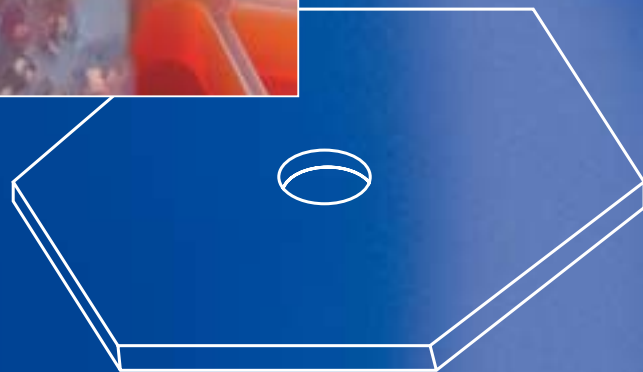
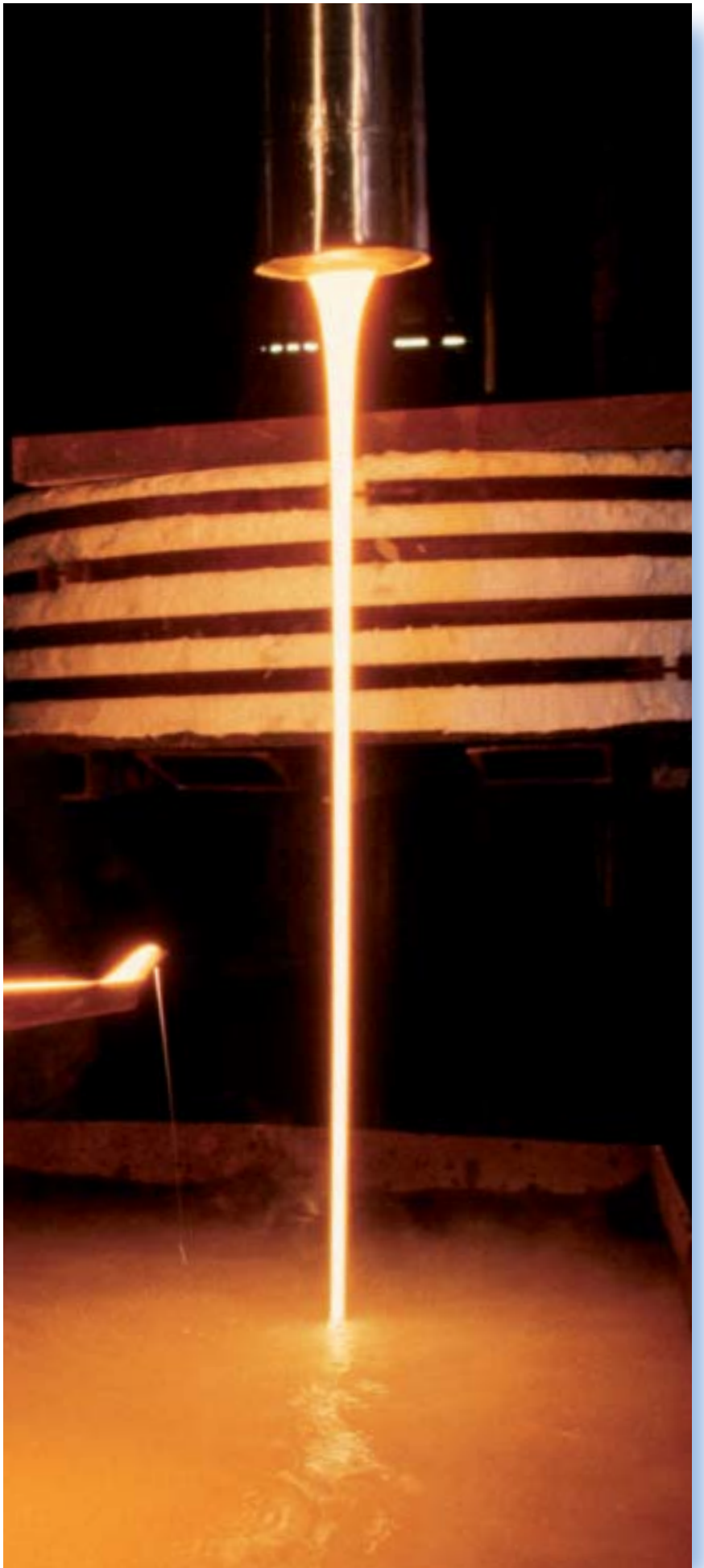


ZERODUR® Glass Ceramic

Temperature stable precision and quality in series





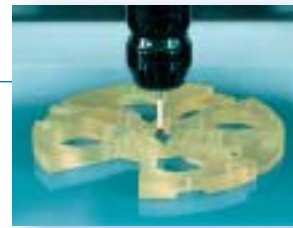
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1. ZERODUR® has Extraordinary Properties

ZERODUR® is a zero expansion glass ceramic with extraordinary properties. It is widely used in applications where unavoidable temperature changes could influence critical size and distance accuracies.

The most important properties of ZERODUR® are:

- an extremely low thermal expansion coefficient
- excellent homogeneity of thermal expansion
- high internal quality
- good workability
- polishable to a high accuracy
- excellent chemical stability

All these properties can be realized in

small components as well as in parts with weights of several tons with extraordinary reproducibility. Hence ZERODUR® has become a performance- and quality-determining factor in many spectacular applications within modern technology:

- Optical elements for lithography equipment
- High precision mechanical parts
- Mirror substrates for large astronomical telescopes
- Standards for precision measurement technology
- Mirror substrates for X-ray telescopes, weather satellites and comet probes

What is ZERODUR® and how is it made?

ZERODUR® is an inorganic, non-porous glass ceramic, characterized by a phase of evenly distributed nano-crystals within a residual glass phase.

It is produced using methods common in modern glass technology, whereby suitable raw materials are molten, refined, homogenized and finally hot formed. After subsequent annealing, stress relaxation and first processing of the glassy blank a pre-

cise ceramization process follows, during which the glass is transformed into a glass ceramic through controlled volume crystallization. During this temperature treatment nuclei form within the glass and crystals subsequently grow at a somewhat higher temperature. ZERODUR® owes its special properties to the exact balance of these glass and crystal phases.

Zero expansion

ZERODUR® contains 70-78 weight percent crystalline phase with a high quartz structure. This has a negative linear thermal expansion, while that of the glass phase is positive.

The volumetric content and the size of the nano – crystallites is adjusted in such a way during the ceramization process that the positive thermal expansion of the remaining

glassy phase and the negative thermal expansion of crystallites effectively neutralize each other. This results in an extremely low thermal expansion behavior, which in certain temperature ranges varies around zero, depending on the ceramization sequence employed.

The ZERODUR® manufacturing sequence is based on established and proven methods used in the production of high homogeneity optical glasses. Therefore ZERODUR® itself is a material of the highest homogeneity, and even in large pieces with dimensions of several

meters exhibits thermal and mechanical characteristics with nearly unmeasurable deviations.

Optimized melting, casting and annealing procedures are the requirements to produce ZERODUR® in high quantities with reproducible excellent quality.

Homogeneity and quality in large quantities



A 2-meter mirror blank casting is transported into the annealing furnace.

ZERODUR® has a completely non-directional, isotropic structure, and possesses a non-porous surface. Crystalline and glass phases have chemical characteristics and hardness

similar to those of optical glass so that ZERODUR® can be processed using the same machines and tools as optical and technical glasses (for example: cutting, grinding and polishing).

ZERODUR®, unusual in its properties, easy to fabricate

Mirror substrates and other important optical components of ZERODUR® allow precise imaging of structures in microlithography. In mechanical applications, ZERODUR®'s unusual linear thermal stability allows precise adjustment of important components. ZERODUR® is the ideal mirror substrate for astronomical telescope mirrors and x-ray telescopes of all sizes where any lack of thermal stability would adversely influence image quality and system resolution. ZERODUR® assures that better optical performance can be achieved using smaller and lighter mirrors.

In several 10 m-class telescope projects, SCHOTT has proven its ability to deliver high quantities of mirror blanks in the 1 to 2 m diameter range reliably and with a consistently high quality level. These are critical points for the construction of future extremely large telescopes with segmented mirrors of 20 to 100 m diameter.

For ring laser gyroscopes ZERODUR® forms the temperature-independent frame, whilst its low helium permeability provides long life.

ZERODUR® versatile in application

2. Thermal Properties

Mean coefficient of linear thermal expansion

The most important and significant properties of the glass ceramic ZERODUR® are the extremely small coefficient of linear thermal expansion as well as the homogeneity of this coefficient throughout the entire piece.

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

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

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

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

If not otherwise expressly specified, expansion class 2 material will be supplied. Closer tolerance will be supplied upon request.

Figure 1 illustrates the typical coefficient of linear thermal expansion α . ZERODUR® exhibits a very slight linear expansion over the entire temperature range. It is especially low near room temperature range.

The measurement accuracy for α in the temperature range of 0°C to 50°C is $\pm 0.01 \cdot 10^{-6}/K$, the repeatability of the single measurement is $\pm 0.005 \cdot 10^{-6}/K$ (95% confidence level). Single measurements with increased repeatability can be carried out upon request.

Figure 1 illustrates the typical coefficient of linear thermal expansion α . ZERODUR® exhibits a very slight linear expansion over the entire temperature range. It is especially low near room temperature range.

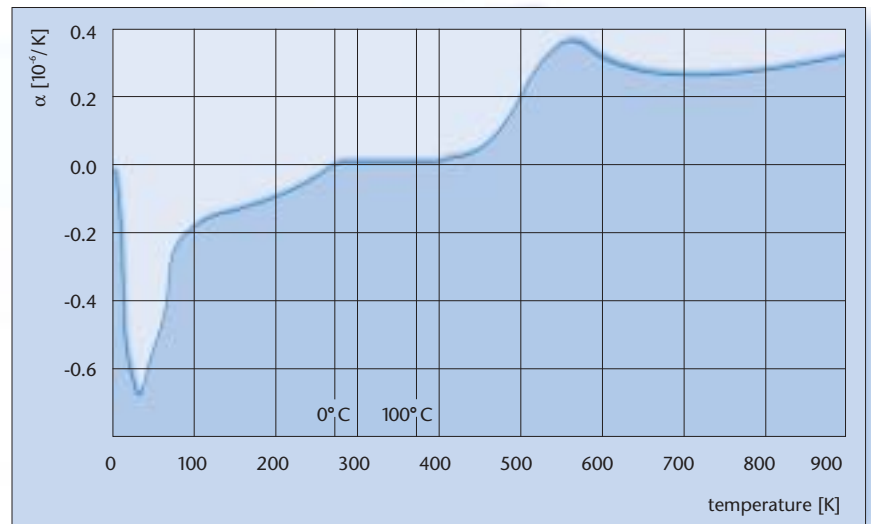


Figure 1: Curve of coefficient of linear thermal expansion of ZERODUR® as a function of temperature

Homogeneity of the coefficient of thermal expansion

Figure 2 shows an evaluation of the homogeneity of the coefficient of linear thermal expansion for more than 200 ZERODUR® mirror blanks. The diagram shows the frequency of the deviation of single measurements, taken evenly distributed on the mirror blanks, from the mean value of the blank. 95.5% of the sin-

gle measurements are located in the range of $\pm 0.007 \cdot 10^{-6}/K$ around the mean value. This range is only slightly larger compared to the range given by the repeatability of the single measurement. Therefore the actual homogeneity of ZERODUR® is in many cases better than the limits of the dilatometer measurement.

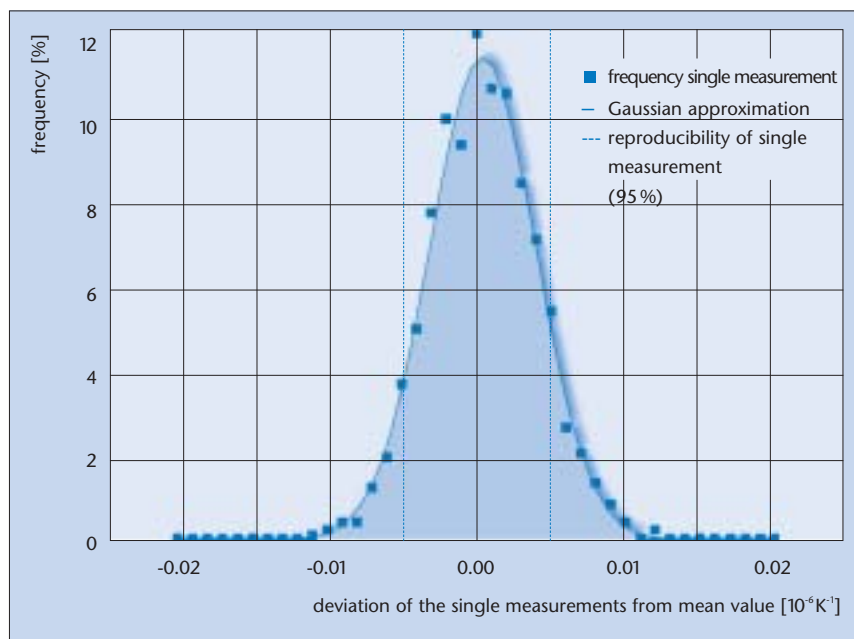


Figure 2: Homogeneity of the linear thermal expansion coefficient: Single measurements of more than 200 mirror blanks with sizes from 1 to 2 m.

The stated tolerances for homogeneity of linear expansion can be guaranteed in the following weight classes for each part, provided that the diameter of the part is at least twice its thickness:

up to 18.0 tons	$\leq 0.03 \cdot 10^{-6}/\text{K}$
up to 6.0 tons	$\leq 0.02 \cdot 10^{-6}/\text{K}$
up to 0.3 tons	$\leq 0.01 \cdot 10^{-6}/\text{K}$

In certain applications, the total change of length of a ZERODUR® part within a specified temperature interval is vital to its function (such as laser gyroscopes). In the region of -50°C to $+100^{\circ}\text{C}$, the total change in length is usually smaller than $10 \cdot 10^{-6}$, based on the total length of the part.

Upon request, ZERODUR® can be

supplied with smaller values. Figure 3 shows the typical relative expansion in length $\Delta l/l$ of ZERODUR® relative to 0°C . The measurements were performed by CSIRO (National Measurement Laboratory in Sydney, Australia) in the temperature range 2 K to 125 K and made by Schott in the temperature range of 90 K to 900 K.

Total change of length is a specified temperature interval

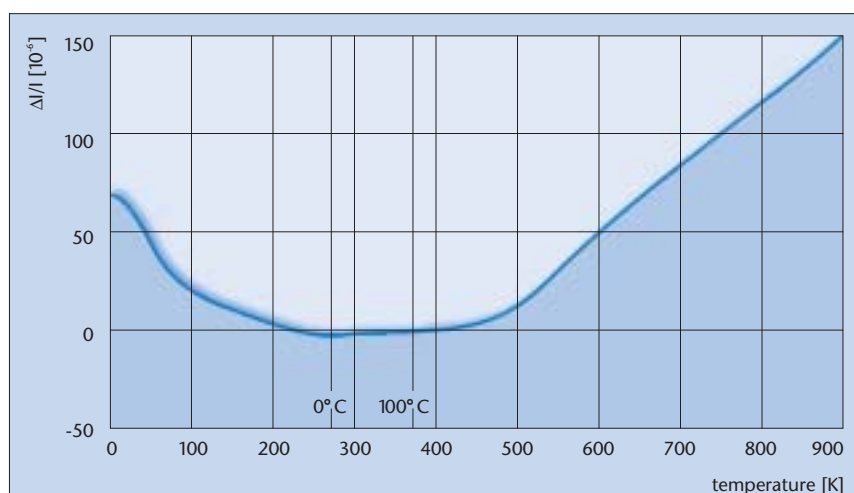


Figure 3: Relative linear expansion $\Delta l/l$ of ZERODUR®

Thermal conductivity

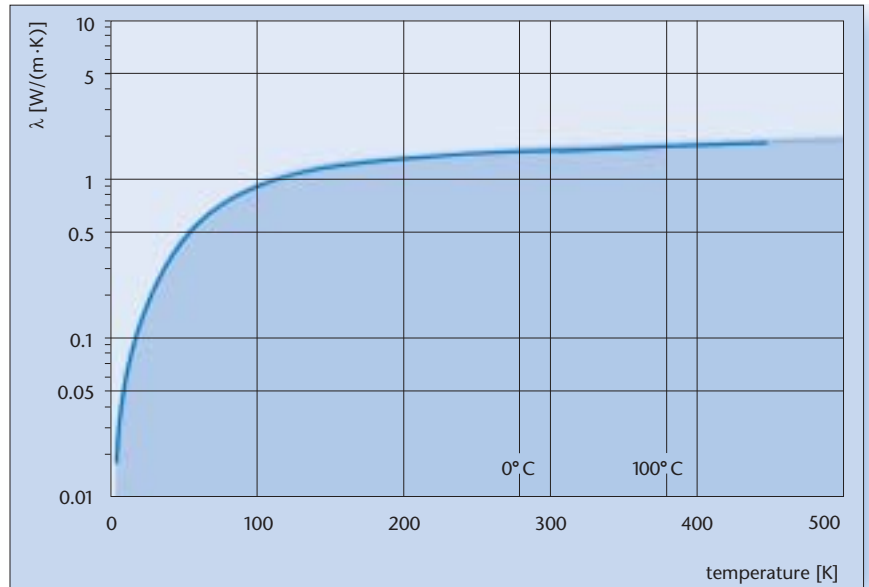


Figure 4: Thermal conductivity of ZERODUR® as a function of temperature.

Thermal conductivity λ at 20°C [W/(m · K)]	1.46
Thermal diffusivity index a at 20°C [10^{-6} m ² /s]	0.72

Specific heat capacity

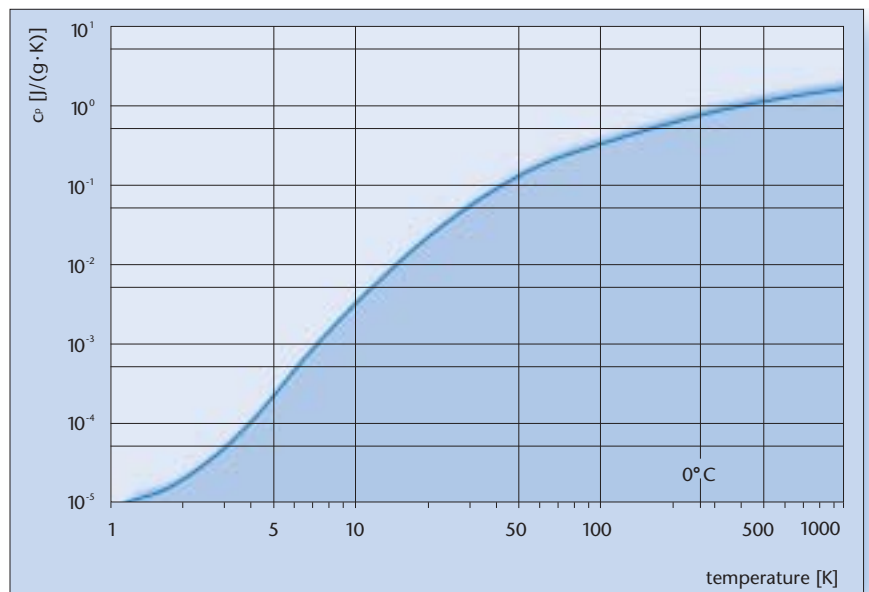
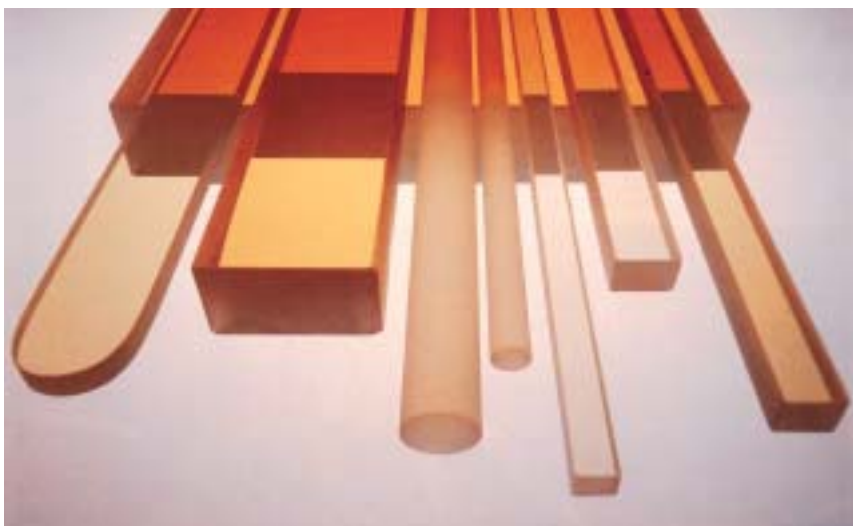


Figure 5: Specific heat capacity of ZERODUR® as a function of temperature

Specific heat capacity c_p at 20°C [J/(g·K)]	0.80
--	------



Different substrates for precision measurement applications

ZERODUR® may be used as a mechanical component as well as a window at temperatures up to 600 °C.

Slight changes may arise in the linear thermal expansion coefficient α (0°C, 50°C) that can affect components of the highest optical precision, due to temperature treatments by the custo-

mer or user. If the final cooling rate R_e differs from the initial cooling rate R_p , especially in the temperature range of 320°C to 130°C, the change of the linear thermal expansion coefficient α (0°C, 50°C) can be estimated by using the following equation:

Maximum application temperature

$$\Delta \alpha (0^\circ\text{C}, 50^\circ\text{C}) = 0.025 \cdot \log_{10} \left\{ \frac{R_e}{R_p} \right\} 10^{-6} / \text{K}$$

ZERODUR® is typically cooled during production at an initial cooling rate between 1°/h and 6°/h.

The linear thermal expansion coefficient does not change when cooling from temperatures above 320°C are carried out at the same rate as the

initial cooling. The glass ceramic ZERODUR® can be subjected to temperature treatments up to 130°C without causing changes in the linear thermal expansion coefficient α (0°C, 50°C).

For highly precise thermal expansion requirements we strongly recommend the avoidance of cooling rates other than the above initial cooling rate in the critical temperature

region during processing.

If a customer cannot influence the cooling rate, we recommend considering the use of ZERODUR® M, a material variation of ZERODUR®.

ZERODUR® M

3. Internal Quality

The internal quality of ZERODUR® is essentially determined through

- Inclusions
- Bulk stress
- Striae

Inclusions

Inclusions in ZERODUR® cannot be completely avoided. As a rule they are mainly bubbles and to some extent individual particles. They have no effect on the function of ZERODUR® as a substrate material for surfaces of the highest quality insofar as they lie completely within the volume. The probability that individual inclusions lie in the optically finished mirror surface is very low. Specifying the volume range in which the final functional surface lies can further reduce this slight risk. When stating this critical volume,

ZERODUR® parts are selected and processed in such a way that more stringent requirements are met. During testing of ZERODUR® parts all inclusions with a diameter > 0.3 mm are considered. If an inclusion has a shape other than spherical, the average diameter is reported as the mean of the length and width.

Inclusions in ZERODUR® are distinguished by the designations "Standard" and Classes 0 to 4. The tolerances of these quality levels are listed in table 1:

	Standard	Class 4	Class 3	Class 2	Class 1	Class 0
Average number of inclusions per 100 cm ³	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
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

Table 1: Quality levels for inclusions in ZERODUR®

Bulk stress

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 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. The edge distance is 5% of the plate width.

Bulk stress is listed in two quality levels for different size classes of ZERODUR® parts in table 2.

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

Table 2: Quality levels for bulk stress in ZERODUR®

Striae are local, very limited transparent regions with composition differing only slightly from the basic material. They are generally ribbon shaped (or often called bandlike), sometimes thread shaped.

The striae quality of ZERODUR® is tested by the stress optical method and is listed as an optical path difference in nm for thread-like striae.

The striae ranges listed in table 3 are

maximum values for 5 quality levels for different dimensions and diagonals of ZERODUR® parts.

For ribbon-shaped striae, the optical path difference is given in nm/cm striae length and the quality levels in table 4 are valid.

For strict requirements, an extremely sensitive shadowgraph technique is used that allows fine visible striae to be found in the test direction.

Striae

Stress birefringence caused by striae [nm/stria] 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*

* Only applies to the critical volume in the area of the operating surfaces.
All others as with class 4 quality.

Table 3: Quality levels for stress birefringence caused by striae in ZERODUR®

Stress birefringence caused by striae [nm/cm length of stria] for parts with diameters or diagonals					
	Standard	Class 4	Class 3	Class 2	Class 1
< 500 mm	2.5	2	1.5	0	0
< 2000 mm	2.5	2	1.5	1	0
< 4000 mm	2.5	2	1.5	1	0

Table 4: Quality levels for stress birefringence caused by ribbon shaped striae in ZERODUR®

We invite inquiries for requirements that go beyond the mentioned inclusion, striae, and bulk stress spe-

cifications. If no quality is specified upon order entry, ZERODUR® is supplied in standard quality.

Special requirements (higher quality level)

4. Mechanical Properties

Length stability over time

Since 1973, 400 mm long gauge blocks maintained at 20°C made from ZERODUR® have been interferometrically connected to a wavelength standard at the PTB (Physikalisch-Technische Bundesanstalt, Germany). Interpolation formulas that have been derived from previous measurements

on the basis of theoretical consideration allow predictions to be made for the expected change in the length of ZERODUR® relation to time. In a formal analogy to the thermal linear expansion coefficient α the following applies:

$$l = l_0 (1 + A \cdot \Delta t)$$

The value of A is always negative for isothermal storage, indicating shrinkage over time. It depends on the cooling process and on the age of the sample

and has an order of magnitude $|A| < 10^{-7}$ per year.

Young's modulus E

The Young's modulus for a typical melt is shown in figure 6 as a function of temperature.

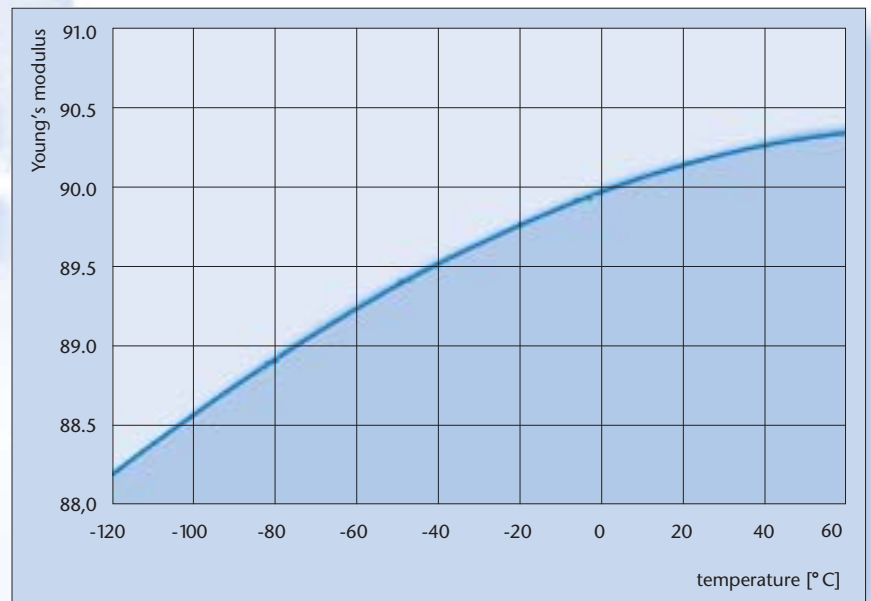


Figure 6: The Young's modulus of ZERODUR® as a function of temperature

Young's modulus E at 20°C [GPa]-mean value

90.3

The practical bending strength of glasses and glass ceramics is not a material constant. It is particularly dependent upon the following factors:

- Micromechanical condition of the tension loaded surfaces
- Size of the tension loaded surfaces subjected to stress
- Rate of load increase
- Surrounding medium, usually air

Owing to the statistical nature of strength experiments, bending

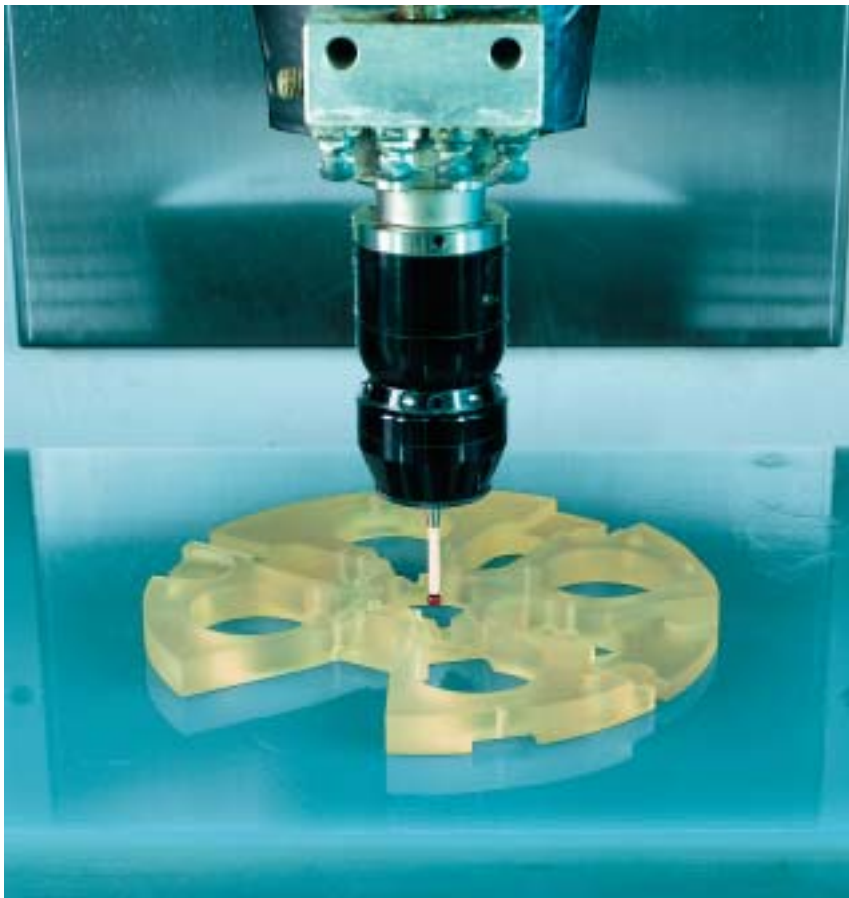
strength is listed as a failure probability. The Weibull distribution is an established tool for the description of the failure probability.

Measurement results for different surface conditions and further information on the bending strength of ZERODUR® are available on request. In many applications, a tensile stress of 10 MPa can be assumed as a limiting value. This applies, for example, to small objects with scratch-free surfaces.

Bending strength

Poisson's ratio μ	0.243
Density ρ [g/cm ³]	2.53
Knoop Hardness HK 0.1/20 according to ISO 9385	620

Other mechanical characteristics



Measurement head of a high precision grinding machine for complex structures

5. Optical Properties

Refractive indices, Abbe number

Wavelength [nm]	Designation	Refractive index n	Abbe number v
656.3	C	1.5394	
643.8	C'	1.5399	
587.6	d	1.5424	56.1
546.1	e	1.5447	55.9
486.1	F	1.5491	
480.0	F'	1.5497	
435.8	g	1.5544	

Table 5: Refractive indices and Abbe number of ZERODUR®

Principal dispersion

$n_F - n_C$	0.00967
$n_{F'} - n_{C'}$	0.00975

Temperature coefficient of refractive index

$\Delta n/\Delta T$ is dependent upon the wavelength λ , the temperature T and the air pressure p. There are two possibilities to express these relations: For the relative temperature coefficient $\Delta n_{\text{relativ}}/\Delta T$, the material and the surrounding air have the same temperature. The information pertains to the air pressure $p = 0.10133$ MPa. The absolute temperature coefficient $\Delta n_{\text{abs}}/\Delta T$ applies to a vacuum.

Both coefficients are listed for different temperature ranges and wavelengths in table 6. These values are guideline values.

Since ZERODUR® has the residual glass phase of approximately 22 - 30 weight %, the refractive index and density are influenced by the actual cooling rate. The effect is smaller than that for pure glass.

Temperature °C	$\Delta n_{\text{relativ}}/\Delta T$ [$10^{-6}/K$]					$\Delta n_{\text{absolut}}/\Delta T$ [$10^{-6}/K$]				
	C'	d	e	F'	g	C'	d	e	F'	g
-100/-80	12.2	12.4	12.5	12.8	13.2	8.6	8.7	8.8	9.1	9.4
-80/-60	12.4	12.6	12.7	13.0	13.4	9.4	9.6	9.7	10.0	10.3
-60/-40	12.7	12.9	13.0	13.4	13.8	10.3	10.4	10.5	10.9	11.2
-40/-20	13.1	13.3	13.4	13.8	14.2	11.0	11.2	11.3	11.7	12.1
-20/0	13.5	13.7	13.9	14.3	14.7	11.8	11.9	12.1	12.5	12.9
0/20	14.0	14.1	14.3	14.7	15.2	12.4	12.6	12.8	13.2	13.6
20/40	14.4	14.6	14.8	15.2	15.7	13.1	13.2	13.4	13.9	14.3
40/60	14.8	15.0	15.2	15.7	16.0	13.6	13.8	14.0	14.5	14.9
60/80	15.2	15.4	15.6	16.1	16.6	14.2	14.4	14.6	15.0	15.5
80/100	15.6	15.8	16.0	16.5	17.0	14.6	14.9	15.1	15.6	16.1
100/120	15.9	16.1	16.3	16.9	17.4	15.4	15.3	15.5	16.0	16.6
120/140	16.2	16.7	16.7	17.2	17.8	15.4	15.7	15.9	16.4	17.0

Table 6: The relative and absolute temperature coefficient of the refractive index of ZERODUR® in the range -100°C to +140°C

ZERODUR® is a clear transparent material. The crystalline phase in ZERODUR® leads to wavelength-dependent scattering, which is typical for Rayleigh scattering.

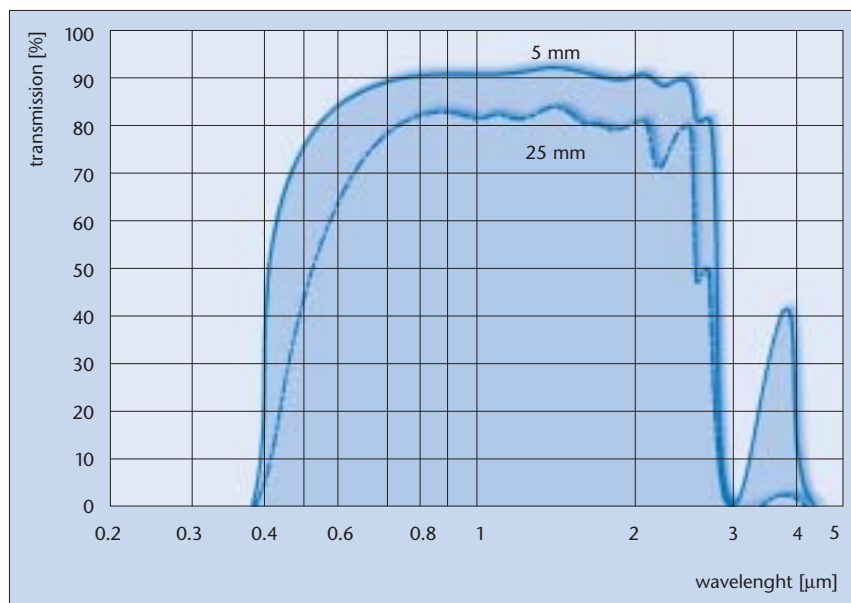
This is shown in table 7 with the help of R_{90} values, a measure of the proportion of light scattered at 90 degrees per path length of the observed primary ray.

Wavelength [nm]	R_{90} [$10^{-3}/\text{cm}$]
404.7	23
435.8	16
546.1	6
578.1	5

Rayleigh scattering

Table 7: Rayleigh scattering of ZERODUR®

The typical light transmission of ZERODUR® in the visible and near infrared spectral range is shown in figure 7. The given values are guideline values.



Transmission

Figure 7: The light transmission of ZERODUR® at sample thickness of 5 mm and 25 mm

K at $\lambda = 589.3 \text{ nm}$ [10^{-6} MPa^{-1}]

3.0

Stress optical coefficient K

6. Electrical Properties

Specific electrical resistivity

The specific electrical resistivity ρ for different temperatures is listed in table 8.

Temperature [°C]	Specific resistivity ρ [$\Omega \cdot \text{cm}$]
20	$2.6 \cdot 10^{13}$
100	$1.3 \cdot 10^{10}$
200	$3.5 \cdot 10^7$
300	$7.4 \cdot 10^5$
400	$4.9 \cdot 10^4$
500	$6.6 \cdot 10^3$
600	$1.4 \cdot 10^3$

Table 8: The specific electrical resistivity of ZERODUR®

t_{k100} [°C], temperature for $\rho = 10^8 \Omega \cdot \text{cm}$

178

Dielectric properties at 20°C

Table 9: Dielectric properties of ZERODUR®

	at 1 kHz	at 1 MHz
Dielectric constant ϵ	8.0	7.4
Loss factor $\tan \delta$	$29 \cdot 10^{-3}$	$15 \cdot 10^{-3}$

Leightweighted mirror:
low weight and stable



7. Chemical Properties

<u>Hydrolytic resistance class (ISO 719)</u>	<u>HGB 1</u>	Hydrolytic resistance
<u>Acid resistance class (ISO 8424)</u>	<u>1.0</u>	Acid resistance (SR)
<u>Alkali resistance class (ISO 10629)</u>	<u>1.0</u>	Alkali resistance (AR)
<u>Climatic resistance</u>	<u>Class 1</u>	Climatic resistance
<u>Stain resistance</u>	<u>Class 0</u>	Stain resistance

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 SiO₂ do not noticeably react with ZERODUR® at temperatures up to 600°C after 5 hours elapsed time. By contrast, enamel reacts with Zerodur above 560°C with surface destruction.

[Reactivity with other materials](#)

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 (see Product Information #3097).

[Repeated metal coatings](#)

8. Helium Permeability

An important application for ZERODUR® are laser gyroscopes. This modern technology of measurement in aircraft navigation, helicopters and other means of transportation is based on the Sagnac effect and requires frame components with particularly low permeability for

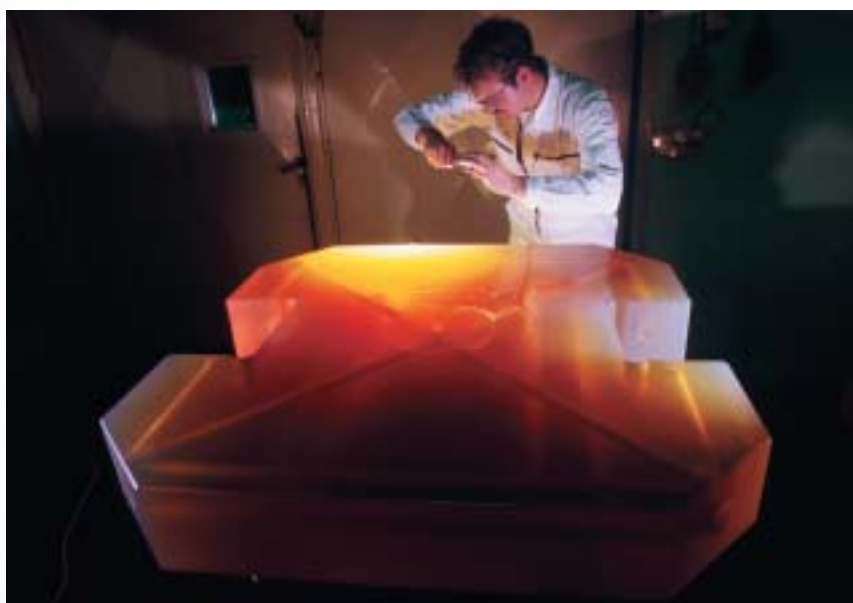
helium atoms. The gas charge should remain constant for the longest time period possible.

Due to its unusually low helium permeability and its low thermal expansion coefficient, the glass ceramic ZERODUR® is especially suited for this application.

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	$7.2 \cdot 10^8$

Low helium permeability makes ZERODUR® the preferred material for laser gyroscopes



9. Forms of supply and tolerances

ZERODUR® can be supplied in the form of disks up to a diameter of 2.5 meters and in the form of rectangular blocks, prisms, rods and cut pieces measuring up to approximately 2.5 meters in length. The technology for manufacturing larger volumes is being mastered. Therefore larger dimensions can be fabricated on special request.

Standard tolerances for simple disc shaped or plate shaped parts are ± 0.5 mm depending on the geometry. Tighter tolerances can be provided upon request. The customer should also request values for angle-, flatness-, shape-, run-out- and other tolerances. For parts that cannot be simply described by length, width and thickness (or diameter and thickness), a drawing will be provided.

Special shapes and processing treatments are possible.

Modern CNC processing equipment, high performance diamond tools and expert know-how allow a multitude of geometric shapes to be produced. Holes, backside grinding, blind holes and freeform surfaces are only a few examples of the variety of possible geometries.

Typically all parts are provided with protective bevels on all sharp edges for protection against edge damage. The surfaces of the parts are usually processed in such a way that the surface roughness is not more than $Ra \leq 3.5 \mu\text{m}$. Finer surfaces can be quoted upon request.

Shapes and dimensional tolerances



Modern coordinate measurement equipment in the final inspection of ZERODUR®

10. Necessary Data for Quotation Preparation

For quick quotation the following details (as a minimum) should be clearly stated. Essential details are marked blue.

	value	tolerance
length [mm] alt. diameter [mm]		
width [mm]		
thickness [mm]		
quantity		
expansion class*		
inclusion class*		
striae class*		
bulk stress*		
* if better than standard		
other geometry or shape tolerances		
other material properties like transmission, homogeneity etc.		
please include drawing/sketch		

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SCHOTT
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