Properties of Zerodur Mirror Blanks for Extremely Large Telescopes

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ABSTRACT

SCHOTT produces the zero expansion glass ceramics material ZERODUR since 35 years. More than 250 ZERODUR mirror blanks were already delivered for the large segmented mirror telescopes KECK I, KECK II, HET, GTC, and LAMOST. Now several extremely large telescope (ELT) projects are in discussion, which are designed with even larger primary mirrors (TMT, OWL, EURO50, JELT, CFGT, GMT). These telescopes can be achieved also only by segmentation of the primary mirror. Based on the results of the recent production of segment blanks for the GTC project the general requirements of mirror blanks for future extremely large telescope projects have been evaluated. The specification regarding the material quality and blank geometry is discussed in detail. As the planned mass production of mirror blanks for ELT´s will last for several years, economic factors are getting even more important for the success of the projects. SCHOTT is a global enterprise with a solid economical basis and therefore an ideal partner for the mirror blank delivery of extremely large telescopes.

Keywords: Extremely Large Telescopes, segmented mirrors, ZERODUR, zero expansion, glass ceramics

1. INTRODUCTION

SCHOTT has a history of more than 100 years in mirror blanks for astronomical telescopes [1]. ZERODUR is produced since 35 years and, due to the continuous improvements, it has been the preferred mirror blank material for most of the existing large segmented telescopes (KECK I, KECK II, HET, GTC, LAMOST). For the future several extremely large telescope (ELT) projects are in discussion, which are designed with even larger primary mirrors ranging from 25 m to 100 m (see table 1). Here segmentation is unavoidable and an effective mass production of mirror segments will be an key element for the success of these projects. The main challenge for a mass production of mirror segments is to master logistics with respect to the requested delivery rates and adequate costs [2]. For the increasing world wide demand on large ZERODUR components for industrial applications SCHOTT recently ramped up its production capacity. This investment in additional melting and ceramisation capabilities was accompanied by improvements of quality assurance and processing technology. SCHOTT is now prepared also for a future mass production of mirror blanks for next generation of extremely large telescopes [3].

Project / Country	M1 Diameter	Number of segments	Segment dimensions	Reference
TMT / USA	30 m	861 hexagons	1.3 m (diagonal)	L. Stepp et al. [4]
OWL / Europe	100 m	3048 hexagons	1.84 m (diagonal)	P. Dierickx et al. [5]
EURO50 / Europe	50 m	400 hexagons	2 m (diagonal)	T. Anderson et al. [6]
CFGT / China	30 m	1122 segments	0.8 x 0.8 m	D. Su et al. [7]
JELT / Japan	30 m	1080 hexagons	0.92 m (diagonal)	M. Iye et al. [8]
GMT / USA	25 m	7 discs	dia. 8.4 m	M. Johns et al. [9]

Table 1: Planned future ELT telescopes with segmented mirrors

Future ELT projects require a continuously maintained quality level for all of the many blanks needed. This is an essential prerequisite to industrialize the subsequent polishing and mounting processes. SCHOTT has demonstrated its

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capability to fulfil this on the occasion of previous projects with comparable specifications. Sizes and quality required for the future mirror blanks are therefore present days work (see figures 1 and 2). All ZERODUR mirror segments presently in discussion for various ELT projects are state of the art; no further process development is needed. An ELT mirror blank production at SCHOTT will use the proven and established technology of ZERODUR glass ceramics.

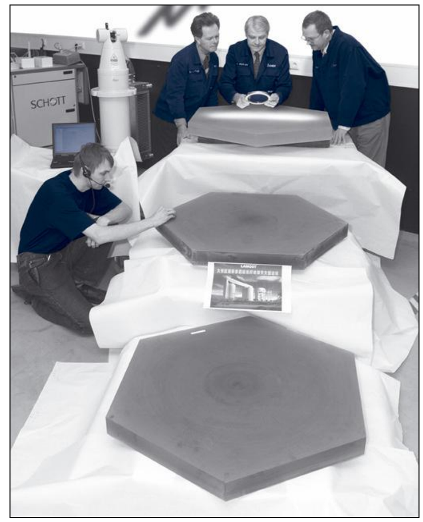

Figure 1: ZERODUR mirror blanks for GTC (left)   Figure 2: ZERODUR mirror blanks for LAMOST (right)

As the ELT projects are progressing, now the optimization of technical specification details become important. It is necessary to define the best interface between the blank manufacturer and the optical finisher. Recently the TMT project recently released a drawing on the potential geometry of TMT mirror banks (confer with: www.tmt.org).
It is the intention of this paper to discuss an ELT segment blank specification from the point of view of a glass manufacturer. Sometimes the specific comment is referring to the TMT specification and has to be generalized for other ELT projects. The recent productions of mirror blanks for the GTC and the VISTA telescopes are excellent examples for the present mirror blank production capacity at SCHOTT. A general specification for ZERODUR consist of: (a) geometrical dimensions, (b) internal quality inspections, and (c) material properties. In the following chapters the influence of the different parameters on costs and manufacturing effort is pointed out. Thereby specific values and their tolerances, results achieved during previous projects, verification methods and their accuracies are discussed in detail.

2. DISCUSSION ON GEOMETRICAL DIMENSIONS

2.1 Measurement equipment

For the metrology of the produced large GTC mirror substrates we used a laser tracker system (Leica LT 500) with an accuracy of ±10µm/m distance. The calibration of the Laser Tracker System was done by an internal calibration routine and reference standards made of ZERODUR. For the GTC profile tolerance measurements the laser tracker system was placed close to the blank (figure 3).
An efficient mass production of large ZERODUR components needs automatic measurement methods. Therefore SCHOTT recently invested (after finishing the GTC project) in a new large coordinate measurement machine (CMM) for a high accuracy verification of the specified geometry. Due to the dimensions of this new CMM (Carl Zeiss, type PRISMO 10 HTG, measurement volume 2400 x 1600 x 1000 mm, see figure 4) most of the discussed ELT segments (OWL, TMT, JELT, CFHT) could be measured automatically. The preferred sizes of hexagonal segments are in the region of 1.0 to 1.6 m (hexagonal flat-flat). Note, that this dimensions are not a principle measurement limit. Also much larger dimensions can be measured presently using of the existing laser tracker system, but this manually handled system would require high manpower and therefore additional personnel during a mass production of blanks.

Figure 3: Measurement of GTC segments with a laser tracker system (left) Figure 4: Large CMM at SCHOTT (right)

2.2 Geometry of mirror blanks

Especially for the TMT project there is a discussion whether circular blanks (followed by a stressed mirror polishing method) or hexagonal blanks (and computer controlled polishing) should be used initially to produce the final hexagonal mirrors.

For the casting of astronomical mirror blanks with diameters of 1 m, 2 m or 4 m usually circular moulds were used at SCHOTT in the past. This leads to an excellent quality of circular mirror blanks. Hexagonal mirror blanks for most of the present 10 m class telescopes were also cut from those circular discs. The main disadvantage of such a procedure is that much more material is needed. Therefore a direct casting of hexagonal shaped castings was developed during the GTC and LAMOST projects to reduce the used amount of raw material. The advantages are less casting time, better (hexagonal) stress distribution and significant material savings. The subsequent machining with cutting devices resulted in a less time consuming operation compared to the previous grinding of circular discs. Therefore hexagonal mirror blanks are recommended by SCHOTT for the coming generation of ELT´s. Due to the effort for logistics regular hexagons of different sizes are preferred against irregular hexagons. Regular hexagons of identical sizes would be the most preferred option. Of course all of these options could be mastered – but would result in different effort.

For practical purposes the definition of vertex positions is preferred for hexagonal blanks, as learned during the GTC project. The achieved manufacturing tolerances for the positions of the GTC hexagon vertices are shown in figure 6. Within the specified range of +/- 0.3 mm most of the positions have been achieved within +/- 0.2 mm. There was also some improvement during production, but the initial specification fits well to the achievable tolerances and should be maintained also for future ELT projects.

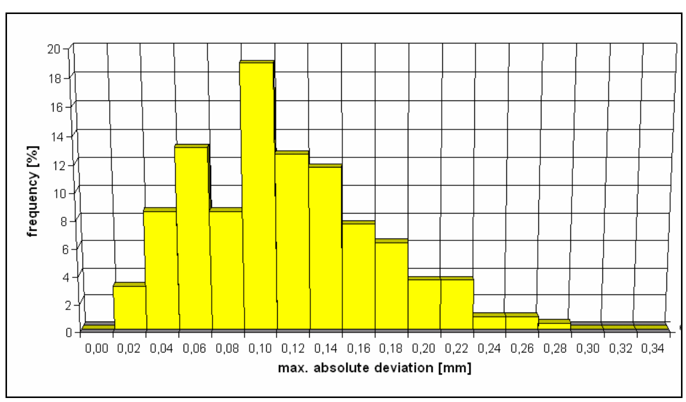

Figure 5: Raw ZERODUR cast in hexagonal shape (left) Figure 6: Achieved GTC mirror blank hexagon vertex tolerances (right)

2.3 Thickness

As ELT segment blanks in mass production would be sliced out of thicker boules (figure 5), the influence of the thickness on costs is mainly reflected in the raw material – as long as the support system during grinding needs no special effort. A thickness specification of +/- 0.2 mm (respectively +0.4/-0 mm) is usual and is less critical in most cases. Nevertheless a certain margin is needed here, if the final surface quality needs to be improved by an additional removal of some fraction of a mm. For tighter tolerances the risk of missing the specification increases for the blank manufacturer and a yield factor has to be considered within the costs. Sometimes a broader specification and a tighter target value or asymmetric tolerances can overcome this problem.

2.4 Radius form tolerance

The profile tolerance of the mirror face is usually evaluated by a 3D coordinate measurement of the surface. Thereby more than 50 measurements are uniformly distributed over the whole surface, the coordinates at all test points are measured. For evaluation the profile tolerance (respectively the flatness) is calculated by fitting a sphere with the specified fixed radius (respectively a flat) to the measured coordinates. The profile tolerance value is given by the peak to valley deviation of the individual coordinates from the sphere. For the GTC project the spherical concave (mirror) side of the meniscus blank was specified with a profile tolerance of 0.2 mm, the convex backside with 0.4 mm. Please note that there is no tolerance on the radius itself, according to the ISO standard 1101 this is included in the profile tolerance. As you can see in figure 7, all tolerances has been achieved well in specification during the manufacturing at SCHOTT.
We want to add some words on the production effort: Please note that meniscus blank options will create some more effort for manufacturing than plano-concave blank options. Also on-axis (!) aspherical surfaces have been produced at SCHOTT, manufacturing of off-axis aspheres is more critical. A grinding of aspheres only makes sense, if the aspherical deviation is larger than the profile tolerance. The profile tolerance has also to take into account the roughness specification respectively the specification on the grinding tools (see later in the text).

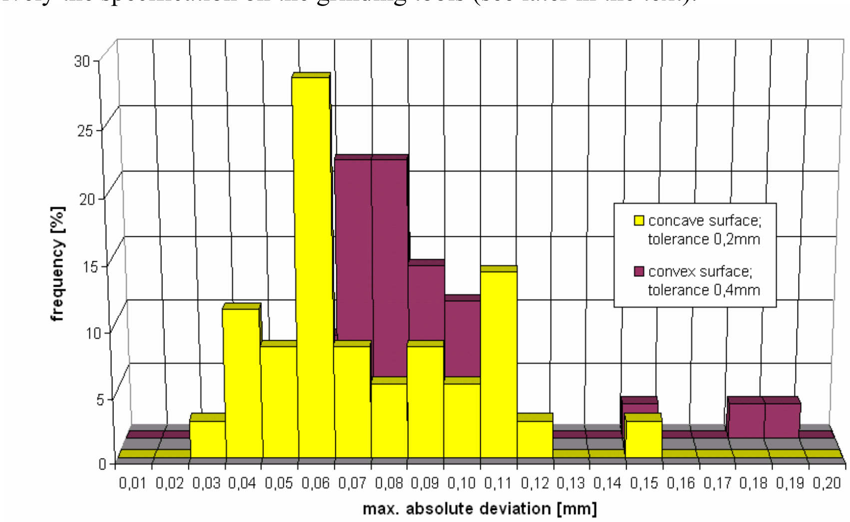

Figure 7: Profile tolerance of radial surfaces as achieved during the GTC project.

2.5 Chamfers

Even the specification of the chamfers is a potential cost driver. For blanks in the class of 1 m to 2 m chamfers of about 3 – 4 mm / 45° are usually recommended by SCHOTT for safety during handling. On the other hand sharp edges are preferred by the astronomers to avoid straylight and scattering. But during the handling, installation and recoating of hundreds or thousands of mirror segments in the telescope for decades (!) the risk of breakage may become critical. A detailed risk analysis may be necessary here.

2.6 Roughness

The surface conditions of ZERODUR parts result from the finishing process. Surface finishing of mirror blanks is made with CNC-machines using tools with bonded diamond grains. The grains exhibit a special size distribution, which result from a defined sieve fraction. Grinding of brittle materials like glass leads to microcracks (figure 8). Parts of these microcracks have directions roughly parallel to the surface (lateral cracks) the other part goes into the material (deep cracks). Empirically it was found for ZERODUR that the maximum crack depths are equal or smaller than the maximum grain size of the sieve fraction [10]. This is about 60 microns for a D64 tool. Since the cracks are not opened their depth cannot be measured with surface roughness inspection devices as commonly used in our workshop (figure 9). Usually the optical finisher takes off a layer by additional lapping and polishing steps that removes the microcracks. With adequate polishing processes extremely smooth surfaces of below 0.3 nm (!) have been achieved for ZERODUR.

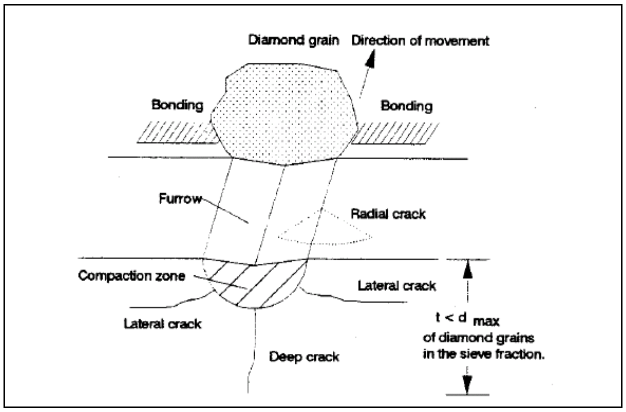

Figure 8: Effect of grinding on roughness

Figure 9: Roughness measurement

With the specification of the type of tool also the removal rate of material is influenced via the grinding parameters. So the roughness specification at least corresponds to manufacturing time and therefore the cost of the blanks. Nevertheless, someone has to grind with fine grains, either the blank manufacturer or the optical finisher. So the optimum interface for the whole project has to be defined. With the usual grinding processes using D151 tools a typical roughness of Ra < 1.6µm is achieved.

3. INTERNAL QUALITY

Beside the geometrical measurements also the verification of the internal quality is important for ZERODUR. Internal quality inspections for ZERODUR blanks consist of bubbles and inclusion inspection, striae inspection respectively striae measurement and stress measurement. These inspections were carried out usually after individual processing steps: (a) after melting and raw annealing for raw ZERODUR casting in the glassy state, (b) after ceramisation of the raw ZERODUR casting, and (c) during final inspection of the finished blank. By orientation of the final blanks within the initial raw material the internal quality for a special blank could be optimised.

3.1 Sizes and positions of bubbles/inclusions

Our inspectors check the internal quality of blanks regarding bubbles and inclusions "manually" by help of a special long distance microscope. The blank surface is thereby prepared either by a test polishing or by using an immersion oil that matches the refractive index of ZERODUR. This measurement equipment was developed by SCHOTT and had a measurement accuracy of bubble diameter ~ +/- 0.1 mm, lateral position +/- 1 mm and depth of +/- 2 mm. Imperfections > 0.1 mm could be detected only through polished surfaces, the detection limit by using immersion oil is about 0.4 mm.
The VISTA specification stated that within a critical zone of 4 mm depth below the mirror surface no bubbles and inclusions larger than 2.5 mm should be present. The results of the inspection demonstrate an excellent internal quality of the material. Due to the ZERODUR production process by melting and casting no large imperfections like no fusions areas were present. The whole VISTA blank of 5.3 tons of weight incorporated only 31 tiny imperfections at the end, demonstrating the excellent quality of ZERODUR [11]. For all the GTC mirror blanks no bubble or inclusion were located at the final mirror surface resulting in perfect mirror surfaces.
The effort of an individual testing of mirror blanks may be to high during mass production. So an automatisation should be considered here. During the production of large ZERODUR boules for the CHANDRA (AXAF) project of NASA a bubble mapping was done with CCD-cameras in the IR, where ZERODUR is very transparent. Also the detection limit should be reconsidered for mass production and may be changed to > 0.3 mm.

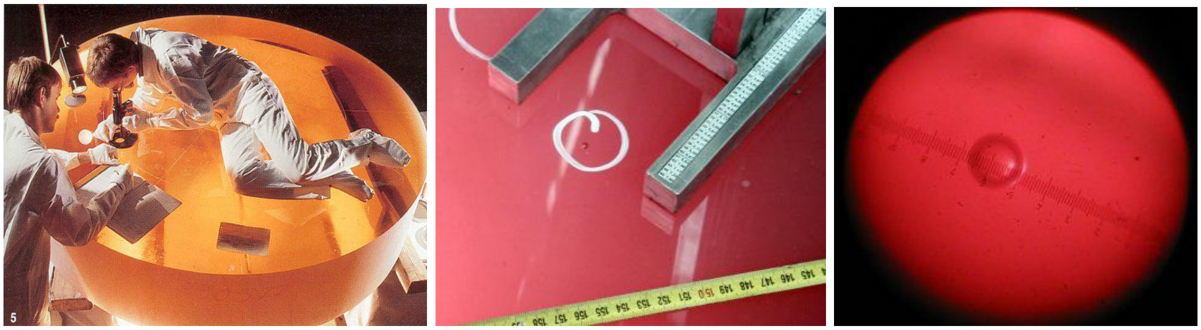

Figure 10 (a-c): Bubble inspection of ZERODUR

3.2 Internal stresses (body stress) and stress caused by striae

All Zerodur parts are subjected to precision optical annealing in order to achieve a permanent bulk stress, which is both low and symmetrically distributed. Bulk stress causes optical birefringence which is measured and expressed as an optical path difference. The measurement of the path difference is performed in axial direction for discs at 5% of the diameter from the edge. The stress birefringence was measured by a polariser / quarter wave plate compensation method according to de Senarmont and Friedel (see standard ISO 11455). The achieved birefringence measurement accuracy corresponds to +/- 1 nm/cm for a GTC blank with a thickness of about 8.4 cm. The excellent stress results below 4 nm/cm for all GTC blanks are shown in figure 11. Please note that the stress distribution is very smooth, no discontinuities due to fusion processes of different parts occurred.

Striae are local, very limited transparent regions with composition differing only slightly from the basic material. They are generally ribbon-shaped (or often called band-like), sometimes thread shaped. The striae quality of ZERODUR is tested by stress optical methods and is listed as an optical path difference in nm for thread-like striae. For ribbon-shaped striae, the optical path difference is given in nm/cm striae length. For strict requirements, an extremely sensitive shadowgraph method is used that allows fine visible striae to be found in test direction. Standard class of Zerodur is defined with striae below 60 nm per striae respectively 2.5 nm/cm. For most of the GTC mirror blanks no significant striae were detected within the blanks, especially none were detected in the critical zones close to the mirror surfaces.

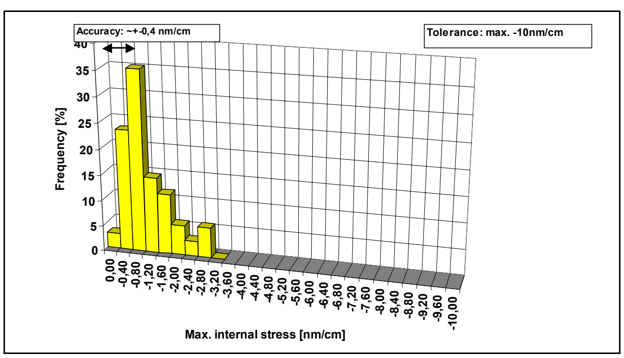

Figure 11: Stress measurement of the GTC mirror segments

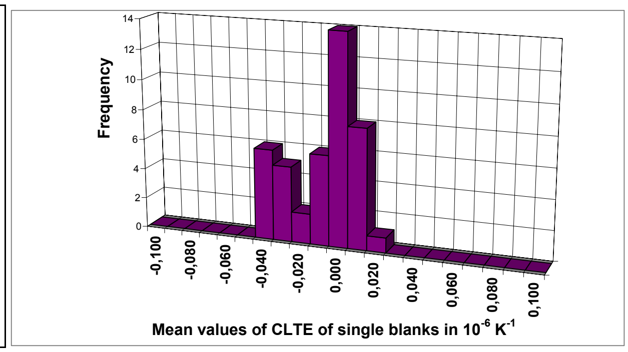

Figure 12: Mean CTE values of the GTC mirror segments

4. MATERIAL PROPERTIES

ZERODUR glass ceramic from SCHOTT has been the material of choice in astronomy for decades, thanks to its special properties. The most important and significant properties of the glass ceramic material ZERODUR are the extremely low coefficient of linear thermal expansion as well as the homogeneity of this coefficient throughout the entire piece. ZERODUR exhibits a very small linear expansion over the entire temperature range, which is especially low near room temperature. A detailed evaluation of the excellent homogeneity of thermal expansion for ZERODUR is given in the recent paper of Jedamzik et al. [12]. CTE (Coefficient of Thermal Expansion) measurements were carried out by high-resolution push-rod dilatometry. The measurement samples were taken from individual pieces of ZERODUR raw material after the ceramisation process. Additionally the homogeneity was tested by taking samples distributed in the blank near the net shape of the finished part. Other material properties (density, heat capacity, Young´s modulus, thermal

conductivity) have been measured in detail during the KECK projects. They revealed themselves to be nearly independent of the melting and the ceramisation respectively the re-annealing process and were measured later on usually only once per melting campaign. Our laboratories for the measurement of physical and chemical properties are certified on the basis of the standard series EN 45000, EN 29000 and ISO 9000.
Individual pieces of ZERODUR can be supplied with a mean coefficient of linear thermal expansion α in the temperature range between 0 °C and 50 °C in three expansion classes as follows:

Expansion class 2: 0 +/- 0.10 $\cdot$ 10^{-6} / K

Expansion class 1: 0 +/- 0.05 $\cdot$ 10^{-6} / K

Expansion class 0: 0 +/- 0.02 $\cdot$ 10^{-6} / K

The reproducibility of the CTE measurement method is $5 \cdot 10^{-9}$/K at a 95% confidence level (2 sigma). The calibration of the dilatometer is done using standards from PTB Braunschweig, Germany. The typical CTE range achieved for ZERODUR is only slightly larger compared to the range given by the repeatability of a single measurement. The mean CTE values of the GTC mirror blanks are given in figure 12 and well within the specified range of 0 +/- $0.05 \cdot 10^{-6}$/K (expansion class 1).
For astronomical projects sometimes a different CTE measurement range closer to the application temperature is requested. Nevertheless we propose to define our standard measurement interval 0 °C, 50 °C here, as proven procedures and calibrated measurement equipment are available to achieve the best measurement accuracy. As a close correlation between CTE results in different temperature ranges is expected, a study on the correlation between the CTE at different temperature ranges may help.
In addition to a low CTE value of the mirror material also the CTE homogeneity within the individual blanks is important for astronomical projects. Astronomers want to avoid bending due to a bimetallic effect, which may occur if the CTE is arranged in layers. The measurement repeatability is a major contribution on the verification of the specified CTE homogeneity of Δ CTE = 0 +/- $20 \cdot 10^{-9}$ / K within individual blanks. For the considered thin ZERODUR blanks the requirement of a CTE orientation top to bottom would reflect mainly the measurement statistics. The actual CTE homogeneity of ZERODUR is in many cases better than the limits of the dilatometer measurement. ZERODUR is probably better than stated up to now – but this is difficult to prove. Currently some improvement of the CTE measurement method is in progress at SCHOTT. Also the number of CTE samples to verify the CTE homogeneity should be defined carefully, as measurement costs would sum up significantly for hundreds of blanks. If measurement cost are critical, we propose to have a limited number of measurement samples to verify the CTE quality of the ELT mirror blanks. We intend to produce the individual mirror blanks from a raw casting in multiple thickness. The CTE samples from one boule may be taken as a common reference for several blanks.

5. SUMMARY, DISCUSSION AND OUTLOOK

We have demonstrated in the previous chapters that the technical issues of ELT mirror blanks can be mastered by use of ZERODUR for this application. “Only” the best interface between the blank manufacturer and the optical finisher has to be found to optimise the whole project. Beside the technical challenges there are also other non-technical points, which have to be considered and are discussed in the following text.
A mass production of mirror blanks for ELTs will last about several years. An astronomical project manager has to take into account that the company must survive the duration of the contract. So a stable supplier for several years is needed. SCHOTT is a company with a solid economical basis. SCHOTT has a history of more than 120 years and is part of the CARL ZEISS foundation. Around the world about 17,000 employees are working within the SCHOTT group, generating a turn-over of about 2 billion Euro per year. These economic attributes make SCHOTT an ideal partner for the mirror blank delivery of extremely large telescopes.
For a period of several years the fluctuations of the exchange rate may become an important factor. There are financial tools how to handle these risk – which is at least daily work for a global enterprise like SCHOTT with production facilities all around the world. The melting and annealing of glass are highly energy consuming process. There is a risk of fluctuating respectively increasing energy costs. Also the costs of high purity raw materials are difficult to forecast for several years.
The large quantities of ELT mirror substrates need logistic work flows, automatic machining and adequate investments. Therefore also the economical situation of potential suppliers will become essential for the success of the project. Especially the financial capability to handle large investments, a professional company logistics and an experienced project management will be important.

We are presently living in very interesting decade for astronomers: With the present planning of extremely large telescopes the future of astronomy is now being designed. Thereby one has to consider that a telescope like OWL with a primary mirror diameter of 100 m represents a collection area of seven times the total collecting area of every optical telescope ever built [13]. The cost estimation for the OWL project is almost 1 billion Euros in capital investment for the final design and construction [14]. So the discussed large astronomical projects have to handle extreme technical challenges, but also an enormous budget and a high economical risks. In 2003 SCHOTT celebrated the event of "100 years delivery of astronomical mirror blanks" [1]. So Schott has been a reliable partner of astronomers for more than a century and would be proud to continue this successful history by participating at the most challenging future projects. May astronomy and industry jointly foster the "Century of Extremely Large Telescopes".

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