Understanding Optical Glass and Color Correction

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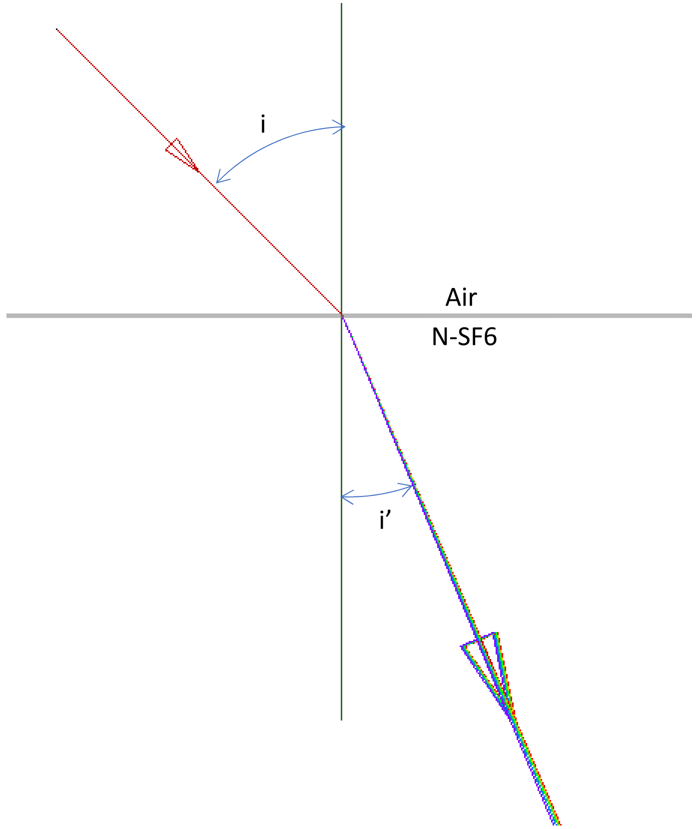
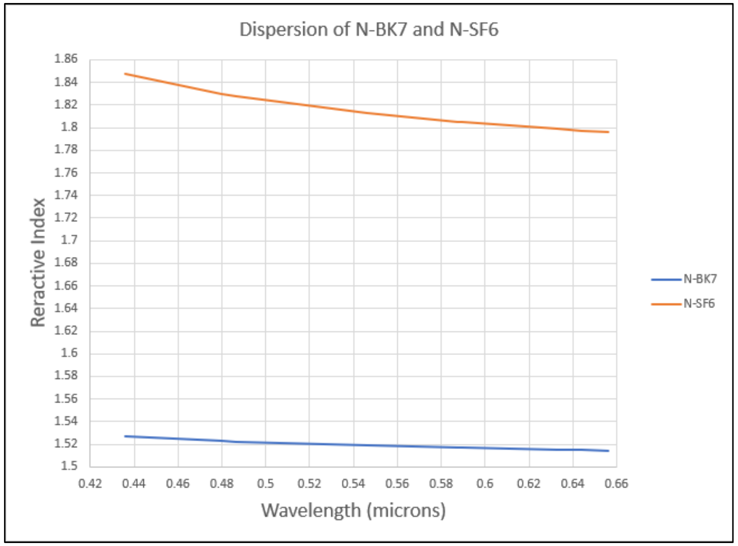
Ultimately It's All About Snell's Law!

$$n(\lambda)\sin(i) = n'(\lambda)\sin(i')$$



Basic Basics



Refractive index varies with wavelength**

Abbe number (dispersion) $$\nu = \frac{n_d - 1}{n_F - n_C}$$

Partial Dispersion $$P_{\lambda F} = \frac{n_\lambda - n_F}{n_F - n_C}$$

Dispersion depends on which wavelengths you select

	Abbe	
Lines	**N-BK7**	**N-SF6**
F d C	64.167	25.359
F' d C'	63.724	24.926
g d C	41.806	15.695
g F' F	121.362	42.445
d D HeNe	302.003	126.677

** If this is a new concept and/or you've never seen it before, the rest of this lecture is probably not going to make sense!

Chromatic Aberration Basics

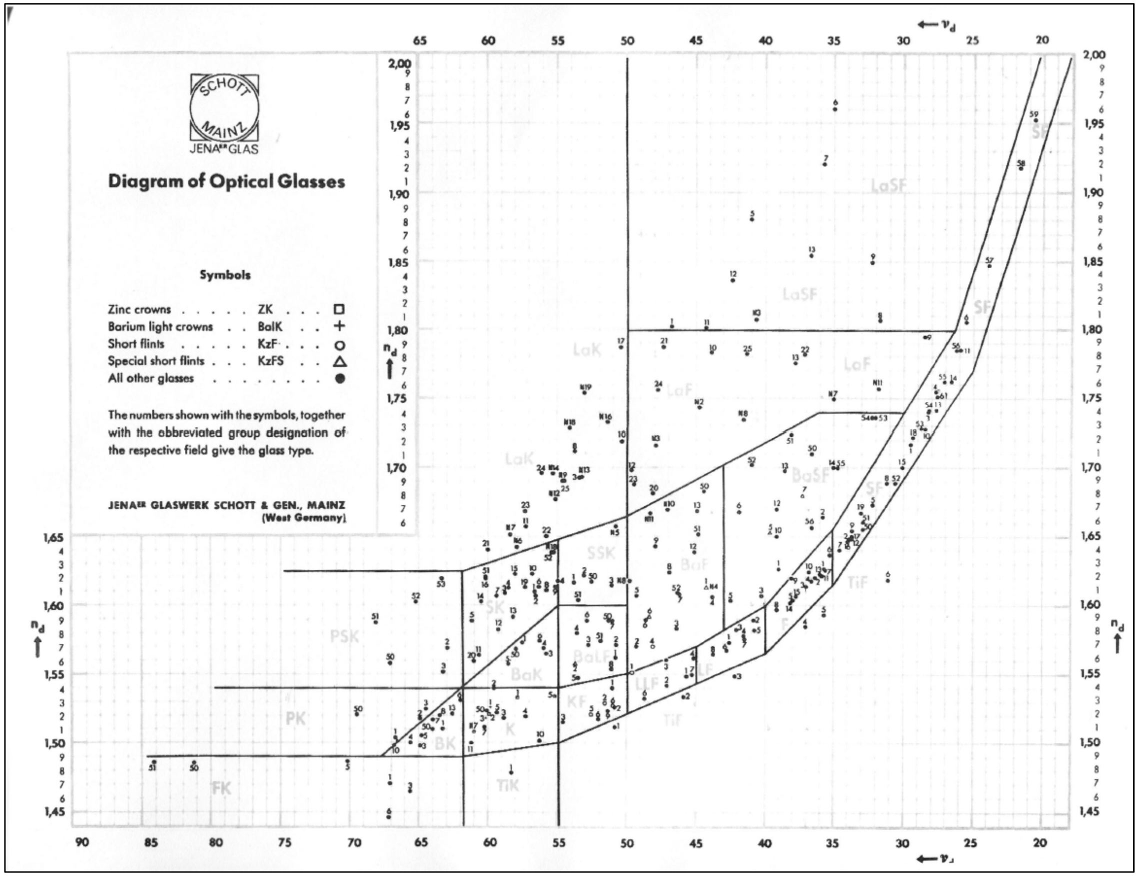
- Defining the basic notation:
  - ν Abbe number
  - y marginal ray height
  - ȳ chief ray height
  - u marginal ray angle (reduced marginal ray angle ω = n u)
  - ū chief ray angle (reduced chief ray angle $\overline{\omega}$ = n ū)
  - Φ power (= 1 / f)
- For paraxial axial color we have

$$\frac{-1}{\omega_k'}\left(\frac{y_1^2\Phi_1}{\nu_1}+\frac{y_2^2\Phi_2}{\nu_2}+\frac{y_3^2\Phi_3}{\nu_3}+\ldots\right)=\frac{-1}{\omega_k'}\sum_{i=1}^{k}\frac{y_i^2\,\Phi_i}{\nu_i}=PAC$$

- For paraxial lateral color we have

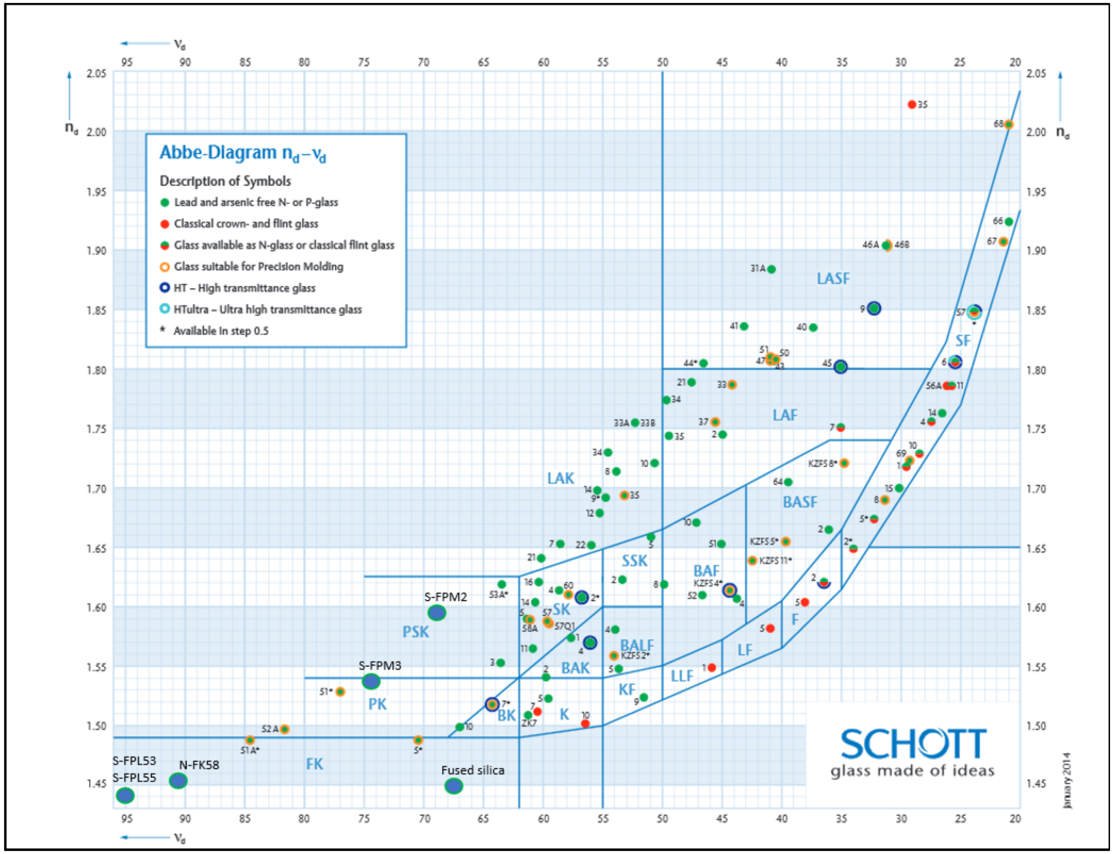
$$\frac{-1}{\omega_k'}\left(\frac{y_1\,\overline{y}_1\Phi_1}{\nu_1}+\frac{y_2\overline{y}_2\Phi_2}{\nu_2}+\frac{y_3\overline{y}_3\Phi_3}{\nu_3}+\ldots\right)=\frac{-1}{\omega_k'}\sum_{i=1}^{k}\frac{\mathrm{y}_i\,\overline{y}_i\,\Phi_i}{\nu_i}=PLC$$

"In the old days, there were lots of glasses...."



- Schott catalog circa 1978
- Over 250 glasses
  - Many had lead, arsenic and other toxic dopants
  - Some were radioactive (i.e., thorium-doped)
- If lens design software had been better, we would have been able to tweak color correction much better than we can today → more subtle glass options

Modern Glass Map



- Fewer choices → approximately 124 glasses
- Under "green" pressure from EU, Schott has announced that it may stop producing optical glasses in 5 years. (Optical glass is only approximately 8% of Schott's market.)

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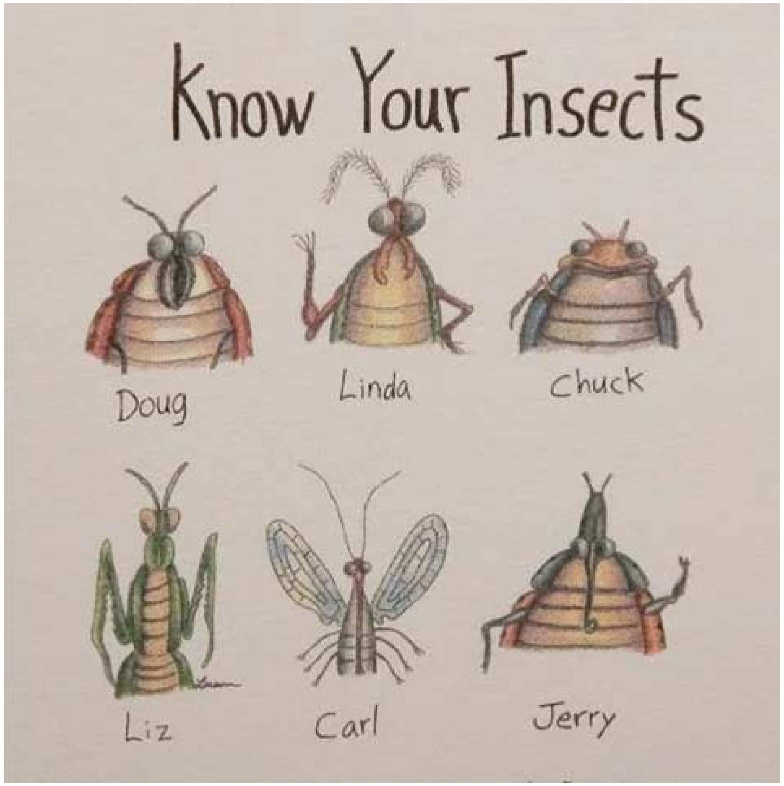
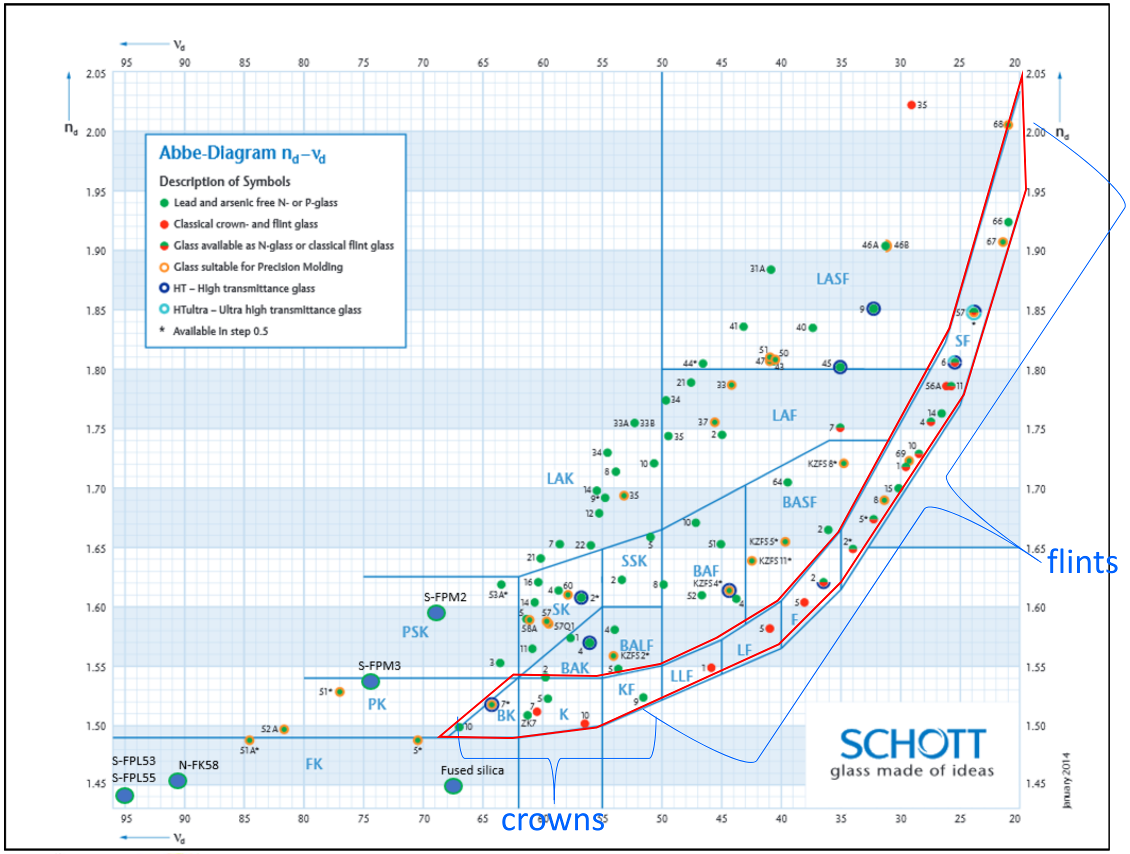
Know Your Glass Families!



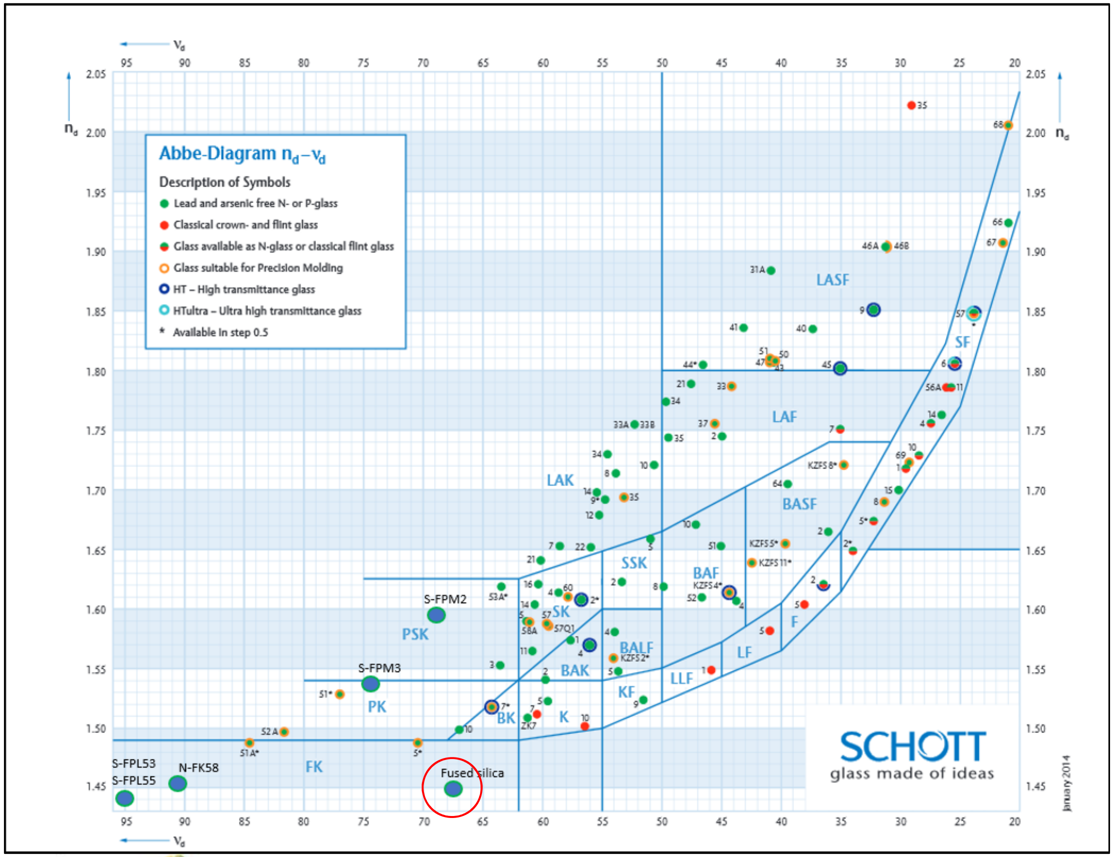
"The Far Side" by Gary Larson

Glass Families: “Old Glass Line” or “Normal Glass Line”



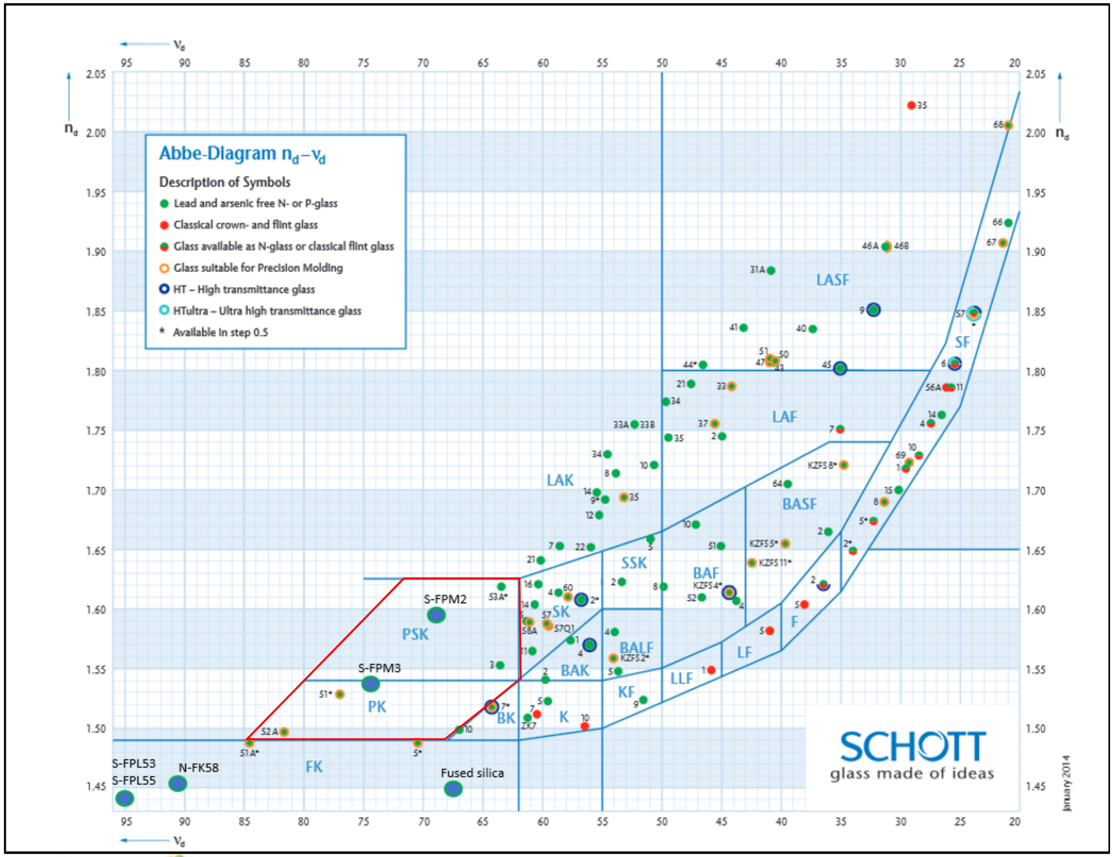
- “Generic” optical glass
- Restriction to these glasses gives little opportunity to correct color over any appreciable bandwidth
- Useful to “tweak” color but won’t give great color correction if used exclusively in a design
- Generally these are the least expensive glasses

Glass Families: Fused Silica



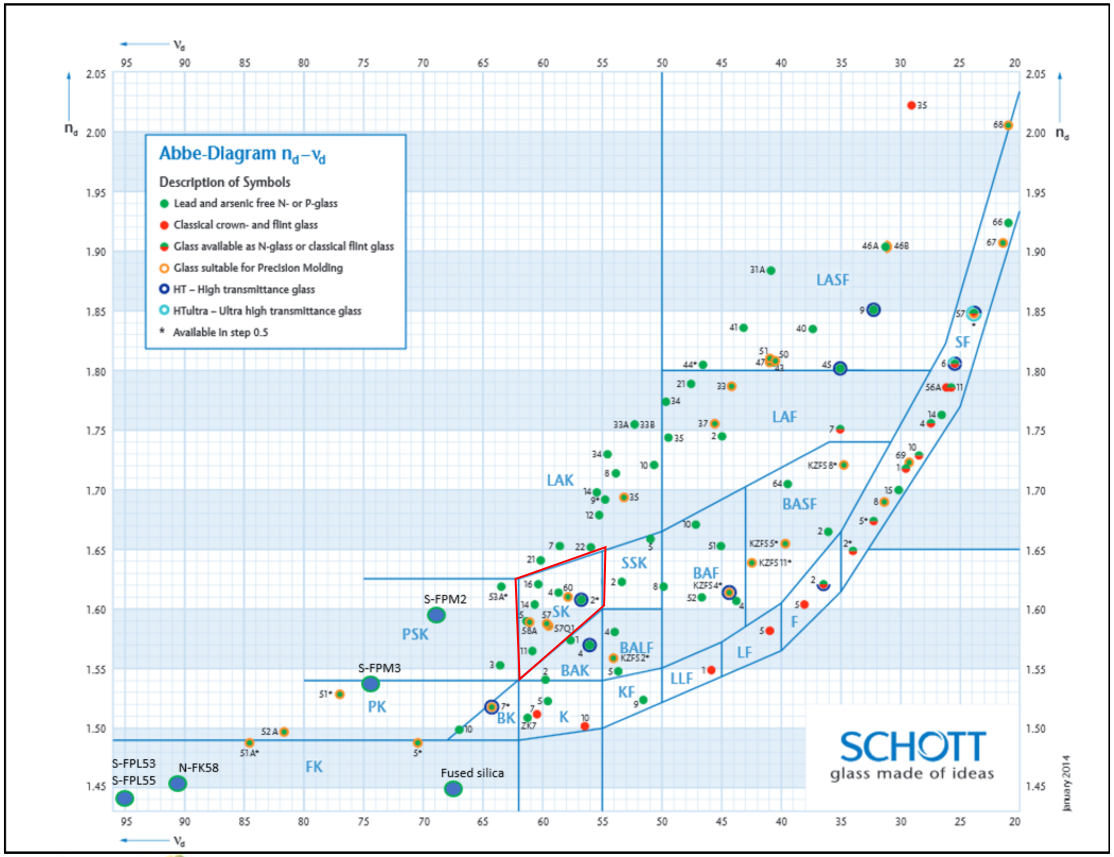
- Boring!
- Looks very much like one of the glasses on the “old glass line” → rarely a better choice than higher index N-BK7
- Principal advantages:
    - Radiation hard
    - Environmentally stable
    - Low cost
    - Transmission into deep UV (<160 nm, depends on specific type/grade)
- Principal disadvantages:
    - Low refractive index
        - Low index can make AR coating a challenge
    - (Yawn!) Unexciting partial dispersion
    - Some grades fluoresce in UV

Glass Families: Phosphate Crowns



- Occupy northwest corner of the glass map → highest refractive indices and lowest dispersions
- Partial dispersions are relatively close to the "normal glass line" and so they can't do "kick butt" color correction on their own, but they are better than generic crowns
- N-PSK53A is a "secret weapon" useful glass to tweak color correction

Glass Families: Dense Crowns



- Higher index “generic glass”
- Opportunity to mate with flint glasses to make a “buried surface”
- Why do we use these glasses? Monochromatic aberrations need love and correction as well! And they can tweak chromatic correction.

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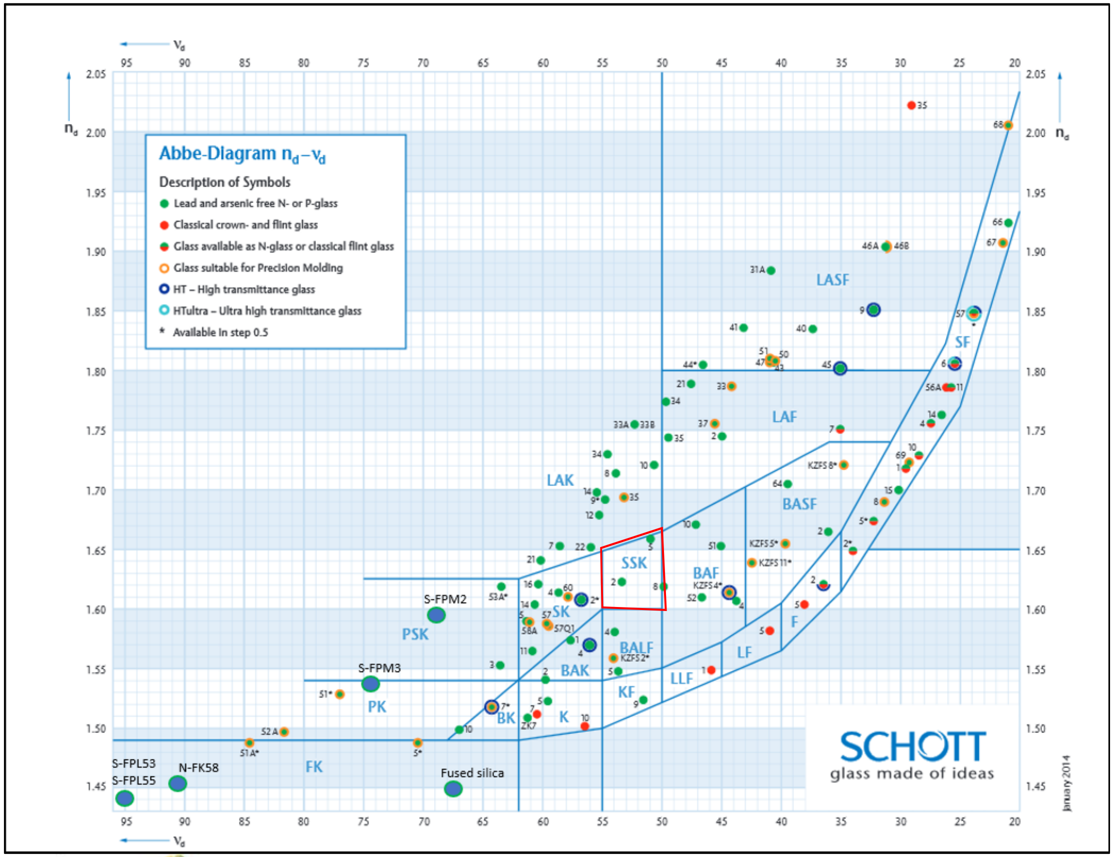
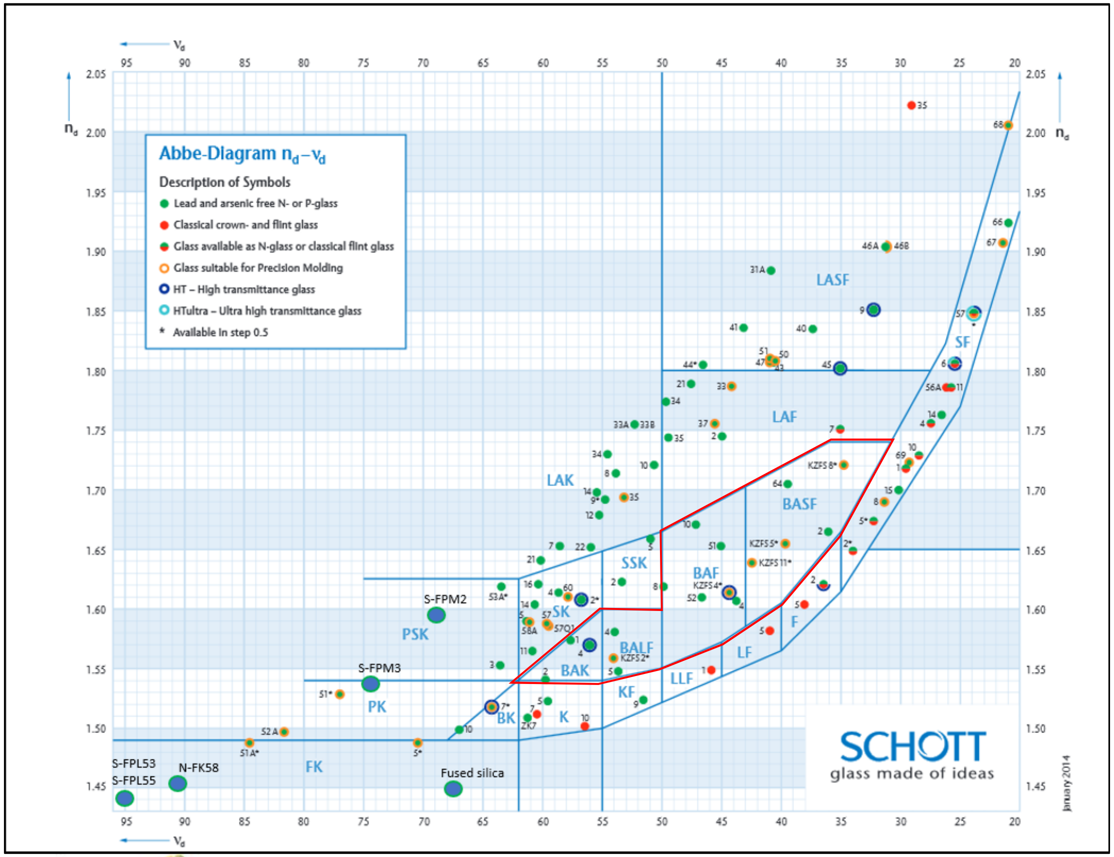
Glass Families: Extra Dense Crowns



- Higher index "generic glass"
- Opportunity to mate with flint glasses to make a "buried surface"
- Why do we use these glasses? Monochromatic aberrations need love and correction as well! And they can tweak chromatic correction.

Glass Families: Barium Crowns/Flints



- Occupy middle of the glass map → higher index "generic glass"
- Why do we use these glasses? Monochromatic aberrations need love and correction as well! And they can tweak chromatic correction.

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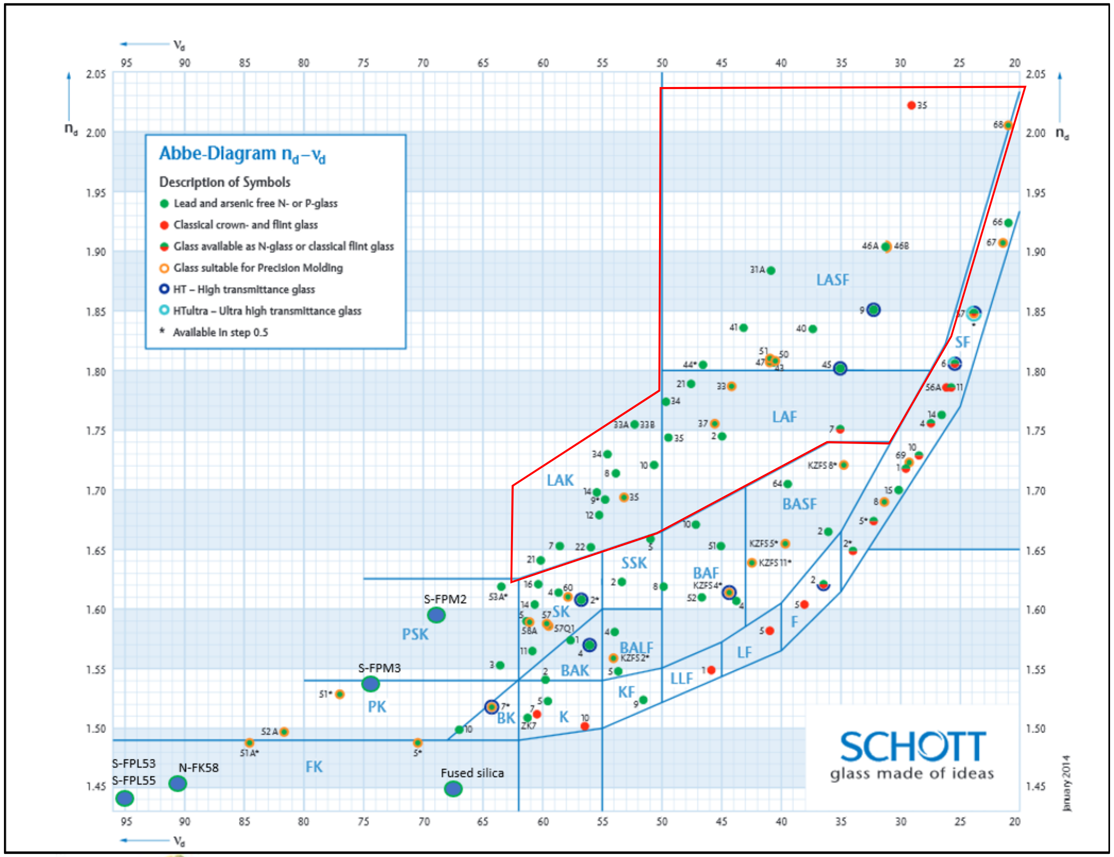
Glass Families: Lanthanum Crowns/Flints



- Occupy north frontier of the glass map → highest index "generic glass"
- Opportunity to mate with flint glasses to make a "buried surface"
- Why do we use these glasses? Monochromatic aberrations need love and correction as well! And they can tweak chromatic correction.

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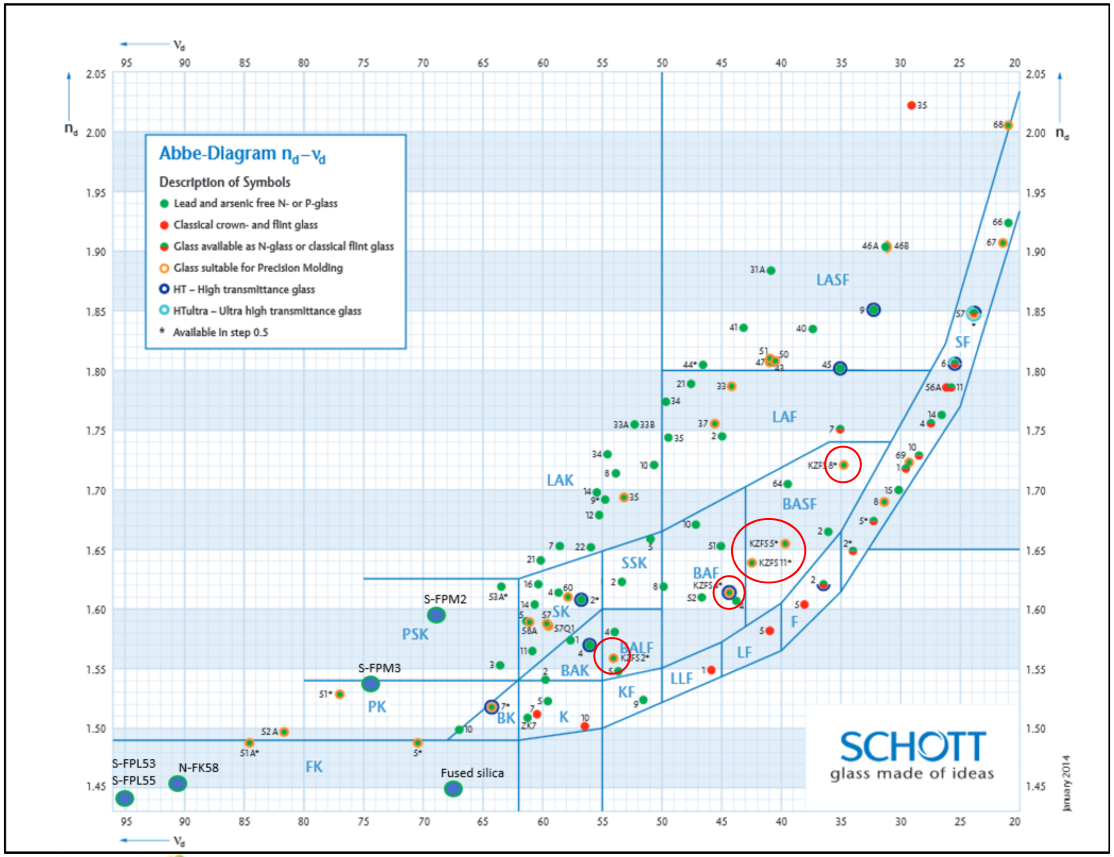
Glass Families: Short Flints



- Super color correcting glasses!
- “Off the glass line” anomalous partial dispersions
- Simple dispersion models used in CODEV and ZEMAX during optimization won’t find these glasses → almost always these glasses have to be added in to the design “by hand”
- Virtually all superachromatic (or apochromat or “apo”) systems uses these glasses

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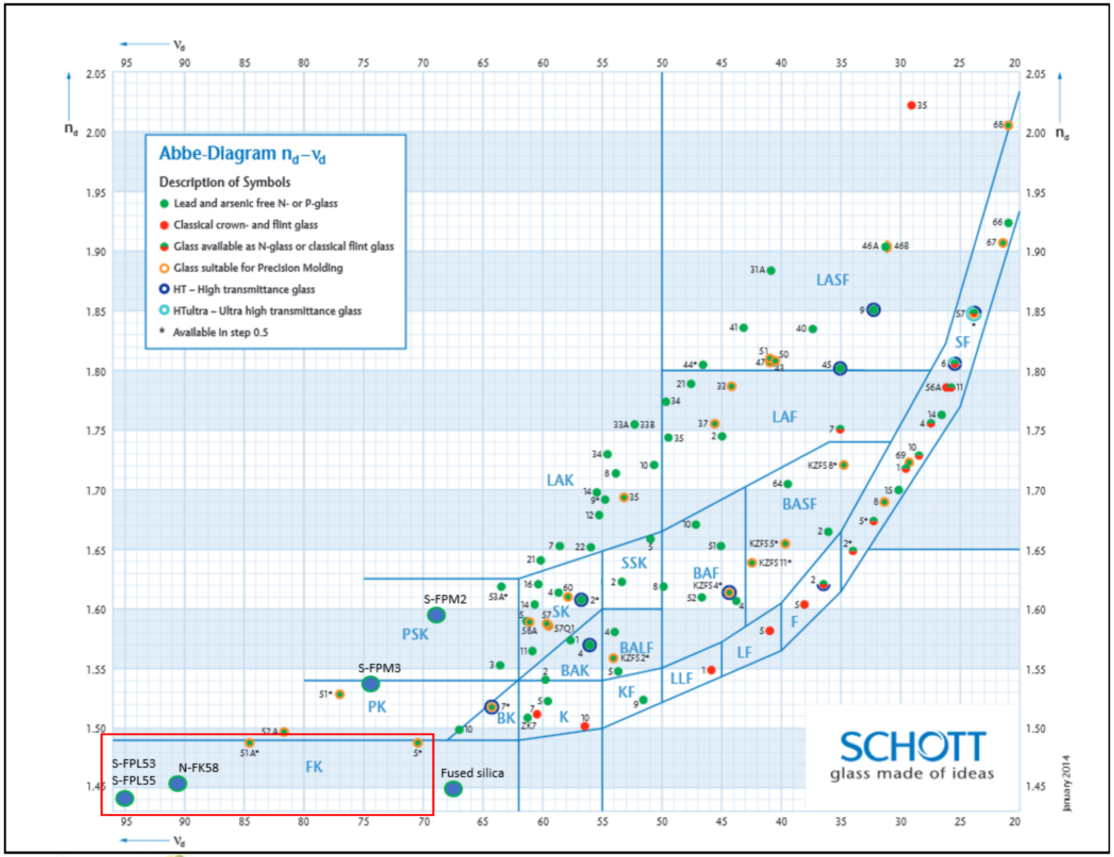
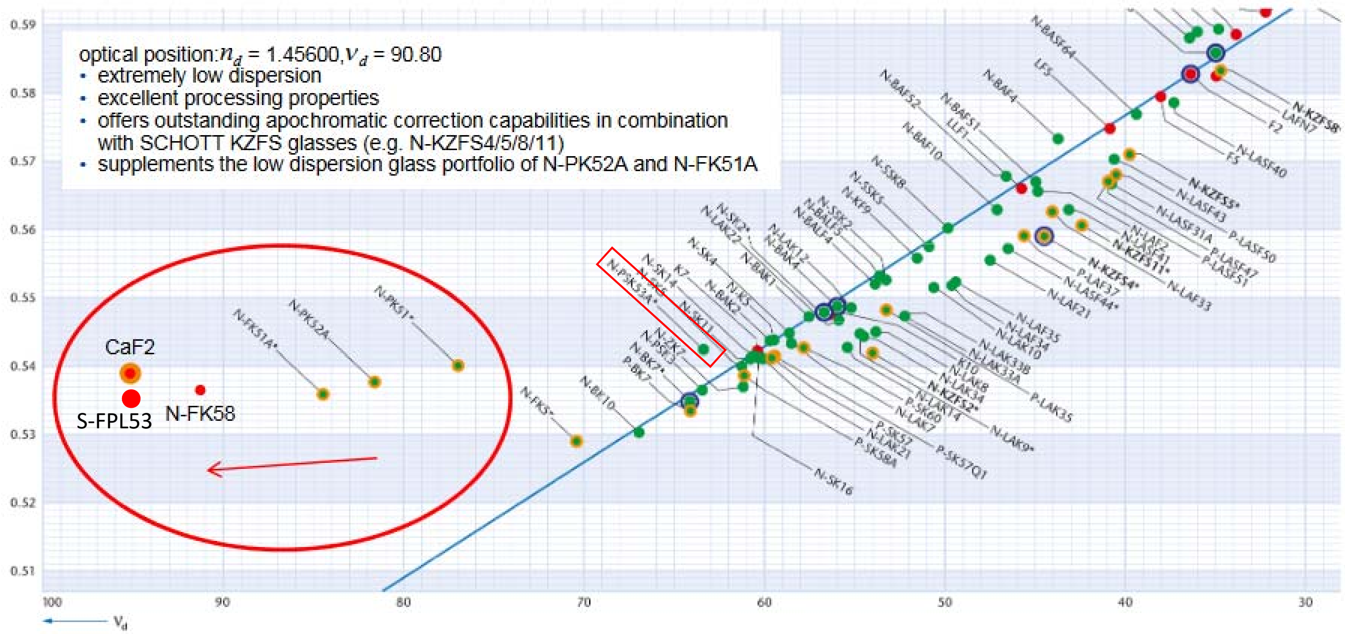
Glass Families: Fluorophosphate Crowns



- Super color correcting glasses!
- Very low dispersion and (unfortunately) very low refractive index glasses
- Can be combined with short flints for apo doublets
- S-FPL53 is almost perfect match for CaF_2 **
(Glass code for CaF_2 is 433952, glass code for S-FPL53 is 439950)
- N-FK58 is a bit farther away from CaF_2 with a glass code of 456908
- S-FPL53 *et al* are not available in large sizes.
- Low refractive index makes AR coating a problem

** Otherwise known as "fluorite"

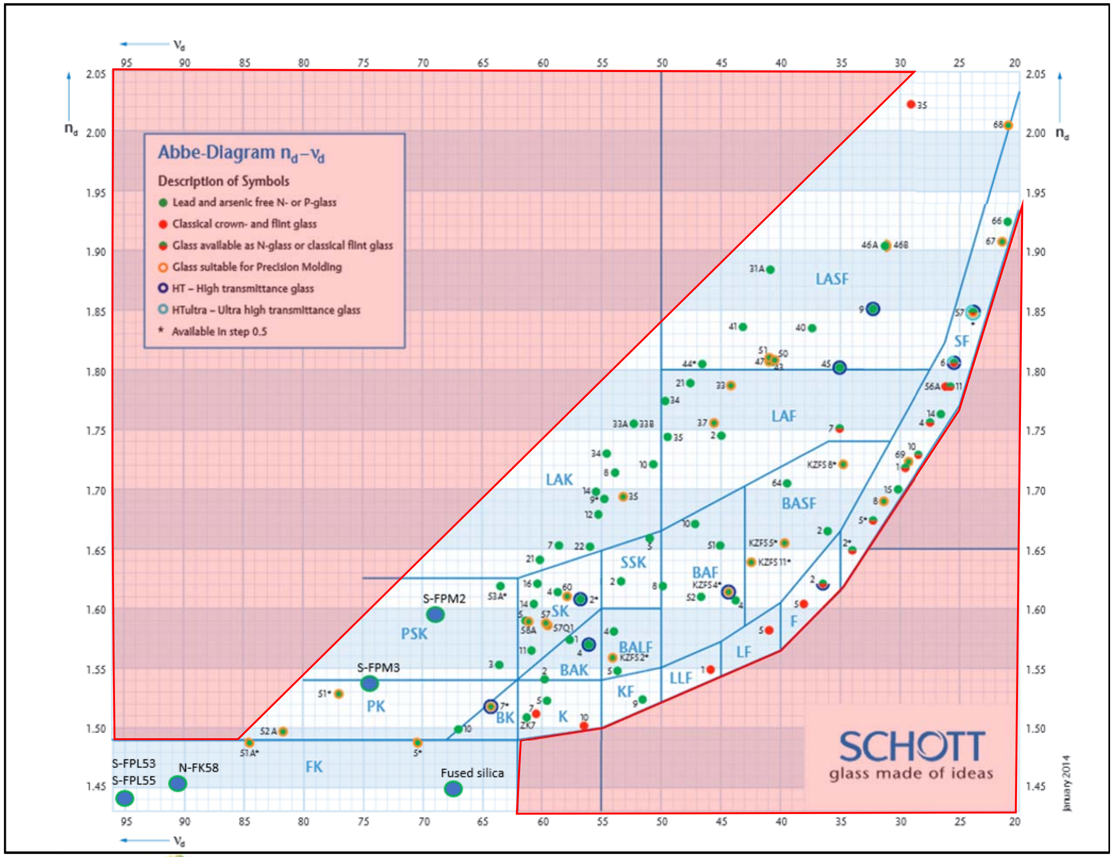
Glass Families: Partial Dispersions of Fluorophosphate Crowns



Color correction in optical systems, Dr. Ralf Jedamzik, May 2014

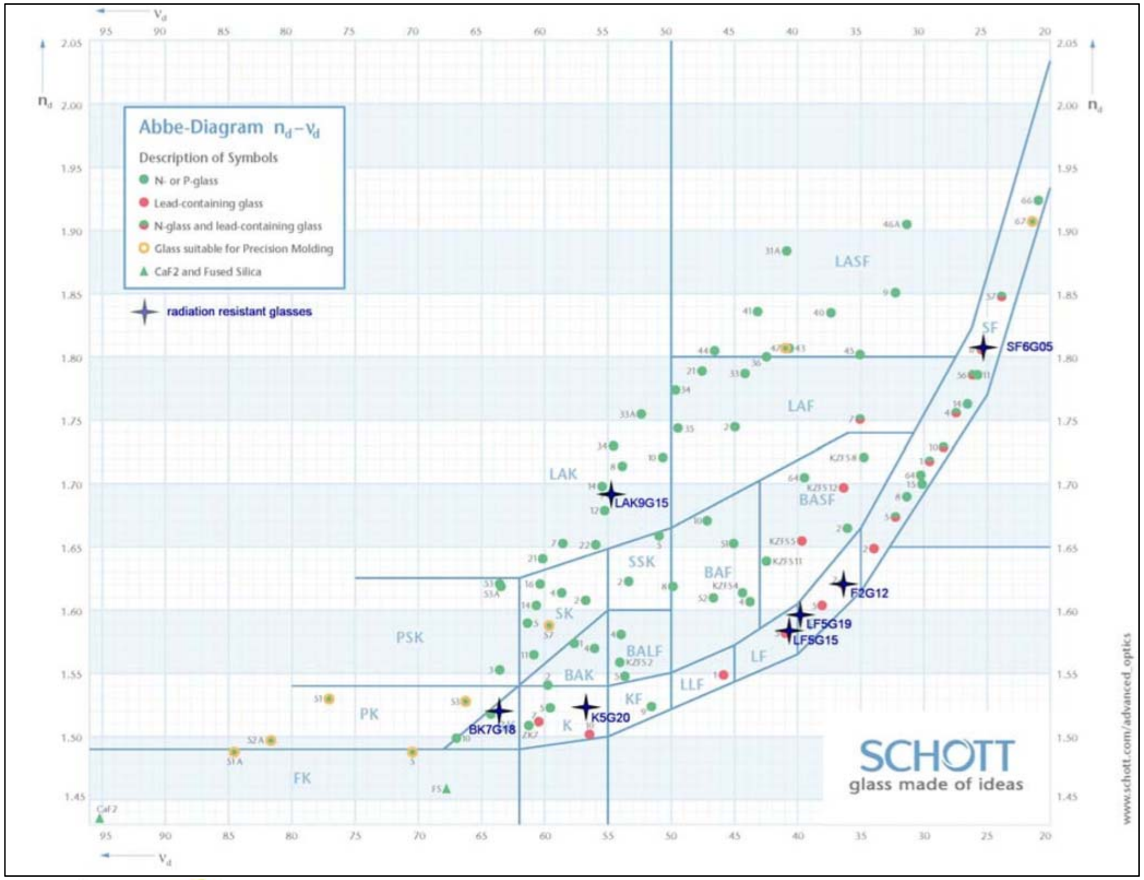
SCHOTT glass made of ideas

Glass Families: “No Man’s Land”



- Nature (i.e., physics and chemistry) doesn’t seem to allow glasses in these areas
- Problem in lens design/optimization software → how do you keep the optimizer from going into these areas?

Glass Families: Radiation Hardened Glasses



- Cerium-doped glass → absorption at short wavelengths
- No really great glasses for color correction → most of the glasses are on the "old glass line"

Glass Families: Previously Available Radiation Hardened Glasses

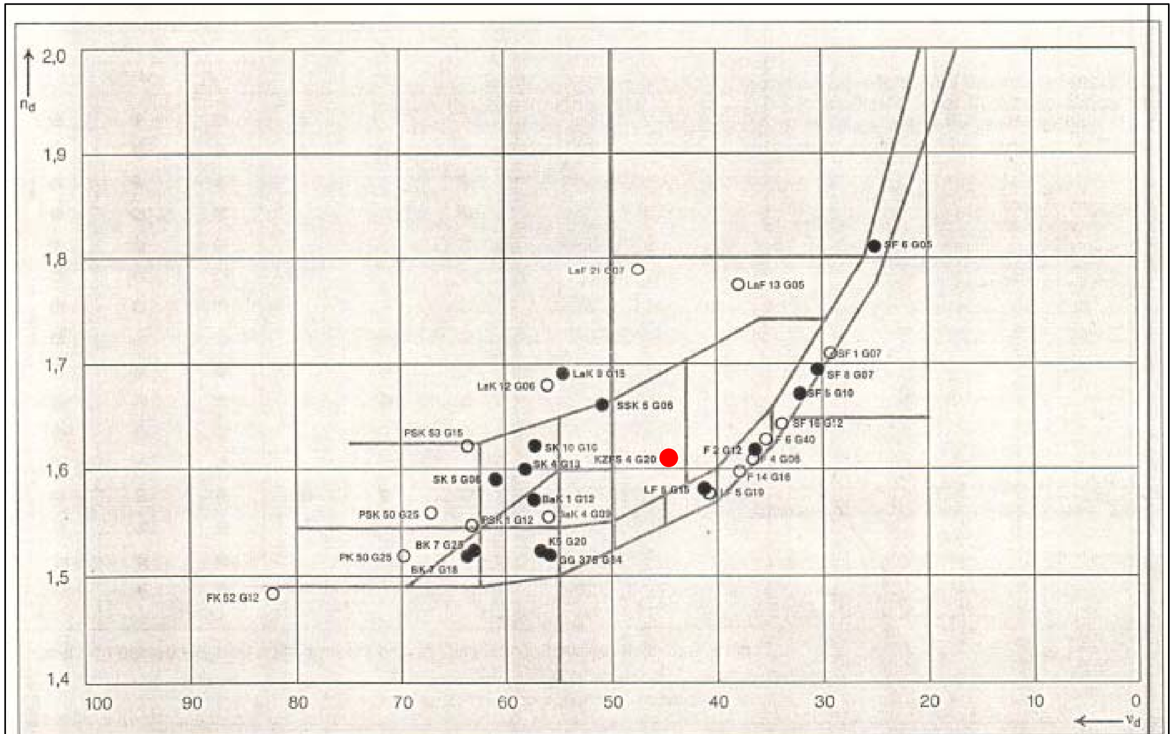
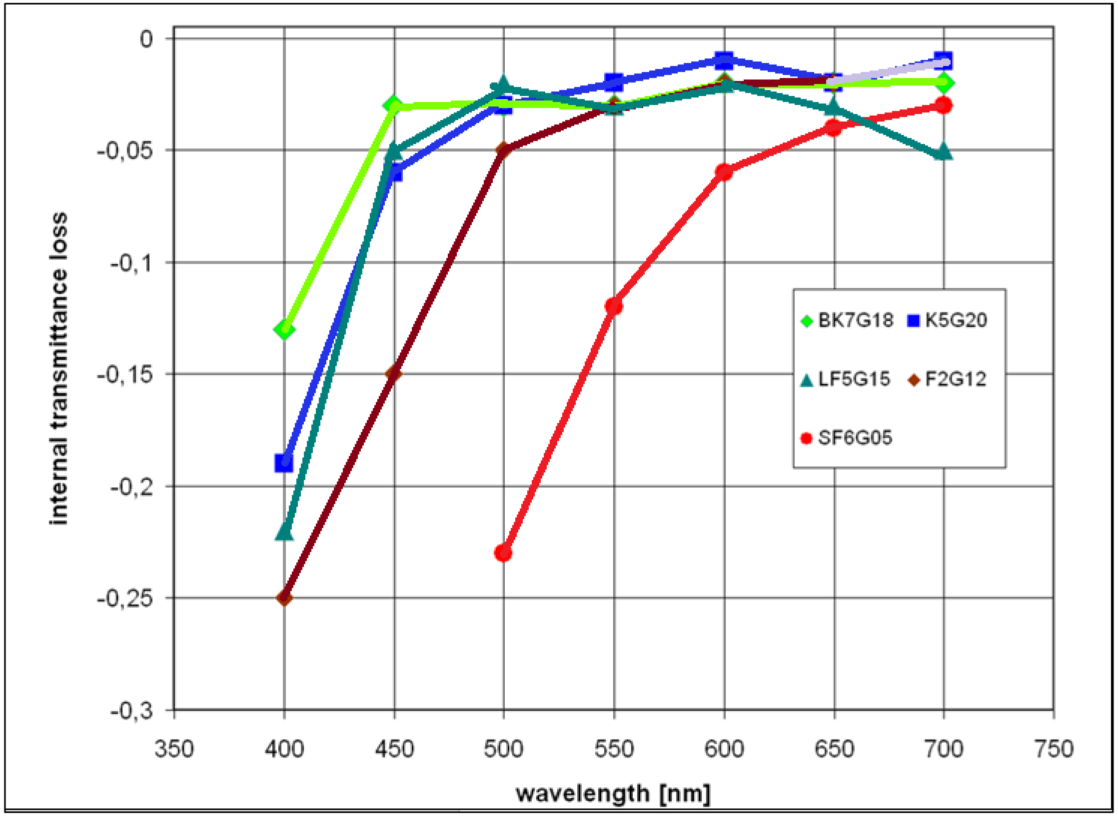


Fig. 3: The optical position of the radiation resistant optical glasses.
● Available glasses, O Inquiry glasses.

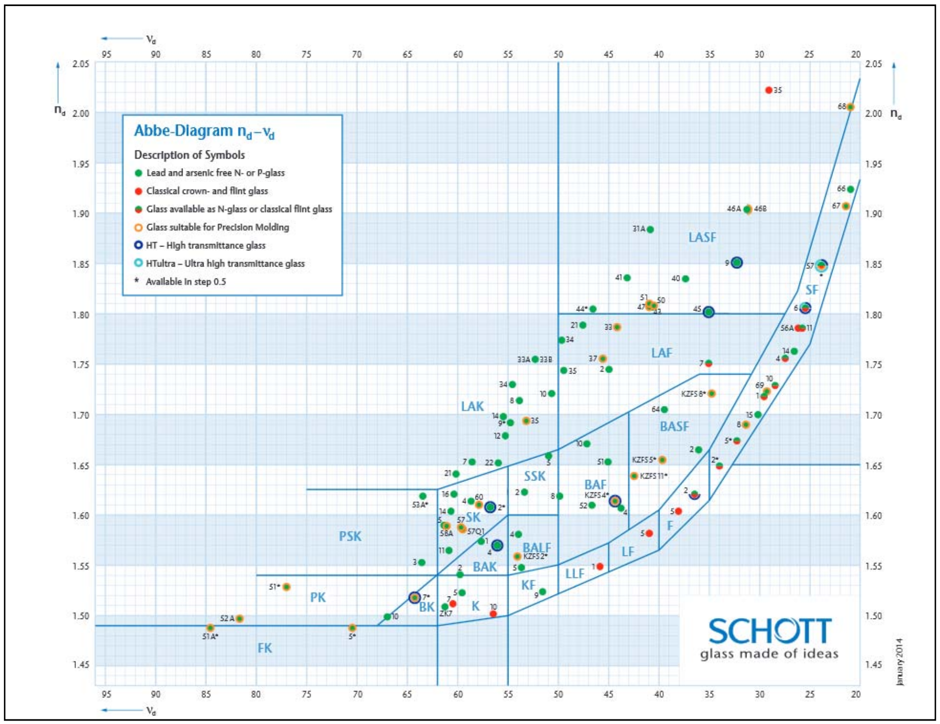
- Circa 1978, lots of choices across the glass map
- Rad hard short flint → KzFS4G20 (In principal, great for color correction. But since most rad hard glasses absorb in the short wavelengths, color correction is/was less of an issue.)

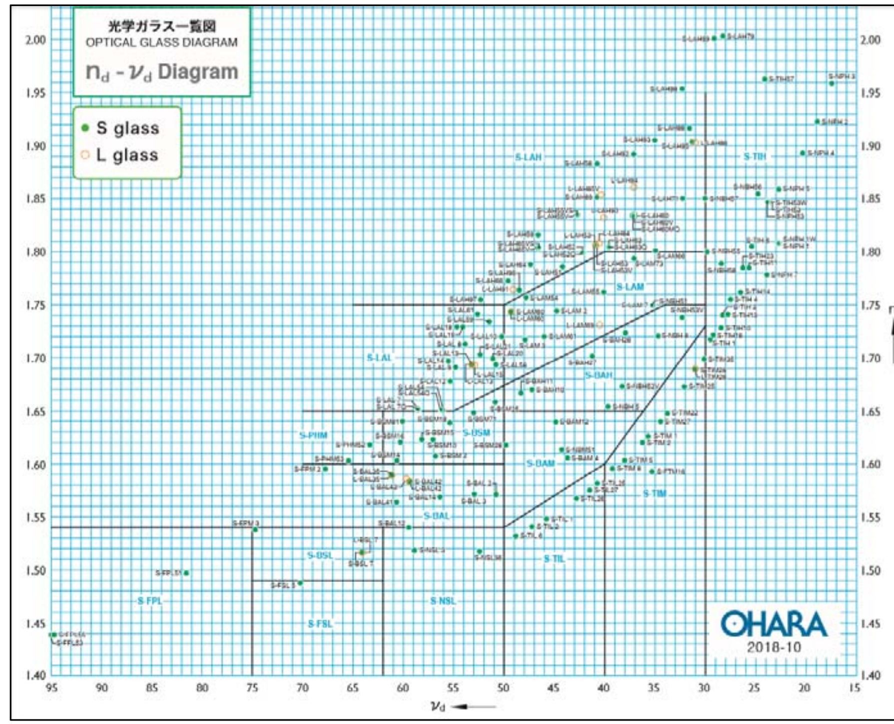
Glass Families: Transmission of Radiation Hardened Glasses



- High absorption at the shorter wavelengths

So Many Glasses, So Little Time!





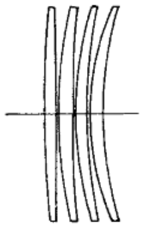
We Know the Problem… What is our Strategy?

- Lots of glasses to pick from
  - 124 Schott glasses
  - 118 Ohara glasses
  - 179 Hoya glasses
  - 177 Chengdu glasses

- Hope that the optical design software will find the solution?
  - Deadline looming? Try every possible combination of glasses… That could take quite a bit of time!

- How do we determine that a color-corrected solution exists? Some lenses simply cannot be corrected for color

- Fortunately the solutions are not hiding! We just need to look in the right place →



Ref: Kingslake, R., Lens Design Fundamentals, Academic Press, 1978.

Correct Primary Axial Color in a Doublet

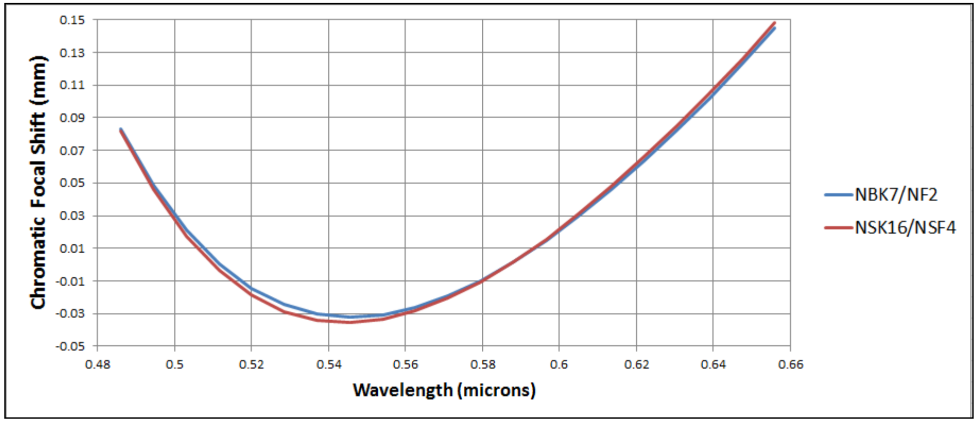
- Optical designers have long been aware of the basic rule for reconciling optical power and dispersion to correct primary color using thin lenses:

$$\Phi = \Phi_1 + \Phi_2 \qquad \Phi = \frac{1}{f} \qquad \text{power}$$

$$0 = \frac{y^2 \Phi_1}{\nu_1} + \frac{y^2 \Phi_2}{\nu_2} \qquad \text{achromatism}$$

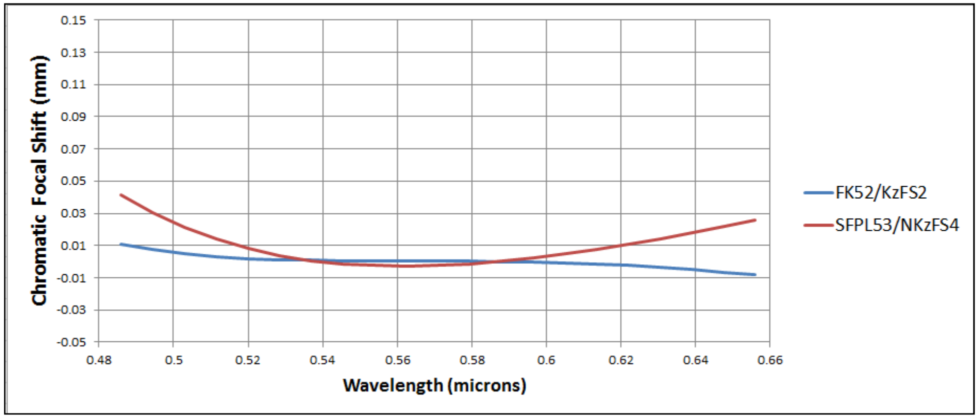
Solution

$$\begin{cases} f_1 = f\left(\dfrac{\nu_1 - \nu_2}{\nu_1}\right) \\ f_2 = f\left(\dfrac{\nu_2 - \nu_1}{\nu_2}\right) \end{cases}$$



Apochromatic Doublet

- Kingslake noted that a simple doublet can be made apochromatic if glasses are chosen that have matching partial dispersions
- There is no magic here! We need a large difference in Abbe numbers to get reasonable individual element powers but now we add the additional constraint that the partial dispersions match



Conrady, Herzberger and Apochromats

- Conrady, and later Herzberger, described the process of designed an apochromatic triplet by recognizing that one of the glasses has to be off the “normal” glass line
- Starting with 3 conditions:

$$\begin{cases} \sum V\, c\, \Delta n = \Phi & \text{power} \\ \sum c\, \Delta n = 0 & \text{achromatism} \\ \sum P\, c\, \Delta n = 0 & \text{secondary color} \end{cases}$$

- Solving for the three thin-lens curvatures c_a, c_b, and c_c

$$c_a = \frac{\Phi}{E(\nu_a - \nu_c)}\left(\frac{P_b - P_c}{\Delta n_a}\right)$$

$$c_b = \frac{\Phi}{E(\nu_a - \nu_c)}\left(\frac{P_c - P_a}{\Delta n_b}\right)$$

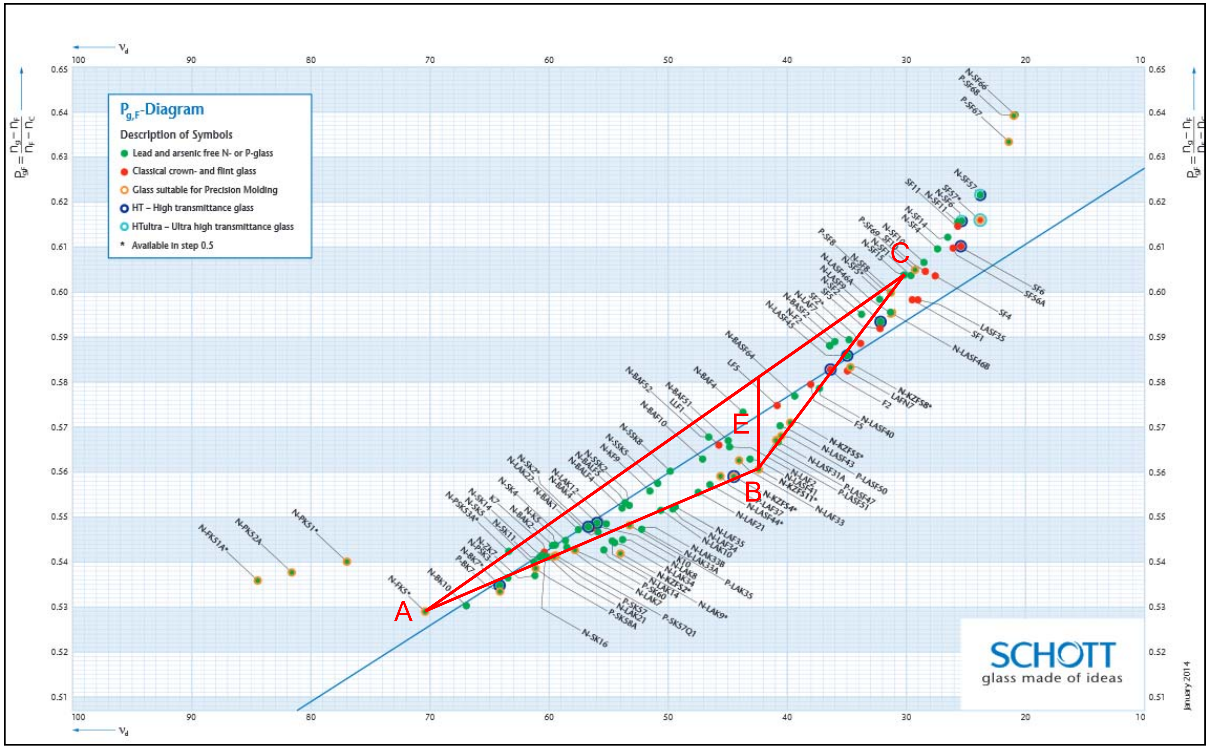
$$c_c = \frac{\Phi}{E(\nu_a - \nu_c)}\left(\frac{P_a - P_b}{\Delta n_c}\right)$$

where Φ = overall focal length and

$$E = \frac{\nu_a(P_b - P_c) + \nu_b(P_c - P_a) + \nu_c(P_a - P_b)}{\nu_a - \nu_c}$$

Ref: Conrady, A. E., “Photo visual objectives”, *Applied Optics and Optical Design*, 159, 166, Dover (1957)
Ref: Herzberger, M., “Color Correction in Optical System and a New Dispersion Formula”, *Opt. Acta* 6, 197 (1959).
Ref: Herzberger, M., McClure, N., “The Design of Superachromatic Lenses”, *Applied Optics*, Vol. 2, 553 (1963).

Geometrical Interpretation of E



Hertzberger and Apochromats (Con't)

- If E were large, then the lens powers would be small → find large E!
- Kingslake's solution:

Lens	Glass	n_e	$\Delta n = n_g - n_C$	$n_g - n_e$	P_{ge}	"V"
a	FK-6	1.4478604	0.0101615	0.0065470	0.6442946	44.07424
b	KzFS-1	1.6163841	0.0215499	0.0140995	0.6542721	28.60264
c	SF-15	1.7044410	0.0371905	0.0249596	0.6711283	18.94142

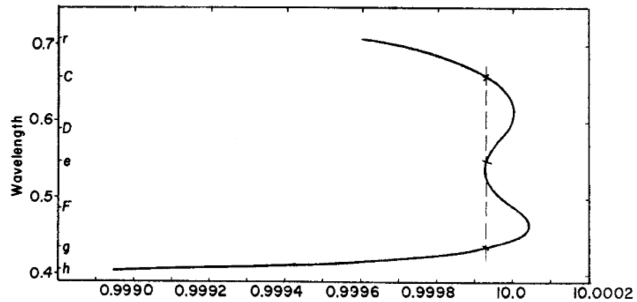


FIG. 45. Tertiary spectrum of a thin three-lens apochromat (the *C*, *e*, and *g* lines are brought to a common focus).

Ref: Kingslake, R., Lens Design Fundamentals, Academic Press, 1978.

Robb and Glass Selection

- At the 1985 IODC in Cherry Hill, NJ, Paul Robb presented a paper describing a new take on selecting optical glasses for doublets and triplets based upon Buchdahl's chromatic coordinate rather than the traditional Abbe number-partial dispersion approach

- Buchdahl's chromatic coordinate is given by

$$\omega(\lambda)=\frac{\lambda-\lambda_0}{1+\alpha(\lambda-\lambda_0)} \quad \text{where } \alpha \text{ is a constant} = 2.5\ \forall \text{ glasses}$$

- The index of refraction is given by

$$N(\omega)=N_0+\nu_1\omega+\nu_2\omega^2+\nu_3\omega^3+\ldots$$

- The power of a single thin lens is given by

$$\Phi=(c_1-c_2)(N-1)=K(N-1)$$
$$\Phi(\lambda)=K\left(N_0+\nu_1\omega+\nu_2\omega^2+\ldots-1\right)=\Phi(\lambda_0)+K\left(\nu_1\omega+\nu_2\omega^2+\ldots\right)$$

Ref: Robb, P., "Selection of optical glasses", *Proc. SPIE*, Vol. 554 (1985).

Robb and Glass Selection (Con't)

- Robb then defines a dispersion function given by

$$D(\lambda)=\frac{\delta N(\lambda)}{N_0-1}$$

$$\delta N(\lambda)=\sum_{i=1}^{\infty}\nu_i\,\omega^i$$

$$D(\lambda)=\sum_{i=1}^{\infty}\eta_i\,\omega^i(\lambda)\quad\text{where}\quad\eta_i=\frac{\nu_i}{N_0-1}$$

- Finally the wavelength-dependent thin lens power is given by

$$\Phi(\lambda)=\Phi(\lambda_0)\left(1+\eta_1\omega+\eta_2\omega^2+\eta_3\omega^3+\ldots\right)$$
$$\Phi(\lambda)=\Phi(\lambda_0)\left(1+D(\lambda)\right)$$

- Robb writes the total optical power of a thin doublet as

$$\Phi(\lambda)=\Phi_1(\lambda)+\Phi_2(\lambda)$$

Robb and Glass Selection (Con't)

- For color correction at three wavelengths

$$\Phi(\lambda_1)-\Phi(\lambda_2)=0$$
$$\Phi(\lambda_2)-\Phi(\lambda_3)=0$$

- Assuming a quadratic dispersion model

$$D(\lambda)=\eta_1\omega+\eta_2\omega^2$$

- Robb could then write the system of equations as $\overline{\Omega}\,\overline{\eta}\,\overline{\Phi}=\overline{0}$ where

$$\overline{\Omega}=\begin{vmatrix}\omega_1-\omega_2 & \omega_1^2-\omega_2^2\\ \omega_2-\omega_3 & \omega_2^2-\omega_3^2\end{vmatrix}\quad \overline{\eta}=\begin{vmatrix}\eta_{11} & \eta_{12}\\ \eta_{21} & \eta_{22}\end{vmatrix}\quad \overline{\Phi}=\begin{vmatrix}\Phi_1\\ \Phi_2\end{vmatrix}\quad \overline{0}=\begin{vmatrix}0\\ 0\end{vmatrix}$$

- This system of equations has a nontrivial solution when the determinant of $\overline{\eta}$ is equal to zero, which occurs when

$$\left.\frac{\eta_1}{\eta_2}\right|_{\text{Glass 1}}=\left.\frac{\eta_1}{\eta_2}\right|_{\text{Glass 2}}$$

Robb and Glass Selection (Con't)

- Robb further solves for the thin-lens element powers, viz.

$$\Phi_1 = \frac{\eta_{12}}{\eta_{12} - \eta_{11}}$$

$$\Phi_2 = \frac{\eta_{11}}{\eta_{12} - \eta_{11}}$$

- By extension, Robb describes the procedure for color correction at 4 wavelengths with three materials

$$\Phi(\lambda_1) - \Phi(\lambda_2) = 0$$
$$\Phi(\lambda_2) - \Phi(\lambda_3) = 0$$
$$\Phi(\lambda_3) - \Phi(\lambda_4) = 0$$

that occurs when

$$\left.\frac{\eta_1}{\eta_2}\right|_{\text{Glass 1}} = \left.\frac{\eta_1}{\eta_2}\right|_{\text{Glass 2}} = \left.\frac{\eta_1}{\eta_2}\right|_{\text{Glass 3}}$$

Robb and Glass Selection (Con't)

- Robb makes several observations about his technique

  1. While it might appear desirable from a monochromatic aberration standpoint to select solutions where the element powers are minimized, Robb found several instances (particularly with triplets) where this was not the case

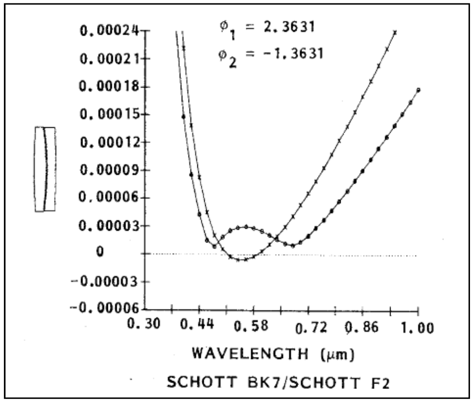
  2. Obtaining color correction in the blue portion of the spectrum ($\lambda < 0.44$ microns) was virtually impossible with doublets and required careful glass selection with triplets

  3. The best solutions involved glass selection from various vendors

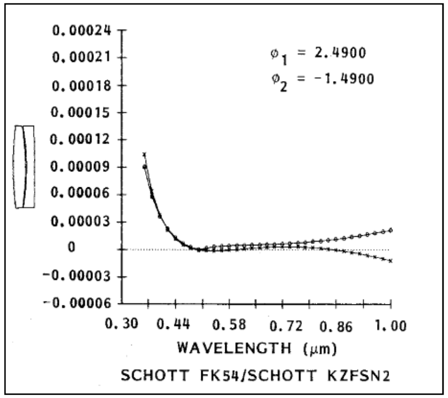
- While Robb's approach was certainly innovative, it still required the designer to search over numerous solutions looking for the optimum one

- We didn't learn anything new about the use of glasses whose partial dispersions are off the "normal" glass line

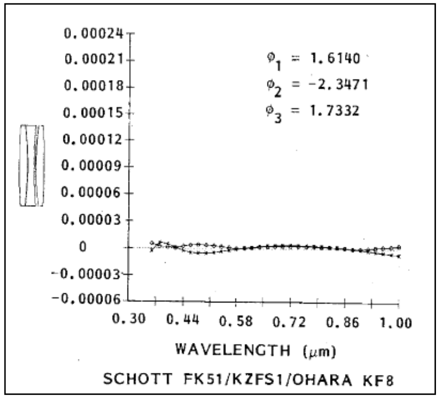
Robb and Glass Selection (Con't)



Conventional glass doublet



Robb-selected glass doublet



Robb-selected glass triplet

Element	Kingslake		Robb	
a	Schott FK 6	446674	Schott FK 51	487845
b	Schott KzFS 1	551497	Schott KzFS 1	551497
c	Schott SF 15	699301	Ohara KF 8	511510
$\nu_a - \nu_c$		37.3		33.5

Color Correction With Airspaced Elements?

- Robb assumes that the thin-lens elements are in contact
- If we instead assume that the elements are airspaced with the object at infinity, then the overall system power Φ is given by

$$y_1\Phi = y_1\Phi_1 + y_2\Phi_2 + y_3\Phi_3 + \ldots = \sum_{i=1}^{k} y_i\Phi_i$$

- Following Robb's derivation, we can write the solution again as $\overline{\Omega}\,\overline{\eta}\,\overline{\Phi} = \overline{0}$ but we find that the power vector contains the axial ray heights as well as the element powers

$$\overline{\Phi} = \begin{vmatrix} y_1\Phi_1 \\ y_2\Phi_2 \\ \ldots \end{vmatrix}$$

- This creates a complex dependency problem because Φ_1 now influences y_2, y_3, …; Φ_2 now influences y_3, y_4, …; etc → no easy solution!

Rayces and Aguilar Glass Selection

- Rayces and Aguilar realized that the whole picture was important: we needed to consider monochromatic aberrations as well as chromatic aberrations (spherochromatism and fifth-order spherical aberration) in our glass selection process.

- Rayces-Aguilar perform a *search over all combinations of glasses*

  - Pass #1: compute powers of elements that yield achromatic solutions and then eliminate unreasonable solutions (i.e., those with steep curves)

  - Pass #2: compute radii to yield an aplanatic solution (to third-order) using aberration coefficients and then eliminate solutions with high residual spherochromatism and fifth-order spherical aberration

  - Pass #3: Sort remaining solutions according to amount of secondary spectrum

- Probably doable for doublet, but inefficient for multi-element systems!

Ref: Rayces, J., Rosete-Aguilar, M., "Selection of glasses for achromatic doublets with reduced secondary spectrum. I. Toleranced conditions for secondary spectrum, spherochromatism, and fifth-order spherical aberration", *Applied Optics,* Vol. 40, No. 31, pp. 5663-5676 (2001).

C. de Albuquerque et al Glass Selection

- C. de Albuquerque *et al* merged Robb's and Rayces' approaches into a "multi-objective approach" where different metrics are imposed at various stages in the calculation
- $F_1 = \sum_{i\ elements} \left|\Phi_i(\lambda_0)\right|$ min. power
- $F_2 = \left|\overline{\Omega}\ \overline{\eta}\ \overline{\Phi}\right|$ min. chromatic residual
- $F_3 = \overline{W}_{040CL} + \overline{W}_{060}$ min. wave aberration
- Whew! Lots of work!

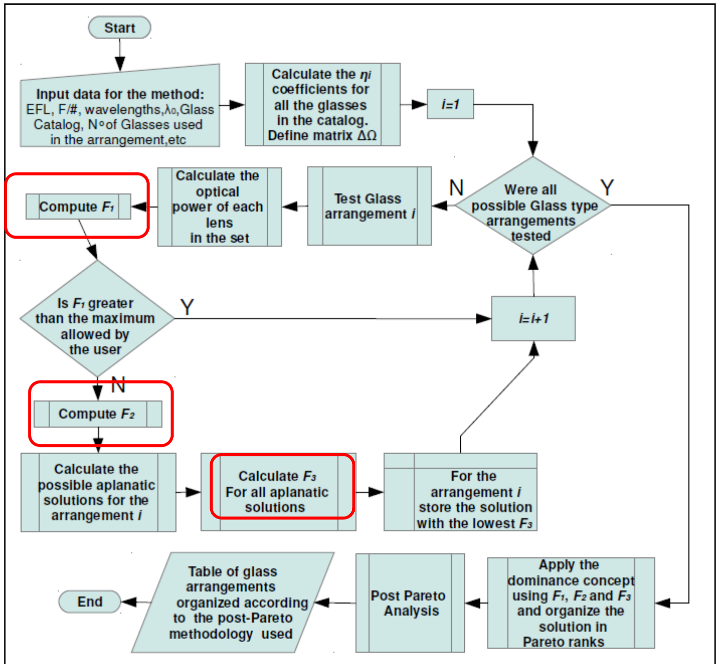


Fig. 3. Flowchart of the proposed method of glass combination selection.

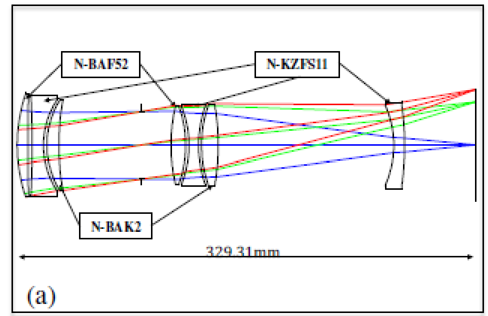
Ref: Carneiro de Albuquerque, B., Sasian, J., Luis de Sousa, F., Montes, A., "Method of glass selection for color correction in optical system design", *Optics Express,* Vol. 20, Issue 13, pp. 13592-13611 (2012).

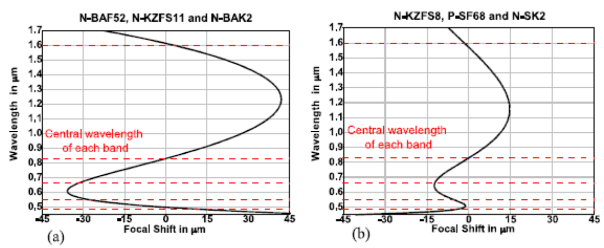
C. de Albuquerque *et al* Triplet Solutions

Table 3. Output table from the glass selection method for 3 glasses sorted by $|\overline{g}_i|$.

N°	Glass 1	Glass 2	Glass 3	r_1	...	r_6	φ_1	φ_2	φ_2	F_1	F_2	F_3
5317	N-BAF52	N-KZFS11	N-SK4	145.26	...	-1056.62	3.12	-4.68	2.56	10.37	2.15E-04	2.98
35786	N-SK4	N-KZFS11	N-BAF52	135.68	...	-2128.74	2.56	-4.68	3.12	10.37	2.15E-04	2.99
11387	N-KZFS11	N-BAF52	N-SK4	-42.02	...	-55.13	-4.68	3.12	2.56	10.37	2.15E-04	3.03
25496	N-LAK8	N-KZFS11	N-BAK2	-20.89	...	-23.05	-3.21	-1.58	5.79	10.59	4.61E-04	1.49
5310	**N-BAF52**	**N-KZFS11**	**N-BAK2**	**110.35**	**...**	**-1266.01**	**3.34**	**-4.71**	**2.38**	**10.43**	**1.88E-04**	**3.14**
26091	N-LASF31A	N-KZFS2	N-BAK1	-16.58	...	-17.83	-2.09	-2.03	5.13	9.26	5.11E-04	0.67
13718	N-KZFS11	N-SSK8	N-SK4	-45.56	...	-62.64	-3.71	2.41	2.29	8.41	4.28E-04	2.04
13672	N-KZFS11	N-SSK8	N-BAK2	-47.45	...	-65.80	-3.67	2.56	2.11	8.35	4.17E-04	2.14
9960	N-FK5	N-KZFS11	N-BAF51	165.17	...	-264.64	2.02	-4.37	3.35	9.74	3.18E-04	2.84
11541	N-KZFS11	N-BAK2	N-SSK8	-43.54	...	-58.25	-3.67	2.11	2.56	8.35	4.17E-04	2.23
6824	N-BAK2	N-KZFS11	N-SSK8	142.16	...	-444.22	2.11	-3.67	2.56	8.35	4.17E-04	2.28
37966	N-SSK8	N-KZFS11	N-BAK2	115.23	...	-1534.96	2.56	-3.67	2.11	8.35	4.17E-04	2.31
20485	**N-KZFS8**	**P-SF68**	**N-SK2**	**98.06**	**...**	**812.98**	**-4.73**	**1.17**	**4.56**	**10.46**	**5.66E-05**	**3.56**
2283	KZFS12	N-SF4	N-SK4	112.05	...	1464.73	-4.48	1.54	3.94	9.96	3.67E-04	2.68
11237	N-KZFS11	LLF1	N-SK14	-42.00	...	-54.57	-4.20	2.49	2.70	9.39	3.75E-04	2.63

Yikes! → (row 37966)





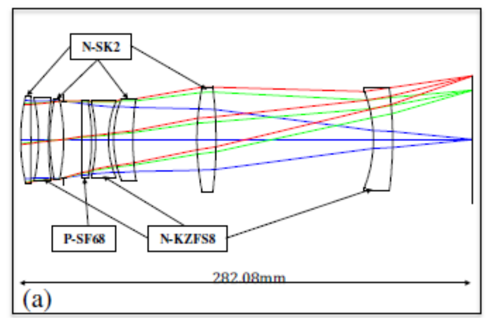


Fig. 5. Chromatic focal Shift for the aplanatic triplets designed with glass combination (a) N-BAF52, N-KZFS11 and N-BAK2, and combination (b) N-KZFS8, P-SF68 and N-SK2.

Note that each of the glass selections in the above table looks very much like a Herzberger triplet solution: a special short flint in combination with a crown and a dense flint

What Have We Learned?

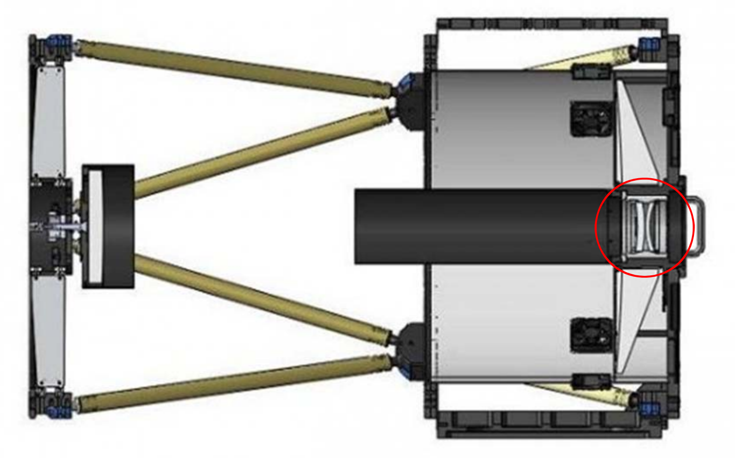
- Glass pairs from “normal glass line” have limited ability to correct color of large wavelength bands
- Doublet achromatization equation suggests that the crown will be the positive element and the flint will be the negative element
- Most successful doublets use a fluorophosphate crown and a short flint
- Most successful triplets use a short flint sandwiched between a crown (or fluorophosphate crown) and a dense flint

Next Lecture

- Doublets are great but people don't hire us to design doublets very often!
- How do we apply the knowledge of glasses to practical lens design of more complex systems?

Stay Tuned!

Intuition Tester #1

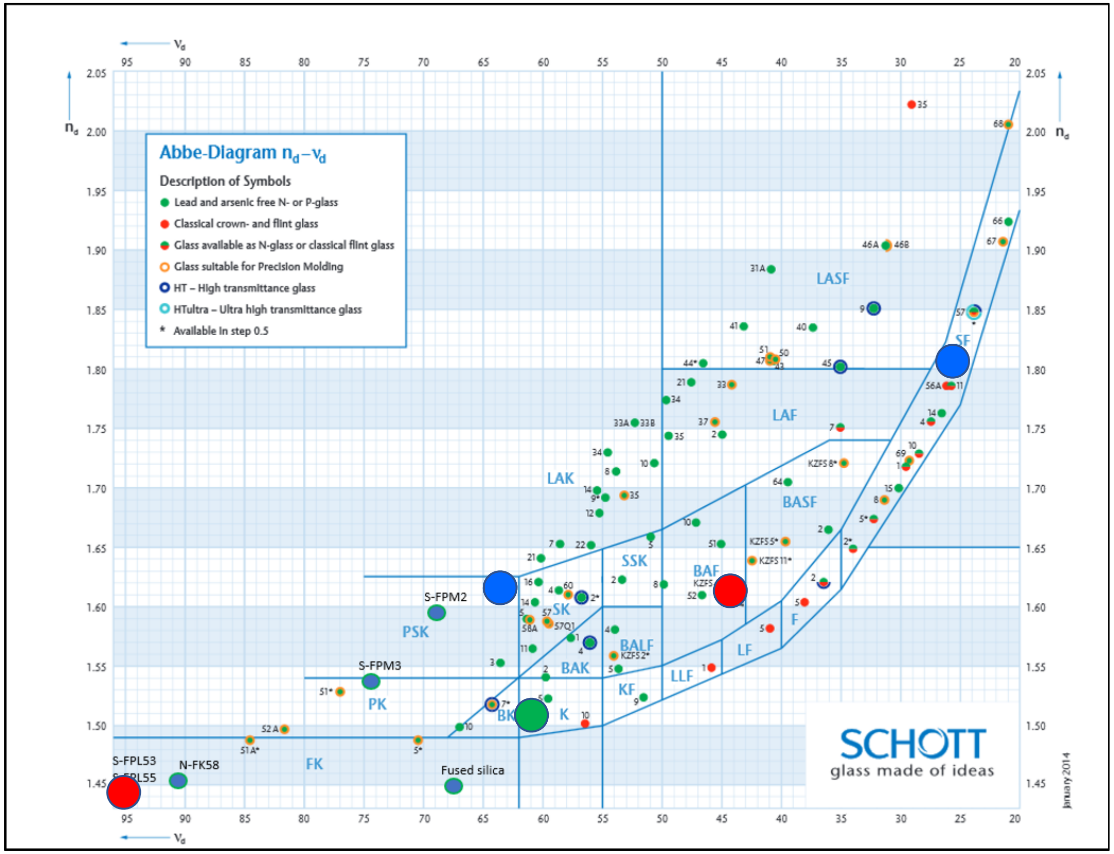


Planewave Instruments (www.planewave.com) sells extremely well-corrected field-corrected Dall-Kirkham (elliptical primary/spherical secondary) telescopes. The field corrector is a two element, zero power group.

Which glass(es) do you think are used in the field correctors?

(1) S-FPL53/N-KzFS4 (fluorophosphate crown/short flint)
(2) N-PSK53A/N-SF6 (high index, low dispersion crown/high index, high dispersion flint)
(3) N-BK7
(4) Cincinnati, OH

Intuition Tester #1



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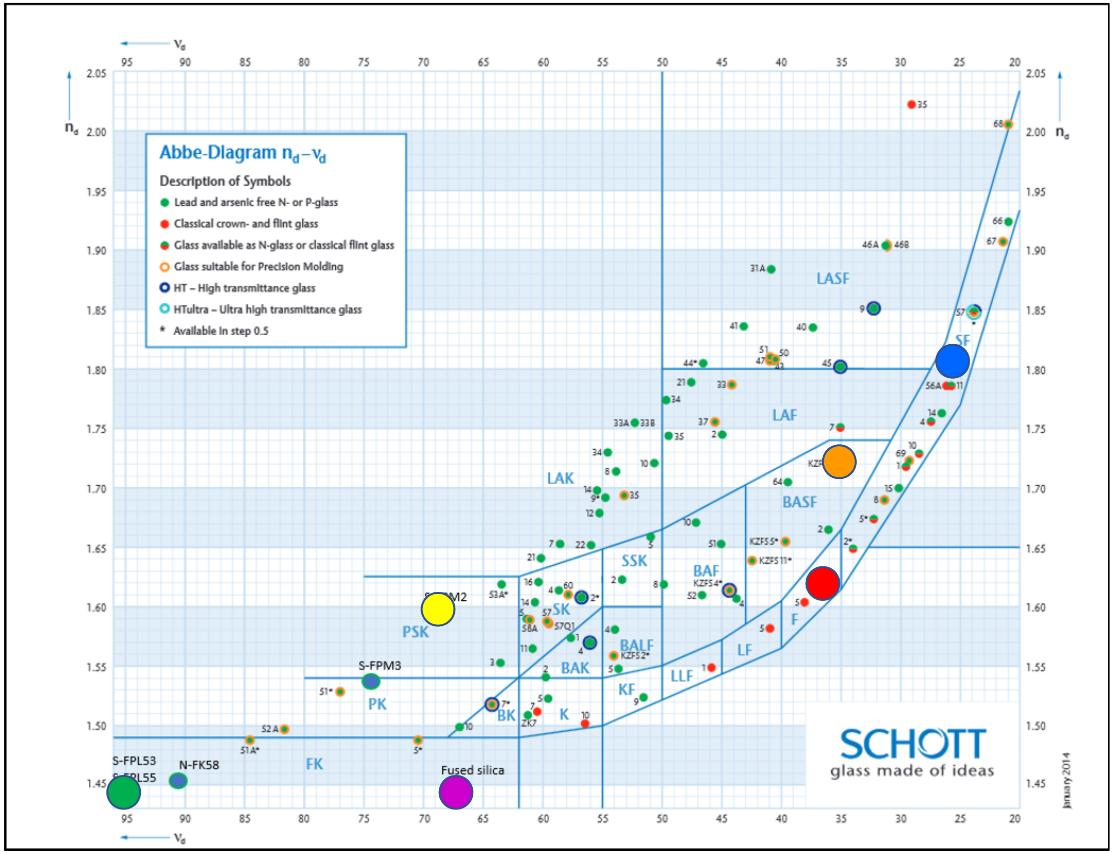
Intuition Tester #2

A consulting customer has asked you to design a 180 deg fisheye lens that covers from 350-1200 nm spectral band. Color correction will be critical!

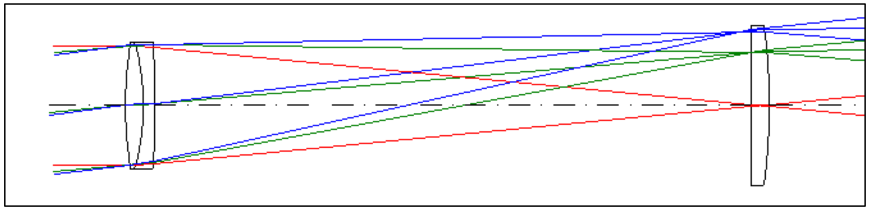
Which glass(es) would you consider using for the front elements?

(1) N-SF6 (high index, high dispersion flint)
(2) F2 (mid index, high dispersion flint)
(3) S-FPL53 (fluorophosphate crown)
(4) N-KzFS8 (short flint)
(5) Fused silica
(6) S-FPM2 (high index, low dispersion)
(7) Portland, OR

Intuition Tester #2



Intuition Tester #3



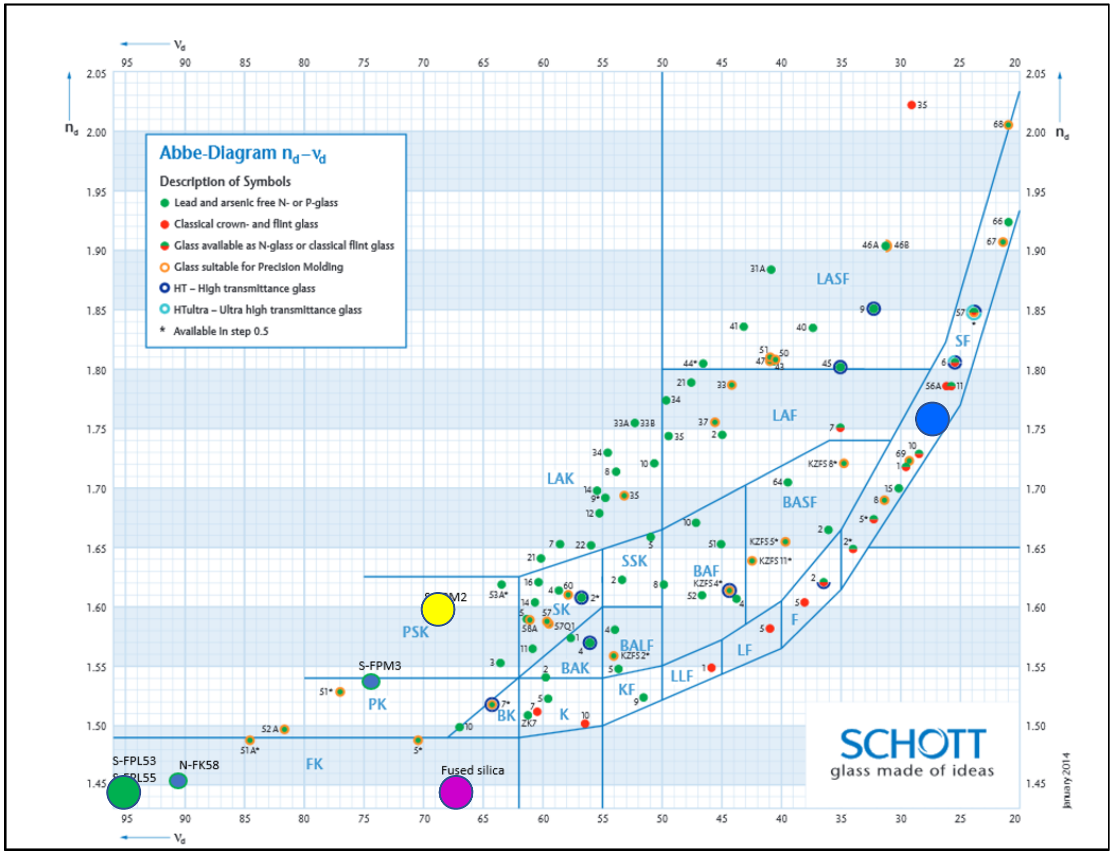
For good stray light control**, you want to put a relay group into the design. But you're also thinking about color correction.

Which glass would you consider using for the relay lens?

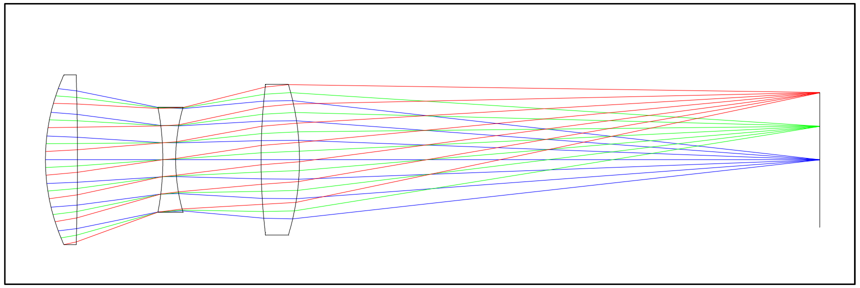
(1) S-FPL53 (fluorophosphate crown)
(2) N-SF4 (relatively high index, high dispersion flint)
(3) Fused silica
(4) S-FPM2 (medium index, low dispersion crown)
(5) Sydney, New South Wales, Australia

** Actually a refractive system is a poor choice for reducing stray light!

Intuition Tester #3



Intuition Tester #4

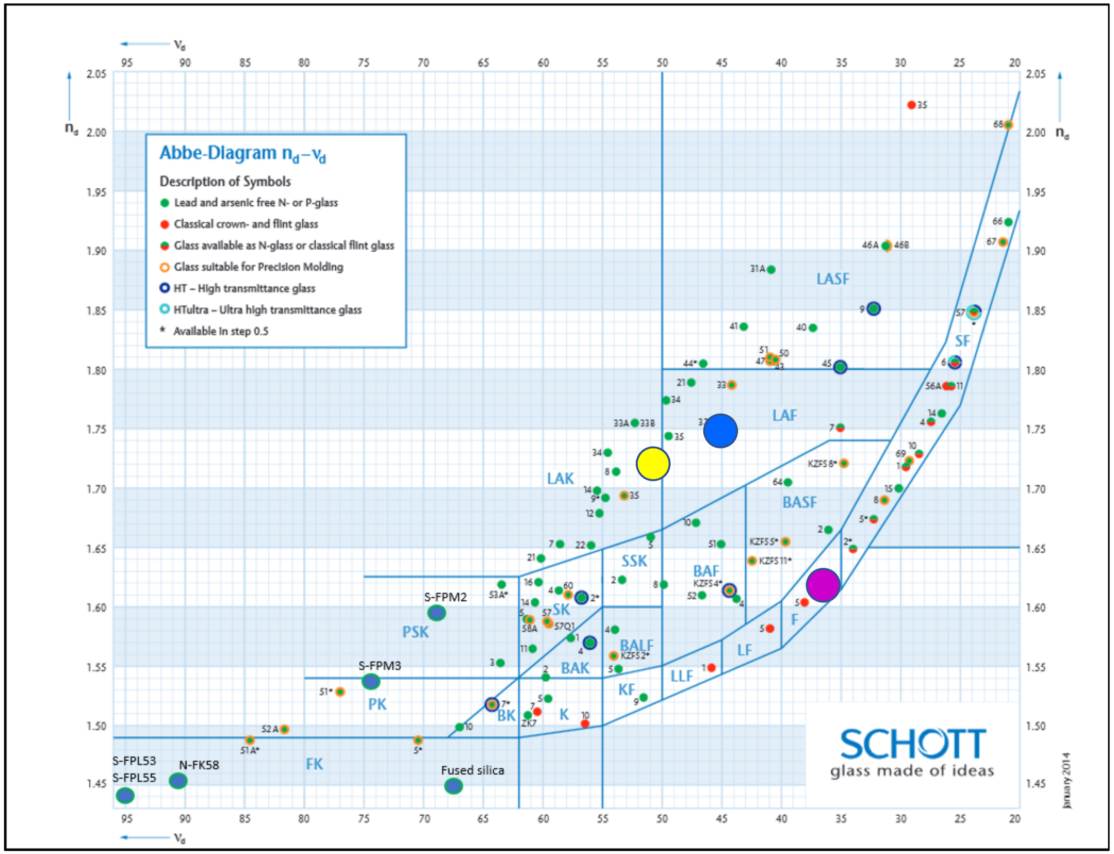


You are designing a classic Cooke triplet with no vignetting (As Shafer has stated "Vignetting is for wimps!") You've picked N-SK16 (620603) for the positive elements.

Which glass would you consider using for the negative element?

(1) N-LaK10 (720506)
(2) N-LaF2 (744449)
(3) F2 (620364)
(4) Timbuktu, Mali

Intuition Tester #4



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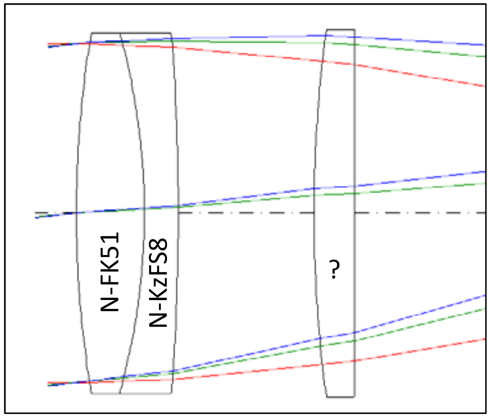
Intuition Tester #5



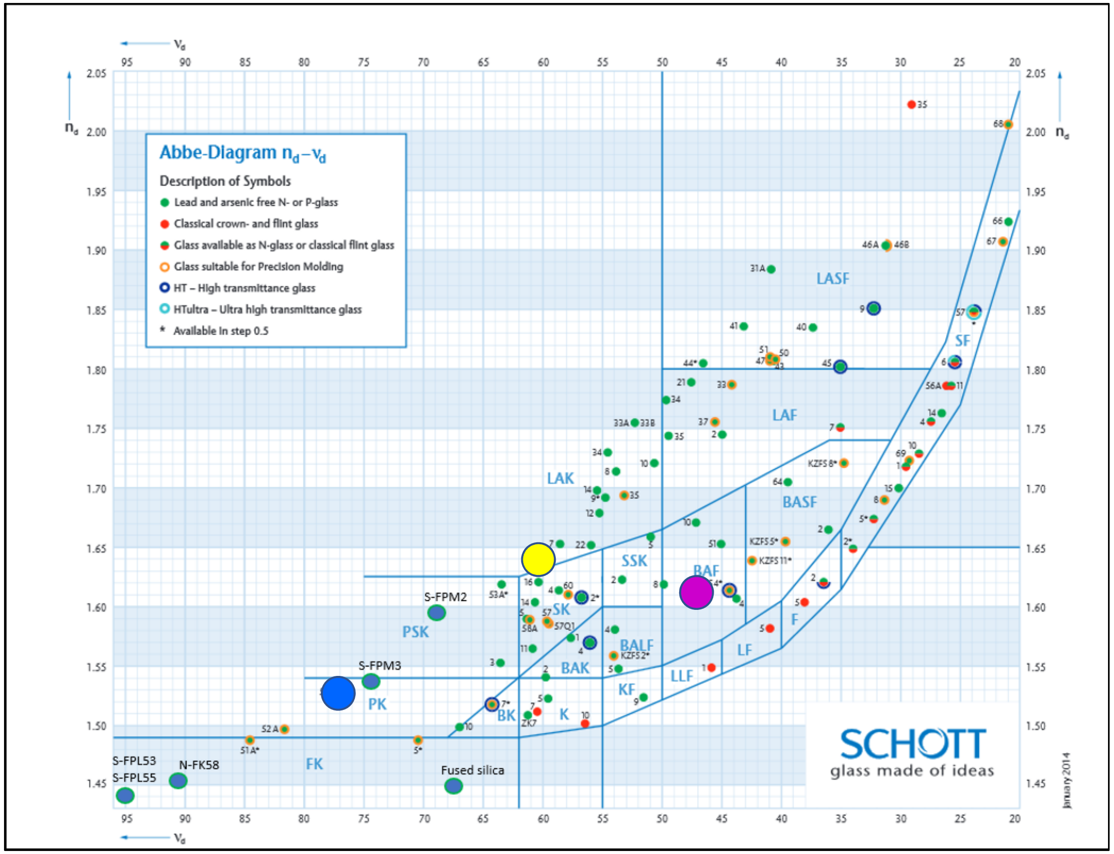
You are designing a complicated lens system for a particularly demanding customer. (Aren't they all?)

You've picked a fluorocrown and short flint for a doublet located in the middle of the system, but now for monochromatic correction, you need to add a singlet just behind it.

Which glass would you consider using for the newly inserted element?

(1) N-LaK21 (640601)
(2) N-BaF52 (608466)
(3) N-PK51 (529770)
(4) Beijing, China

Intuition Tester #5



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