Final Report

ANALYSIS OF ADVANCED OPTICAL GLASS AND SYSTEMS

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1. Introduction

In the history of optical lens design, revolutionary advances resulted from the discovery and development of various optical materials. Today, scientists at NASA/MSFC have made and continue to make progress in the formation and analysis of new optical materials with special properties. In order to understand the potential importance of having such glasses available in the near future, it was necessary to perform studies of generic optical lens configurations to access the impact of these new glasses on optical lens system design.

The scope of this research effort was mainly concerned with understanding optical lens systems performance utilizing optical materials comprising reluctant glass forming compositions. Such special glasses are being explored by NASA/MSFC researchers utilizing techniques such as containerless processing in space on the MSFC Acoustic Levitation Furnace and on the High Temperature Acoustic Levitation Furnace in the conceptual design phase for the USML series of shuttle flights.

During the conduct of this effort the application of high refractive index and low dispersive power glasses in optical lens design has been investigated. The potential benefits and the impacts to the optical lens design performance have been evaluated. The results of the studies revealed that the use of these extraordinary glasses can result in significant optical performance improvements. Recommendations of proposed optical properties for potential new glasses have also been made.

In the following sections applications of these new glasses will be discussed, including the impact of high refractive index and low dispersive power, improvements of the system performance by using glasses which are located outside of traditional glass map, and considerations in establishing glass properties beyond conventional glass map limits.

2. Optical Glasses and Lens Design

Optical glasses differ from one another in respect to refractive index, dispersive power, and partial dispersion ratio. There are several well-known manufacturers of optical glass. Commercially available optical glasses are classified roughly as crowns, flints, barium crowns, etc. Figure 1 is a glass map given by Schott Glass Technologies, Inc. One of a lens designer's critical decisions is how to make a wise choice of glass types.

Consider first a simple single thin lens. Figure 2 shows various aberrations as well as surface curvatures and bending vs. index. The lens is bent for minimum spherical aberration and the aperture stop is at lens. The effective focal length is 100 inches, F/# = 10, and semi-field angle is 17 degrees. Spherical aberration (SC), which is the dominant aberration, is reduced sharply with the increase in index. Coma (CC), the second largest aberration, is reduced almost linearly with the increase in index. As is generally known, the higher the index the less the aberrations. Reviewing other curves, it is seen that the curvature of surface 1 (C1) is decreased by using higher index material. Less curvature typically results in lower manufacturing cost and component weight. Bending factor (K) increases slightly with increasing index. The relevant relations are as follows:

$$K = \frac{n(2n+1)}{2(n+2)}$$

$$SC = \frac{1}{8}\frac{y^4}{u^2}\frac{1}{f^3}\frac{n(4n-1)}{(n-1)^2(n+2)}$$

$$CC = \frac{h}{16(n+2)\ (F/no.)^2}$$

$$C1 = \frac{fn(2n+1)}{2(n+2)\ (n-1)}$$

$$C2 = \frac{f(2n^2-n-4)}{2(n+2)\ (n-1)}$$

where K is the lens bending, n is the index, f is the focal length, SC is the spherical aberration, y is the aperture radius, u is the aperture angle, CC is the coma, h is the image height, C1 is the first curvature, and C2 is the second curvature.

Generalizations for a single thin lens are plotted in Figs. 3 and 4. In these two drawings, the aperture stop is at the coma-free position. Aberrations and stop location vs. lens bending can also be observed in these Figures. The indices for these two cases are 1.517 and 2.2 respectively.

There can be no chromatic aberration control in the single element system. However, a lens system with more than one material may be able to affect chromatic aberration correction. It has been shown that chromatic aberration can be greatly reduced if new optical materials with high index of refraction and lower dispersion could be produced [1]. Glasses with unique partial or analmous dispersion are needed for the correction of secondary spectrum. Over a hundred years ago, flint glasses (lead-alkali-silicates) were discovered to correct the color aberration of the crown glasses (soda-lime-silicate) making the first achromatic color corrected multi-element lens system possible. Over the following years, demand for better quality lenses led to the development of numerous glass compositions with unique combinations of refractive index and dispersive power.

Generally speaking, besides chromatic aberrations, the introduction of advanced glass with high refractive index and low dispersive power can improve spherical aberration, petzval sum, field curvature, zonal spherical, and astigmatism.

The performance of optical lens system depends on the specific selection of glasses incorporated into the design and the properties of these glasses. Lens designers have observed that the iamge quality of most lens configurations significantly benefit from the use of glasses with high refractive index [2][3]. Further discussion is contained in the next section.

Although color correction of lenses is typically accomplished by using a combination of glasses having both low and high dispersive properties, the difference in refractive index at the reference wavelength often cannot be very great without adversely impacting the state of correction of the optical aberrations. In order to exploit the anticipated advantages of using high refractive index glasses, it appears to be generally necessary for high refractive index, low dispersive glasses to be available for the lens designer.

Optical lens design utilizes not only variations of the refractive index and dispersion, but also the partial dispersion for a given mean dispersion. Dispersion is not a constant for a given composition. The blue portion of the spectrum has different dispersive properties than the red portion of the spectru. The vast majority of glasses have a linear relationship between the blue partial dispersion and average dispersion because silicate glasses in general do not have special dispersion curves. This linear relationship will apply with an acceptable degree of accuracy for most glasses (so-called "normal glass") as was observed by Abbe. Correction of the secondary spectrum, i.e., achromatisation for more than two wavelength, is known to necessitate the use of at least one glass type that does not conform with this rule. For this study, K2 and F7 were selected as representative of the "normal glasses:"

In our investigations of hypothetical glasses, we use the below relation to compute the refractive index at three wavelengths from given mean index and dispersion when the partial dispersion information is not available.

$$P_{F,d} = \frac{n_F - n_d}{n_F - n_C} = 0.7229 - 0.000461 V_d .$$

In an achromat, there are residual chromatic aberrations (the secondary spectrum) which can be reduced with apochromats utilizing optical elements with different mean dispersion but equal partial dispersion in the critical range. The general correction of secondary chromatic aberration requires new glasses with large anomalous dispersion, and particular positive partial dispersion, be made available.

Detailed investigation of some widely used lens configurations reveals that the importance of high-index, low-dispersion glasses. It also showed the importance of partial dispersion.

3. Advanced Glass and Its Basic Impacts on Optical Lens Design

In our research effort, we have explored the impacts of incorporating one or more of these special glasses in wisely-used classical lens configurations. Results show that the optical performances can be significantly enhanced by utilizing advanced glasses with similar configurations. Conversely, use of the new glasses may yield a somewhat simpler optical design, i.e., less complex, fewer surfaces, and smaller sizes, with optical performance.

Lens types analyzed include Double Gauss, Aplanatg, Tessar, and Petzval. Optical performance characteristics we analyzed cover transverse aberrations, longitudinal aberrations, distortion, and multi-field MTF.

Figures 5 through 8 show the comparison of four-piece Double Gauss lens for three designs; (1) depicted from Kingslake's *Lens Design Fundamentals*, (2) optimized with current available glasses, (3) reoptimized with hypothetical material with n = 2.2, V = 90. The focal length is 10 with F/# = 8. Semi-field angle is 25 degrees. The overall length of the lens system is 2.33. For comparison of these lens systems, the first-order specifications were kept unchanged in the design. Table 1 lists the lens data of three designs and sample macro used in optimizing the design. The optical performance was improved by using high-index, low-dispersion glass. As we expected, coma and spherical aberrations were greatly reduced by using high-index glass. Some chromatic residuals means that more work is needed to find appropriate glass combination for this design.

To see changes in the optical performance of Aplanats with glass selections, Fig. 9 shows the aberration curves for index changes from 1.8 to 2.2 and dispersion from 50 to 70. The focal length of the Aplanats are 9.9 with F/# = 5 and semi-field angle of 1 degree. The total length of the Aplanats is 0.58. Table 2 gives the corresponding lens data with sample macro. From the aberration curves, one observes that most of the aberrations will be reduced with an increase of index and decrease of dispersion. However, chromatic aberrations, especially secondary color, do not behave in this way.

Figures 10 and 11 show the comparison of Tessar lens for three designs like those for Double Gauss. The Tessar lenses depicted from Kingslake's book have a focal length of 10, F/# of 4.5, semi-field angle of 20 degrees, and total length of 2.33. Table 3 shows the lens data and optimization macro. Figures 12 and 13 show the aberration changes for different indices and dispersions for this Tessar. Table 4 gives the resultant lens parameters. The aberration changes with the index and dispersion changes are similar to those of the double Gauss and Aplanats. Figures 14 and 15 show the effect of partial dispersion. Table 5 lists the corresponding lens data. The curves depict the obvious aberration changes with slight partial dispersion change, which reveals the sensitivity of lens performance to partial dispersion.

Figures 16 and 17 compare two Petzval lens designs. The focal length is 6.7, F/# is 3.7, semi-field is 15 degrees, and total length is 3.8. Not only are aberration changes obvious, but also the lens configuration has been changed significantly. Table 6 shows the lens data with the optimization macro. Significant performance improvement can be found in these drawings.

The general benefit of using high-index, low-dispersion material is obvious. Results of this study also showed that the partial dispersion is quite important.

It was often observed that the proper selection of glass with high-index, low-dispersion, and suitable partial dispersion would improve the optical performance up to a factor of 5 to traditional designs given in the literature using conventional glass.

4. Applications of Advanced Glass in Optical Lens Design

4.1 Expansion of the Glass Map

Due to the limitation of commercially available lens design software, the computer could not effectively search index and dispersion in high index low dispersion lens design outside of the normal glass map. There is also no way to control and adjust partial dispersion.

Determination of desirable new glass properties necessitated a search of a modified glass map permitting searches outside of normal glass properties by extending the normal limit on the crown side to what we call the advanced-crown limit.

We have found that we can utilize parameter array (Q array) of SYNOPSYS to customize glass search region. Using this technique, we can define the "valid" glass region with any values as well as any shape! Not only rectangular or triangular, but also curved areas. Moreover, partial dispersion can also be searched under certain limitations by using a similar method. To manipulate index at different wavelengths, we use:

$$n_{W_n}(S_n) = Q(6S_n + W_n + 3)$$

where W_n is the wavelength number and S_n is the surface number. Thus, index, dispersion, and partial dispersion are controlled by the corresponding Q array elements.

Glasses in the conventional glass map are mostly limited by the boundaries $V_d = -88 n_d + 206.6$ for crown-side limit and $V_d = (n_d - 1) / (0.0713 n_d - 0.0978)$ for flint-side limit.

As stated, we can define any new mathematic formulas for multi-boundary curves that allow the formulation of a general glass map. Table 7 lists the macro for this purpose which expands the crown limit to the advanced limit. Using the one-sided aberration construction of SYNOPSYS to form boundaries, we can define any kind of desired limits for glass searcing.

4.2 Trends in ideal advanced glass

It is often very difficult to decide whether or not a given lens systgem is sufficiently well corrected for a particular application. The usual method is to trace a large number of rays from a point source in an uniformly distributed array over the entrance pupil of the lens, and then plot a "spot diagram" of the points at which these rays pierce the image plane. It may be necessary to trace hundreds of rays before a realistic geometric appearance of the point image is obtained. Chromatic errors can be included in the spot diagram by tracing sets of rays in several wavelengths. One criterion we used in the evaluation is the average resolution, which averages all the fields and colors with user specified spectral weights.

In the Double Gauss optical system, the best combination of glasses was found using available commercial glasses. Transverse aberrations, longitudinal aberrations, rms. spots, and multi-field MTF were calculated. The process was repeated with lanthium-calcium-aluminate glass prepared by NASA, with crystalline sapphire, and a hypothetical optimized glass with properties close to sapphire. A quantative measure is shown in Figs. 19 and 20 with the values of the average resolution. One can see that for the La203-CaO-A1203 reluctant glass, the system resolution is significantly improved. The resolution of the system with the optimized glass has an even better improvement in performance with over twice the average resolution of the best conventional system.

The starting point we used for a six-element Double Gauss with SK16 (620603) and SK8 (6899309) (both in the conventional region) was taken from Ref. 4.[4]. The design specifications are as follows:

1.	Focal length:	35
2.	Aperture:	f/3.5
3.	Full field of view:	51 degrees
4.	Total length:	29
5.	Working conjugate:	18.1

It is a well refined design with very good performances. We checked the original design in SYNOPSYS and tried to reoptimize it without glass changes. The conclusion was that the lens was essentially optimum.

We next attempted two designs optimizing the lens using as the crown material first a sapphire-like material (768721) and then a reluctant glass sample (850500). These two materials are outside the conventional glass map. The corresponding flint glasses were selected by the optimization routine in lens design program. Results show that the lens with the reluctant sample has better performance than that with the conventional glass; however, the lens with sapphire-like properties has even better performance.

In an attempt to establish some general rules for selecting crown glass that lie outside the conventional boundary, we moved the crown-side limit to up left (V_d = -100 n_d + 250), which we denoted as advanced-crown limit, and let optimization routine search nF, nd, nC separately in the defined region by using the Q array of SYNOPSYS. At the same time, the flint glass region was searched by the program in the conventional region using the glass model of SYNOPSYS. The results provided a lens with lower dispersive power and moderate refractive index (735769) that has much better performance, (see Fig. 18). By moving the crown limit even further (v_d = -100 n_d + 270), we found that the performance can be even further improved.

As noted above, Fig. 19 shows the improvement made by glass changes. Table 8 contains multi-field and average resolution for all of these designs. Fig. 20 presents the geometric spot diagram for these designs at various field angles. Fig. 21 shows the aberrations and configurations for the conventional and proposed glasses. Table 9 lists the lens data and the macro for searching in the advanced-crown limit as well as for optimizing the lens already listed in Table 7.

In this analysis, we find that lenses with conventional glass, sapphire-like, advanced, and hypothetical have very similar n_d and V_d differences between the "crown" and "flint" glasses.

One verification we made is the validity of the SYNOPSYS GLM (glass model), which is a series of empirical formula presenting the glass by n_d and V_d, and calculated n_F, n_d, and n_C. The result is that this model is quite precise in the conventional region as is claimed in the SYNOPSYS User Manual. But huge errors can occur when applying this model outside the conventional glass map even slightly. So, in the flint glass search, we simply use GLM if the flint is still in the conventional region. Fortunately, all the flint glasses we used are within the conventional glass map. For the crown glass, we used either the search method or set specific values for the hypotehtical sample (explicit n_F, n_d, n_C) since no GLM is allowed.

Reoptimization for the classic triplet lens was performed by searching other glass combinations. Almost all previous researchers used a triplet as an example to analyze glass selection. The reason for using a triplet is that it has the exact degrees of freedom to balance the (3rd order) aberrations and also glass selection provides a necessary design tool.

To find trends in glass selection, we searched first in the conventional glass boundaries and then in expanded boundaries with crown-side limit V_d −100 n_d + 250 and then with crown-side limit V_d = −100 n_d + 270. The locus of the optimum glass pair for different boundaries showed a trend of glass preference which is very similar to that previously plotted for the Double Gauss. Again, lower dispersion is more preferable than higher index. Also, roughly constant differences between indices and dispersions were observed.

In short, some trends in glass selection and their benefits to lens design have already been observed due to this investigation. Further investigations may bring additional interesting results to light.

5. Conclusion

We have investigated the potential application of certain advanced glasses, their impact on lens design, and have identified certain preferred optical properties for development of new glasses.

We have investigated the impact of advanced materials with high refractive index and low dispersive power on the commonly used optical system configurations such as the Tassar, Aplanat, Petzval and Double Gauss. The fact of the benefits has been simply checked up by substituting one or several glasses in original design and reoptimizing the lens. The aberration curves obviously have been changed with the changes of index and dispersion. It was observed that a lens can be designed using the new (or potentially new) glasses that yield better optical performance.

It was observed that, when using the new materials, partial dispersion appears to be a more sensitive property than index and dispersion.

As for material property recommendations of the optimum lens performance, we carried out general search of the glass property selection in optimization. Conventional glass map has been expanded. The lens design program searched the newly defined glass map to find optimum glass combinations for various of lens configurations.

For a given starting point, the optimum glass-pair locus for different material limits showed new material research and development. Interestingly, it was noted that the optimum combination glasses were direct to low dispersion instead of high index, which means the lower dispersion is more important than high index. Again, appropriate partial dispersion was also more important than lower dispersion.

Both Double Gauss and triplet searches confirm the above trends and characteristics.

During general search, one traditional concept has shown up; the difference between index and difference between dispersions keep almost constant.

Further research efforts will be the continuation of the research in depth.

a. Continue general search of glass pair combinations for different start point and different performance requirement (different merit function). The result of this effort will provide a series of recommended glass property data, i.e., preferred indices, dispersions, and partial dispersions for various lens configurations.

b. Search three or even more glass combinations in lens optimization. Allow one or more than one glass search off the conventional glass map. Realize multicolor-achromats or superchromats. Refine recommended glass zone.

c. Investigate in detail all the possible impact of the advanced glass on lens design, i.e., first order properties, third order properties, transverse and longitudinal aberrations, and chromatic aberrations. List all the benefits of the new material and property requirements for the new materials.

d. Give both material scientist and lens designer some constructive suggestions about the glass property requirements for new material developing and glass combination selection for new lens design.

The ultimate objective is to develop a set of specifications that identifies desirable optical properties for new non-traditional glass formers. The results of this effort will provide a series of recommended glass property data, i.e., preferred indices, dispersion, and partial dispersions for various lens configurations as design goals for proposed new material development by material engineers.

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Optical Systems Design, Inc., SYNOPSYS

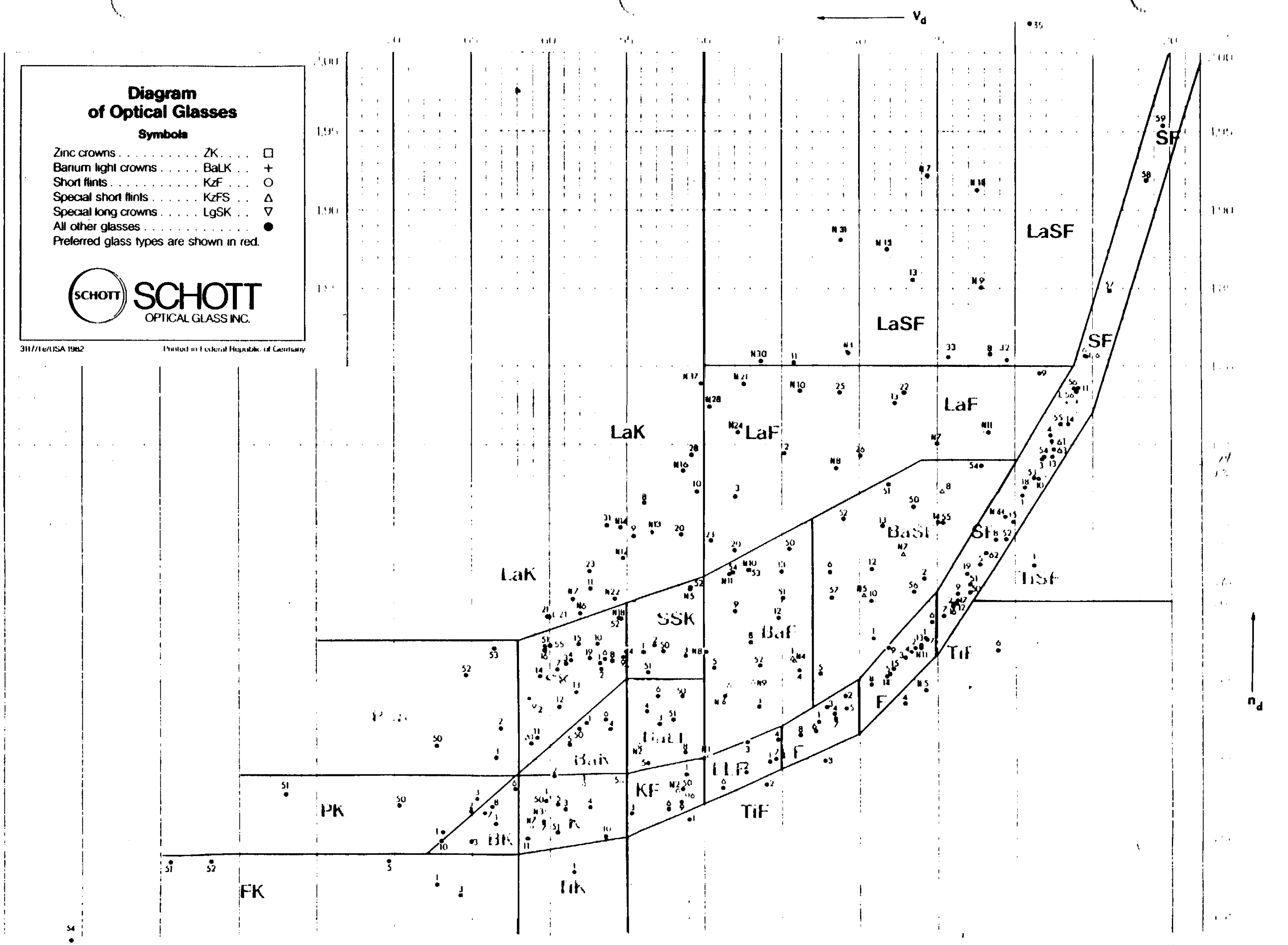
Diagram
of Optical Glasses
Symbols
Zinc crowns . . . . ZK . . . . □
Barium light crowns . . . . . BaLK . . +
Short flints . . . . KzF . . . ○
Special short flints . . . . . KzFS . . △
Special long crowns . . . . . LgSK . . ▽
All other glasses . . . . ●
Preferred glass types are shown in red.
SCHOTT
SCHOTT
OPTICAL GLASS INC.
3117/1e/USA 1982
Printed in Federal Republic of Germany
ν_d
n_d
SF
LaSF
LaF
BaSF
SSK
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LF
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PK
BK
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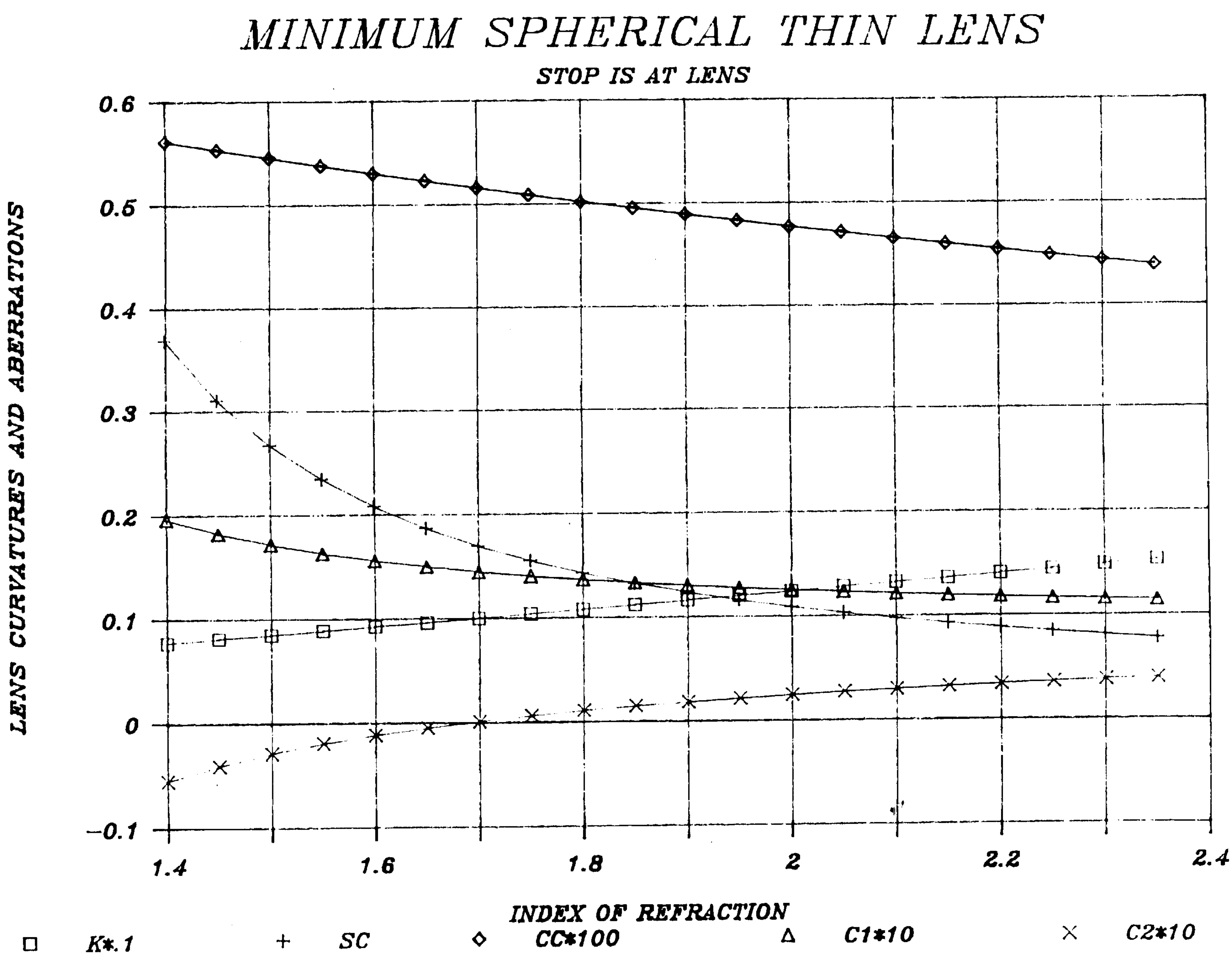
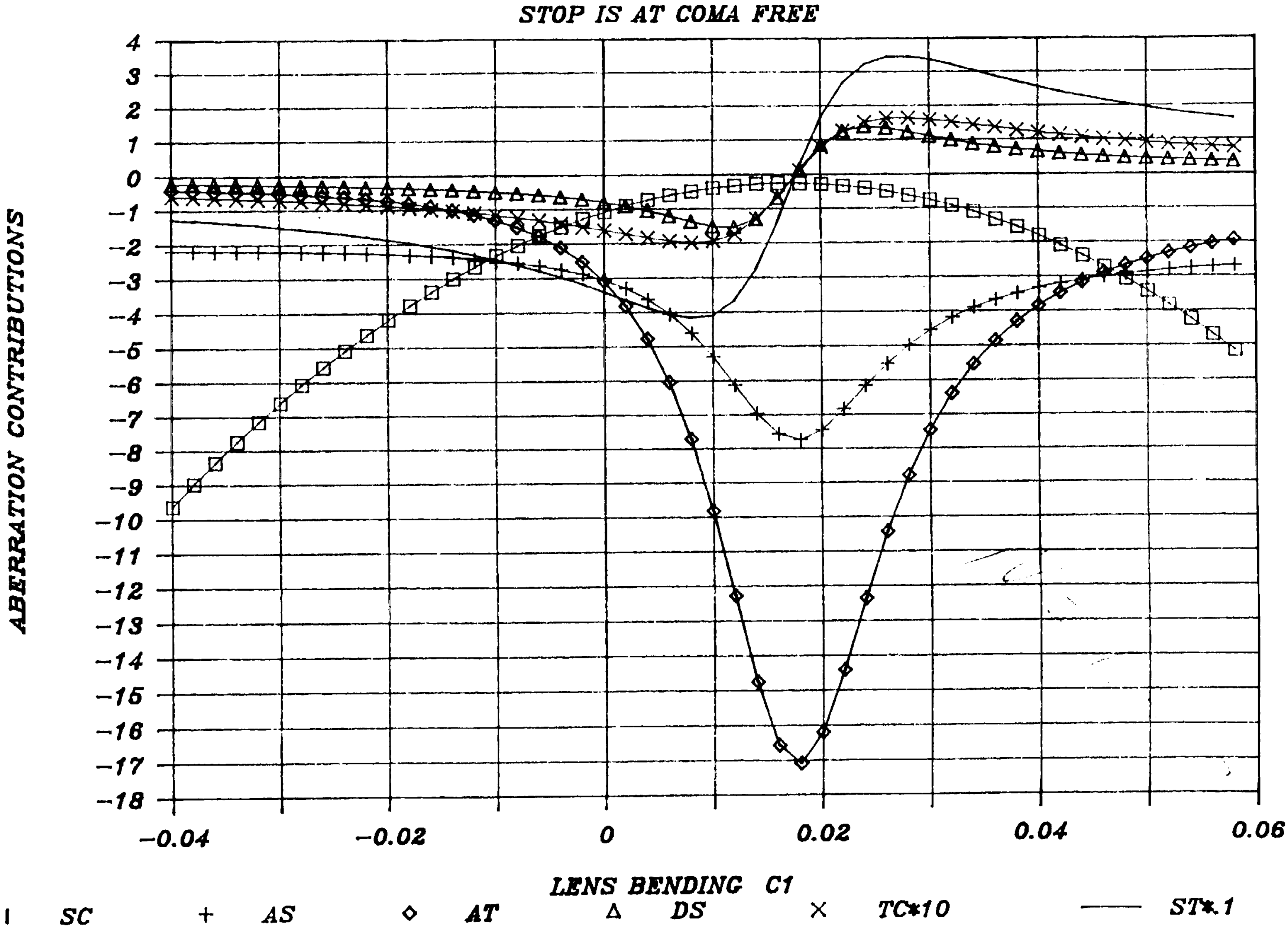
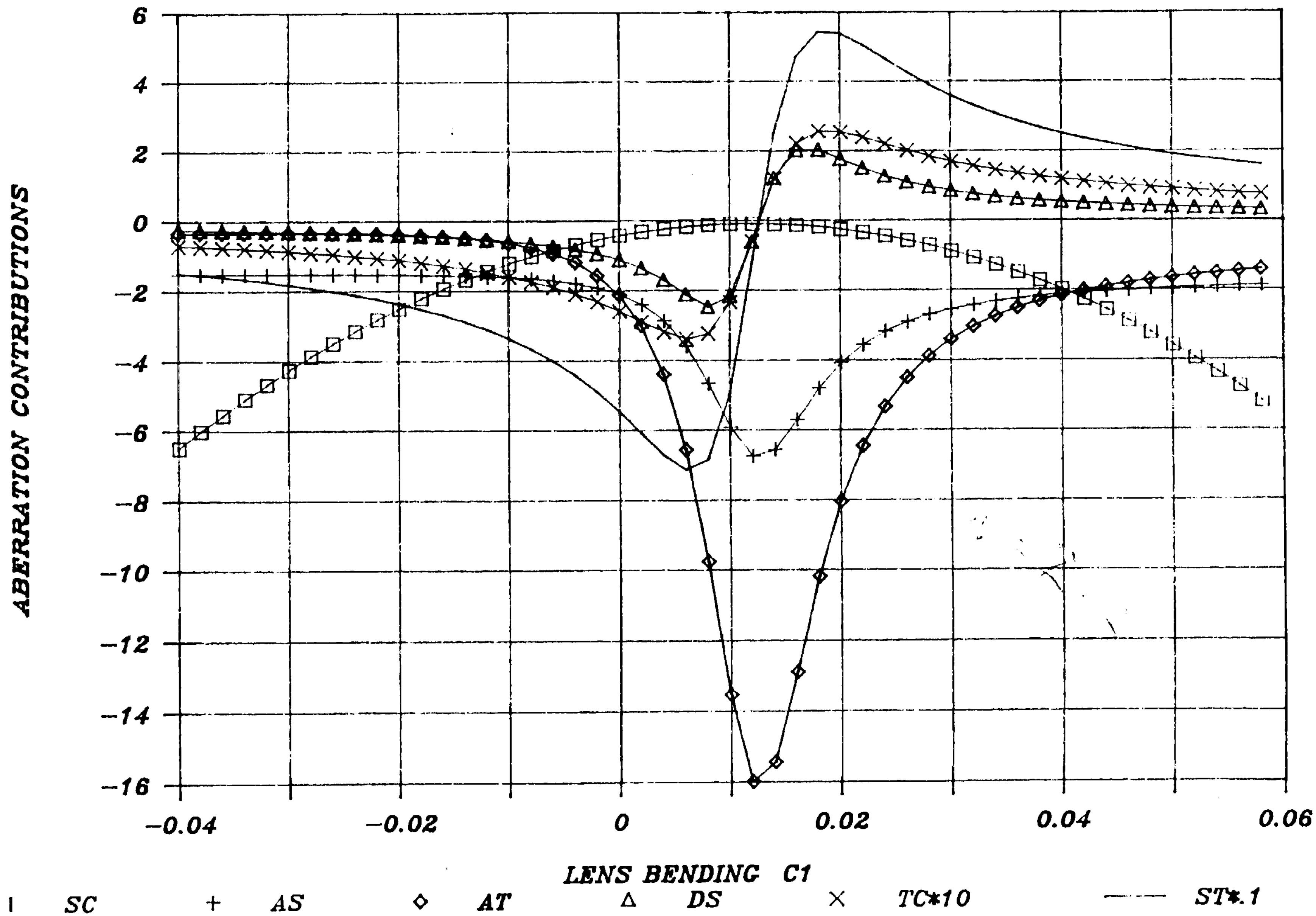

MINIMUM SPHERICAL THIN LENS
STOP IS AT LENS
LENS CURVATURES AND ABERRATIONS
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
1.4
1.6
1.8
2
2.2
2.4
INDEX OF REFRACTION
K*.1
SC
CC*100
C1*10
C2*10

ABERRATIONS OF SINGLE THIN LENS

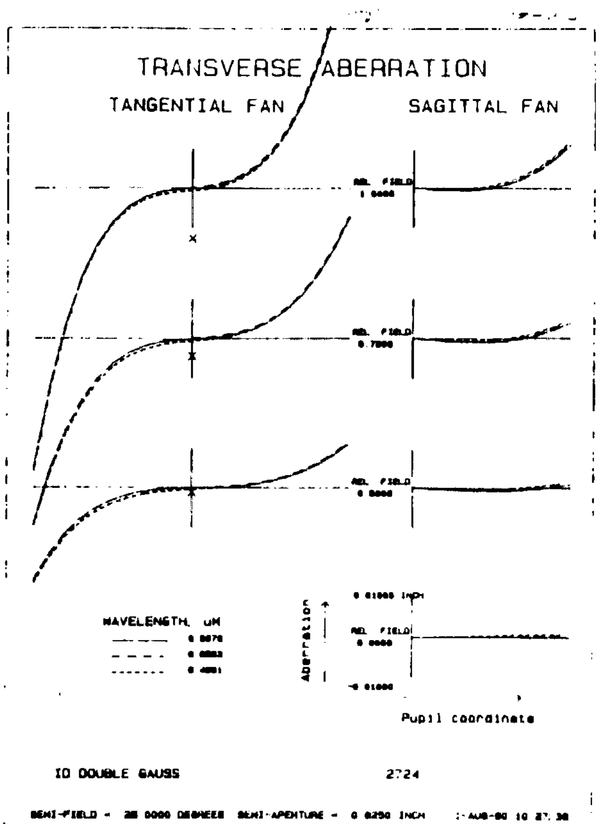


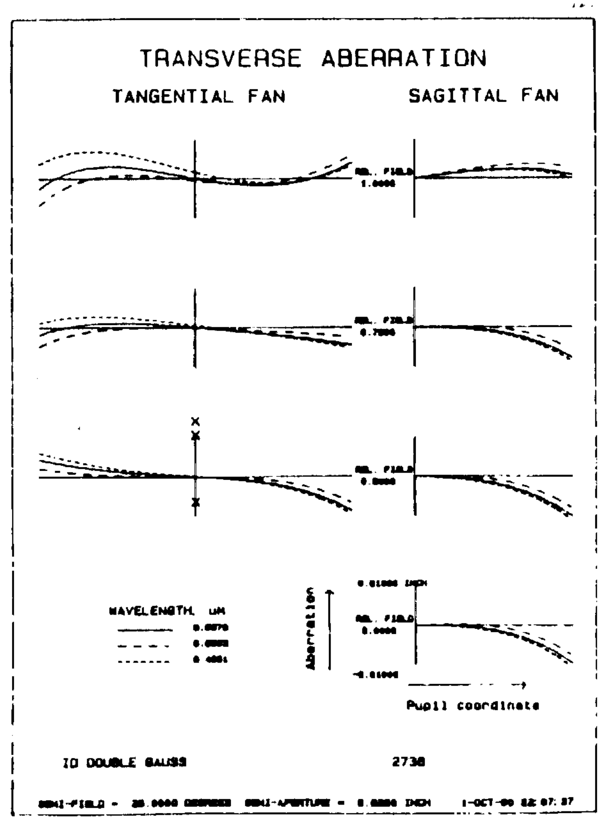
ABERRATIONS OF SINGLE THIN LENS

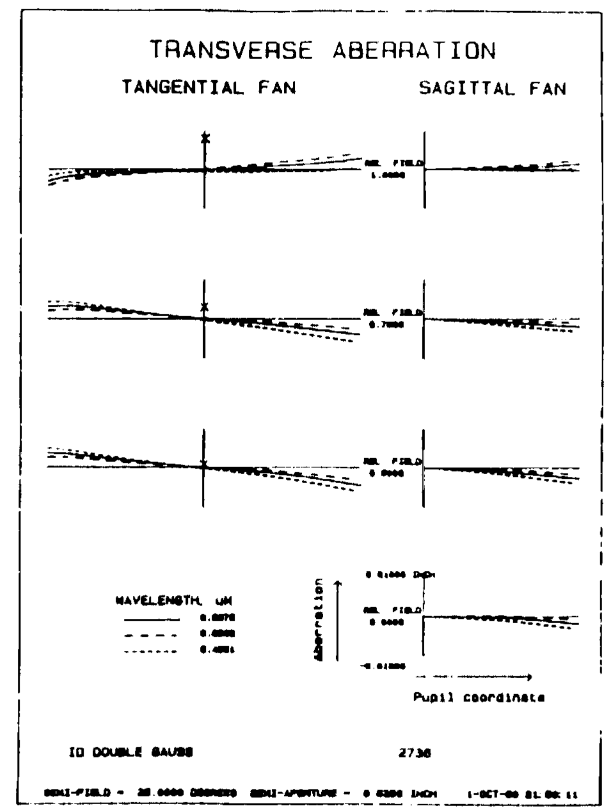
STOP IS AT COMA FREE



Double Gauss





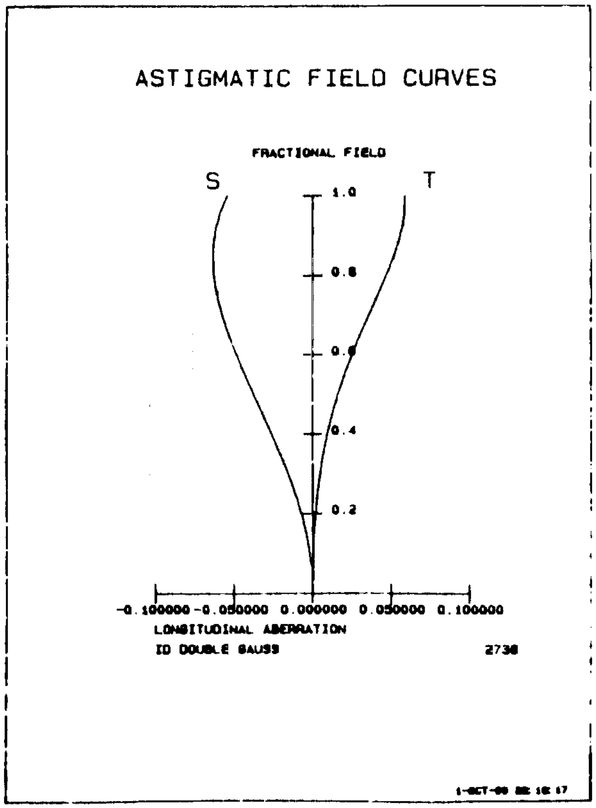


Kingslake

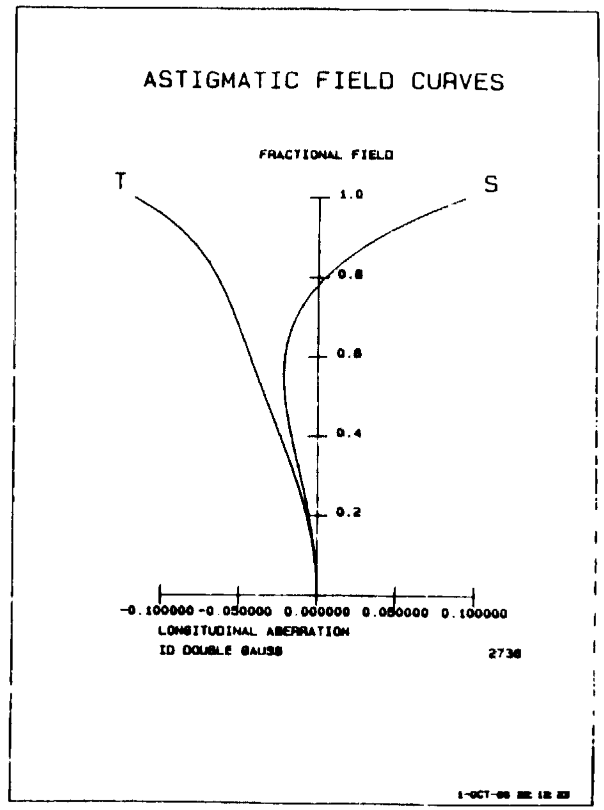
Synopsys limit

n=2.2 V=90

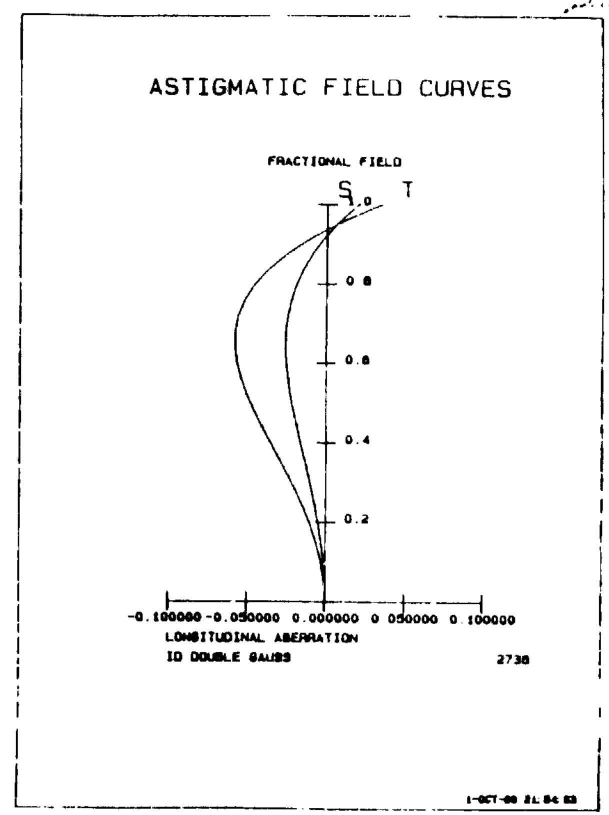
Double Gauss



Kingslake

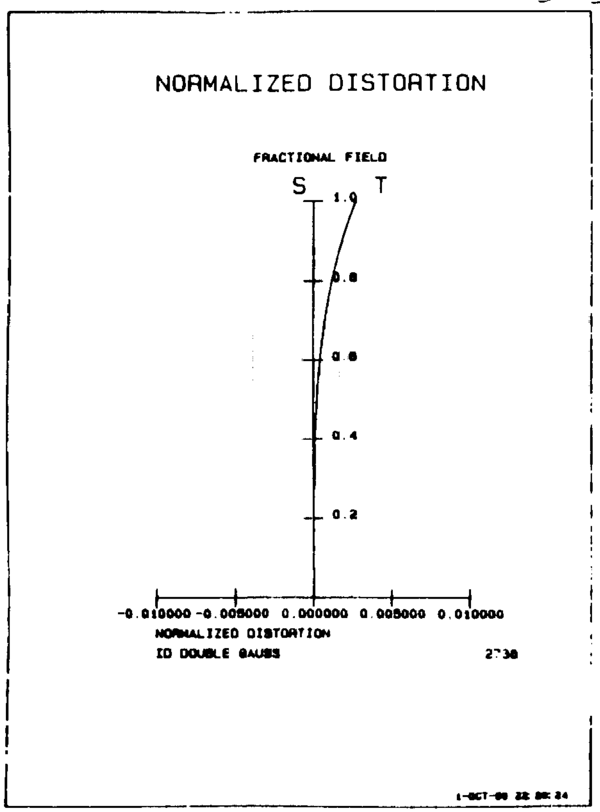


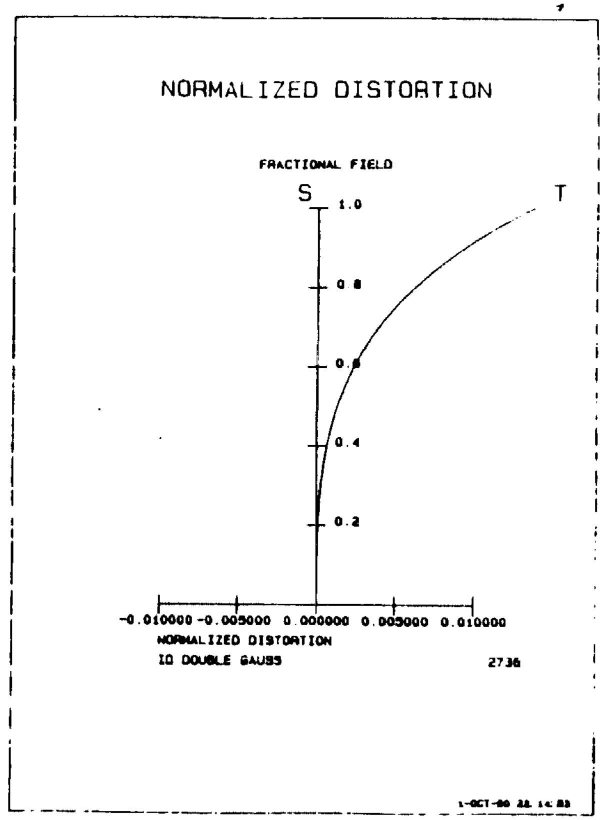
Synopsys limit

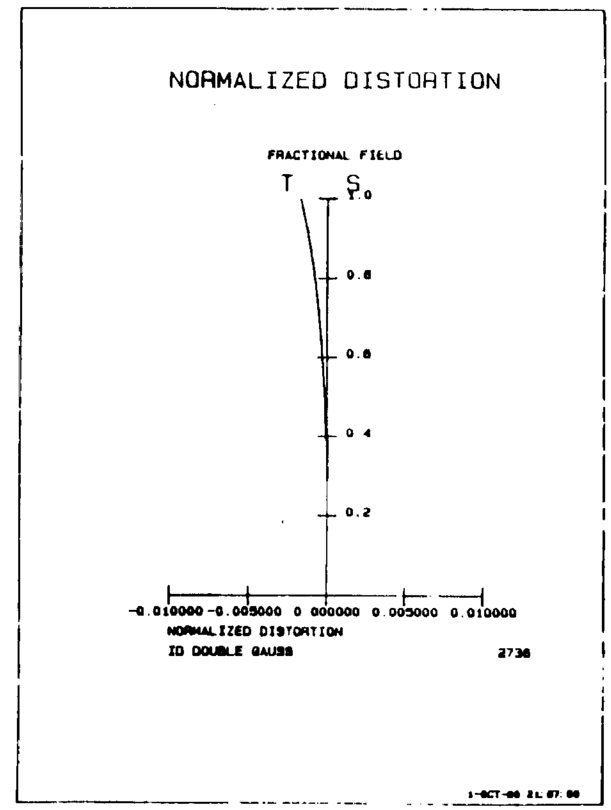


n=2.2 V=90

Double Gauss





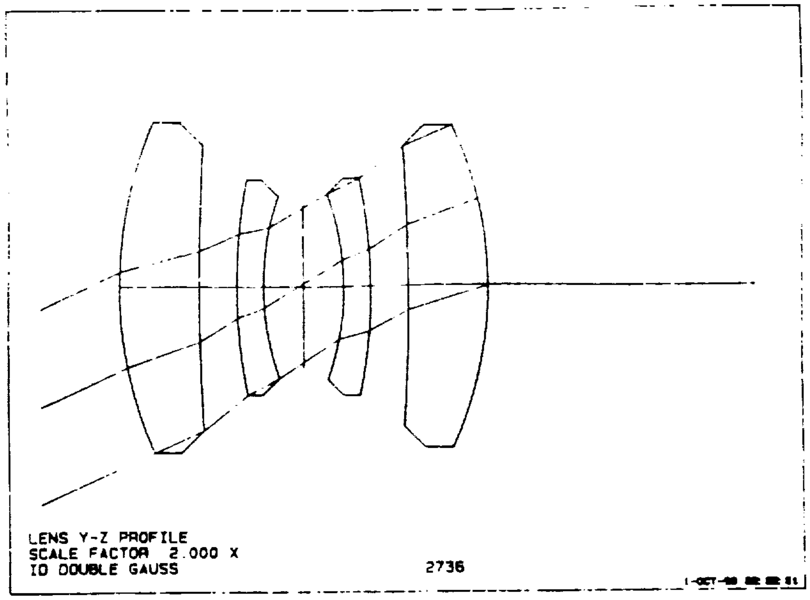


Kingslake

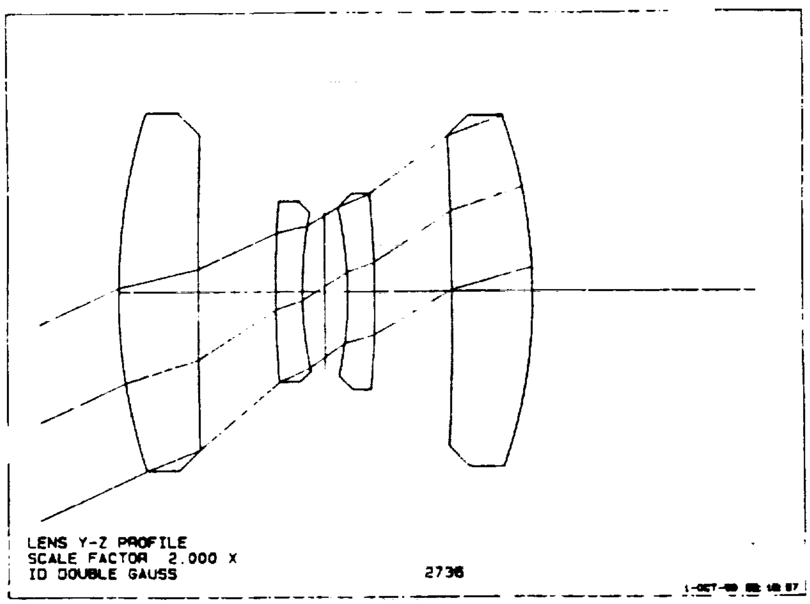
Synopsys limit

n=2.2 V=90

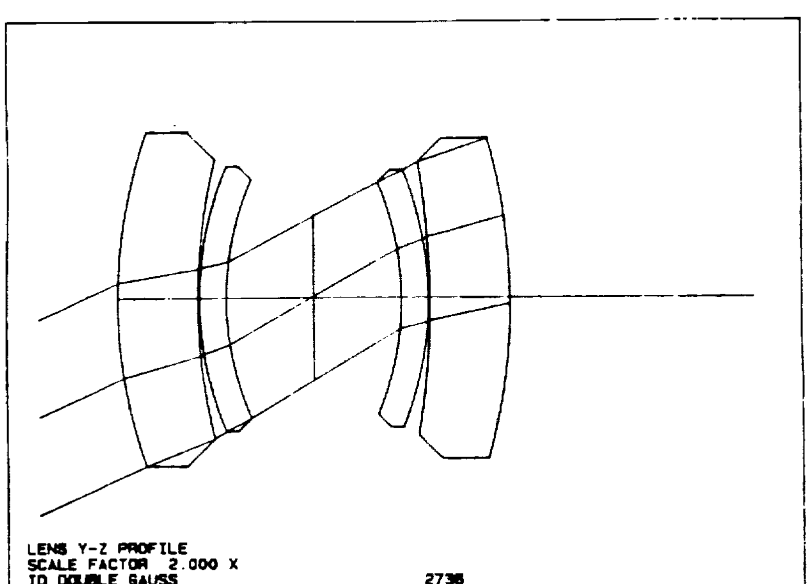
Double Gauss



Kingslake



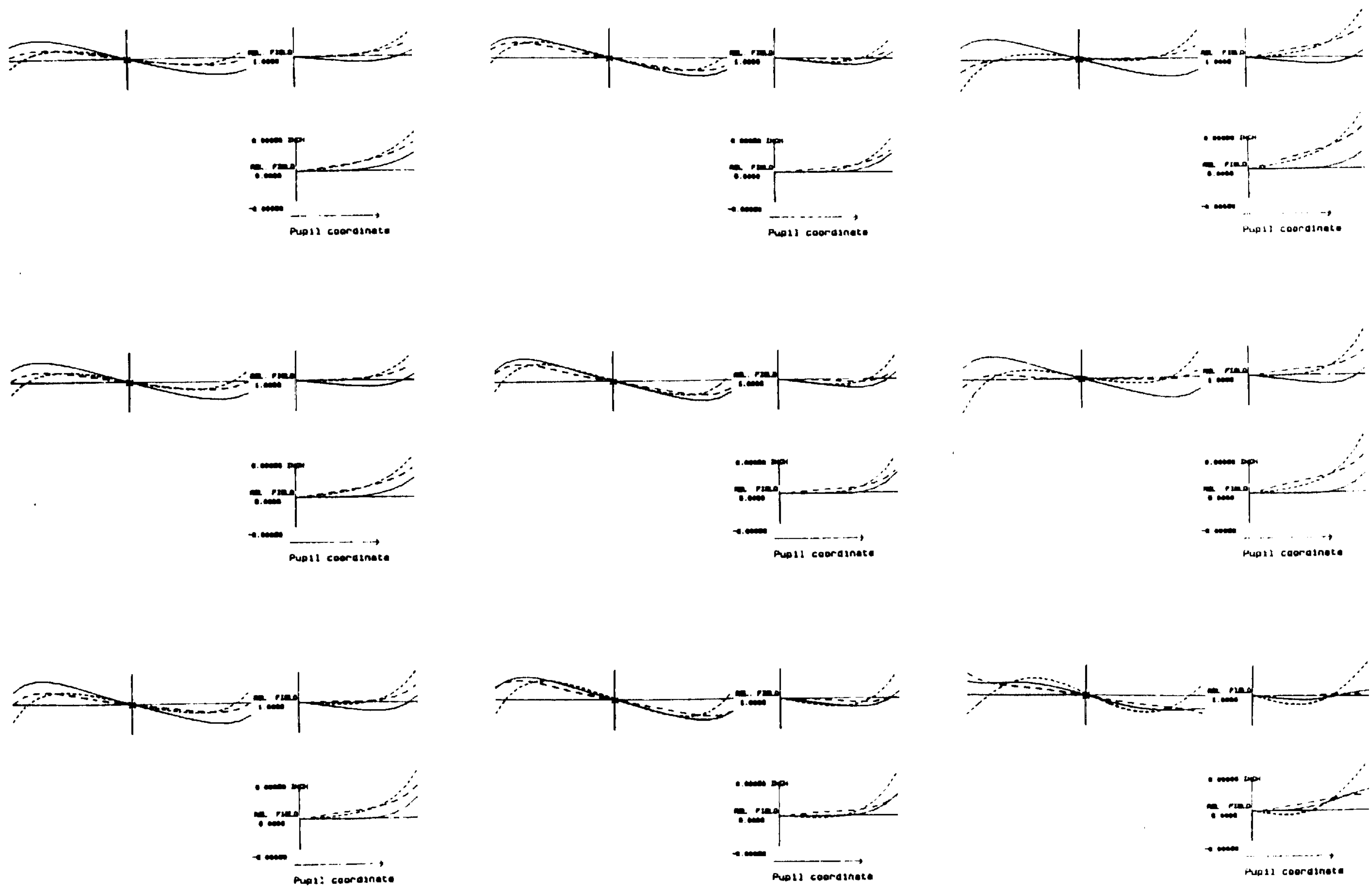
Synopsys limit



n=2.2 V=90

Aplanat

n=



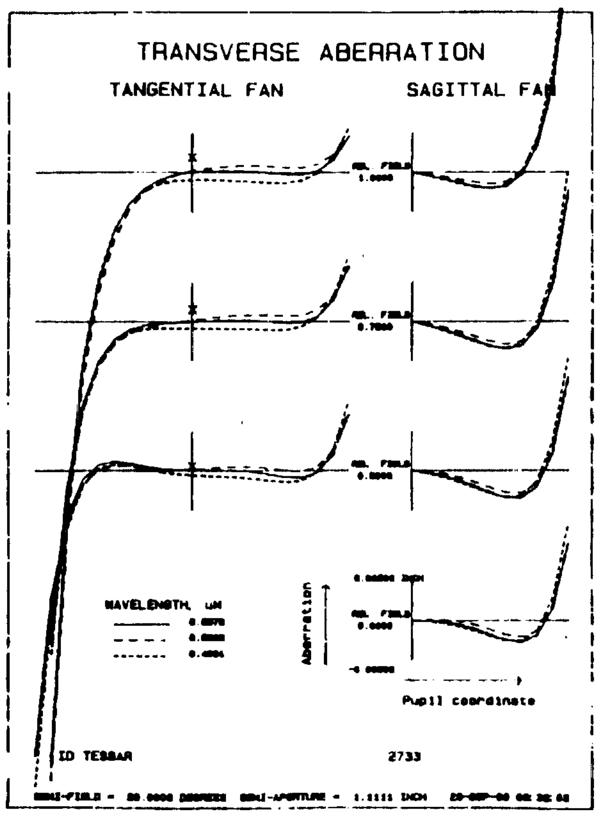
2.2

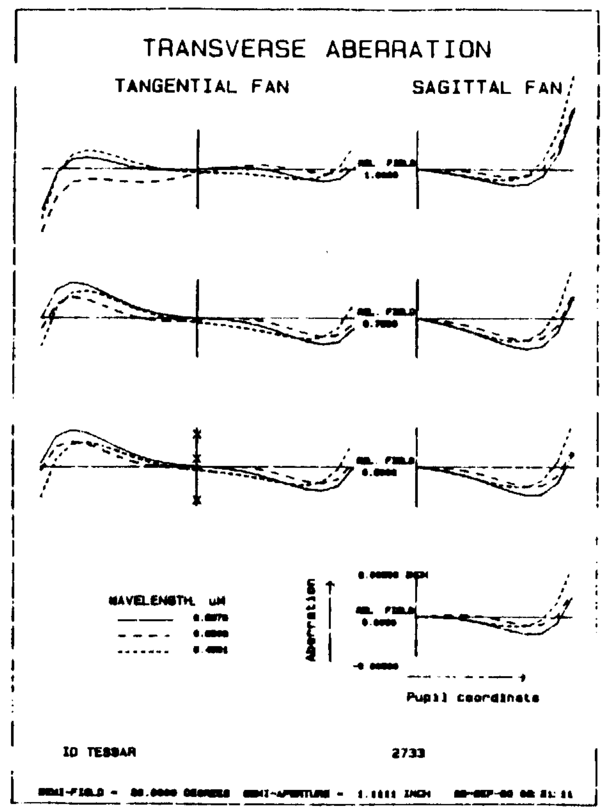
2.0

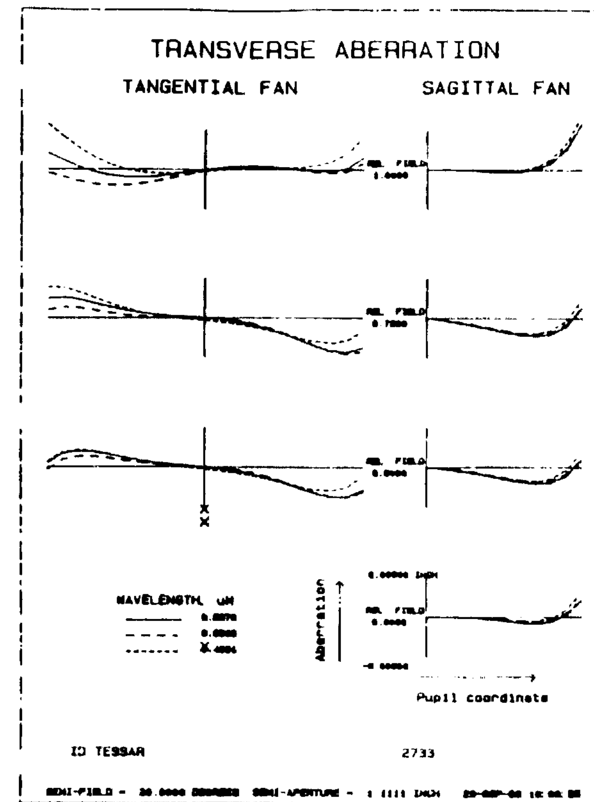
1.8

V= 90 70 50

Tessar





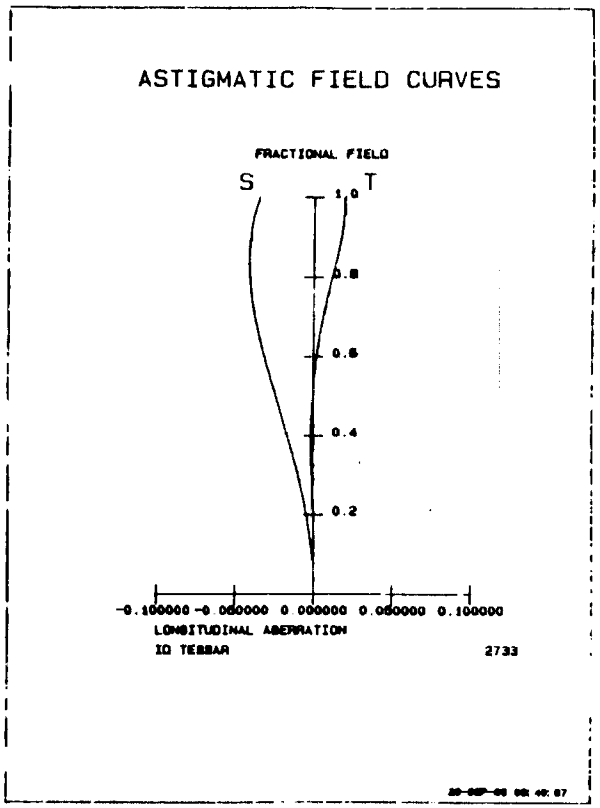


Kingslake

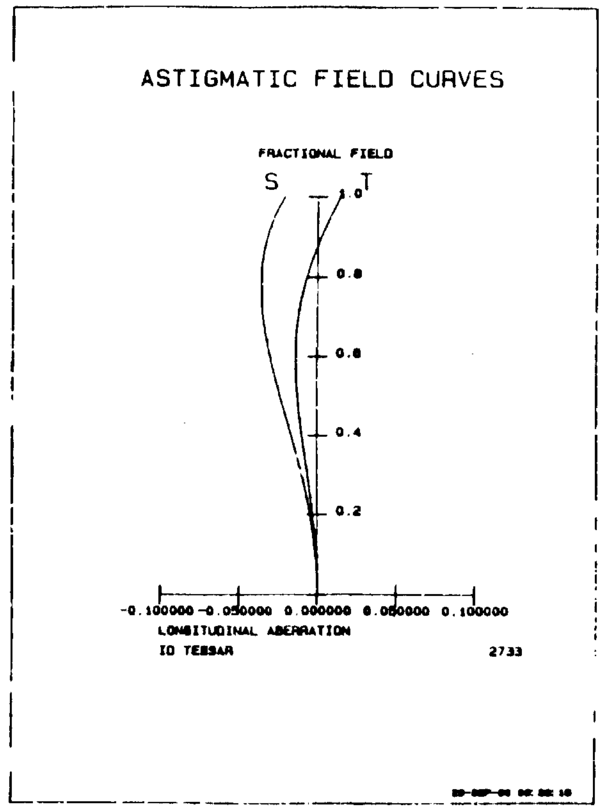
Synopsys limit

n=2.2 V=90

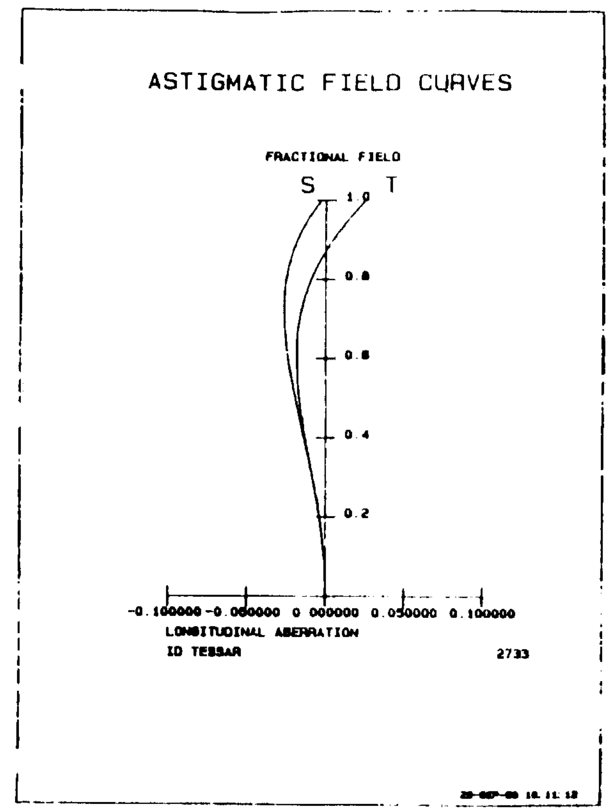
Tessar



Kingslake



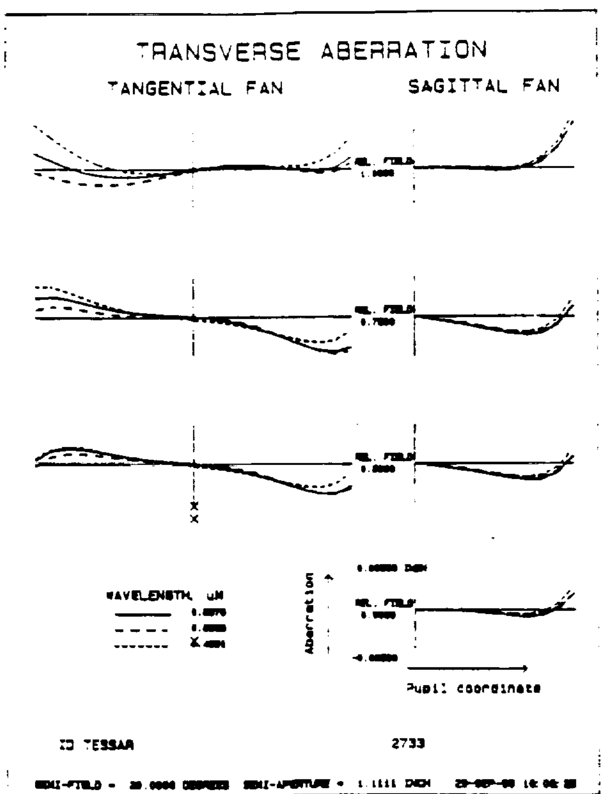
Synopsys limit

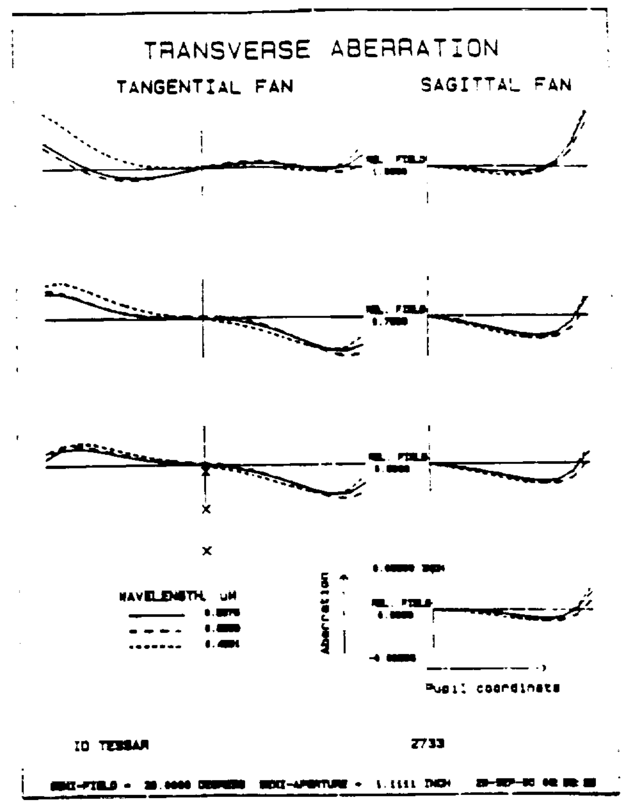


n=2.2 V=90

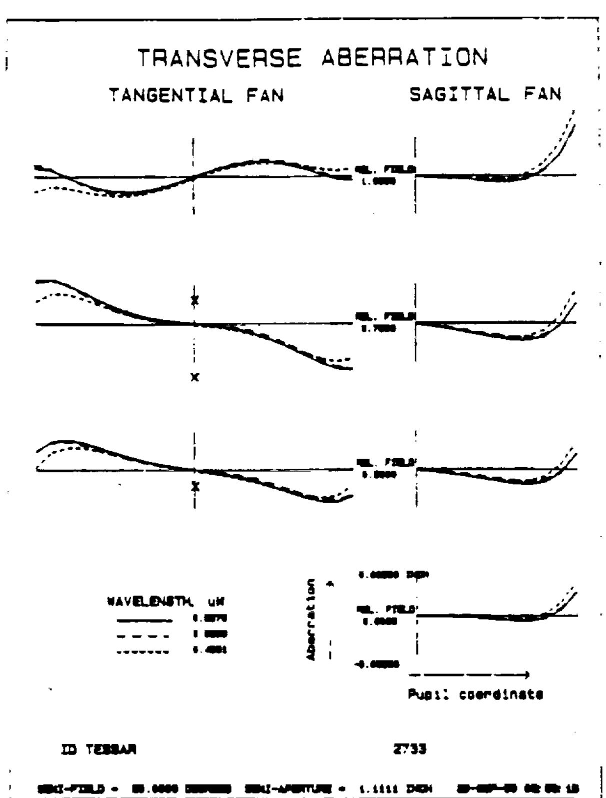
Tessar

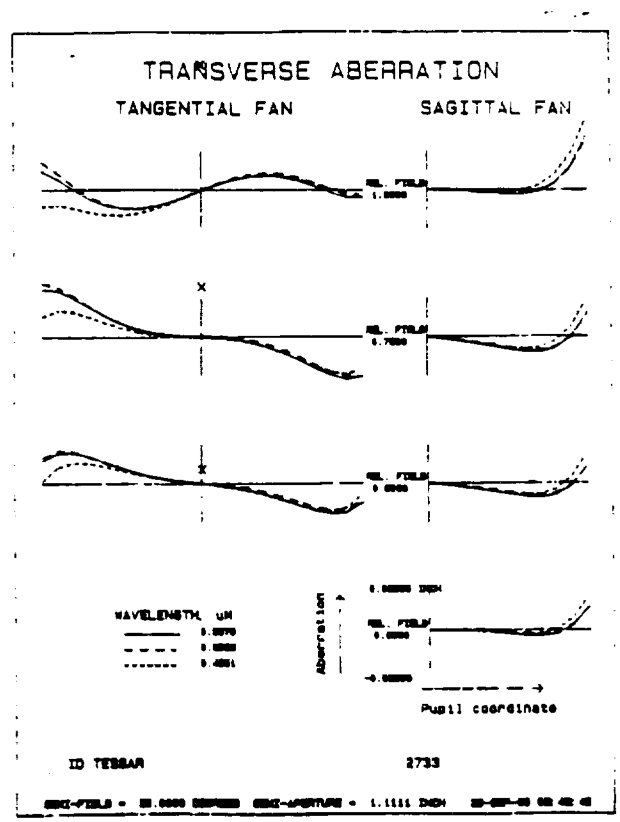
n=





2.2



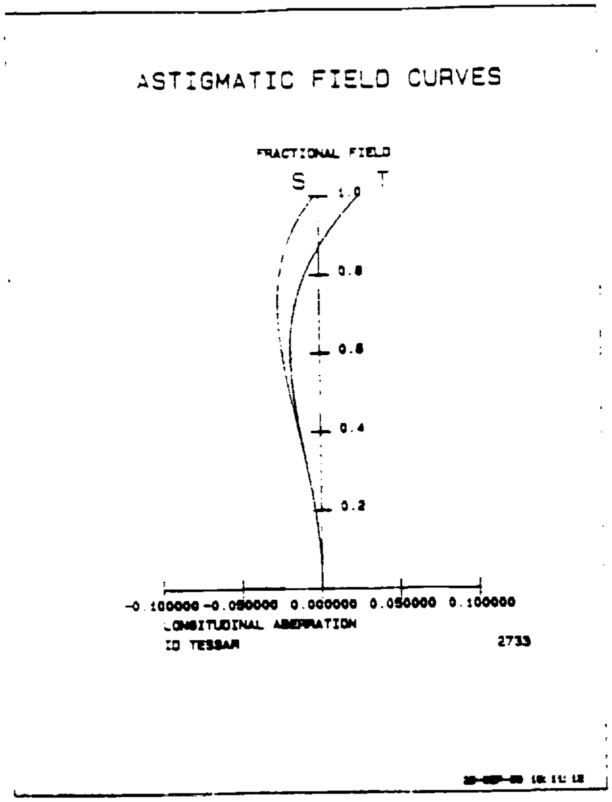


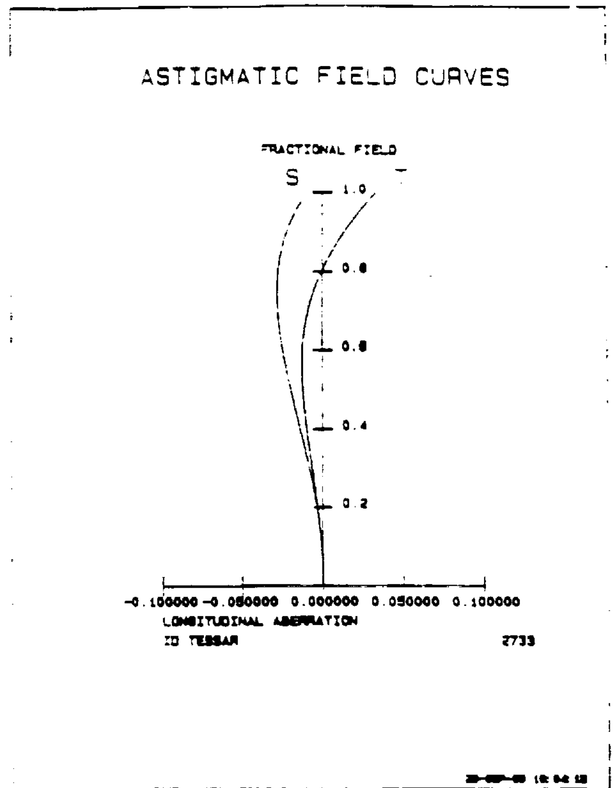
2.0

V= 90 70

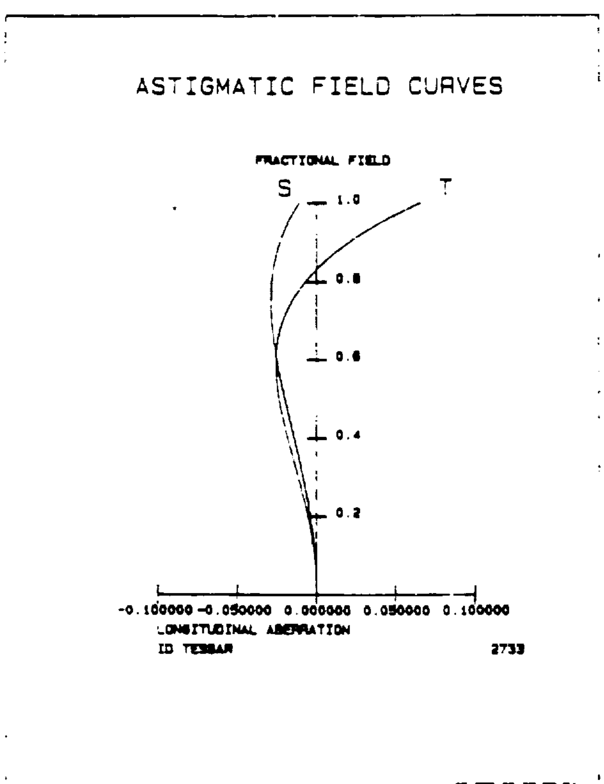
Tessar

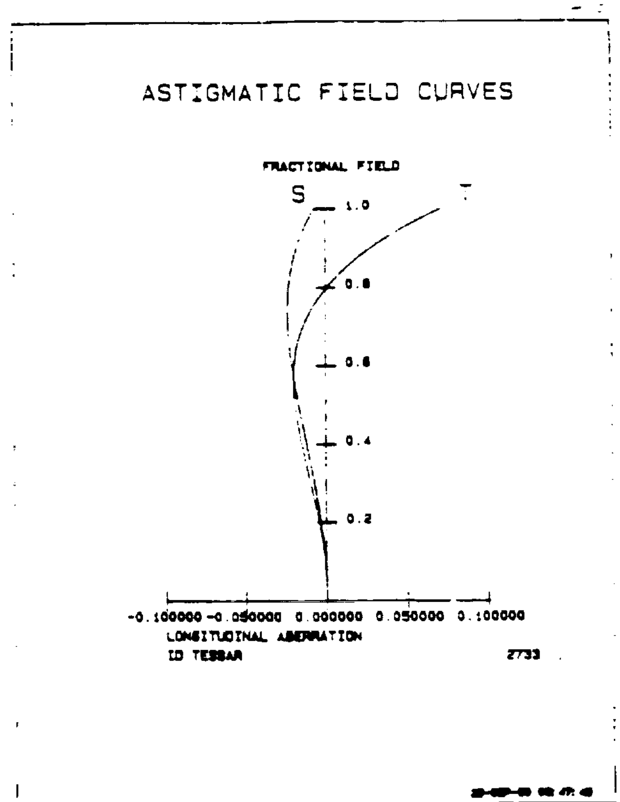
n=





2.2

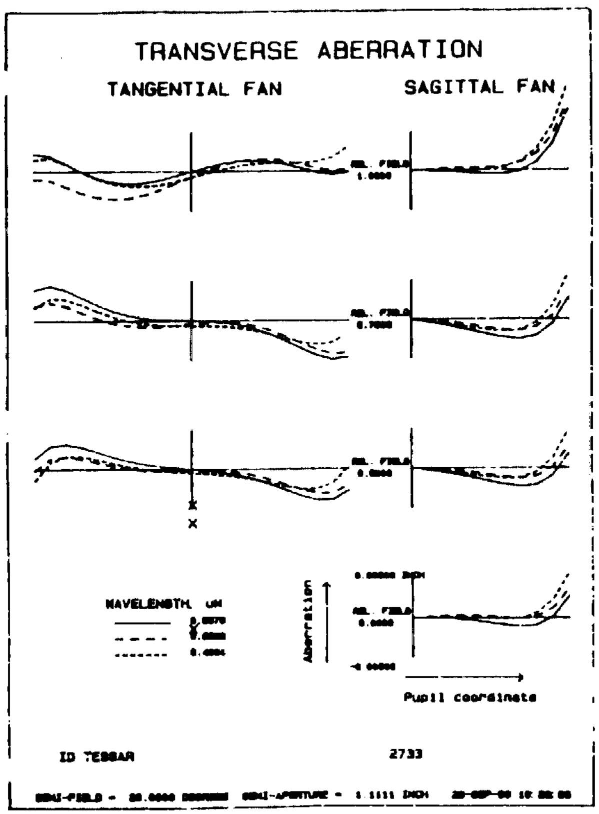


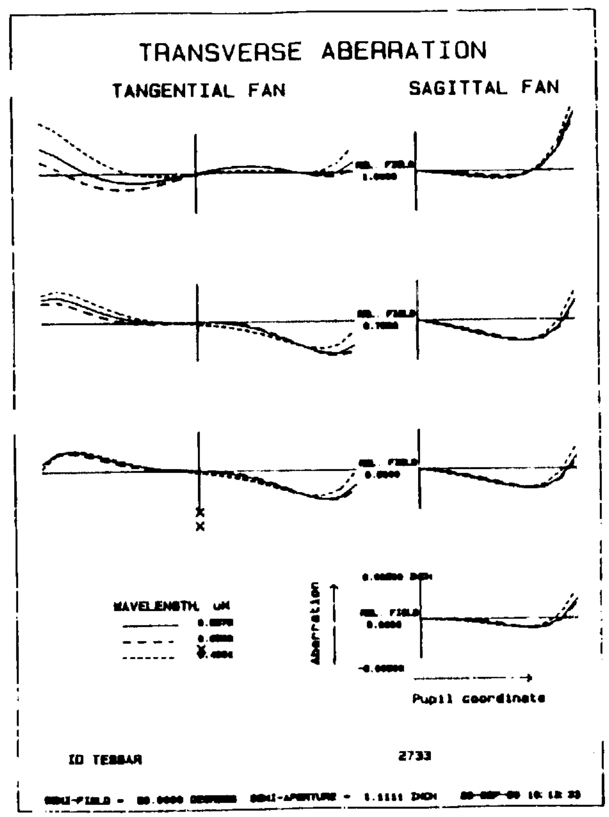


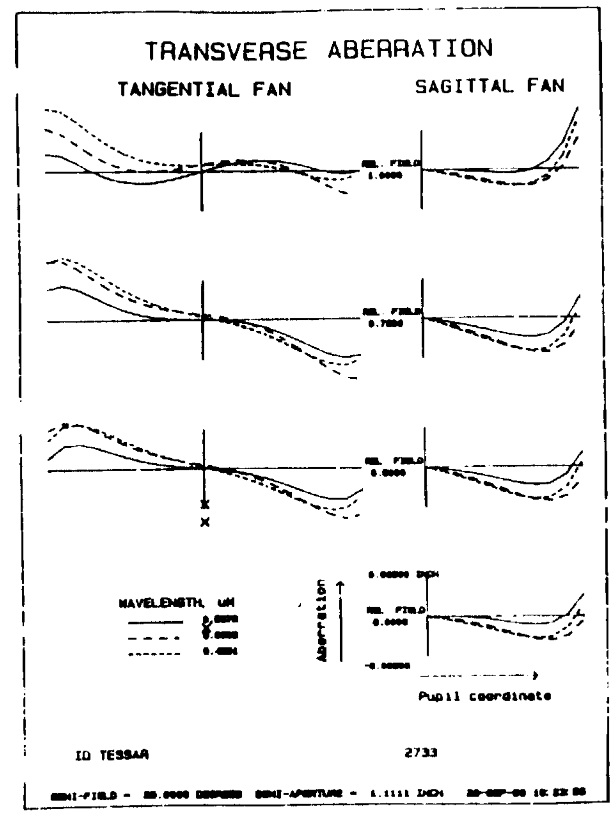
2.0

V= 90 70

Tessar



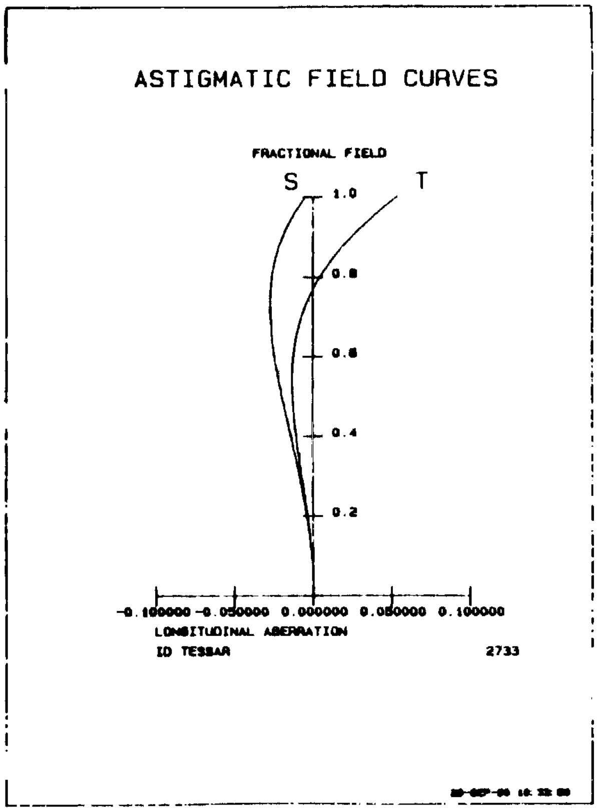


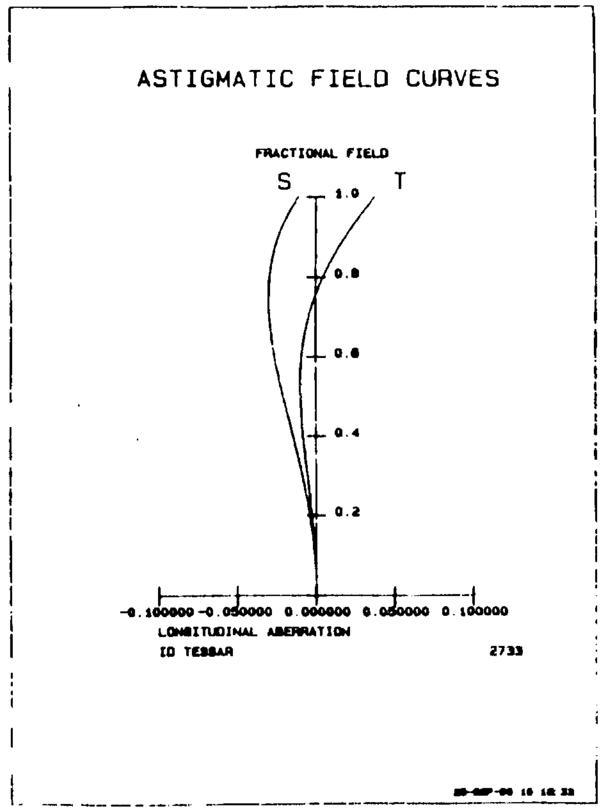


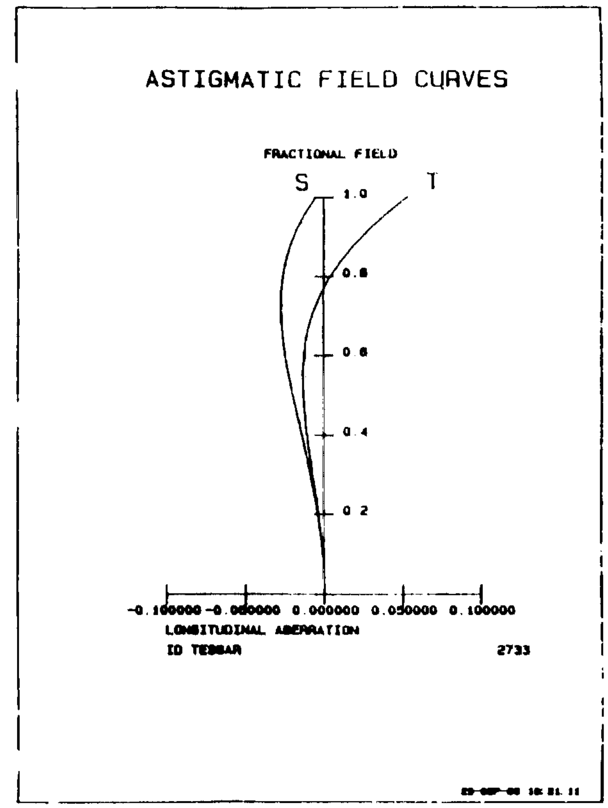
$P_{Fd}=$ 0.65 0.70 0.75

n=2.1 V=80

Tessar



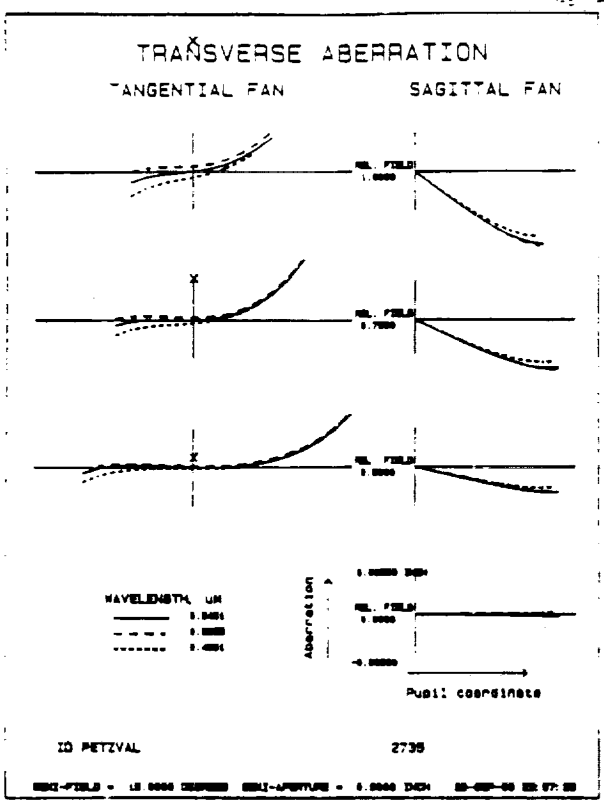


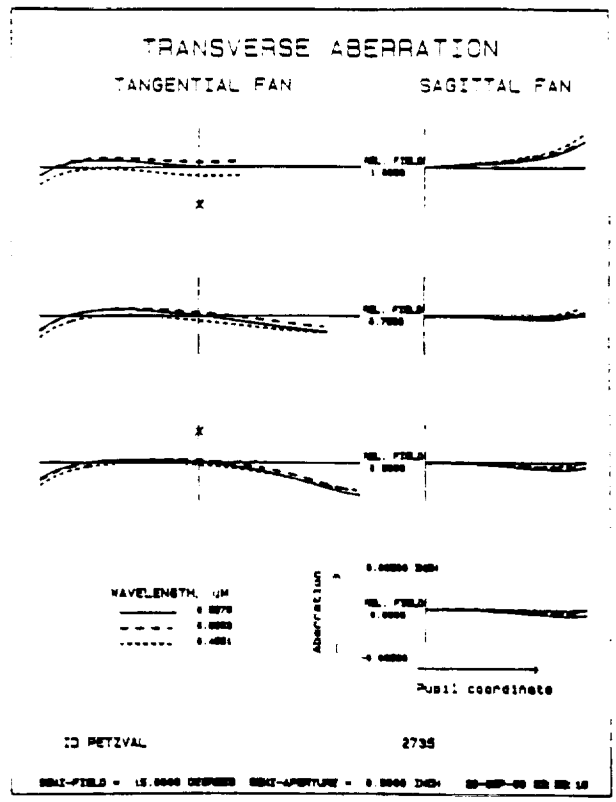


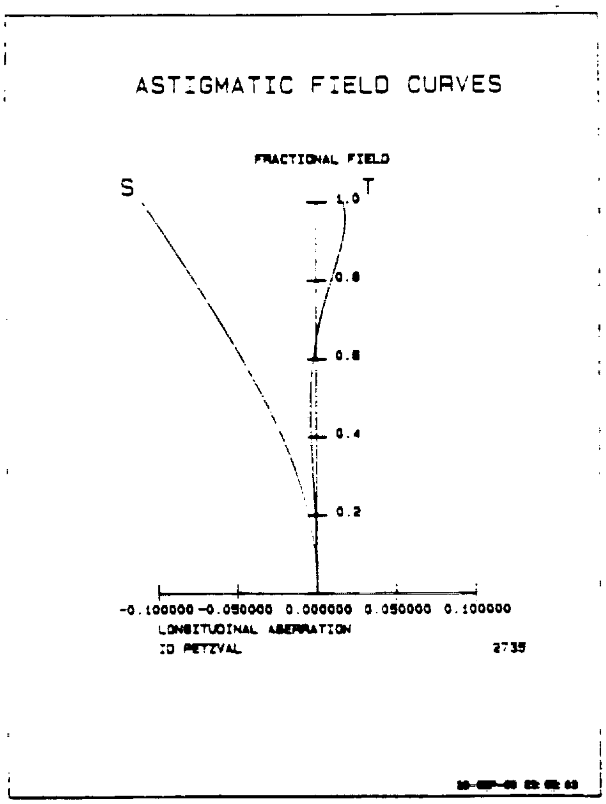
$P_{Fd}=$ 0.65 0.70 0.75

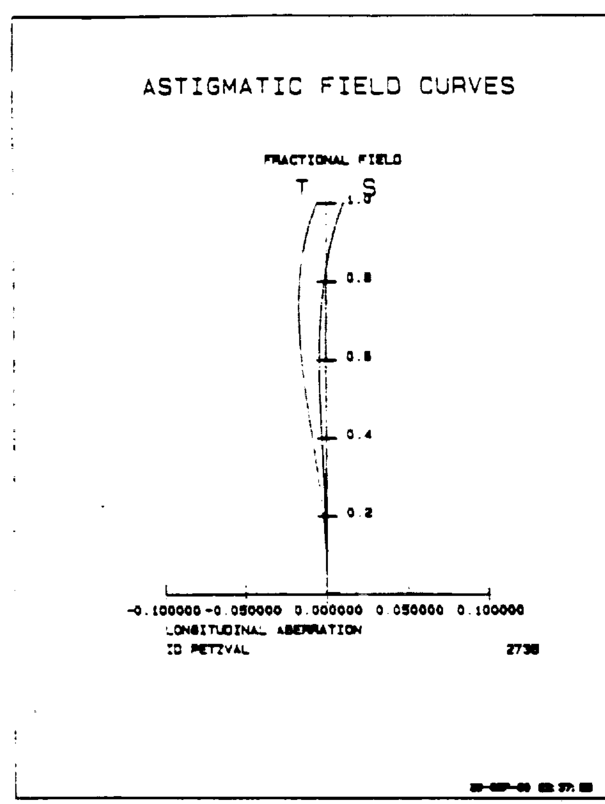
n=2.1 V=80

Petzval





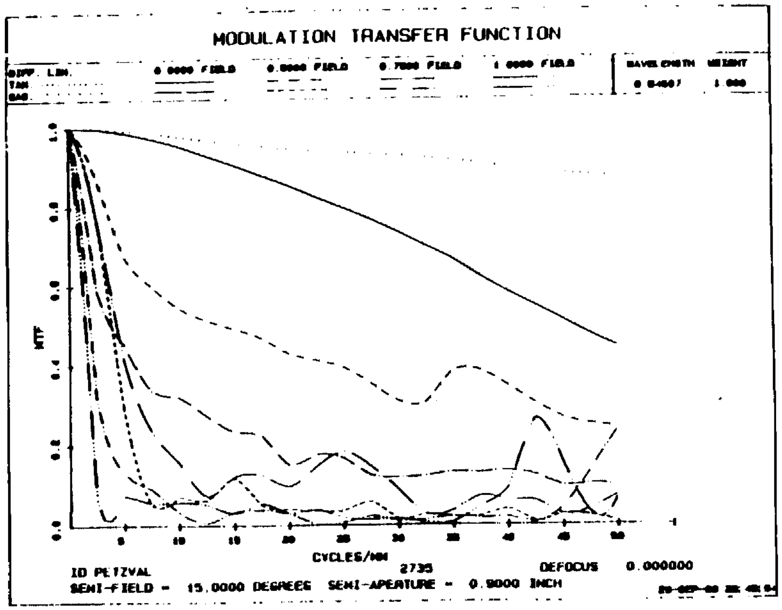


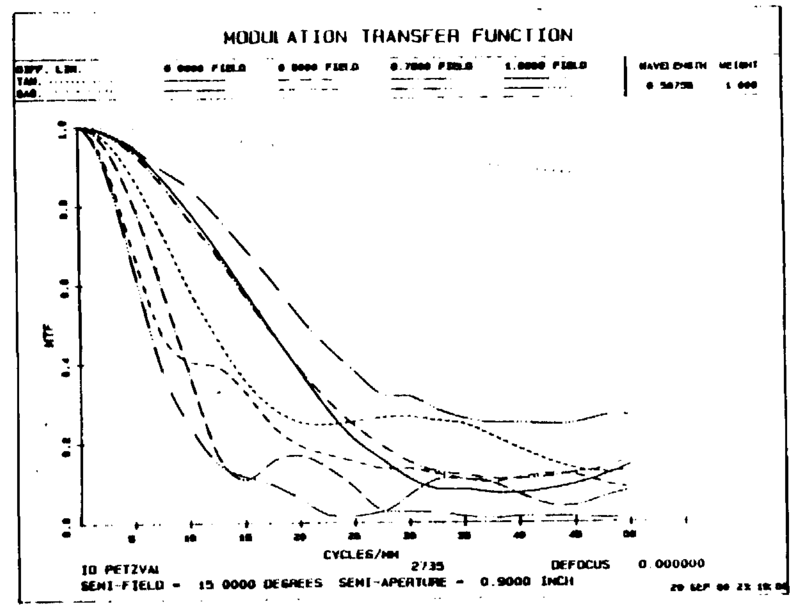


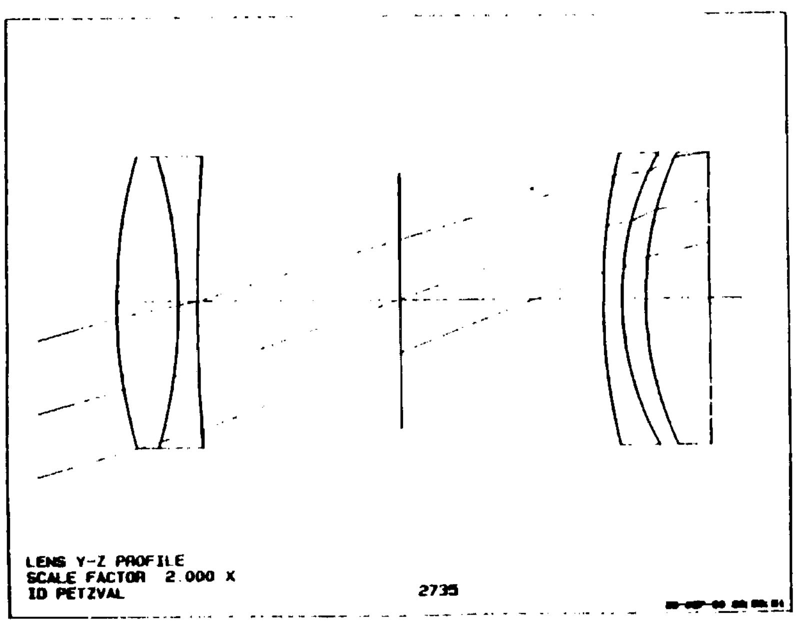
Kingslake

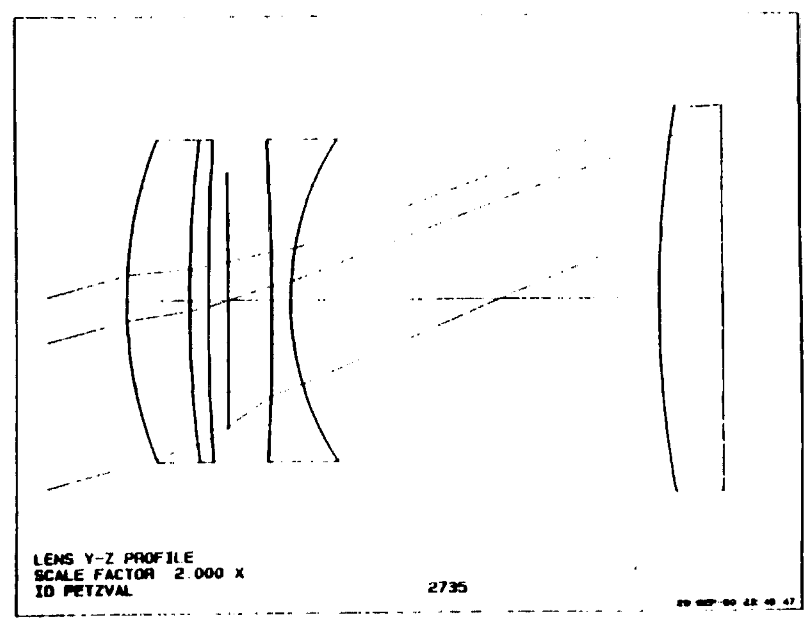
n=2.1 V=80

Petzval







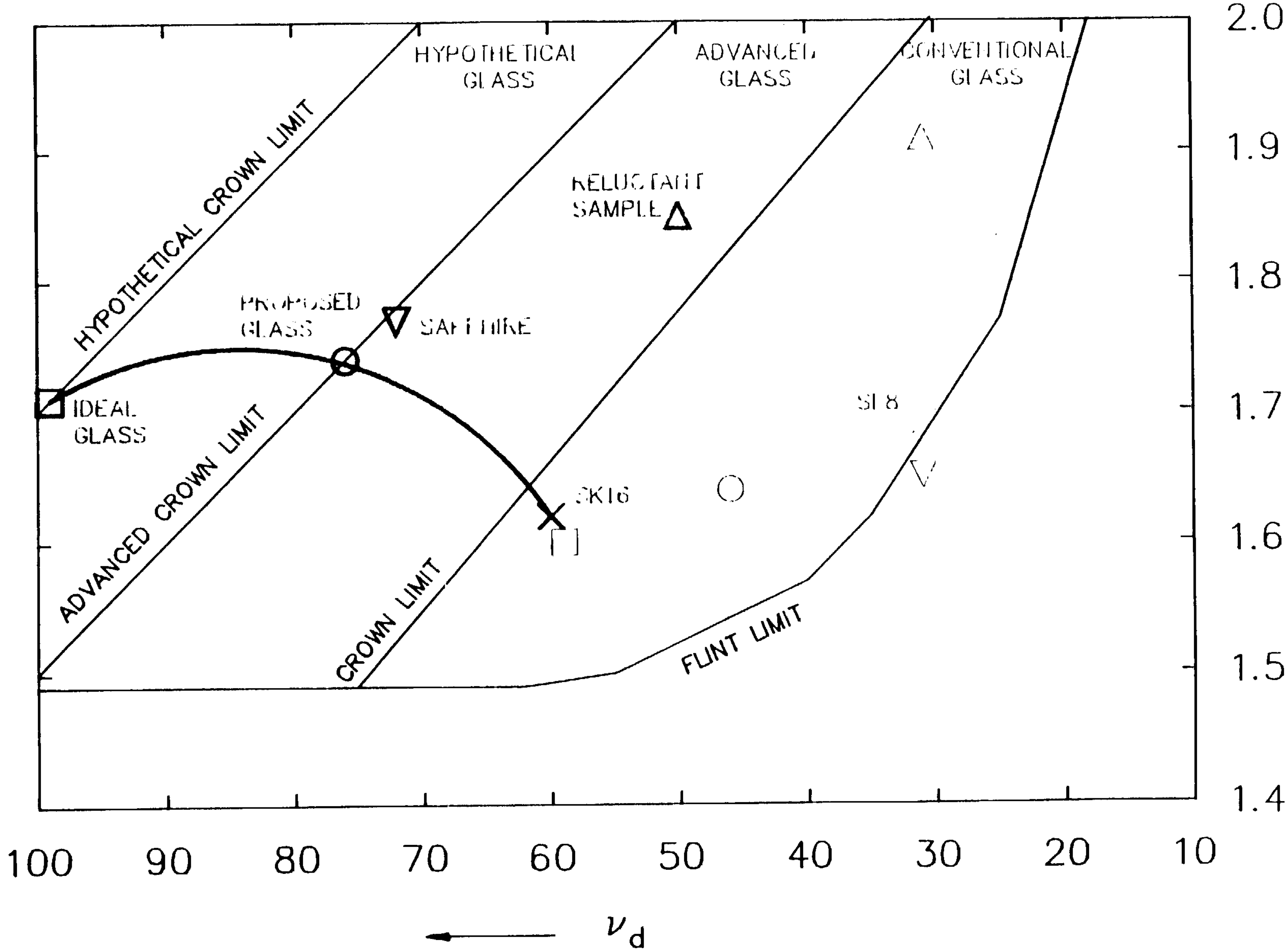


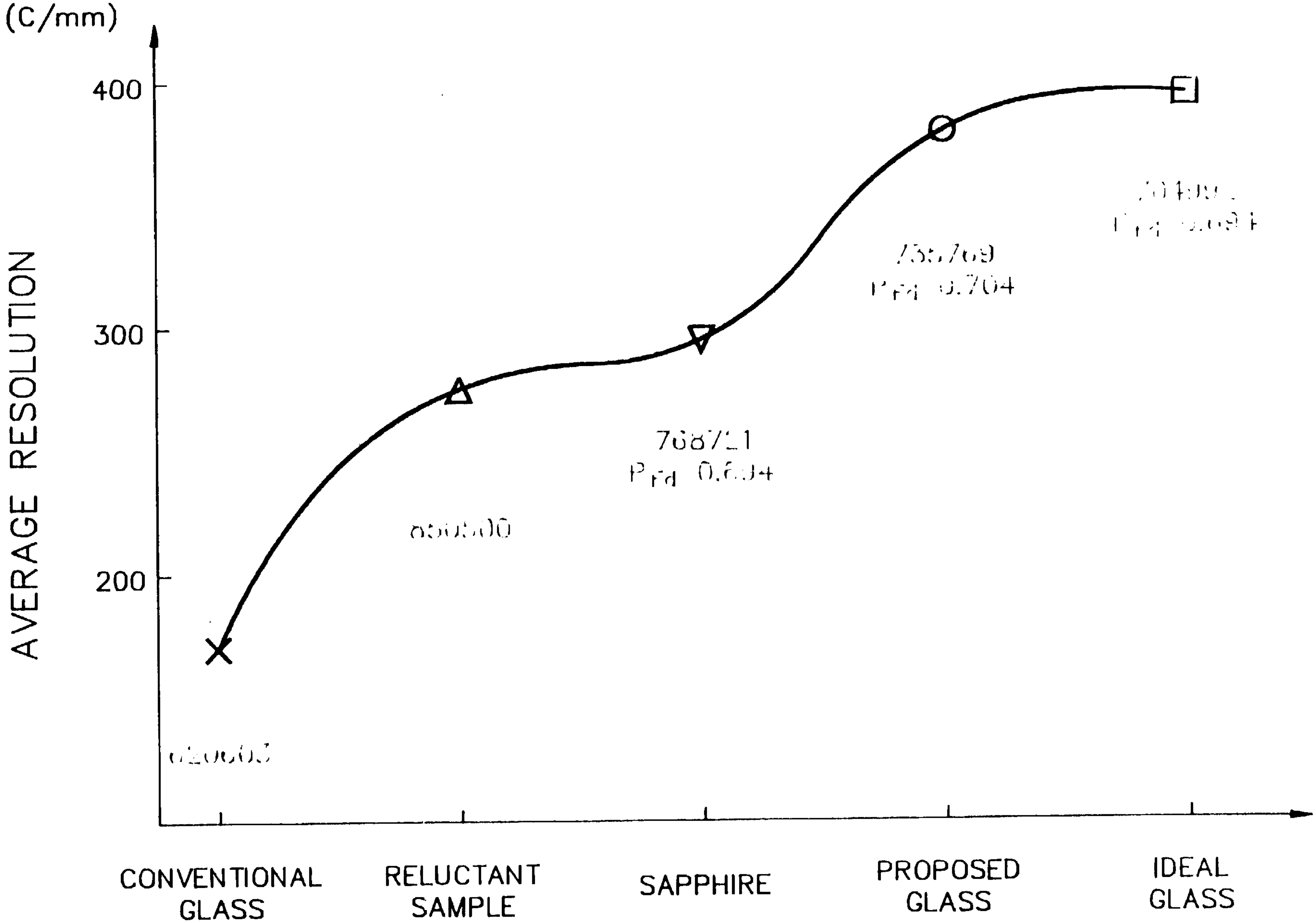
Kingslake

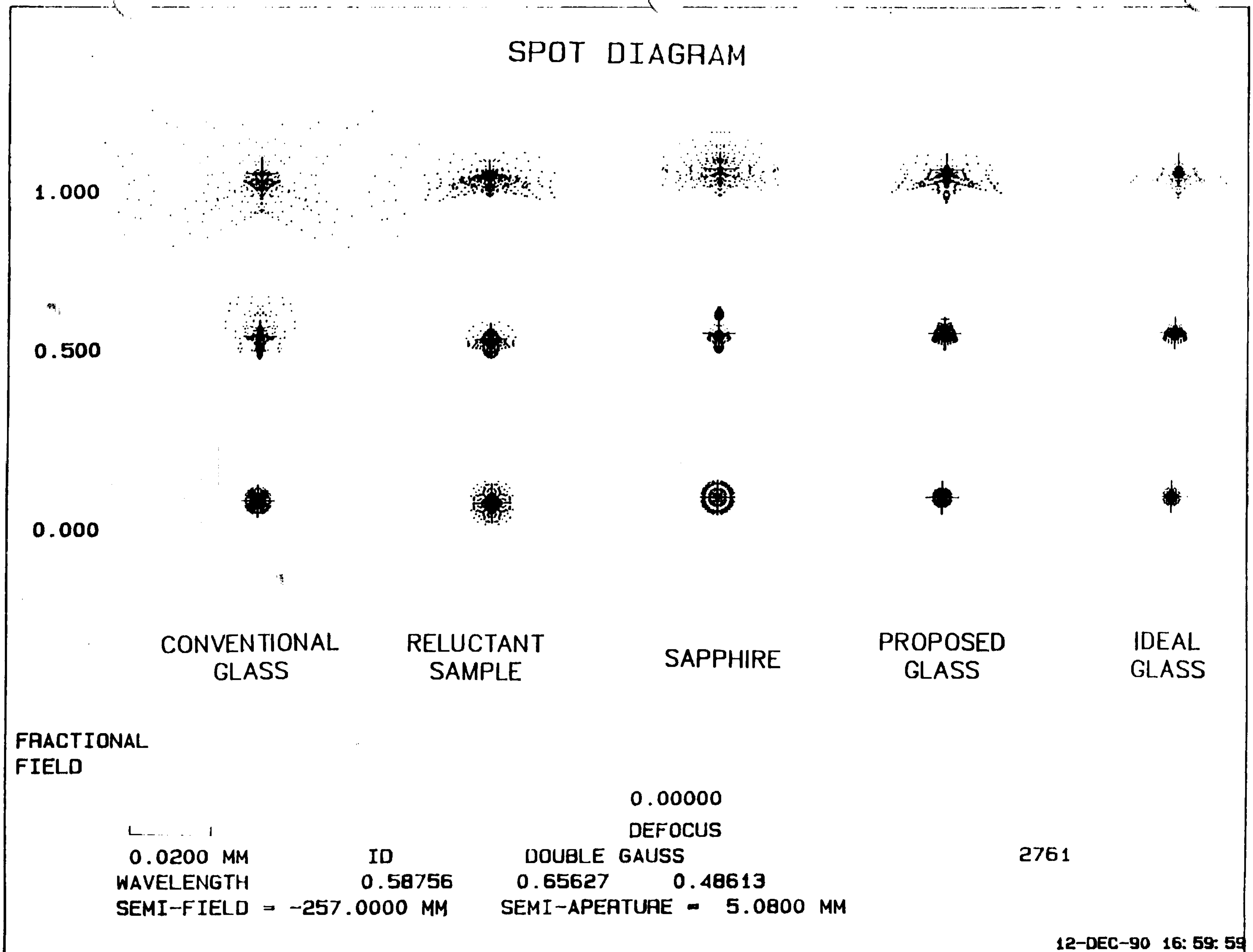
n=2.1 V=80

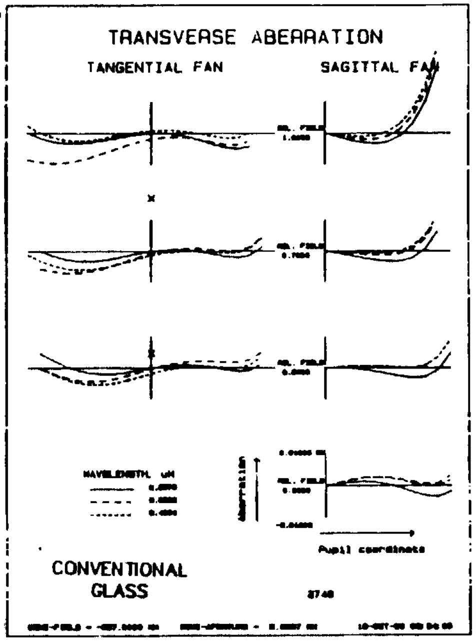
(17)

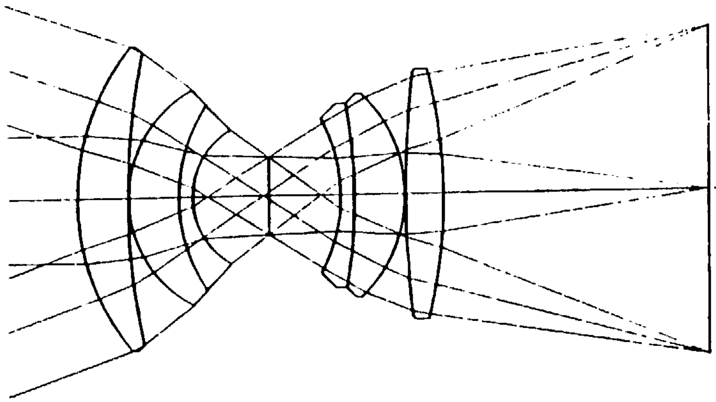
ADVANCED GLASS ANALYSIS



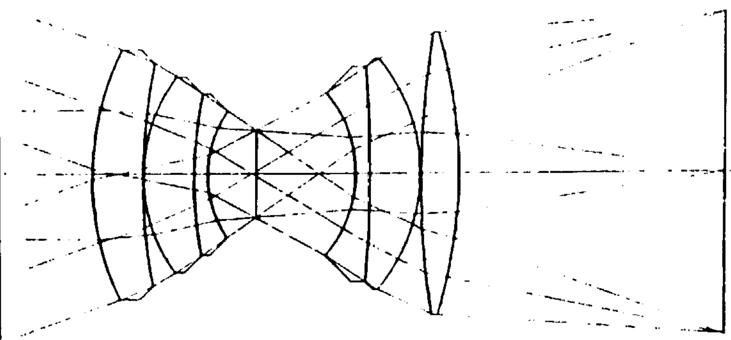

(C/mm)
AVERAGE RESOLUTION
400
300
200
CONVENTIONAL GLASS
RELUCTANT SAMPLE
SAPPHIRE
PROPOSED GLASS
IDEAL GLASS


SPOT DIAGRAM
1.000
0.500
0.000
CONVENTIONAL GLASS
RELUCTANT SAMPLE
SAPPHIRE
PROPOSED GLASS
IDEAL GLASS
FRACTIONAL FIELD
0.00000
DEFOCUS
0.0200 MM
ID
DOUBLE GAUSS
2761
WAVELENGTH
0.58756
0.65627
0.48613
SEMI-FIELD = -257.0000 MM
SEMI-APERTURE = 5.0800 MM
12-DEC-90 16:59:59

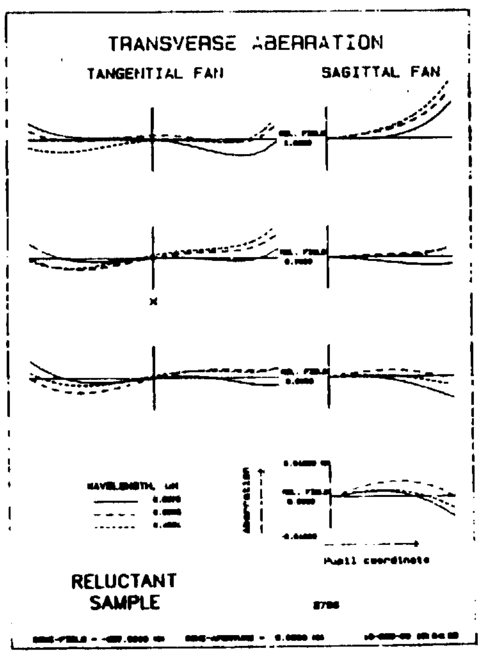


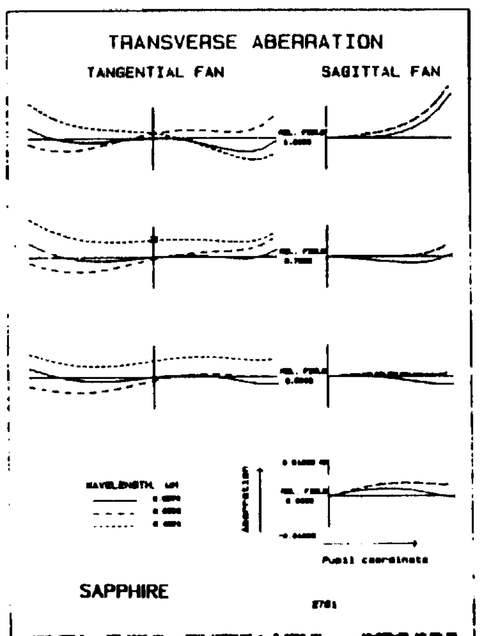


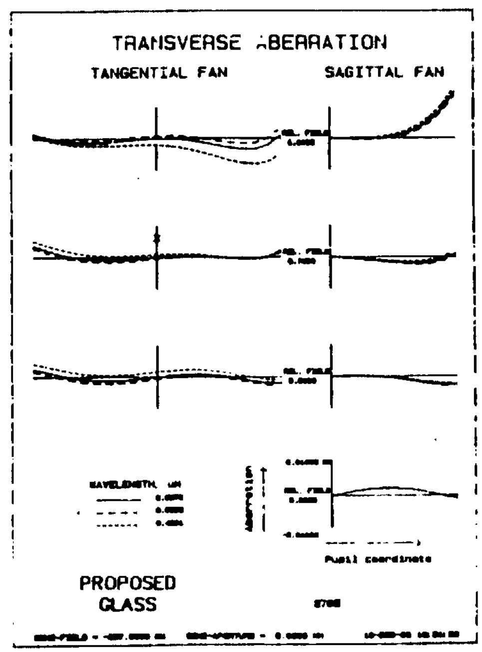
CONVENTIONAL GLASS



PROPOSED GLASS







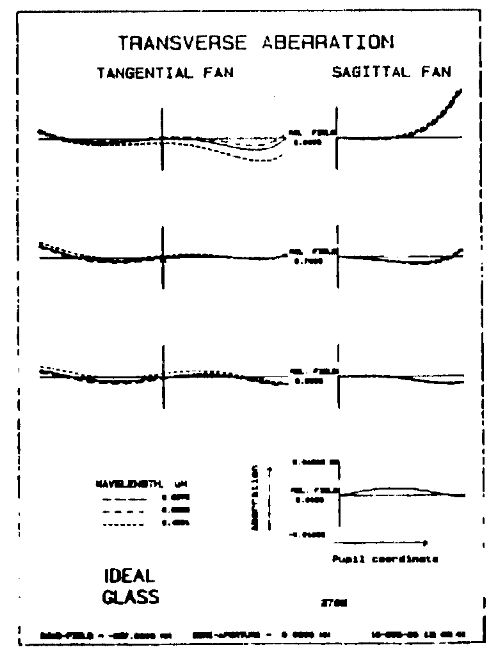


Table 1 Double Gauss lens data

Double Gauss depicted from Kingslake:

```
RLE P
ID DOUBLE GAUSS                                  2631
WAVL       0.65627    0.58756    0.48613
APS        5
UNITS INCH
OBB     0.00000   25      .625
1 CV   0.386          TH  0.5083           GLM  1.6109  57.20
2 CV   0.06787       TH  0.2355
3 CV   0.28732        TH  0.1694           GLM  1.617   36.60
4 CV   0.5767         TH  0.2542
5 CV   0              PTH 4
6 PCV -4              PTH 3                PIN  3
7 PCV -3              PTH 2
8 CV -0.07201         PTH 1                PIN  1
9 CV -0.4099          YMT 0
10 CV  0
END
```

Optimization macro

```
pant
vlist rd 1 2 3 4 8 9
vlist th   2   4
vlist glm 1  3
end
aant
ecn .1  .1 4
M 10 .1 a focl
M 2.33 .1 a totl
m 0 5  a 2 ya 0 0 1
m 0 5  a 2 yc 1 0 1
m 0 5  a 2 yc 1 0 -1
m 0 5  a 2 yc 1 0 .5
m 0 5  a 2 yc 1 0 -.5
m 0 10 a 2 yc .7 0 .7
m 0 10 a 2 yc .7 0 -.7
m 0 5  a 2 xa 1 1
m 0 5
a 1 ya 0 0 .7
s 3 ya 0 0 .7
m 0 5
a 1 ya 1
s 3 ya 1
END
```

Table 1   Double Gauss lens data (cont.)

Double Gauss optimized using conventional glass:

```
 RLE P
ID DOUBLE GAUSS                                        2777
 WAVL       0.65627     0.58756     0.48613
 APS        5
 UNITS INCH
 OBB  0.00    25.00000      0.62500     -0.59764      0.00000      0.00000
 0  AIR
  1 RAD     3.7385400       TH   0.50830000       GLM   1.82307 46.17000
  2 RAD     44.975590       TH   0.48676000       AIR
  3 RAD     6.9860000       TH   0.16940000       GLM   1.69054 30.37000
  4 RAD     2.5114200       TH   0.14314000       AIR
  5 PTH         4      1.00000000         0.000000000E+00
  5 CV    0.00000000E+00
  5 AIR
  6 PCV        -4      1.00000000         0.000000000E+00
  6 PTH         3      1.00000000         0.000000000E+00
  6 PIN         3
     6 GID
 PICKUP
  7 PCV        -3      1.00000000         0.000000000E+00
  7 PTH         2      1.00000000         0.000000000E+00
  7 AIR
  8 PTH         1      1.00000000         0.000000000E+00
  8 PIN         1
  8 RAD    -20.669250
     8 GID
 PICKUP
  9 YMT    0.00000000E+00
  9 RAD    -3.4544500
  9 AIR
 10 CV   0.00000000E+00 TH   0.00000000E+00 AIR
 END
```

Table 1 Double Gauss lens data (cont.)

Double Gauss optimized using hypothetical glass:

```
 RLE P
ID DOUBLE GAUSS                                   2736
 WAVL      0.65627    0.58756    0.48613
 APS        5
 UNITS INCH
 OBB    0.00000  25.00000   0.62500  -0.52606   0.00000   0.00000
 0  AIR
  1 CV  0.30825169     TH  0.50830000     N1  2.19575 N2  2.20000
N3  2.20909
    1 GID
GLASS
  2 CV  0.26600799     TH  0.98550268E-02 AIR
  3 CV  0.45305472     TH  0.16940000     GLM  1.71168 29.35635
  4 CV  0.51884900     TH  0.55168478     AIR
  5 PTH       4   1.00000000      0.000000000E+00
  5 CV   0.00000000E+00
  5 AIR
  6 PCV      -4   1.00000000      0.000000000E+00
  6 PTH       3   1.00000000      0.000000000E+00
  6 PIN       3
    6 GID
PICKUP
  7 PCV      -3   1.00000000      0.000000000E+00
  7 PTH       2   1.00000000      0.000000000E+00
  7 AIR
  8 PTH       1   1.00000000      0.000000000E+00
  8 PIN       1
  8 CV  -0.19526193
    8 GID
PICKUP
  9 YMT   0.00000000E+00
  9 CV  -0.26257409
  9 AIR
 10 CV  0.00000000E+00 TH  0.00000000E+00 AIR
 END
```

Table 2 Aplanat lens data

Aplanat with crown glass (n=1.8, V=50)

```
 RLE P
ID APLANAT                                    2732
 WAVL        0.65627     0.58756     0.48613
 APS       4
 UNITS INCH
 OBB     0.00000    1.00000    1.00000   -0.00584    0.00000    0.00000
 0  AIR
  1 CV  0.14135490      TH   0.42000000      N1   1.79520 N2   1.80000
N3  1.81120
     1 GID
GLASS
  2 CV -0.22534319      TH   0.10000000E-01 AIR
  3 CV -0.22446337      TH   0.15000000      GLM  1.89588 32.05091
  4 YMT    0.00000000E+00
  4 CV   -0.84674041E-02
  4 AIR
  5 CV  0.00000000E+00 TH   0.00000000E+00 AIR
 END
```

Aplanat with crown glass (n=1.8, V=70)

```
 RLE P
ID APLANAT                                    2729
 WAVL        0.65627     0.58756     0.48613
 APS       4
 UNITS INCH
 OBB     0.00000    1.00000    1.00000   -0.00587    0.00000    0.00000
 0  AIR
  1 CV  0.13834416      TH   0.42000000      N1   1.79646 N2   1.80000
N3  1.80789
     1 GID
GLASS
  2 CV -0.18037863      TH   0.10000000E-01 AIR
  3 CV -0.18346091      TH   0.15000000      GLM  1.85740 43.14923
  4 YMT    0.00000000E+00
  4 CV   -0.27742674E-02
  4 AIR
  5 CV  0.00000000E+00 TH   0.00000000E+00 AIR
 END
```

Table 2 Aplanat lens data (cont.)

Aplanat with crown glass (n=1.8, V=90)

```
 RLE P
ID APLANAT                                    2732
 WAVL      0.65627    0.58756    0.48613
 APS      4
 UNITS INCH
 OBB    0.00000   1.00000   1.00000  -0.00590   0.00000   0.00000
 0  AIR
  1 CV  0.13527065     TH  0.42000000     N1  1.79717 N2  1.80000
N3  1.80606
    1 GID
GLASS
  2 CV -0.12221020     TH  0.10000000E-01 AIR
  3 CV -0.13180995     TH  0.15000000     GLM  1.81423 46.94786
  4 YMT   0.00000000E+00
  4 CV  -0.20145143E-02
  4 AIR
  5 CV  0.00000000E+00 TH  0.00000000E+00 AIR
 END
```

Aplanat with crown glass (n=2.0, V=50)

```
 RLE P
ID APLANAT                                    2732
 WAVL      0.65627    0.58756    0.48613
 APS      4
 UNITS INCH
 OBB    0.00000   1.00000   1.00000  -0.00545   0.00000   0.00000
 0  AIR
  1 CV  0.12586967     TH  0.42000000     N1  1.99400 N2  2.00000
N3  2.01400
    1 GID
GLASS
  2 CV -0.10441462     TH  0.10000000E-01 AIR
  3 CV -0.11631340     TH  0.15000000     GLM  1.86413 27.27818
  4 YMT   0.00000000E+00
  4 CV   0.35164327E-01
  4 AIR
  5 CV  0.00000000E+00 TH  0.00000000E+00 AIR
 END
```

Table 2 Aplanat lens data (cont.)

Aplanat with crown glass (n=2.0, V=70)

```
 RLE P
ID APLANAT                                    2729
 WAVL       0.65627    0.58756    0.48613
 APS        4
 UNITS INCH
 OBB     0.00000    1.00000    1.00000  -0.00545    0.00000    0.00000
 0  AIR
  1 CV   0.12598579      TH   0.42000000      N1   1.99558 N2   2.00000
N3  2.00987
     1 GID
GLASS
  2 CV -0.10589437      TH   0.10000000E-01 AIR
  3 CV -0.11727252      TH   0.15000000     GLM   1.87483 39.65449
  4 YMT    0.00000000E+00
  4 CV    0.34177994E-01
  4 AIR
  5 CV   0.00000000E+00 TH   0.00000000E+00 AIR
 END
```

Aplanat with crown glass (n=2.0, V=90)

```
 RLE P
ID APLANAT                                    2732
 WAVL       0.65627    0.58756    0.48613
 APS        4
 UNITS INCH
 OBB     0.00000    1.00000    1.00000  -0.00545    0.00000    0.00000
 0  AIR
  1 CV   0.12340738      TH   0.42000000      N1   1.99646 N2   2.00000
N3  2.00757
     1 GID
GLASS
  2 CV -0.66909312E-01 TH   0.10000000E-01 AIR
  3 CV -0.81889569E-01 TH   0.15000000     GLM   1.85972 42.94432
  4 YMT    0.00000000E+00
  4 CV    0.23486306E-01
  4 AIR
  5 CV   0.00000000E+00 TH -0.13780926E-15 AIR
 END
```

Table 2 Aplanat lens data (cont.)

Aplanat with crown glass (n=2.2, V=50)

```
RLE P
ID APLANAT                                      2732
 WAVL       0.65627     0.58756     0.48613
 APS       4
 UNITS INCH
 OBB     0.00000    1.00000    1.00000   -0.00512    0.00000    0.00000
 0  AIR
  1 CV  0.11775232      TH   0.42000000      N1   2.19280 N2   2.20000
N3  2.21680
     1 GID
GLASS
  2 CV -0.60181371E-01 TH   0.10000000E-01 AIR
  3 CV -0.77035192E-01 TH   0.15000000     GLM   1.86194 25.71786
  4 YMT    0.00000000E+00
  4 CV   0.56132001E-01
  4 AIR
  5 CV  0.00000000E+00 TH   0.00000000E+00 AIR
 END
```

Aplanat with crown glass (n=2.2, V=70)

```
 RLE P
ID APLANAT                                      2729
 WAVL       0.65627     0.58756     0.48613
 APS       4
 UNITS INCH
 OBB     0.00000    1.00000    1.00000   -0.00510    0.00000    0.00000
 0  AIR
  1 CV. 0.11802657      TH   0.42000000      N1   2.19470 N2   2.20000
N3  2.21193
     1 GID
GLASS
  2 CV -0.62869359E-01 TH   0.10000000E-01 AIR
  3 CV -0.78763260E-01 TH   0.15000000     GLM   1.88478 36.91951
  4 YMT    0.00000000E+00
  4 CV   0.55007358E-01
  4 AIR
  5 CV  0.00000000E+00 TH   0.00000000E+00 AIR
 END
```

Table 2 Aplanat lens data (cont.)

Aplanat with crown glass (n=2.2, V=90)

```
 RLE P
ID APLANAT                                          2732
 WAVL        0.65627    0.58756    0.48613
 APS       4
 UNITS INCH
 OBB     0.00000   1.00000   1.00000  -0.00510   0.00000    0.00000
 0  AIR
  1 CV  0.11582641      TH  0.42000000      N1  2.19575 N2  2.20000
N3  2.20909
     1 GID
GLASS
  2 CV -0.37023674E-01 TH  0.10000000E-01 AIR
  3 CV -0.54731152E-01 TH  0.15000000      GLM  1.88216 40.97000
  4 YMT   0.00000000E+00
  4 CV   0.40850275E-01
  4 AIR
  5 CV  0.00000000E+00 TH  0.13780927E-15 AIR
 END
```

Optimization macro

```
PANT
VLIST RD 1 2 3 4
VY 3 GLM
END
AANT
ECN 0.01 0.1 2
M 9.9302 1 A FOCL
M 0 10
A 1 YA 0 0 .7
S 3 YA 0 0 .7
M 0 10  A 2 YA 0 0 1
M 0 10  A 2 YA 0 0 .7
M 0 10  A 2 YC 1 0 1
M 0 10  A 2 YC 1 0 .5
M 0 10  A 2 YC 1 0 -1
M 0 10  A 2 YC 1 0 -.5
M 0 10  A 2 XA 1 1
M 0 10  A 2 XA 1 .5
END
```

Table 3 Tessar lens data

Tessar depicted from Kingslake:

```
 RLE P
ID TESSAR                                                   2631
  WAVL       0.65627    0.58756    0.48613
  APS        5
  UNITS INCH
  OBB      0.00000    20.0000    1.11111
  1 CV   0.328              TH  0.4                 GLM  1.61128 59.12000
  2 CV  -0.0757715          TH  0.347
  3 CV  -0.24               TH  0.18                GLM  1.57628 42.91000
  4 CV  0.3564288           TH  0.37
  5 CV   0                  TH  0.13
  6 CV  -0.135              TH  0.18                GLM  1.51354 51.15
  7 CV   0.325              TH  0.62                GLM  1.61377 56.05
  8 CV  -0.3216593          YMT 0
  9
  END
```

Optimization macro

```
PANT
VY 1 RD
VY 2 RD
VY 3 RD
VY 4 RD
VY 6 RD
VY 7 RD
VY 8 RD
VLIST TH 2 4 5
VLIST GLM 3 6
END
AANT
ECN 0.1  0.1 4
ECP 0.1  0.1 5 6
M 10      1   A FOCL
M 2.227   1   A TOTL
GNR 0 5 3 2 1
GNR 0 5 3 2 .5
GNR 0 5 3 2
M 0 20
A 1 YA 0 0 .7
S 3 YA 0 0 .7
M 0 20
A 1 YA 1
S 3 YA 1
END
```

Table 3   Tessar lens data (cont.)

Tessar optimized using conventional glass:

```
 RLE P
ID TESSAR                                        2731
 WAVL       0.65627    0.58756    0.48613
 APS        5
 UNITS INCH
 OBB     0.00000  20.00000   1.11111  -0.48814   0.00000   0.00000
 0  AIR
  1 CV  0.31510205      TH   0.40000000      GLM  1.82016 46.42604
  2 CV  0.17173494E-01  TH   0.47095138      AIR
  3 CV -0.14735744      TH   0.18000000      GLM  1.75419 27.65261
  4 CV  0.32917965      TH   0.23557089      AIR
  5 CV  0.00000000E+00  TH   0.16277715      AIR
  6 CV -0.96574384E-01  TH   0.18000000      GLM  1.56201 41.41126
  7 CV  0.30060122      TH   0.62000000      GLM  1.67964 37.64630
  8 YMT   0.00000000E+00
  8 CV  -0.27833331
  8 AIR
  9 CV  0.00000000E+00 TH   0.12494182E-15 AIR
 END
```

Tessar optimized using hypothetical glass:

```
 RLE P
ID TESSAR                                        2731
 WAVL       0.65627    0.58756    0.48613
 APS        5
 UNITS INCH
 OBB     0.00000  20.00000   1.11111  -0.51676   0.00000   0.00000
 0  AIR
  1 CV  0.28692182      TH   0.40000000      N1  2.19575 N2  2.20000
N3  2.20909
     1 GID
GLASS
  2 CV  0.57057516E-01 TH   0.40287019      AIR
  3 CV -0.67323786E-01 TH   0.18000000      GLM  1.78634 49.40200
  4 CV  0.35099533     TH   0.35150519      AIR
  5 CV  0.00000000E+00 TH   0.10481570      AIR
  6 CV -0.61586925E-01 TH   0.18000000      GLM  1.59949 65.84520
  7 PIN      1
  7 CV  -0.44362927
  7 TH    0.62000000
     7 GID
PICKUP
  8 YMT   0.00000000E+00
  8 CV  -0.31600859
  8 AIR
  9 CV  0.00000000E+00 TH -0.12490968E-15 AIR
 END
```

Table 4 Tessar lens data

Tessar with crown glass (n=2.0, V=70)

```
 RLE P
ID TESSAR                                             2731
 WAVL      0.65627    0.58756    0.48613
 APS       5
 UNITS INCH
 OBB    0.00000  20.00000   1.11111  -0.34547   0.00000   0.00000
 0  AIR
  1 CV  0.29830168      TH  0.40000000     N1  1.99558 N2  2.00000
N3  2.00987
  2 CV  0.71273347E-01 TH  0.19567183     AIR
  3 CV -0.62998989E-01 TH  0.18000000     GLM  1.70919 56.19140
  4 CV  0.31754040      TH  0.28340029     AIR
  5 CV  0.00000000E+00 TH  0.38315238     AIR
  6 CV -0.81685088E-01 TH  0.18000000     GLM  1.78173 26.73722
  7 PIN       1
  7 CV  -0.32334240E-01
  7 TH   0.62000000
  8 YMT   0.00000000E+00
  8 CV  -0.18553121
  8 AIR
  9 CV  0.00000000E+00 TH  0.00000000E+00 AIR
 END
```

Tessar with crown glass (n=2.0, V=90)

```
 RLE P
ID TESSAR                                             2731
 WAVL      0.65627    0.58756    0.48613
 APS       5
 UNITS INCH
 OBB    0.00000  20.00000   1.11111  -0.41558   0.00000   0.00000
 0  AIR
  1 CV  0.29066611      TH  0.40000000     N1  1.99646 N2  2.00000
N3  2.00757
  2 CV  0.71649547E-01 TH  0.33970059     AIR
  3 CV -0.79792908E-01 TH  0.18000000     GLM  1.68828 58.03100
  4 CV  0.31162234      TH  0.26450524     AIR
  5 CV  0.00000000E+00 TH  0.25473503     AIR
  6 CV -0.60347926E-01 TH  0.18000000     GLM  1.64943 61.45041
  7 PIN       1
  7 CV  -0.96658970E-01
  7 TH   0.62000000
  8 YMT   0.00000000E+00
  8 CV  -0.19224875
  8 AIR
  9 CV  0.00000000E+00 TH  0.00000000E+00 AIR
 END
```

Table 4 Tessar lens data (cont.)

Tessar with crown glass (n=2.2, V=70)

```
 RLE P
ID TESSAR                                      2735
 WAVL      0.65627    0.58756    0.48613
 APS       5
 UNITS INCH
 OBB     0.00000  20.00000   1.11111  -0.51878   0.00000   0.00000
 0  AIR
  1 CV  0.29895661     TH  0.40000000     N1  2.19470 N2  2.20000
N3  2.21184
  2 CV  0.56076002E-01 TH  0.35312333     AIR
  3 CV -0.66450165E-01 TH  0.18000000     GLM  1.86678 42.32344
  4 CV  0.34829453     TH  0.40991356     AIR
  5 CV  0.00000000E+00 TH  0.98816092E-01 AIR
  6 CV -0.27645867E-01 TH  0.18000000     GLM  1.52456 51.54507
  7 PIN      1
  7 CV  -0.34354385
  7 TH   0.62000000
  8 YMT   0.00000000E+00
  8 CV  -0.28488938
  8 AIR
  9 CV  0.00000000E+00 TH -0.12491127E-15 AIR
 END
```

Tessar with crown glass (n=2.2, V=90)

```
 RLE P
ID TESSAR                                      2731
 WAVL      0.65627    0.58756    0.48613
 APS       5
 UNITS INCH
 OBB     0.00000  20.00000   1.11111  -0.51676   0.00000   0.00000
 0  AIR
  1 CV  0.28692182     TH  0.40000000     N1  2.19575 N2  2.20000
N3  2.20909
  2 CV  0.57057516E-01 TH  0.40287019     AIR
  3 CV -0.67323786E-01 TH  0.18000000     GLM  1.78634 49.40200
  4 CV  0.35099533     TH  0.35150519     AIR
  5 CV  0.00000000E+00 TH  0.10481570     AIR
  6 CV -0.61586925E-01 TH  0.18000000     GLM  1.59949 65.84520
  7 PIN      1
  7 CV  -0.44362927
  7 TH   0.62000000
  8 YMT   0.00000000E+00
  8 CV  -0.31600859
  8 AIR
  9 CV  0.00000000E+00 TH -0.12490968E-15 AIR
 END
```

Table 5 Tessar lens data

Tessar with crown glass (P=65)

```
 RLE P
ID TESSAR                                        2731
 WAVL       0.65627    0.58756    0.48613
 APS        5
 UNITS INCH
 OBB     0.00000  20.00000   1.11111  -0.51035   0.00000    0.00000
 0  AIR
  1 CV  0.29414814      TH  0.40000000     N1  2.09519 N2  2.10000
N3  2.10894
  2 CV  0.50154556E-01 TH  0.41495429     AIR
  3 CV -0.90180038E-01 TH  0.18000000     GLM  1.83222 45.36436
  4 CV  0.32050556     TH  0.33486651     AIR
  5 CV  0.00000000E+00 TH  0.11444784     AIR
  6 CV -0.42183626E-01 TH  0.18000000     GLM  1.54016 44.96225
  7 PIN       1
  7 CV  -0.25839484
  7 TH   0.62000000
  8 YMT   0.00000000E+00
  8 CV  -0.25672747
  8 AIR
  9 CV  0.00000000E+00 TH  0.00000000E+00 AIR
 END
```

Tessar with crown glass (P=70)

```
 RLE P
ID TESSAR                                        2731
 WAVL       0.65627    0.58756    0.48613
 APS        5
 UNITS INCH
 OBB     0.00000  20.00000   1.11111  -0.51676   0.00000    0.00000
 0  AIR
  1 CV  0.28692182      TH  0.40000000     N1  2.19575 N2  2.20000
N3  2.20909
  2 CV  0.57057516E-01 TH  0.40287019     AIR
  3 CV -0.67323786E-01 TH  0.18000000     GLM  1.78634 49.40200
  4 CV  0.35099533     TH  0.35150519     AIR
  5 CV  0.00000000E+00 TH  0.10481570     AIR
  6 CV -0.61586925E-01 TH  0.18000000     GLM  1.59949 65.84520
  7 PIN       1
  7 CV  -0.44362927
  7 TH   0.62000000
  8 YMT   0.00000000E+00
  8 CV  -0.31600859
  8 AIR
  9 CV  0.00000000E+00 TH -0.12490968E-15 AIR
 END
```

Table 5 Tessar lens data

Tessar with crown glass (P=75)

```
 RLE P
ID TESSAR                                            2731
 WAVL       0.65627     0.58756     0.48613
 APS       5
 UNITS INCH
 OBB     0.00000  20.00000   1.11111  -0.50995   0.00000    0.00000
 0  AIR
  1 CV  0.29419007     TH  0.40000000     N1  2.09656 N2  2.10000
N3  2.11031
  2 CV  0.50166316E-01 TH  0.41495101     AIR
  3 CV -0.90146626E-01 TH  0.18000000     GLM  1.83229 45.35815
  4 CV  0.32055895     TH  0.33411246     AIR
  5 CV  0.00000000E+00 TH  0.11521033     AIR
  6 CV -0.42162383E-01 TH  0.18000000     GLM  1.54019 44.95783
  7 PIN      1
  7 CV  -0.25842273
  7 TH   0.62000000
  8 YMT   0.00000000E+00
  8 CV  -0.25672427
  8 AIR
  9 CV  0.00000000E+00 TH  0.12491054E-15 AIR
 END
```

Table 6 Petzval lens data

Petzval depicted from Kingslake:

```
 RLE P
ID PETZVAL                                              2735
 WAVL       0.65627    0.54607    0.48613
 APS        4
 UNITS INCH
 OBB    0.00000  15.00000   0.90000  -0.54699   0.00000   0.00000
 0  AIR
  1  CAO  0.900000      0.000000E+00  0.000000E+00
  1 CV  0.31853000     TH  0.40000000     N1  1.50725 N2  1.51173
N3  1.51546
  1 GTB O
K1
  2  CAO  0.900000      0.000000E+00  0.000000E+00
  2 CV -0.31853000     TH  0.12000000     N1  1.56339 N2  1.57046
N3  1.57663
  2 GTB S
LF6
  3  CAO  0.900000      0.000000E+00  0.000000E+00
  3 CV  0.86680004E-01 TH   1.3000000     AIR
  4 CV  0.00000000E+00 TH   1.3000000     AIR
  5 PIN      2
  5  CAO  0.900000      0.000000E+00  0.000000E+00
  5 CV   0.25000000
  5 TH   0.12000000
     5 GID
 PICKUP
  6  CAO  0.900000      0.000000E+00  0.000000E+00
  6 CV  0.54000000     TH  0.15000000     AIR
  7 PIN      1
  7  CAO  0.900000      0.000000E+00  0.000000E+00
  7 CV   0.46800000
  7 TH   0.40000000
     7 GID
 PICKUP
  8 YMT   0.00000000E+00
  8  CAO  0.900000      0.000000E+00  0.000000E+00
  8 CV   0.28106996E-02
  8 AIR
  9 CV  0.00000000E+00 TH  0.00000000E+00 AIR
 END
```

Table 6 Petzval lens data (cont.)

Petzval depicted using hypothetical glass:

```
 RLE P
ID PETZVAL                                        2735
 WAVL       0.65627    0.58756    0.48613
 APS        4
 UNITS INCH
 OBB     0.00000  15.00000   0.90000  -0.12484   0.00000   0.00000
 0   AIR
  1  CAO    1.00000       0.000000E+00  0.000000E+00
  1 CV  0.38448254      TH  0.40000000      N1  2.09568 N2   2.10000
N3  2.10943
     1 GID
GLASS
  2  CAO    1.00000       0.000000E+00  0.000000E+00
  2 CV  0.13937948      TH  0.12000000      N1  1.57723 N2   1.58144
N3  1.59146
  2 GTB S
LF5
  3  CAO    1.00000       0.000000E+00  0.000000E+00
  3 CV  0.71555485E-01 TH  0.12642461      AIR
  4 CV  0.00000000E+00 TH  0.27425138      AIR
  5 PIN       2
  5  CAO    1.00000       0.000000E+00  0.000000E+00
  5 CV  -0.48185461E-01
  5 TH   0.12000000
     5 GID
PICKUP
  6  CAO    1.00000       0.000000E+00  0.000000E+00
  6 CV  0.56519297      TH   2.3488847      AIR
  7 PIN       1
  7  CAO    1.20000       0.000000E+00  0.000000E+00
  7 CV   0.14440130
  7 TH   0.40000000
     7 GID
PICKUP
  8 YMT   0.00000000E+00
  8  CAO    1.20000       0.000000E+00  0.000000E+00
  8 CV   0.28106981E-02
  8 AIR
  9 CV  0.00000000E+00 TH  0.00000000E+00 AIR
 END
```

Table 6 Petzval lens data (cont.)

Optimization macro

```
PANT
VY 1 RD
VY 2 RD
VY 3 RD
VY 5 RD
VY 6 RD
VY 7 RD
VLIST TH      3 4   6
VY 2 GLM
END
AANT
ECN 0.1  0.1 3
M 6.669 .1   A FOCL
M 3.79  .1   A TOTL
M 0 4 A 2 YA 0 0 1
M 0 2 A 2 YA 0 0 0.7
M 0 2 A 2 YC .75 0 -.6
M 0 8 A 2 YC .75 0  .6
M 0 4 A 2 XA .75 .6
M 0 8 A 2 YC 1 0 -.5
M 0 8 A 2 YC 1 0 .5
M 0 15 A 2 XA 1 .5
M 0 20
A 1 YA 0 0 .7
S 3 YA 0 0 .7
M 0 20
A 1 YA .5
S 3 YA .5
END
```

Table 7 Macro for glass map expansion

```
pant
vlist rd 1 2 3 4 5   7 8 9 10 11
vlist th         5 6
VY 4 GLM
vy 10 q
vy 11 q
vy 12 q
end
aant
LL -10 10 0 0.01 COMPOSITE
CD1 Q 10
CD2 Q 11
CD3 Q 12
= (250 -100*CD2)-(CD2-1)/(CD3-CD1)
LL 2.3 10 2.2 0.01 A Q 11
M 35.266 .05 A focl
M 29.12 .05 a totl
GNR 0 10 3 2
GNR 0 10 3 1
GNR 0 10 3 3
GNR 0 15 3 2 .75
GNR 0 12 3 1 .75
GNR 0 12 3 3 .75
GNR 0 5 3 2 1
GNR 0 5 3 1 1
GNR 0 5 3 3 1
END
```

Table 8 Resolution comparison

Glass selection	Color	r.m.s. spot size (mm) Relative Field 0	0.5	1	Mean
Within conventional glass map	2	.00225	.00279	.01070	
	1	.00204	.00383	.01300	.05901
	3	.00160	.00370	.01320	
With reluctant sample	2	.00283	.00303	.00408	
	1	.00349	.00237	.00566	.03592
	3	.00186	.00174	.00727	
With sapphire	2	.00151	.00184	.00423	
	1	.00365	.00199	.00642	.03417
	3	.00367	.00094	.00650	
Within expanded glass map 1	2	.00158	.00172	.00438	
	1	.00158	.00184	.00407	.02616
	3	.00148	.00165	.00524	
Within expanded glass map 2	2	.00145	.00175	.00421	
	1	.00147	.00180	.00394	.02516
	3	.00135	.00175	.00492	

Equivalent average resolution (cycle/mm)

169.5	277.8	294.1	381.7	396.8

Table 9 Six-element double Gauss

Original six-element double Gauss:

```
 RLE P
ID ORIGINAL DOUBLE GAUSS                          2749
 WAVL       0.65627     0.58756     0.48613
 APS         6
 UNITS MM
 OBA  705.000      -257.000           5.0800   -7.9936 0.000000E+00
0.0000
 0  AIR
  1 CV  0.40713341E-01 TH   4.0000000      GLM  1.73600 53.83215
  2 CV  0.17465619E-01 TH  0.50000033E-01 AIR
  3 PIN       1
  3 CV   0.80803102E-01
  3 TH    4.0000000
     3 GID
PICKUP
  4 CV  0.52172312E-01 TH   1.1000000      GLM  1.68620 28.20926
  5 CV  0.11283801     TH   6.7769749      AIR
  6 CV  0.00000000E+00 TH   5.0311810      AIR
  7 PTH       4    1.00000000      0.000000000E+00
  7 PIN       4
  7 CV  -0.95315727E-01
     7 GID
PICKUP
  8 PTH       3    1.00000000      0.000000000E+00
  8 PIN       1
  8 CV  -0.27572219E-01
     8 GID
PICKUP
  9 PTH       2    1.00000000      0.000000000E+00
  9 CV  -0.70772649E-01
  9 AIR
 10 PIN       1
 10 CV   0.18092570E-01
 10 TH    3.0000000
    10 GID
PICKUP
 11 CV -0.23371991E-01 TH   21.071408      AIR
 12 CV  0.00000000E+00 TH  0.63252268E-01 AIR
 END
```

Table 9 Six-element double Gauss (cont.)

Six-element double Gauss using advanced glass:

```
 RLE P
ID ADVANCED DOUBLE GAUSS RLC                      2765
 WAVL      0.65627    0.58756    0.48613
 APS       6
 UNITS MM
 OBA  705.000      -257.000        5.0800   -7.1710 0.000000E+00
0.0000
 0  AIR
  1 CV  0.44112872E-01 TH   4.0000000     GLM  1.85000 50.00000
  2 CV  0.17900796E-01 TH  0.50000040E-01 AIR
  3 PIN       1
  3 CV   0.77804918E-01
  3 TH    4.0000000
     3 GID
PICKUP
  4 CV  0.21160466E-01 TH   1.1000000     GLM  1.90000 30.77828
  5 CV  0.11438061     TH   5.6073563     AIR
  6 CV  0.00000000E+00 TH   8.4312265     AIR
  7 PTH       4   1.00000000      0.000000000E+00
  7 PIN       4
  7 CV  -0.86424304E-01
     7 GID
PICKUP
  8 PTH       3   1.00000000      0.000000000E+00
  8 PIN       1
  8 CV   0.36807770E-02
     8 GID
PICKUP
  9 PTH       2   1.00000000      0.000000000E+00
  9 CV  -0.72761756E-01
  9 AIR
 10 PIN       1
 10 CV   0.15487247E-01
 10 TH    3.0000000
    10 GID
PICKUP
 11 CV -0.21321468E-01 TH   21.071408     AIR
 12 CV  0.00000000E+00 TH  0.48968945E-01 AIR
 END
```

Table 9 Six-element double Gauss (cont.)

Six-element double Gauss using sapphire like glass:

```
 RLE P
ID ORIGINAL DOUBLE GAUSS                        2759
 WAVL      0.65627    0.58756    0.48613
 APS      6
 UNITS MM
 OBA  705.000     -257.000         5.0800  -5.2563 0.000000E+00
0.0000
 0  AIR
  1 CV  0.49275008E-01 TH   4.0000000     N1  1.76494 N2  1.76823
N3  1.77559
  1 GTB U
SAPPHIRE
  2 CV  0.23583707E-01 TH  0.50000033E-01 AIR
  3 PIN       1
  3 CV   0.72224159E-01
  3 TH    4.0000000
     3 GID
PICKUP
  4 CV  0.68172605E-01 TH   1.1000000     GLM  1.64792 30.57165
  5 CV  0.10905643     TH   3.5077279     AIR
  6 CV  0.00000000E+00 TH   8.4211566     AIR
  7 PTH       4   1.00000000      0.000000000E+00
  7 PIN       4
  7 CV  -0.10433072
     7 GID
PICKUP
  8 PTH       3   1.00000000      0.000000000E+00
  8 PIN       1
  8 CV  -0.49438617E-01
     8 GID
PICKUP
  9 PTH       2   1.00000000      0.000000000E+00
  9 CV  -0.73931196E-01
  9 AIR
 10 PIN       1
 10 CV   0.16864218E-01
 10 TH    3.0000000
    10 GID
PICKUP
 11 CV -0.24055168E-01 TH   21.071408     AIR
 12 CV  0.00000000E+00 TH  0.54265477E-01 AIR
 END
```

Table 9   Six-element double Gauss (cont.)

Best searching in expanded glass map:

```
 RLE P
ID ADVANCED DOUBLE GAUSS 250              2765
 WAVL      0.65627    0.58756    0.48613
 APS      6
 UNITS MM
 OBA  705.000     -257.000        5.0800  -5.4882 0.000000E+00
0.0000
 0  AIR
  1 CV  0.45171531E-01 TH   4.0000000     N1  1.73217 N2  1.73500
N3  1.74172
    1 GID
GLASS
  2 CV  0.23227147E-01 TH  0.50000037E-01 AIR
  3 PIN       1
  3 CV   0.79127886E-01
  3 TH    4.0000000
    3 GID
PICKUP
  4 CV  0.32741787E-01 TH   1.1000000     GLM  1.64228 45.12079
  5 CV  0.11520556     TH   3.8473269     AIR
  6 CV  0.00000000E+00 TH   7.9103439     AIR
  7 PTH       4   1.00000000      0.000000000E+00
  7 PIN       4
  7 CV  -0.10370553
    7 GID
PICKUP
  8 PTH       3   1.00000000      0.000000000E+00
  8 PIN       1
  8 CV  -0.95245351E-02
    8 GID
PICKUP
  9 PTH       2   1.00000000      0.000000000E+00
  9 CV  -0.72095007E-01
  9 AIR
 10 PIN       1
 10 CV   0.14703595E-01
 10 TH    3.0000000
   10 GID
PICKUP
 11 CV -0.26381678E-01 TH   21.071408     AIR
 12 CV  0.00000000E+00 TH  0.57814983E-01 AIR
 END
```

Table 9 Six-element double Gauss (cont.)

Best searching in extended glass map:

```
 RLE P
ID ADVANCED DOUBLE GAUSS 250              2765
 WAVL      0.65627    0.58756    0.48613
 APS      6
 UNITS MM
 OBA  705.000     -257.000         5.0800   -5.5416 0.000000E+00
0.0000
 0  AIR
  1 CV   0.47580187E-01 TH   4.0000000      N1   1.70225 N2   1.70442
N3  1.70935
     1 GID
GLASS
  2 CV   0.24897194E-01 TH  0.50000037E-01 AIR
  3 PIN       1
  3 CV    0.79507016E-01
  3 TH     4.0000000
     3 GID
PICKUP
  4 CV   0.28008194E-01 TH   1.1000000      GLM  1.60100 58.97927
  5 CV   0.11666779     TH   3.8386061      AIR
  6 CV   0.00000000E+00 TH   7.6550418      AIR
  7 PTH       4    1.00000000      0.000000000E+00
  7 PIN       4
  7 CV   -0.10965402
     7 GID
PICKUP
  8 PTH       3    1.00000000      0.000000000E+00
  8 PIN       1
  8 CV   -0.11676794E-01
     8 GID
PICKUP
  9 PTH       2    1.00000000      0.000000000E+00
  9 CV   -0.73771001E-01
  9 AIR
 10 PIN       1
 10 CV    0.12249025E-01
 10 TH     3.0000000
    10 GID
PICKUP
 11 CV -0.30185184E-01 TH   21.071408      AIR
 12 CV   0.00000000E+00 TH  0.58361630E-01 AIR
 END
```