TIE-43: Properties of ZERODUR®

0. Introduction

The technical information “Properties of ZERODUR®” compiles thermal, mechanical, electrical and optical properties also those not displayed in detail in the ZERODUR® catalog. All data presented in this technical information are typical values for ZERODUR®. Measurement results of single batches can vary slightly from these data.

1. Thermal Properties

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 cp at 20°C [J/(g·K)]	0.80

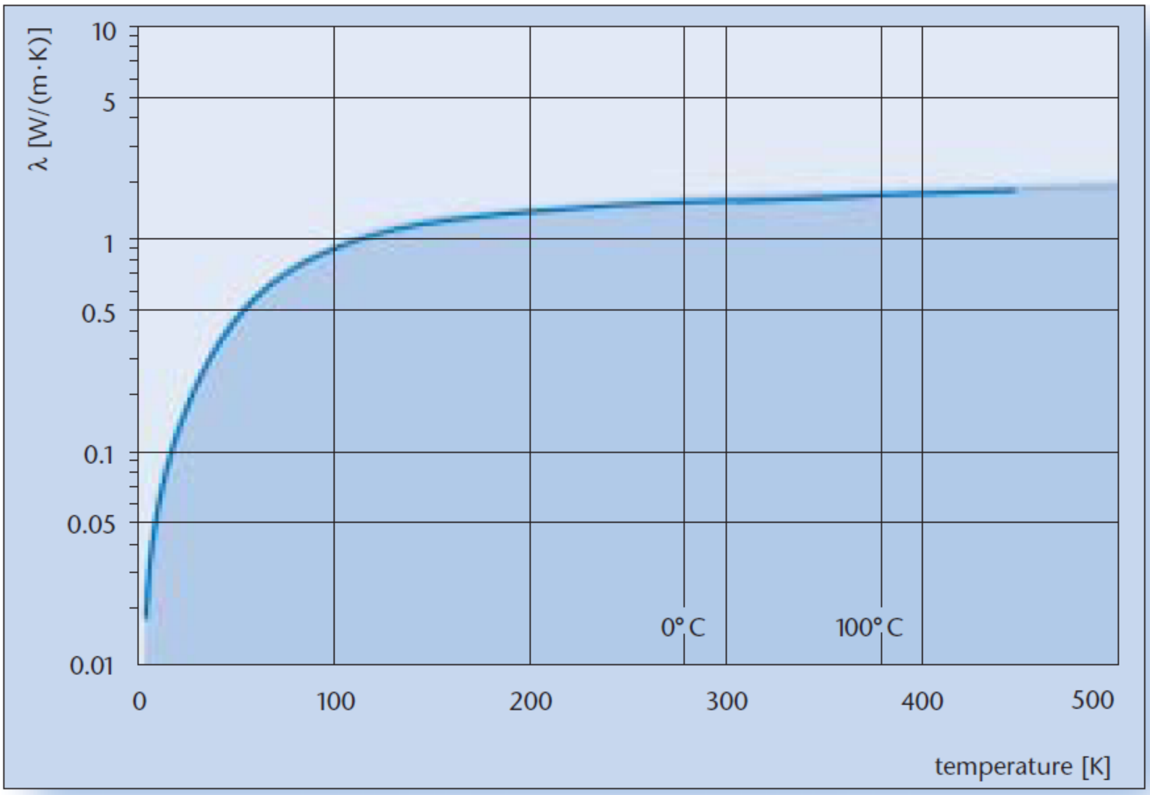

Figure 1: Thermal conductivity of ZERODUR® as a function of temperature.

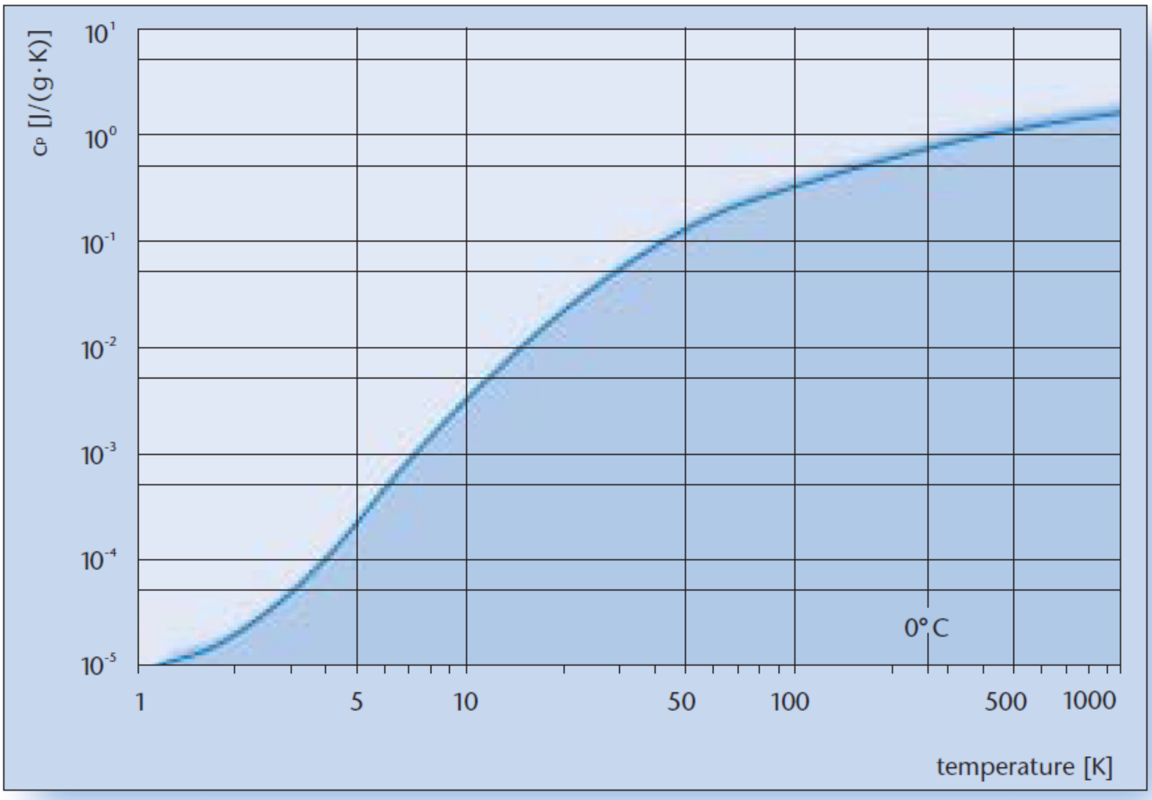

Figure 2: Specific heat capacity of ZERODUR® as a function of temperature.

2. Mechanical Properties

Young's modulus E at 20°C [GPa]-mean value	90.3
Poisson number μ	0.24
Density ρ [g/cm^3]	2.53
Knoop hardness HK 0.1/20 according ISO 9385	620

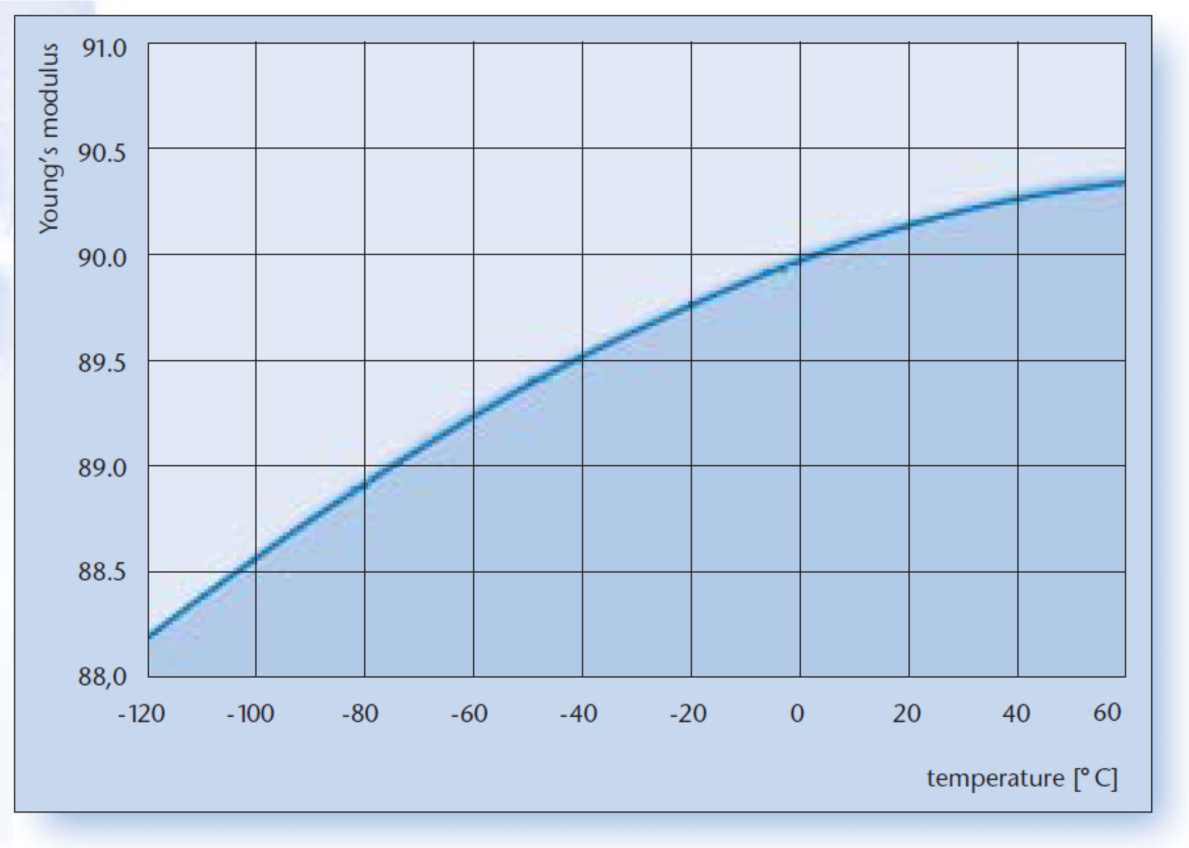

Figure 3: Young's modulus of ZERODUR® as a function of temperature.

3. Electrical Properties

Temperature [°C]	Specific Resistivity ρ [Ω 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 1: The specific electrical resistivity of ZERODUR® as a function of temperature.

t_{K100} [°C], temperature for $\rho = 10^8$ Ωcm 178

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

Table 2: Dielectric properties of ZERODUR®.

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4. Optical Properties of ZERODUR®

The manufacturing process of ZERODUR® is mastered at SCHOTT in such a way that optical quality for transmittance optics can be achieved. With additional production effort involving an extensive selection it is possible to fulfil standard tolerances as given by the optical glass catalog [1] in geometries up to 300 mm in diameter and larger. To ease the selection process it is necessary to specify the optical requirements as precisely as possible in advance in close cooperation between the customer and SCHOTT.

Figure 4: 1.33 m diameter ZERODUR® testing lens for the secondary mirror of GRANTECAN.

4.1. Refractive Index

The following table 3 presents the refractive index values of ZERODUR® for different wavelengths. The refractive index of distinctive ZERODUR® batches will only be measured on customer request. The applicable tolerances for the refractive index at the d-line are in the range of ±0.0005. Tighter tolerances can be fulfilled on request. Unlike optical glass, the refractive index of ZERODUR® can not be adjusted to tighter tolerances by a subsequent annealing process.

The standard measurement accuracy for the refractive index is $\pm 3 \cdot 10^{-5}$ and covers the g- to C-line. Using a special spectrometer a refractive index measurement accuracy of $\pm 0.4 \cdot 10^{-5}$ covering a wavelength range from 365 nm to 2325 nm can be achieved on request [2].

Wavelength [µm]	Fraunhofer Designation	Refractive Index Measured	Refractive Index from Sellmeier Dispersion
0.3650146	i		1.56685
0.4046561	h	1.55894	1.55894
0.4358343	g	1.55444	1.55444
0.4799914	F’	1.54966	1.54966
0.4859975			1.54912
0.4861327	F	1.54911	1.54911
0.546074	e	1.54468	1.54468
0.5875618	d	1.54238	1.54238
0.5892938	D		1.54229
0.6328			1.54035
0.6438469	C’	1.53991	1.53991
0.6561			1.53945
0.6562725	C	1.53944	1.53944
0.7065188	r	1.53777	1.53777
0.85211	s	1.53422	1.53422
1.01398	t	1.53145	1.53145
1.06			1.53077
1.12864		1.52981	1.52981
1.395055		1.52639	1.52639
1.529582		1.52469	1.52469
1.81307		1.52092	1.52092
1.97009		1.51866	1.51866
2.24929		1.51423	1.51423
2.32542		1.51292	1.51292

Table 3: Refractive index of the ZERODUR® catalog melt at different wavelengths (typical values, not guaranteed).

The third column of table 3 lists the measured refractive index of a representative melt. These results were used to estimate the constants of the Sellmeier dispersion equation (formula 1 [2]) that can be determined to calculate the refractive index at wavelengths that are not directly accessible by the refractive index measurements.

$$n(\lambda)^2 - 1 = \frac{B_1 \cdot \lambda^2}{(\lambda^2 - C_1)} + \frac{B_2 \cdot \lambda^2}{(\lambda^2 - C_2)} + \frac{B_3 \cdot \lambda^2}{(\lambda^2 - C_3)} \qquad (1)$$

The coefficients of the representative melt are displayed in table 4

	1	2	3
B_x	1,3182408	2,44E-02	1,08915181
C_x	8,79E-03	6,09E-02	1,10E+02

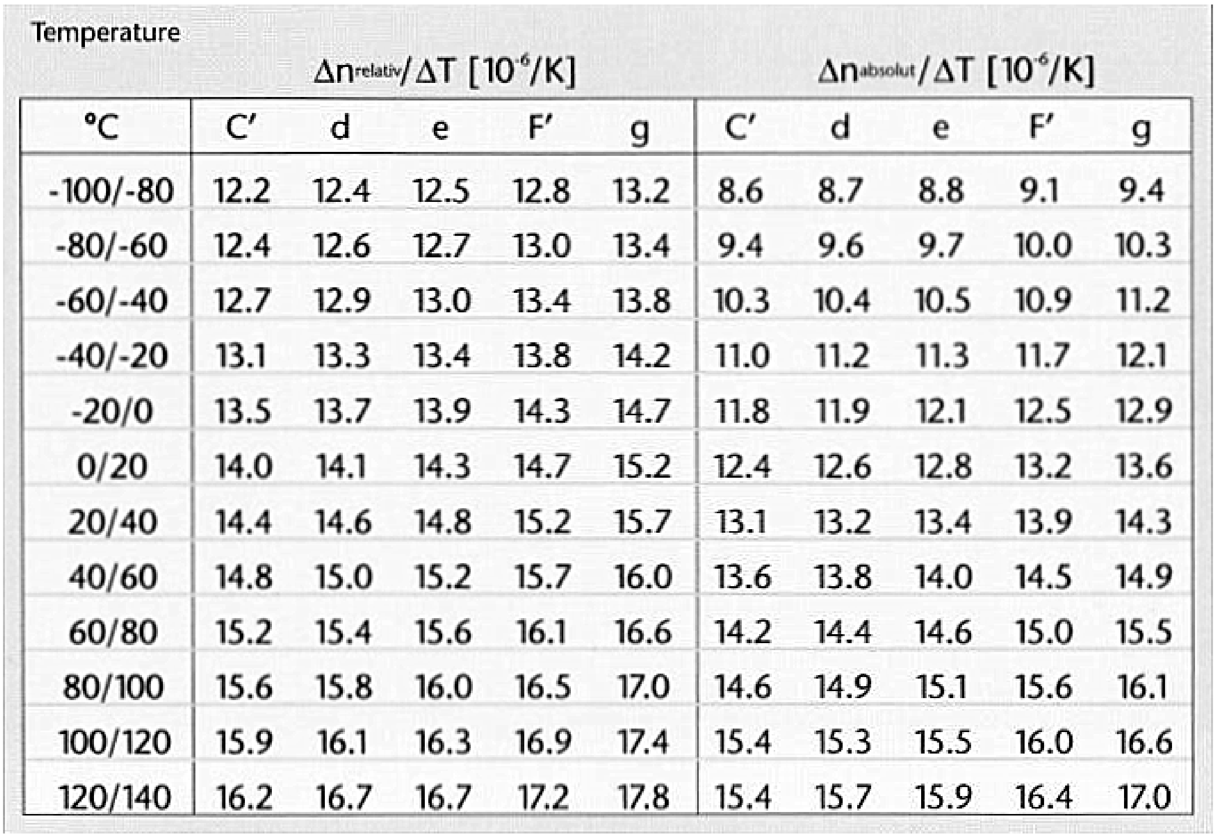
Table 4: Sellmeier coefficients of the ZERODUR® catalog melt (typical, not guaranteed).

The fourth column of table 1 shows the results of the refractive indices calculated using the Sellmeier dispersion formulae.

4.1.2 Temperature Coefficients of Refractive Index

Although ZERODUR® comprises a very low thermal expansion coefficient the temperature has a recognizable influence on the refractive index. The dependence of the refractive index on temperature is as high as that of those optical glasses that are most sensitive in this respect. The change of refractive index with temperature depends on the wavelength λ, the temperature T and the air pressure p. There are two ways to express these relations. For the relative temperature coefficient $\Delta n_{relativ}/\Delta T$, the material and the surrounding air have the same temperature. The information pertains to air pressure p=0.10133 MPA.

The absolute temperature coefficient $\Delta n_{absolut}/\Delta T$ applies to vacuum. Both coefficients are listed for different temperature ranges and wavelengths in table 5. More detailed information on how to calculate these parameters can be found in [2].



Temperature	$\Delta n_{relativ}/\Delta T$ $[10^{-6}/K]$					$\Delta n_{absolut}/\Delta T$ $[10^{-6}/K]$				
°C	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 5: Relative and absolute temperature coefficients of refractive index of ZERODUR®.

4.2. Internal Transmittance

The reference transmittance values for ZERODUR® are given in table 6. The internal transmittance (transmittance curve corrected for reflection losses) might vary from batch to batch due to slight variations in the purity of the raw materials. Depending on the specified value the material has to be selected in advance. Therefore transmission specifications can only be treated on request.

Wavelength [nm]	Internal Transmittance at 5 mm Thickness	Internal Transmittance at 10 mm Thickness	Internal Transmittance at 25 mm Thickness
2500	0.859	0.737	0.467
2325	0.961	0.924	0.820
1970	0.971	0.943	0.864
1530	0.976	0.952	0.884
1060	0.981	0.962	0.907
800	0.984	0.969	0.924
700	0.977	0.955	0.890
680	0.974	0.949	0.877
660	0.971	0.942	0.861
640	0.966	0.934	0.842
620	0.962	0.925	0.823
600	0.955	0.913	0.796
580	0.948	0.899	0.766
560	0.940	0.884	0.734
546	0.933	0.870	0.706
540	0.929	0.863	0.692
520	0.916	0.839	0.644
500	0.901	0.812	0.593
480	0.881	0.776	0.530
460	0.856	0.734	0.461
440	0.825	0.681	0.382
436	0.818	0.669	0.367
420	0.781	0.611	0.291
405	0.712	0.506	0.182
400	0.650	0.422	0.116
390	0.370	0.137	0.007
380	0.076	0.006	0.000

Table 6: Typical internal transmittance values of ZERODUR® at 5 mm, 10 mm and 25 mm thickness.

Figure 5 shows an internal transmittance curve of ZERODUR® batch measured with a wavelength resolution of 1 nm. Additionally the catalog reference values are displayed. Obviously the transmittance values of the measured batch are slightly higher compared to the catalog values. Also the transmittance curve is not linear between the reference wavelengths but influenced by several absorption bands (similar to optical glass [3]). The sample melt displayed is slightly better than the catalog reference melt, reflecting normal variations from batch to batch.

Compared to other optical glasses ZERODUR® has an improved transmittance at wavelengths >2000 nm. Figure 6 presents the transmittance of a 0.6 mm thick ZERODUR® at wavelengths >2500 nm, displaying a residual transmittance between 3000 nm and 4000 nm which cannot be detected at larger material thicknesses.

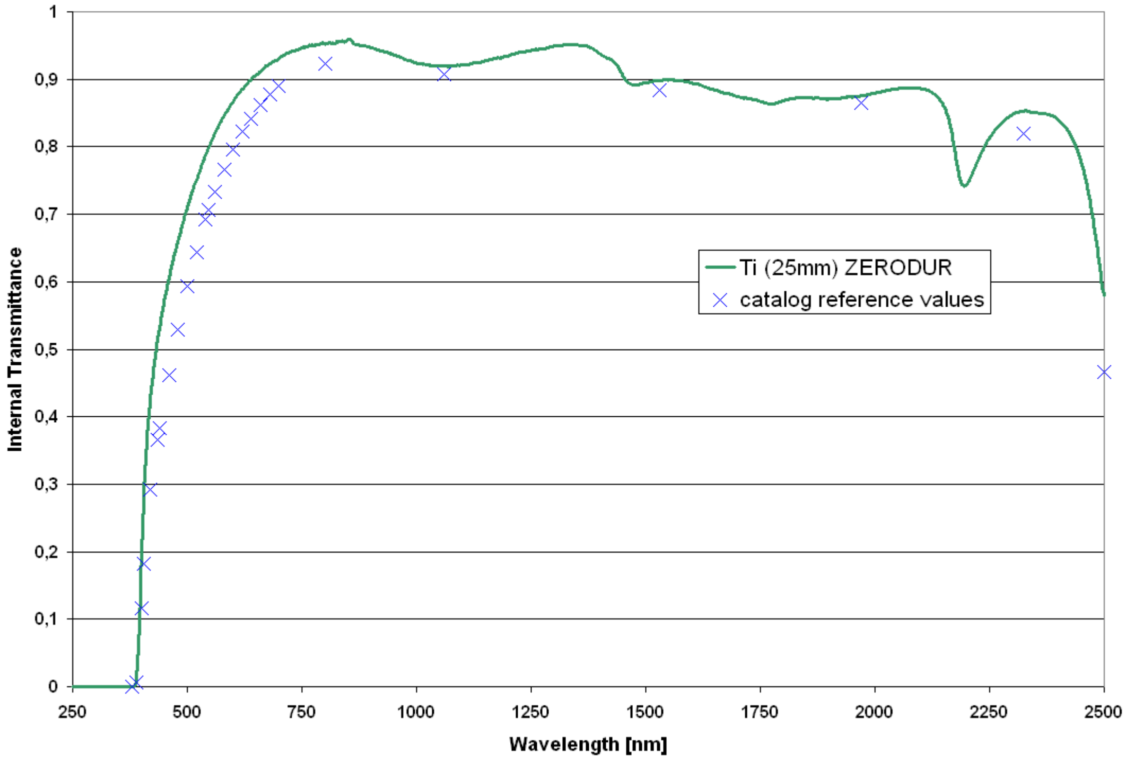


Figure 5: Internal Transmittance curve of a ZERODUR® sample at 25 mm thickness compared to the catalog reference values.

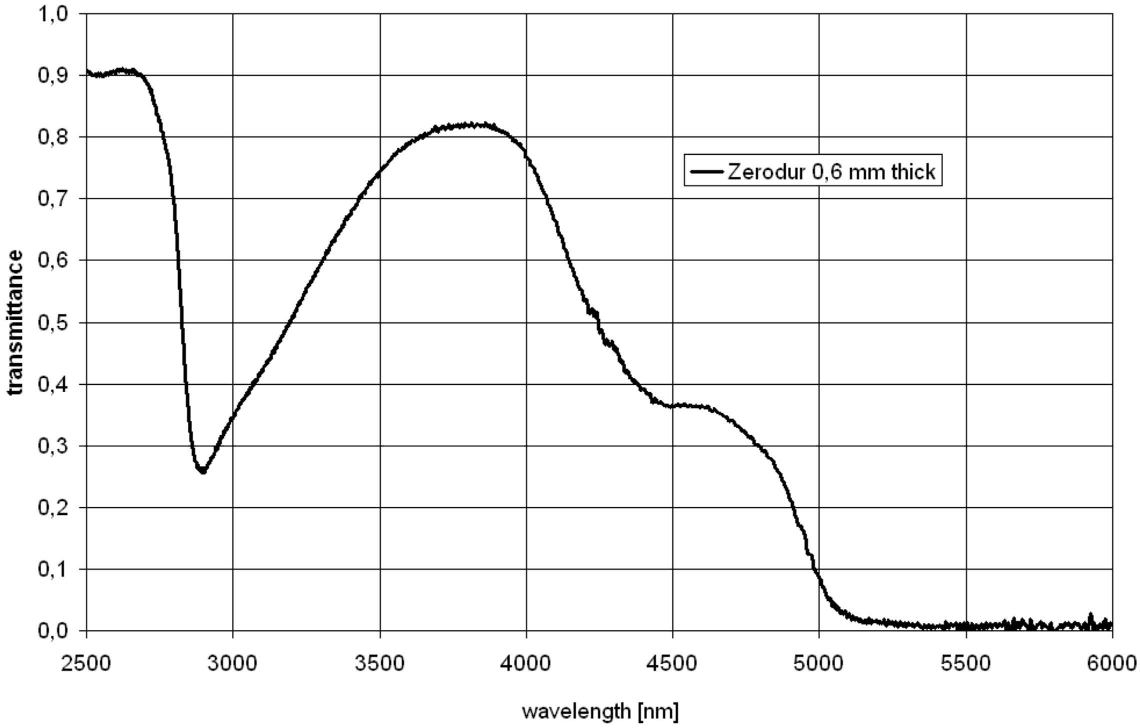


Figure 6: Transmittance curve of ZERODUR® at 0.6 mm thickness.

4.2.1 Rayleigh Scattering

The reason for the low transmittance of ZERODUR® in the visible and near UV spectral range is the Rayleigh scattering due to the crystal phase within the material. This scattering behavior is wavelength depended. Table 7 displays the fraction of light scattered in 90° direction per path length of the observed primary ray as a function of the selected wavelength.

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

Table 7: Rayleigh-scattering of ZERODUR® at different wavelengths.

The strong decline of the scattering with increasing wavelength leads to the high transmittance of ZERODUR® observed in the far red and near infrared. This has been exploited for the internal quality inspection of the huge and bulky cylindrical boules for the AXAF/CHANDRA Projects (figure 7). Even today this method is frequently used for the inspection of up to 1 m thick ZERODUR® boules.

Figure 7: Focal scanning of large thickness ZERODUR® boules with an IR sensitive CCD camera (for AXAF/ Chandra).

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4.4. Refractive Index Homogeneity

One of the most important properties of optical glass is the excellent spatial homogeneity of the refractive index of the material. In general one can distinguish between the global or long-range homogeneity of refractive index in the material and short-range deviations from glass homogeneity. Striae are spatially short-range variations of the homogeneity in a glass, typical extending over a distance of about 0,1 mm up to 2 mm [5]. Whereas the global homogeneity of refractive index denotes long range variations extending from the cm range to the full cross section of the optical element [4].

4.4.1 Global Refractive Index Homogeneity

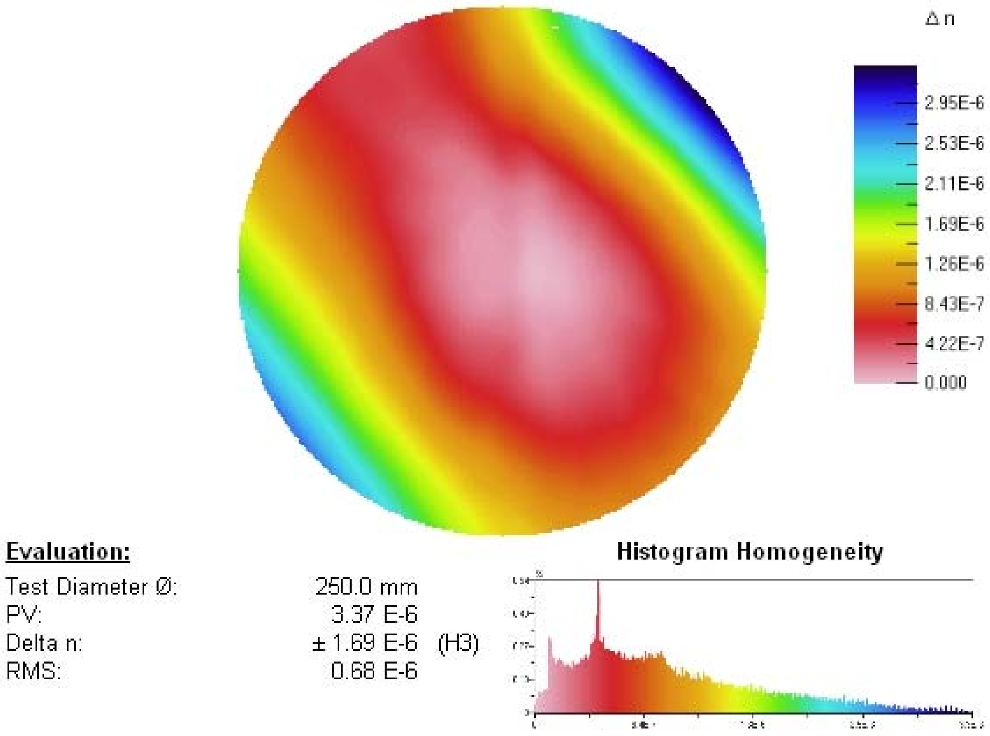
The availability of optical glasses with increased requirements for refractive index homogeneity comprises 5 classes in accordance with ISO standard 10110 part 4 [4]. The SCHOTT homogeneity grade H1 to H5 for single parts comprises ISO grades 1 to 5. Table 8 exhibits an overview of the homogeneity grades.

class	H1	H2	H3	H4	H5
Maximum peak to valley variation of refractive index (ISO 10110)	$40 \cdot 10^{-6}$	$10 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$1 \cdot 10^{-6}$

Table 8: Refractive index homogeneity classes of optical glasses according to the SCHOTT glass catalog.

Figure 8 shows the refractive index homogeneity map of a 250 mm diameter ZERODUR® blank. The homogeneity is within H3 class. In smaller areas of the center of the blank the homogeneity in general is much higher. The homogeneity map was derived from a measurement using a Zeiss Direct 100 interferometer with a maximum aperture of 500 mm [4].

Refractive index homogeneity up to H3 quality can be achieved on dimensions up to 350 mm, H4 quality on dimensions up to 250 mm. The achievable global refractive index homogeneity quality strongly depends on the size of the part. Nevertheless, special production measures including an intensive selection process are necessary; therefore refractive index homogeneity specifications are treated on special request only.



Evaluation:

Test Diameter Ø: 250.0 mm
PV: 3.37 E-6
Delta n: ± 1.69 E-6 (H3)
RMS: 0.68 E-6

Figure 8: Homogeneity map of a 250 mm diameter ZERODUR® disc.

4.4.2 Striae

Striae in optical glass are inspected and characterized using the shadowgraph method [5]. SCHOTT standard striae quality for optical glass fulfills ISO 10110 part 5, class 5 exhibiting a wavefront deformation of 30 nm maximum.

In contrast to optical glass, striae in ZERODUR® are evaluated according to the mechanical stress they exhibit to the surrounding material by measuring the stress birefringence. These values can not be compared to the results from the shadowgraph measurement that is used to characterize the striae quality in optical glass.

Nevertheless the striae inspection by stress birefringence measurement is a necessary tool for the preselection of ZERODUR® material for optical application. After preselection of material with a low amount of stress birefringence caused by striae ZERODUR® will be polished on both surfaces for the optical striae testing using the shadowgraph method.

Therefore on special request and with additional effort in stress birefringence preselection and shadowgraph qualification (including polishing of the blanks) it is possible, depending on the geometry, to select ZERODUR® material with optical striae quality sufficient to fulfill ISO 10110 part 4 classes 1 to 5.

The following figure 9 is showing a shadowgraph of a ZERODUR® blank. The shadowgraph measurement is a very sensitive method to detect striae in optical glasses. Even striae wavefront deviations as faint as 10 nm can be detected using this method.

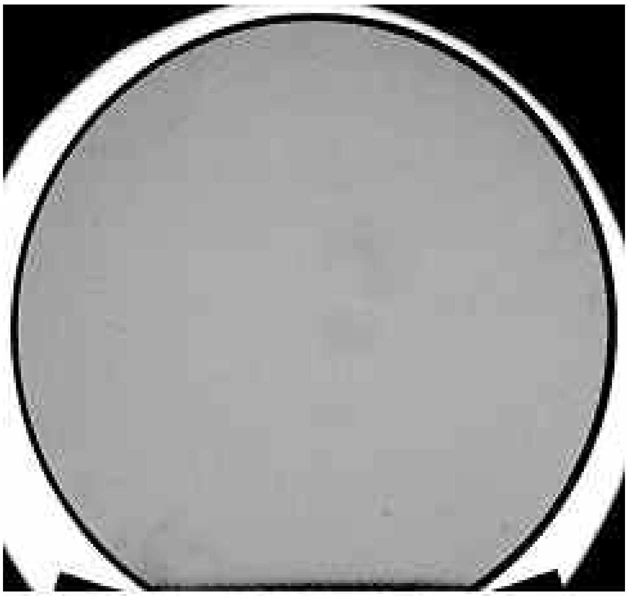


Figure 9: Shadowgraph of a specially selected and produced 250 mm diameter ZERODUR® blank. No striae above 10 nm wavefront deviation are visible in this setup.

As indicated before, the achievable striae quality also strongly depends on the size of the blank and the selected part of a blank. Figure 10 displays a 1.5 m diameter ZERODUR® blank. This blank has been selected out of a number of blanks by starting with a measurement of the stress birefringence caused by striae. After this preselection the blanks with the lowest stress birefringence caused by striae have been polished for optical striae testing to finally select the displayed blank for the application. Within this blank optical standard grade striae quality was achieved. Additionally this blank also contains a very small amount of bubbles and inclusions.

4.5. Stress Birefringence

The stress birefringence in ZERODUR® depends on the diameter to thickness ratio of the part. The thicker the part is in relation to its diameter the higher the remaining internal stress will be. Nevertheless precision annealing quality (SSK, [1]) with stress birefringence values below 4 nm/cm can also be achieved for ZERODUR® blanks with sizes in the 1.5 m range.

Figure 10: ZERODUR® blank with a diameter of 1.53 m a thickness of 176 mm and a weight of 819 kg, in optical standard grade striae quality and with excellent bubbles and inclusion quality.

4.6. Bubbles and Inclusions

For general ZERODUR® applications only bubbles and inclusions of diameters >0.3 mm are taken into account. The bubbles and inclusion specification of optical glass is in general much tighter. The evaluation starts at bubble and inclusions diameters of >0.03 mm [1]. For smaller and thinner parts with a maximum thickness of up to ~100 mm optical grade inclusion quality for ZERODUR® can be achieved by precise selection. For large and thick ZERODUR® blanks (>800 mm in diameter and >100 mm in thickness) such a selection process is not applicable due to the low visibility of very small inclusions inside such a ZERODUR® blank. In this case the actual inclusion specification has to be fixed in close cooperation with the customer. In general for the selection of ZERODUR® based on optical quality bubbles and inclusion grades, it is mandatory to polish the inspection surfaces of the material, therefore optical grade bubbles and inclusions specifications are treated on special request only.

5. Literature

[1] SCHOTT Optical Glass Pocket Catalog
[2] SCHOTT Technical Information TIE-29 “Refractive index and dispersion”
[3] SCHOTT Technical Information TIE-35 “Transmittance of optical glass”
[4] SCHOTT Technical Information TIE-25 “Homogeneity of optical glass”
[5] SCHOTT Technical Information TIE-26 “Striae in optical glass”

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