SCHOTT
glass made of ideas

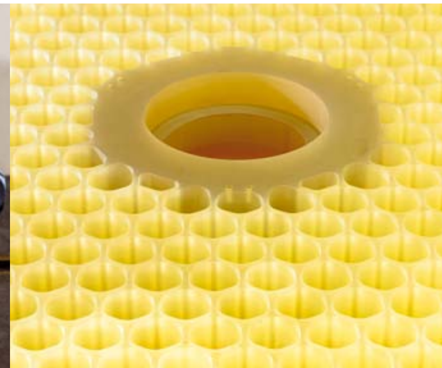
ZERODUR®

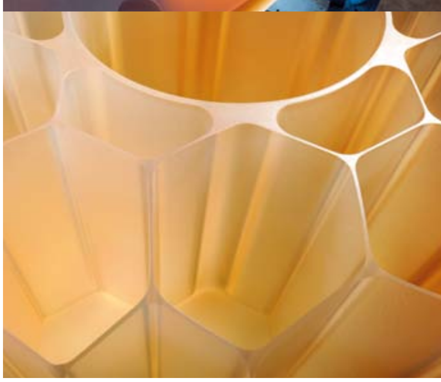
Zero Expansion Glass Ceramic

SCHOTT is an international technology group with more than 125 years of experience in the areas of specialty glasses and materials and advanced technologies. With our high-quality products and intelligent solutions, we contribute to our customers' success and make SCHOTT part of everyone's life.

SCHOTT Advanced Optics, with its deep technological expertise, is a valuable partner for its customers in developing products and customized solutions for applications in optics, lithography, astronomy, opto-electronics, life sciences, and research. With a product portfolio of more than 100 optical glasses, special materials and components, we master the value chain: from customized glass development to high-precision optical product finishing and metrology.

SCHOTT: Your Partner for Excellence in Optics.



Contents

A Superlative High-Tech Material

For more than 40 years, ZERODUR® glass ceramic has been the material of choice for astronomy, both on earth and in space. Here, a brief summary of some of the spectacular projects involving ZERODUR® glass ceramic substrates.

1968

The first 4 m-class mirror blank order from the Max Planck Institute for Astronomy (MPIA) telescope on Calar Alto in Southern Spain

1984

Eight ZERODUR® cylinders for the German X-ray telescope known as ROSAT (ROentgen SATellite), which was used in space from 1990 through 1999

1986 – 1990

43 disks for hexagonal segments made from ZERODUR® with a diameter of 1.8 m for Keck I, a 10 m telescope on Mauna Kea, Hawaii, USA

1991 – 1993

42 ZERODUR® disks for hexagonal segments for Keck II, Hawaii, USA

1993 – 1996

Four 8.2 m mirror substrates for the Very Large Telescope (VLT) of the ESO at the Cerro Paranal, Chile, the world's largest monolithic glass ceramic pieces

1970 – 1975

Delivery of mirror substrates with diameters of 1.3 m, 2.3 m and 3.6 m for the MPIA

1986

A thin 3.6 m mirror substrate for the New Technology Telescope (NTT) of the ESO, the first large telescope equipped with active optics, that is located in Cerro La Silla, Chile

1990

3.6 m mirror substrate for the Galileo TNG Telescope on La Palma, Spain
24 cylindrical mirror substrates for the X-ray telescope known as "Chandra", which was launched with a space shuttle in 1999

1993 – 1996

96 ZERODUR® hexagonal segments of 1 m in size for the 9 m American-German Hobby Eberly Telescope (HET) in Texas, USA

1997

2.7 m mirror substrate for the Stratospheric Observatory for Infrared Astronomy (SOFIA), an infrared telescope on board a jumbo jet

Two weight-reduced secondary mirror substrates with a diameter of 1.7 m for the American "Magellan" Telescope, as well as for the MMT (Multi-Mirror-Telescope) on Mount Hopkins, Arizona, USA

1997/2002

A 4.25 m base plate for the world's largest ring laser gyroscope for measuring Earth's rotation for the German Terrestrial Reference Station in Wettzell, Germany

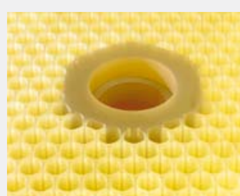
2000 – 2001

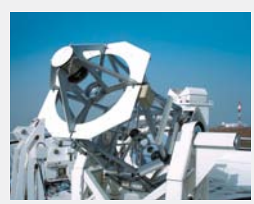
4.1 m mirror substrate with a particularly strong curvature for the Visible and Infrared Survey Telescope for Astronomy (VISTA), the world's largest wide field Survey Telescope located near the Cerro Paranal, Chile

2002 – 2003

1.5 m light weighted primary mirror for the GREGOR solar telescope. The mirror with a curved front plate incorporates 420 pockets on the backside for active cooling during observation at the Teide Observatory on Tenerife

2009





1999 – 2002

42 ZERODUR® substrates with a diameter of 1.9 m for the 10.4 m telescope GTC (Gran Telescopio Canarias) on La Palma, Spain

2001 – 2003

40 ZERODUR® hexagonal segments with a diameter of 1 m for the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) in China

2009

3.7 m mirror substrate for the ARIES Telescope, the largest in India, loated at Nainital in the Himalayas

2011

Production of a 4.25 m primary mirror substrate for the Advanced Technology Solar Telescope (ATST), the largest solar telescope in the world, to be erected on Haleakala, Maui, Hawaii

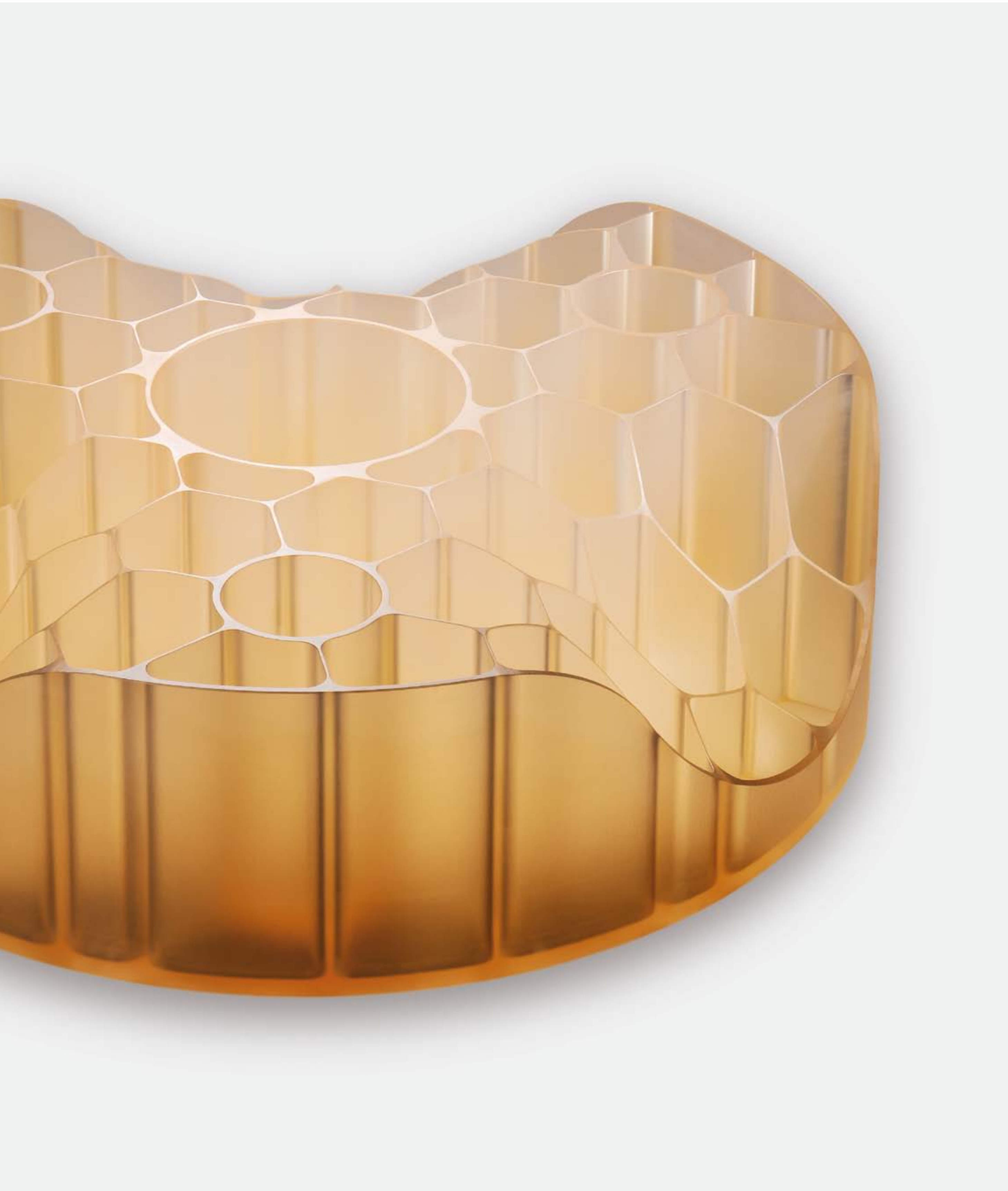
1. Introduction

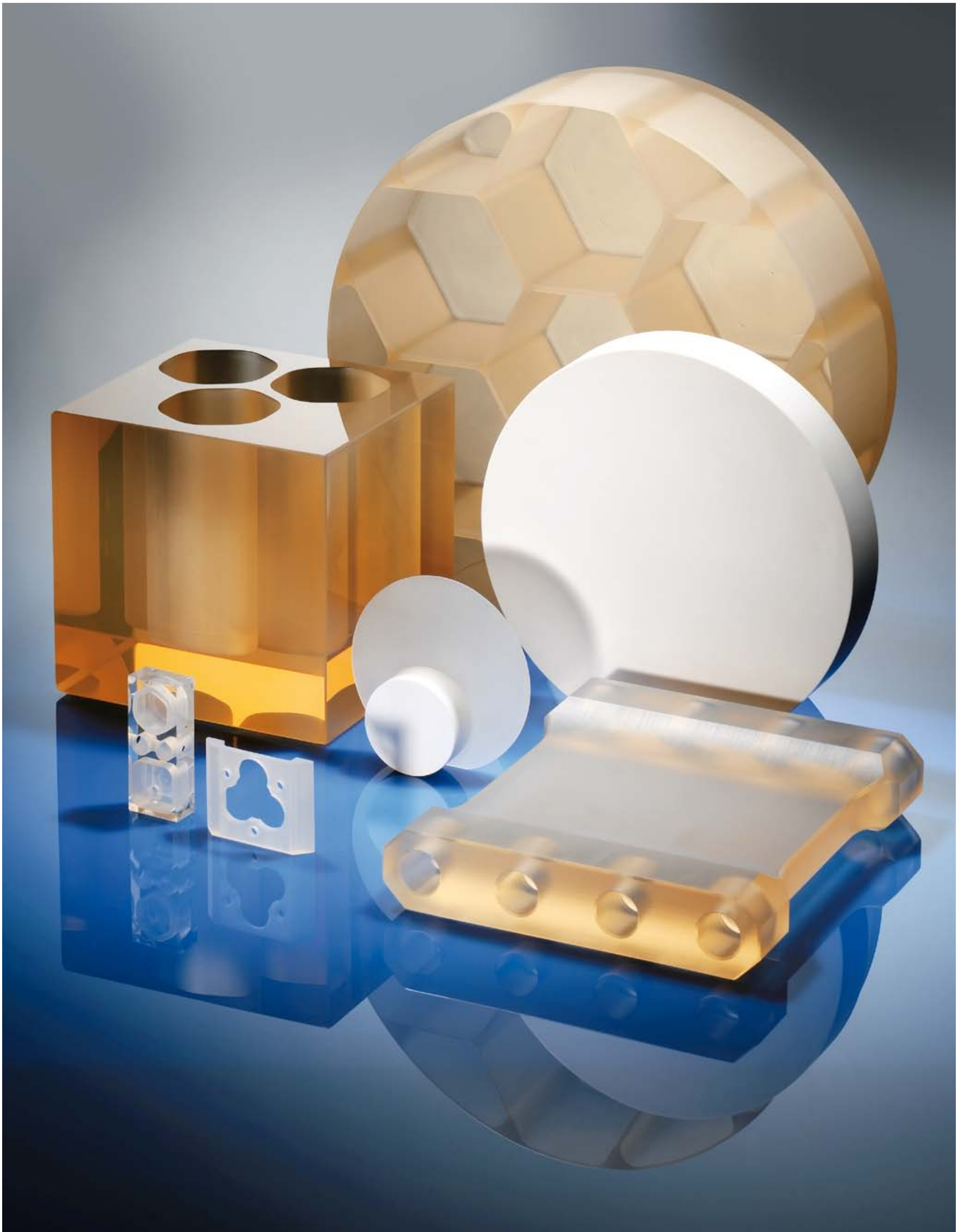
SCHOTT invented ZERODUR®, the zero expansion glass ceramic, in 1968 and thus introduced a new era for various applications, of which the most challenging ones are telescope mirror substrates for astronomy. The most important properties of ZERODUR® are presented in this catalog.
Information is also available on the SCHOTT website:
http://www.us.schott.com/advanced_optics/zerodur

Detailed articles that contain technical information, or so-called TIEs, are available for some of the properties listed in this catalog. A stamp refers to the relevant TIEs, an overview of which can be found on page 23.
The respective technical information can be found at:
http://www.us.schott.com/advanced_optics/technical_information

TIE available

Figure 1.1
700 mm diameter ZERODUR® mirror with 90% weight reduction (rib thickness of 2 mm up to 190 mm in height, 8 mm curved face sheet)





Extraordinary Properties

ZERODUR® is a zero expansion glass ceramic with extraordinary properties for demanding applications in which geometrical shape and distance changes must be kept as small as possible during changes in temperature.

The key properties of ZERODUR® are:

- An extremely low coefficient of thermal expansion (CTE) for a wide range of temperatures
- Excellent CTE homogeneity throughout its entire volume
- Very low level of imperfections
- A wide range of precise geometrical shapes are possible using grinding processes
- An extremely smooth surface is possible with residual roughness of less than 1 nm
- Excellent chemical stability

All of these properties are realized with extraordinary reproducibility for small components as well as large telescope mirror blanks for use in astronomy that weigh several tons.

High-Tech Application

ZERODUR® has become a determining factor in the performance and quality of many spectacular applications that employ modern technology:

- Stages and mirrors for IC and LCD lithography equipment
- Mirror substrates for segmented and large monolithic astronomical telescopes
- Ultra light weight mirror blanks
- Standards for precision measurement technology
- High precision mechanical parts, e.g. ring laser gyroscope bodies
- Reference standards for precision measurement technology

Composition and Production

ZERODUR® is an inorganic, non-porous lithium aluminum silicon oxide glass ceramic characterized by evenly distributed nano-crystals within a residual glass phase. ZERODUR® is produced using a two-step process. During the first step, it is molten from selected raw materials, refined, homogenized and cast into moulds similar to the optical glass melting process introduced by SCHOTT and continuously improved since then. Following subsequent annealing for stress relaxation, a precise ceramization process transforms ZERODUR® in the second step into the glass ceramic through controlled volume crystallization. The negative linear thermal expansion coefficient of the crystals compensates for the positive expansion of the remaining 30 % glass matrix.

Homogeneity and Reproducibility of Properties

The excellent homogeneity and internal quality of ZERODUR® can be attributed to the well-established optical glass melting process, which has been continuously improved to yield such excellent quality in high volume ZERODUR® blanks up to 8 m in diameter. The thermal expansion coefficient variations are in the order of the detection limit of $\pm 1.2 \cdot 10^{-9}$/K (95 %). The melting, casting and annealing procedures have been improved to establish continuous production, which reproduces the excellent quality that is needed to be able to supply mirror substrates, in particular, for extremely large segmented astronomy telescopes for years and years. SCHOTT has already proven its ability to consistently deliver large quantities of mirror substrates in the 1 to 2 m diameter range reliably while maintaining a high level of quality: ZERODUR® was selected to be the mirror substrate material for all of the world´s segmented telescopes currently in operation.

Figure 1.2
Different supply forms and processing stages of ZERODUR® and ZERODUR® K20

2. Thermal Expansion of ZERODUR®

TIE available

Mean Coefficient of Linear Thermal Expansion

ZERODUR® can be supplied with a mean coefficient of linear thermal expansion (CTE) in the temperature range 0°C to 50°C in three expansion classes as follows:

CTE (0°C; 50°C) Specification tolerances	
Expansion Class 0	0 ± 0.02 · 10^{-6}/K
Expansion Class 1	0 ± 0.05 · 10^{-6}/K
Expansion Class 2	0 ± 0.10 · 10^{-6}/K
Tighter tolerance available upon request.	

Table 2.1
CTE tolerances

CTE-Measurement Accuracy

in the temperature range of 0°C to 50°C

	Accuracy	Repeatability (95 %)
Standard	± 0.01 · 10^{-6}/K	± 0.005 · 10^{-6}/K
Improved	± 0.006 · 10^{-6}/K	± 0.0012 · 10^{-6}/K

Table 2.2
CTE-Measurement accuracy and repeatability

Figure 2.1 below shows the typical relative expansion in length Δl/l and CTE of ZERODUR® as a function of temperatures between 2 K and 800 K.
The low temperature measurement was performed by the National Measurement Laboratory in Sydney, Australia (CSIRO).

> Relative Change of Length
> Coefficient of Thermal Expansion

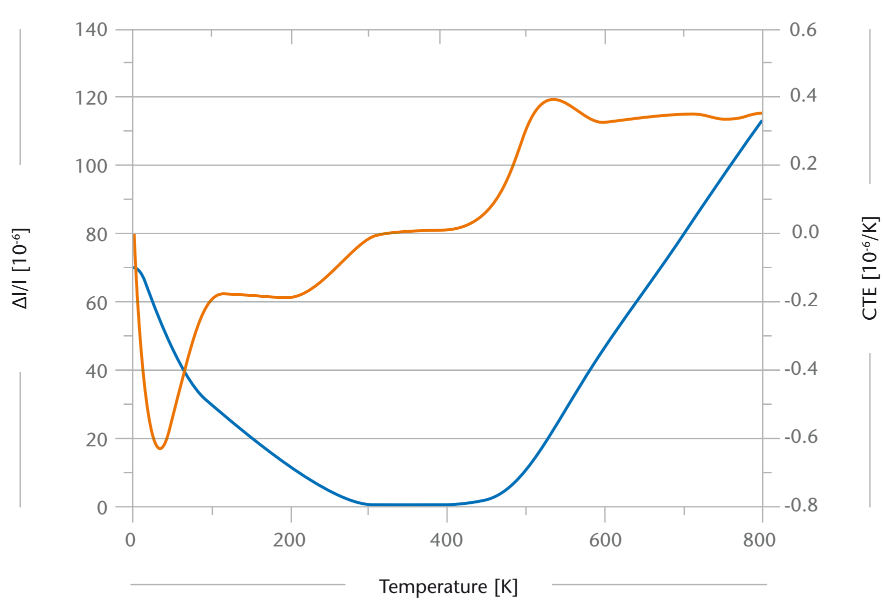


Figure 2.1
Δl/l and CTE of ZERODUR® as a function of temperature

Total Change of Length between -50°C to +100°C

< 10 · 10^{-6}/K per length of the part

Homogeneity of the Coefficient of Thermal Expansion

The homogeneity is evaluated by measuring CTE samples homogeneously distributed throughout the blank and calculating the difference in CTE between the highest and the lowest value measured. The homogeneity of linear expansion can be guaranteed in the following weight classes:

Table 2.3
CTE homogeneity tolerances

CTE (0°C; 50°C) Homogeneity tolerances	
up to 18 tons	< 0.03 · 10^{-6}/K
up to 6 tons	< 0.02 · 10^{-6}/K
up to 0.3 tons	< 0.01 · 10^{-6}/K

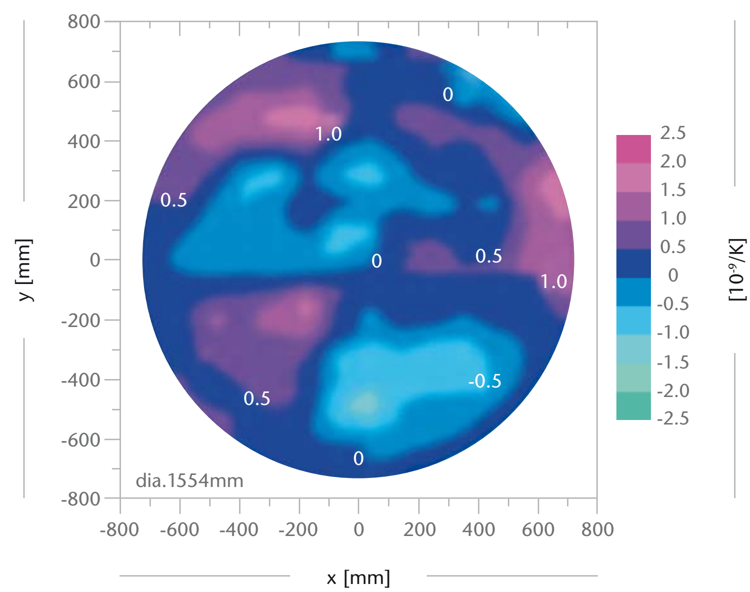


Figure 2.2
CTE distribution within a 1.5 m diameter blank with a measured CTE homogeneity of 0.004 · 10^{-6}/K

Recommended Application Temperature Cooling Rates between 130°C and 320°C

Slight changes in the CTE may occur if ZERODUR® is cooled down from application temperatures between 130°C and 320°C to room-temperature with a rate that differs from the initial cooling rate. ZERODUR® is generally cooled during production at an initial cooling rate of between 1°/h and 6°/h. Each factor of 10 difference between application and initial cooling rate can lead to a permanent CTE change of 0.025 · 10^{-6}/K.

Maximum Application Temperature

600°C

Length Stability over Time

Gauge blocks with a length of 400 mm made from ZERODUR® have been connected interferometrically to a wavelength standard at the PTB (Physikalisch-Technische Bundesanstalt, Germany). The rods that were maintained at 20°C showed shrinkage over time. The shrinkage rate is hardly measurable and decreases exponentially over time. The shrinkage is irrelevant for most applications.

Modelling of CTE Behavior

The structural relaxation behavior of glass ceramics can be described by a theoretical model. With this model, the relaxation behavior of a ZERODUR® cast can be predicted at any application temperature and temperature change rate upon special request. In applying the model, ZERODUR® batches that offer the best performance can be selected for extremely demanding applications.

ZERODUR® K20 for High Application Temperatures

ZERODUR® K20, a low thermal expansion version of ZERODUR®, has been optimized to withstand higher application temperatures. The material has a white color and offers good IR transmittance of between 3.5 and 5 μm and homogeneous high reflectivity properties. The non-porous ZERODUR® K20 exhibits good polishing ability and excellent vacuum properties.

Table 2.4
CTE of ZERODUR® K20

Mean coefficient of linear thermal expansion of ZERODUR® K20	
CTE (20°C; 700°C)	$2.4 \cdot 10^{-6}$/K
CTE (20°C; 300°C)	$2.2 \cdot 10^{-6}$/K
CTE (0°C; 50°C)	$1.6 \cdot 10^{-6}$/K

Maximum application temperature 850°C

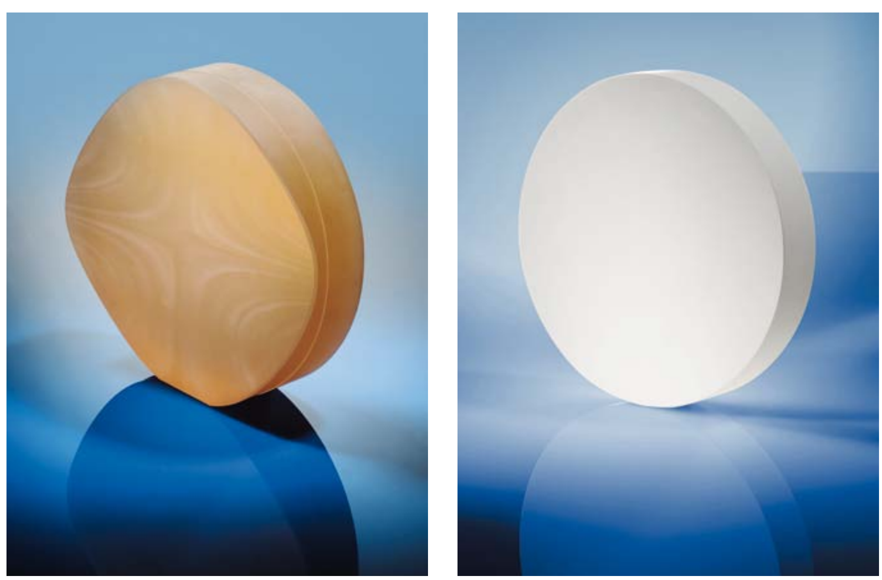


Figure 2.3
ZERODUR® (left) and ZERODUR® K20 (right) in comparison

3. Internal Quality

Inclusions

Inclusions in ZERODUR® are mainly bubbles. For optical surfaces, a critical volume can be defined by setting tighter requirements. During inspection of ZERODUR® parts, all inclusions with a diameter > 0.3 mm are taken into consideration. If an inclusion has a shape other than spherical, the average diameter is reported as the mean of the length and width.

	Standard	Class 4	Class 3	Class 2	Class 1	Class 0
Average number of inclusions per 100 cm³:	5.0	5.0	4.0	3.0	2.0	1.0
Maximum diameter of individual inclusions in mm for different diameters or diagonals of the ZERODUR® part						
In the critical volume: < 500 mm	1.4	1.2	1.0	0.8	0.6	0.4
< 2000 mm	2.0	1.8	1.6	1.5	1.2	1.0
< 4000 mm	3.0	2.5	2.0	1.8	1.6	1.5
Individual specifications upon request						
In the uncritical volume: < 500 mm	3.0	2.0	1.5	1.0	0.8	0.6
< 2000 mm	6.0	5.0	4.0	3.0	3.0	3.0
< 4000 mm	10.0	8.0	6.0	6.0	6.0	6.0
Individual specifications upon request						

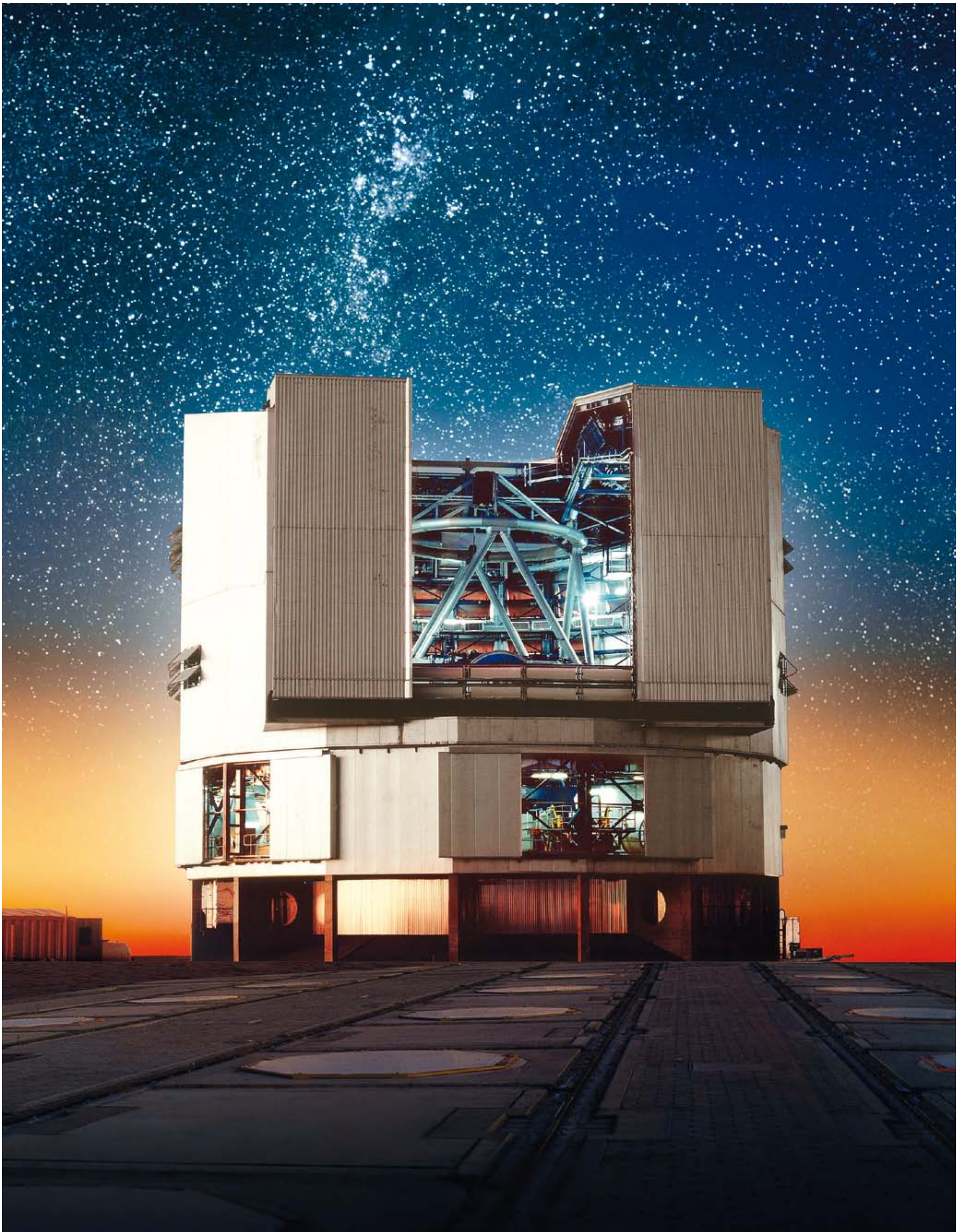
Table 3.1
Quality levels for inclusions in ZERODUR®

Bulk Stress

All ZERODUR® parts are precision annealed to achieve low and symmetrically distributed permanent bulk stress. The bulk stress birefringence is measured in axial direction for discs and rods at 5 % of the diameter from the edge.
For rectangular plates, the measurement is performed in the middle of the longer side perpendicular to the plate's surface. It is recorded in path difference per thickness in inspection direction.

Bulk stress birefringence [nm/cm] for parts with diameters or diagonals	Standard	Class 4
< 500 mm	6	4
< 2000 mm	12	10
< 4000 mm	15	12
Individual specification on customer request		

Table 3.2
Quality levels for bulk stress in ZERODUR®



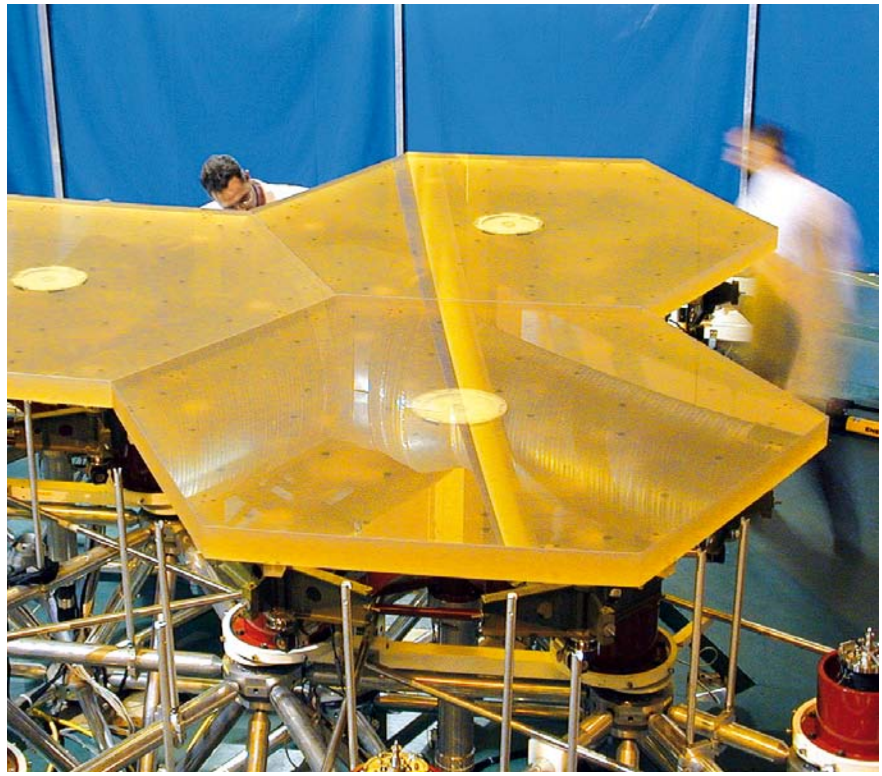


Figure 3.1
ZERODUR® - the material of choice for segmented mirror telescopes
Photo: Sagem Défense Sécurité

Striae

Striae are locally confined transparent regions with compositions that differ from the basic material only very slightly. They are generally ribbon-shaped (or often called band-like) but are occasionally thread-shaped. The stress birefringence of striae is measured as a path difference in nm as listed in the table 3.3. In parts with thicknesses of more than 250 mm, the path difference is expressed in nm/cm striae length and will be specified on an individual basis.

Table 3.3
Quality levels for stress birefringence caused by striae in ZERODUR®

Stress birefringence caused by striae [nm/striae] for parts with diameters or diagonals	Standard	Class 4	Class 3	Class 2	Class 1
< 500 mm	60	45	30	5	
< 2000 mm	60	45	30	30	5
< 4000 mm	60	45	30	30	30

Feel free to send us inquiries on requirements that go beyond the inclusions, striae, and bulk stress specifications mentioned. If no quality is specified upon receipt of an order, then ZERODUR® will be supplied in standard quality.

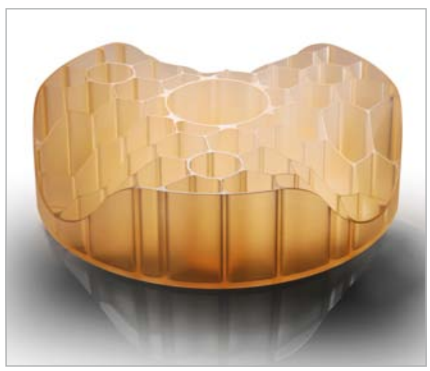
Figure 3.2
One of the four Very Large Telescopes of ESO in Chile, equipped with 8.2 m mirrors made from ZERODUR®, the largest monolithic mirrors ever cast from single melts

4. Processing ZERODUR®

TIE available

Processing ZERODUR®

ZERODUR® is processed into complex geometries based on technical drawings from customers and specifications using diamond grinding with modern CNC machines. SCHOTT uses a variety of CNC machines, from precision smaller geometry 5-axis up to a 4.5 m machine for large mirror substrates for use in astronomy. The highlight of ZERODUR® processing is the light weighting for satellite mirror applications. Continuous process development has enabled SCHOTT to grind challenging aspect ratios of pocket height to rib thickness. Walls of 190 mm in height and only 2 mm in thickness result in a light weighting factor of 90 % and a remaining weight of only 22 kg for the 700 mm diameter mirror blank in figure 4.1 to the left.



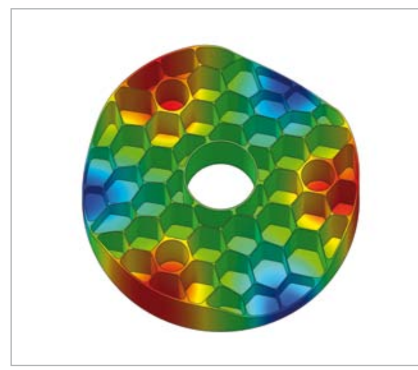


Figure 4.1 left
A 700 mm diameter ZERODUR® mirror demonstrates aggressive light weighting of 90 %

Figure 4.1 right
Construction with 3D CAD software drawing. The SCHOTT internal Finite Element Modeling capabilities are used to support customers in designing complex leading edge light weighted mirror structures.

Forms of Supply and Tolerances

ZERODUR® is supplied in the form of disks, rectangular blocks, prisms, rods and any other customer-specific cut piece geometry. The CNC grinding machines allow for precise fabrication of parts of up to 4.5 m in diameter.

Table 4.1
Maximum part sizes for CNC grinding at SCHOTT

Maximum part size	Rectangular shape L · W · H [mm]	Round shape Dia. · H [mm]
5-axis CNC grinding	2000 · 2000 · 1200	2000 · 1200
3-axis CNC grinding	4000 · 5000 · 1150	4500 · 1150

Diamond tools are used for machining ZERODUR®. Standard tool diamond grain sizes are between D64 and D251. Tools with finer grains are available upon request. Typical mean surface roughness values of $R_a < 3.5$ µm are obtained in rough grinding and cutting. Based on the combination of the process and tool, smoother roughness of $R_a < 1$ µm can be realized upon customer request.

The dimensional tolerances of ISO 2768, the standard for general tolerances, (classes v, c, m, and f) and the form and position tolerances listed in ISO 2768 (classes L, K and H) can be met. Depending on the geometry, tighter tolerances are possible as indicated in table 4.2. Tighter tolerances depend on the geometry and size of the parts and cannot be combined freely. Even narrower tolerances are possible upon special request.

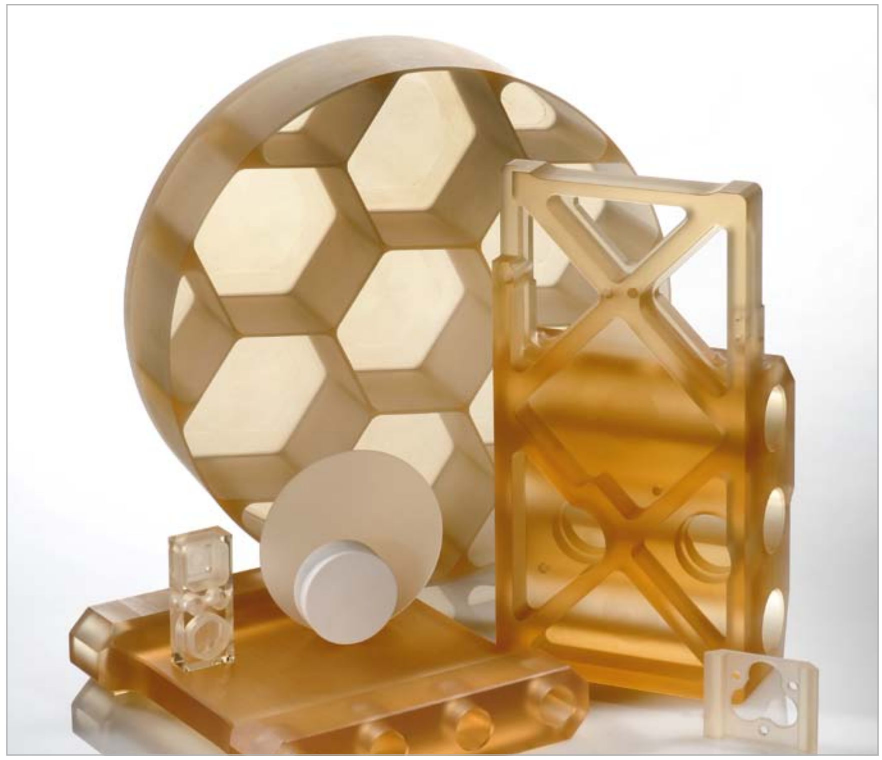


Figure 4.2
ZERODUR® in various shapes

Table 4.2
Proposed CNC grinding tolerances for dimensions and shapes

* tighter tolerances depend on the size and geometry. They cannot be combined freely.

** according ISO 1101

		Dimension < 2000 mm		Dimension ≤ 4000 mm	
		Tolerances [mm]	Tighter tolerances [mm] *	Tolerances [mm]	Tighter tolerances [mm] *
Length, width, height		± 0.3	± 0.1	± 0.4	± 0.2
Diameter		± 0.3	± 0.1	± 0.4	± 0.2
Angle		± 5′	± 1′	± 5′	± 1′
Flatness **	⏥	0.1–0.2	0.05	0.2	0.1
Cylindricity **	⌭	0.1	0.05	0.2	0.1
Profile **	⌓	0.2	0.1	0.4	0.2
Parallelism **	//	0.1–0.2	0.05	0.2	0.1
Position **	⌖	0.1	0.05	0.2	0.1
Concentricity **	◎	0.1	0.05	0.2	0.1
Run-out **	↗	0.1	0.05	0.2	0.1

All parts are supplied with bevels on all sharp edges to prevent edge damage. Modern CNC processing allows for a multitude of geometric shapes to be produced, including holes, blind holes, semi-closed holes and freeform surfaces in all geometries. Due to the brittle nature of the material, threads cannot be produced directly in the material and bonding of e.g. metal inserts with threads into the ZERODUR® part is recommended.

5. Bending Strength

TIE available

The design bending strength of glass and glass ceramics is not usually a material constant. This mainly depends on the surface state of a specific part and the conditions of its intended application.
The main influence is the presence of sub-surface micro cracks. In regions of tensile stress, their maximum depth determines the load that a specific part can endure. Smaller micro cracks generally lead to higher strength.
With increases in the size of the tensile stress loaded area, deeper cracks may occur according to their probability distribution. Therefore, larger loaded areas lead to lower design strengths.
Micro cracks cannot follow a fast rise in tension with their growth as well as a slow rise in a tension of the same extent. Hence, surfaces exposed to rapid rises in stress appear to be stronger than those with slow rise rates.
When tension in loaded areas surpasses a threshold value, micro cracks begin to grow slowly, only to speed up with increasing stress. This process is supported by the presence of humidity. A dry environment and ultimately a vacuum offer the best conditions with respect to design strength.

In general, the design bending strength is calculated on the basis of the parameters of the Weibull statistical distribution, which allows to take the influences listed above into account. The Weibull parameters for different surface conditions and further information on the bending strength of ZERODUR® are provided in a separate Technical Information.
ZERODUR® withstands loads of up to 10 MPa without any difficulty, as long as its surfaces is not severely damaged. For higher loads, we recommend analysis on the basis of the Weibull model and introducing precautions to prevent degrading of surface quality. Even higher loads than approximately 50 MPa may require special surface treatments, like optical polishing or acid etching.

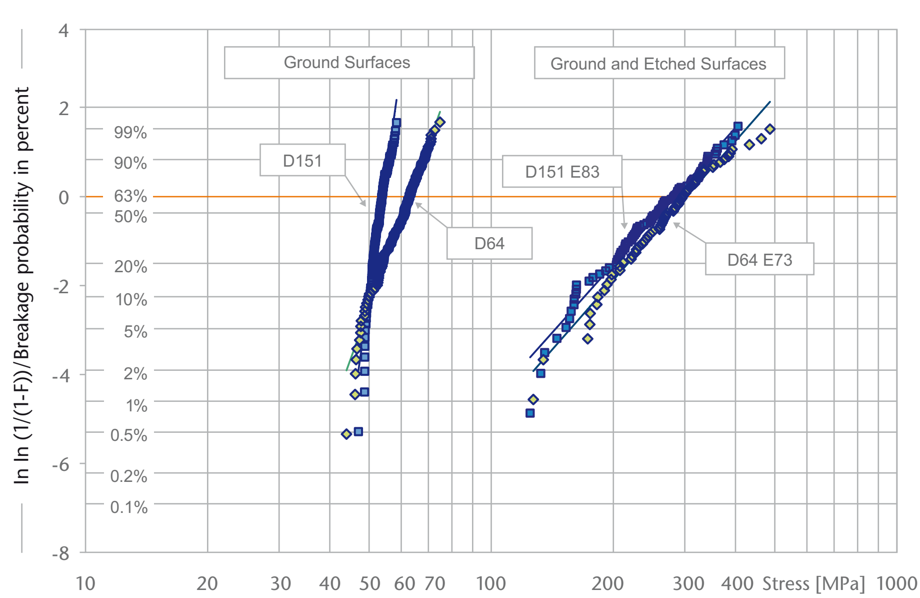


Figure 5.2
ZERODUR® cumulative breakage probability distributions

D64 and D151 are diamond grain size distributions;
E83 denominates the layer thickness in µm etched off - here 83 µm.

Straight lines are two-parameter Weibull distributions fitted to the data. For the two different diamond grain sizes D151 (coarse grains) and D64 (fine grains), distributions are given only for ground surfaces (left data sets) and for ground and subsequently acid-etched surfaces, taking off layers of the given thickness per surface (73 µm and 83 µm resp.). For more details, please refer to the literature quoted.

Figure 5.1
The structured rear surface of the 3.7 m primary mirror blank of the ARIES Telescope

6. Additional Properties

TIE available

Reactivity with Other Materials

At room temperature, acids (with the exception of hydrofluoric acid), alkalis, salts and dye solutions, leave no residual traces on ZERODUR® surfaces (elapsed time 170 hours). Concentrated sulfuric acid attacks the material at high temperatures. The construction and insulating materials mica, chamotte, MgO and SiO_2 do not react noticeably with ZERODUR® at temperatures of up to 600°C after 5 hours of elapsed time. By contrast, enamel reacts above 560°C by having its surface destroyed.

Repeated Metal Coatings

ZERODUR® can be coated with aluminum, for example. Based on the good chemical resistance of the material, the mirror coating can be removed repeatedly. The polished surface can be cleaned and recoated. A process has been optimized for coating and cleaning of the polished surface.

Typical mechanical, optical and chemical properties

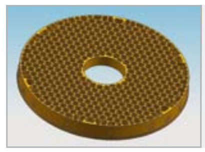
	ZERODUR®	ZERODUR® K20
Thermal conductivity λ at 20°C [W/(m · K)]	1.46	1.63
Thermal diffusivity index a at 20°C [10^{-6} m²/s]	0.72	-
Heat capacity c_p at 20°C [J/(g · K)]	0.80	0.90
Young's modulus E at 20°C [GPa]-mean value	90.3	84.7
Poisson's ratio	0.24	0.25
Density [g/cm³]	2.53	2.53
Knoop Hardness HK 0,1/20 (ISO9385)	620	620
Refractive index n_d	1.5424	-
Abbe number ν_d	56.1	-
Internal transmittance at 580 nm		
5 mm thickness	0.95	-
10 mm thickness	0.90	-
Stress optical coefficient K at λ = 589.3 nm [10^{-6} MPa^{-1}]	3.0	-
Hydrolytic resistance class (ISO 719)	HGB 1	-
Acid resistance class (ISO 8424)	1.0	-
Alkali resistance class (ISO 10629)	1.0	-
Climate resistance	Class 1	-
Stain resistance	Class 0	-
Electrical resistivity ρ at 20°C [Ω · cm]	$2.6 \cdot 10^{13}$	-
T_{k100} [°C], Temperature for $\rho = 10^8$ [Ω · cm]	178	-
Helium permeability [Atoms/(cm · s · bar)]		
at 20°C	$1.6 \cdot 10^6$	-
at 100°C	$5.0 \cdot 10^7$	-
at 200°C	$7.2 \cdot 10^8$	-

Table 6.1
Typical mechanical, optical and chemical properties of ZERODUR® and ZERODUR® K20

7. ZERODUR® & More

ZERODUR®: more than just a product

For many years, SCHOTT has been serving the high-tech industry and the astronomical community with a team of well-trained application and process engineers who enable our customer to get the most out of ZERODUR® properties for their individual application demands. With its skilled and experienced team, SCHOTT is dedicated to serving its customers in many different ways:



Engineering support and consulting during the design phase

Usage of CAD / CAM software for fast exchange of 3D models on step file format

Continuous optimization of melting, ceramization and machining processes

Finite Element Modeling

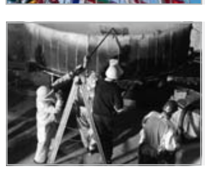
Regular scientific publications on the results achieved in R&D

Designing of well adapted packaging for up to 4 m class blanks

Professional project management

After-sales service, including onsite support

World-wide sales network of a globally established company



Reliable partner to astronomy for more than 125 years

Integrated quality, environmental and safety management system according to ISO 9001 and ISO 14001.
Accredited testing laboratory for many glass properties, certification laboratory for glass ceramic reference samples for expansion characteristics according to DIN EN ISO/IEC 17025

8. Selected Publications & Technical Information (TIE)

Title	Authors	Publications	Year
Overview Articles			
Optical glass and glass ceramic historical aspects and recent developments: a SCHOTT view	Peter Hartmann, Ralf Jedamzik, Steffen Reichel, Bianca Schreder	Applied Optics Vol. 49, No. 16	2010
Forty years of ZERODUR® mirror substrates for astronomy: review and outlook	Thorsten Döhring, Ralf Jedamzik, Armin Thomas, Peter Hartmann	Proc. SPIE 7018, 70183B	2008
Optical materials for astronomy from SCHOTT: the quality of large components	Ralf Jedamzik, Joachim Hengst, Frank Elsmann, Christian Lemke, Thorsten Döhring, Peter Hartmann	Proc. SPIE 7018	2008
100 years of mirror blanks from SCHOTT	Peter Hartmann, Hans F. Morian	Proc. SPIE 5382, 331	2004
Coefficient of Thermal Expansion and Mechanical Strength			
Modeling of the thermal expansion behavior of ZERODUR® at arbitrary temperature profiles	Ralf Jedamzik,Thoralf Johansson, Thomas Westerhoff	Proc. SPIE 7739	2010
ZERODUR® glass ceramics for high stress applications	Peter Hartmann, Kurt Nattermann, Thorsten Döhring, Ralf Jedamzik, Markus Kuhr, Peter Thomas, Guenther Kling, Stefano Lucarelli	Proc. SPIE 7425, 74250M	2009
Homogeneity of the linear thermal expansion coefficient of ZERODUR® measured with improved accuracy	Ralf Jedamzik, Rolf Müller, Peter Hartmann	Proc. SPIE 6273, 627306	2006
Ground Based Telescopes			
Mirrors for solar telescopes made from ZERODUR® glass ceramic	Thorsten Döhring, Ralf Jedamzik, Peter Hartmann	Proc. SPIE 6689, 66890X	2007
Properties of ZERODUR® mirror blanks for extremely large telescopes	Thorsten Döhring, Ralf Jedamzik, Peter Hartmann, Armin Thomas, Frank-Thomas Lentes	Proc. SPIE 6148, 61480G	2006
Production of the 4.1-m ZERODUR® mirror blank for the VISTA Telescope	Thorsten Döhring, Ralf Jedamzik, Volker Wittmer, Armin Thomas	Proc. SPIE 5494, 340	2004
Performance of the four 8.2-m ZERODUR® mirror blanks for the ESO/VLT	Hans F. Morian, Reiner H. Mackh, Rudolf W. Müller, Hartmut W. Höness	Proc. SPIE 2871, 405	1997
Light Weighted Mirror Blanks and Space Applications			
Manufacturing of the ZERODUR® 1.5-m primary mirror for the solar telescope GREGOR as preparation of light weighting of blanks up to 4 m diameter	Thomas Westerhoff, Martin Schäfer, Armin Thomas, Marco Weisenburger, Thomas Werner, Alexander Werz	Proc. SPIE Vol. 7739	2010
Heritage of ZERODUR® glass ceramic for space applications	Thorsten Döhring, Peter Hartmann, Frank-Thomas Lentes, Ralf Jedamzik, Mark J. Davis	Proc. SPIE 7425, 74250L	2009
Manufacturing of light weighted ZERODUR® components at SCHOTT	Thorsten Döhring, Armin Thomas, Ralf Jedamzik, Heiko Kohlmann, Peter Hartmann	Proc. SPIE 6666, 666602	2007

Technical Information

All technical information is also available on our website:
http://www.us.schott.com/advanced_optics/technical_information

TIE available

TIE-33: Design strength of optical glass and ZERODUR®	Chapter 5
TIE-37: Thermal expansion of ZERODUR®	Chapter 1, 2
TIE-38: Light weighting of ZERODUR®	Chapter 4
TIE-43: Properties of ZERODUR®	Chapter 6
TIE-44: Processing of ZERODUR®	Chapter 4
TIE-45: ZERODUR® adhesive bonding recommendations	Chapter 5

Abbreviations

ARIES: Aryabhatta Research Institute of Observational Sciences
CNC: Computer Numerical Control
CTE: Coefficient of Thermal Expansion
ESO: European Southern Observatory
IC: Integrated Circuits
LCD: Liquid Crystal Display
VLT: Very Large Telescope

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