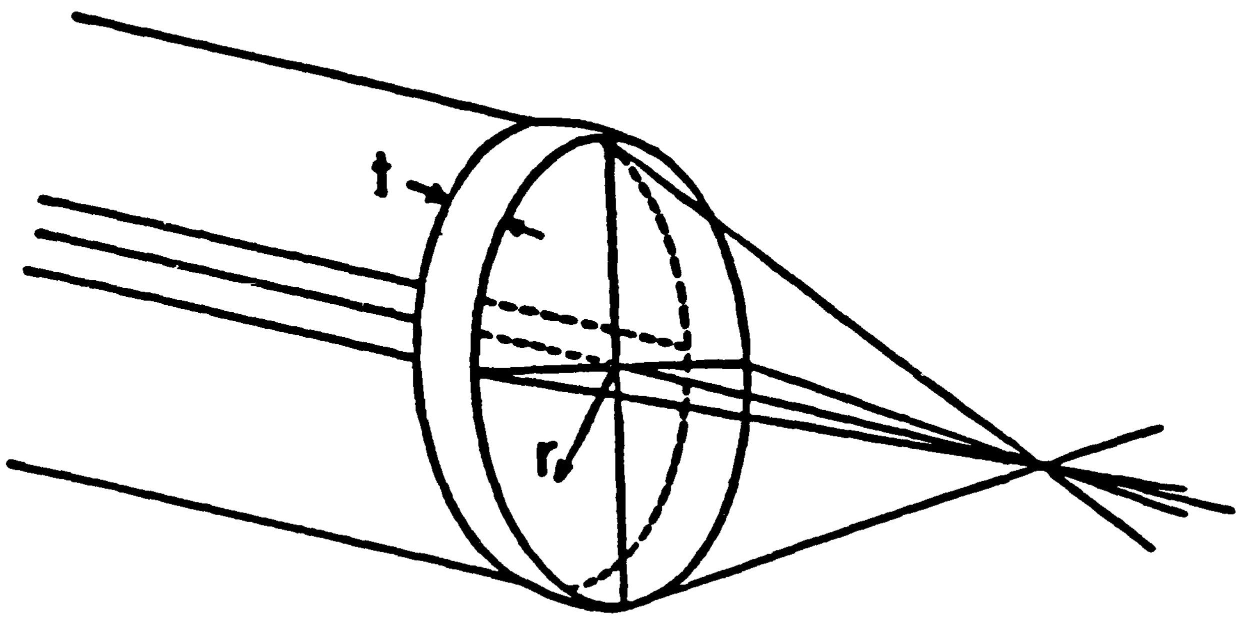
Implications

1. Weight reduction
2. Improved reliability
3. Improved performance with the same number of elements
4. Cost

RADIAL GRADIENT

DEGREES OF FREEDOM	CORRECTION
N_{10}	COMA
FIRST CURVATURE	ASTIGMATISM
N_{20}	SPHERICAL ABERRATION
STOP POSITION	DISTORTION
SECOND CURVATURE	FOCAL LENGTH
THICKNESS	

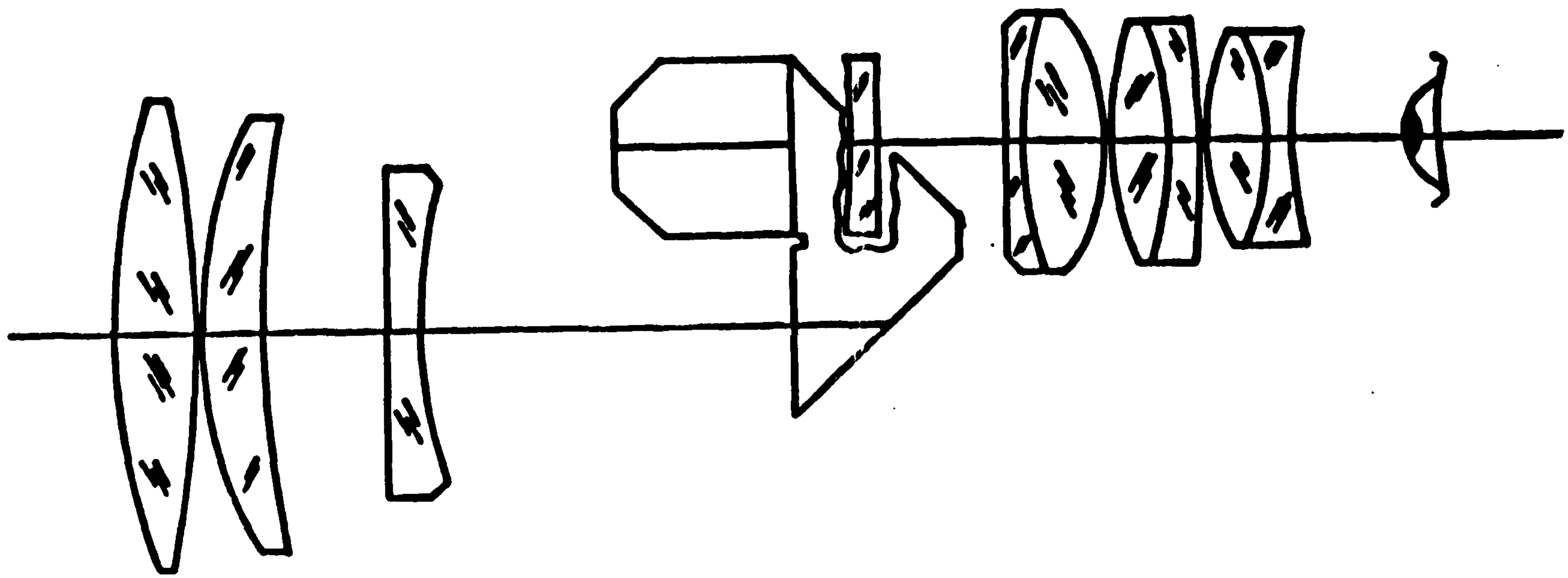
WOOD LENS



$$N(r) = N_{00} + N_{10} r^2 + N_{20} r^4 + \cdots$$

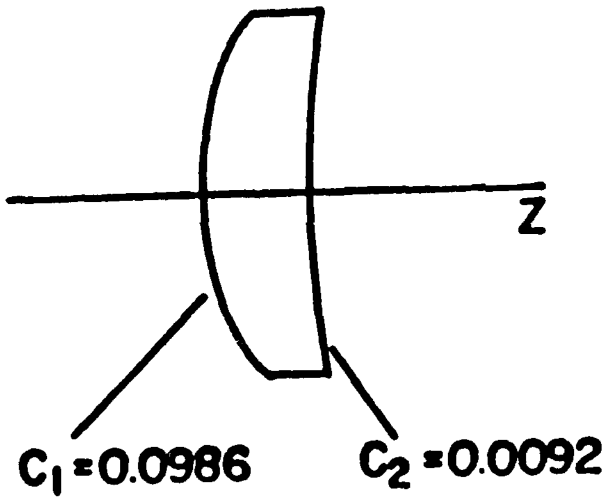
$$\text{POWER} = -2 N_{10} t$$

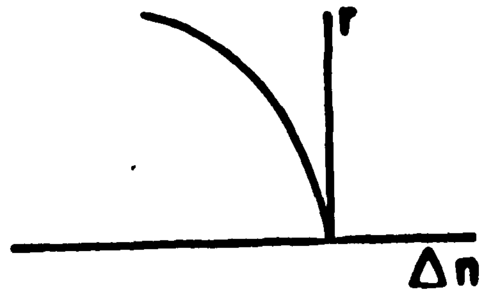
	WOOD LENS	HOMOGENEOUS
ower	$-2N_{10}t$	$(N_{00}-1)(C_1-C_2)$
bbe No	$V_{10} = \dfrac{N_{10,d}}{N_{10,F}-N_{10,C}}$	$V_{00} = \dfrac{N_{00,d}-1}{N_{00,F}-N_{00,C}}$
	$V_{10} \in \begin{matrix}(2,\infty)\\(-5,-\infty)\end{matrix}$	$V_{00} \in (20,90)$
etzval	$\dfrac{\phi}{N_{00}^2}$	$\dfrac{\phi}{N_{00}}$
iffusion	$V_{10} \sim 18$	Thallium - Potassium
	~ 60	Cesium - Potassium
	~ 250	Lithium - Potassium



BINOCULAR SYSTEM

P.R. YODER, JR., J. OPT. SOC. AM. 50, 491 (1960)



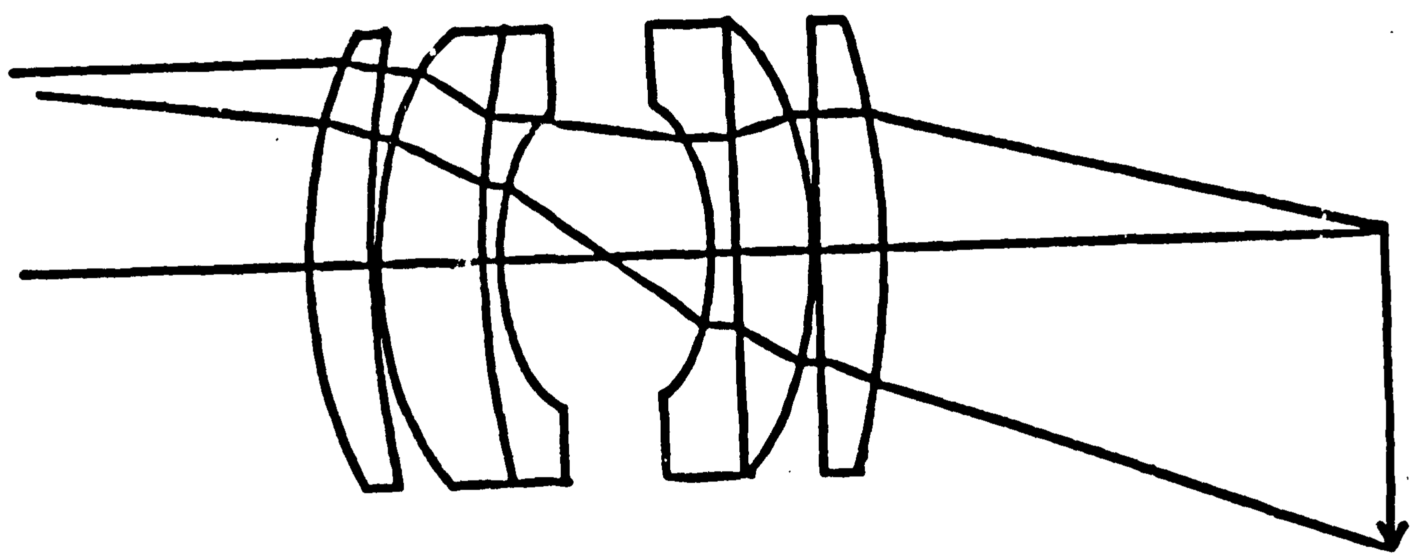


$$n = 1.51454 - 0.005 r^2 - 9.97 \times 10^{-5} r^4 - 3.06 \times 10^{-6} r^6$$

BINOCULAR OBJECTIVE

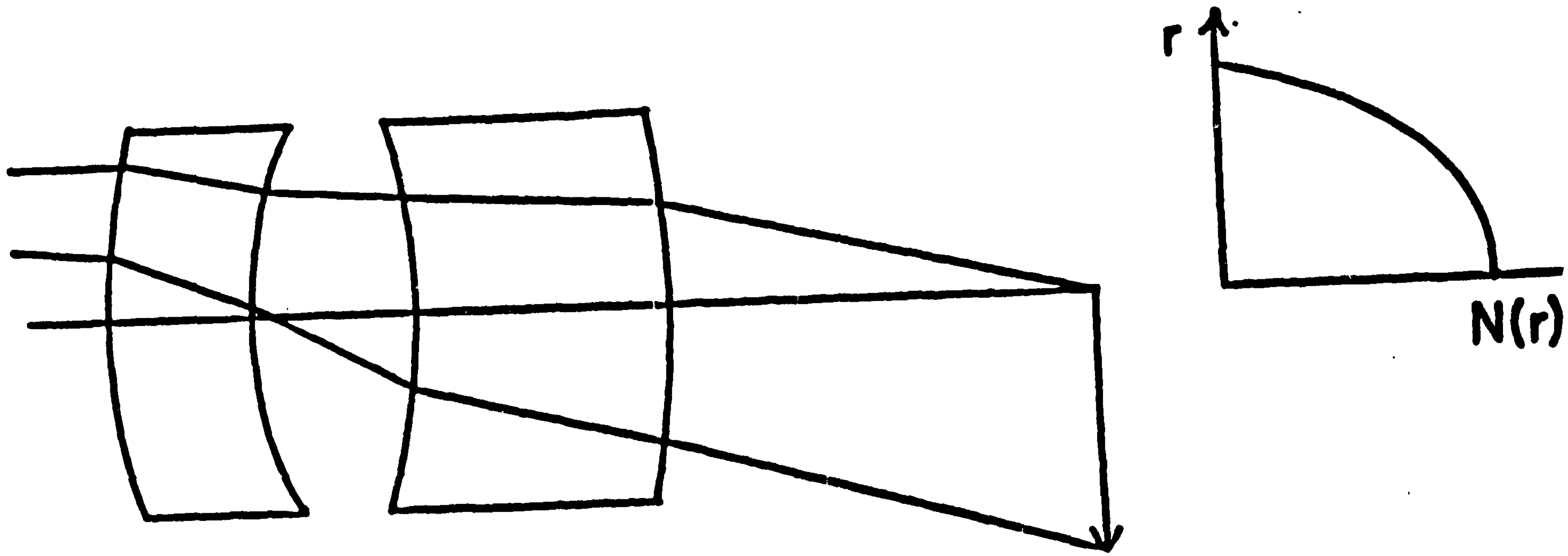
CONVENTIONAL PHOTOGRAPHIC OBJECTIVE

fl=50mm f/2 hfov=21°

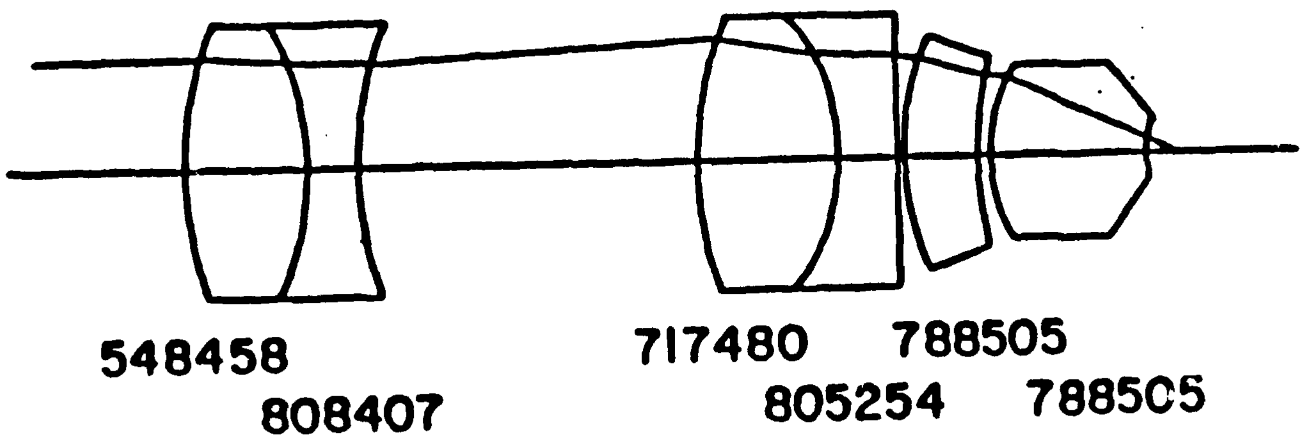


GRADIENT INDEX PHOTOGRAPHIC OBJECTIVE

fl = 50 mm   f/2   hfov = 21°

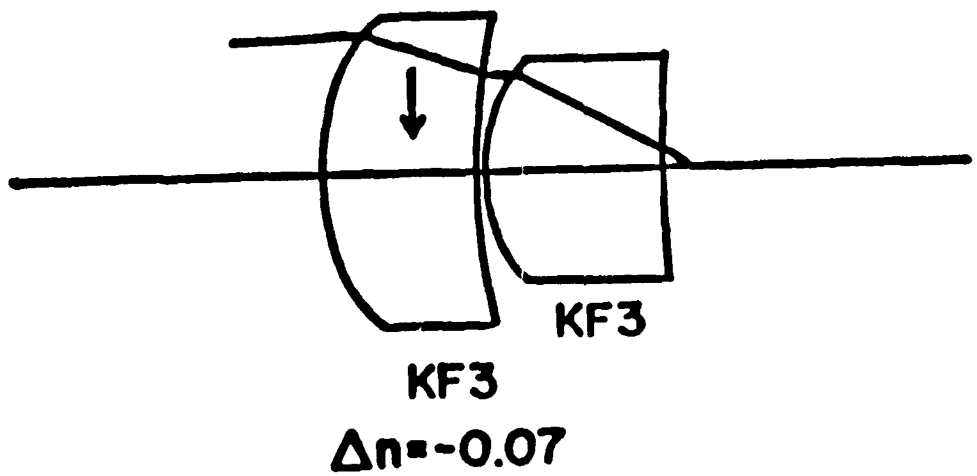


CONVENTIONAL 40X MICROSCOPE OBJECTIVE



CONVENTIONAL 40X MICROSCOPE OBJECTIVE

GRADIENT 40X MICROSCOPE OBJECTIVE



GRADIENT 40X MICROSCOPE OBJECTIVE

FIRST ORDER PROPERTIES

NUMERICAL APERTURE	0.45
FOCAL LENGTH	~8.0MM.
FULL FIELD OF VIEW	700µM.
LENS DIAMETER	<8MM.
COVER PLATE	1.1MM.

TWO APPROACHES

I. WOOD LENS (RADIAL GRADIENT WITH PLANO SURFACES)

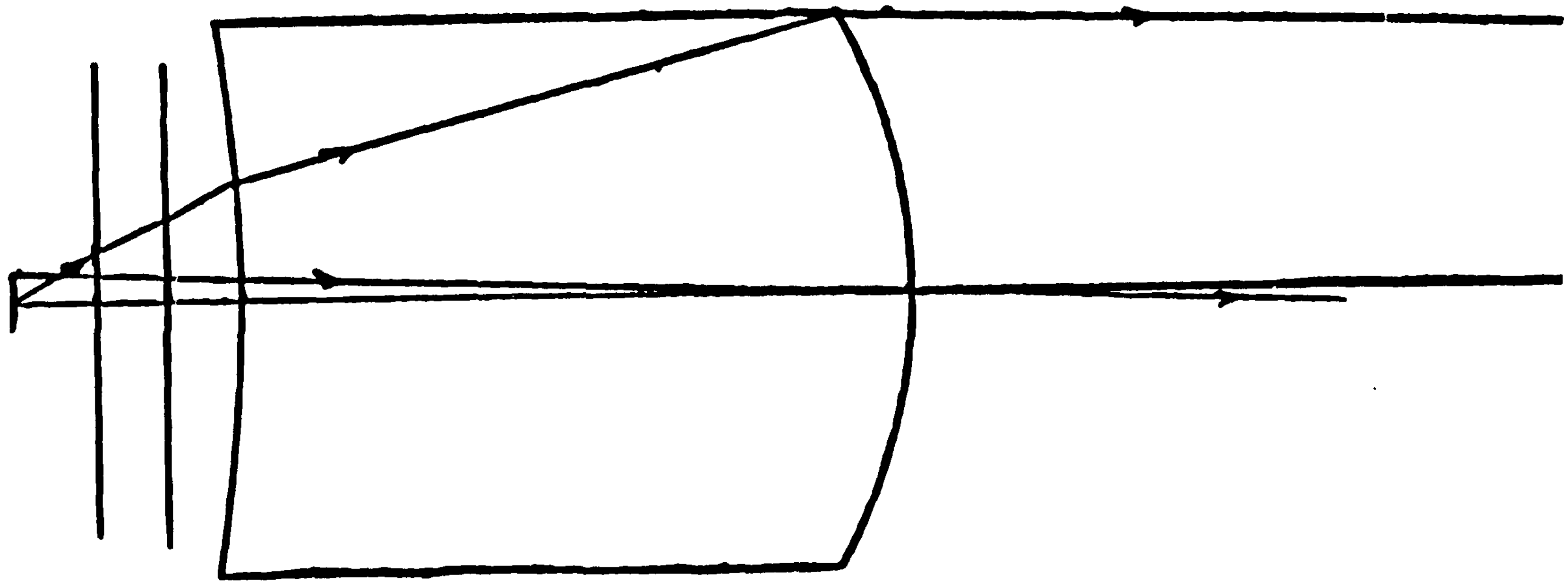
II. RADIAL GRADIENT WITH CURVED SURFACES

$$N(r) = N_{00} + N_{10}\,r^2 + N_{20}\,r^4 + N_{30}\,r^6 + .$$

TOLERANCE DATA

PARAMETER	NOMINAL VALUE	TOLERANCE
TH	8.0 mm	±0.15 mm
N_{00}	1.70	±0.001
N_{10}	$-0.358\text{-}02\ mm^{-2}$	$\pm 0.002\text{-}02\ mm^{-2}$
N_{20}	$-0.902\text{-}05\ mm^{-4}$	$\pm 0.030\text{-}05\ mm^{-4}$
Tilt	0.0 radians	±0.003 radians
Decentration	0.0 mm	±0.100 mm
CV_1	$0.1346\ mm^{-1}$	5 rings
CV_2	$0.0455\ mm^{-1}$	5 rings

Assumes all parameters are independent. Focal shift correction allowed in all cases.



$$N(r) = 1.7 - 0.36 \times 10^{-2} r^2 - 0.90 \times 10^{-5} r^4$$

$t = 8.9$ mm

$c_1 = 0.135$ mm^{-1}

$c_2 = 0.046$ mm^{-1}

Manufacture of Gradients

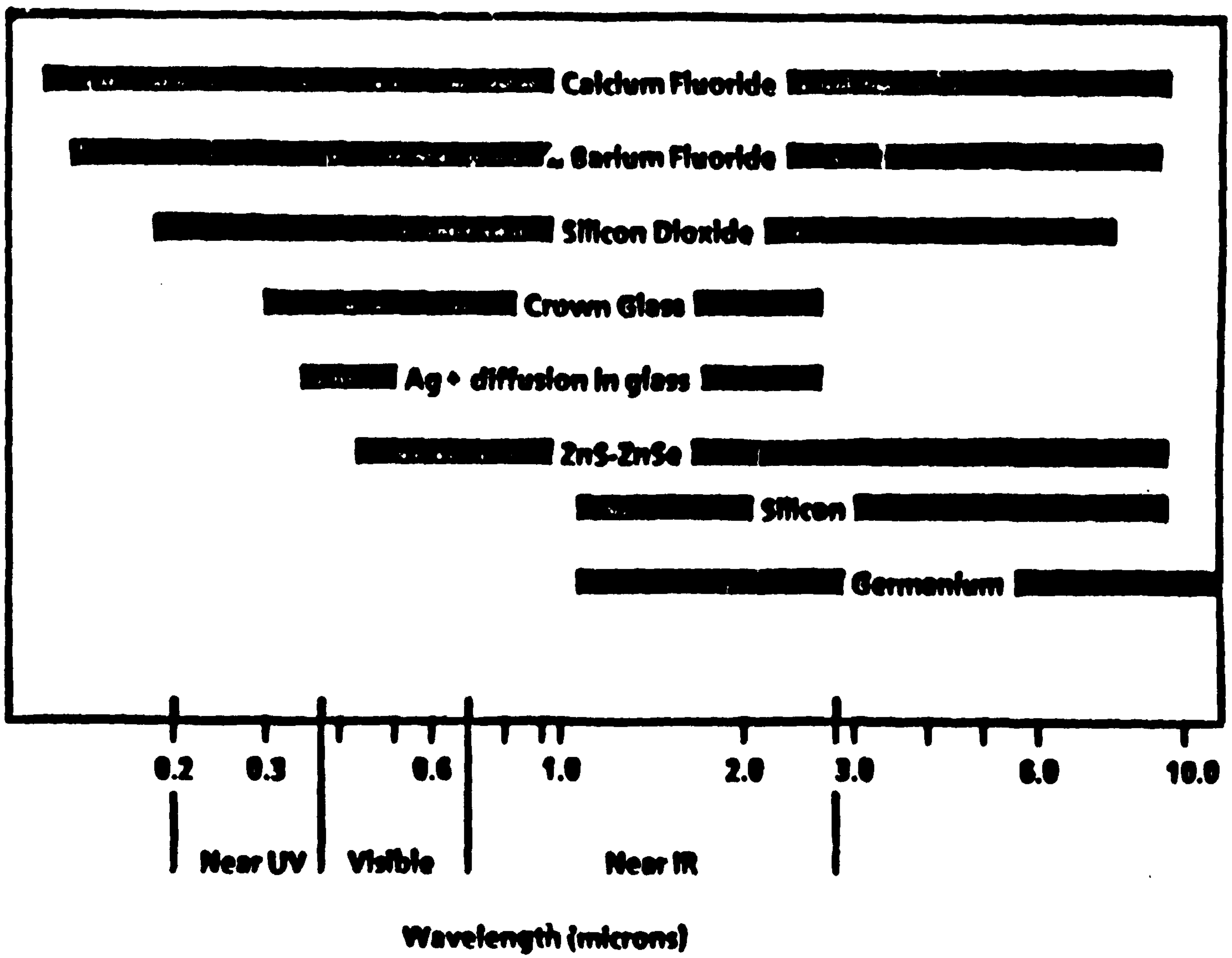
Glass

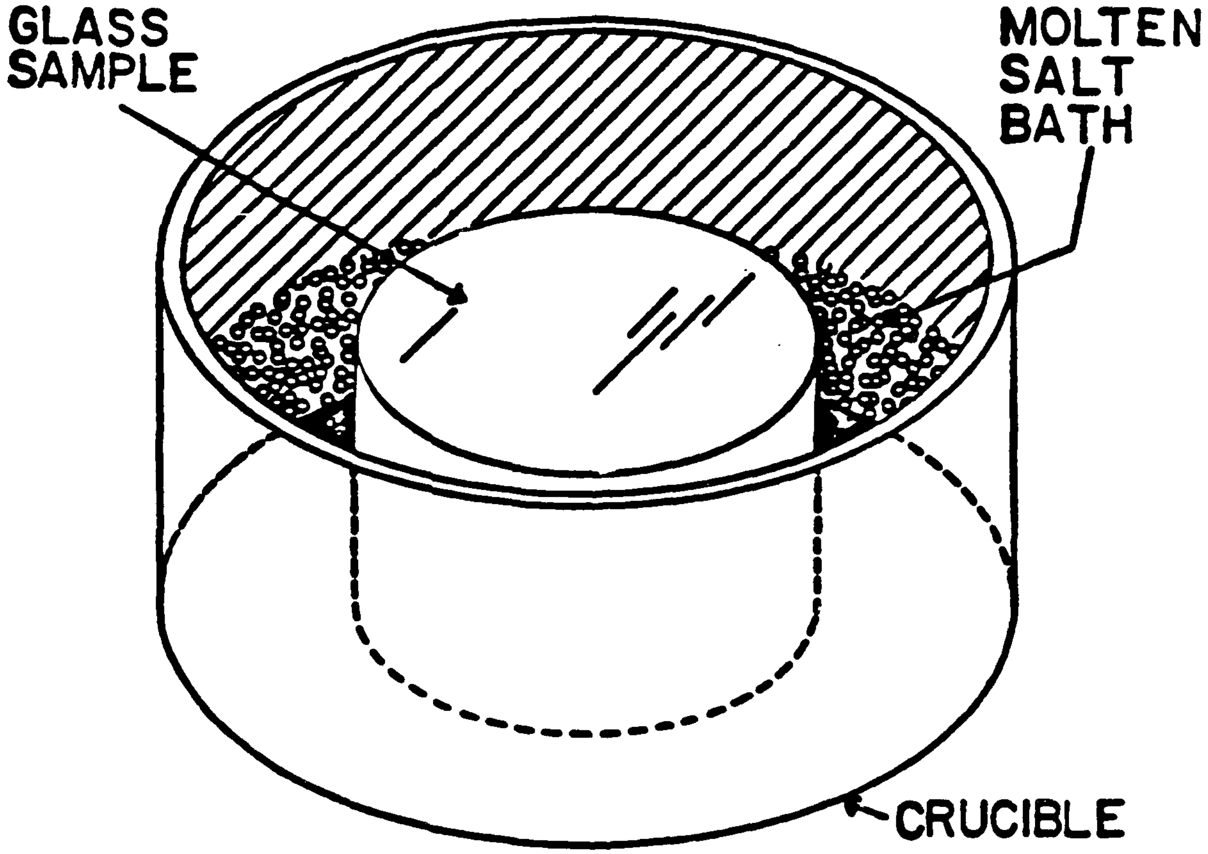
	Size	ΔN
Neutron Irradiation	0.1 mm	0.02
Chemical Vapor Deposition (CVD)	1.0 mm	0.03
Polymerization Techniques	20.0 mm	0.04
Ion Exchange	18.0 mm	0.15
Stuffing	10.0 mm	0.04

Infrared Materials

Ge–Si	20.0 mm	0.15
ZnSe–ZnS	10.0 mm	0.24

Transmission Range for Some Optical Materials





GRADIENT INDEX FABRICATION
METHOD OF ION EXCHANGE

LIST OF BASE GLASSES

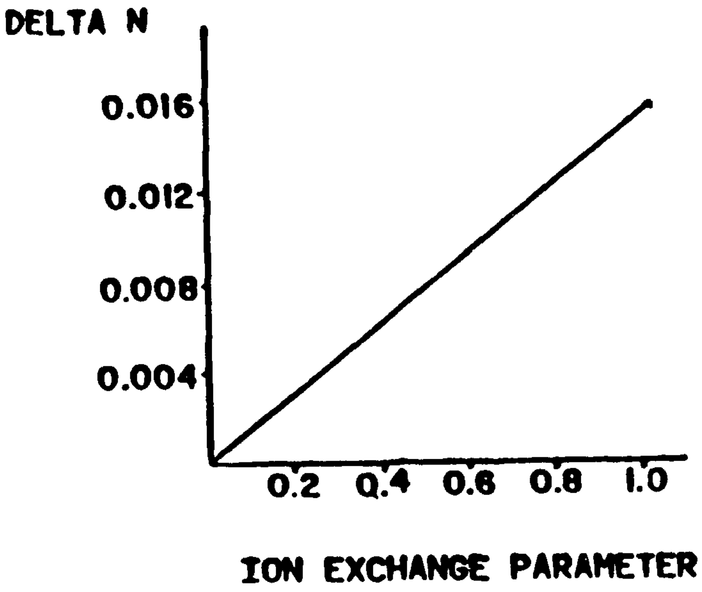
BK-7	517.642
BK-13	521.628
SK-3	609.589
FK-5	487.704
BaF-3	583.465
BaLF-3	571.529
BaK-1	573.575
LaK-23	669.574
LaF-N2	744.448
LaF-24	757.478
SF-2	648.339
SF-4	755.276
SF-6	805.254
SF-64	706.308
S-8000	518.599
BaSF-51	724.381
LaSF-5	881.410
LaK-N14	697.554
BaSF-1	626.390
KF-3	515.547

MODELS

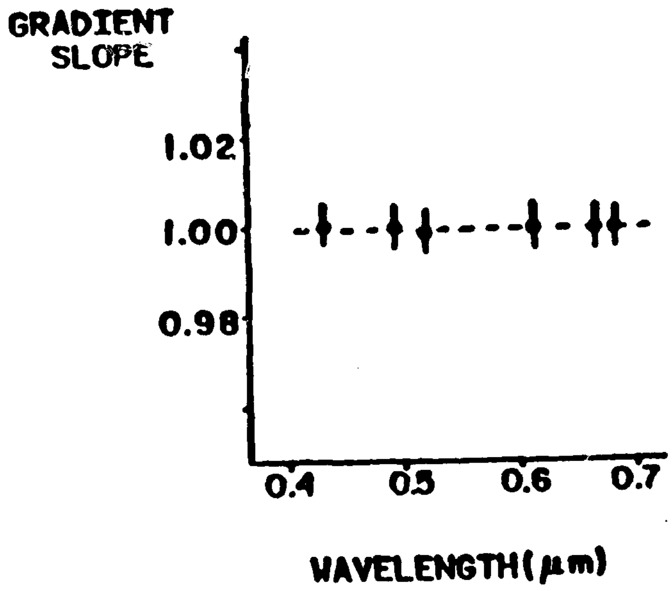
1. DIFFUSION COEFFICIENT
2. INDEX OF REFRACTION
3. SPECTRAL PROPERTIES
4. THERMAL AND MECHANICAL PROPERTIES

ION EXCHANGE

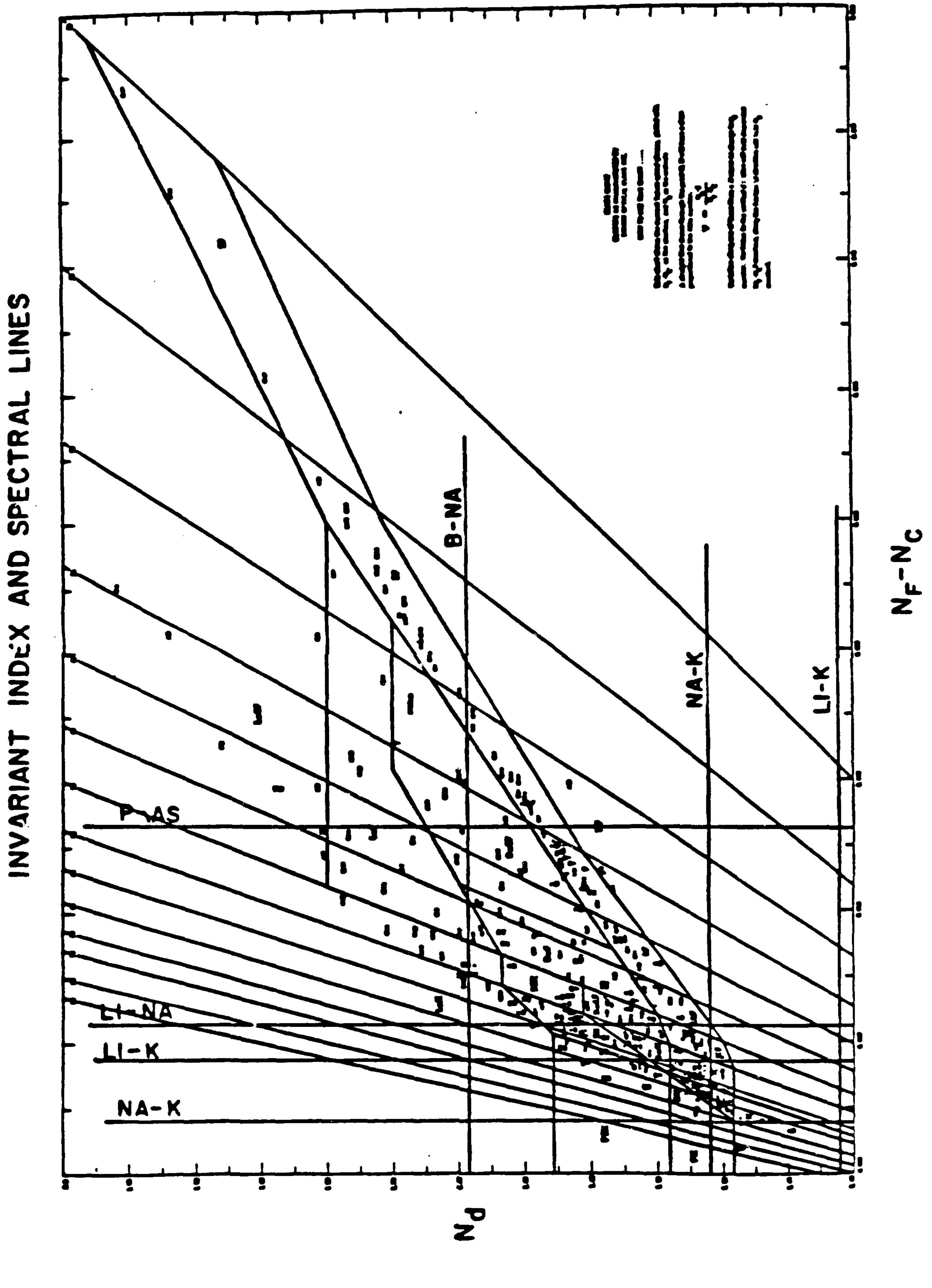
GLASS KF3
DIFFUSANT LIBR



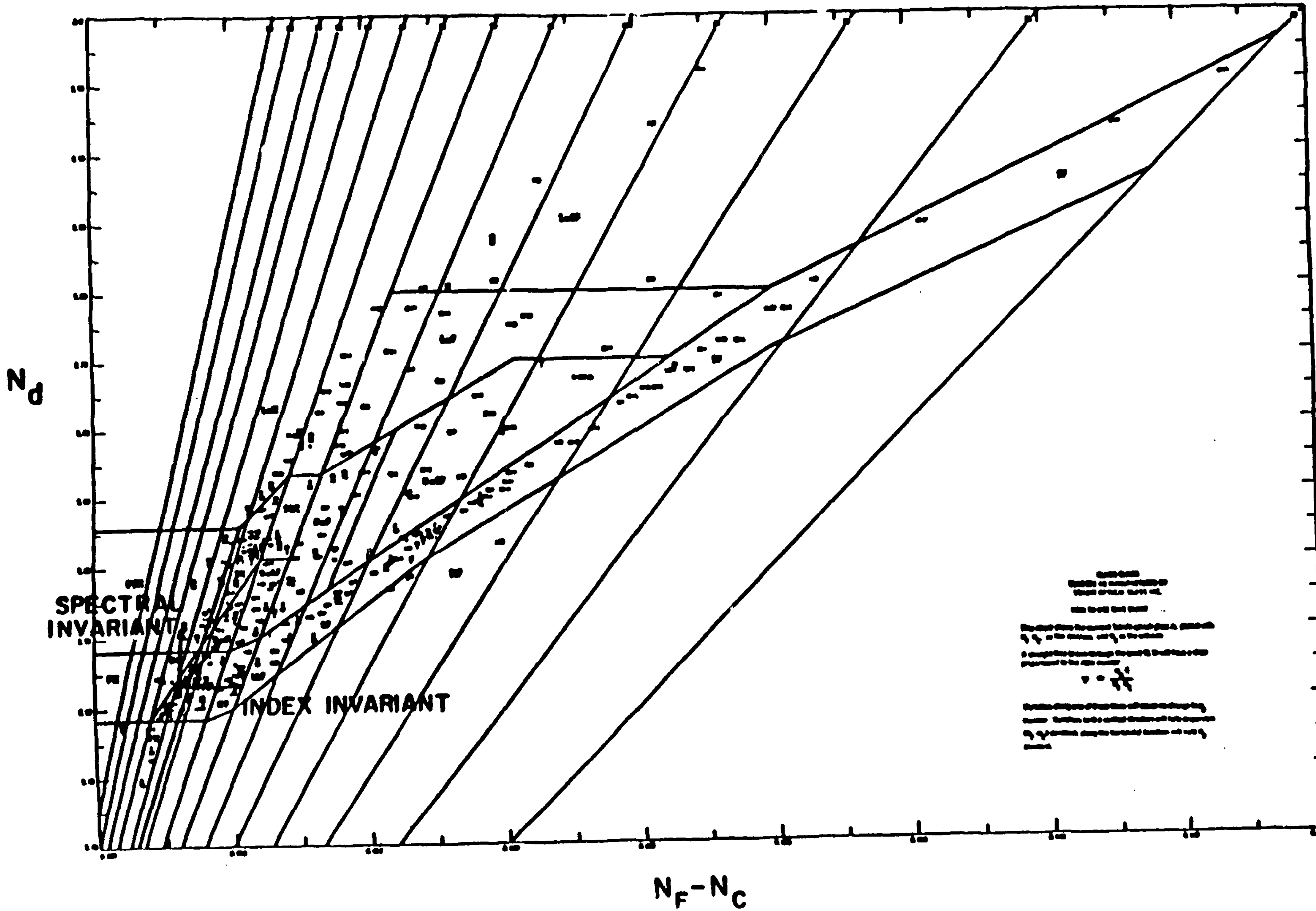
INDEX CHANGE

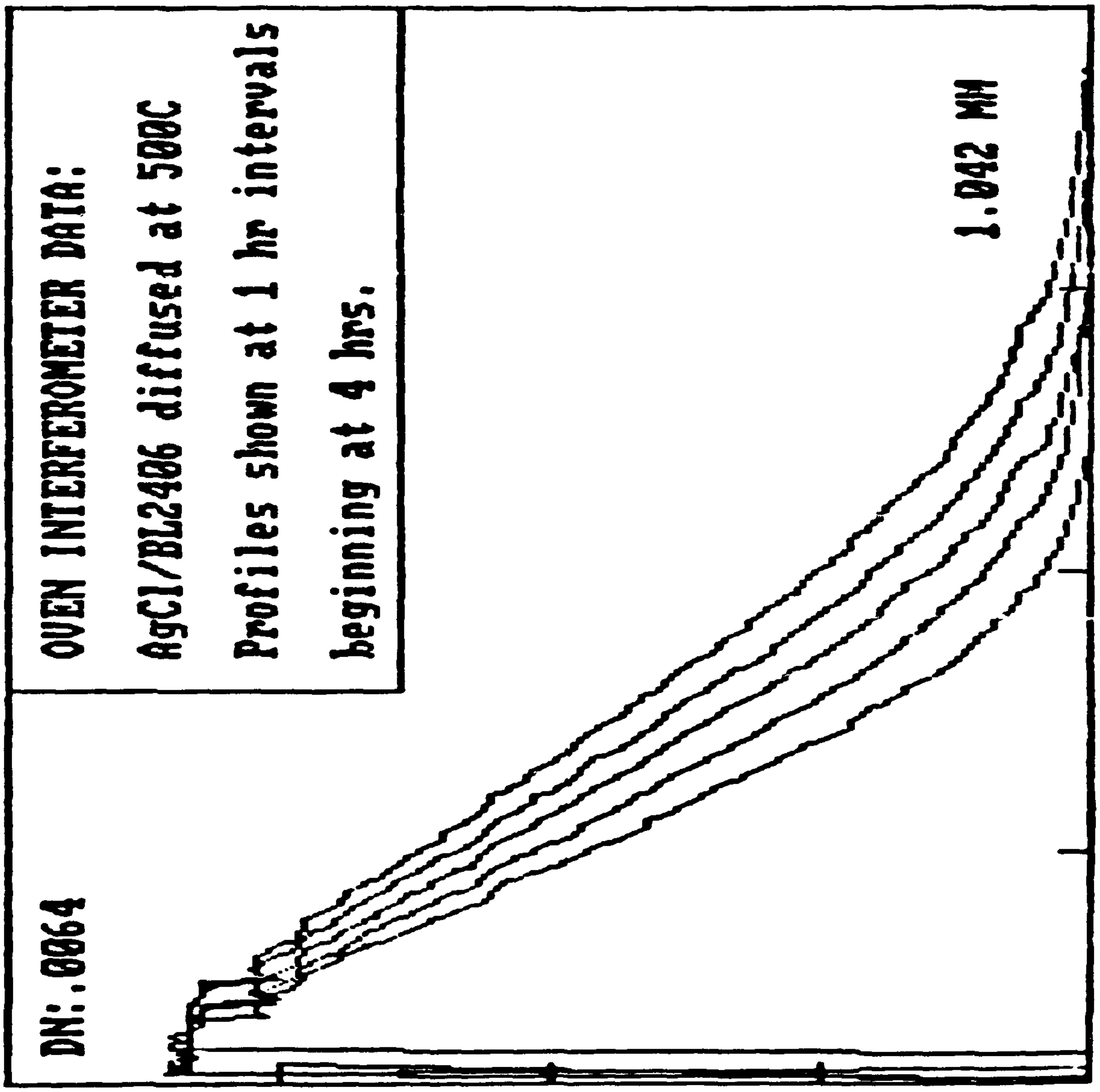


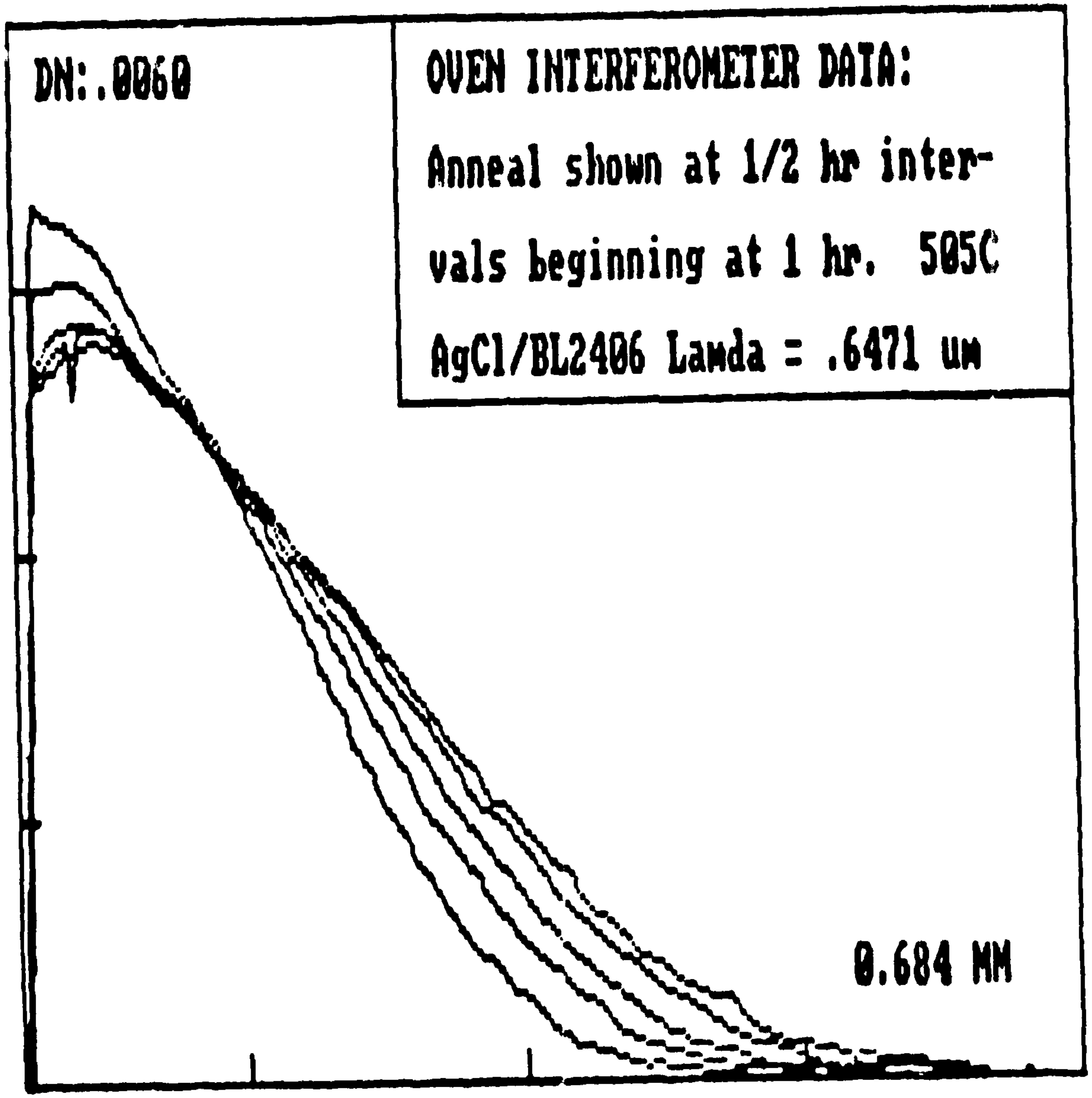
DISPERSION CURVE


INVARIANT INDEX AND SPECTRAL LINES
B-NA
NA-K
LI-K
P-AS
LI-NA
LI-K
NA-K
N_d
N_F-N_C

EFFECT OF ION EXCHANGE




OVEN INTERFEROMETER DATA:
AgCl/BL2406 diffused at 500C
Profiles shown at 1 hr intervals
beginning at 4 hrs.
DN:.0064
1.042 MM


DN:.0060
OVEN INTERFEROMETER DATA:
Anneal shown at 1/2 hr inter-
vals beginning at 1 hr. 505C
AgCl/BL2406 Lamda = .6471 um
0.684 MM

GLASS: Bausch and Lomb 2406

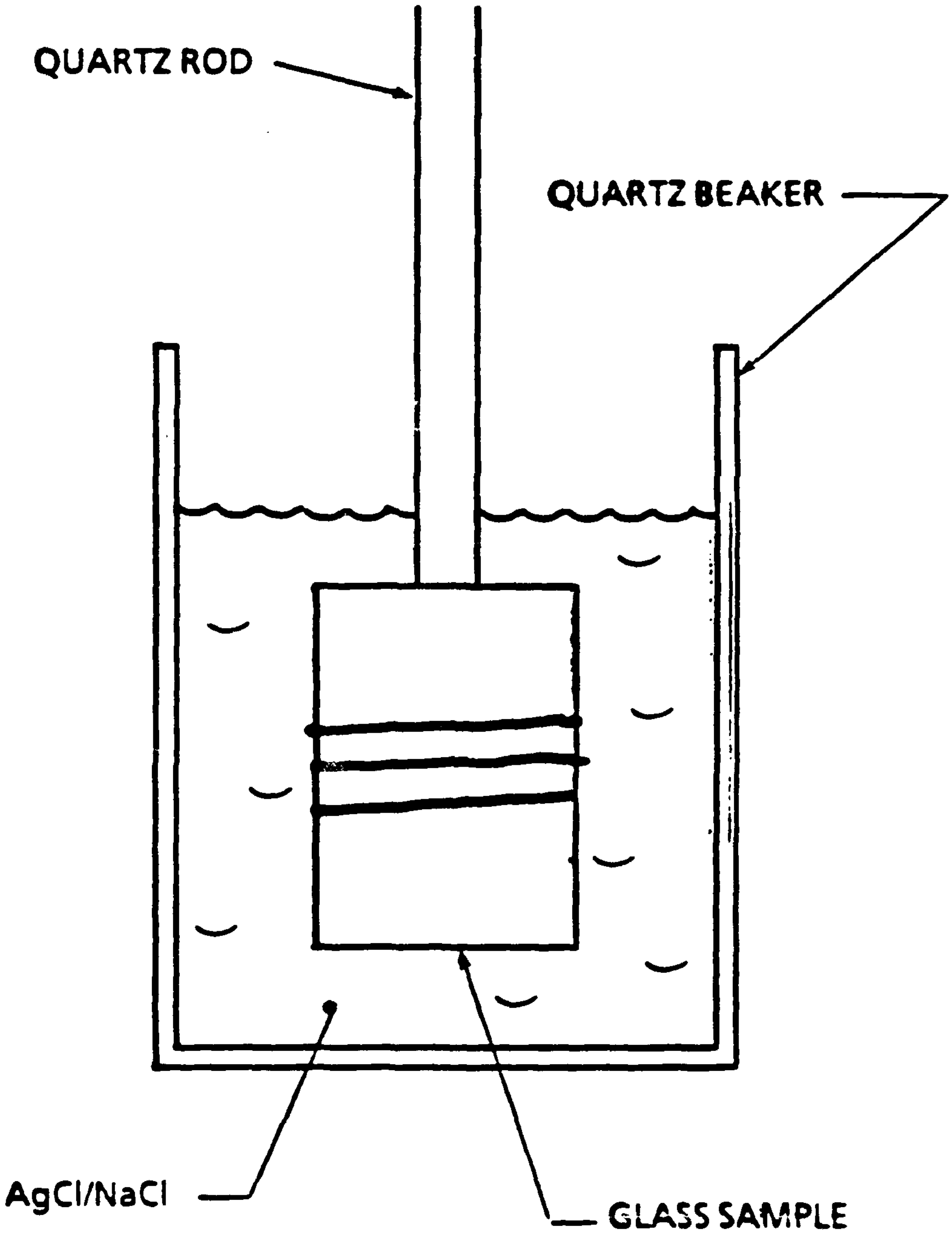
SiO_2 67.0%
Na_2O 25.6%
Al_2O_3 7.4%

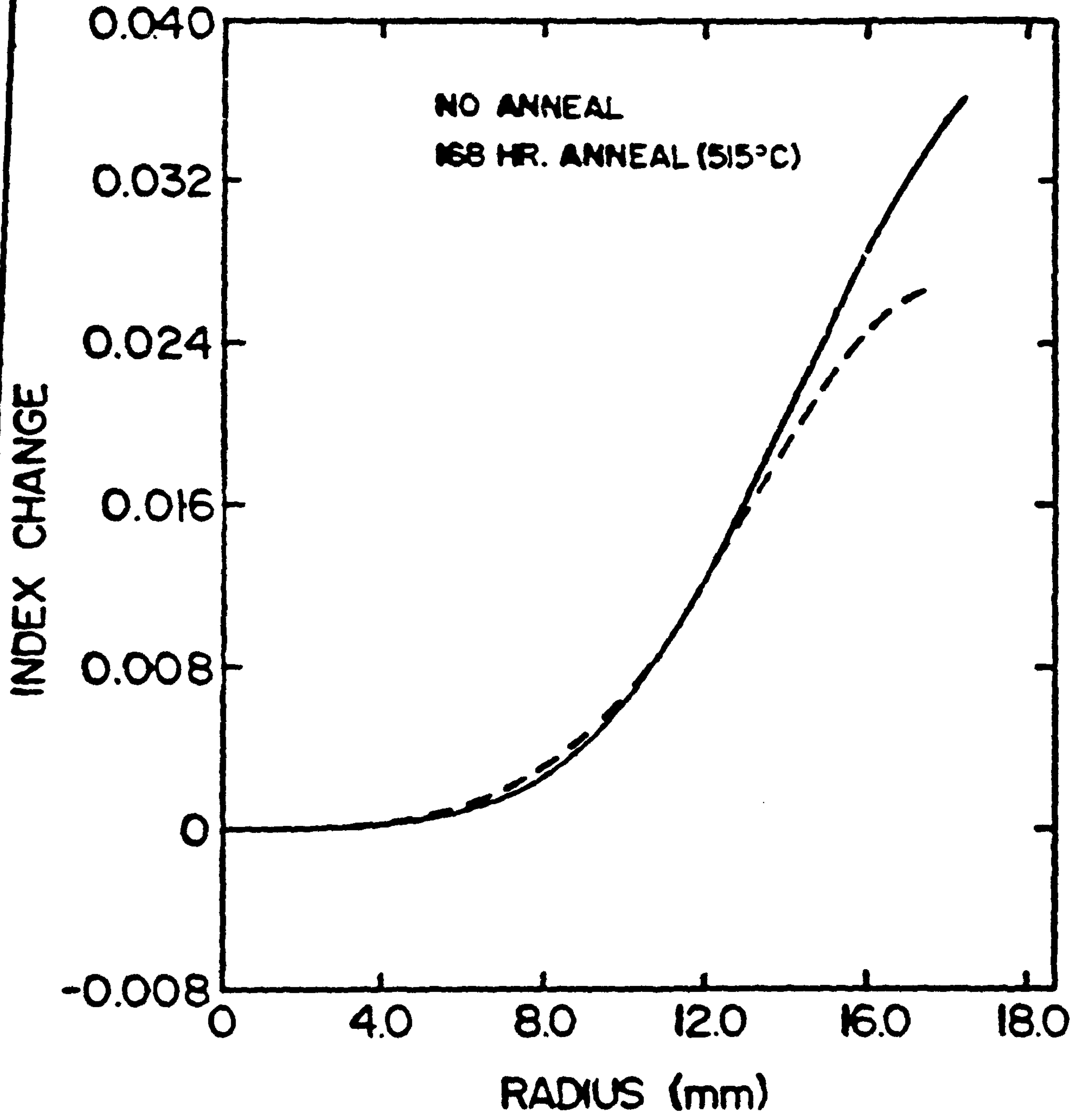
Cylindrical sample, 40mm dia. x 50mm long

SALT: 1.0 kg AgCl with approx. 1% NaCl due to previous experiments

TEMPERATURE: 515 °C

TIME: 960 hours (40 days and 40 nights)


QUARTZ ROD
QUARTZ BEAKER
AgCl/NaCl
GLASS SAMPLE


NO ANNEAL
168 HR. ANNEAL (515°C)
0.040
0.032
0.024
0.016
0.008
0
-0.008
INDEX CHANGE
0
4.0
8.0
12.0
16.0
18.0
RADIUS (mm)

RESULTS

1) The sample surface was significantly degraded, but no bulk deformation was evident.

2) The sample was not devitrified.

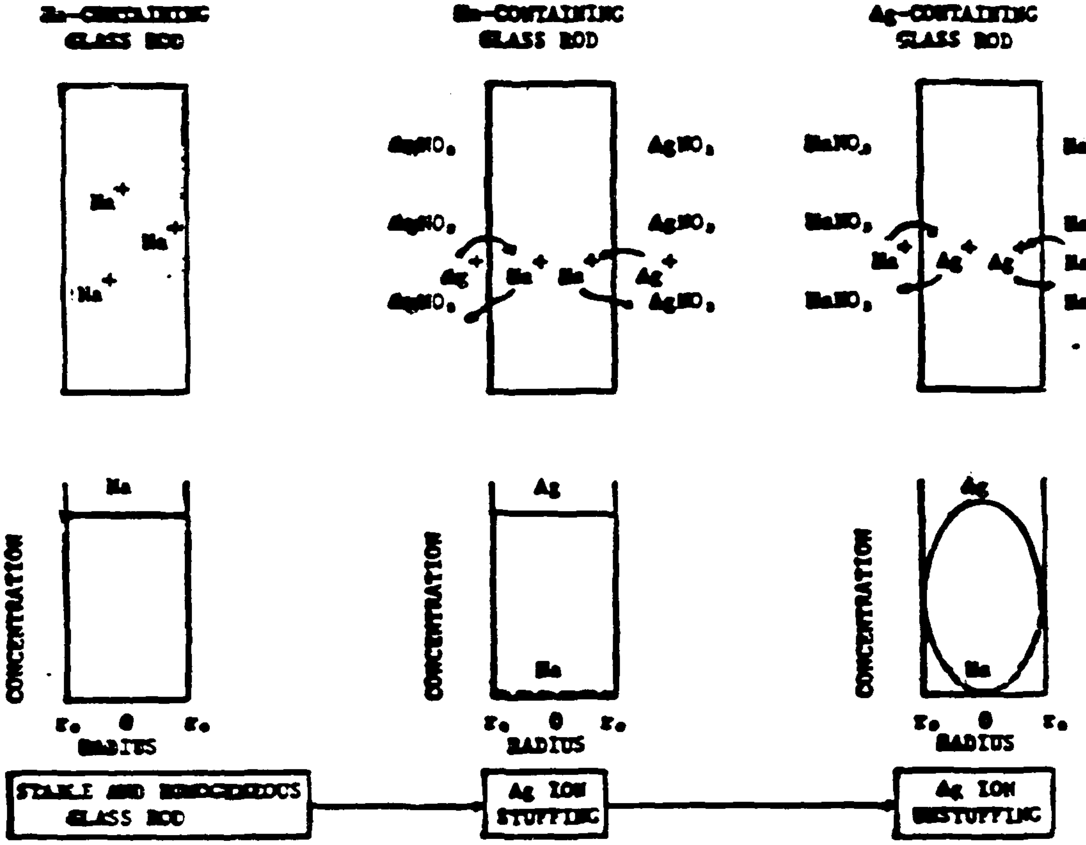


Fig.1. Ion stuffing process for fabricating GRIN rod lens.

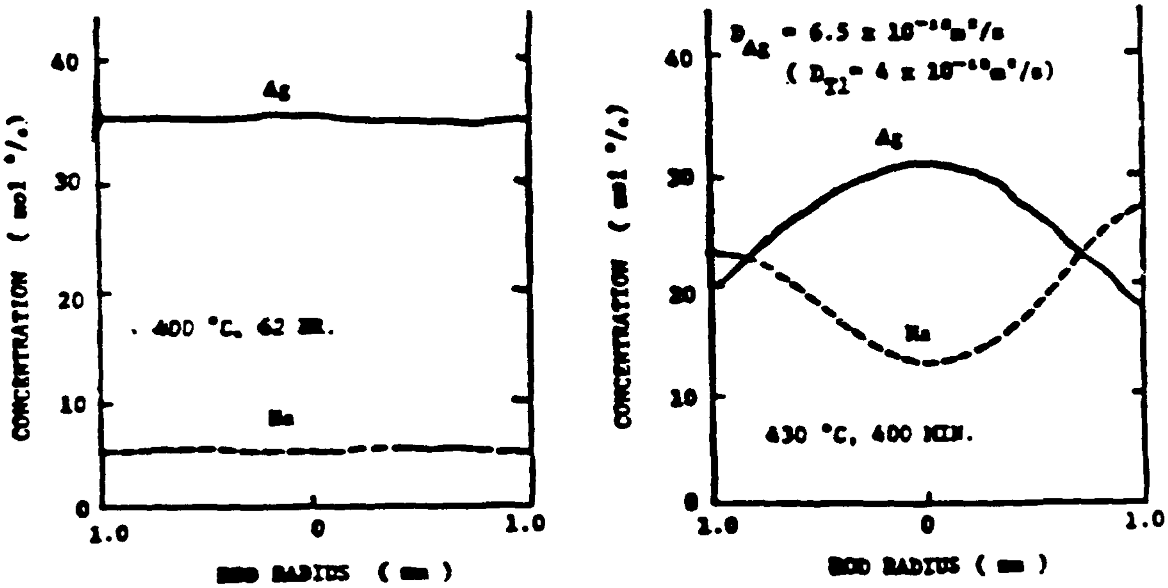


Fig.2. Ag and Na concentration profile in the glass rod after ion stuffing (left) and after ion unstuffing (right).

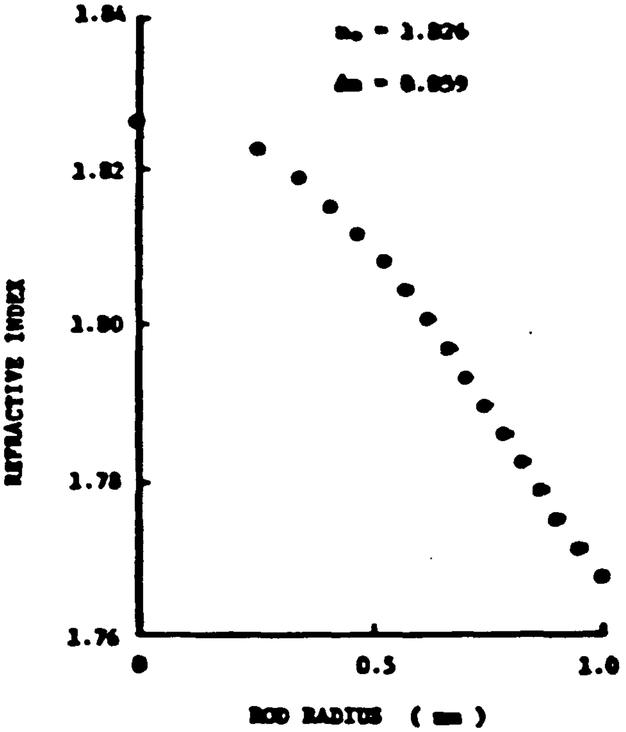


Fig.3. A typical example of the radial variation of refractive index of the 2.0 mm diameter lens.

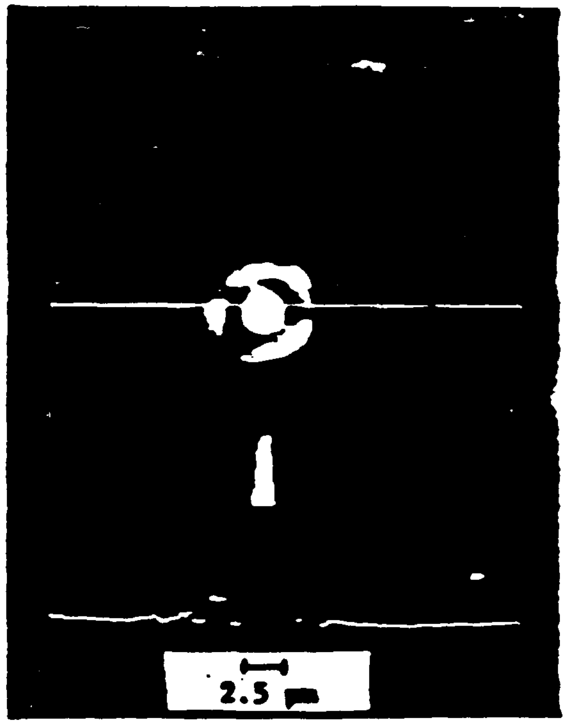


Fig.4. Image of spot formed by the 2 mm diameter rod lens.

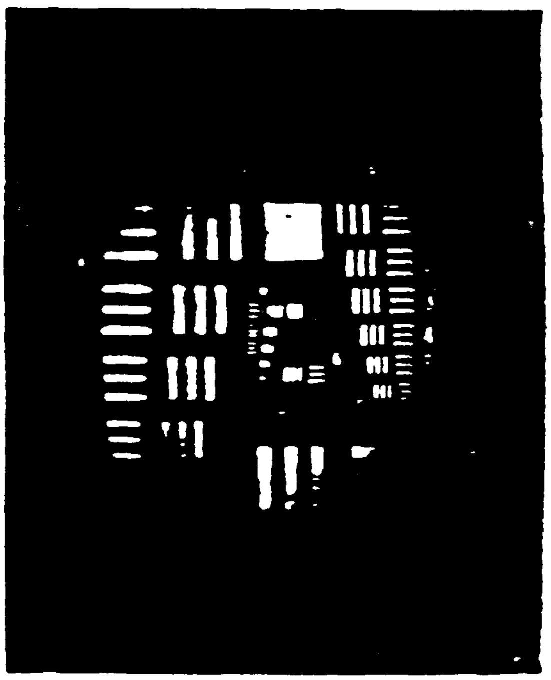


Fig.5. Optical micrograph of the image of the resolution target formed by the 2 mm diameter lens.

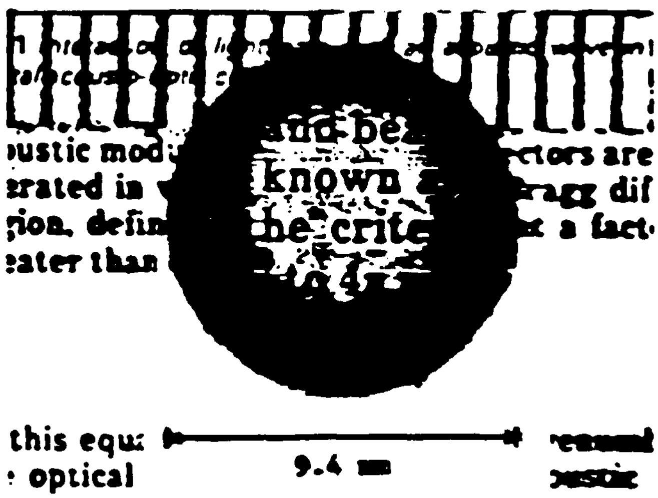
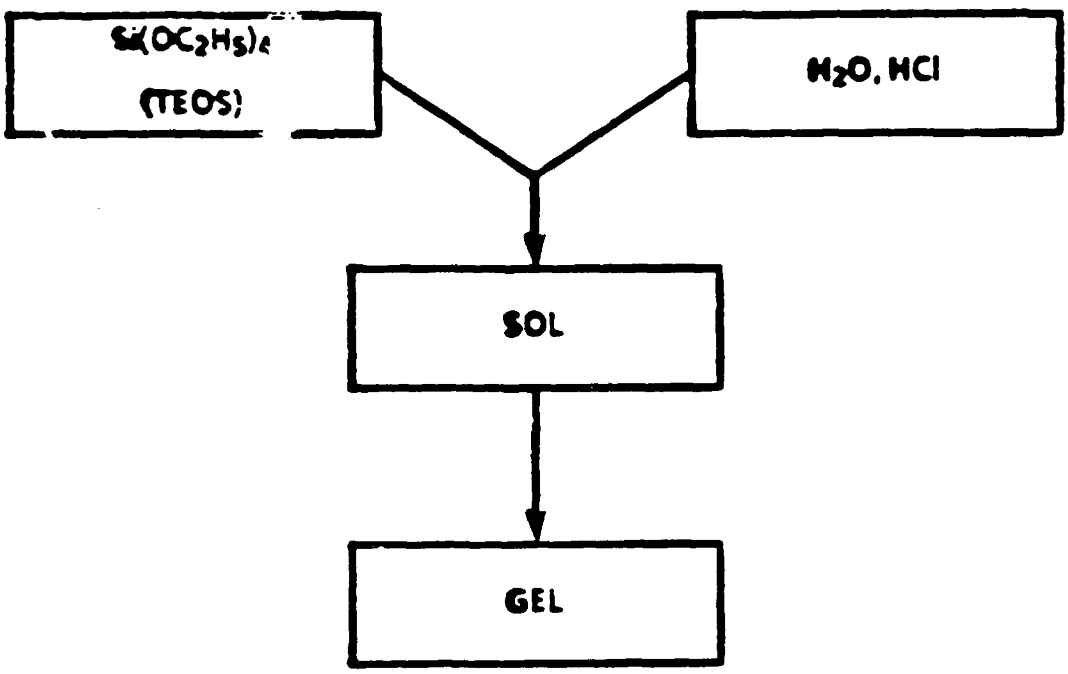


Fig.6. Photograph of a GRIN lens 9.4 mm in diameter and 5.3 mm in thickness.

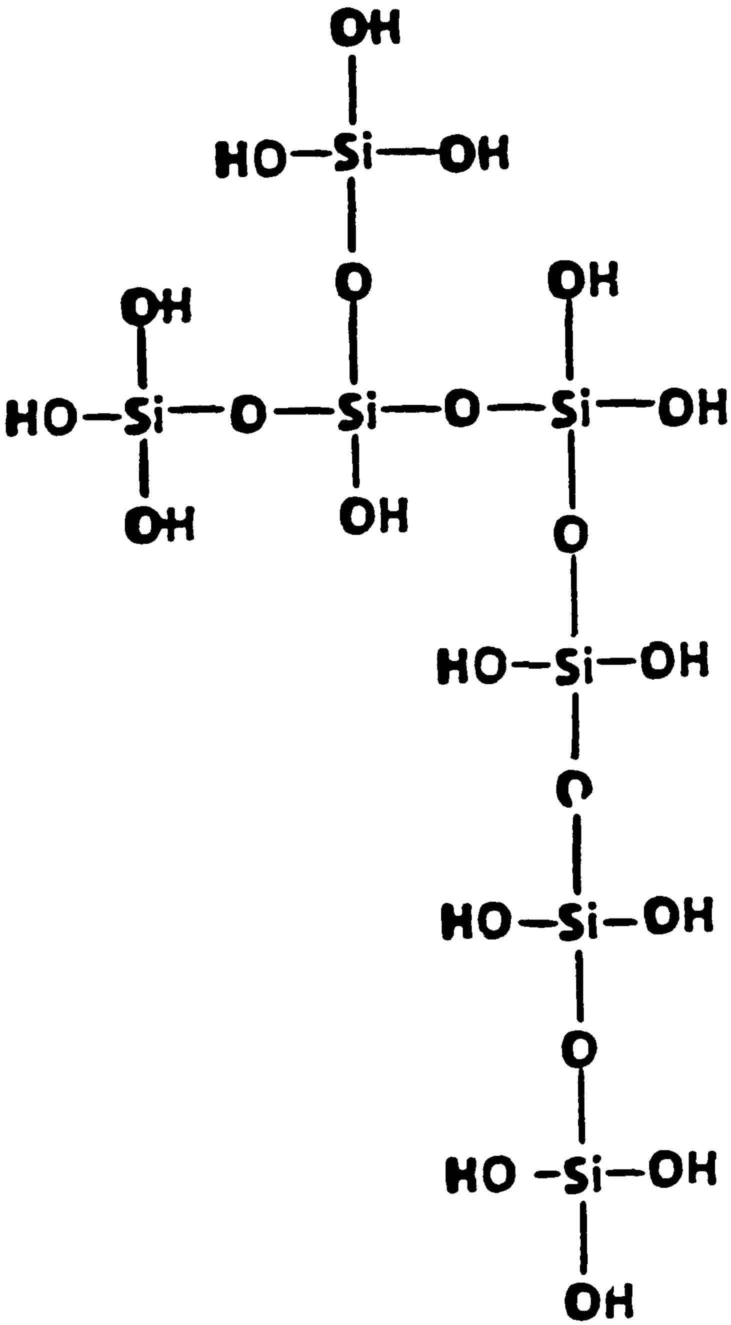
SOL-GEL

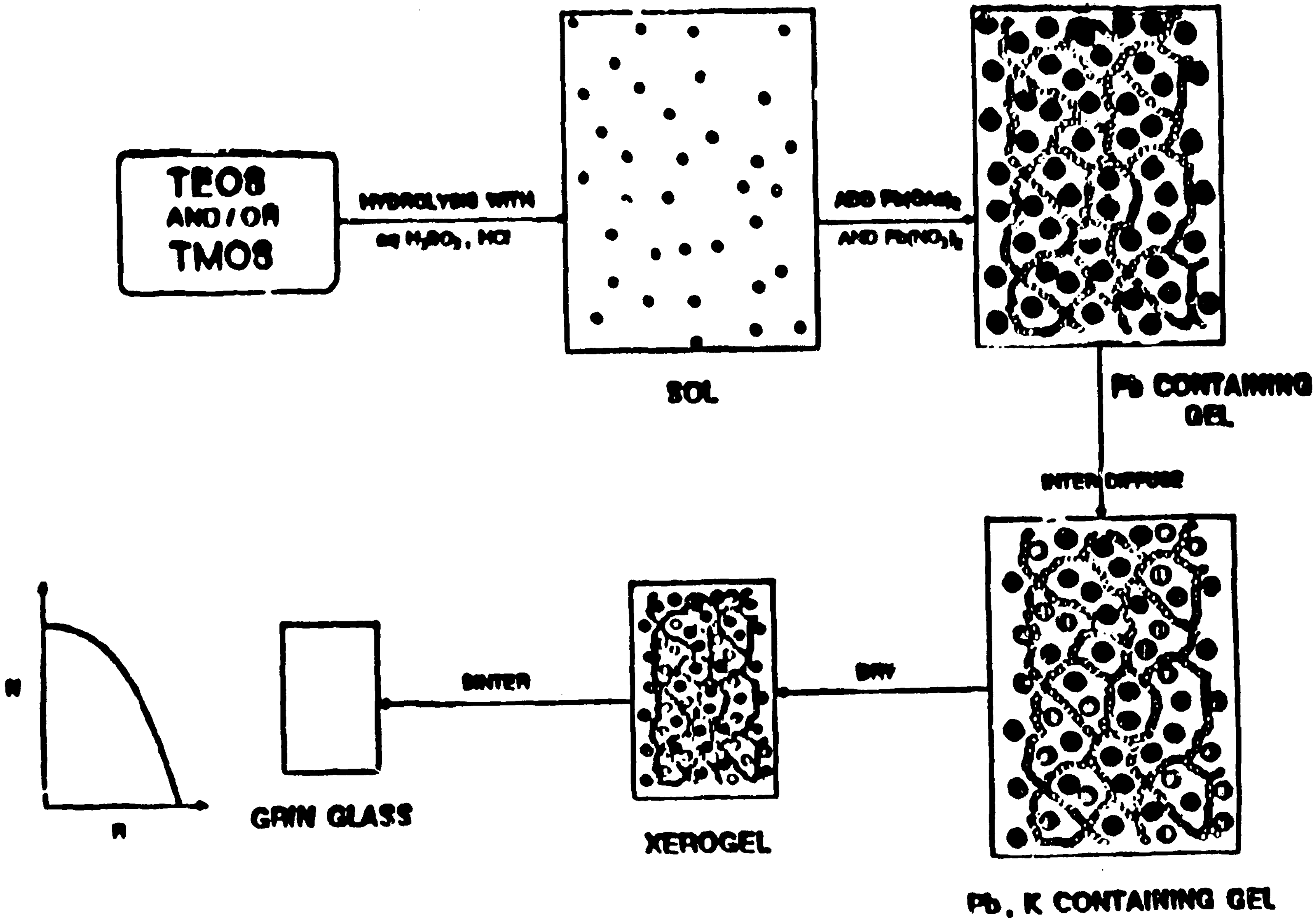


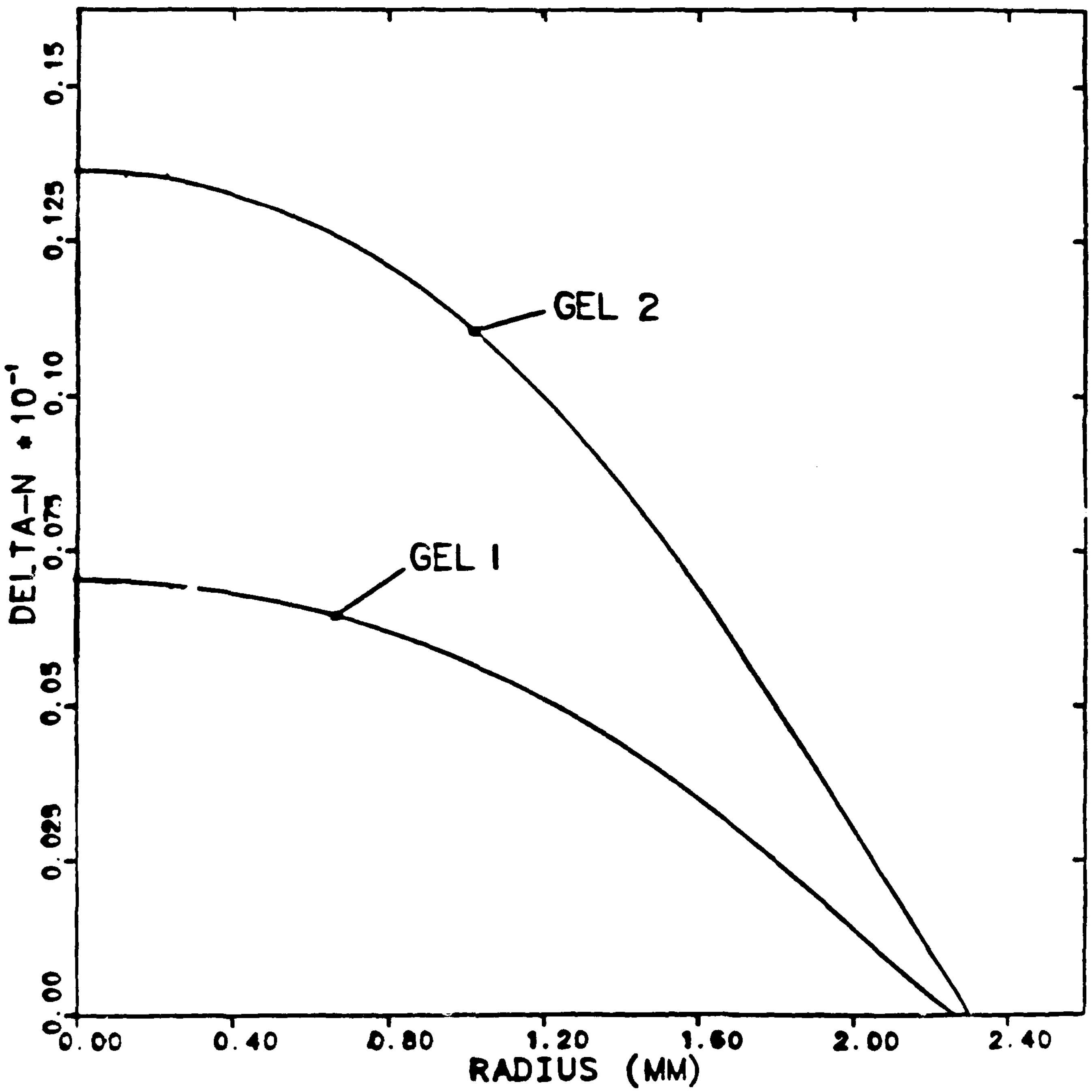
HYDROLYSIS: $Si(OC_2H_5)_4 + 4H_2O \rightarrow Si(OH)_4 + 4C_2H_5OH$

POLYMERIZATION: $Si(OH)_4 \rightarrow SiO_2 + 2H_2O$

SCHEMATIC GEL STRUCTURE




TEOS
AND / OR
TMOS
HYDROLYSIS WITH
SOL
Pb CONTAINING
GEL
INTER DIFFUSE
Pb, K CONTAINING GEL
DRY
XEROGEL
SINTER
GRIN GLASS


GEL 2
GEL 1
DELTA-N * 10^-1
0.00
0.025
0.05
0.075
0.10
0.125
0.15
0.00
0.40
0.80
1.20
1.60
2.00
2.40
RADIUS (MM)

GRADIENT SYSTEMS FOR IR

SPECIAL GLASSES TO 3.5 MICRONS

GERMANIUM DIFFUSIONS

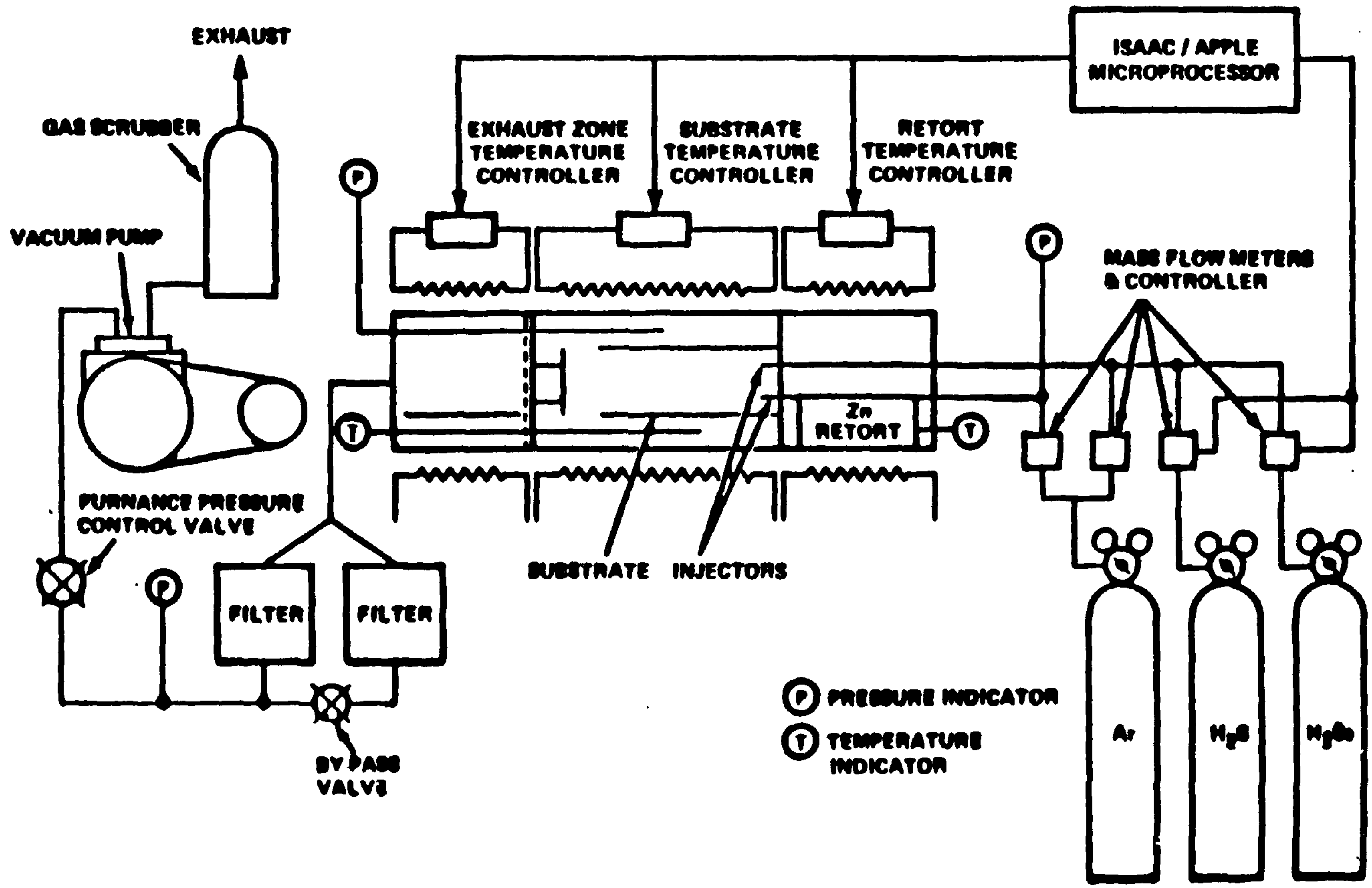
ZN SE - ZN S CVD

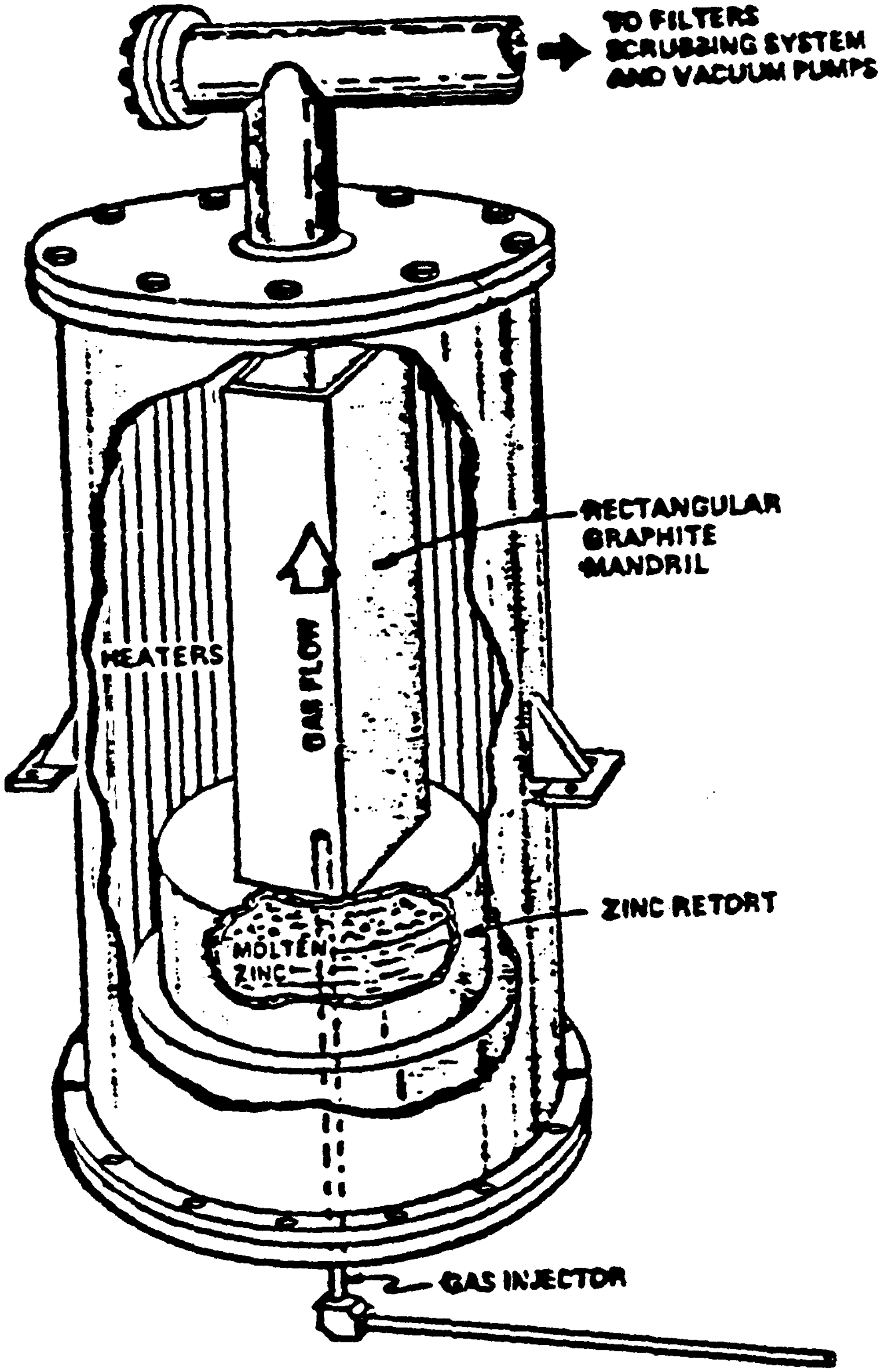
GRADIENT NA CL - AG CL

INTRODUCTION TO CHEMICAL VAPOR DEPOSITION PROCESS

- ZINC (VAPOR) + {HYDROGEN SELENIDE (GAS) / HYDROGEN SULFIDE (GAS)} ⟶ {ZINC SELENIDE (SOLID) / ZINC SULFIDE (SOLID)} + HYDROGEN (GAS)
- HETEROGENEOUS REACTION, NOT GAS PHASE
- CONDITIONS:
  - PRESSURE LESS THAN 100 TORR
  - TEMPERATURE APPROXIMATELY 600–750 C
- DEPOSITION RATE
  - 50–75 μm PER HOUR
  - HIGHER DEPOSITION RATE DEGRADES OPTICAL QUALITY
- HIGH PURITY, 99.9999
- POLYCRYSTALLINE MATERIAL
  - GRAIN SIZE, 10–100 μm
- THEORETICALLY DENSE MATERIAL, NEGLIGIBLE VOIDS

EXPERIMENTAL CVD CHAMBER USED FOR DEPOSITS OF GRADIENT INDEX MATERIAL




TO FILTERS
SCRUBBING SYSTEM
AND VACUUM PUMPS
RECTANGULAR
GRAPHITE
MANDRIL
HEATERS
GAS FLOW
ZINC RETORT
MOLTEN
ZINC
GAS INJECTOR

CVD FURNACE

CONCEPT TO DEVELOP A GRADIENT INDEX IR MATERIAL

- ZnS AND $ZnSe$ ARE WIDELY USED INFRARED OPTICAL MATERIALS
  - PRODUCED VIA CHEMICAL VAPOR DEPOSITION (CVD)
  - HAVE DIFFERENT INDICES OF REFRACTION
  - ARE MIXABLE IN SOLID STATE, I.E., ALLOY ZnS_xSe_{1-x} WITH $0 \leq x \leq 1$ EXISTS.

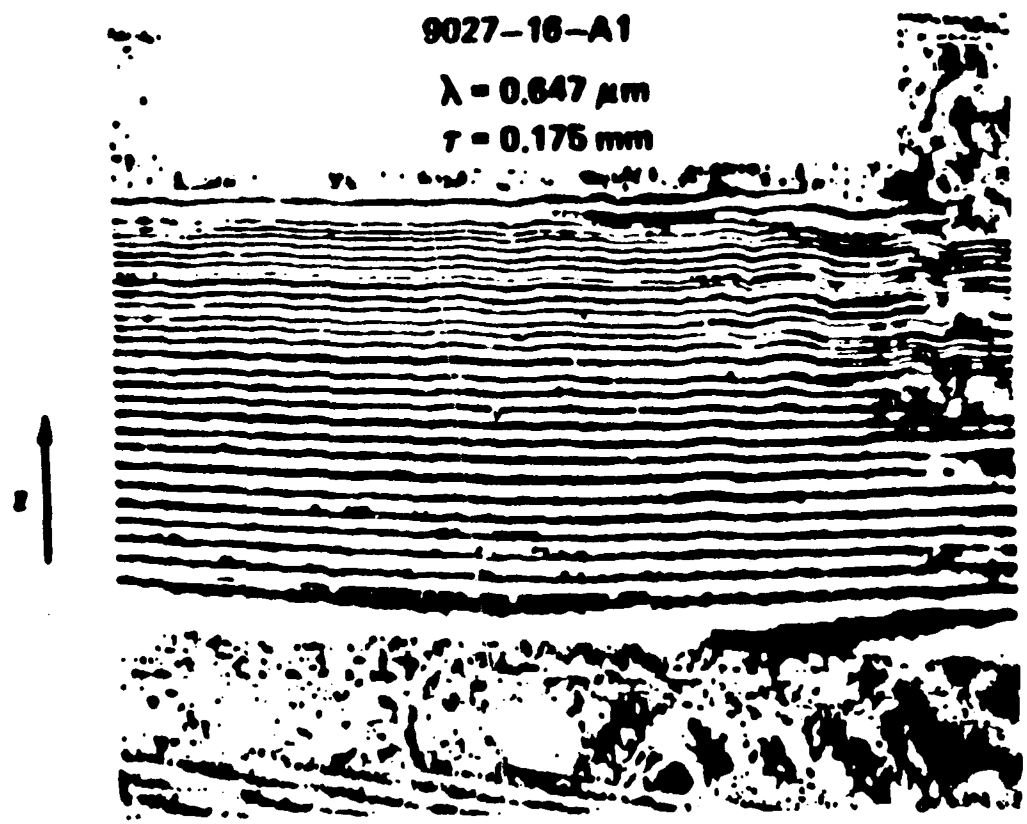
- CODEPOSIT ZnS_xSe_{1-x} WITH x VARYING WITH DISTANCE, z
  - INDEX IS A FUNCTION OF MOLAR COMPOSITION

    $n = An_S[S] + Bn_{Se}[Se]$ with A and B ~ 1.0.

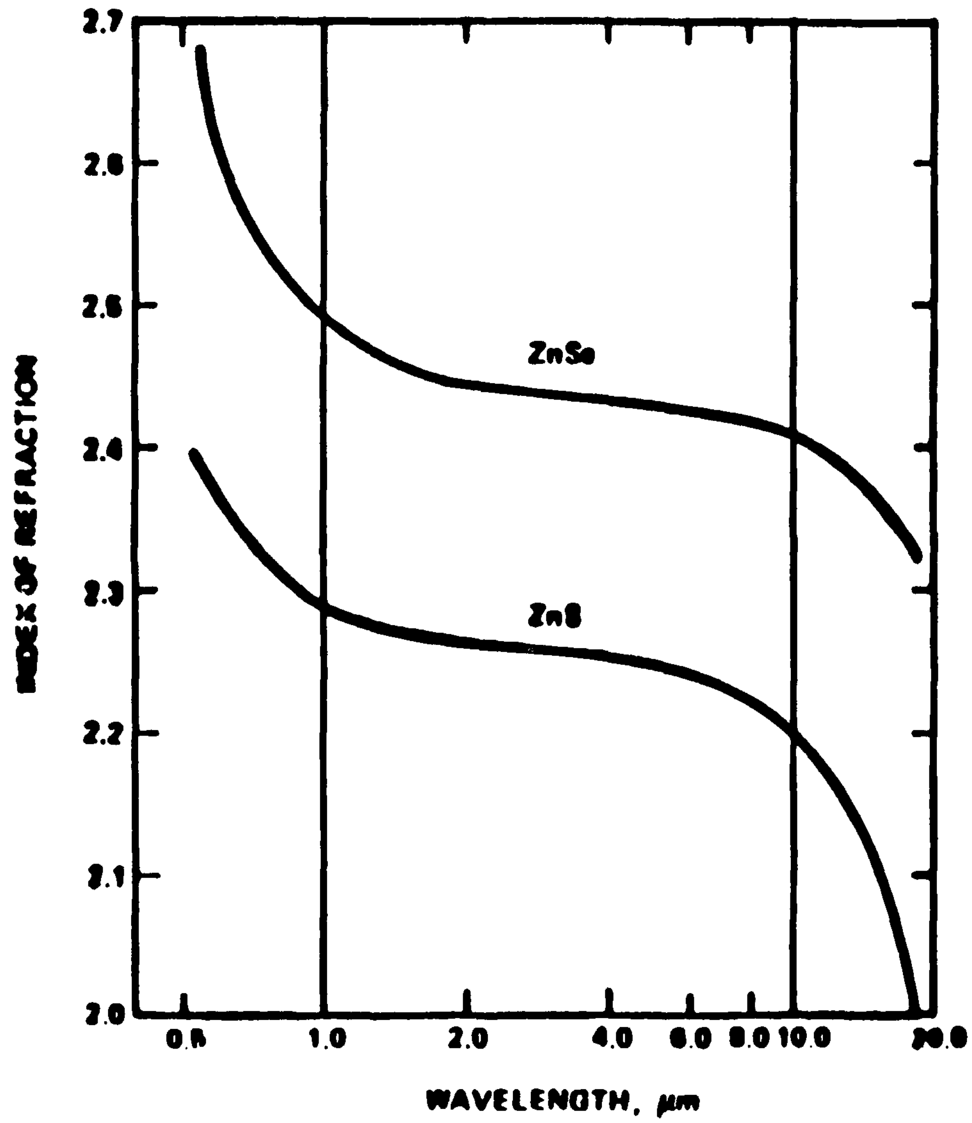
- CONCENTRATE ON AXIAL INDEX GRADIENTS.

1070

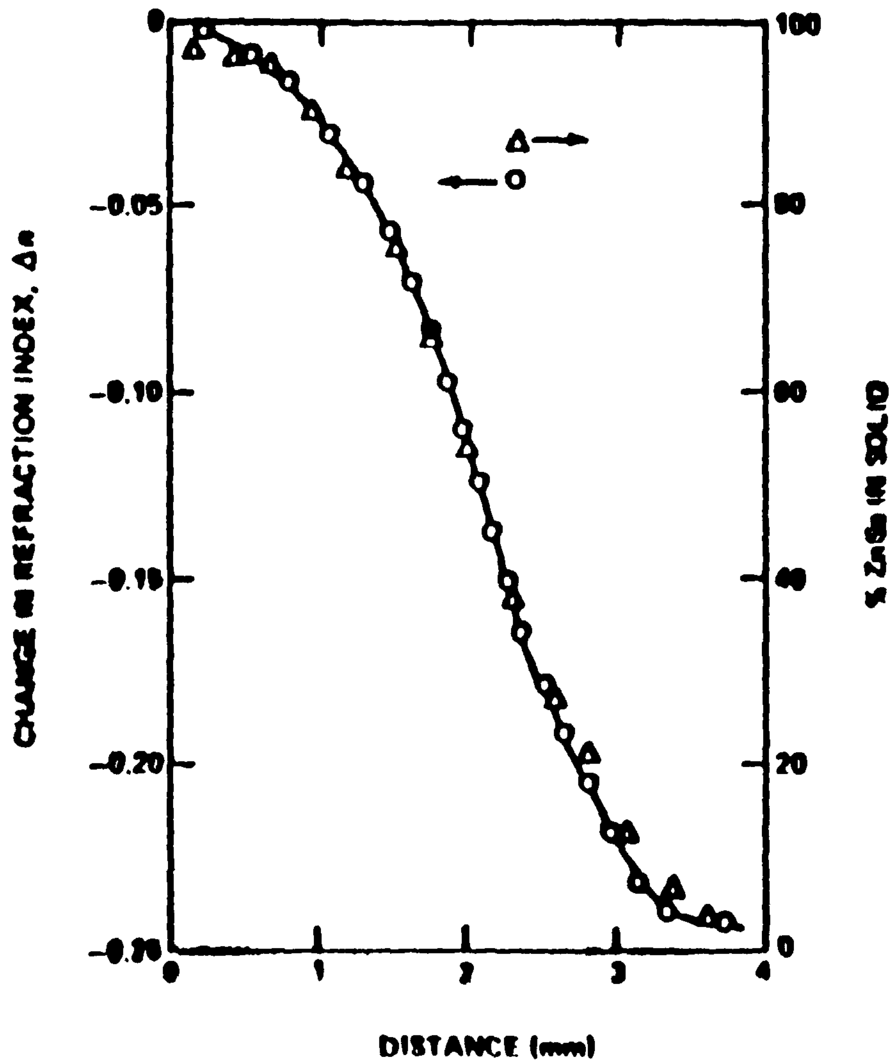
INTERFEROGRAM OF GRADIENT INDEX MATERIAL



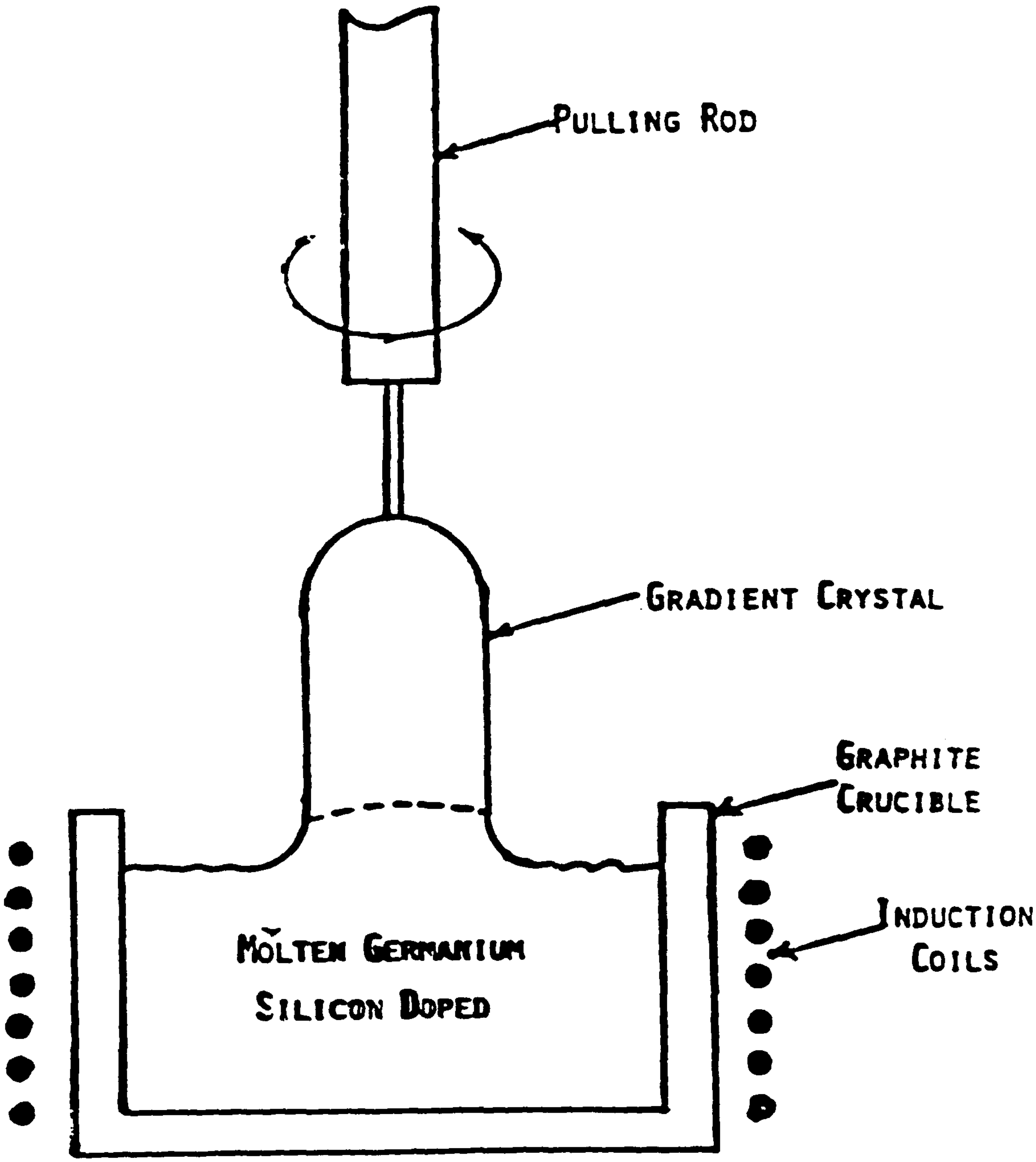
INDEX OF REFRACTION OF ZnS and ZnSe



COMPARISON OF INDEX GRADIENT VERSUS CHEMICAL COMPOSITION

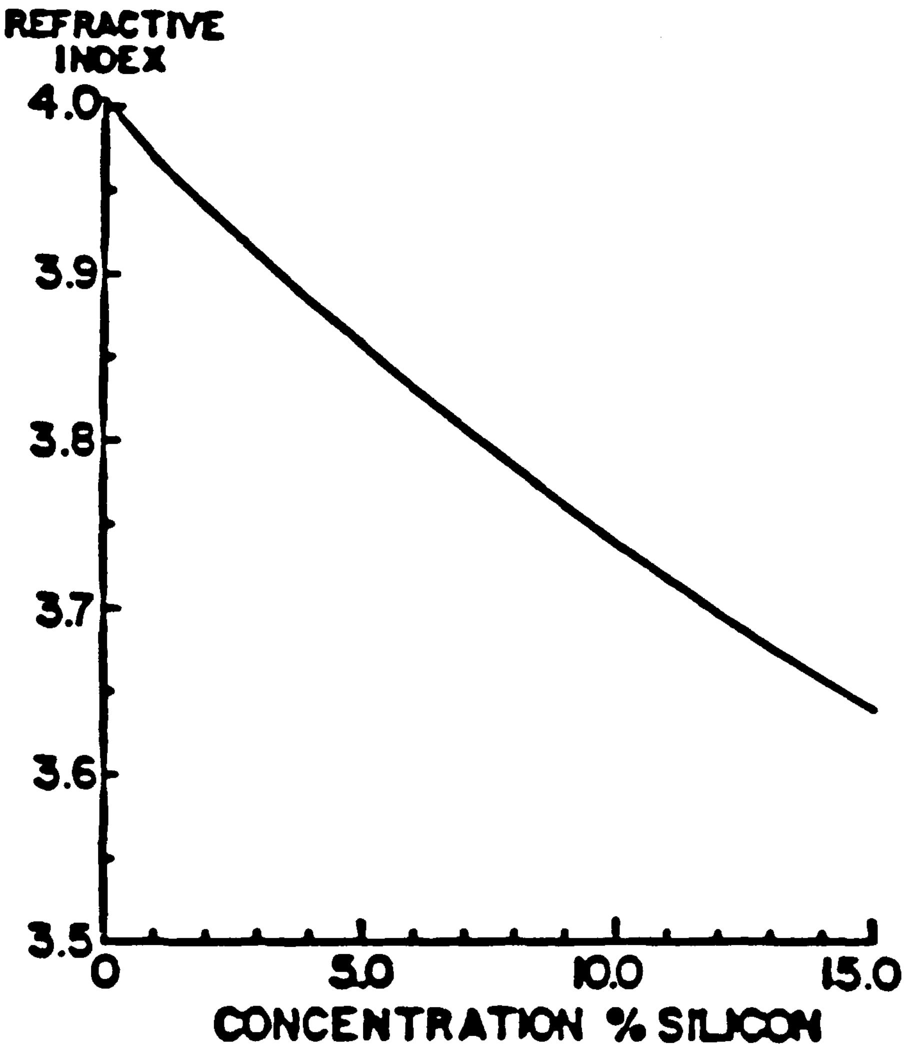


CZOCHRALSKI CRYSTAL GROWING

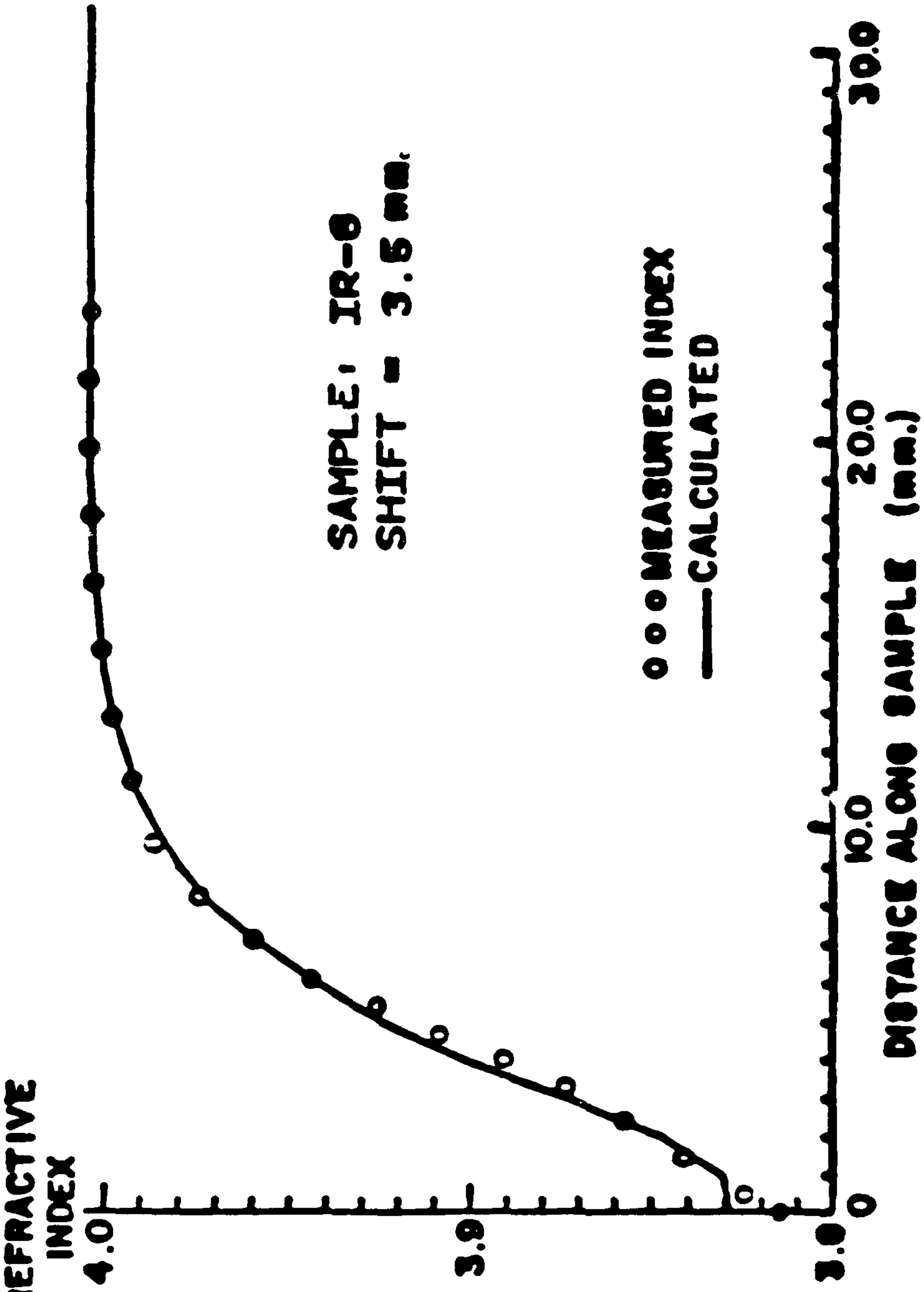


Crystal Grower Sketch

Figure 4-5



Refractive Index versus Ge-Si Alloy Composition



Sample IR-8 Calculated and Measured Index Profiles

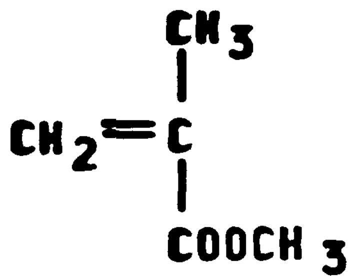
Gradient-Index Polymers

Leo R. Gardner

MONOMER :

MONO (single)- MEROS (parts)

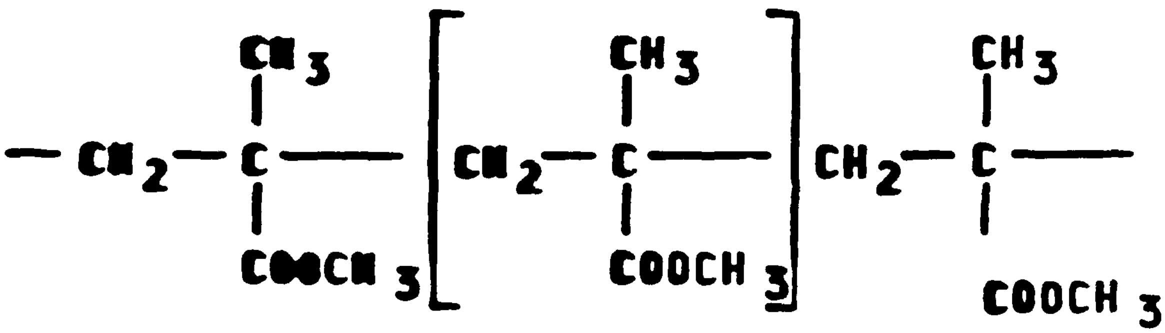
Methylmethacrylate (MMA):



POLYMER :

POLY (many) - MEROS (parts)

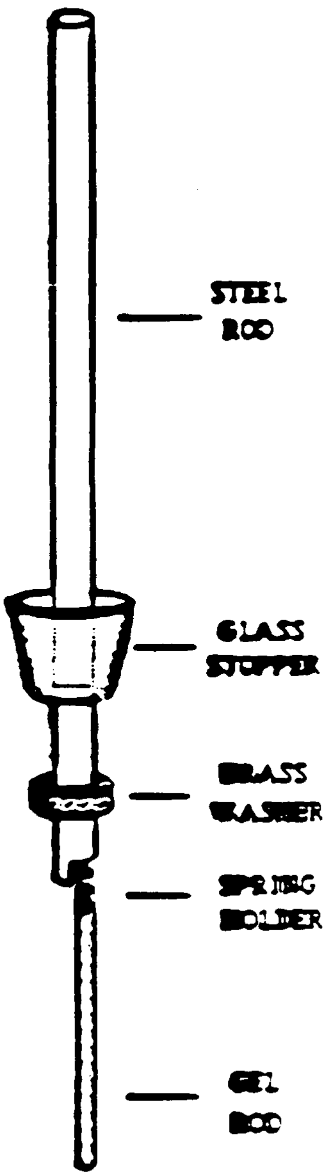
Polymethylmethacrylate (PMMA):

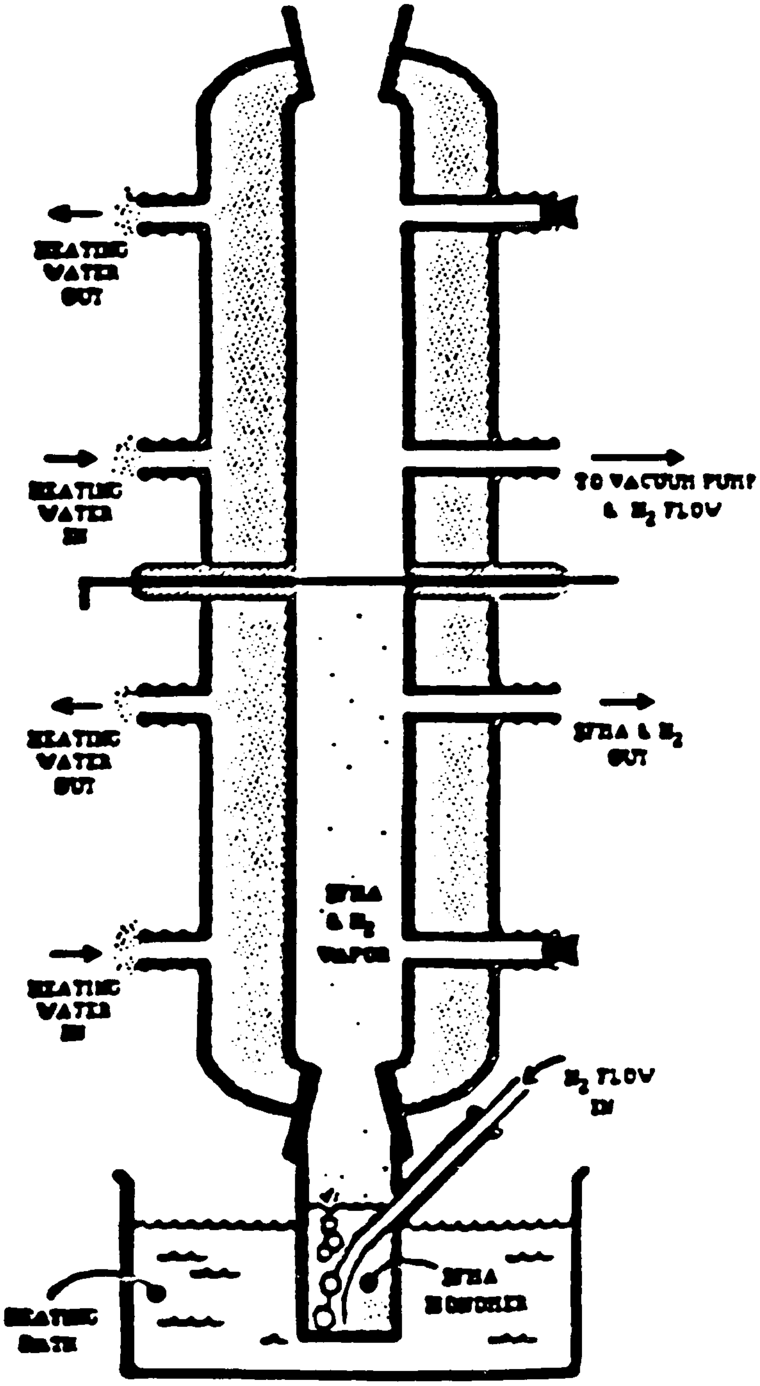


CR-39®

2.2.2 - TRIFLUOROETHYL METHACRYLATE

3FMA

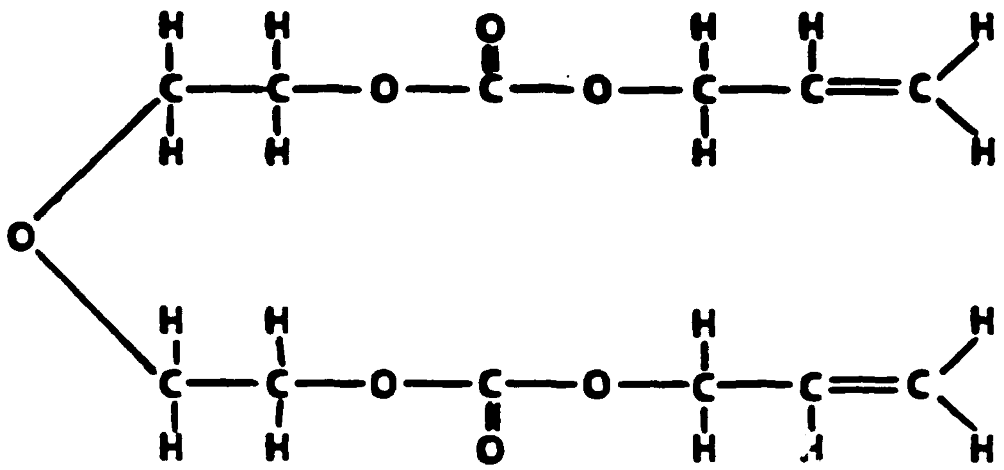




TYPICAL PROPERTIES	HOMOPOLYMER from CR39® MONOMER	HOMOPOLYMER from HIRI™ II CASTING RESIN
Visible Light Transmittance	89-91% 2.7 mm thick	92-93% 2.5 mm thick
Refractive Index (at 20° C)	n_D = 1.4[illegible]	n_D = 1.5563
Abbe number	59.3	37.7
Density	1.31 g/cc	1.216 g/cc
Heat Distortion Temperature (for 10 mil deflection)	131-149° F	168° F

information courtesy of PPG Industries, Inc.

(diethylene glycol *bis* (allyl carbonate) n_D (polymer) = 1.50)

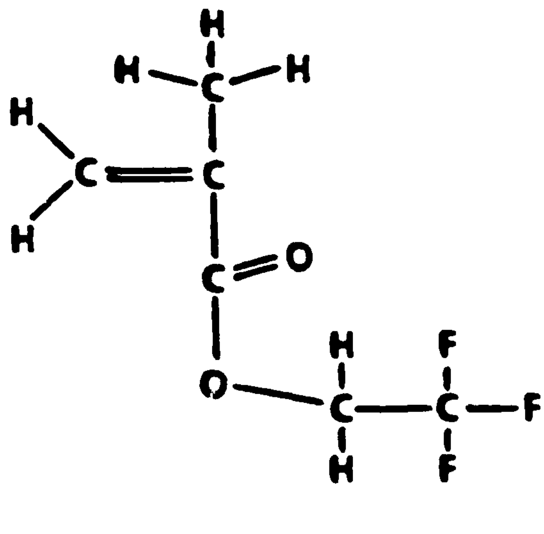


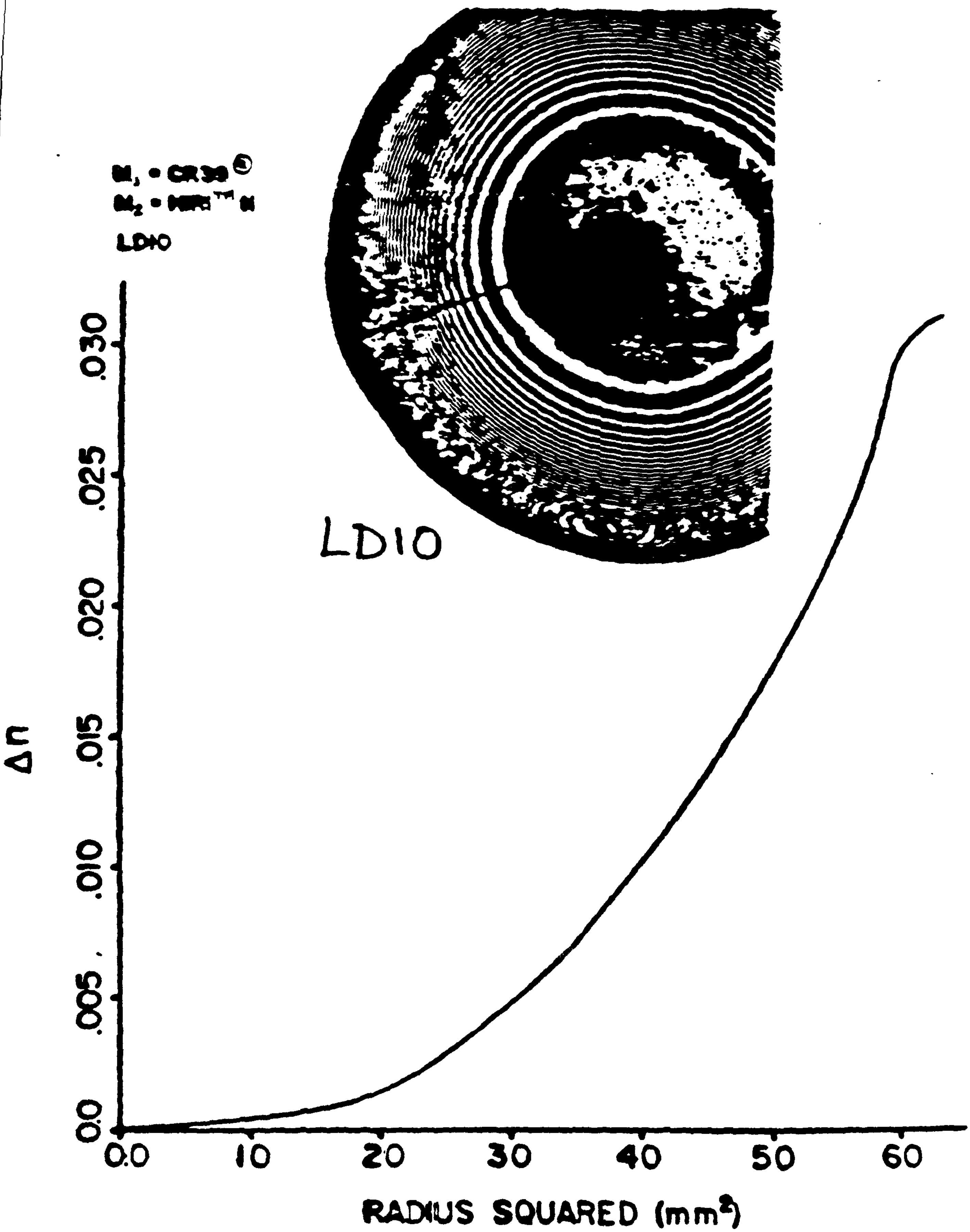
HIRI™ II casting resin

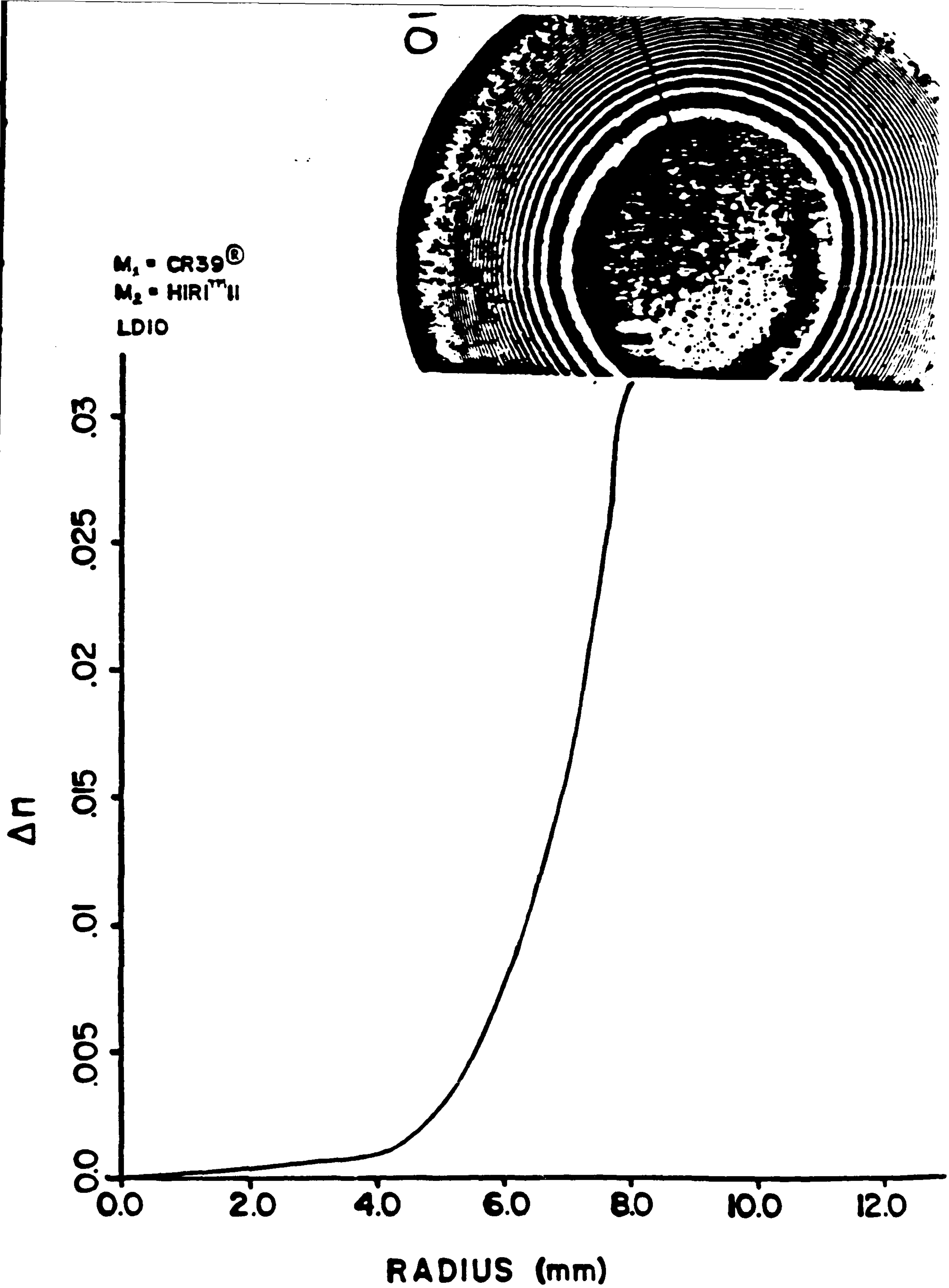
(a proprietary mixture of the carbonate ester family n_D (polymer) = 1.56)

3FMA

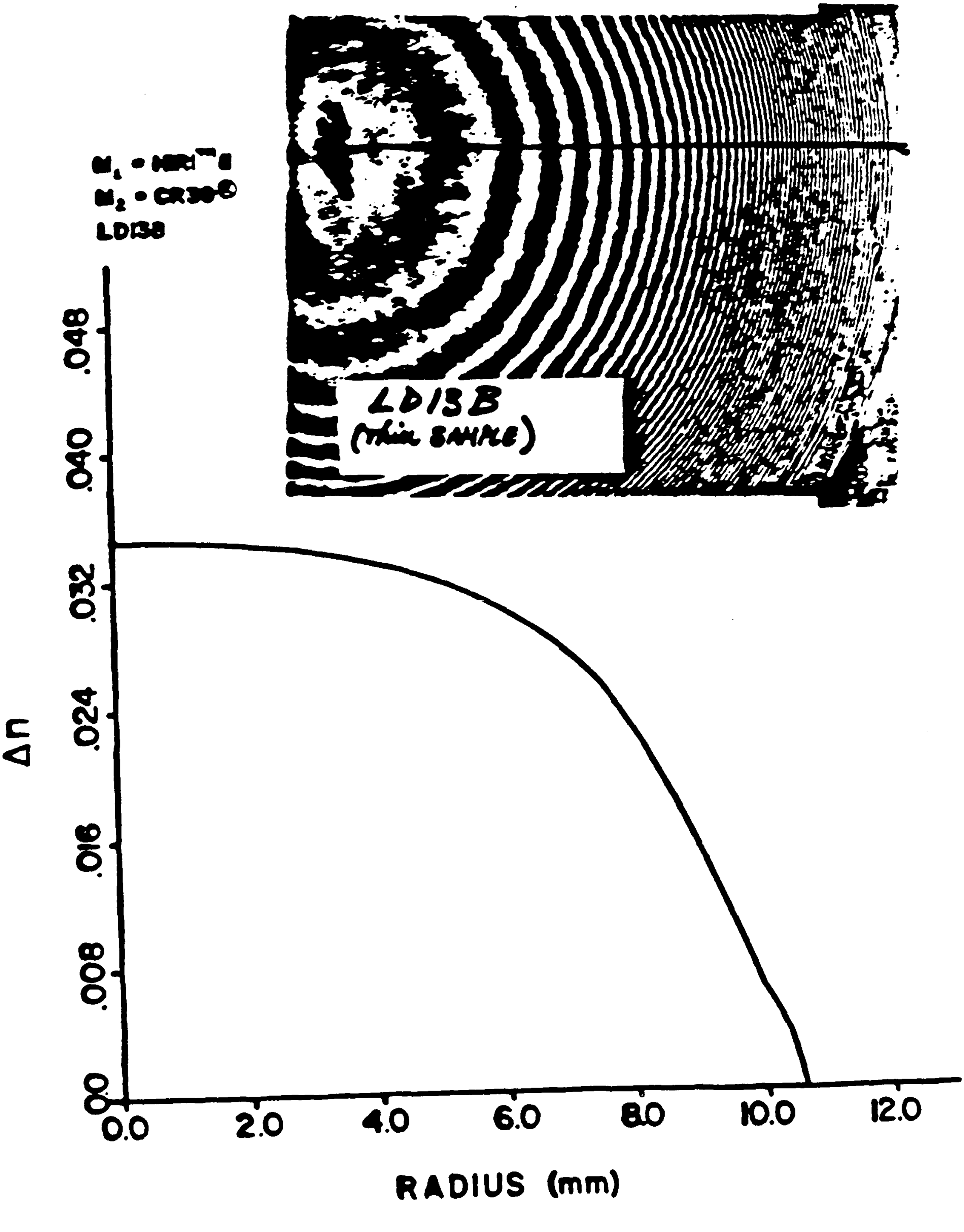
(2, 2, 2 - trifluoroethyl methacrylate n_D (polymer) = 1.42)

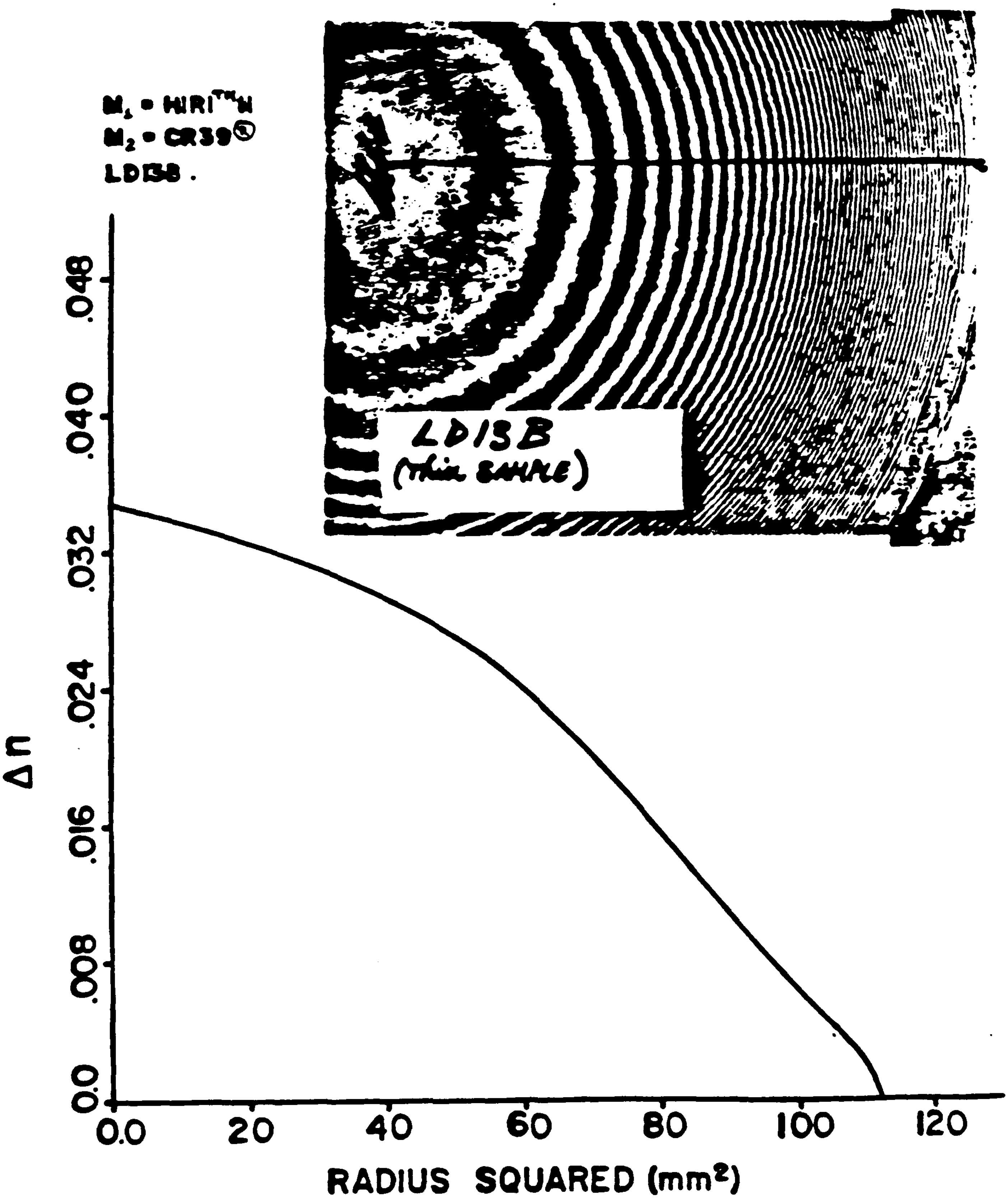



LD10
LD10
Δn
.030
.025
.020
.015
.010
.005
0.0
0.0
10
20
30
40
50
60
RADIUS SQUARED (mm²)



M1 = CR39®
M2 = HIRI™ II
LD10
Δn
0.0
.005
.01
.015
.02
.025
.03
0.0
2.0
4.0
6.0
8.0
10.0
12.0
RADIUS (mm)


LD13B
(thin SAMPLE)
Δn
.048
.040
.032
.024
.016
.008
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
RADIUS (mm)


M1 = HIRI™N
M2 = CR39®
LD13B.
LD13B
(thin SAMPLE)
Δn
0.0
.008
.016
.024
.032
.040
.048
0.0
20
40
60
80
100
120
RADIUS SQUARED (mm²)

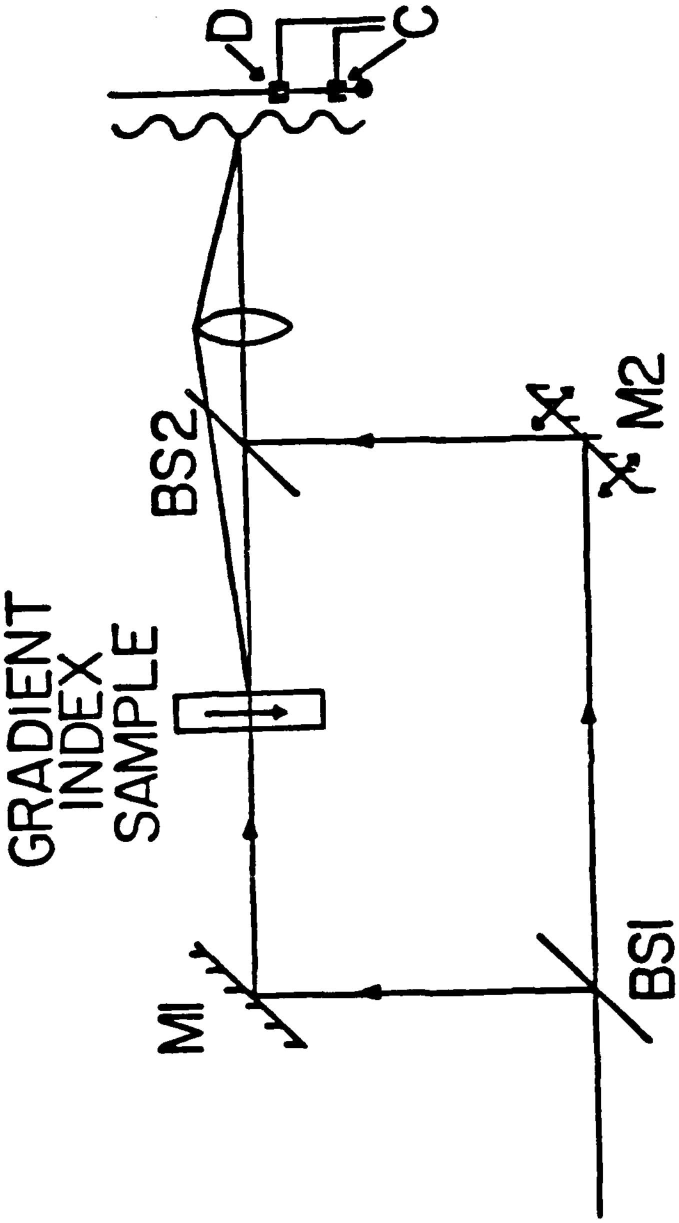
MEASUREMENT OF GRADIENTS

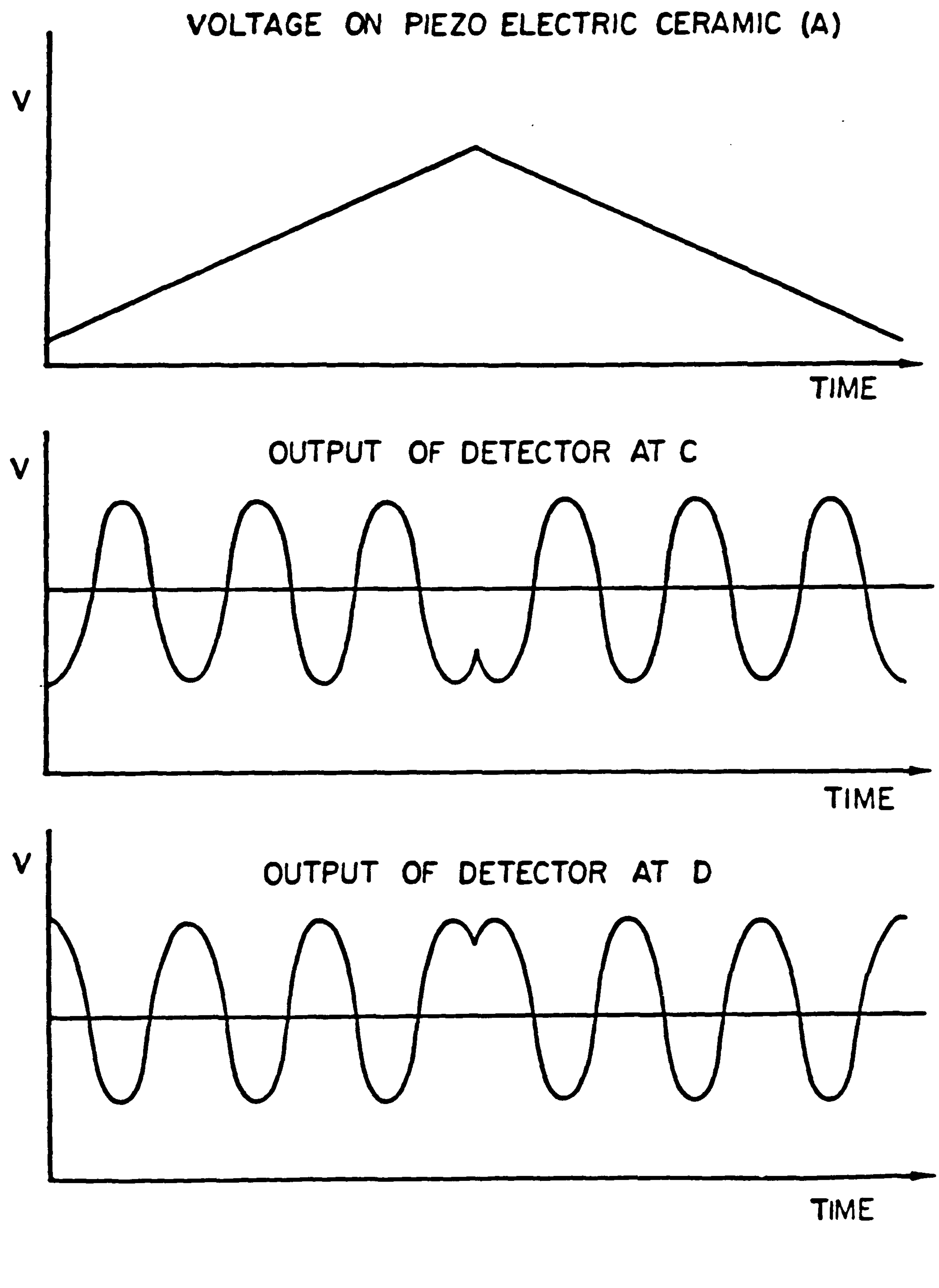
PRESENT

- INDEX OF REFRACTION PROFILE
- CHROMATIC DISPERSION
- MAXIMUM SLOPE OF GRADIENT
- TRANSMISSION
- ION CONCENTRATION

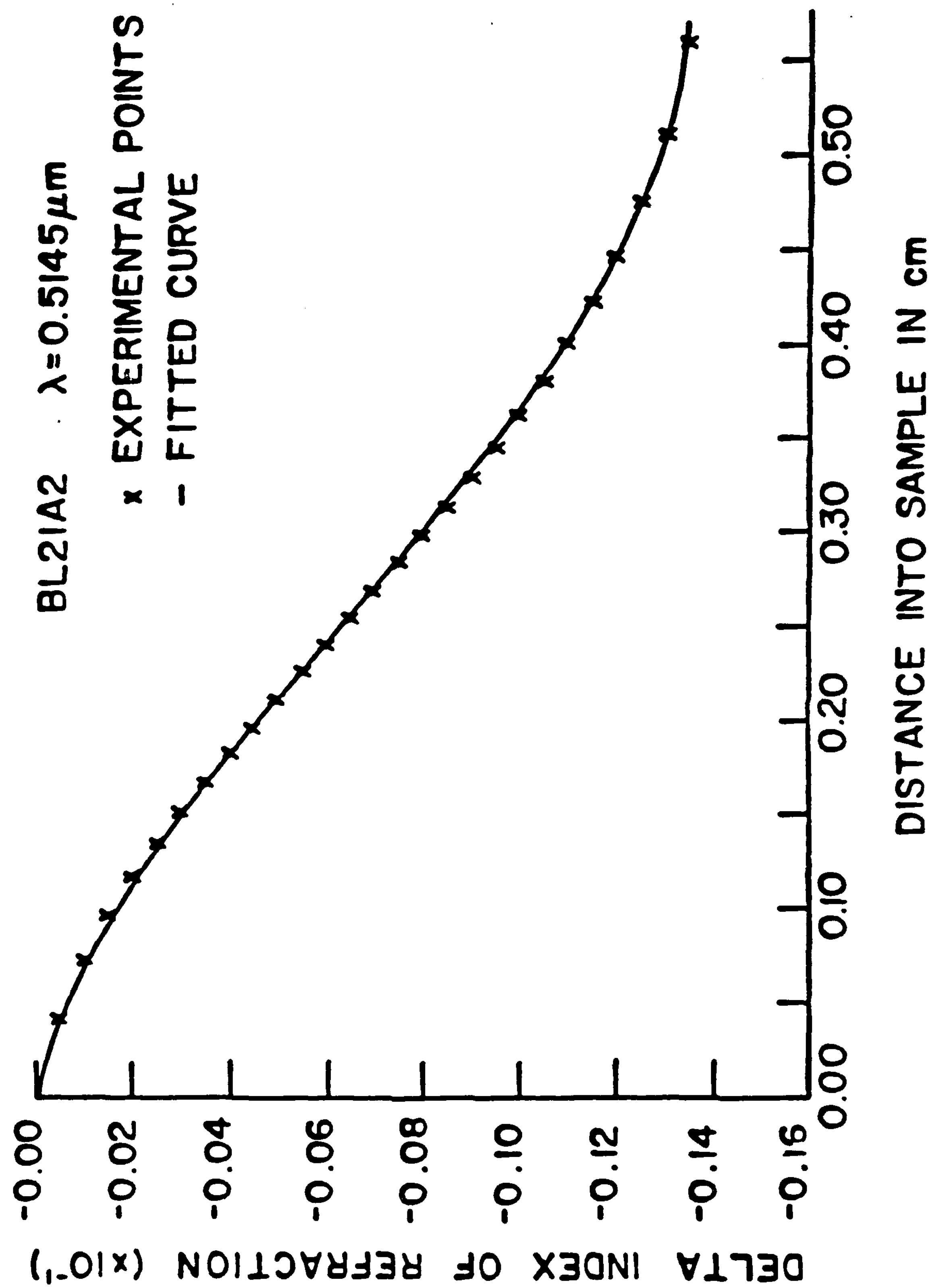
FUTURE

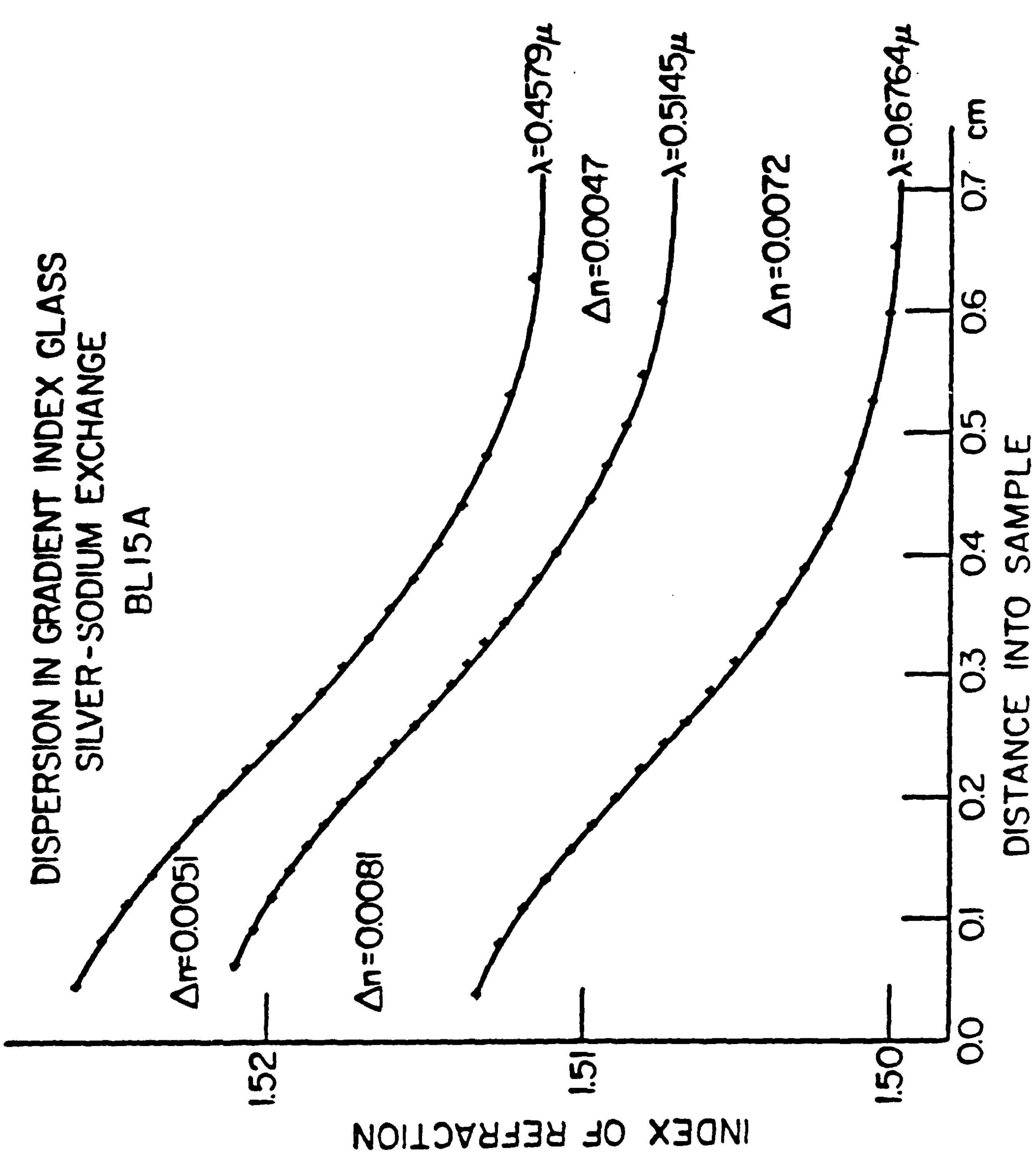
- INCREASE ACCURACY OF SLOPE TO 0.1%
- MORE DATA

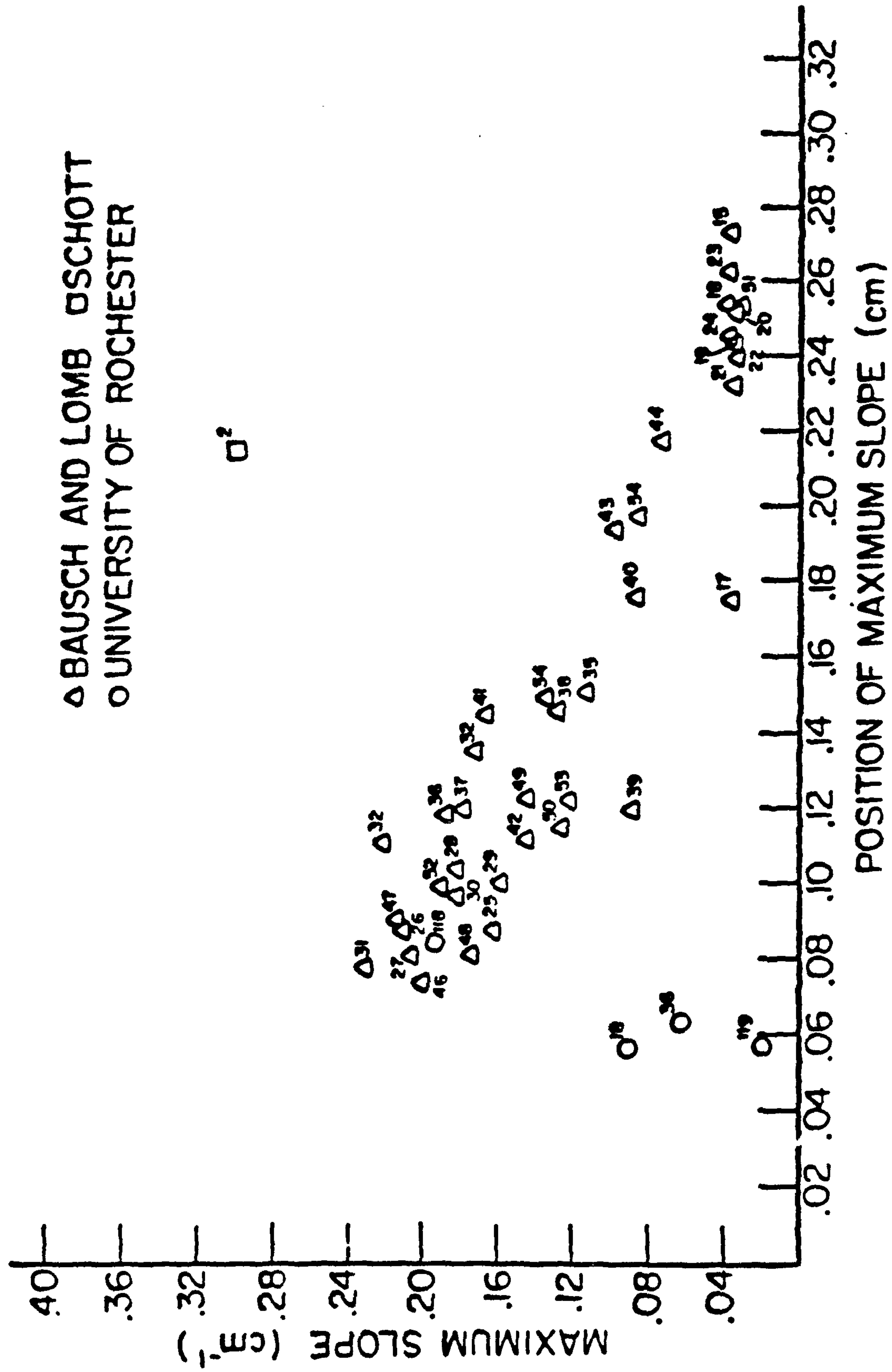

D
C
BS2
M2
GRADIENT
INDEX
SAMPLE
MI
BSI



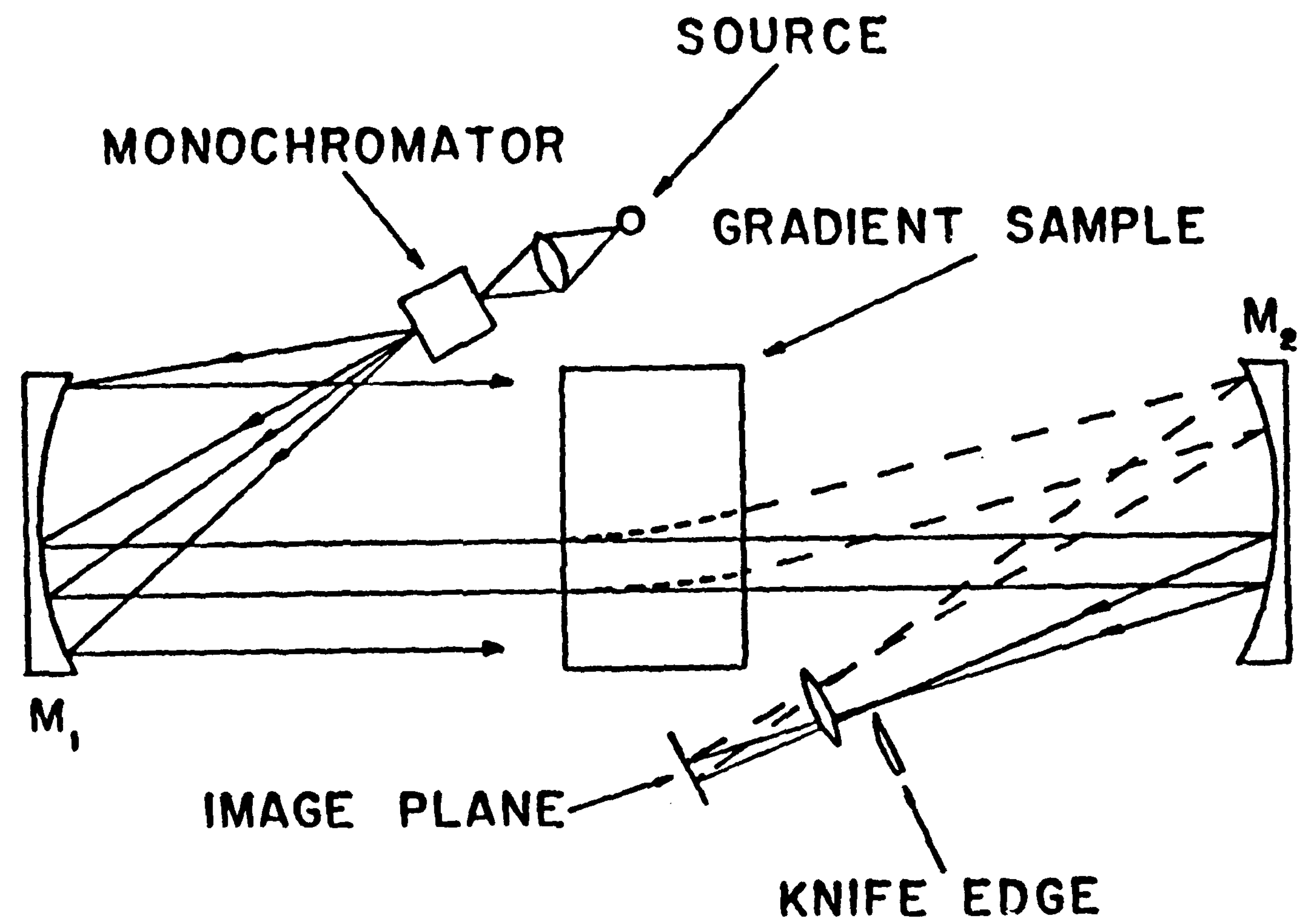
VOLTAGE ON PIEZO ELECTRIC CERAMIC (A)
V
TIME
OUTPUT OF DETECTOR AT C
V
TIME
V
OUTPUT OF DETECTOR AT D
TIME


BL21A2 λ=0.5145μm
x EXPERIMENTAL POINTS
– FITTED CURVE
DELTA INDEX OF REFRACTION (x10⁻¹)
-0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
0.00
0.10
0.20
0.30
0.40
0.50
DISTANCE INTO SAMPLE IN cm

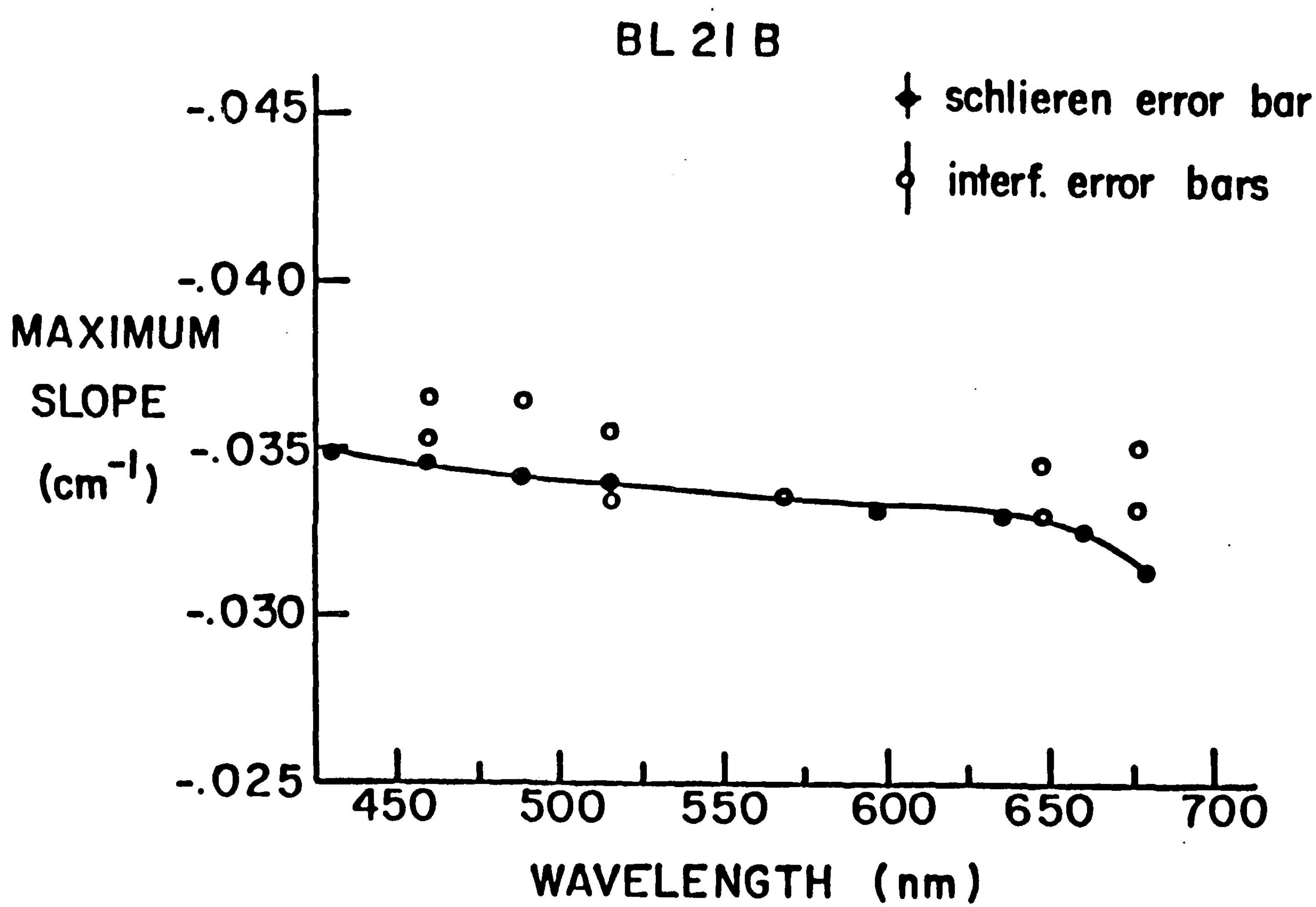

DISPERSION IN GRADIENT INDEX GLASS
SILVER-SODIUM EXCHANGE
BL 15A
Δn=0.0051
Δn=0.0081
Δn=0.0047
Δn=0.0072
λ=0.4579μ
λ=0.5145μ
λ=0.6764μ
1.52
1.51
1.50
INDEX OF REFRACTION
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
cm
DISTANCE INTO SAMPLE

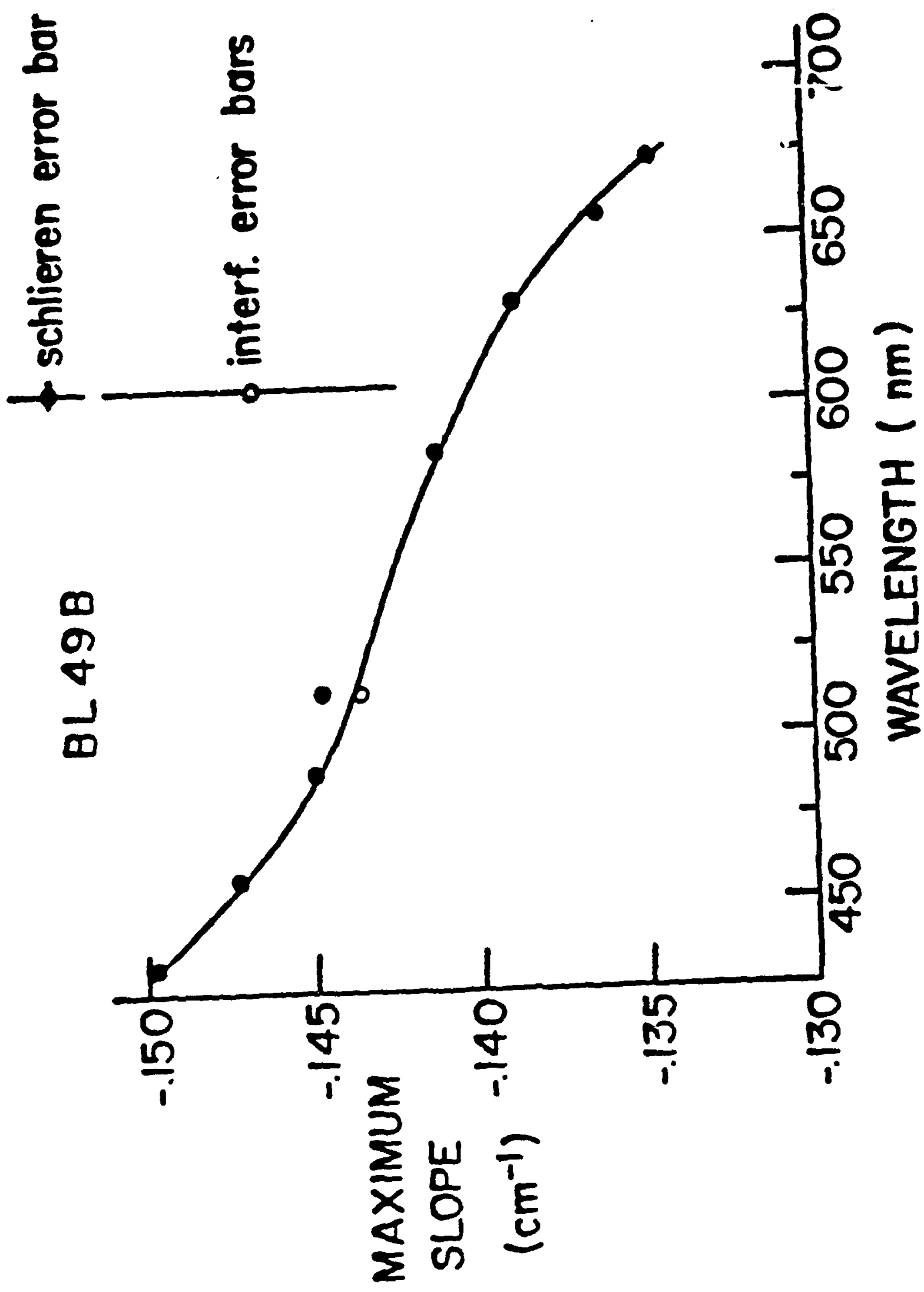


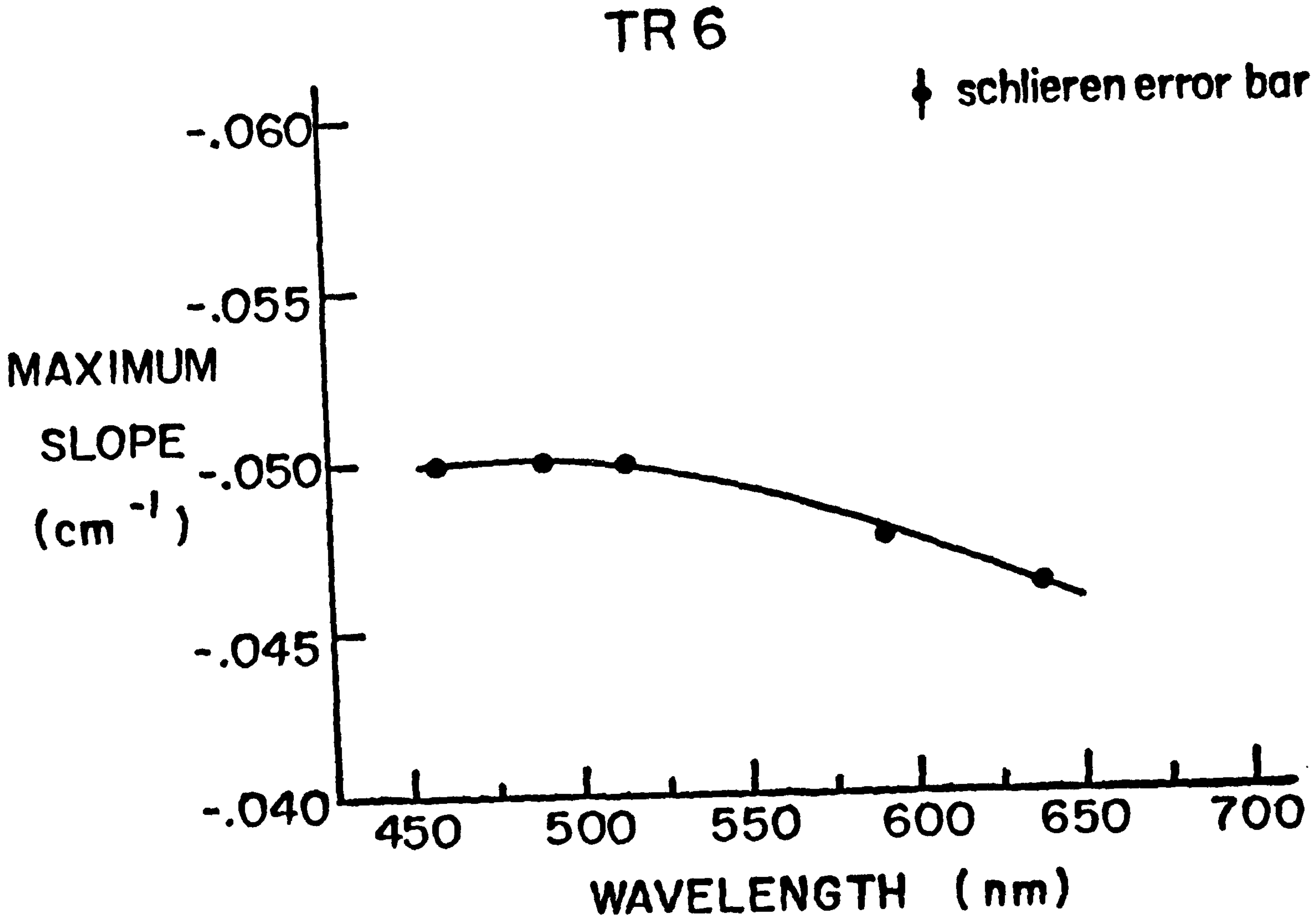
Δ BAUSCH AND LOMB □ SCHOTT
○ UNIVERSITY OF ROCHESTER
MAXIMUM SLOPE (cm⁻¹)
.40 .36 .32 .28 .24 .20 .16 .12 .08 .04
.02 .04 .06 .08 .10 .12 .14 .16 .18 .20 .22 .24 .26 .28 .30 .32
POSITION OF MAXIMUM SLOPE (cm)

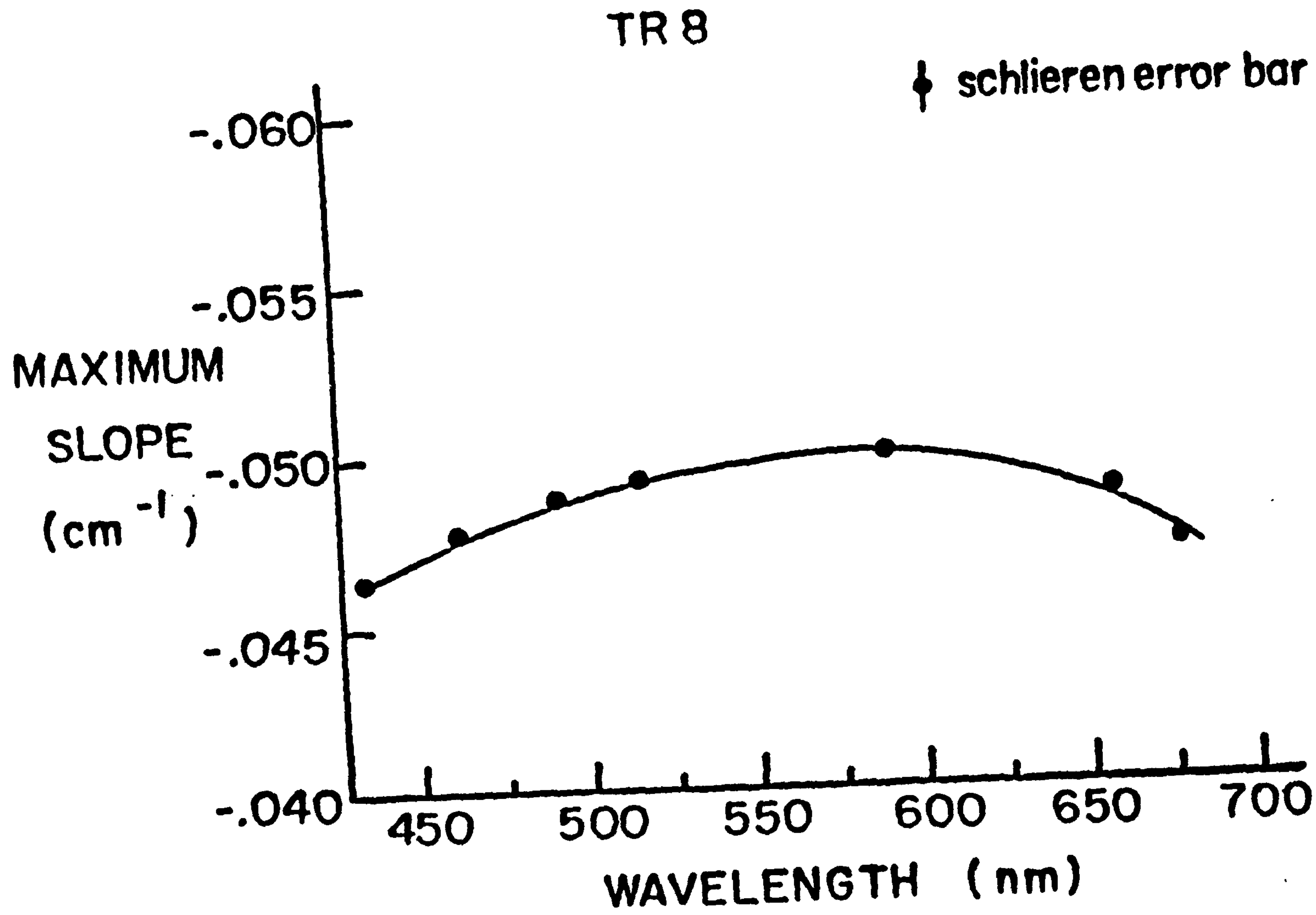


GRADIENT INDEX SCHLIEREN SYSTEM

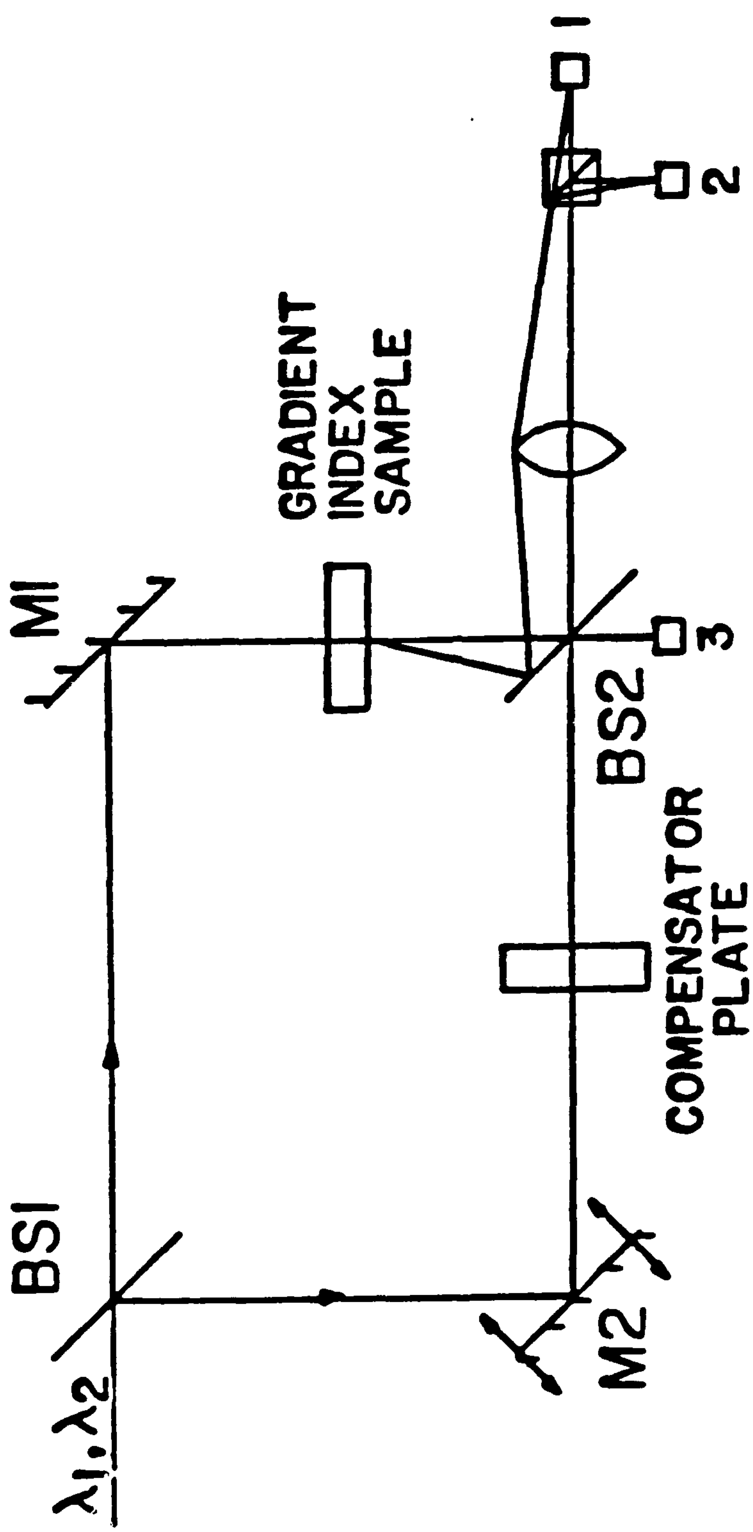

BL 21 B
schlieren error bar
interf. error bars
-.045
-.040
-.035
-.030
-.025
MAXIMUM
SLOPE
(cm⁻¹)
450
500
550
600
650
700
WAVELENGTH (nm)


BL 49 B
schlieren error bar
interf. error bars
MAXIMUM
SLOPE
(cm⁻¹)
-.150
-.145
-.140
-.135
-.130
450
500
550
600
650
700
WAVELENGTH (nm)


TR 6
schlieren error bar
MAXIMUM SLOPE (cm^-1)
-.060
-.055
-.050
-.045
-.040
450
500
550
600
650
700
WAVELENGTH (nm)



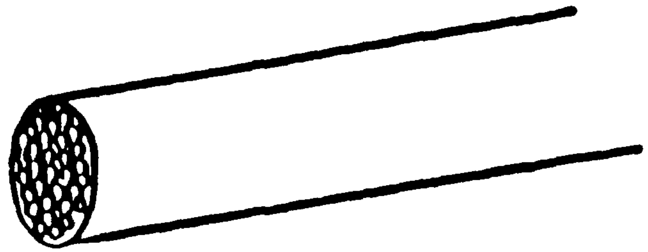
TR 8
schlieren error bar
MAXIMUM
SLOPE
(cm -1)
-.060
-.055
-.050
-.045
-.040
450
500
550
600
650
700
WAVELENGTH (nm)



λ1,λ2
BSI
MI
M2
COMPENSATOR
PLATE
BS2
GRADIENT
INDEX
SAMPLE
3
2
1

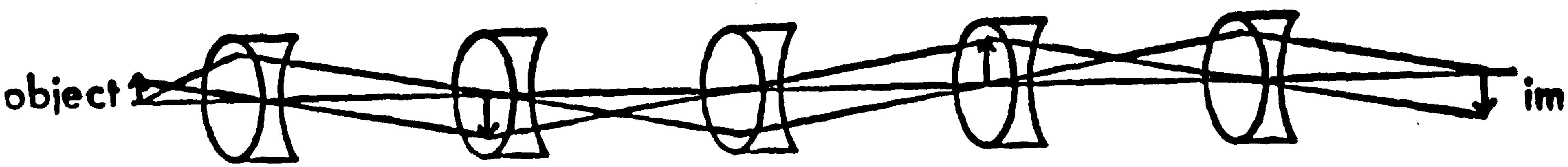
CONVENTIONAL ENDOSCOPIC SYSTEM

Homogeneous Fiber Bundle



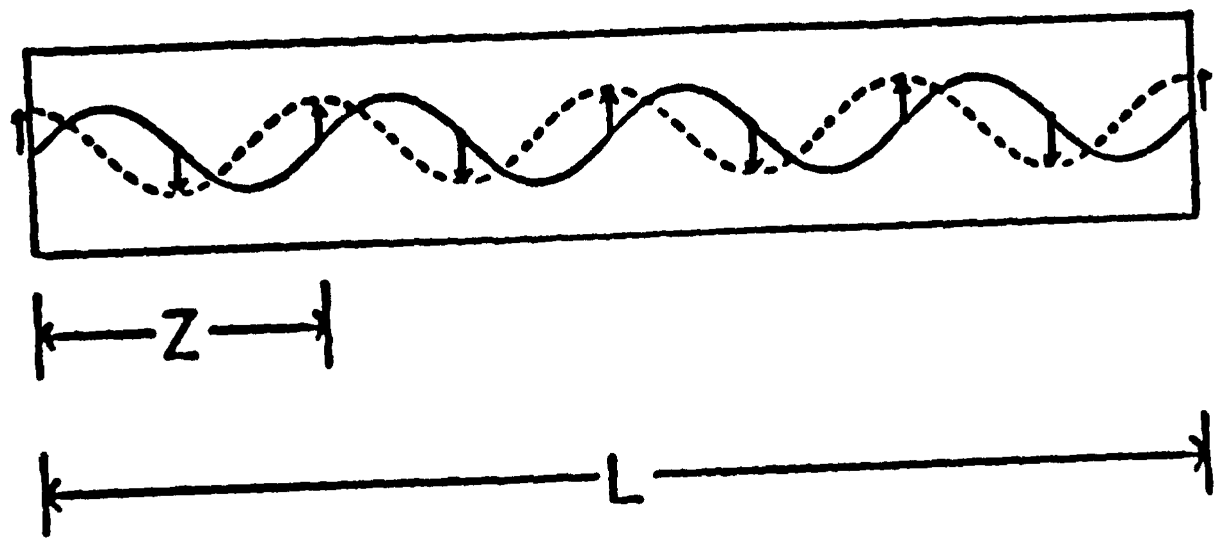
10,000 fibers

Relay System

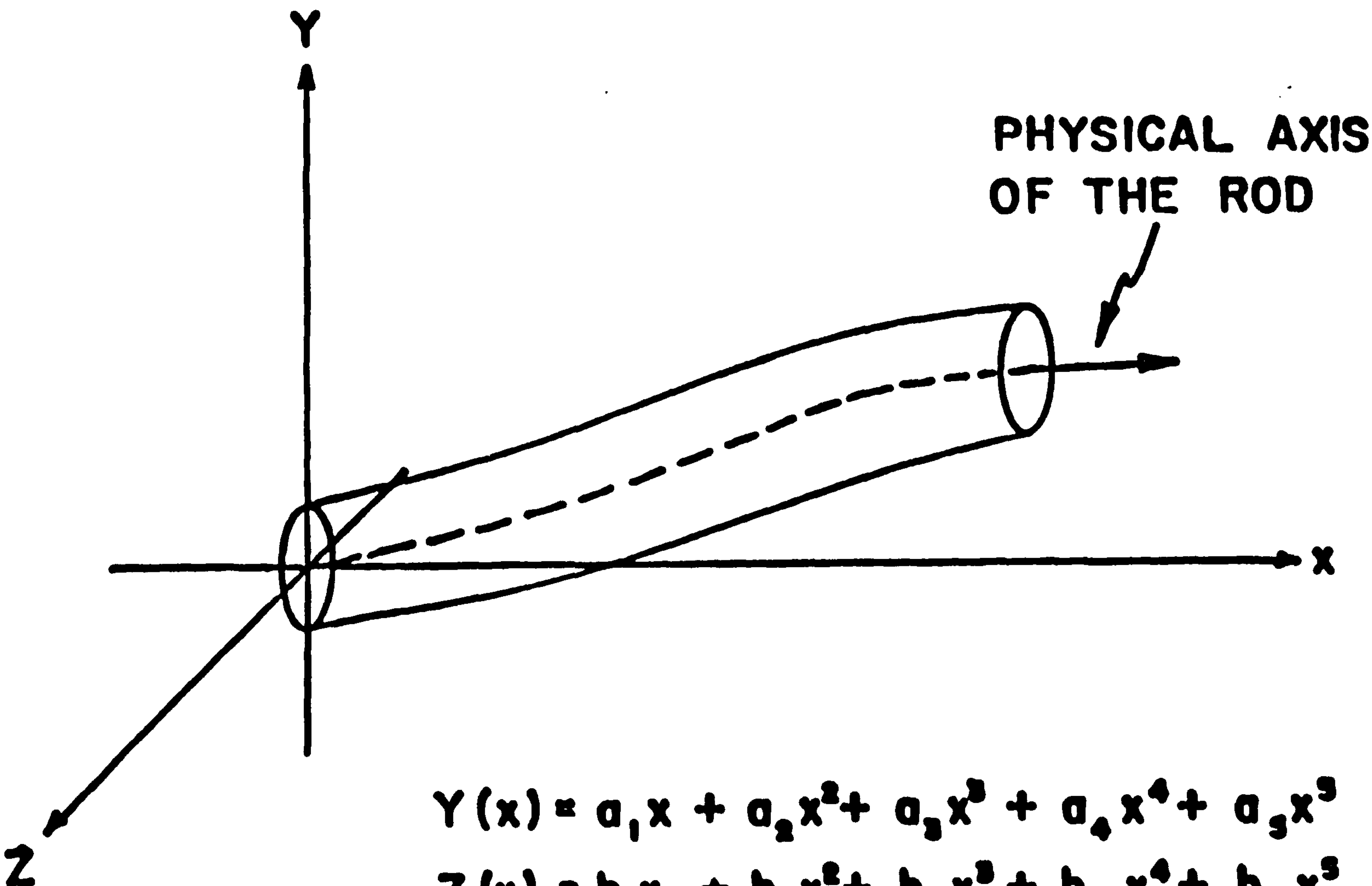


many relay elements

INHOMOGENEOUS SINGLE FIBER

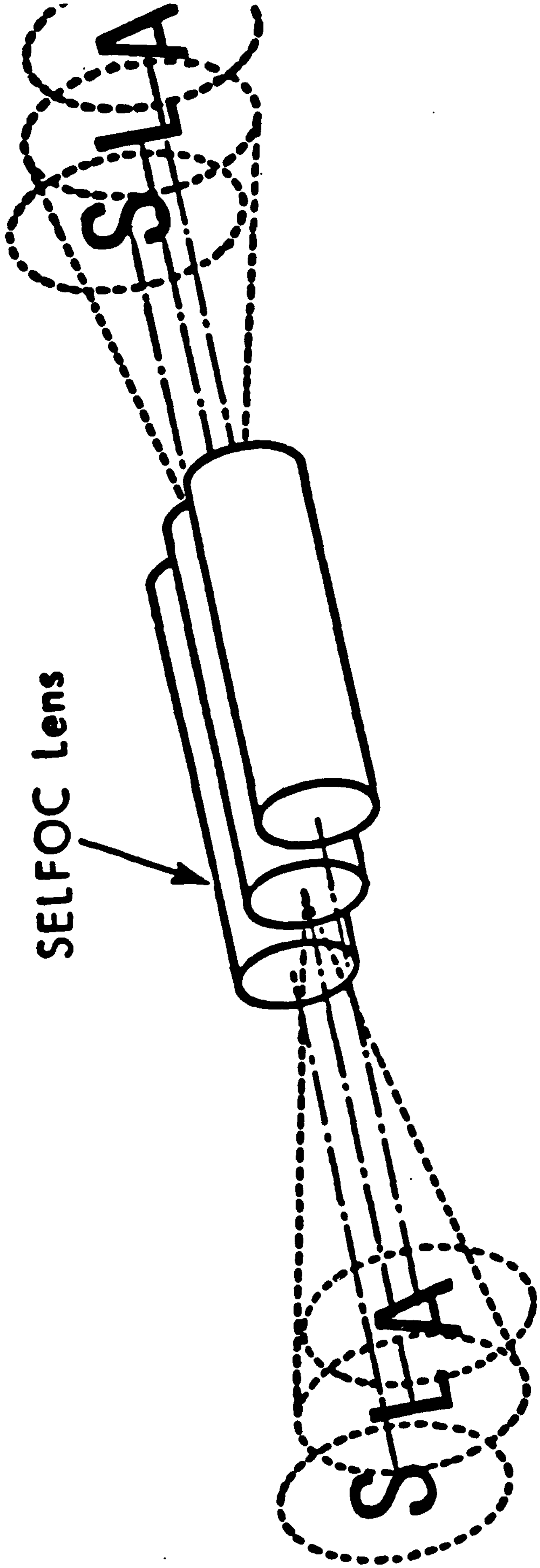


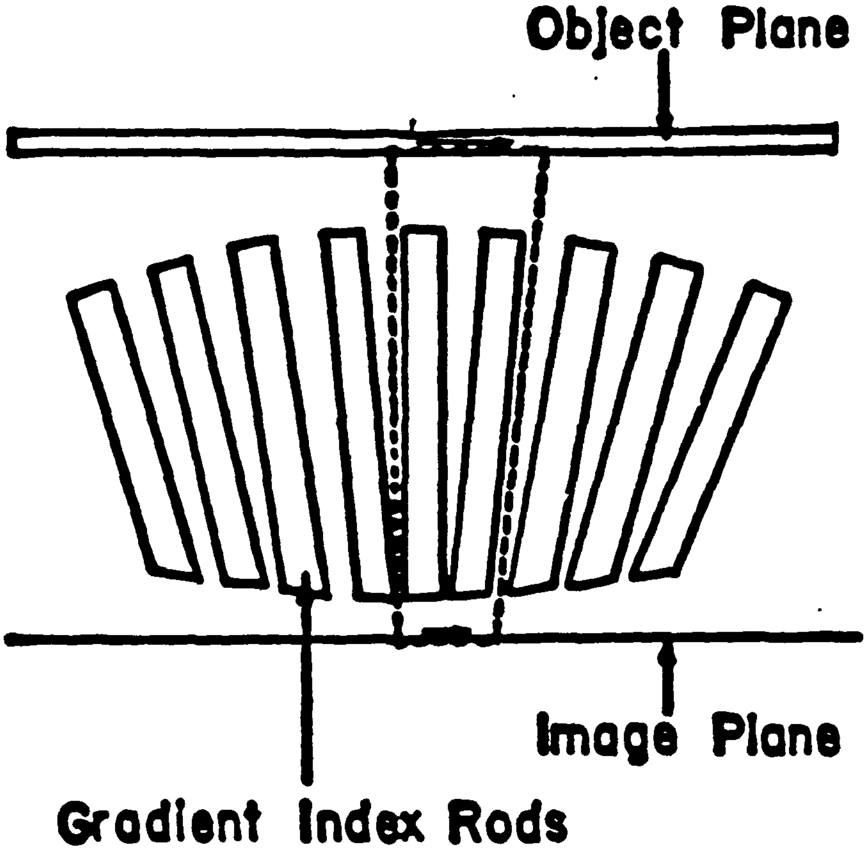
Space Bandwidth = number of resolution elements across field

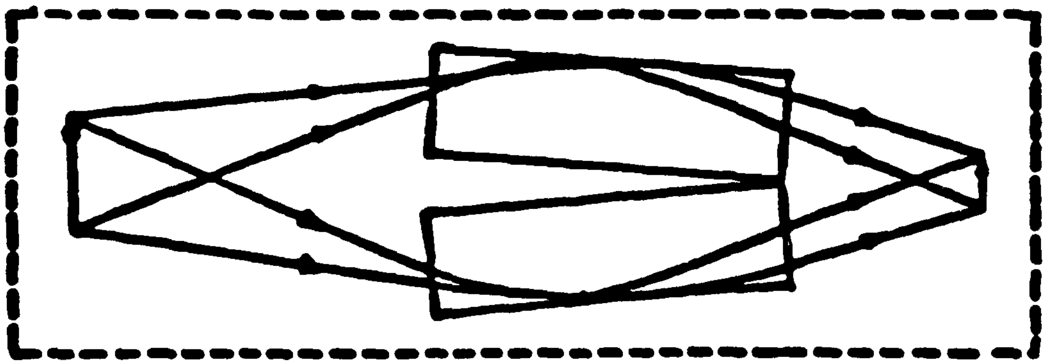


$$Y(x) = a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5$$
$$Z(x) = b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + b_5 x^5$$

Axis Representation of the Curved GRIN Rod

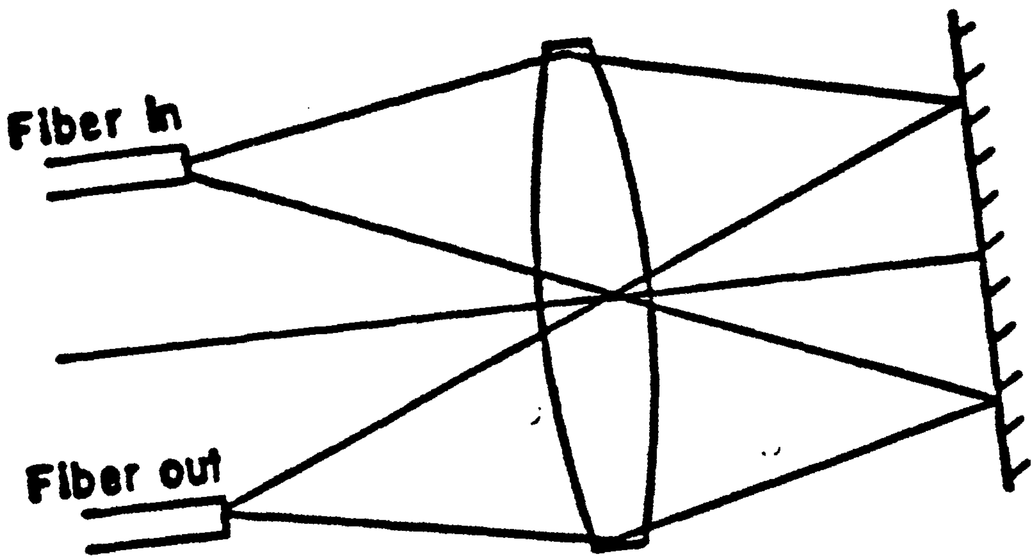

SELFOC Lens
SLA
SLA





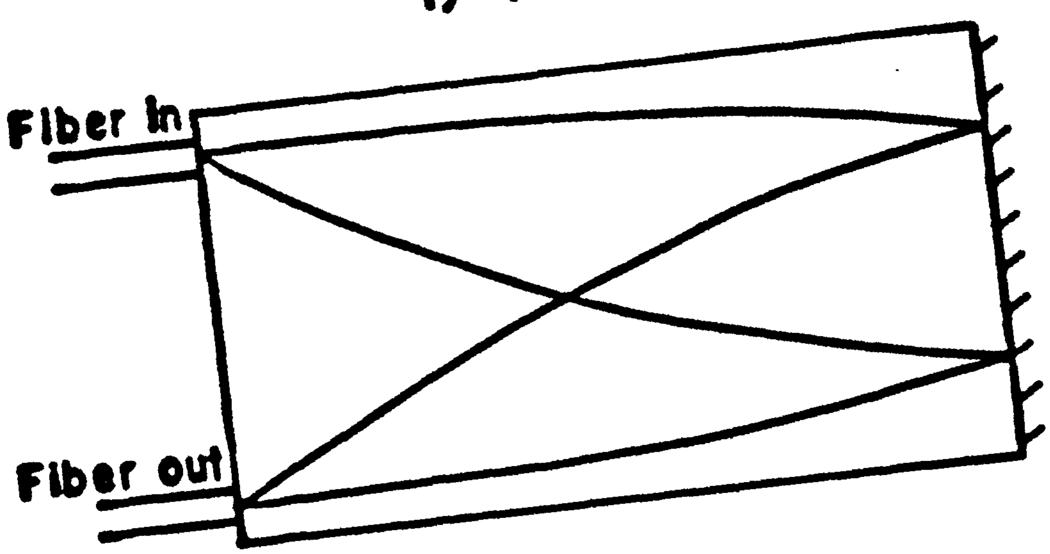
Gradient Index Array: Non-Unit Magnification

Conventional System



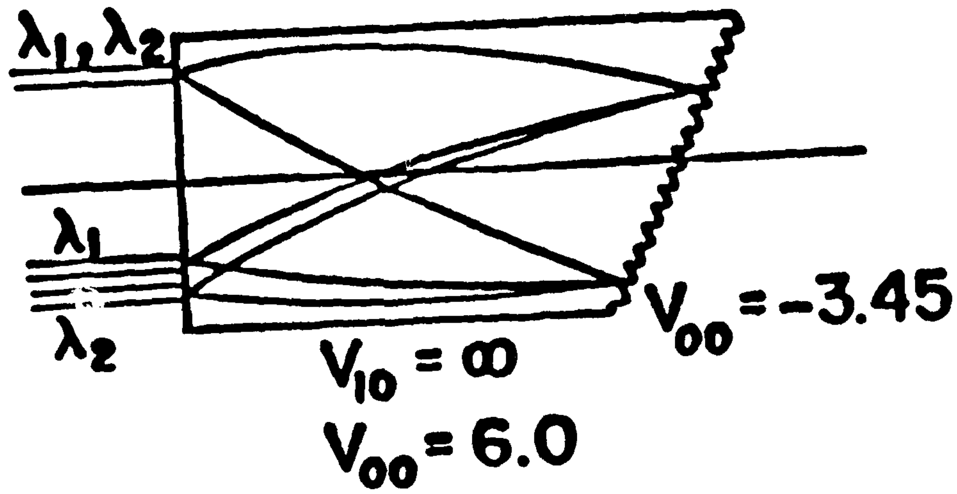
Gradient Index Rod

1/4 Pitch

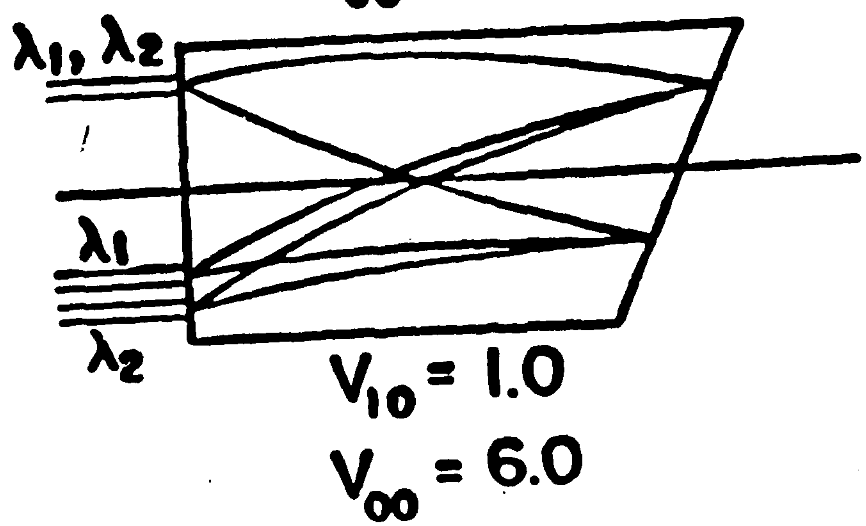


PLC = 0.0

MULTIPLEXER
Non Rotational Symmetry
1/4 Period Rod



PLC = large
PAC = small



PLC = large
PAC = large

CECOM CENTER FOR NIGHT VISION AND ELECTRO-OPTICS

INTRODUCTION

OPTOELECTRONICS WORKSHOP
GRADIENT INDEX/ CAD OPTICAL FABRICATION

Gradient Index as a concept has been around since the nineteenth century. While practical applications have appeared only within the last decade. The first application is for fiber optics, where very long lengths are required in communication systems. The use of gradient index technology improved fiber optic transmission efficiency, making possible longer communication distances with gradient index fibers.

Today the technology has extended into optics for binoculars, both the objective and the eyepieces. Currently CCNVEO is developing gradient optics for the far infrared, where cost and performance benefits are will be realized above homogeneous optics. With these technology demonstrators future gradient index optics applications include night vision goggles, displays, both helmet and heads-up and IR/Visual optical trains.

With the advent of the microcomputer it is possible to grind and polish optics through a computer controlled processing. A system will be described that can fabricate greater than 80% of the all the different geometries required for U.S. Army's weapon systems.

OPTOELECTRONICS WORKSHOP

GRADIENT INDEX/ CAD OPTICAL FAB.

OVERVIEW
- SYSTEM REQUIREMENTS
  - SENSOR REQUIREMENTS
    - COMPONENT REQUIREMENTS

OPTICAL DESIGNS

- SPHERICAL SURFACES - HOMOGENOUS MATERIAL
- ASPHERIC SURFACES - MIRRORS, GERMANIUM
- GRADIENT INDEX - VISIBLE, INFRARED

OPTICAL MANUFACTURING
- CONVENTIONAL GRINDING AND POLISHING
- COMPUTER CONTROLLED GRINGING AND POLISHING

24 MAY, 1988

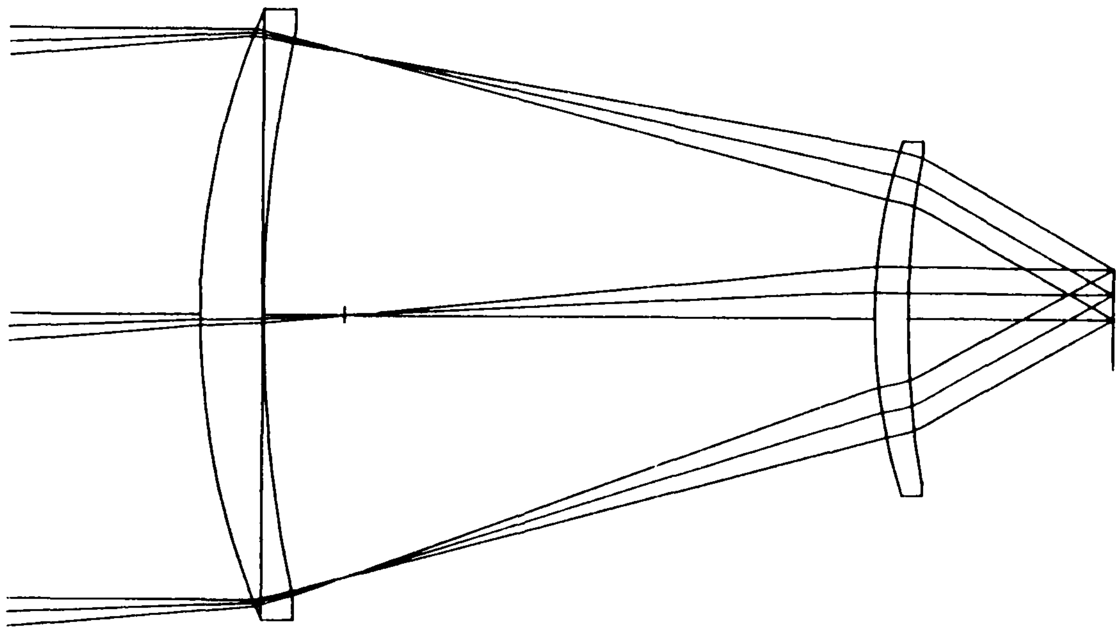
OPTOELECTRONICS WORKSHOP
GRADIENT INDEX APPLICATIONS

VISIBLE APPLICATIONS
- NV GOGGLE OBJECTIVE LENSES
- HELMET MOUNTED DISPLAYS
- DISPLAYS

IR APPLICATIONS
- RIFLE SIGHT APPLICATIONS
- IR OPTICAL TRAINS
- IR GOGGLES

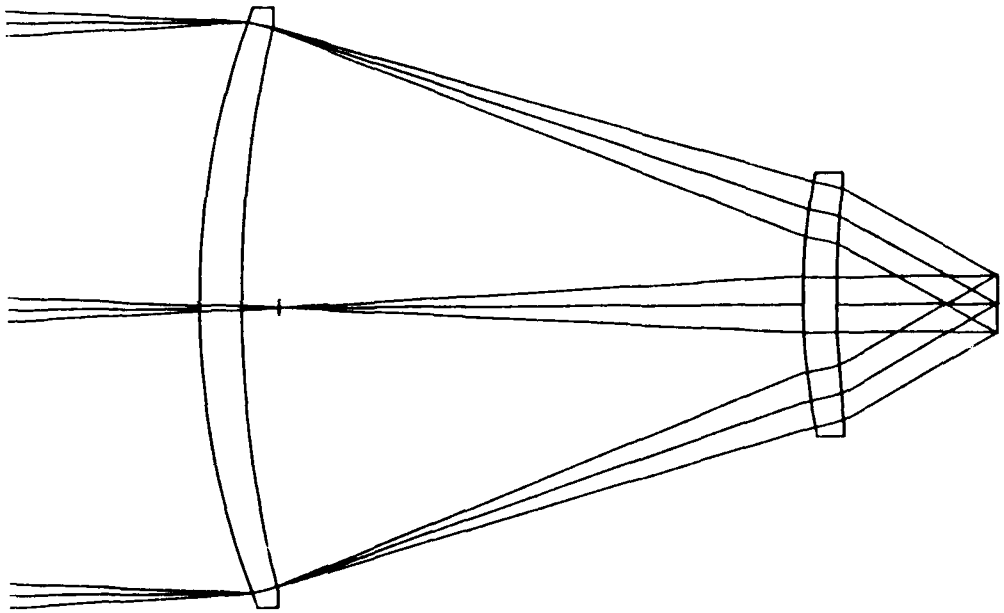
24 MAY, 1988

OPTOELECTRONICS WORKSHOP
SPHERICAL - AXIAL GRADIENT



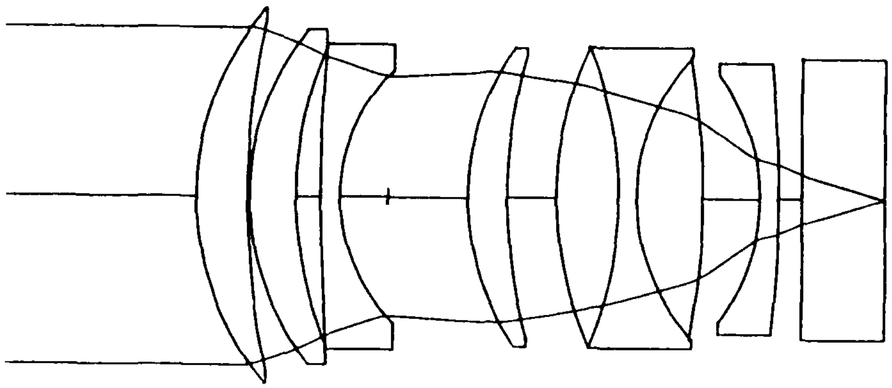
3" APERTURE, F/1.0
28 MAY, 1988

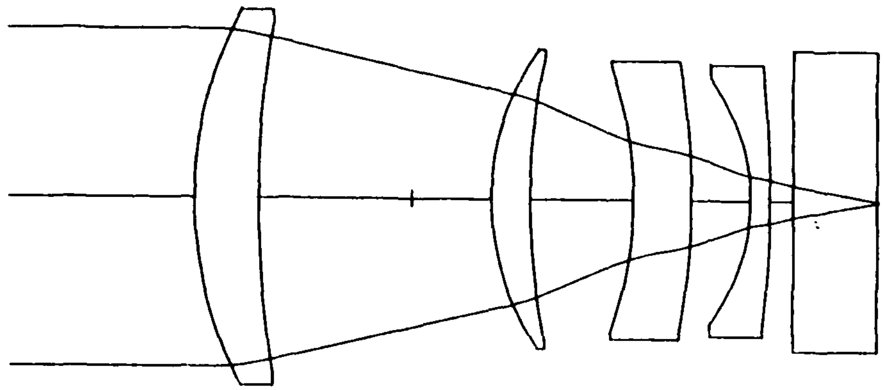
OPTOELECTRONICS WORKSHOP
ASPHERIC -HOMOGENEOUS



3" APERTURE, F/1.0
28 MAY, 1988

OPTOELECTRONICS WORKSHOP
ANVIS GRIN OBJECTIVE LENS

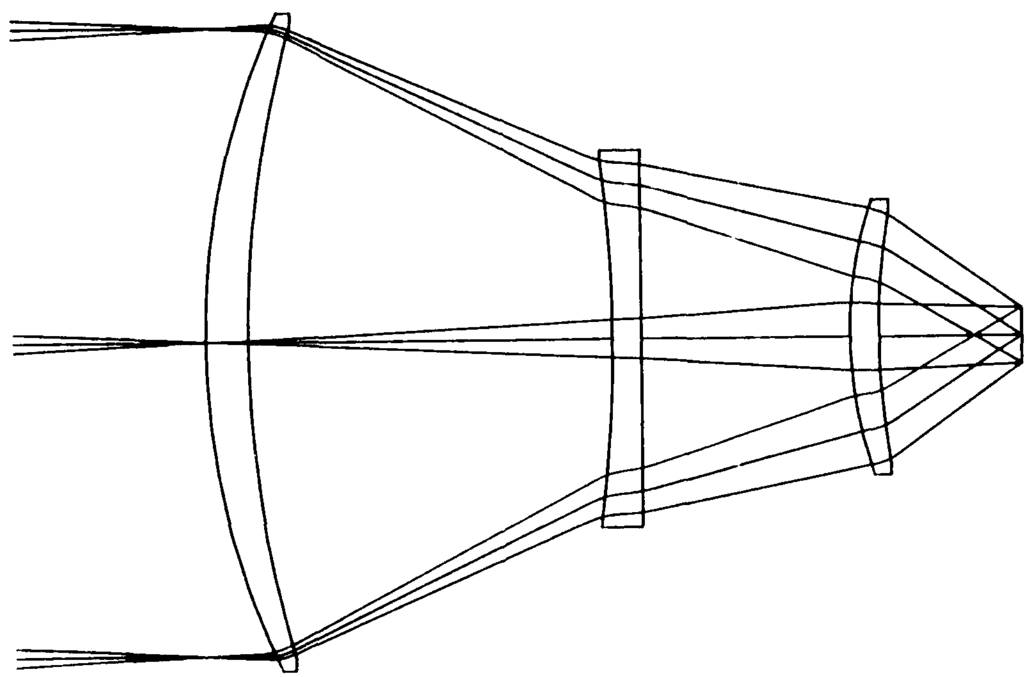




HOMOGENEOUS **GRADIENT INDEX**

28 MAY, 1988

OPTOELECTRONICS WORKSHOP
SPHERICAL - HOMOGENEOUS



3" APERTURE, F/1.0
28 MAY, 1988

CVD CORPORATION/GRADIENT LENS CORPORATION

GRADIENT INDEX INFRARED OPTICS

AGENDA

O PROGRAM INTRODUCTON	H. DESAI
O AXIAL GRADIENT (AGRIN) AND RADIAL GRADIENT (RGRIN) DESIGNS	R. ZINTER
O AGRIN MATERIAL DEVELOPMENT	H. DESAI

CHEMICAL VAPOR DEPOSITION

- DEFINITION

  CONDENSATION OF A COMPOUND OR COMPOUNDS FROM THE GAS PHASE ONTO A SUBSTRATE WHERE HETEROGENEOUS REACTION OCCURS TO PRODUCE A SOLID DEPOSIT

- TYPICAL APPLICATIONS
  - HARD COATINGS (TIC, AL_2O_3, C)
  - PROTECTION AGAINST CORROSION (TA, BN, $MOSI_2$, SIC)
  - SOLID STATE ELECTRONIC DEVICES AND ENERGY CONVERSION (SI, GAAS)
  - IR MATERIALS (ZNSE, ZNS, CDS, CDTE, ETC)
  - MANUFACTURE OF CERAMICS (PYROLYTIC C, BN, POLY-SI, ETC.)

- GENERAL CHARACTERISICS OF CVD PROCESS
  - HIGH PURITY MATERIALS PRODUCED (99.9999% TYPICAL)
  - DEPOSITED MATERIAL IS POLYCRYSTALLINE, THEORETICALLY DENSE
  - MICROSTRUCTURE (GRAIN SIZE, CRYSTAL ORIENTATION) CONTROLLED BY CVD PARAMETERS
  - COMPOSITE MATERIALS CAN BE PRODUCED CVD
  - COST-EFFECTIVE (AUTOMATION POSSIBLE)
  - REPLICATION DOWN TO MOLECULAR LEVEL POSSIBLE
  - SCALABLE PROCESS

X177

CVD OF ZNSE AND ZNS

- REACTIONS

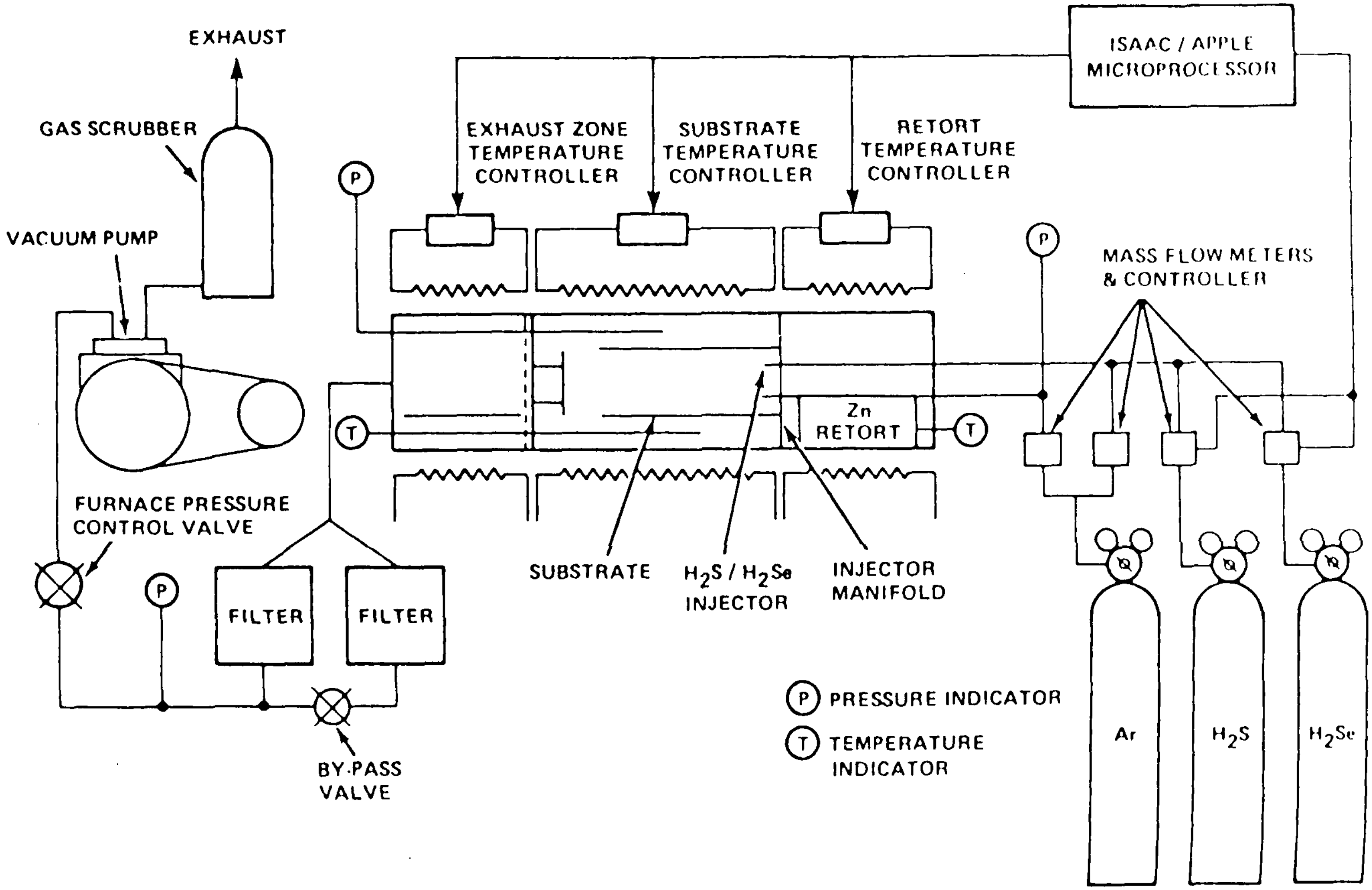
$$ZN(G) + H_2S(G) \xrightarrow[\substack{40\ \text{torr} \\ 670\ \text{C}}]{AR} ZNS(S) + H_2(G)$$

$$ZN(G) + H_2SE(G) \xrightarrow[\substack{25\ \text{torr} \\ 750\ \text{C}}]{AR} ZNSE(S) + H_2(G)$$

- DETAILED REACTION MECHANISM NOT FULLY UNDERSTOOD

- DEPOSITION RATE CRITICAL TO MATERIAL QUALITY ($R_D \cong 1.2\ \mu M\ MIN.^{-1}$)

- POLYCRYSTALLINE, RANDOM ORIENTATION, GRAIN SIZE ~ 5 μM FOR ZNS AND ~ 70 μM FOR ZNSE

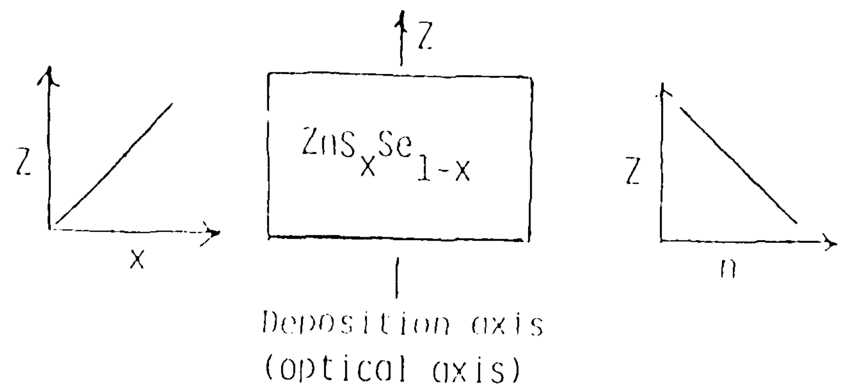


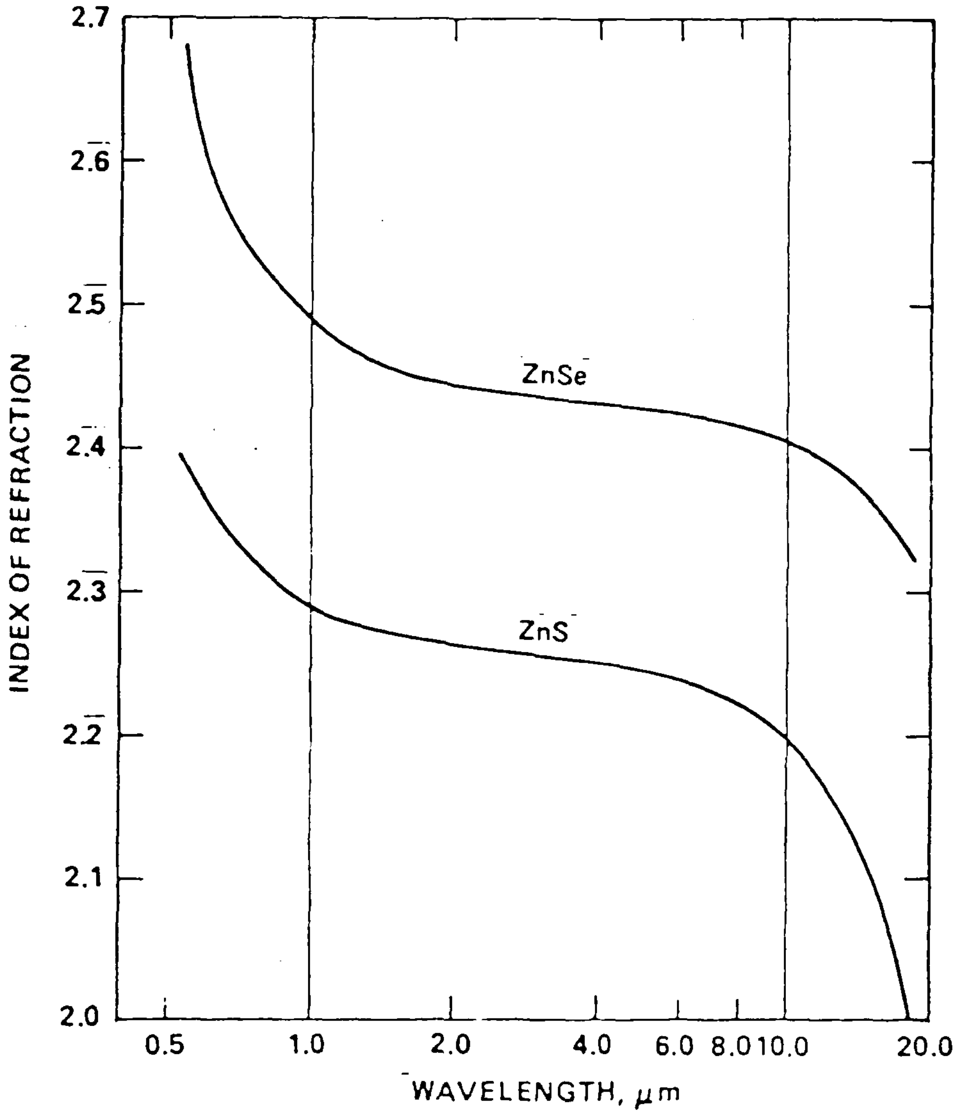
Schematic of research CVD furnace to be used in proposed program.

GRIN CONCEPT

- ZnS AND ZnSe HAVE DIFFERENT REFRACTIVE INDICES IN IR
- ZnS AND ZnSe ARE COMPLETELY MISCIBLE SOLIDS, I.E., ZnS_xSe_{1-x} EXIST FOR ALL VALUES OF x
- INDEX OF ZnS_xSe_{1-x} RELATED TO x,

  $N = N_{ZnSe}(1-x) + N_{ZnS}(x)$
- CODEPOSIT ZnS AND ZnSe IN A CONTROLLED MANNER, I.E., VARY x AS A FUNCTION OF THICKNESS (DEPOSITION TIME)





Indices of refraction of ZnS and ZnSe as a function of wavelength.

PROGRAM: CHEMICAL VAPOR DEPOSITION OF INFRARED GRADIENT INDEX MATERIALS

SPONSOR: U.S. ARMY MISSILE COMMAND
GUIDANCE AND CONTROL DIRECTORATE
CONTRACT NUMBER DAAH01-84-C-0085

OBJECTIVE: DEMONSTRATE THE FEASIBILITY OF PRODUCING AN IR AXIAL GRADIENT MATERIAL.

PERIOD OF PERFORMANCE: 3/1/84 - 9/30/85

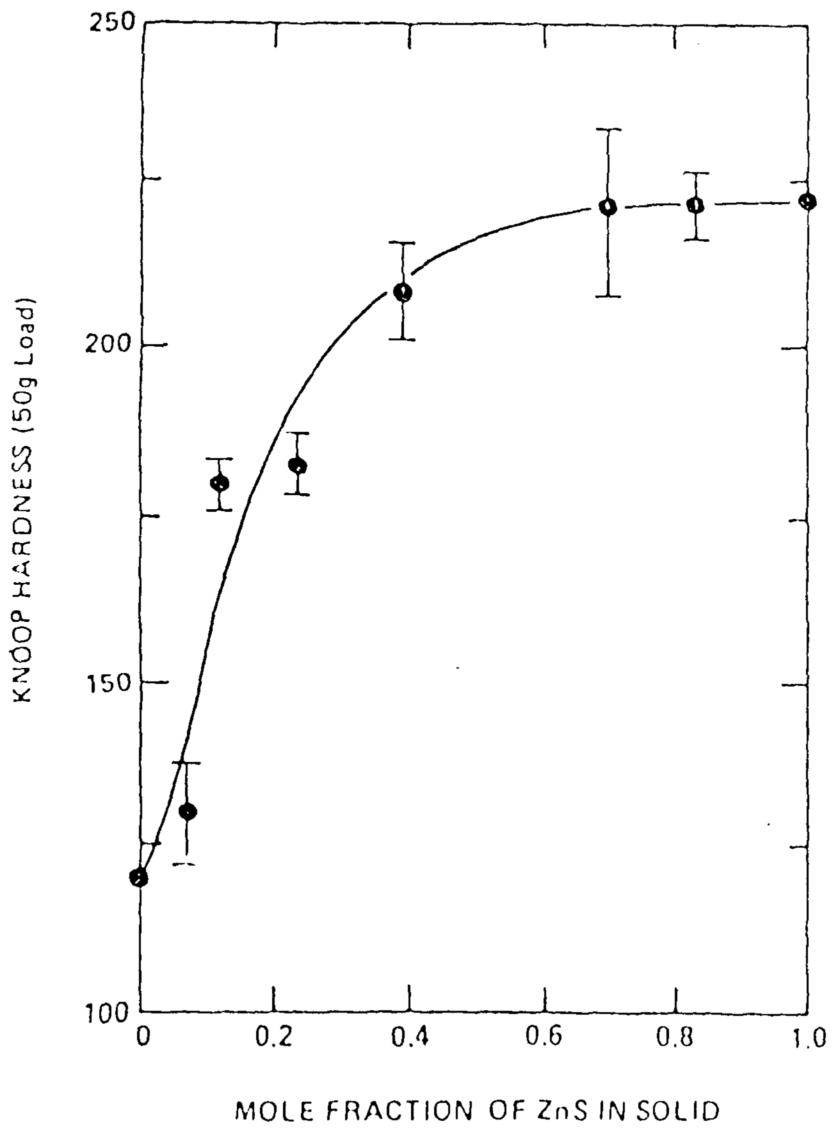


Figure 1.

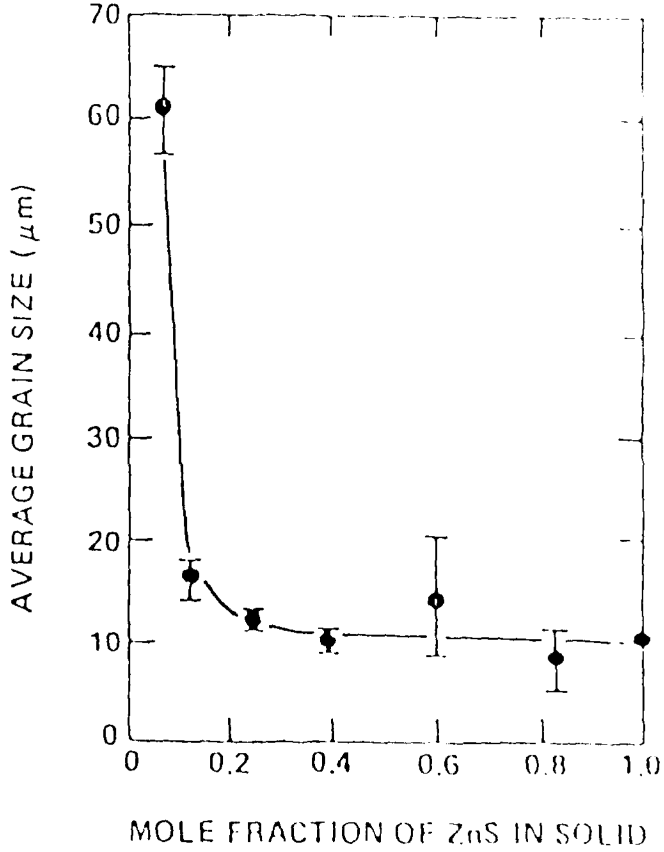
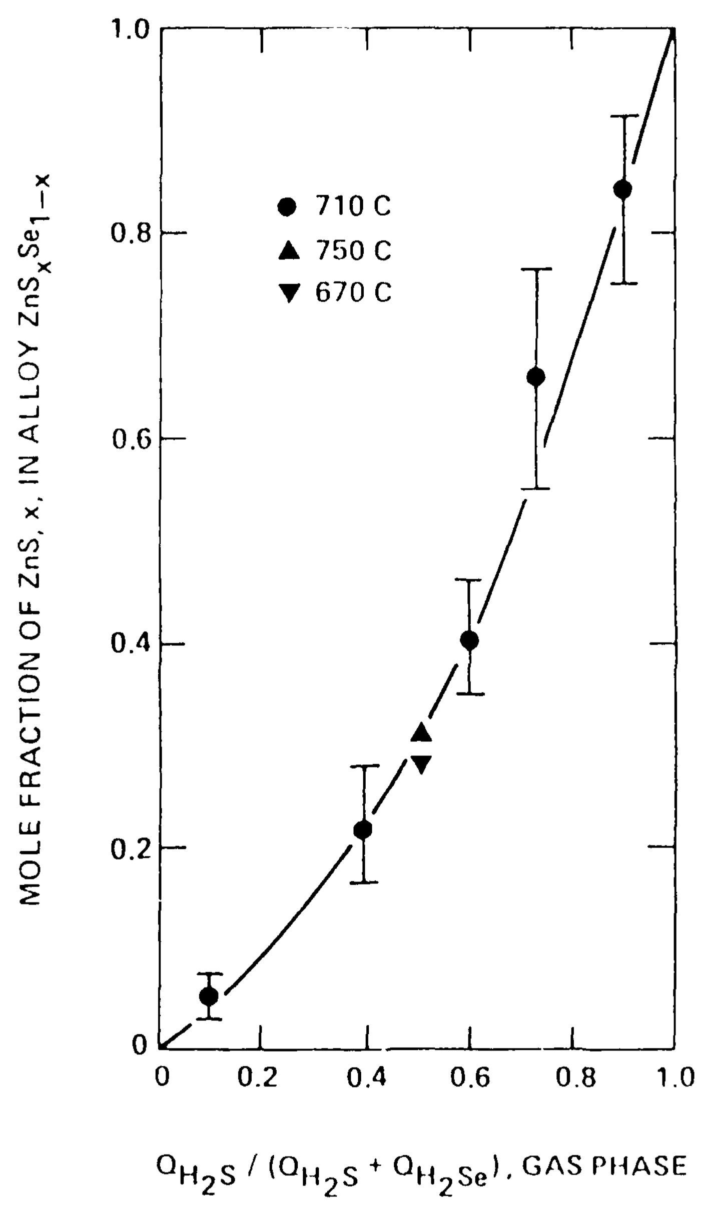
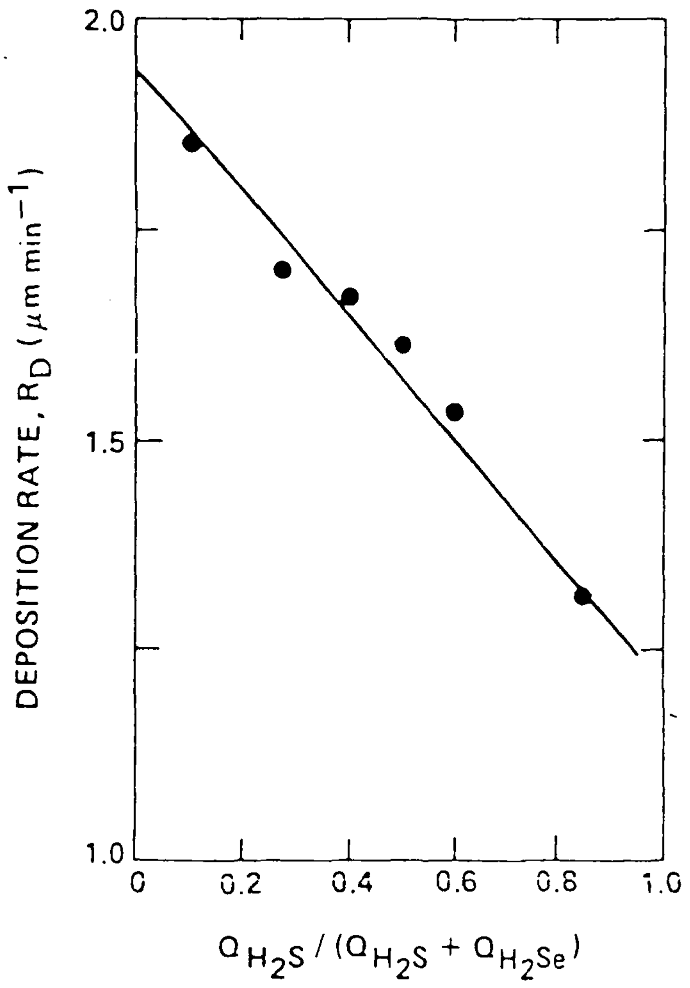


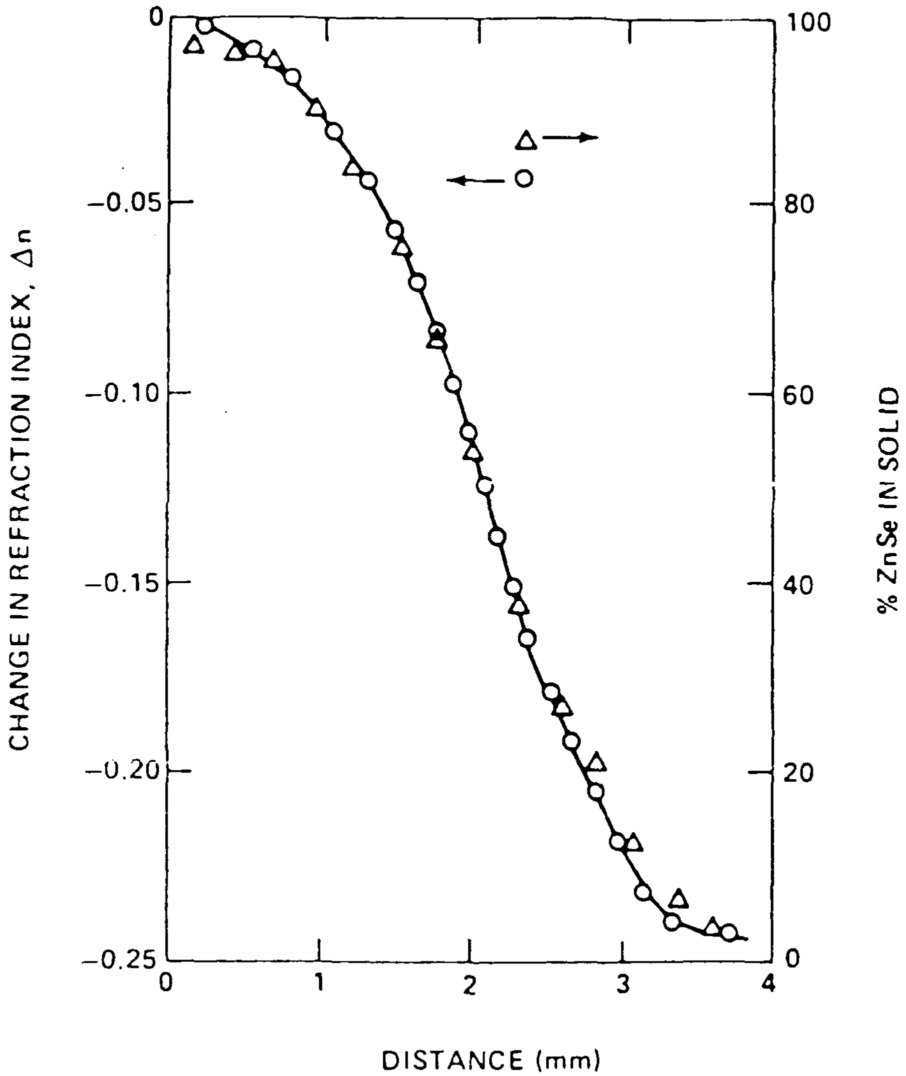
Figure 2.



● 710 C
▲ 750 C
▼ 670 C
MOLE FRACTION OF ZnS, x, IN ALLOY ZnS_xSe_{1-x}
$Q_{H_2S} / (Q_{H_2S} + Q_{H_2Se})$, GAS PHASE
0
0.2
0.4
0.6
0.8
1.0

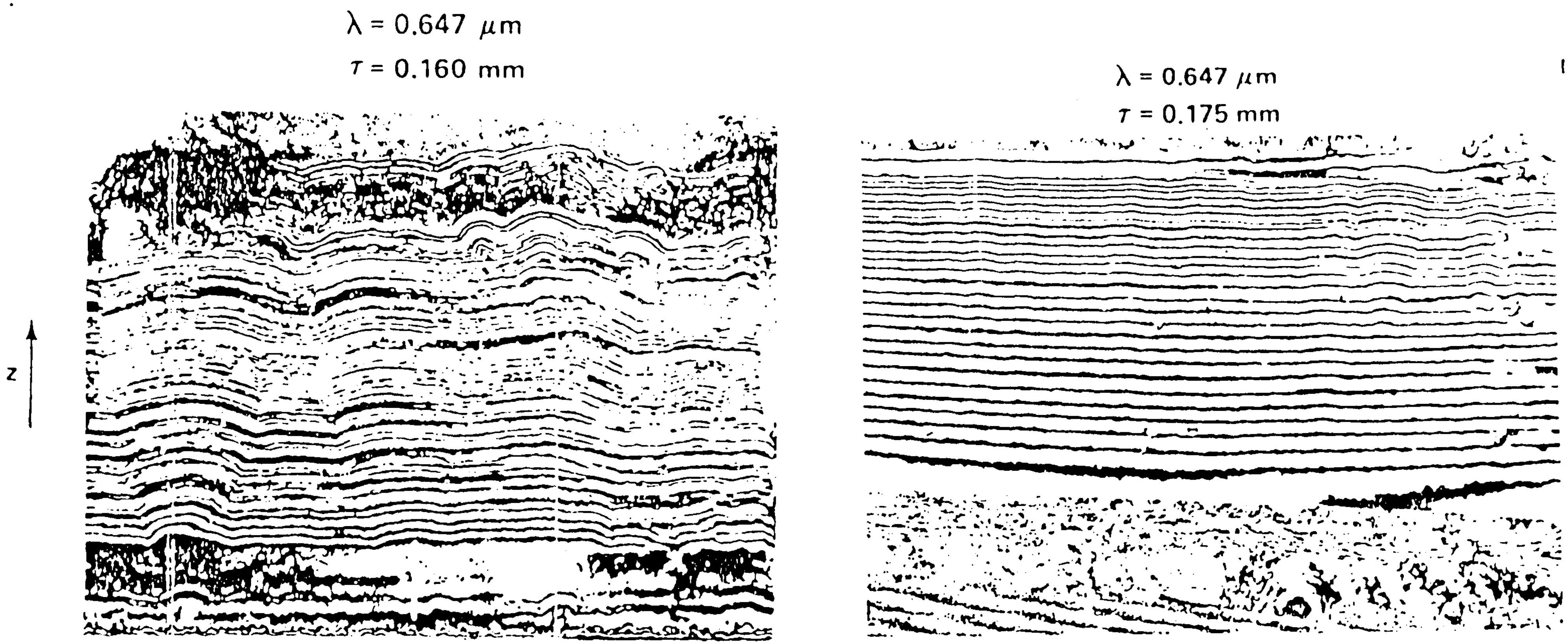


Deposition rate, R_D, of alloy ZnS_xSe_{1-x} vs. gas phase composition. Solid line is a linear least squares fit to the data points.



Change in refractive index (0) and % ZnSe in solid vs. distance from substrate for ZnS_xSe_{1-x} gradient index material. Solid line through circles is a curve fit.

0.6471 μm



Photographs of fringe pattern produced when a beam of light (λ = 0.647 μm) is moved along deposition axis (Z) of gradient index material ZnS_xSe_{1-x}. They clearly show the nonuniform growth along deposition axis discussed in Section 2.1.

PROGRAM: GRADIENT INDEX OPTICS

SPONSOR: U.S. ARMY/CECOM

CONTRACT NUMBER DAAB07-87-C-F108

OBJECTIVES: TO DESIGN, TOLERANCE, FABRICATE AND TEST GRADIENT INDEX MATERIALS IN AN INFRARED OBJECTIVE LENS ASSEMBLY.

PERIOD OF PERFORMANCE: 10/1/87 - 9/30/89

<u>OBJECTIVES</u>

PHASE I ≈ $400K

- 0 DESIGN OF AGRIN LENS
- 0 FABRICATION AND TESTING OF (3) AGRIN LENS ASSEMBLIES
- 0 DESIGN OF RGRIN LENS

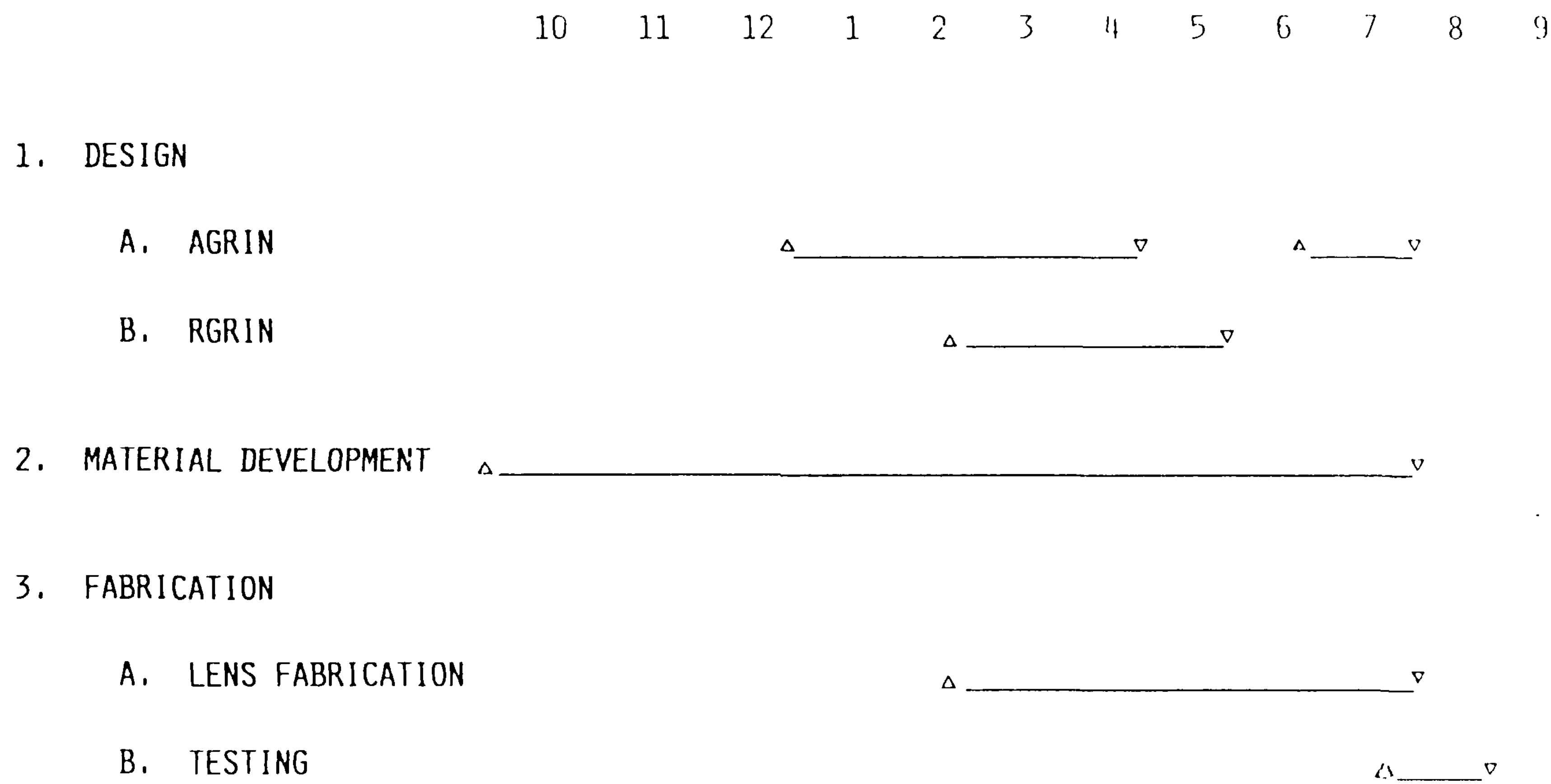
PHASE II ≈ $300K

- 0 FABRICATION AND TESTING OF (3) RGRIN LENS ASSEMBLIES

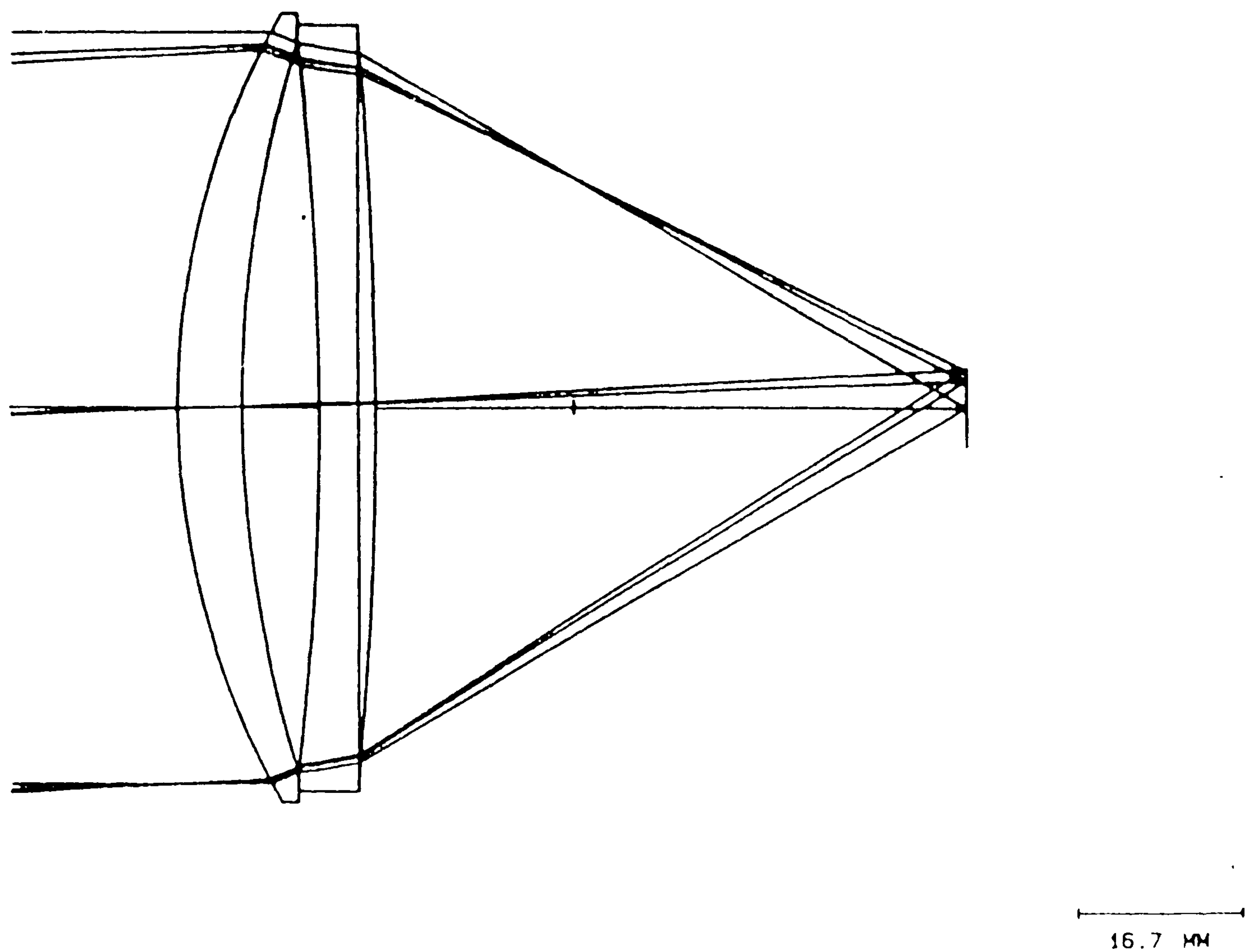
REQUIREMENTS

	AGRIN	RGRIN
F/#	1	1
FOCAL LENGTH	3.0"	1.0"
# OF ELEMENTS	2	1-2
HFOV	3°	5°
WAVELENGTH RANGE (mm)	7.5 - 11.75	7.5 - 11.75

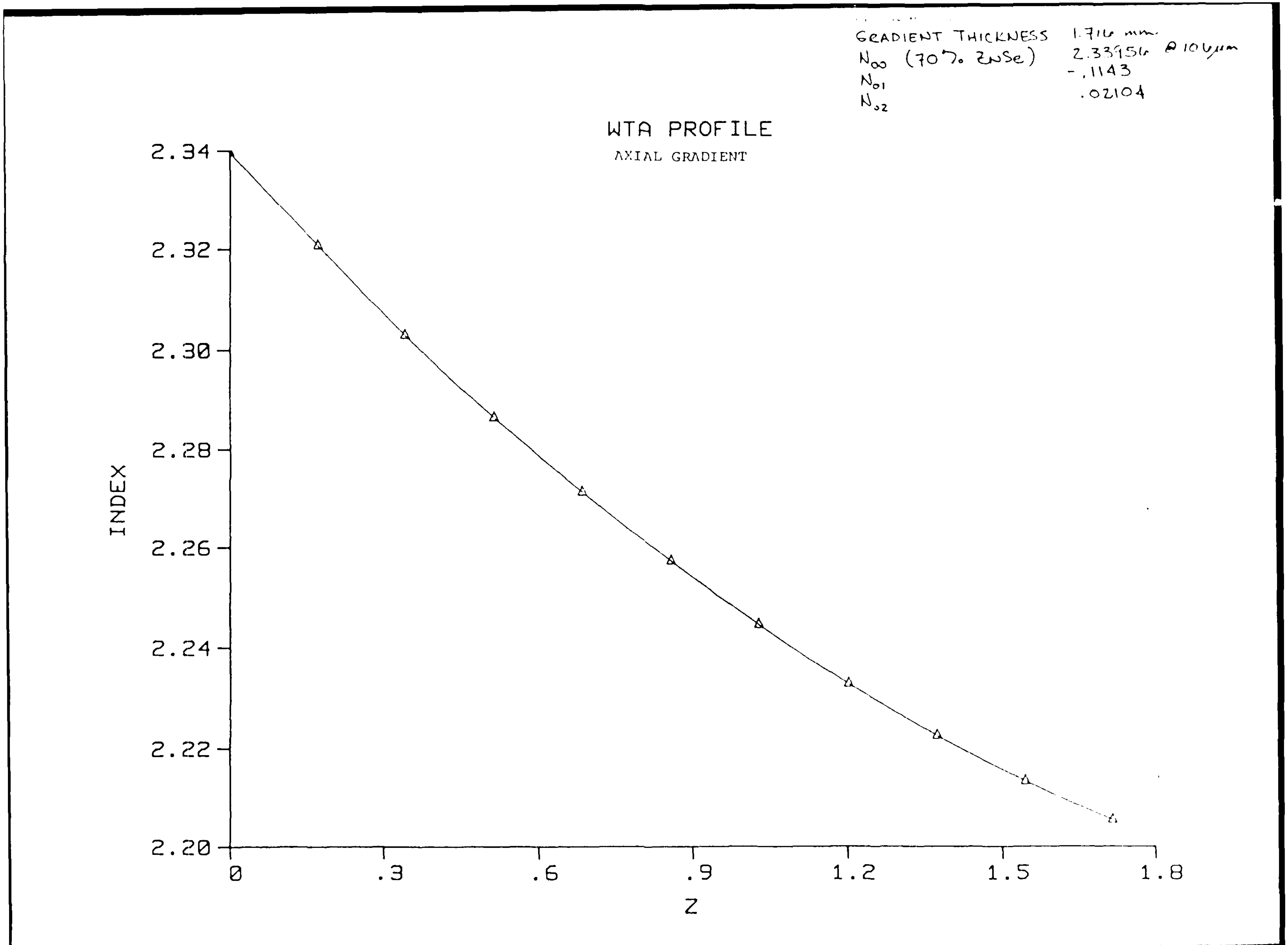
SCHEDULE



10
11
12
1
2
3
4
5
6
7
8
9
1. DESIGN
A. AGRIN
B. RGRIN
2. MATERIAL DEVELOPMENT
3. FABRICATION
A. LENS FABRICATION
B. TESTING



GERM/70% ZnSe GRIN AXIAL GRADIENT, WIDE-ANGLE DESIGN SCALE 1.5 KAR 10-MAR-88


GRADIENT THICKNESS 1.716 mm
N00 (70% ZnSe) 2.33956 @10μm
N01 -.1143
N02 .02104
WTA PROFILE
AXIAL GRADIENT
2.34
2.32
2.30
2.28
2.26
2.24
2.22
2.20
INDEX
0
.3
.6
.9
1.2
1.5
1.8
Z

MATERIAL DEVELOPMENT

0 STEP-INDEX GROWTH ($\Delta n = .014$)

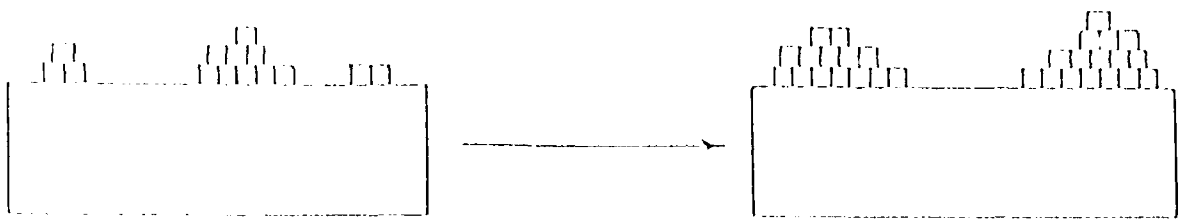
0 MICROPROCESSOR BASED PROCESS CONTROL

0 CONTINUOUS INDEX CHANGE ($\Delta n = 1 \times 10^{-4}$)

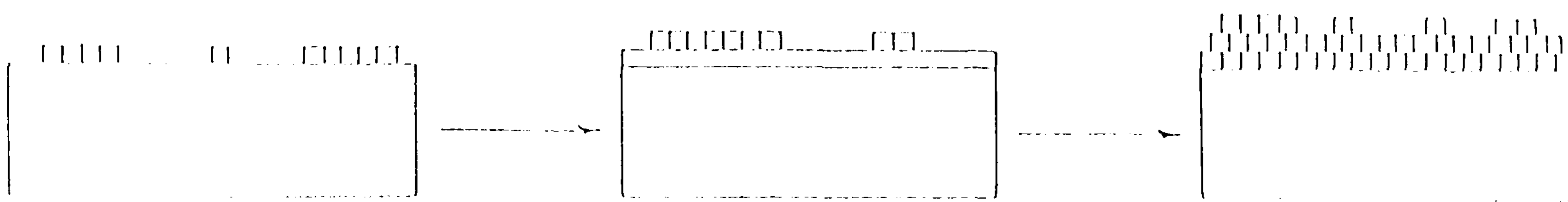
0 ELIMINATION OF NODULES

BASIC MODES OF THIN FILM GROWTH

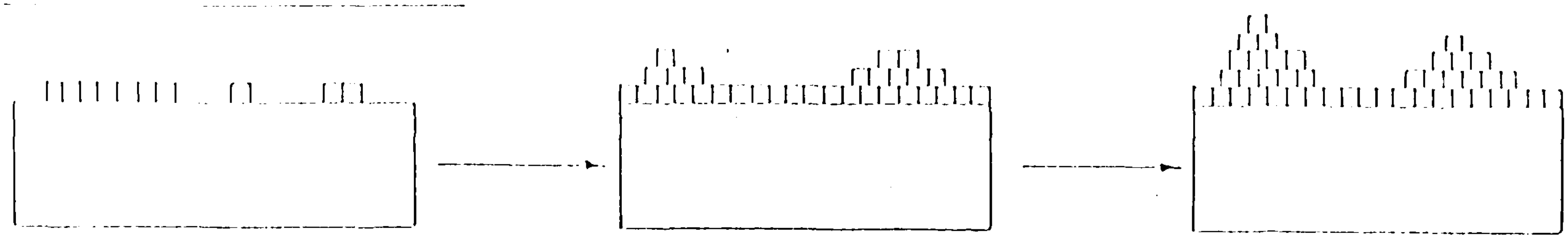
a. ISLAND



b. LAYER



c. STRANSKI — KRASTANOV



MATERIAL DEVELOPMENT

0 PULSED H_2s AND H_2Se FLOWS

(50 SEC. - ON; 10 SEC. OFF)

0 RANDOMIZING OF GROWTH DIRECTIONS

CONCLUSIONS

- O AGRIN DESIGN COMPLETE
  - O COMPRABLE TO PRESENT LENS DESIGNS
  - O ALL SPHERICAL SURFACES
- O RGRIN DESIGN
  - O SUPERIOR TO AGRIN
  - O ALL SPHERICAL SURFACES
- O MATERIAL DEVELOPMENT
  - O DEMONSTRATION OF CVD PROCESS TO PRODUCE AGRIN LENSES
  - O PRODUCTION OF LENS BLANKS (6/88)
- O PROGRAM ON SCHEDULE
- O WILL ACHIEVE ALL OBJECTIVES

GRADIENT LENS CORPORATION

INFRARED GRADIENT OBJECTIVE DESIGNS

Gradient Lens Corporation
207 TREMONT STREET ROCHESTER, NEW YORK 14608 PHONE: (716) 235-2620 FAX: (716) 235-5645

Infrared Gradient Objective Designs

Subcontract No. CVD SC-9091-1

Presented By:

Leland G. Atkinson, III
J. Robert Zinter

May 25, 1988

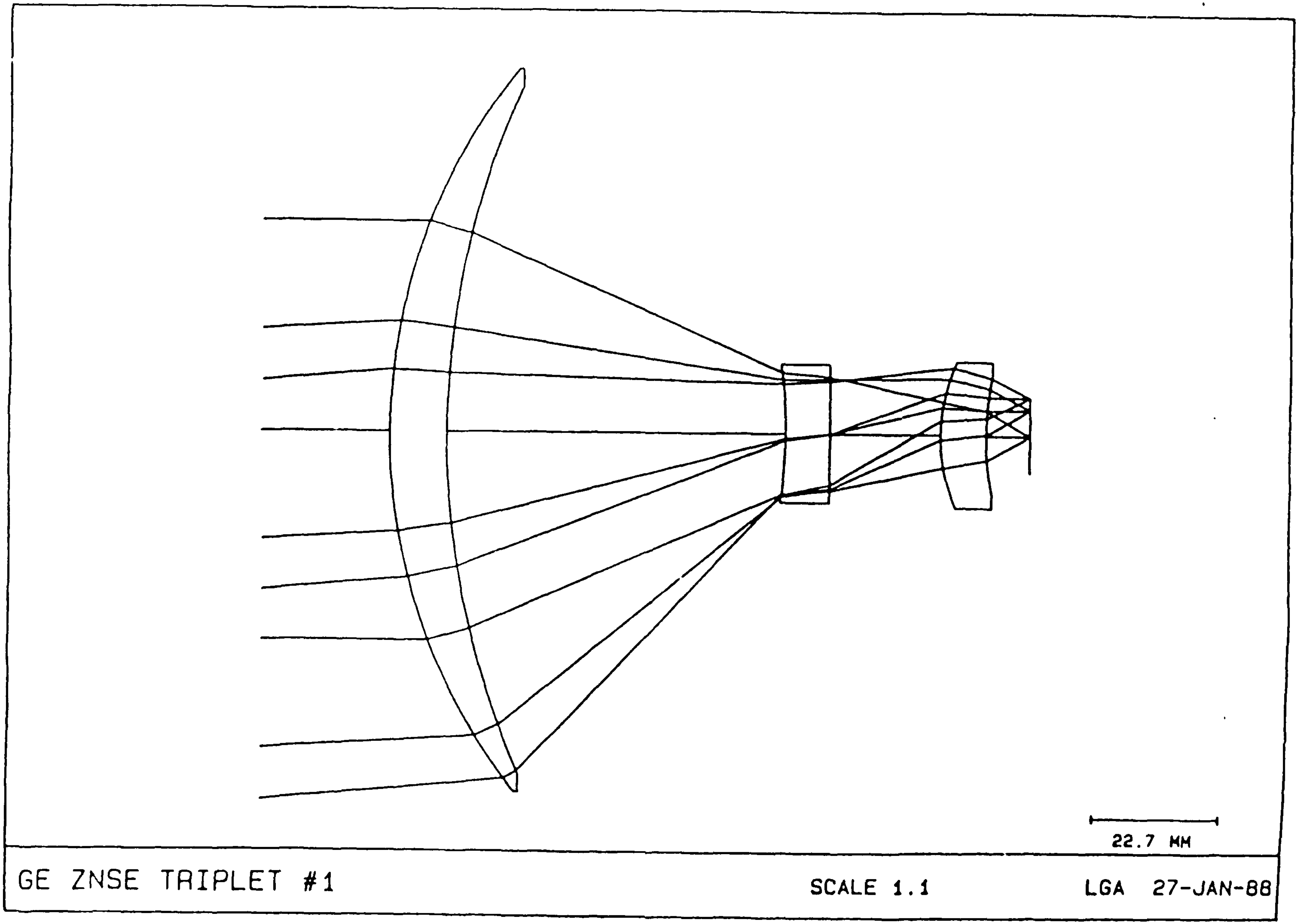
GRADIENT INDEX DESIGN OVERVIEW

I) Homogeneous Triplet

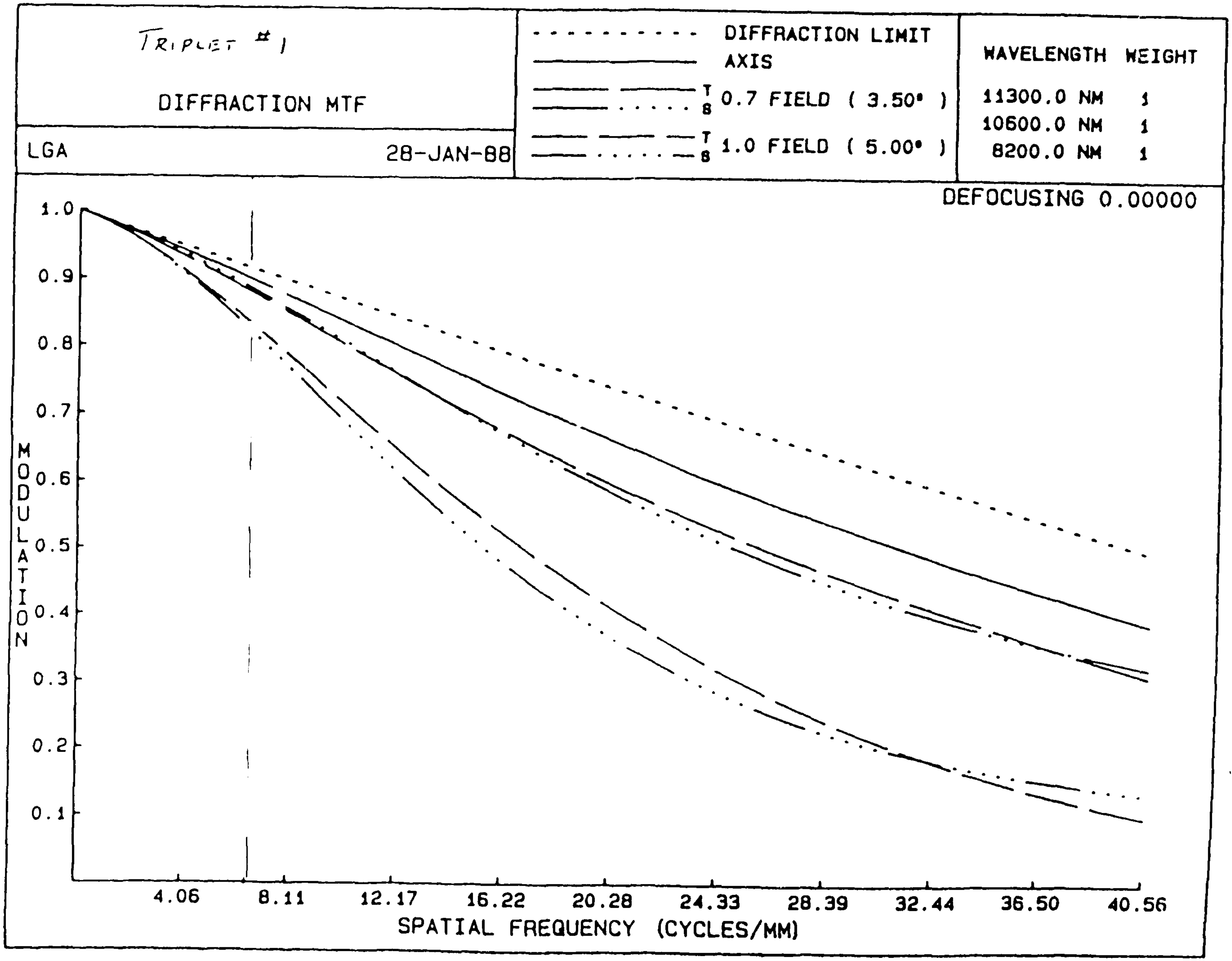
II) Development of Axial Gradient (AGRIN)
- Possible Combinations
- AGRIN Design
- AGRIN Tolerancing

III) Developmet of Radial Gradient (RGRIN)
- Singlet Design
- Two Element Design

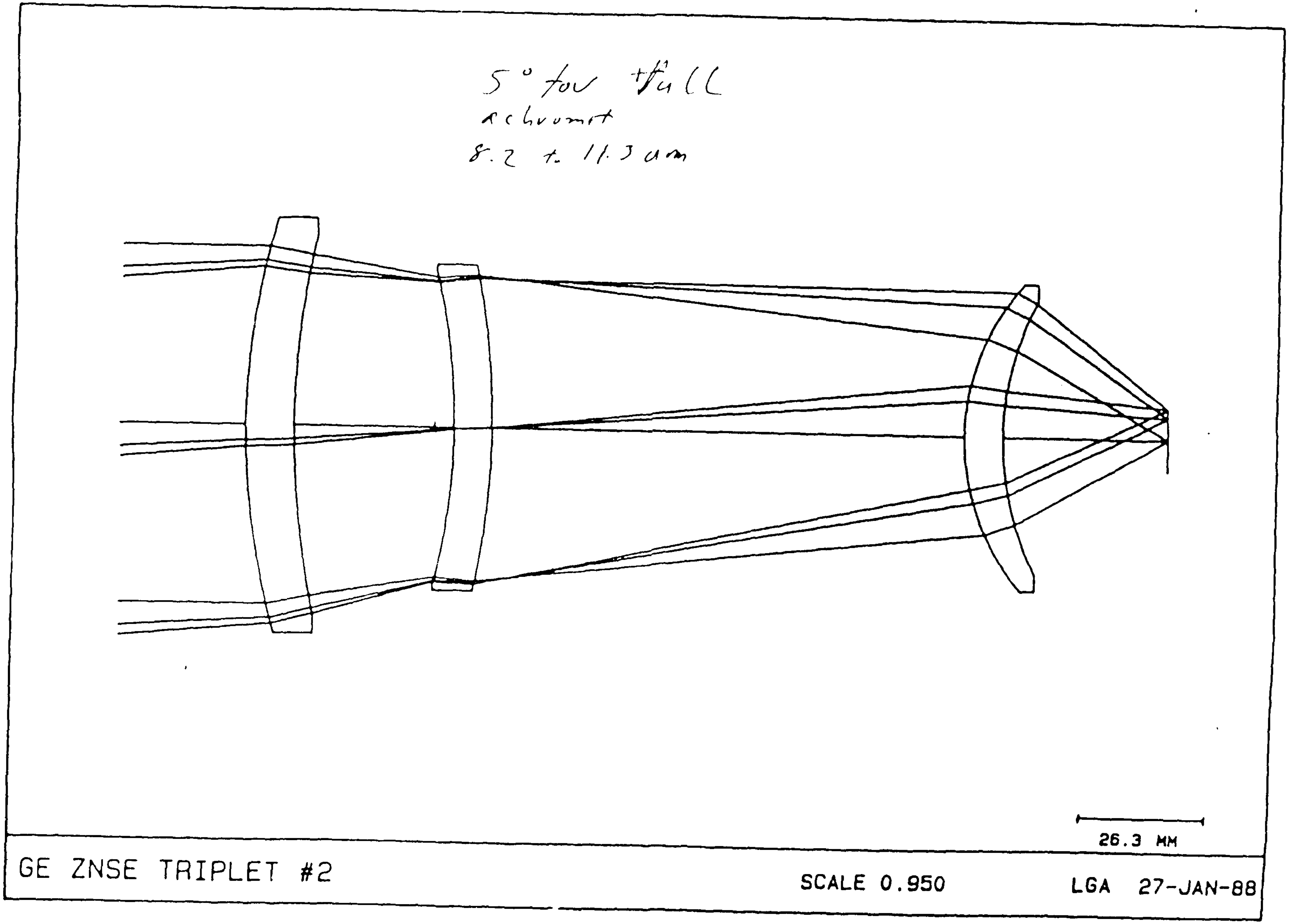
IV) Conclusions and Future Work

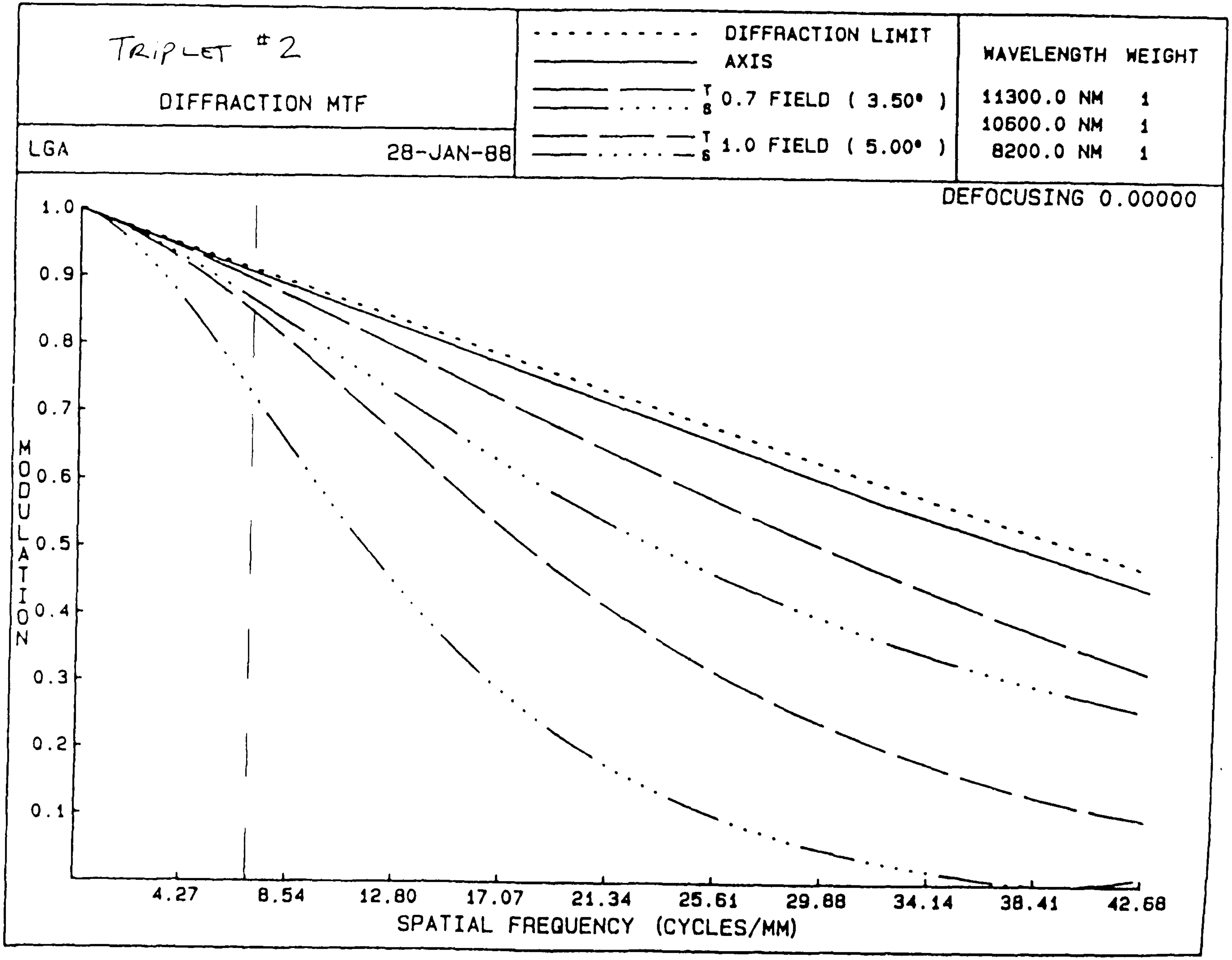


22.7 MM
GE ZNSE TRIPLET #1
SCALE 1.1
LGA 27-JAN-88



Triplet #1
DIFFRACTION MTF
LGA
28-JAN-88
DIFFRACTION LIMIT
AXIS
T S 0.7 FIELD (3.50°)
T S 1.0 FIELD (5.00°)
WAVELENGTH WEIGHT
11300.0 NM 1
10600.0 NM 1
8200.0 NM 1
DEFOCUSING 0.00000
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
MODULATION
4.06
8.11
12.17
16.22
20.28
24.33
28.39
32.44
36.50
40.56
SPATIAL FREQUENCY (CYCLES/MM)


achromat
8.2 to 11.3 um
26.3 MM
GE ZNSE TRIPLET #2
SCALE 0.950
LGA 27-JAN-88


TRIPLET #2
DIFFRACTION MTF
LGA
28-JAN-88
DIFFRACTION LIMIT
AXIS
T S 0.7 FIELD (3.50°)
T S 1.0 FIELD (5.00°)
WAVELENGTH WEIGHT
11300.0 NM 1
10600.0 NM 1
8200.0 NM 1
DEFOCUSING 0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
4.27
8.54
12.80
17.07
21.34
25.61
29.88
34.14
38.41
42.68
SPATIAL FREQUENCY (CYCLES/MM)

Design Guidelines

An axial Gradient-index Doublet (delta N < 0.2)

E.P.D = 75 mm
F# = 1.0

Half Field of View 0°- 5°

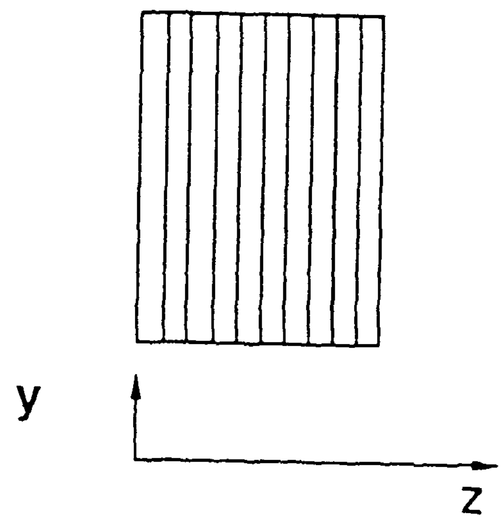
Wavelengths
11.3, 10.6, 8.2 microns

Color corrected

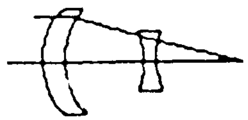
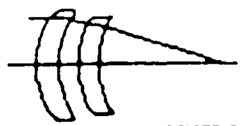
Axial Gradients

A material whose index of refraction varies as a function of z only, a series of planar surfaces each with a specific index given by the polynomial . . .

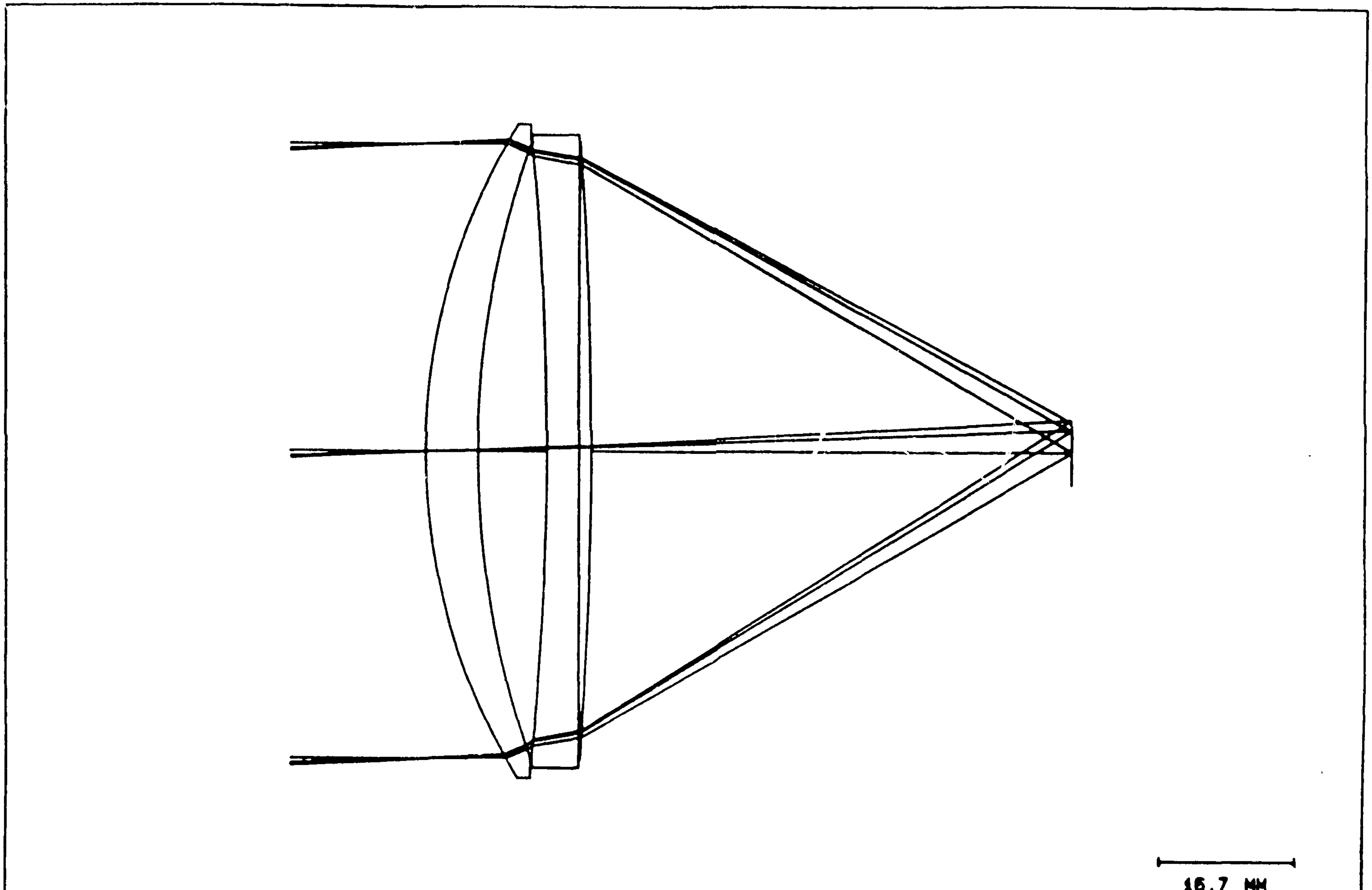
$$N(z) = N_{OO} + N_{01}Z + N_{02}Z^2 + N_{03}Z^3 + \dots$$



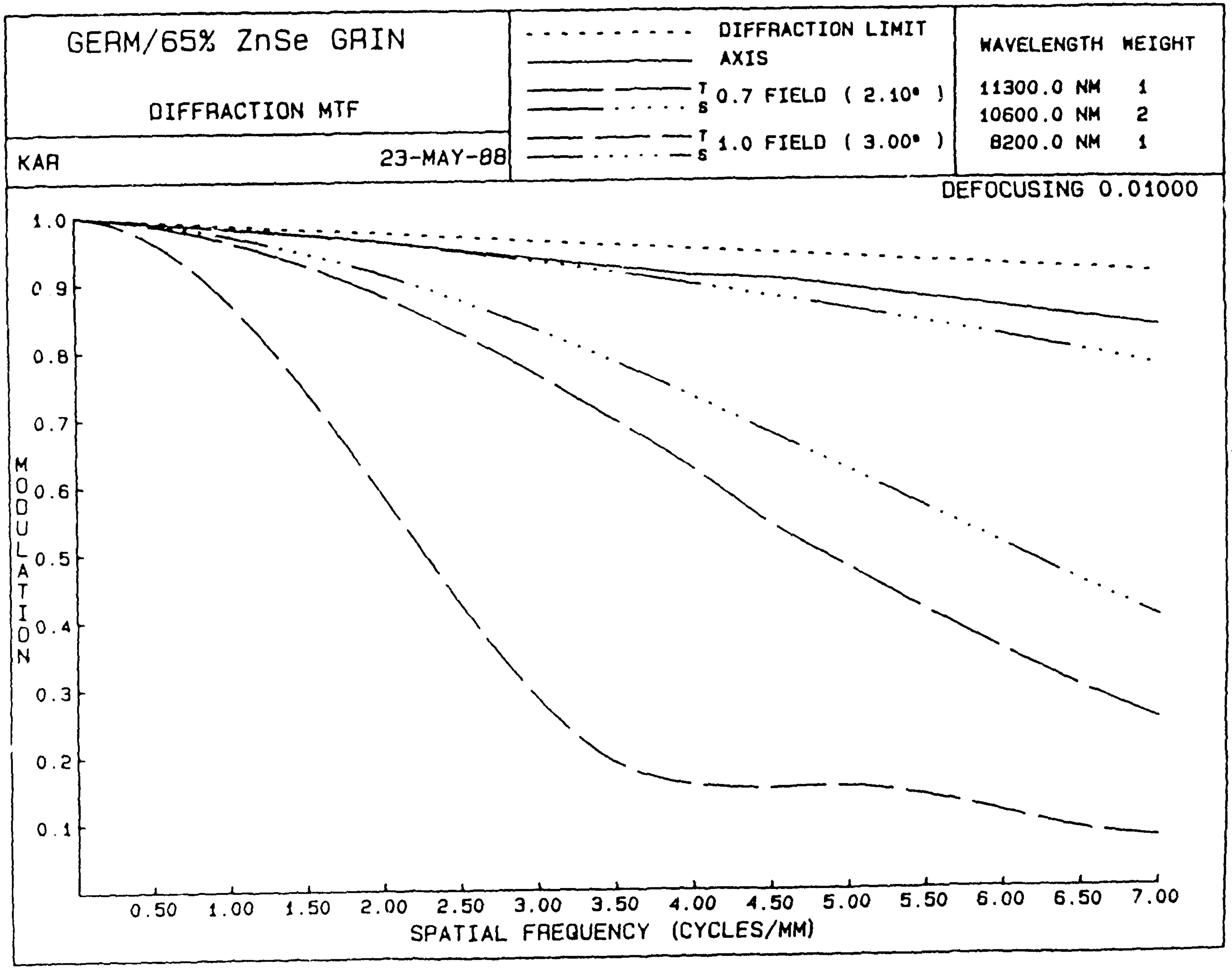
Third Order Starting Designs

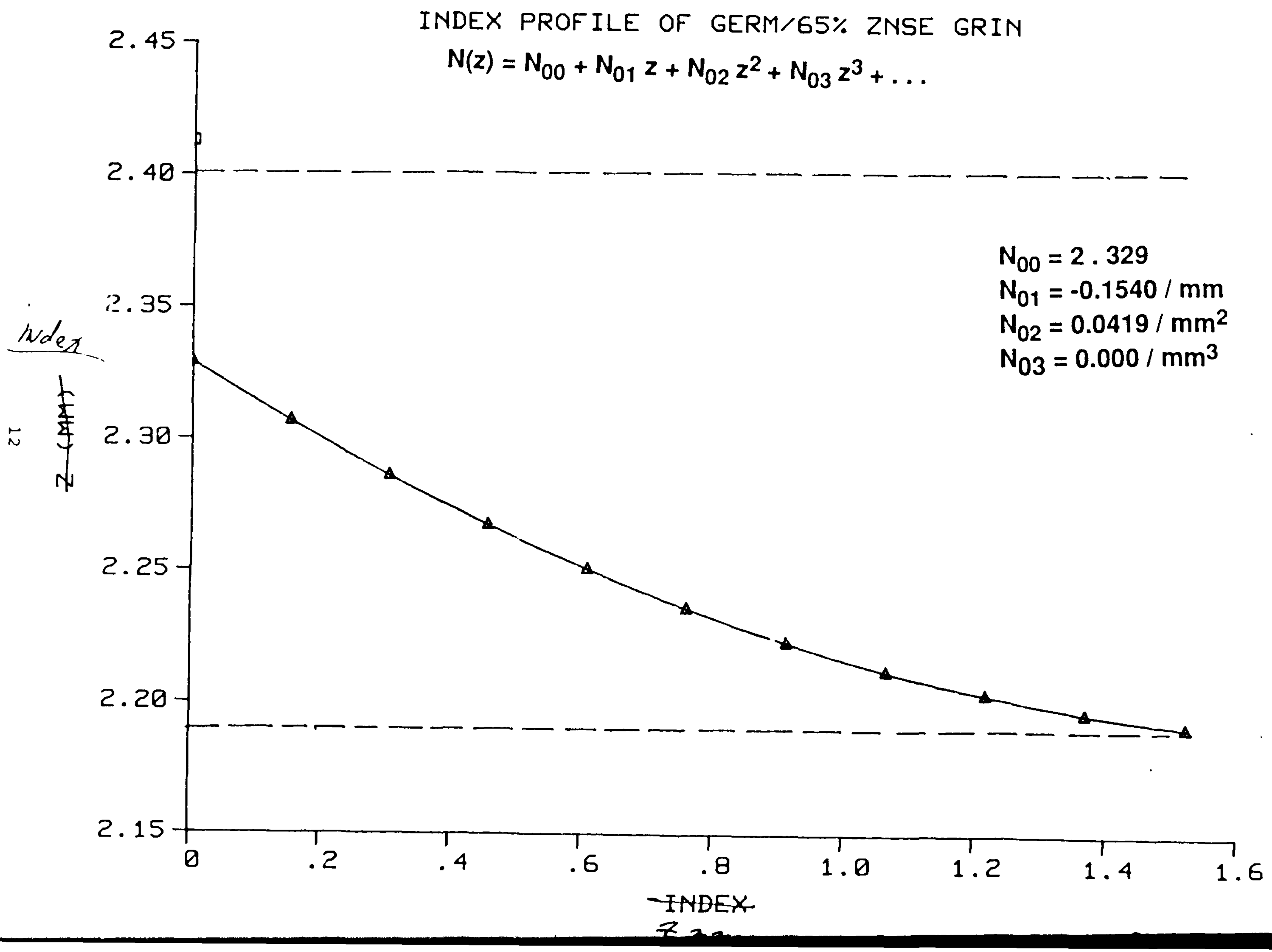
	V Ratio	Power 1	Power 2	Separation	Sigma 1	Sigma 2	Sigma 3	Sigma 4	PAC
Ge/ZnS 	35.27	65.79	-120.48	50.86	-0.72	0	0	0	0
Ge/ZnSe 	13.91	59.52	-99.01	38.9	0	0	-0.15	0	0
GaAs/ZnS 	4.53	46.08	-68.97	19.68	0	0	-0.2	-0.012	0

Material	Abbe #	n (8.2μm)	n (10.6μm)	n (11.3μm)	v/n (10.6)
ZnS	30.41	2.221	2.192	2.182	13.87
ZnSe	77.08	2.416	2.403	2.398	32.08
Ge	1072.43	4.005	4.003	4.002	267.92
GaAs	137.64	3.283	3.271	3.267	42.08



GERM/65% ZnSe GRIN SCALE 1.5 KAR 23-MAY-88


GERM/65% ZnSe GRIN
DIFFRACTION MTF
KAR
23-MAY-88
DIFFRACTION LIMIT
AXIS
T S 0.7 FIELD (2.10°)
T S 1.0 FIELD (3.00°)
WAVELENGTH WEIGHT
11300.0 NM 1
10600.0 NM 2
8200.0 NM 1
DEFOCUSING 0.01000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50 6.00 6.50 7.00
SPATIAL FREQUENCY (CYCLES/MM)



INDEX PROFILE OF GERM/65% ZNSE GRIN
$N(z) = N_{00} + N_{01} z + N_{02} z^2 + N_{03} z^3 + \ldots$
$N_{00} = 2.329$
$N_{01} = -0.1540$ / mm
$N_{02} = 0.0419$ / mm^2
$N_{03} = 0.000$ / mm^3
2.45
2.40
2.35
2.30
2.25
2.20
2.15
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
INDEX
Z (MM)

Axial Gradient Preliminary Tolerances :

Tolerances:	Germanium	70% ZnSe
Front Radius (mm)	77.251(8/2)	-384.474(10/2)
Back Radius	113.735(8/2)	-520.154(12/3)
*Thickness (mm)	6.500 +/- 0.04	5.522+/- 0.04
N_{00} (@ 10.6 um)	4.003 +/- 0.002	2.329+/- 0.002
TIR (mm)	0.008	0.006
Tilt (mrad)	0.3	1.5
Decenter (mm)	0.100	0.100

*Stop Distance (mm) - - > 0.000 +/- 0.04
*Separation (mm) - -> 8.618 +/- 0.025

Compensators:

Focal Plane Shift (mm) +/- 0.146

* Most sensitive tolerances

MTF Effects from tolerances and compensation:

Probable change in MTF at 6.7lines/mm

	Cumulative Probability	Nominal MTF	Change in MTF
On Axis	97.7%	0.827	-0.153
0.7 Field	97.7%	0.271	-0.106

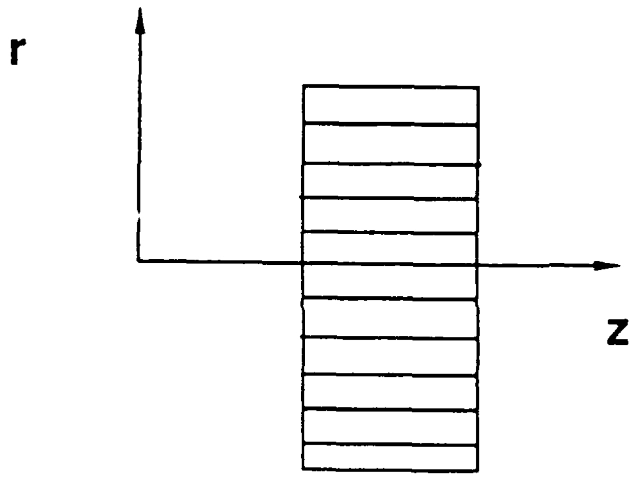
Note: Length tolerances are most sensitive, if lengths are held 0.02mm, then the tolerance and compensator effects are . . .

On Axis	97.7%	0.827	-0.084
0.7 Field	97.7%	0.271	-0.062

Radial Gradients

A material whose index of refraction varies as a function of radius, a series of concentric cylinders each with a specific index, given by the polynomial . . .

$$N(r) = N_{00} + N_{10}r^2 + N_{20}r^4 + N_{30}r^6 + \ldots$$



$$r^2 = x^2 + y^2$$

Development of RGRIN Design

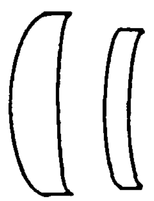
Design Step	Degrees of Freedom	Correction
First order Achromat; Stopped down	N_{10}, t, C, N_{00}	Focal length and Axial Color
Third Order	Bending (C_1), N_{20}	Spherical and Coma aberration
Fifth Order (Opened to F#/1)	N_{30}	5th order Spherical aberr.
Singlet Design	Stop shifting (Unable to correct Astig.)	Astigmatism

*** Singlet design dominated by third order astigmatism and Petaval field curvature

Design Step	Degrees of Freedom	Correction
Addition of Field Corrector	Power and bending	Petzval Field Curvature

Two Element Design --- Additional Element displaced from image plane, providing for Astigmatism, rather than Petzval Field correction

Radial GRIN Designs

Design	Field of View	ΔN	Dominant Aberration	Tangential MTF at 2 lines/mrad. On axis	Tangential MTF at 2 lines/mrad. Full Field
	4	-0.0736	Petzval Field and Astigm.	0.58	0.52
	10	-0.0549	Petzval Field	0.66	0.64
	16	-0.0556	Petzval Field	0.66	0.10

Notes:

1) Both Designs are f#/1 , E.P.D. = 1"
$N_{00} = N_{ZnSe} = 2.4028$ at 10.6 microns

2) For ZnSe/ZnS Gradients the $V\#_{gr} = -10.09$,
Consequence: f.l. hmg (+) and f.l. gr (+) for an Achromat, ie. $1/f.l._a V_a = -1/f.l._b V_b$

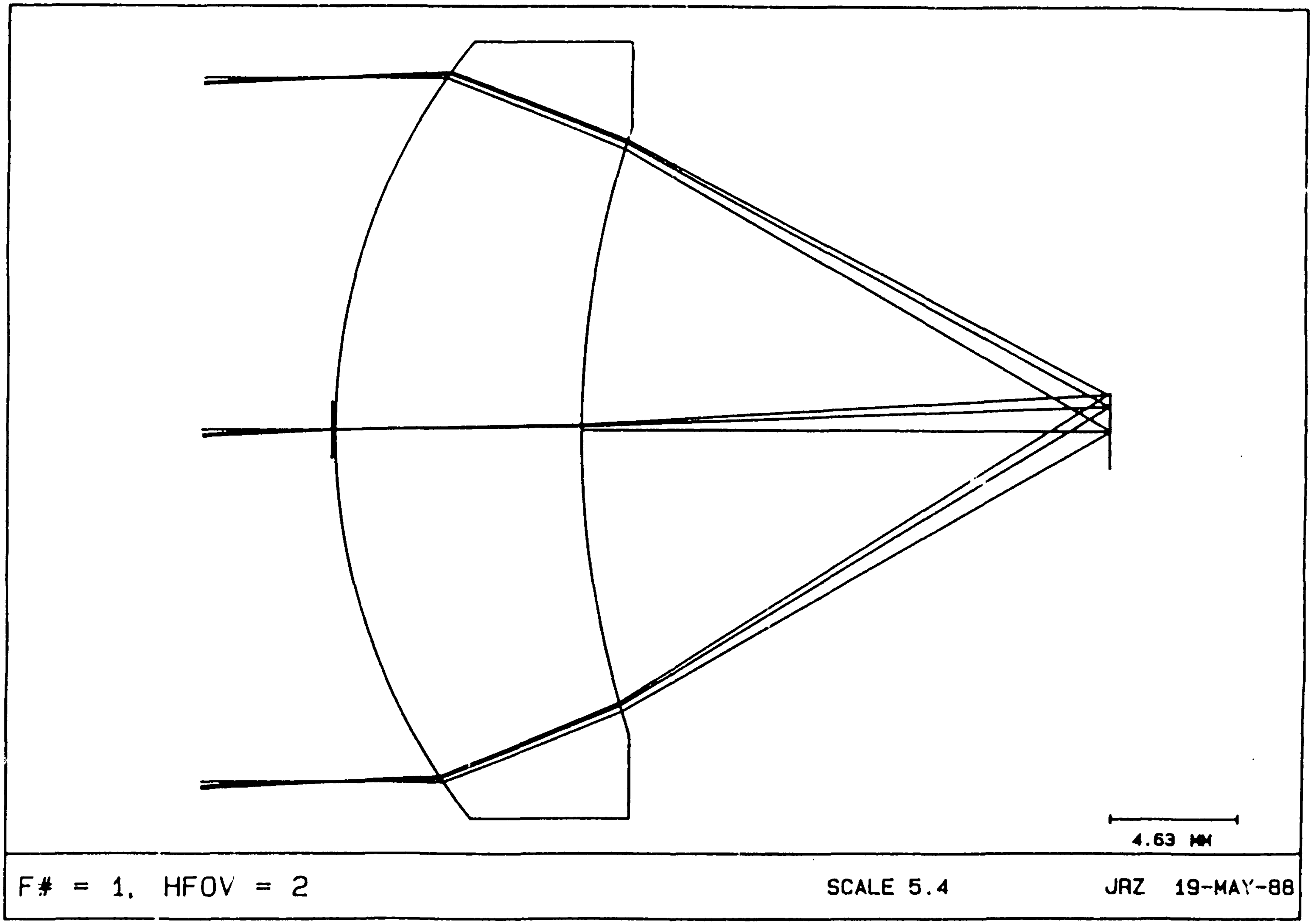
3) For Petzval Field correction . . .

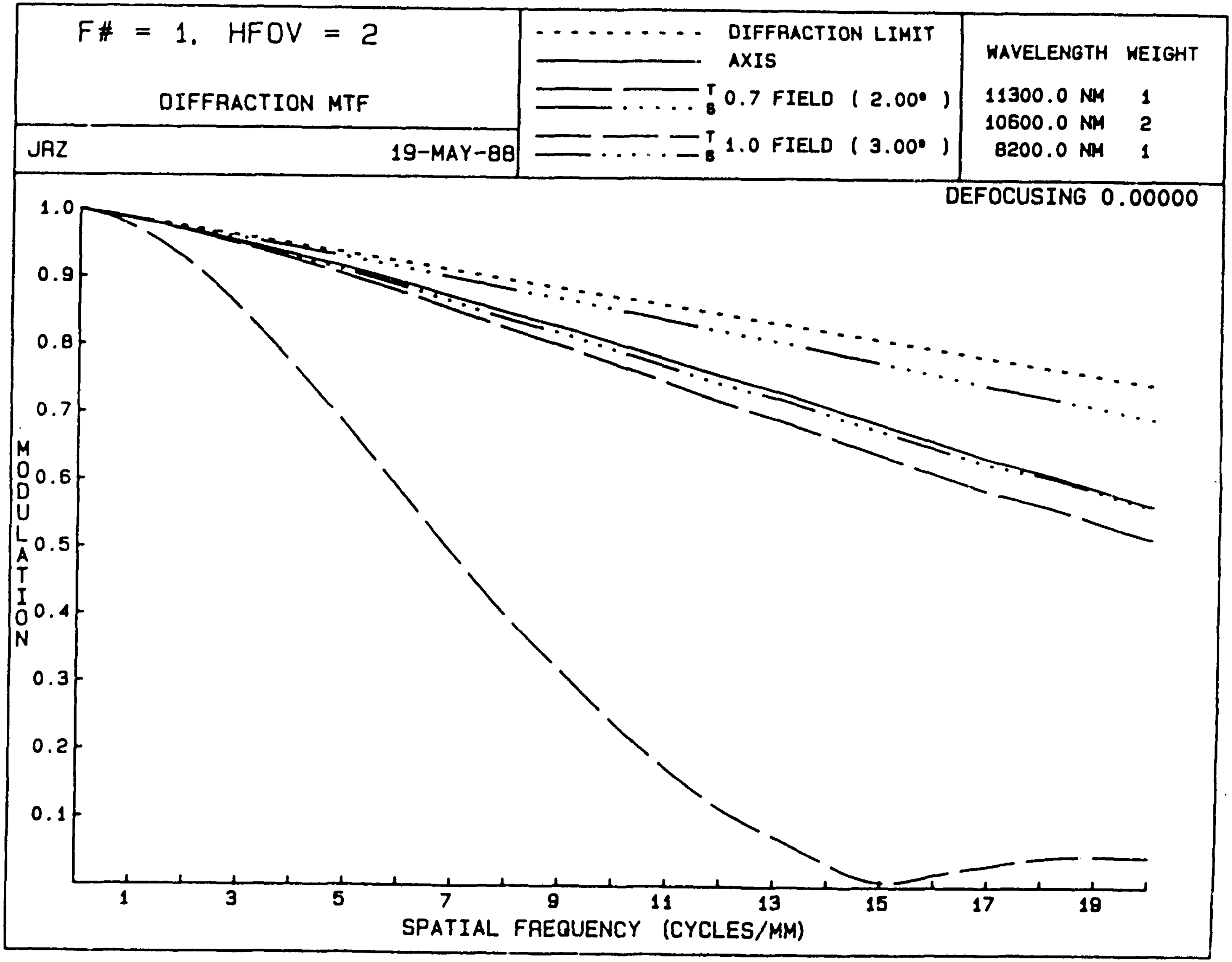
Ptz α $1/f.l.N_{00}$ hmg

Ptz α $1/f.l.N_{00}^2$ GRIN

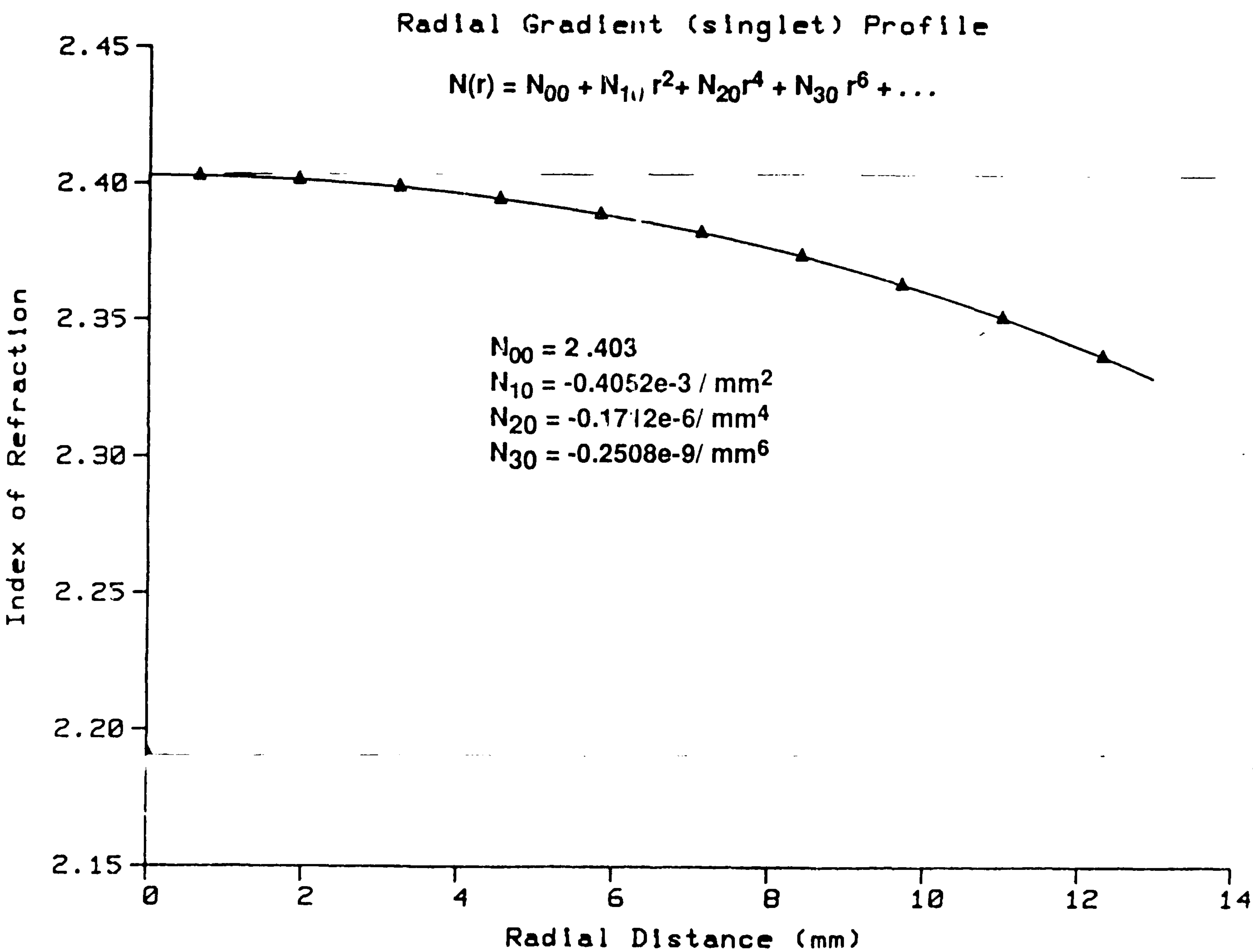
Consequence : Petzval and Axial Color cannot be simultaneously corrected for this type of singlet

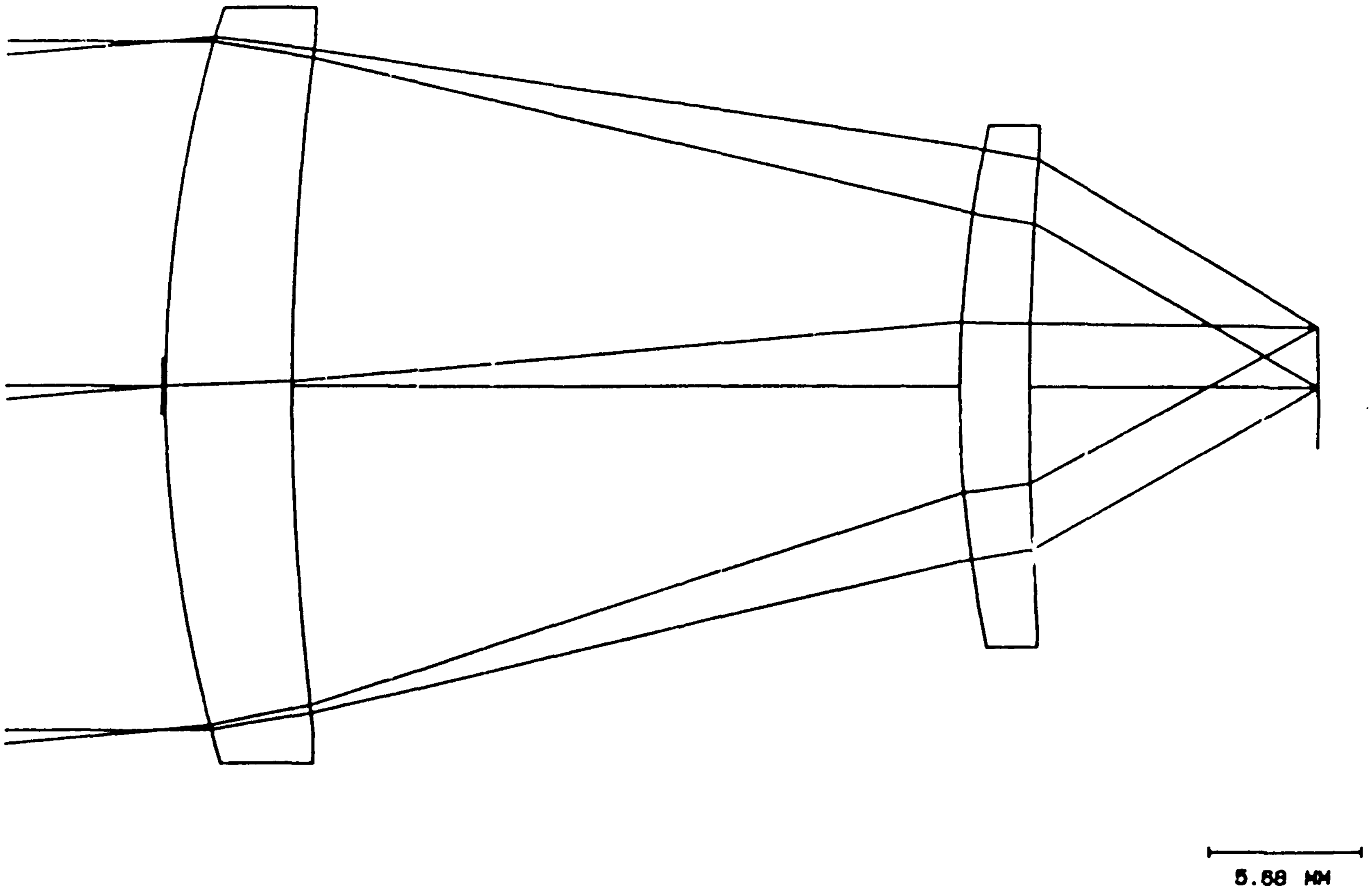
4) Addition of second element aids in greater field of view.


4.63 MM
F# = 1. HFOV = 2
SCALE 5.4
JRZ 19-MAY-88

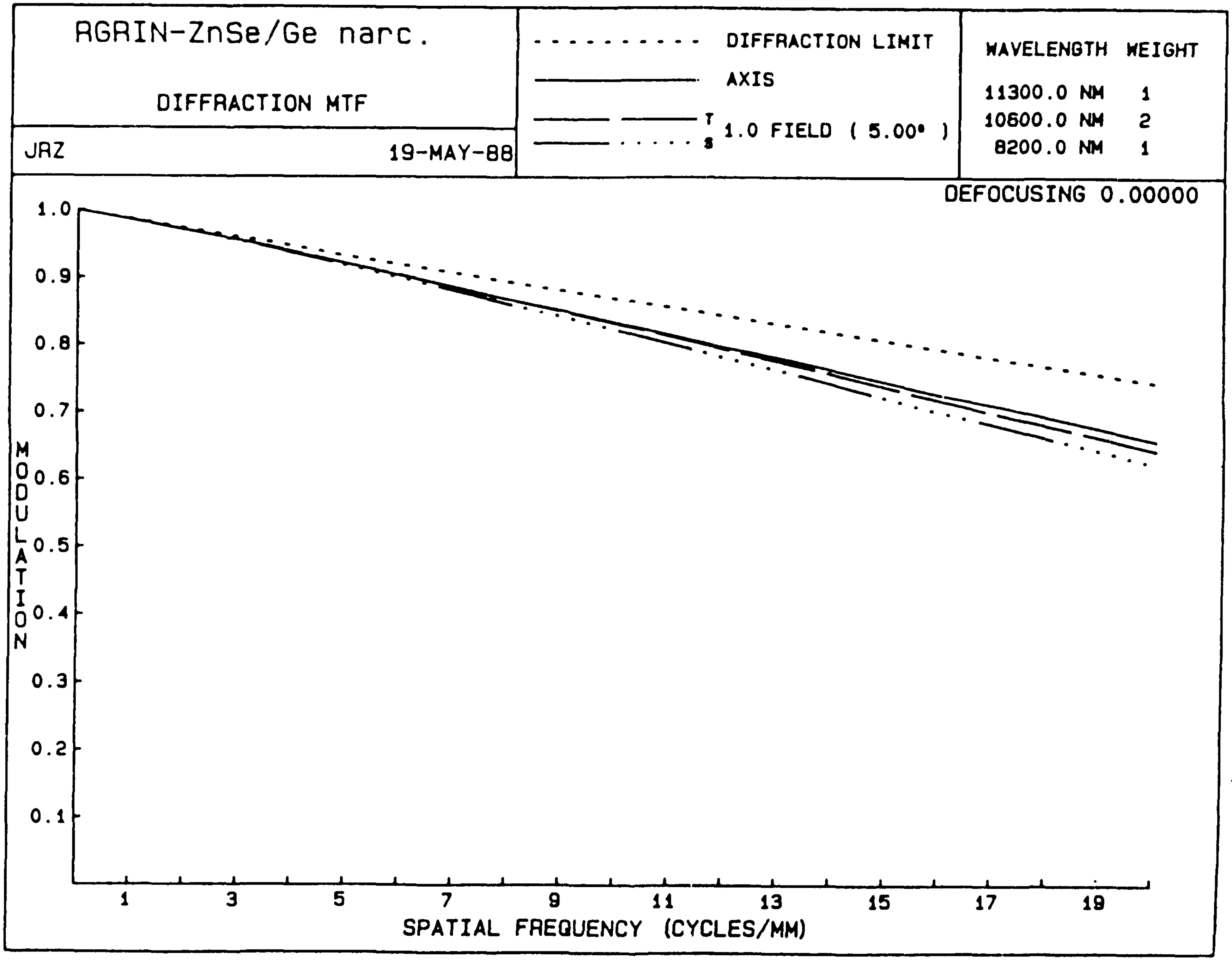


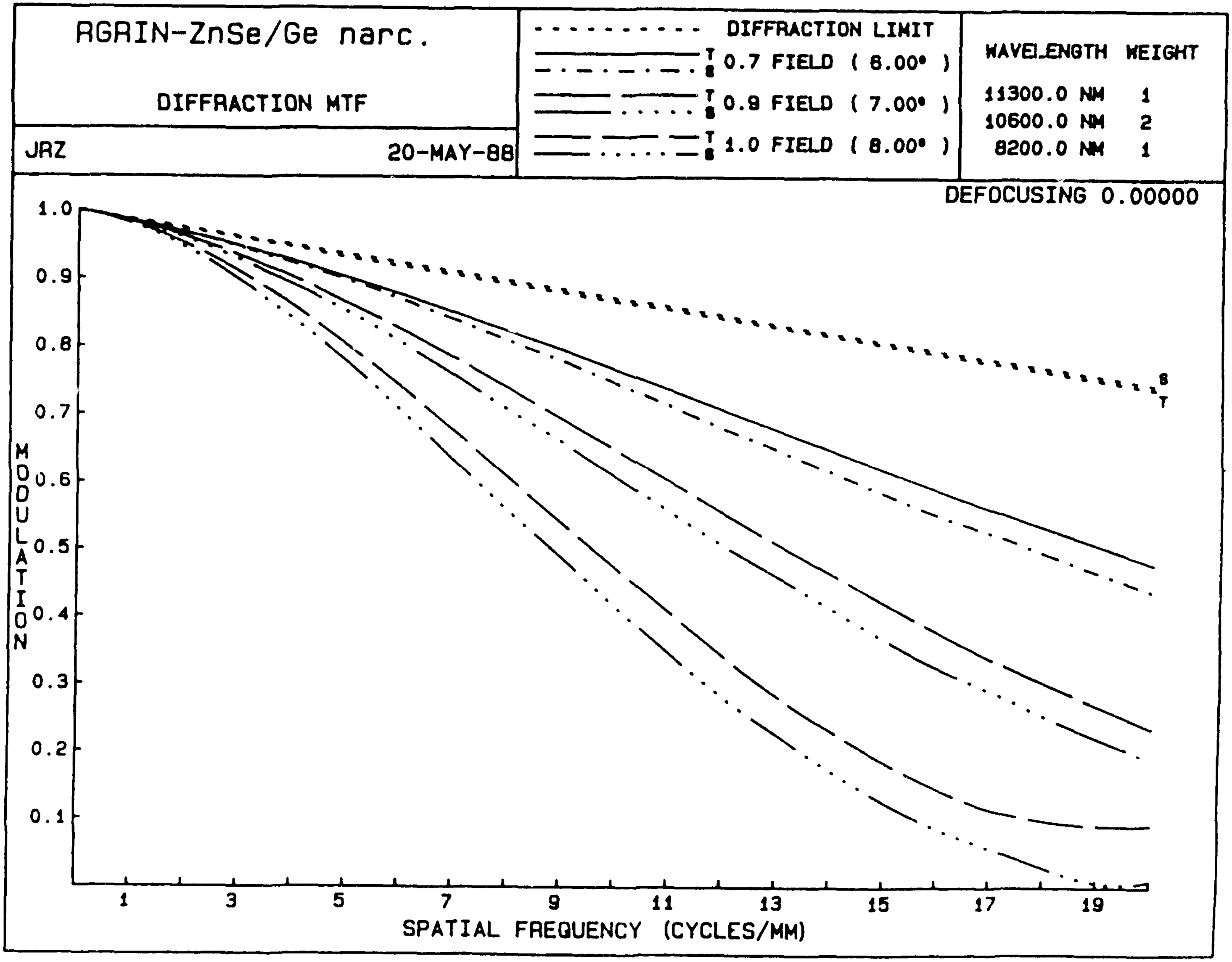
F# = 1. HFOV = 2
DIFFRACTION MTF
JRZ
19-MAY-88
DIFFRACTION LIMIT
AXIS
T
S
0.7 FIELD (2.00°)
T
S
1.0 FIELD (3.00°)
WAVELENGTH WEIGHT
11300.0 NM 1
10600.0 NM 2
8200.0 NM 1
DEFOCUSING 0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
3
5
7
9
11
13
15
17
19
SPATIAL FREQUENCY (CYCLES/MM)


Radial Gradient (singlet) Profile
$N(r) = N_{00} + N_{10} r^2 + N_{20} r^4 + N_{30} r^6 + \ldots$
$N_{00} = 2.403$
$N_{10} = -0.4052e-3 / mm^2$
$N_{20} = -0.1712e-6 / mm^4$
$N_{30} = -0.2508e-9 / mm^6$
Index of Refraction
2.45
2.40
2.35
2.30
2.25
2.20
2.15
Radial Distance (mm)
0
2
4
6
8
10
12
14

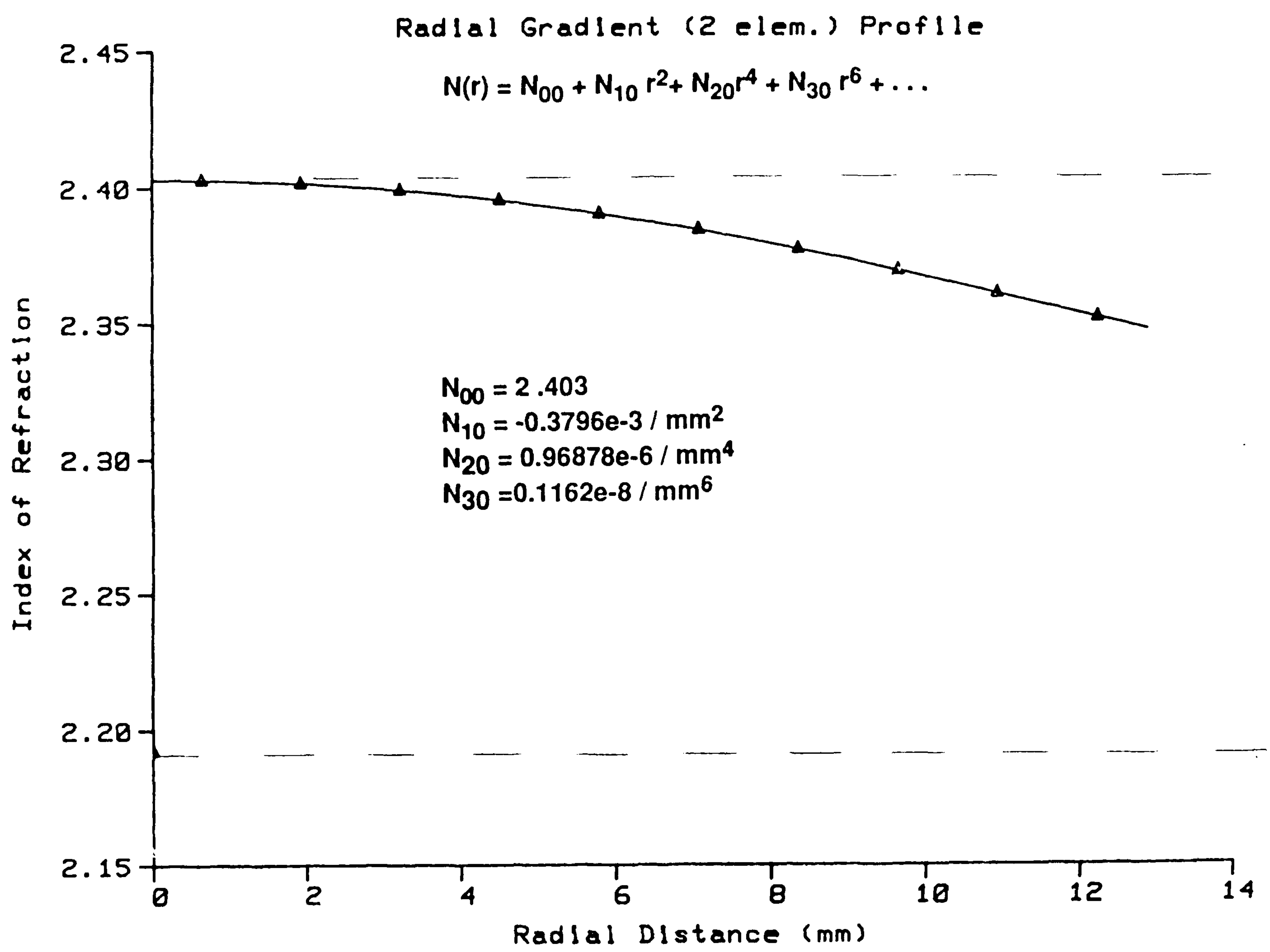


RGRIN-ZnSe/Ge narc. SCALE 4.4 JRZ 19-MAY-88


RGRIN-ZnSe/Ge narc.
DIFFRACTION MTF
JRZ
19-MAY-88
DIFFRACTION LIMIT
AXIS
T
S
1.0 FIELD (5.00°)
WAVELENGTH WEIGHT
11300.0 NM 1
10600.0 NM 2
8200.0 NM 1
DEFOCUSING 0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
3
5
7
9
11
13
15
17
19
SPATIAL FREQUENCY (CYCLES/MM)



RGRIN-ZnSe/Ge narc.
DIFFRACTION MTF
JRZ
20-MAY-88
DIFFRACTION LIMIT
T S 0.7 FIELD (6.00°)
T S 0.9 FIELD (7.00°)
T S 1.0 FIELD (8.00°)
WAVELENGTH WEIGHT
11300.0 NM 1
10600.0 NM 2
8200.0 NM 1
DEFOCUSING 0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
3
5
7
9
11
13
15
17
19
SPATIAL FREQUENCY (CYCLES/MM)



Radial Gradient (2 elem.) Profile
N(r) = N00 + N10 r2+ N20r4 + N30 r6 + . . .
N00 = 2 .403
N10 = -0.3796e-3 / mm2
N20 = 0.96878e-6 / mm4
N30 =0.1162e-8 / mm6
2.45
2.40
2.35
2.30
2.25
2.20
2.15
Index of Refraction
0
2
4
6
8
10
12
14
Radial Distance (mm)

Conclusions :

AGRIN - Limited by Astigmatism and Petzval field curvature
- Restrictive length tolerances due to to steep ray angles

RGRIN - Singlet limited by Astigmatism and Petzval field curvature
- Two Element limited by Petzval field curvature

Future Work :

RGRIN - Search for possible second solution to Two Element design.
- Where the second element must be negative to correct for the inward curving Petzval field.

GRADIENT LENS CORPORATION

PRECISION OPTICAL COMPUTER AIDED MANUFACTURING

Gradient Lens Corporation
207 TREMONT STREET ROCHESTER, NEW YORK 14608 PHONE: (716) 235-2620 FAX (716) 235-6645

Precision Optical Computer Aided Manufacturing (PCAM)

Leland G. Atkinson, III

This work was partially
supported by the U. S. Army
DAAK10-80-C-0268

May 24, 1988

PCAM Objectives

Automation of Optical Fabrication

Integration of Grinding, Polishing and Testing

Use Standard CNC Machinery

High Speed Fabrication

High Quality Surfaces (1 Fringe)

Close Design – Fabrication Gap

Optical Fabrication Review

Cut Blank to Rough Size

Rough Grinding (Generation)

- Full Surface Loose Abrasive Laps
- Fixed Abrasive Full Surface Laps
- Fixed Abrasive Ring Tools

Fine Grinding (Lapping)

- Full Surface Loose Abrasive Laps
- Fixed Abrasive Full Surface Laps
- Fixed Abrasive Ring Tools

Polishing

- Full Surface Loose Abrasive Polisher
  - Pitch - rosin, bees wax, asphalt compounds
  - Polyurethane
  - Felt

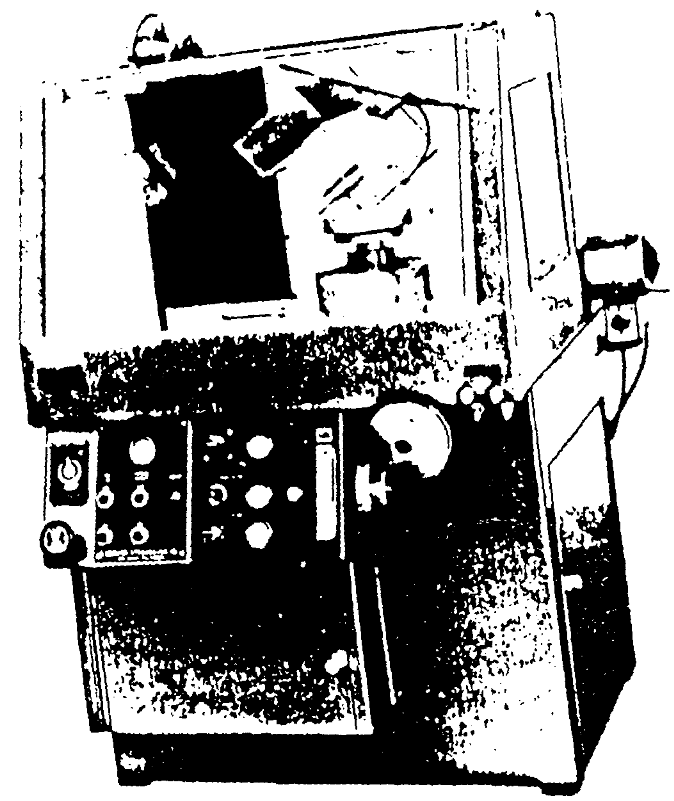


Fig. 2.8. Strabaugh Model 7-M curve generator and grinder for 24-in. (60 cm) diameter elements. Glass thicknesses of 7 in. (17.8 cm) can be handled.

Appendix 13

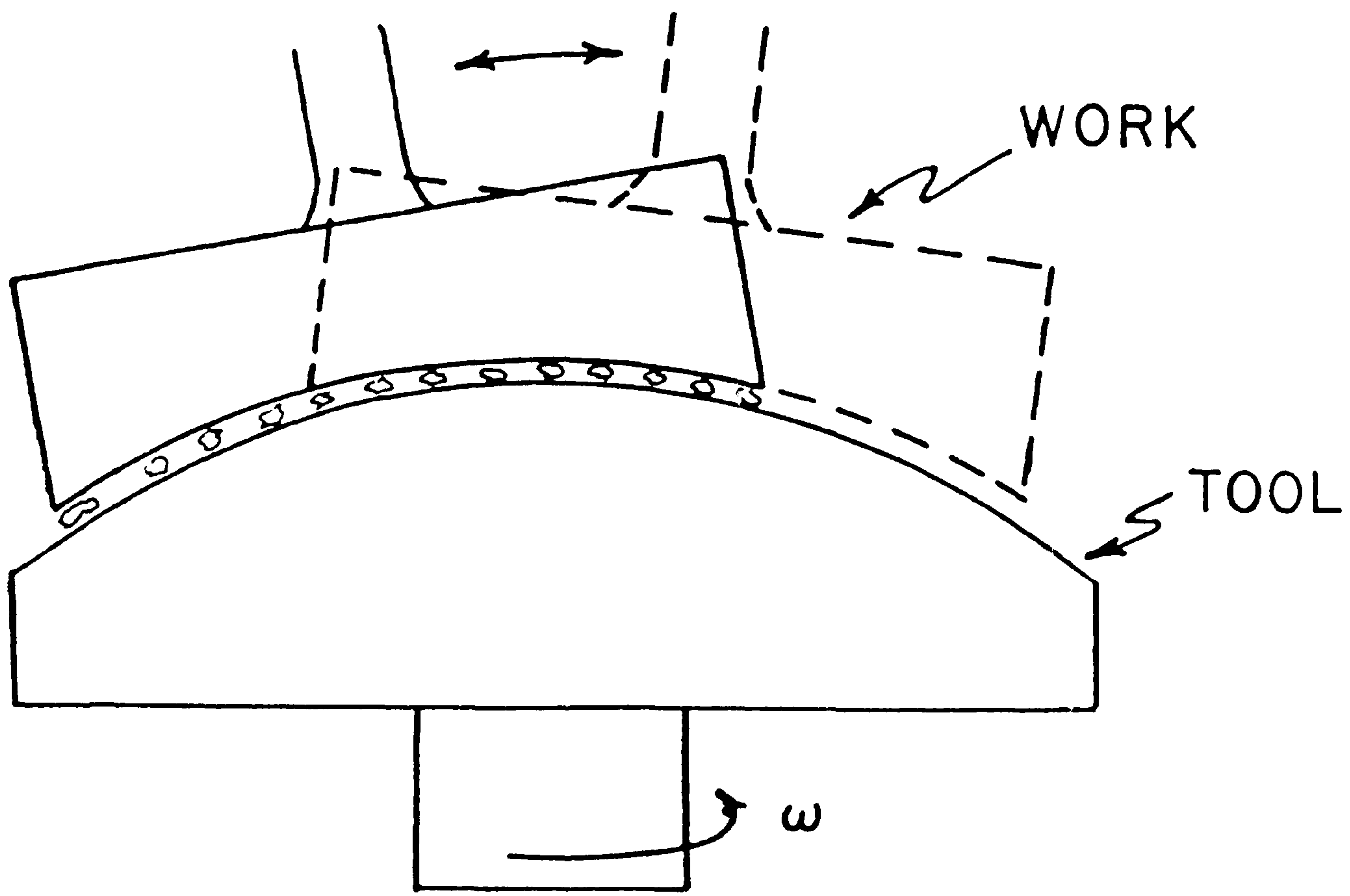
Angular Settings for Radius Generating

These tables are based on the formula $\sin t = D/2r$, where D equals the cutting edge of the cutter. For concave-surface generation the cutting edge is the peripheral edge and for convex surfaces, the inside edge; r is the required radius. Example: 53.5 in. concave radius. Diameter of cutter 4 in. $\sin t = 4/2 \times 53.5$, $\sin t = 4/107$, or $\sin t = 0.0373$. From a table of natural sine functions 0.0373 equals 2° 9′.

CIRCLE SETTINGS FOR RADIUS GENERATOR

1.0 in. OD Cutter

Concave		Convex	
D = 1.0 in.		ID = 0.750 in.	
Radius required	Circle setting	Radius required	Circle setting
2.00″	14°-29′	2.00″	10°-48′
2.25	12°-50′	2.25	9°-35′
2.50	11°-33′	2.50	8°-38′
2.75	10°-29′	2.75	7°-50′
3.00	9°-36′	3.00	7°-11′
3.25	8°-51′	3.25	6°-37′
3.50	8°-13′	3.50	6°-9′
3.75	7°-40′	3.75	5°-45′
4.00	7°-11′	4.00	5°-23′
4.25	6°-45′	4.25	5°-4′
4.50	6°-23′	4.50	4°-47′
4.75	6°-2′	4.75	4°-32′
5.00	5°-45′	5.00	4°-18′
5.25	5°-28′	5.25	4°-6′
5.50	5°-13′	5.50	3°-54′
5.75	4°-59′	5.75	3°-44′
6.00	4°-47′	6.00	3°-35′
6.25	4°-36′	6.25	3°-27′
6.50	4°-22′	6.50	3°-18′
6.75	4°-15′	6.75	3°-11′
7.00	4°-6′	7.00	3°-4′


WORK
TOOL
ω

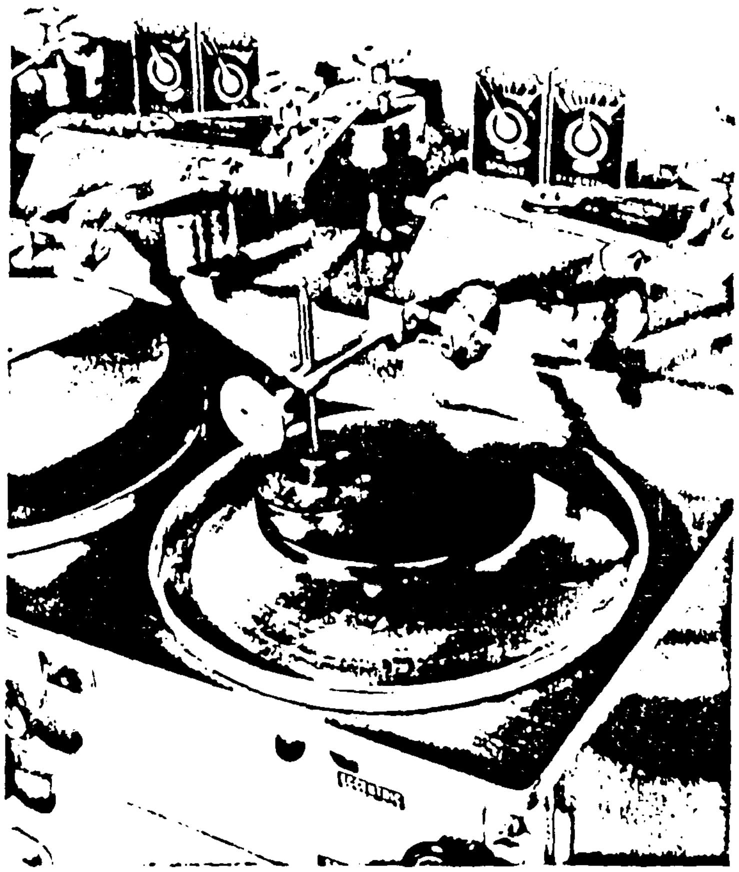


Fig. 2.26. This four-spindle Strasbaugh polisher and grinder Model P6Y shows a setup for grinding.

Optical Fabrication Methods

Transfer Techniques

- Easily Automated
- Accuracy Limited by Machine
  - Examples
    - Tracer Machines
    - Replication
    - Molding

Transformation Techniques

- Hard to Automate
- Accuracy Limited by Models
  - Examples
    - Loose Abrasive Grinding
    - Pitch Polishing

Computer Controlled Techniques

Modified Tracer

Examples

- LODTM - LLL
- PCAM Grinding - GLC

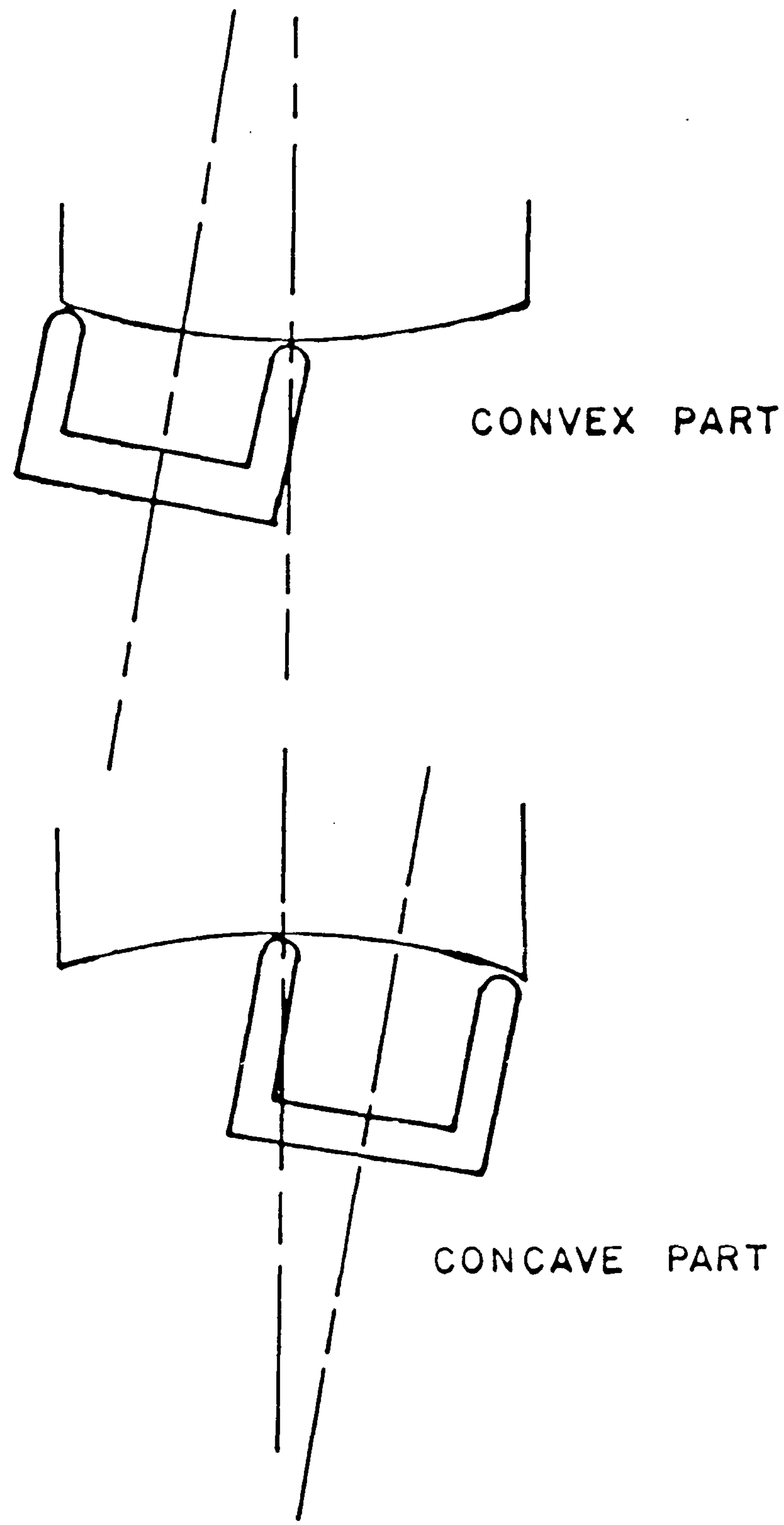
Uses a computer to control a HARD tool in a predictable path.

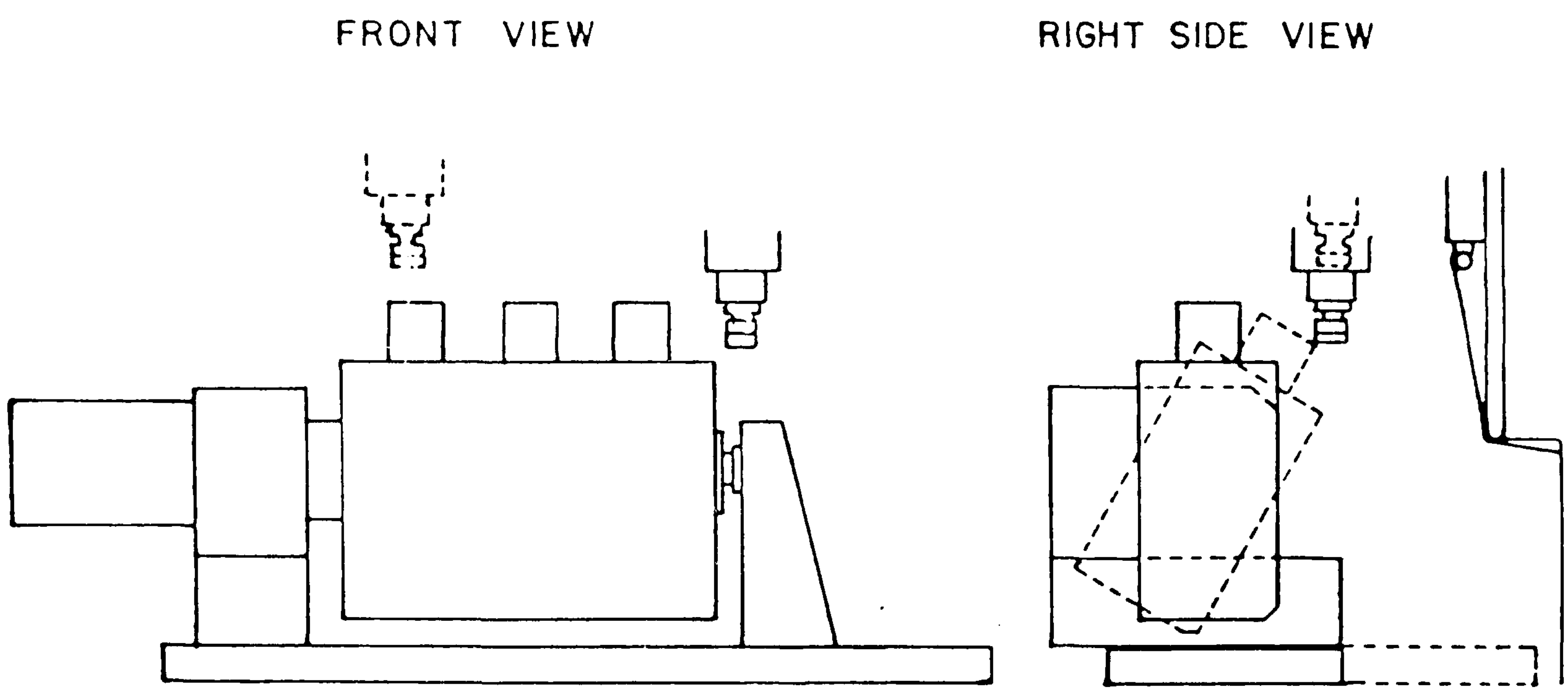
Modified Transformation

Examples

- CCP - PE
- CCOS - Itek
- PCAM Polishing - GLC

Uses a computer to control a SOFT tool motion and/or characteristics.


CONVEX PART
CONCAVE PART



OPTICAL SURFACING CENTER

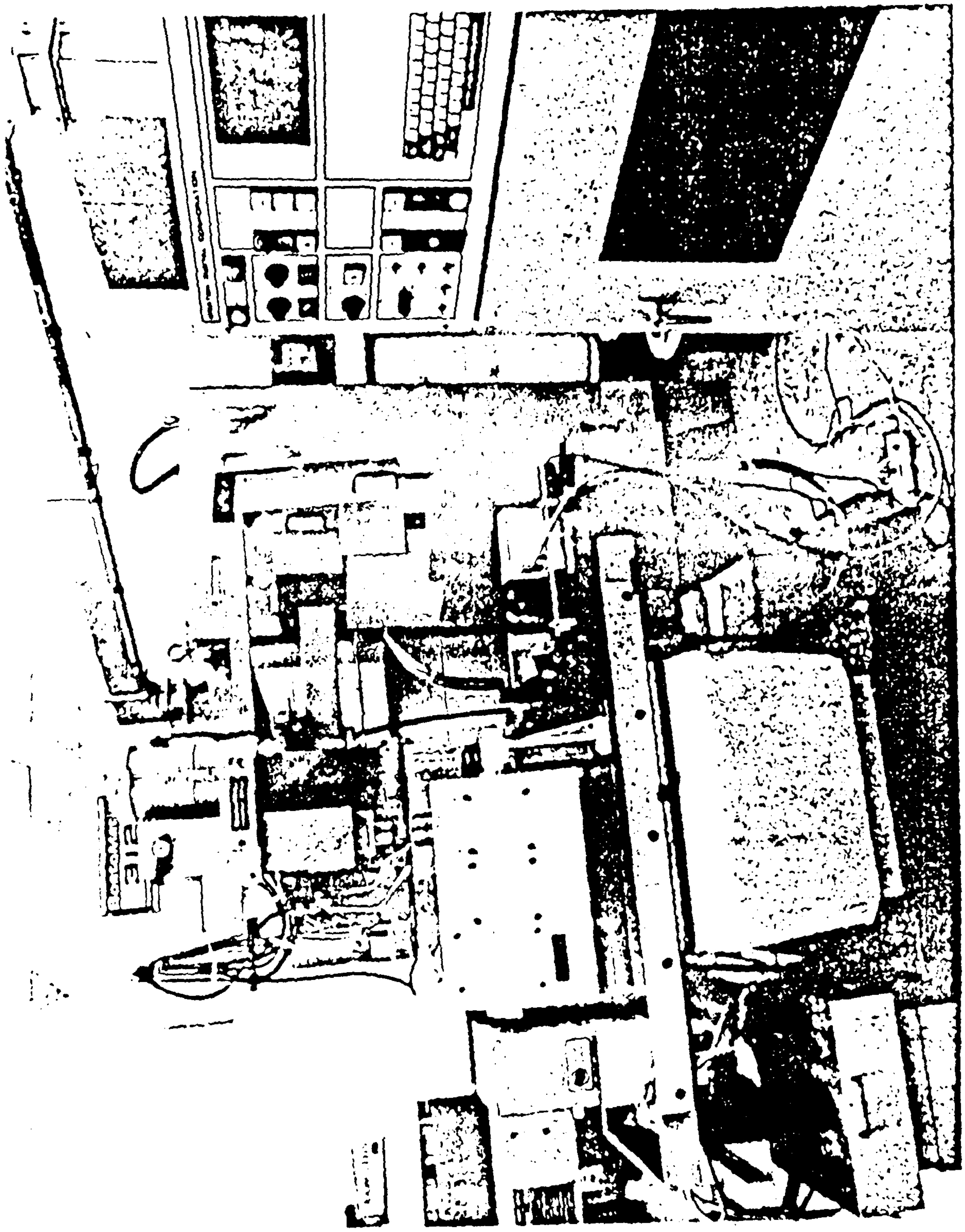
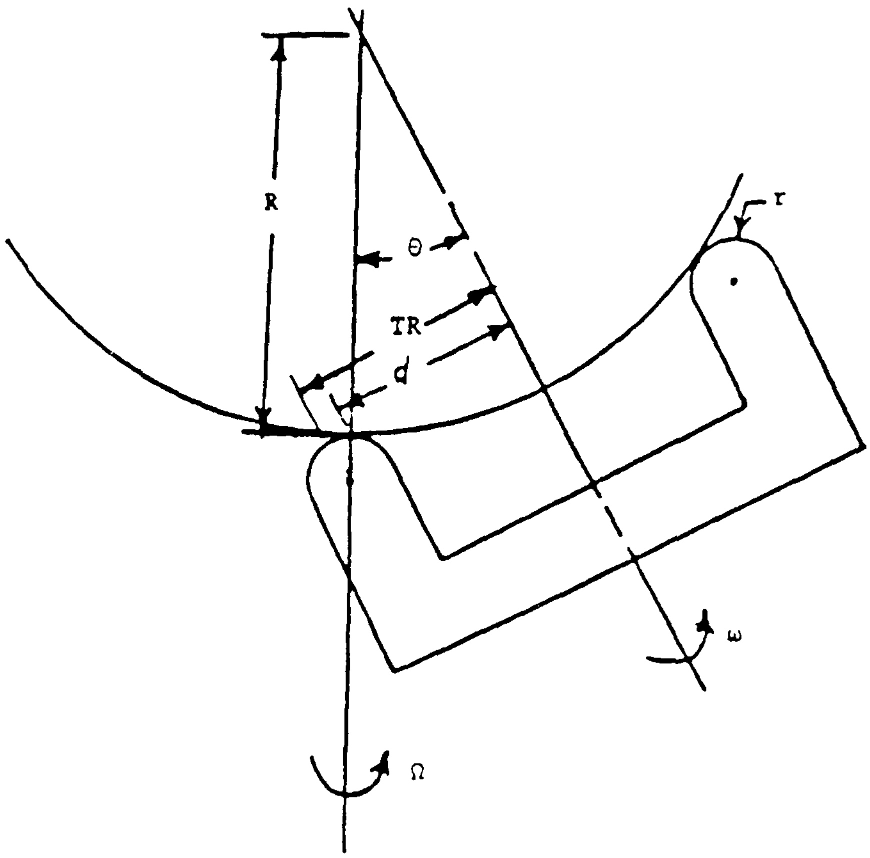


Figure 3.1a: Optical Surfacing CAM Machine



$$\sin \theta = \frac{TR}{R + r}$$

Figure 2.1: Ring Tool Generation Geometry - Sphere

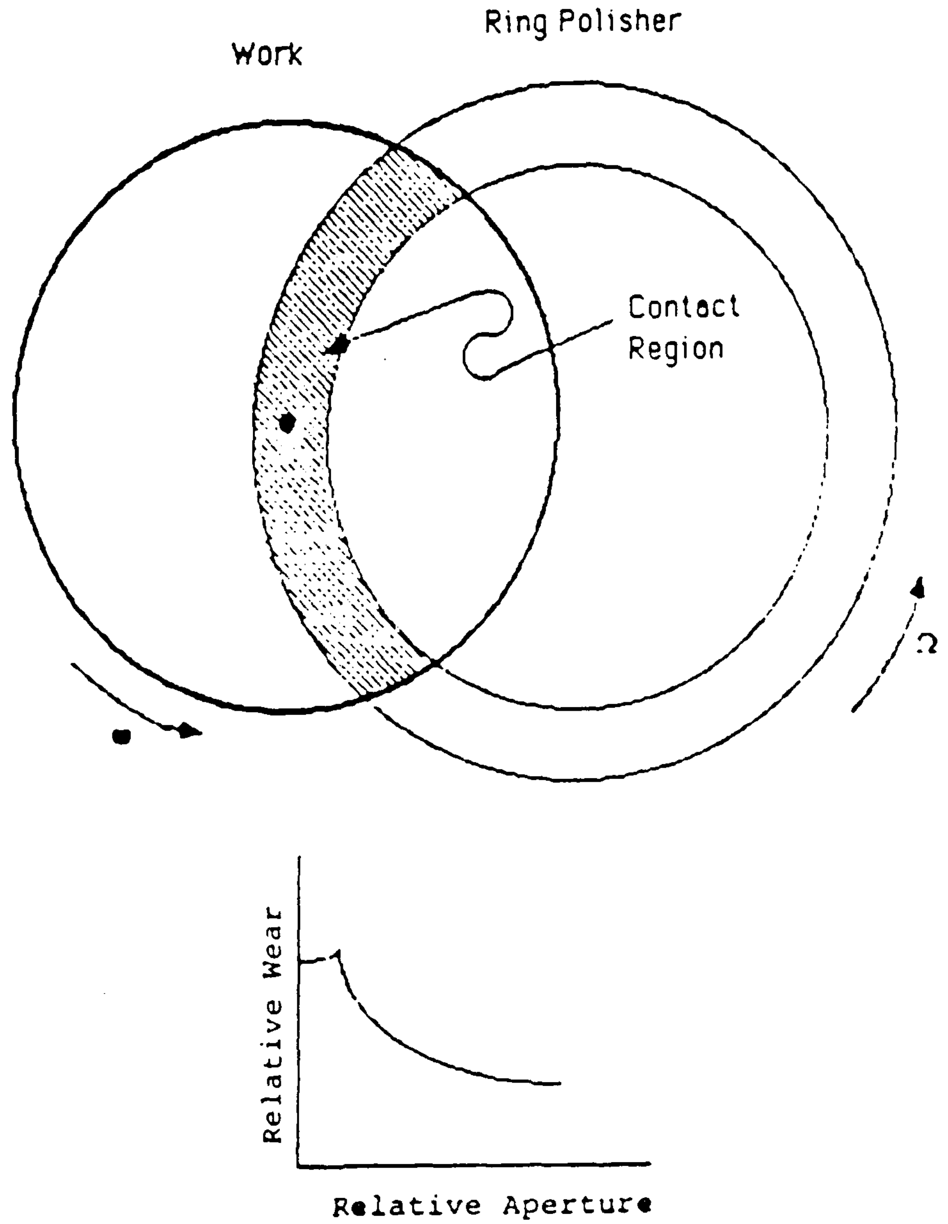


Figure 4.1: Planar Polishing Model a) Polisher Geometry, b) Relative Wear.

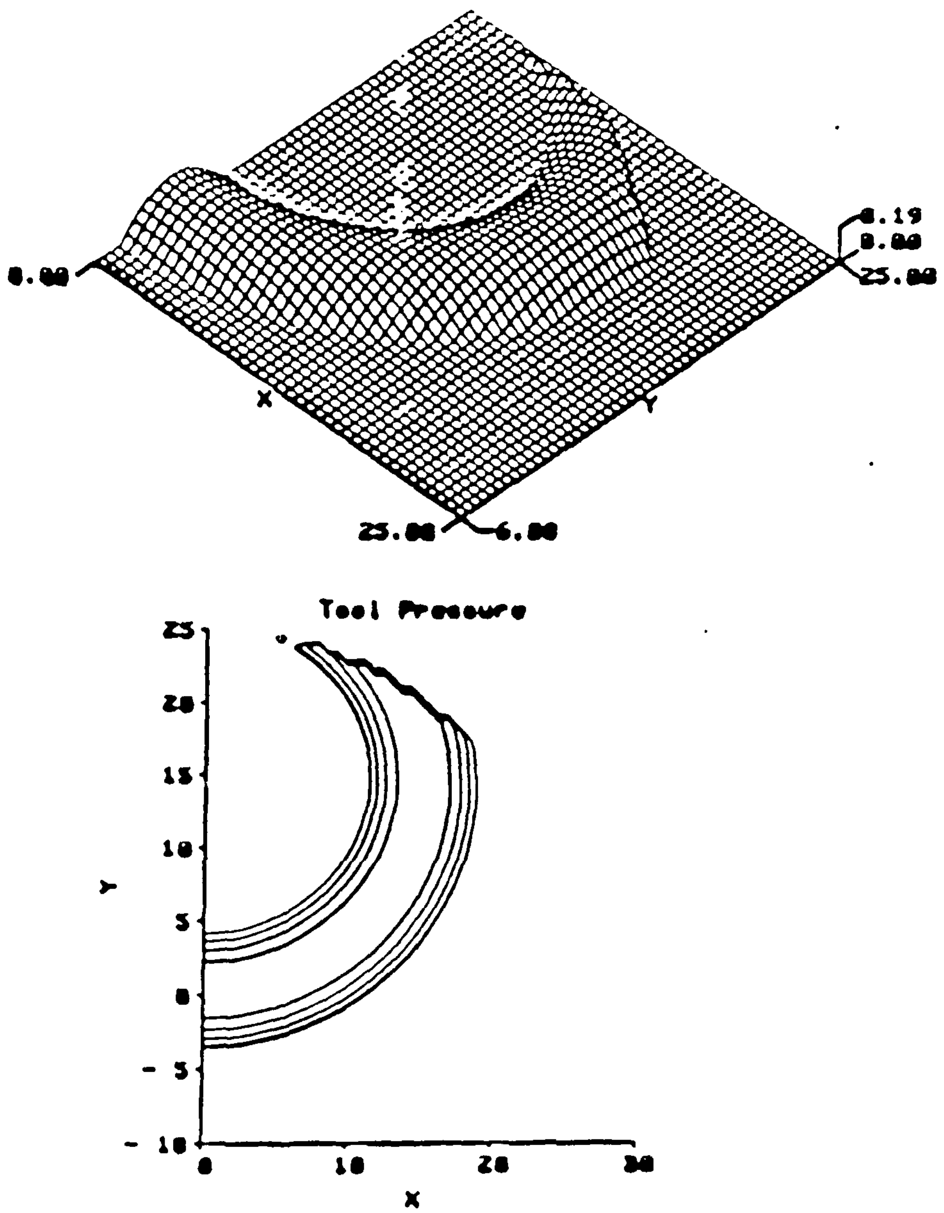
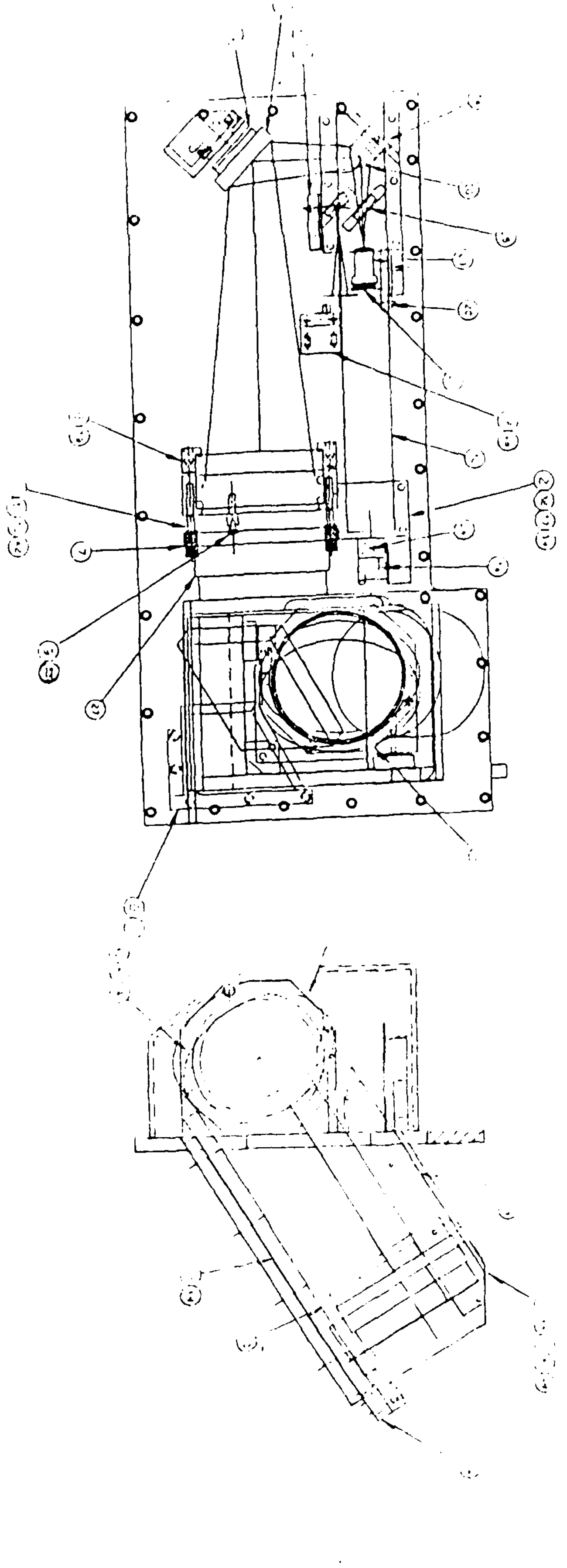


Figure 4.13: Pressure Distribution for Convex Tool with k=0.01 units.



PCAM Summary

Automation of Spherical Surface Fabrication

Achieve High Quality Optics

Fast Cycle Times

Integration of Interferometric Surface Testing

Close the Design Fabrication Gap

Ideal for Prototyping of Optical Systems

LIST OF ATTENDEES

5. LIST OF ATTENDEES

Name	Affiliation
Dr. Edward Bender	NVEOC
Dr. Thomas Coty	NVEOC
Dr. Mark Gahler	NVEOC
Dr. James Miller	NVEOC
Mr. Mark Norton	NVEOC
Dr. Robert Rohde	NVEOC
Dr. Robert Spande	NVEOC
Dr. Duncan Moore	UR
Dr. Hemit Desai	CVD
Dr. Raymond Taylor	CVD
Dr. Leland Atkinson	GLC
Dr. Robert Zinte	GLC