

TIE-41 Large Optical Glass Blanks

1. Introduction

At present, plans for large wide-field telescopes and extremely large telescopes (ELTs) are progressing at increasing speeds. Studies for the design and manufacture of large mirror optics have been performed (ESO-OWL) [1] or are in progress (TMT, GMT) [2, 3].

The telescope optics design involves not only the design of large reflecting mirror systems but also the design of optical components. With increasing the collecting area of future ELT projects to dimensions up to 30 m and larger, the aperture of the instruments also increases, generating a demand for large optical glass lenses and prisms.

Even though large transmitting lenses and prisms have been produced in the past, this cannot be taken for granted. The optical elements in the future will be even larger and the specifications will be much more stringent, reflecting the ambitious scientific goals of the new telescope generations.

The optical glass production is optimized for optical parts of small dimensions. Typical dimensions for consumer optics range from 100 mm diameter lenses for digital single lens reflex cameras down to about 1 mm diameter lenses for mobile phones. A linear scaling up of dimensions by a factor of 5 to 20 increases the influence of effects by quadratic or cubic powers. In addition, effects previously of no concern may turn out to be the final restriction.

This technical information will address questions that arise with the production of optical glasses in large formats: Which glass types can be produced in large dimensions? What are the maximum dimensions that can be produced? How to specify a large optical glass blank? What restrictions regarding performance of large optical glass blanks have to be considered during the design of optical components? The availability of large wave band filters based on colored glasses is discussed in a separate publication [4].

2. Glass types and formats

In former times large lenses have been produced from discontinuous clay pot melts. This technique does not exist anymore. Since the 1950s and 1960s it has been replaced by continuous melting tanks, driven by the need for large volumes of economical optical glass.

In the continuous melting process the raw material is constantly fed into the melting section of the tank. The molten glass then flows to the refining chamber where gases are eliminated to minimize the bubble content. After passing the refining chamber, the melt is stirred to further improve the homogeneity before the glass is finally cast. The melting and casting takes place continuously and simultaneously in different sections of the tank. The flow rate of the glass material during casting is relatively low.



Figure 1: Production of optical glasses

Left: The clay pot melting technology is the historical method used until the 1950s. It is still in use but only for special colored glass types produced for small dimensions and thicknesses. Right: Modern optical glass production uses continuous melting tanks to achieve competitive prices and delivery conditions.

There are several limiting factors in the production of large optical glass formats with respect to the glass itself. The specific chemical composition of the glass not only influences its optical properties but also, for example, the thermo-mechanical properties like viscosity, the reactivity of the melt with the tank materials, the tendency of crystallization and the necessary sensitivity to handle the melting and casting process [5]. Different optical glasses have different viscosity behavior. The viscosity of the glass limits the glass flow rate but also influences the achievable homogeneity. The glass flow rate must be limited to ensure a continuous isotropic flow into the mould to prevent striae. This leads to long casting times which can range from several hours to almost one day. During this time all technical and environmental parameters have to be kept as stable as possible. In addition, the compositions of many glasses with exotic optical properties have high tendencies to crystallize thus limiting the chances of an integer solid large piece.

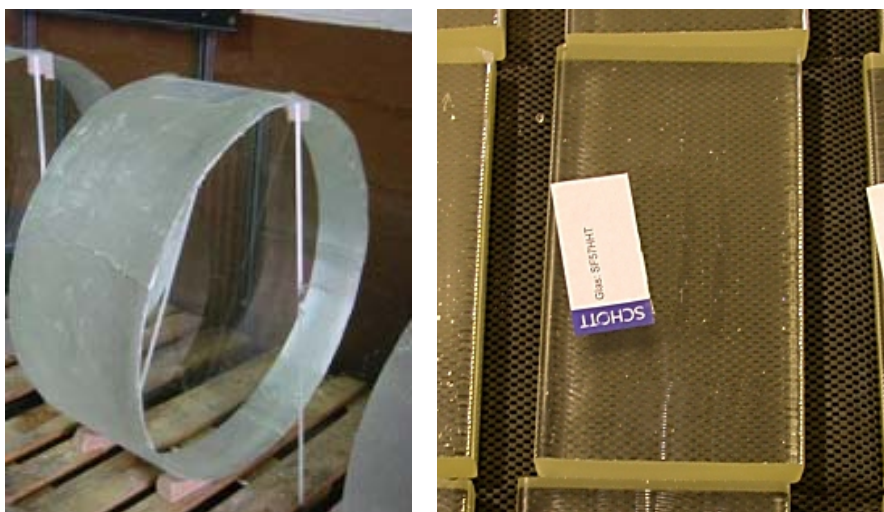


Figure 2: Left: 900 mm diameter N-BK7 blank
Right: SF57HHT in strip glass format

Typical production formats of optical glasses with the continuous melting technique are strip glass, blocks and round disks. Most optical glasses can be fabricated as strip glass with cross section of 160 x 38 mm. Some glasses are restricted to smaller thickness because of their tendency to crystallize. The length of the strip, in principle, is not limited. The casting process (with respect especially to the glass flow rate), limits the producible strip cross section. Typical formats can be seen in figure 2.

The most common production format out of a continuous melting process, other than strip glass, is block glass. The size of a typical block glass format is 200 x 200 x 180 mm. Glasses that can be produced in block format, for example, include LF5, LLF1, N-BAK, N-BK7, N-F2, N-FK5, some SK, F and SF glasses. Upon special request, disk-shaped glass formats can also be produced from a continuous melting tank. In the past, disk-shaped glass formats have been produced from 280 mm diameter up to about 1500 mm.

Table 1 gives an overview of the possible optical glass sizes and preferred glass types for the most common glass families. The following examples are based on publications [6, 7].

The most common optical glasses that can be produced in large dimensions of up to 1.5 m are N-BK7 and F2. With a large continuous melting tank providing the best chances of achieving high optical homogeneity, the maximum achievable dimensions for BK glasses are 1.5 m diameter and 500 mm thickness, corresponding to 2.2 tons of N-BK7. Figure 2 (left) shows an N-BK7 glass part with a dimension of 900 mm and a thickness 400 mm.

Flint glasses have been produced as radiation shielding glass blocks with dimensions up to 1500 x 1000 x 200 mm.

The glasses N-FK5, LLF1 and LF5 were optimized for the lithography industry, to cope with the demand on extremely high quality glass. They can be found in microlithography equipment with sizes up to 300 mm in diameter.

In addition, SF-type glasses with refractive index of up to 1.8 are also possible. SF1 has been produced in diameters of up to 500 mm in the past, and SF6 can be produced in diameters equal to or larger than 1000 mm.

LLF, LF, F and SF glasses, in principle, can be produced in formats up to 1000 mm diameter and 300 mm thickness with present capabilities in big continuous tanks. The maximum achievable dimensions with additional development effort are 1500 mm diameter and 500 mm thickness or other dimensions with equivalent volume. The dimensions are mainly restricted by casting time and striae quality.

Some of the SF glasses can also be ordered as lead-free N-types. These N-type glasses exhibit nearly the same refractive index and Abbe number but often behave totally different in melting and casting. In principle, all N-type SF glasses are restricted to strip glass formats with maximum diameters of 160 mm.

Lanthanum (LAK, LAF and LASF), phosphate (PSK, PK) and fluorine (FK) glasses tend to crystallize during the casting and cooling processes. These glasses have extreme positions in the Abbe diagram. To prevent uncontrolled crystallization, it is necessary to cross the critical temperature range of crystallization as quickly as possible in a very controlled way. This becomes more and more difficult with increasing sizes of the mould. Therefore many glasses cannot be produced in large formats.

LAK, LAF, LASF and also KZFS glasses can be produced in long, wide strip formats with relative low thickness. Therefore lenses with diameters up to 160 mm and 43 mm thickness are currently possible. Dimensions of 360 x 280 x 80 mm might be realizable with additional development efforts.

FK and PK glass types can be produced up to diameters of 360 mm and 60 mm thickness. With additional development efforts, dimensions of 460 mm diameter and 100 mm thickness are also possible.

Glass Type Family	Melting Technology Min Prod*	Max Dim present capabilities	Max Dim with development	Restricted by	Preferred Glass Types
BK	Cont. Tank 5 tons	Ø1000 x 300	Ø1500 x 500 or equiv. Vol	CT, CS, ES	N-BK7
LLF, LF, F, SF	Cont. Tank 5 tons	Ø1000 x 300	Ø1500 x 500 or equiv. Vol	CT, CS, ES	LLF1, LF5, F2, SF6
FK, PK	Discont. Pot	Ø360 x 60	Ø460 x 100	Cryst, VS	N-FK51A
LAK, LAF, LASF	Discont. Pot	300 x 160 x 43 GD	360 x 280 x 80 GD	Cryst, VS	LAK8, LAK9
KZFS	Discont. Pot	300 x 160 x 43 GD	360 x 280 x 80 GD	Cryst, VS	KZFSN4

Table 1: Glass types and their associated production information

Min Prod*	Minimum production amount needed for high quality
CT:	Casting Time
CS:	Center-
ES:	Edge-
VS:	Volume Striae
Cryst:	Crystallization
GD:	Gross diameter

Larger diameters with some pre-forming of curvatures may be achieved with the slumping method. The glass will be reheated until it becomes soft enough to flow under its own weight. Standing in a mould with larger diameters and a curved bottom will help it acquire the new desired shape when sufficient total volume is available. In general, this process does not affect the quality of the glass. The total production sequence of a slumped glass part is described in chapter 3.

Complementary to optical glass are fused silica and calcium fluoride (CaF₂). Fused silica is fabricated by flame-hydrolytic combustion of a gaseous silicon compound in a H₂/O₂ flame. The raw ingots have a maximum diameter of about 300 mm. The raw ingot can be slumped into larger formats. The maximum possible size is in the range of 800 x 1100 mm. CaF₂ can

be fabricated in formats up to 350 mm diameter, with slightly reduced quality up to 400 mm, and approximately 250 mm thickness.

3. Production Sequence

The total production cycle for a slumped large blank easily extends to one year. Table 2 shows a list of the different production steps and the corresponding time required in weeks. The preparation process and the melting, refining and casting process steps of a blank with 1.5 m diameter blank would take about 7 weeks in total.

With today's continuous tanks it is not possible to produce glass for just a single large blank. The need for high homogeneity requires casting over a time range, where the refractive index has to be very constant. Normal variations at the start of a new tank melt have to be eliminated before casting may begin. Only after one or two days of production can the first casting begin. Therefore if only one blank is needed, the price of the blank has to cover the total costs of all the glass which has to be produced along with that blank. The remaining glass may possibly not be sold due to restricted demand and special optical positioning with respect to the refractive index and dispersion. This is especially so with lead-containing glass types, which are not used in consumer optics anymore.

Directly after the casting process, the still viscous melt has to be taken to a coarse annealing furnace. The hot glass melt will be cooled down to room temperature in special coarse annealing ovens for about 6 weeks. The time required depends on the size and the type of glass involved and needs to be done slowly in order to preserve the blanks from breakage due to internal stress. During coarse annealing, the temperature field around the mould must be kept as stable as possible.

Production step	Weeks
1. Production of large moulds	16
2. Melting, refining, casting	1
3. Coarse annealing and first inspection	6
4. Fine annealing	17
5. Pre-machining for inspection (polished faces with moderate flatness specification for striae and inclusion inspection, fine lapping for interferometric measurements), cutting samples for the measurement of optical properties (refractive index, Abbe number, internal transmittance)	2
6. Inspection of internal quality (striae, bubbles and inclusions, stress birefringence)	1
7. Homogeneity measurement with Fizeau interferometer	1
8. Slumping and repeated fine annealing (if larger diameter has to be achieved than could be cast or shape has to be changed)	17
9. Final machining to requested blank shape - Geometrical inspection	2
Total time optimum when all resources are available in time	63

Table 2: Production sequence of large optical glass blanks. The typical production times needed per step are given in weeks. The total production of a large slumped glass blank will take more than 1 year.

After a first inspection for striae, bubbles and inclusions, the glass blank will be fine-annealed. This is the most time-consuming process in the production of large optical glass blanks. The fine-annealing process determines the final refractive index, the optical homogeneity and the stress birefringence. The refractive index of a piece of glass is given by its chemical composition only in the range of 10^{-3} . The final values down to the 6th or 7th decimal place will be fixed by the temperature history the glass piece has undergone in the temperature range, from the so-called transformation temperature to about 150 to 200°C downwards. At the transformation temperature, a glass type specific value, stress in the glass relaxes within short time.

During cooling down over this temperature range, one must keep the temperature differences in a large piece of glass as small as possible. Otherwise, this would lead to refractive index in-homogeneities. Glass, in general, is a poor temperature conductor. Therefore in order to keep temperature differences at a minimum, the temperature changes with time have to be kept very low. In addition, the differences induced in a volume of a poor thermal conductor are not linear with its dimensions. They are proportional to the square of the thickness of a plate. So even if larger and hence thicker blanks could be cast, the annealing times necessary to achieve high homogeneity would become extremely long - too long to be practical.

After fine-annealing, the glass goes through internal quality inspection and homogeneity measurement. The homogeneity measurement is restricted at SCHOTT to apertures of 500 mm at maximum. Larger interferometer apertures are difficult and very expensive to realise. The slumping process does not significantly influence the homogeneity of the glass and therefore no additional homogeneity measurement will be necessary. The subsequent slumping process is followed by a fine-annealing step that actually takes about the same amount of time as the initial fine-annealing.

Theoretically the second fine-annealing can be skipped by combining the slumping process with the first fine-annealing step. The disadvantage of this is that it will not be possible to estimate the homogeneity of the blank after slumping due to the large dimensions of the blank.

4. Properties and Specification

The main properties essential for the function of a piece of optical glass are: the refractive index, the Abbe number as a measure of dispersion, the optical homogeneity, the spectral internal transmittance, bubbles and inclusions, striae and stress birefringence. Detailed information about these properties can be found in literature [5, 8]. The nominal values and tolerances cannot just be used or extrapolated to very large pieces of these glass types.

The temperature dependence of glass properties may be neglected for many applications of small elements with moderate quality requirements. However going to large elements with utmost optical quality requirements the temperature dependence of several properties have to be taken into account since they may restrict or even prevent the intended application. The main reasons are the sharp increases in temperature gradients within the glass with its dimensions and the significant increases in the light path through the.

In the following chapters, an overview is given on the impact of special production processes on the properties and therefore on the specification of large optical glass blanks.

4.1 Refractive index and Dispersion

In general optical glass in big formats can be delivered with the refractive index tolerance grades given in the optical glass catalogue. The optical data for a glass type are chiefly determined by the chemical composition and the subsequent thermal treatment of the melt. The annealing rate in the transformation range of the glass can be used to influence the refractive index within certain limits. Basically, slower annealing rates yield higher refractive indices [8, TIE-29].

The very long fine-annealing times, necessary to reduce the stress birefringence of large blanks, will lead to an increase in the refractive index. The glass composition of block glass is adjusted for 1°C per hour of fine-annealing. Annealing such glass with 0.1°C/h, as necessary for large blanks, will increase the refractive index n_d by 0.00093 and the Abbe number v_d by 0.08 for N-BK7 (for example), thus lying out of the catalogue tolerance range. The index d denotes the spectral d-line at 587.6 nm.

Glass Type	n_d Cat	v_d Cat	Δn_d (1:10)	Δv_d (1:10)	n_d LE	v_d LE
LLF1	1,54814	45,75	0,00040	0,02	1,54854	45,77
LLF6	1,53172	48,76	0,00045	0,03	1,53217	48,79
F2	1,62004	36,37	0,00043	0,04	1,62047	36,41
SF6	1,80518	25,43	0,00058	0,05	1,80576	25,48
N-BK7	1,51680	64,17	0,00093	0,08	1,51773	64,25

Table 3: Refractive index and Abbe number for some optical glasses with especially low annealing rate, 10 times less than for usual production, to be used for large elements (LE)

The absolute values of the refractive index and the dispersion are measured with samples cut from the fine-annealed blank. SCHOTT introduced a precision method capable of measuring the refractive index in the range from 0.185 μm , which is below the UV-edge of all glass types, up to 2.3 μm with an accuracy of 4×10^{-6} (3σ). The results are recorded in a precision test certificate giving the constants of the Sellmeier dispersion curve from the near UV to the near IR. With this data, all partial dispersion values can be calculated with high accuracy.

4.2 Optical Homogeneity

One of the most important properties of optical glass is the excellent spatial homogeneity of the refractive index of the material. Striae are spatially short range variations of the refractive index in a glass, whereas the spatially long range global homogeneity of refractive index covers the complete glass piece. The global refractive index homogeneity is strongly influenced by the temperature homogeneity of the material.

4.2.1 Striae

Striae are variations of the refractive index in short ranges with typical periods between 0.1 and 1 mm. The most common kind of striae in the glass production process is band-like striae. These striae do not exhibit sharp edges and their shape is similar to a frozen convection pattern (figure 3). For striae inspection the shadowgraph method is used.

Striae are mainly categorized by their effect on the wave front deviation of a plane wave (referred to as striae intensity given in nm). The most prominent standards for striae are the ISO 10110 part 4 [5]. In general, SCHOTT standard optical glass fulfills the requirements of the ISO 10110 class 1-4. The striae intensity depends on the thickness of the glass in view direction if the striae are spread through the glass and the viewing direction. More general information on striae can be found in [8, TIE-25].

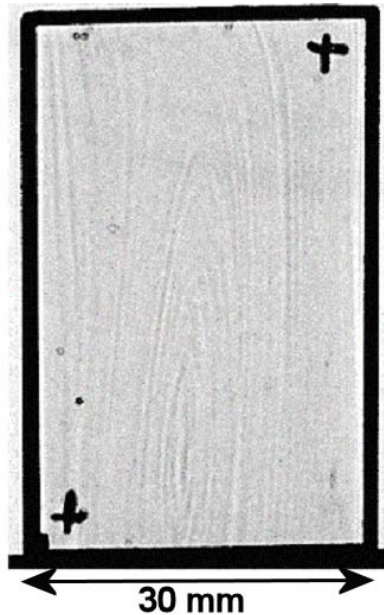


Figure 3: Band-like striae D-grade which is close to 60 nm wave front deformation

In the present day production method with continuous tanks striae may cover larger parts of the total element volume and thus projected area. However, they are much smaller with respect to the wave front distortion. For common and even advanced optical glass applications striae quality resulting in an optical path difference better than 30 nm has proved to be sufficient. The main effect of striae with wave front distortions smaller than 60 nm in an optical system is deflected light. Aberration and deflected light effects caused by such striae cannot be traced with significance within the aberration and deflected light effects which result from the design and production of a lens system in any way is shown in TIE-25.

The candidate glass types for large lenses have the potential for high quality is shown from practical experience. But to keep the striae content at a low level will really be a challenge with large glass blanks. Striae can appear especially at areas close to the edges. But since part of the optical elements' edge zone will be hidden by mounting frames, there may be some room for relaxation of the striae tolerance in this outer zone.

Another possibility of minimizing the striae content is to fabricate the raw casting with a larger diameter than the final lens diameter. Sometimes existing striae in the outer region can be moved out of the necessary aperture by additional slumping of the raw glass to a bigger diameter.

Special fluor-crown and lanthanum glass types will often be produced with the platinum pot melting method. It is applied only in exceptional conditions, mainly for dimensions larger than are feasible with the continuous strip production. Here striae may occur from the glass flow during casting while the melt is still very fluid. The sharply increasing probability of such striae with larger mould diameters is the main reason for size restrictions of the fluor-crown and lanthanum glass types. SCHOTT has successfully cast fluor-crown glass disks, with a diameter of 200 mm, with exceptionally high striae quality (better than 10 nm). But going beyond this size limit would most probably lead to a decision between balancing assessments - which requirement will be more important: The existence of larger blanks with striae up to 30 – 60 nm wave front distortions or the extremely low striae level but then with only restricted diameters? This question cannot be answered easily, but has to be investigated in co-operation with the optical designers and the glass manufacturer.

4.2.2 Global refractive index homogeneity of optical glass

A first assessment of the achievable optical homogeneity is possible by the striae inspection of the glass blank after coarse annealing. A high striae quality is a necessary precondition to attaining a high chance that the homogeneity will be excellent after fine-annealing. The final success of the production, however, will be proven only after the lengthy fine-annealing process, about half a year after casting.

The global homogeneity of optical glass is measured by evaluating wavefront deviations using a DIRECT 100 Fizeau Interferometer from Zeiss with a free aperture of about 500 mm. The overall accuracy of the wavefront measurement is in the range of ± 10 nm wavefront deviation (peak to valley). The repeatability is limited by the "noise" of the interferometer and lies in the range of 3-4 nm (more information on the experimental setup can be found in [10]). The measurement result is displayed in a homogeneity map showing the color coded relative refractive index variation inside the measured glass part. The total global homogeneity, the so-called H-grade, is the peak to valley (p-v) variation within this homogeneity map.

The deliverable quality grades of glasses with increased requirements for refractive index homogeneity comprises 5 classes in accordance with ISO standard 10110 part 4 [9]. The SCHOTT homogeneity grade H1 to H5 for single parts comprises ISO grades 1 to 5. An overview on the homogeneity grades can be found in [8, TIE-26]

Even though the glass format is either circular or block shaped, most homogeneity distributions exhibit a certain degree of rotational symmetry. The strongest deviations from homogeneity usually lie near the edge of the glass disk. In general, if the diameter of a large casting is reduced by cutting and grinding, the homogeneity will increase [8, TIE-26].

The shape of the wavefront deviation (and therefore the homogeneity distribution) can be mathematically described as a Zernike polynomial function being a summation of independent aberrations terms [11]. These terms contain coefficients expressing the amount of focus, astigmatism, coma and spherical aberration within a wavefront. Piston and tilt deviations are subtracted from the wavefront in advance.

Not all contributions of the wave front deviation adding up to the p-v value are really critical for the function of an optical element. The defocusing term can easily be corrected in the optical system. Also, astigmatism may be compensated by the rotation of other astigmatic elements in the system to a certain extent. This may allow relaxing the homogeneity specification, because the terms normally mentioned contribute a significant amount to the p-v value. In addition, adapted polishing may compensate for other long-range deviations. High-end polishing companies are familiar with this method. The example in figure 4 shows that the peak to valley homogeneity after subtracting the focal term from the complete wavefront is, in most cases, much lower than the initial value.

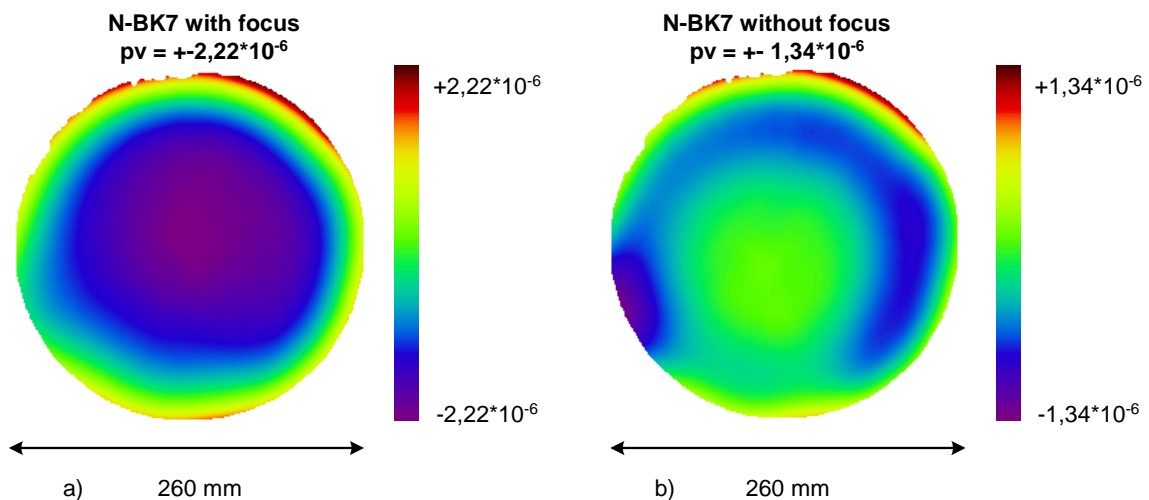


Figure 4: N-BK7 blank with and without focal aberration.

The measurement of the optical homogeneity is the most challenging inspection to be made for large glass blanks. The Fizeau interferometers presently used for this purpose have a maximum aperture of 500 to 600 mm. It would not be possible to measure elements up to an effective diameter of 1.5 m with a single large aperture. In order to build such interferometers, lenses of 1.5 m would be needed – a bootstrapping problem. Other influences such as the variations in the environmental conditions, like the temperature field around the blank to be measured and around the total interferometer with its large optical elements, vibrations and air flow in the interferometer cavity also limit the maximum possible aperture [10].

In order to assess the quality of the large blank in totality, it can be sufficient to look at the sub-aperture results individually or to stitch sub-apertures. This has already been done [12] but only for much smaller sizes. Especially for the specification and verification of the homogeneity, it is urgent for telescope optics designers, glass manufacturers and polishers to agree on the specification values needed.

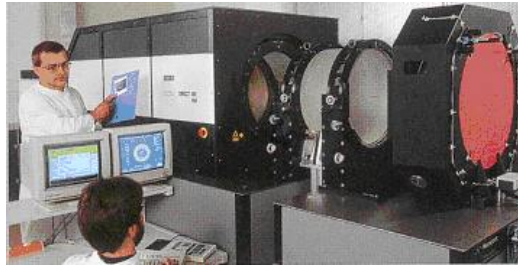


Figure 5: 500 mm Fizeau-Interferometer at SCHOTT Mainz. The time to develop and build an interferometer of this size and accuracy with all the necessary equipment and room infrastructure requires typically 3 years

If new larger interferometers and evaluation methods have to be developed, one must take into account long time periods (several years) and high costs. These costs will not be borne by the glass manufacturer. The total demand for large optical glass blanks within a range of several years is expected to be so small that such investments would be far from being economical.

4.2.3 Thermally induced refractive index homogeneity

Even perfectly homogenous glass disks would show in-homogeneity during interferometric measurement when they are not in thermal equilibrium. This also holds true for their application as optical elements. Table 4 gives values for the wave front deformations ΔW caused by temperature differences of 0.1 K at 20°C and 100 mm path length.

The wave front deviation ΔW for plane waves travelling through an optical transparent material with thickness t and temperature in-homogeneity ΔT is calculated according to Reitmayer and Schröder [13] with the formula:

$$\Delta W = t \cdot \left(\alpha \cdot (n(\lambda) - 1) + \frac{dn}{dT_{rel}}(\lambda; T) \right) \cdot \Delta T$$

α : coefficient of thermal expansion
 n : refractive index
 dn/dT_{rel} thermo-optical coefficient of the glass type relative to air

These deformations have significant values even for the small temperature difference used in the calculation example. This also holds true for zero-expansion materials, when they are used in transmittance. The comparison between absolute values (relative to vacuum) in column 9 and values relative to air in column 8 of table 4 shows that these differences cannot be neglected totally. In both cases, measurement and optical element operations require stable environmental temperature.

1	2	3	4	5	6	7	8	9
T = 20 °C							ΔT [K]	0,1
							Thickness t [mm]	100
Material	CTE (-30/70°) K ⁻¹	dn/dT rel (20/40°) e-line K ⁻¹	dn/dT abs (20/40°) e-line K ⁻¹	n (e-line)	Thermo-Opt Coefficient G rel 10 ⁻⁶ /K	Thermo-Opt Coefficient G abs 10 ⁻⁶ /K	ΔW Wave front deformation relative to air nm	ΔW Wave front deformation absolute nm
LLF1	8,10E-06	2,90E-06	1,50E-06	1,55099	7,36	5,96	74	60
LLF6	7,50E-06	3,70E-06	2,30E-06	1,53431	7,71	6,31	77	63
F2	8,20E-06	4,40E-06	3,00E-06	1,62408	9,52	8,12	95	81
SF6	8,10E-06	1,11E-05	9,50E-06	1,81265	17,68	16,08	177	161
N-BK7	7,10E-06	3,00E-06	1,60E-06	1,51872	6,68	5,28	67	53
Vitreous Silica	5,10E-07	1,01E-05	n.a.	1,46008	10,33	n.a.	103	n.a.
CaF2	1,67E-05	-1,14E-05	n.a.	1,43493	-4,14	n.a.	-41	n.a.
Zerodur	2,00E-08	1,48E-05	1,34E-05	1,54470	14,81	13,41	148	134
Air	n.a.	n.a.	-9,33E-07	1,000273	n.a.	-0,93	n.a.	-9

Table 4: Wave front deformation of plane waves caused by temperature in-homogeneity

4.3 Internal Transmittance

The internal transmittance in the visible range is normally of no big concern even for large thicknesses. However, when travelling into the IR wavelength range, the internal transmittance starts to decrease, as can be seen in figure 6. Large thicknesses will amplify this effect. The measurement using samples is common practice and is representative for a large blank. In recent years, improvements have been achieved in the transmittance of lead silicate glass types at the UV-edge by making it steeper.

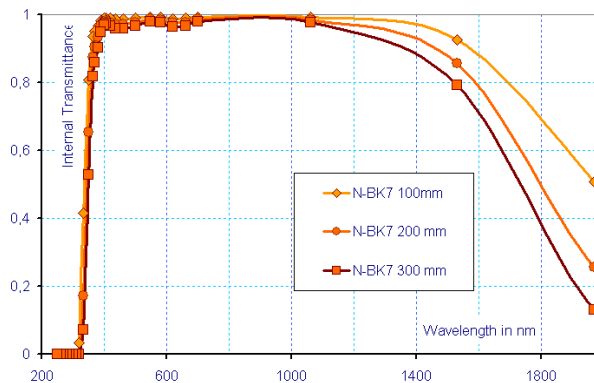


Figure 6: Spectral internal transmittance of N-BK7 and F2 for three different thicknesses

4.4 Bubbles and Inclusions

The glass types suitable for large lenses have very low levels of bubbles and inclusions. However it is not possible to produce large volumes of glass that is totally free from bubbles and inclusions. Some few scattered bubbles will have to be accepted. Usually one specifies the ratio of the sum of the effective areas of all inclusions to the area of the optical element. This ratio is a measure for the stray light produced in the element.

4.5 Stress Birefringence

In principle two types of stress birefringence occur in glass. One is a component varying in time, depending on the temperature fluctuations within the glass. The other one, the permanent stress birefringence, comes from the production of the glass and will remain in the glass for its lifetime, superposed by the temporal/transient stress birefringence.

Stress birefringence is generated by mechanical stress in the glass. The permanent bulk stresses result from temperature differences in the blank's volume arising during the ramp down in the range below the transformation temperature. In order to keep these temperature differences small enough to reach low permanent stress birefringence, one has to strive for the lowest possible annealing rates and the smallest possible glass thickness (see chapter 4.5.1). In addition to optical homogeneity, this is the other reason for the very long annealing times.

The standard tolerances as applied for small optical elements will probably not be sufficient. The admissible limit of 10 nm/cm birefringence in block or strip glass is harmless since most elements made out of such glass have only optical path lengths of some centimeters. In addition, stress collapses significantly while cutting blocks to smaller pieces.

For large optical glass blanks birefringence may become fully effective. There is no cutting to reduce bulk stress and the large optical path lengths sum up birefringence to significant amounts. An element with a thickness of 100 mm and 10 nm/cm specific birefringence would end up with 100 nm birefringence in total close to the outer edge. A well-annealed piece of glass bulk shows its highest stress (compressive, represented with negative values) at the outer edge. The stress approaches zero towards the centre, crosses zero and reaches a local maximum (tensile, represented with positive values) at the centre. This local maximum is significantly lower in absolute values than at the outer edge.

The optical design would have to take into account wavefront retardations of 100 nm between orthogonal polarized light rays at maximum varying locally over the elements area. The effective birefringence results from the interaction of the light with its different polarization directions and the bulk stress tensor field, which makes things very complicated.



Figure 7: Breakdown of stress with cutting. Fine-annealed block of optical glass N-BK7 in crossed polarizers. Left: Original format L: 191 x W: 180 x H: 162 SBF: -13 nm/cm top-bottom. Right: After cutting in the middle L: 191 x W: 90 x H: 162 SBF: -4,5 nm/cm top-bottom. For large blanks such breakdown may not be expected since they are not cut.

So the best will be to reduce the total stress birefringence to the best possible value. But this is limited by practically possible annealing times. The best stress birefringence values achieved with N-BK7 blanks up to 1 m with annealing cycles of several months have been in the range 2 – 4 nm/cm, which still results in 20 – 40 nm birefringence in a 100 mm thick optical element. This has to be considered in the design of the optical system.

Temperature fluctuations in the volume lead to transient birefringence. Table 5 column 22 gives values of the birefringence in nm wave front retardation per cm path length and per Kelvin temperature difference. They are only approximate values since they are calculated from the product of the thermal stress factor φ and the stress optical constant K, neglecting the special geometrical influences. A temperature difference of 1 K in a 10 cm thick N-BK7 disk will lead to 200 nm wave front retardation. The transient birefringence can only be minimized by the stabilization of the environmental temperature.

4.5.1 Mechanical stress

The temperature gradients within glass are proportional to the square of its thickness. The time needed for a temperature difference extending over a range of thickness (t) to relax to equilibrium is in the range of 4 to 10 hours for a 10 cm thick glass disk. With higher requirements on temperature homogeneity and larger thickness, they will easily get much longer – up to the order of several days. Typical values for t_r are listed in table 5 column 21.

The mechanical stress σ is proportional to the temperature difference ΔT , the thermal expansion, Youngs modulus and to $(1-\mu)^{-1}$. The multiplication of these three characteristics is called the thermal stress factor φ - some values are listed in table 4 column 20. Therefore a slow coarse annealing is necessary for large blanks to keep the mechanical stress low enough to prevent breakage.

Such stress endangers element integrity if sharp temperature changes happen during storage, transportation, grinding or polishing (thermo-shock breakage). Large blanks and elements of the glass types mentioned in chapter 2 like boro-silicate crowns or lead flints have to be checked with respect to cracks. Each visible crack has to be smoothen out with a fine grain grinding tool, since it may be the starting point of a long crack travelling into the volume.

Especially with low dispersion glass types like N-FK51A, N-PK52A and other glass types of that range, special care has to be taken. They are very sensitive against thermo-shock breakage. Even disks of only some cm thickness have to be handled very carefully. For example the cooling liquid for grinding has to be temperature matched and stabilized [10, TIE-16]. It is highly recommended to give grinding and polishing contracts only to companies who are well experienced in processing such sensitive, high-valued and hard-to-replace glass pieces. The relative thermo-shock sensitivity of some glass types compared to N-BK7 is given in table 5 column 23 [7]. The thermo-shock sensitivity has been defined as a figure of merit taking into account the thermal stress factor φ (column 20) and the bending strength of the glass type (column 19). The values given in table 5 column 23 are relative values as compared to N-BK7.

σ_0 is the characteristic strength according to the statistical Weibull-distribution used to describe the breakage behaviour of glass. It is the value where 63 % of a given set of samples have broken. The value depends mainly on the surface condition of the glass.

The surfaces quoted in table 4 have been lapped with SiC600 loose grain, hence removing the micro-cracks from previous grinding steps. For more information please refer to the SCHOTT Technical Information 33 on design strength of optical glass and ZERODUR® [10].

Temporal mechanical stress can lead to figure deformation during the polishing process. Interferometric shape measurements are only possible in thermal equilibrium. This requires long waiting times before measurements can be performed.

1	2	3	4	7	8	12	13	14	15	16	17	19	20	21	22	23
	Refractive Index n_d	Abbe Number ν_d	Main Dispersion n_F-n_C	Stress-optical constant K nm/cm MPa-1 (*0,1)	Density ρ g/cm ³	Heat Capacity c_p J/gK	Thermal conductivity λ W/mK	Thermal diffusivity κ 100° cm ² /s	Young's Modulus E GPa	Poisson's Ratio μ	CTE - 30°C /+70°C 10 ⁻⁶ /K	Charac-teristic Strength SiC600 α_0 MPa	Thermal stress factor φ MPa/K	Time constant t = 10 cm t_f hours	Thermally induced birefringence $K \times \varphi$ nm/cm /K	Thermo-shock sensitivity relative to N-BK7
N-FK5	1,487490	70,41	0,00692	2,91	2,45	0,808	0,925	0,467	62	0,232	9,2	70	0,74	5,9	21,6	1,0
N-FK51A	1,486560	84,47	0,00576	0,70	3,68	0,690	0,760	0,300	73	0,302	12,7	33	1,33	9,3	9,3	3,9
N-PK52A	1,497000	81,61	0,00609	0,67	3,75	0,670	0,730	0,291	71	0,298	13,0	33	1,32	9,6	8,8	3,9
N-BK7	1,516800	64,17	0,00805	2,77	2,51	0,858	1,114	0,517	82	0,206	7,1	71	0,73	5,4	20,3	1,0
N-ZK7	1,508470	61,19	0,00831	3,63	2,49	0,770	1,042	0,543	70	0,214	4,5	69	0,40	5,1	14,5	0,6
N-BAK1	1,572500	57,55	0,00995	2,62	3,19	0,687	0,795	0,363	73	0,252	7,6	59	0,74	7,7	19,4	1,2
N-SK16	1,620410	60,32	0,01029	1,90	3,58	0,578	0,818	0,395	89	0,264	6,3	62	0,76	7,0	14,5	1,2
N-LAK9	1,691000	54,71	0,01263	1,83	3,51	0,649	0,908	0,399	110	0,285	6,3	65	0,97	7,0	17,7	1,4
LLF1	1,548140	45,75	0,01198	3,05	2,94	0,650	0,800	0,419	60	0,208	8,1	65	0,61	6,6	18,7	0,9
LLF6	1,531720	48,76	0,01090	3,06	2,81	0,700	0,800	0,407	63	0,203	7,5	65	0,59	6,8	18,1	0,9
F2	1,620040	36,37	0,01705	2,81	3,60	0,557	0,780	0,389	57	0,220	8,2	57	0,60	7,1	16,8	1,0
SF6	1,805180	25,43	0,03166	0,65	5,18	0,389	0,673	0,334	55	0,244	8,1	49	0,59	8,3	3,8	1,2
KZFSN4	1,613400	44,29	0,01385	3,13	3,20	0,636	0,766	0,376	60	0,275	4,5	49	0,37	7,4	11,7	0,7
ZERODUR	1,542400	56,10	0,00967	3,00	2,53	0,800	1,460	0,721	90	0,243	0,1	108	0,01	3,9	0,4	0,01

Table 5: Thermal properties of selected glass types [7]

5. Recommendations

Optical transmitting elements are essential for large telescopes. More attention should be given towards supplying large transmitting optical components. SCHOTT is sufficiently capable at supplying a large number of 1.6 m glass-ceramic hexagons since its production process has been proven and is at reasonably economic conditions, as compared to manufacturing a single 1.6 m lens blank with extreme quality which involves quite a number of till-now unanswered questions and adverse economic conditions. Here are some concluding recommendations:

- Keep dimensions of the transmissive optical elements as small as possible. This holds especially true for the thickness of large lenses. The thickness determines the thermal inertia of the lens, which is the cause for many problems in production and in operation of the optical element. Due to the quadratic influence on temperature differences in the volume even small thickness reductions will help.

- Large lenses will be unique and sensitive pieces. They play a key role in the optical system and require very long periods of time in order to replace them during cases of accidents. Therefore it is recommended to apply special risk management procedures to the entire production process, right from the very start until the final mounting of the lenses in the structure of the telescope.
- Most of the internal imperfections like striae or inclusions will lead to stray light or deflected light. They may also become visible if they are close to an intermediate image plane. Simulation calculations should be considered to assess the effects of these imperfections to prevent over-specification and to find restrictions early enough to look for remedial solutions. The same holds for the temperature gradient induced inhomogeneity. The most promising ways of minimizing it, is the thermal stabilization and its inclusion in the adaptive optics correction feedback loop.

Use as much large reflective optics as possible.

SCHOTT is confident of producing large glass blanks. With existing methods, it offers products that can be manufactured on a best-effort basis. This will represent a high quality. However, certain specification limits as needed by future telescopes cannot be guaranteed. If this risk appears to be too high, there is a strong need for development projects. They should be started as soon as possible, since development times and production cycles will take long periods of time, which are comparable to the realization times for the entire telescopes!

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Optics for Devices
SCHOTT North America, Inc.
400 York Avenue
Duryea, PA 18642
USA
Phone: +1 (570) 457-7485
Fax: +1 (570) 457-7330
E-mail: sgt@us.schott.com
www.us.schott.com/optics_devices