

# TIE-43 Properties of ZERODUR®

## 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 ..... 1
- 2. Mechanical Properties ..... 3
- 3. Electrical Properties ..... 4
- 4. Optical Properties ..... 4
- 5. Literature ..... 12

## 1. Thermal Properties

|   |      |
|---|------|
| Thermal conductivity $\lambda$ at 20 °C [W/(m · K)]                   | 1.46 |
| Thermal diffusivity index $a$ at 20 °C [ $10^{-6}$ m <sup>2</sup> /s] | 0.72 |
| Specific heat capacity $c_p$ at 20 °C [J/(g · K)]                     | 0.80 |

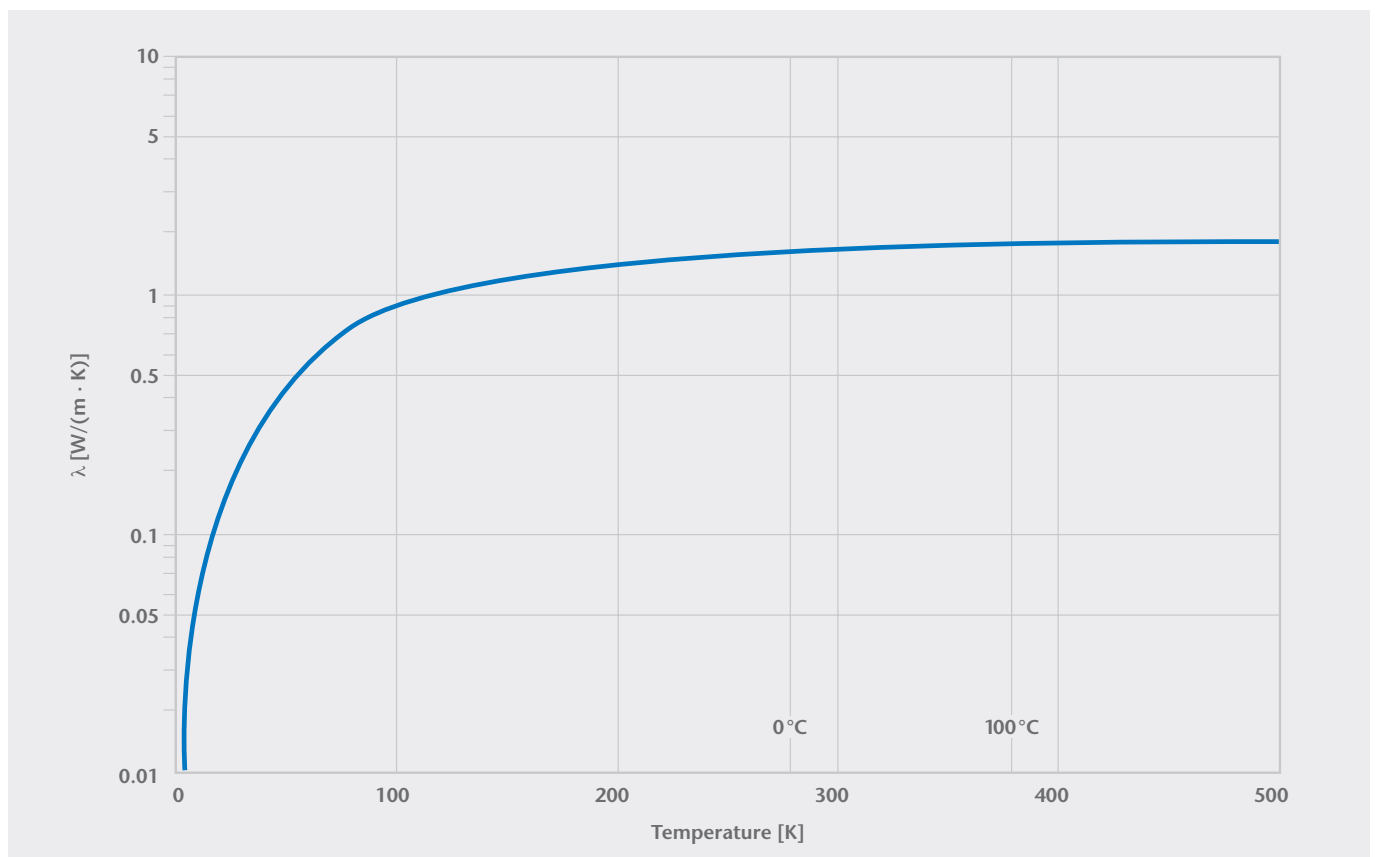


Fig. 1: Thermal conductivity of ZERODUR® as a function of temperature



## TIE-43 Properties of ZERODUR®

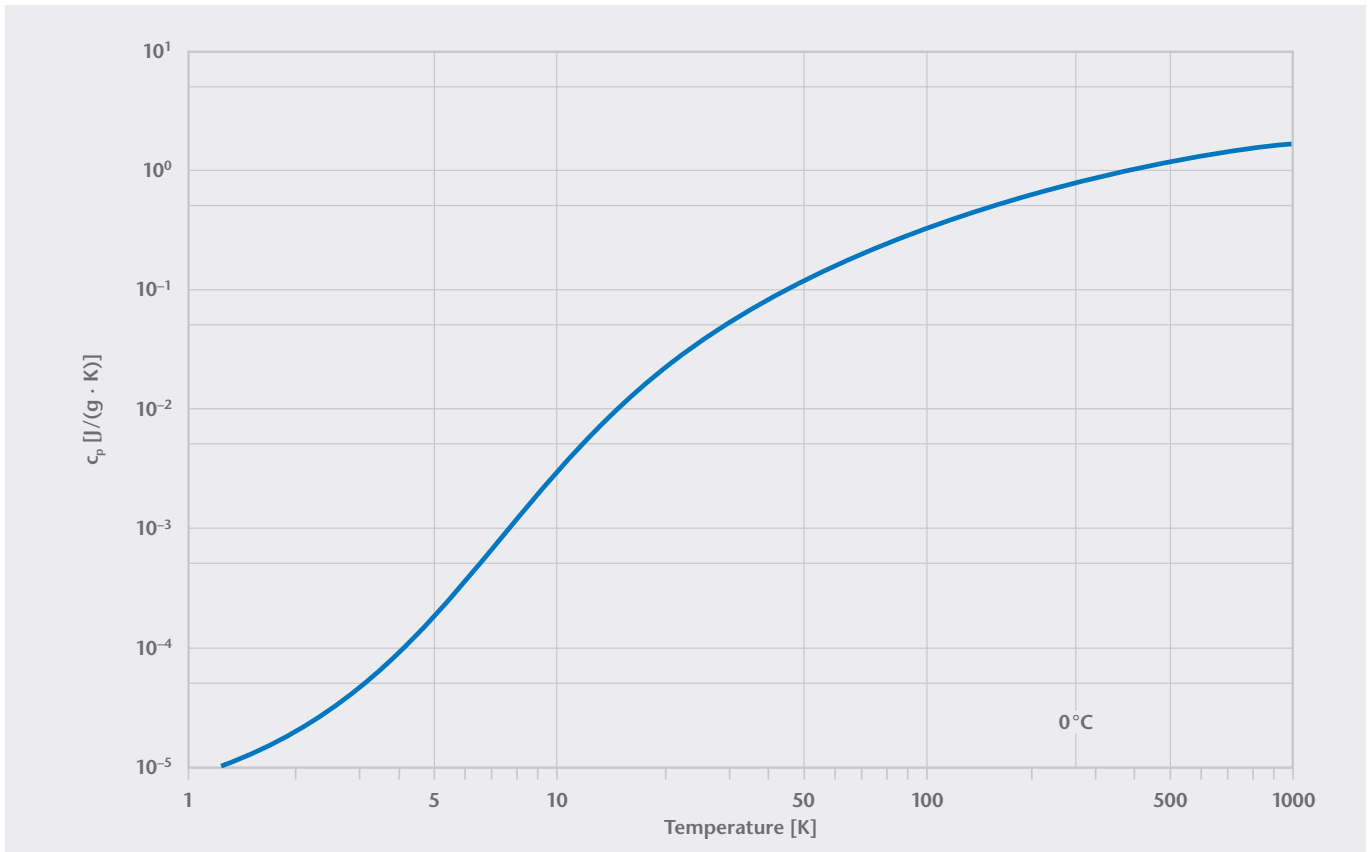


Fig. 2: Specific heat capacity of ZERODUR® as a function of temperature

[→](#) [←](#) | [Back to index](#)

## TIE-43 Properties of ZERODUR®

### 2. Mechanical Properties

|   |      |
|---|------|
| Young's modulus E at 20°C [GPa]-mean value  | 90.3 |
| Poisson number $\mu$                        | 0.24 |
| Density $\rho$ [g/cm <sup>3</sup> ]         | 2.53 |
| Knoop hardness HK 0.1/20 according ISO 9385 | 620  |

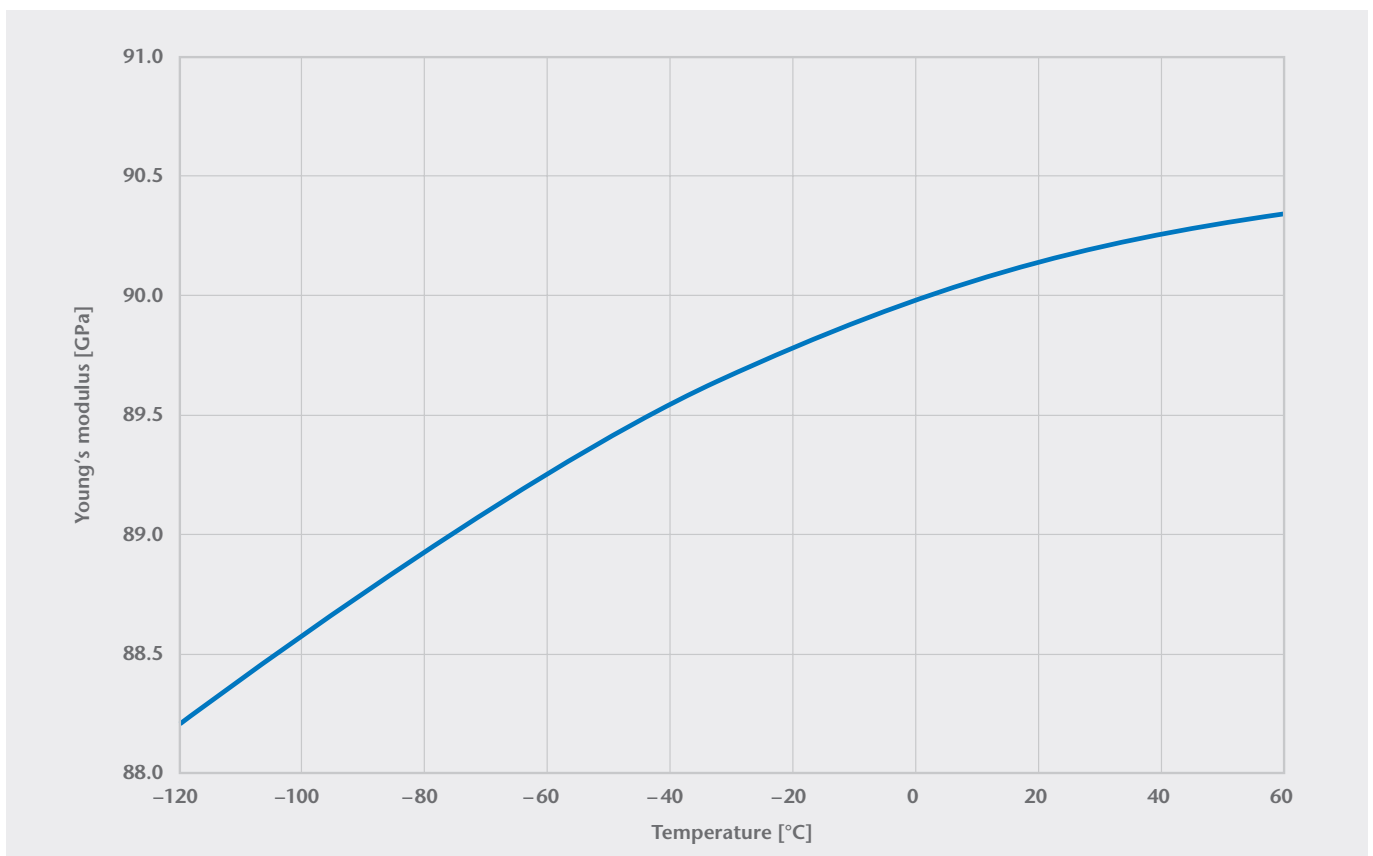


Fig. 3: Young's modulus of ZERODUR® as a function of temperature

→ ← | [Back to index](#)

## TIE-43 Properties of ZERODUR®

### 3. Electrical Properties

| Temperature [°C] | Specific Resistivity $\rho$ [ $\Omega$ 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              | $1.4 \cdot 10^3$                           |

Tab. 1: The specific electrical resistivity of ZERODUR® as a function of temperature

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

178

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

Tab. 2: Dielectric properties of ZERODUR®

### 4. Optical Properties



Fig. 4: 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.

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.

→ ← | [Back to index](#)

## TIE-43 Properties of ZERODUR®

### 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  $\pm 0.0005$ . 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                                    |

Tab. 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.

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

The coefficients of the representative melt are displayed in table 4.

|       | 1                    | 2                    | 3                 |
|-------|----------------------|----------------------|-------------------|
| $B_x$ | 1.3182408            | $2.44 \cdot 10^{-2}$ | 1.08915181        |
| $C_x$ | $8.79 \cdot 10^{-3}$ | $6.09 \cdot 10^{-2}$ | $1.10 \cdot 10^2$ |

Tab. 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.

→ ← | [Back to index](#)

## TIE-43 Properties of ZERODUR®

### 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  $\lambda$ , the temperature T and the air pressure p. There are two ways 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 air pressure  $p=0.10133$  MPa.

The absolute temperature coefficient  $\Delta n_{\text{absolut}}/\Delta T$  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<br>°C | $\Delta n_{\text{relativ}}/\Delta T$ [10 <sup>-6</sup> /K] |      |      |      |      | $\Delta n_{\text{absolut}}/\Delta T$ [10 <sup>-6</sup> /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 |

Tab. 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.

Figure 5 shows an internal transmittance curve of a 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 ZERODUR® sample of 0.6 mm thickness at wavelengths >2500 nm, displaying a residual transmittance between 3000 nm and 4000 nm which cannot be detected at larger material thicknesses.

→ ← | [Back to index](#)

## TIE-43 Properties of ZERODUR®

| 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                                     |

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

→ ← | [Back to index](#)

## TIE-43 Properties of ZERODUR®

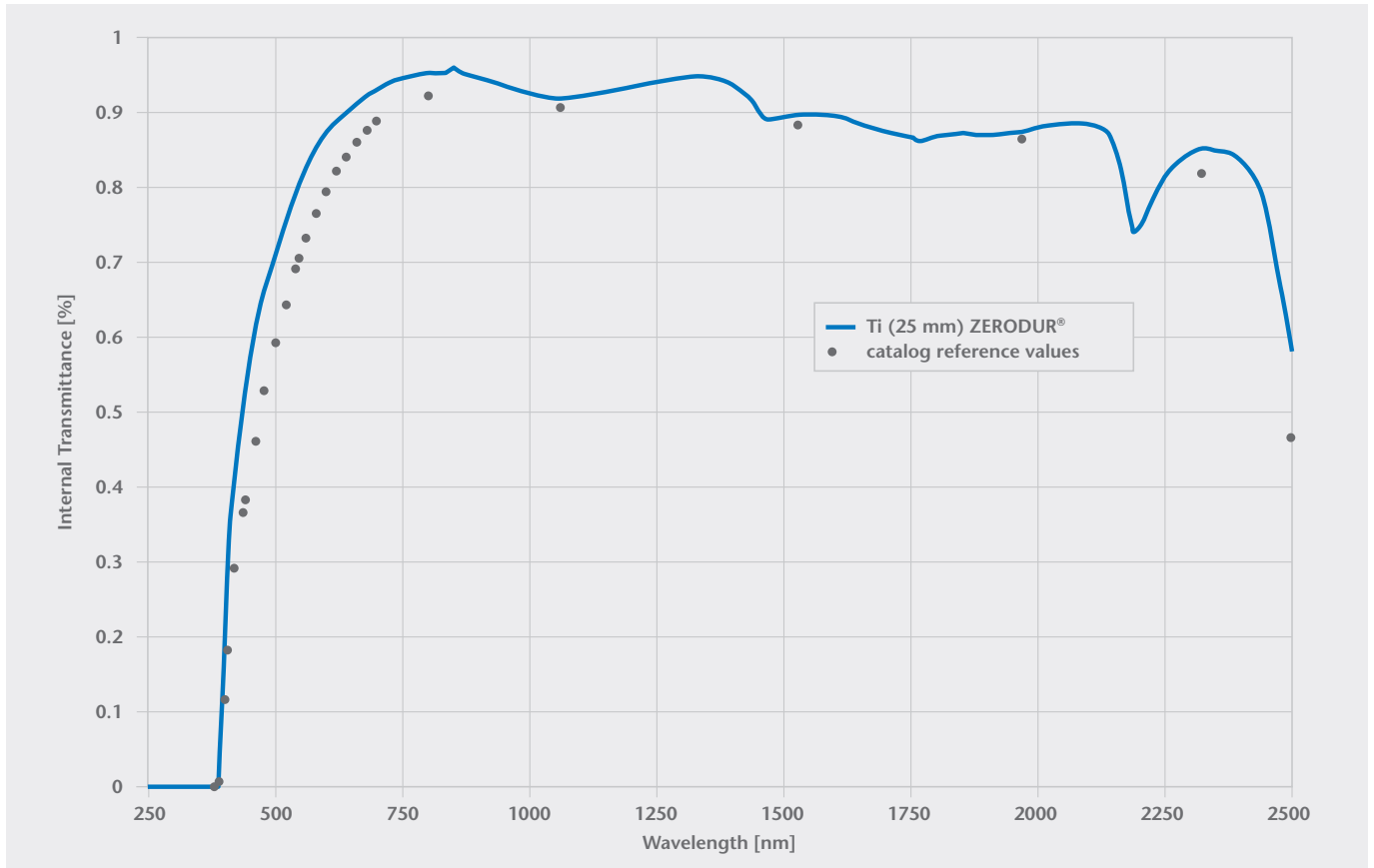


Fig. 5: Internal Transmittance curve of a ZERODUR® sample at 25 mm thickness compared to the catalog reference values

[→](#) [←](#) | [Back to index](#)



## TIE-43 Properties of ZERODUR®

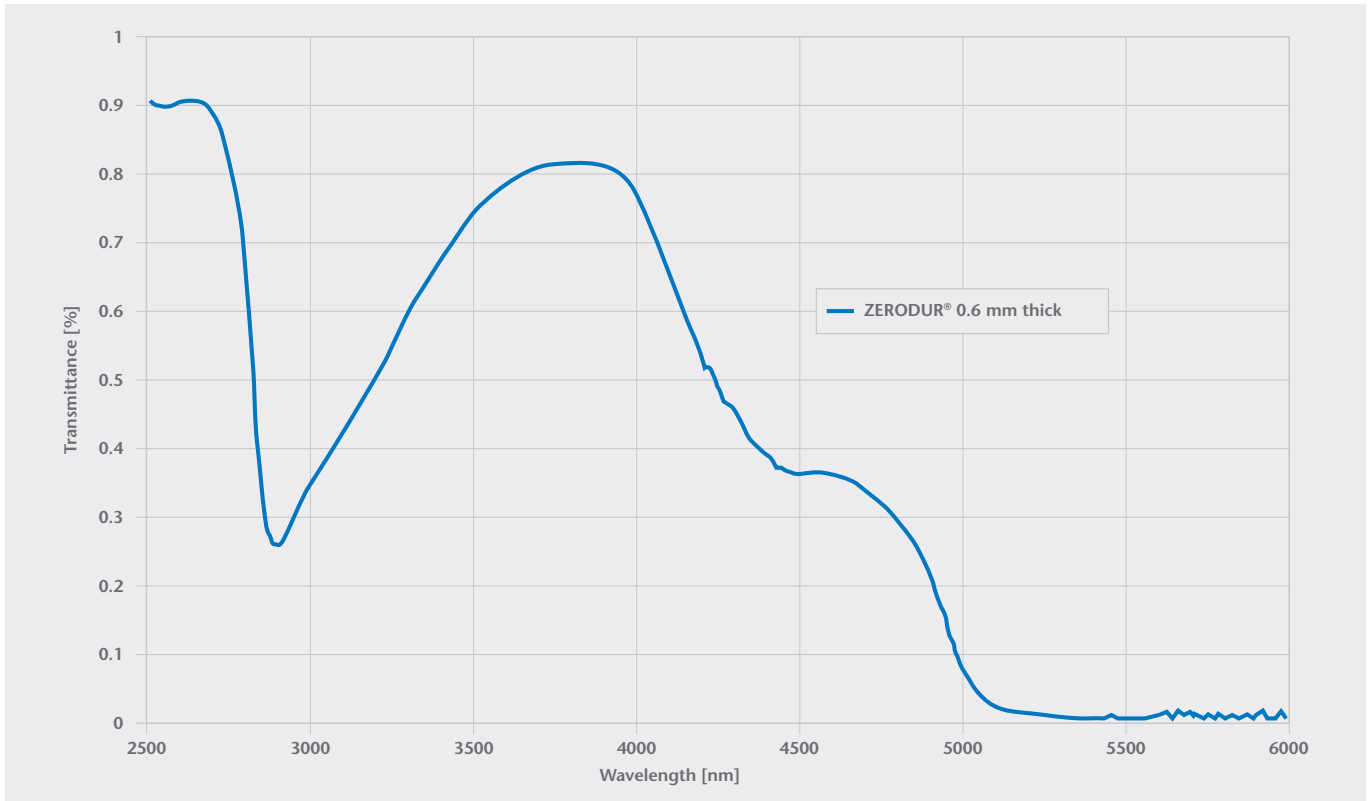


Fig. 6: Transmittance curve of ZERODUR® at 0.6 mm thickness

→ ← | [Back to index](#)

## TIE-43 Properties of ZERODUR®

### 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 <sub>90</sub> [10 <sup>-3</sup> /cm] |
|-----------------|--|
| 404.7           | 23                                     |
| 435.8           | 16                                     |
| 546.1           | 6                                      |
| 578.1           | 5                                      |

Tab. 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.



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

### 4.3 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].

#### 4.3.1 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 and ISO 12123 [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, ISO 12123) | 40 · 10 <sup>-6</sup> | 10 · 10 <sup>-6</sup> | 4 · 10 <sup>-6</sup> | 2 · 10 <sup>-6</sup> | 1 · 10 <sup>-6</sup> |

Tab. 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].

→ ← | [Back to index](#)

## TIE-43 Properties of ZERODUR®

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.

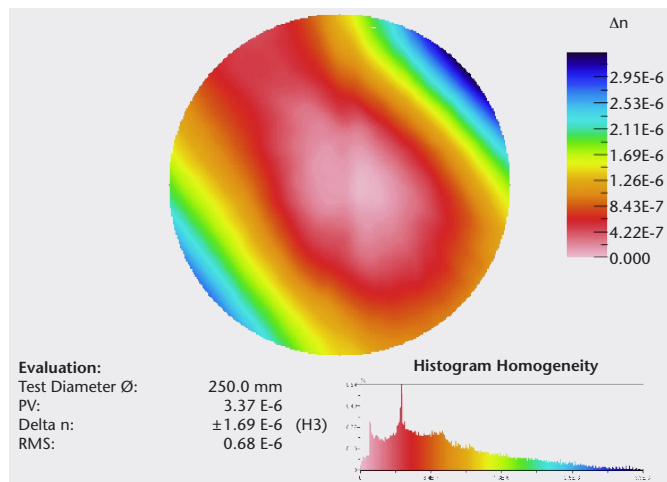


Fig. 8: Homogeneity map of a 250 mm diameter ZERODUR® disc

### 4.3.2 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.

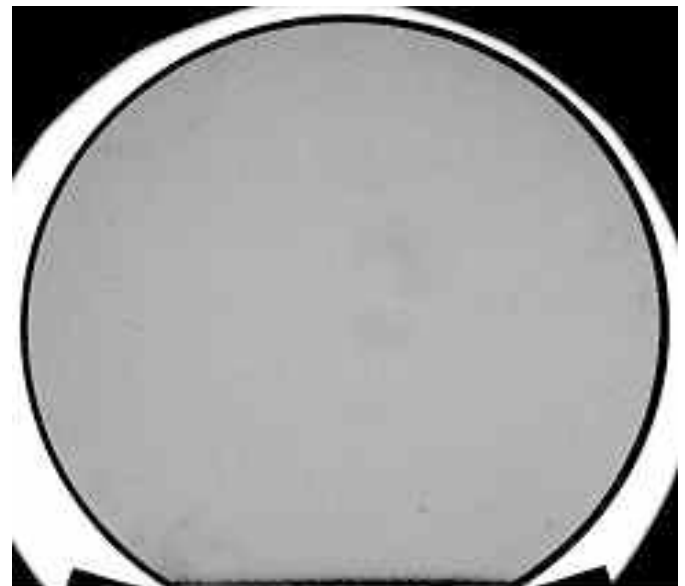


Fig. 9: Shadowgraph of a specially selected and produced 250 mm diameter ZERODUR® blank. No striae above 10 nm wavefront deviation are visible in this setup.

As indicated before, the achievable striae quality also strongly depends on the size of the blank and the selected part of a blank. Figure 4 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.

→ ← | [Back to index](#)

## TIE-43 Properties of ZERODUR®

### 4.4 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.

### 4.5 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"



Advanced Optics  
SCHOTT North America, Inc.  
400 York Avenue  
Duryea, PA 18642  
USA  
Phone +1 570/457-7485  
Fax +1 570/457-7330  
info.optics@us.schott.com

[www.us.schott.com/advanced\\_optics](http://www.us.schott.com/advanced_optics)

[←](#) | [Back to index](#)

**SCHOTT**  
glass made of ideas