February 24, 2021

SCHOTT ZERODUR® Glass-Ceramic

Advanced Glass-Ceramic Stands up to the Rigors of Space

Introduction

SCHOTT Academy of Optics is a free, online seminar series designed to take your industry knowledge and expertise to new levels.

Throughout the series, you will learn from leading glass and material experts as they cover various topics pertaining to the optics industry.

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High-tech mirrors and other optics are enabling advanced telescopes that help us see deeper into space and provide higher resolution images of the earth. Whether these telescopes are on earth or aboard satellites, their optics must exhibit exceptionable precision even when exposed to changes in temperature.

If the telescopes are designed for use aboard a satellite, these precision optics must also survive the high mechanical loads and vibrations experienced during a rocket launch. There are also strict size and weight limitations because it costs thousands of dollars to launch every kilogram of payload into space.

Achieving all these requirements with a single material may seem like a tall order, but SCHOTT's unique ZERODUR® glass-ceramic has been meeting the most demanding astronomy requirements for more than 50 years.

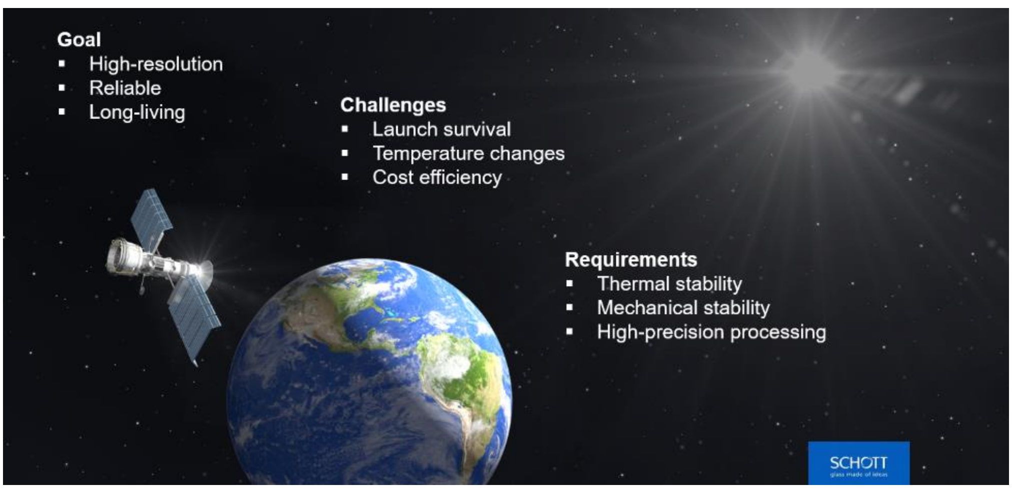


Figure 1: High-resolution optics in space need to be highly reliable but face challenges that require a high thermal and mechanical stability as well as high-precision processing.

1. Precision in extreme environments

ZERODUR® is a glass-ceramic with extremely low thermal expansion. Glass-ceramics consist of a crystalline phase that is embedded into a glass matrix. When exposed to a change in temperature, the crystalline and glass phases interplay in a way that prevents macroscopic expansion or contraction.

For ZERODUR® – which is made of lithium, aluminum and silicate – this equates to a near zero coefficient of thermal expansion (CTE) over a large temperature range.

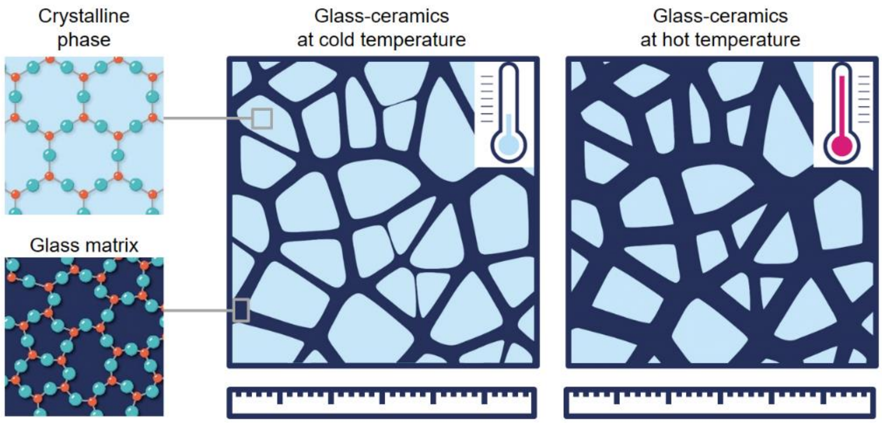


Figure 2: These schematics show the microscopic structure of a glass-ceramics composed of a crystalline phase (light blue) embedded in a glass matrix (dark blue). With changes in temperatures (indicated by the thermometer), the two phases expand and shrink in opposite directions resulting in almost no macroscopic expansion (indicated by the scale).

In addition, ZERODUR's thermomechanical properties show stability under gravitation and are robust against vibrations. We also have extensive data showing that we can achieve CTE homogeneity across the entire volume of a large component.

Over the years, ambitious astronomy projects have pushed ZERODUR® to its limits while also bringing about new technology developments for the material (see **Fehler! Verweisquelle konnte nicht gefunden werden.**). One of the first milestones came in 1968, when ZERODUR® was used to make a 4-meter mirror substrate for use in the Calar Alto Observatory in Spain.

In 1984, light-weighting was performed on ZERODUR® components used aboard the Meteosat series of geostationary meteorological satellites.

In 1996, an even larger mirror substrate of 8 meters was created for the Very Large Telescope in Chile. Just a few years later, we fabricated a special tube-shaped mirror substrate for the satellite-based Chandra X-ray Observatory.

In 2009, ZERODUR® with CTE tolerances of less than five parts per billion per K (ppb/K) was used in the ARIES telescope in India. Most recently, the glass-ceramic was used to make the largest convex mirror ever fabricated, which will be used in the Extremely Large Telescope under construction in Chile.

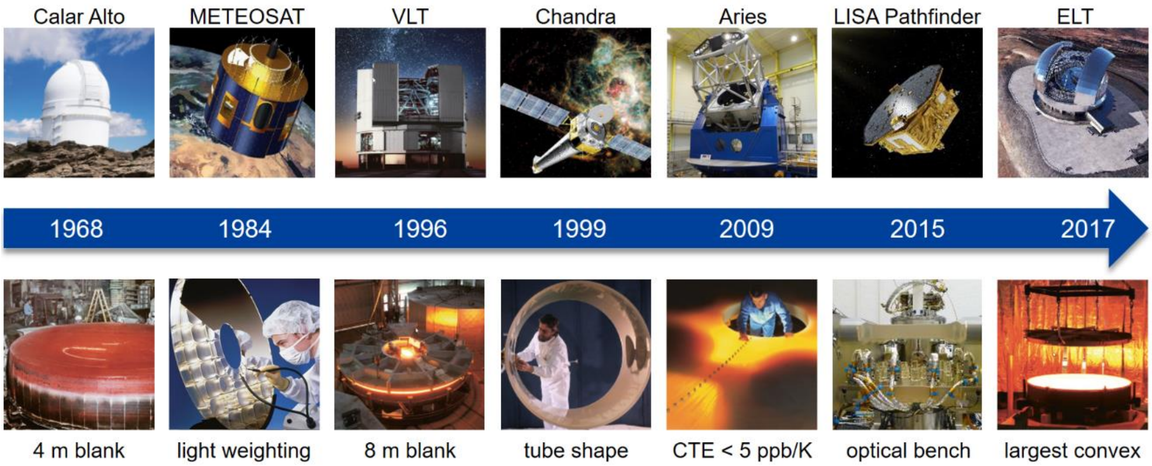


Figure 3: ZERODUR® development challenged by ambitious projects for astronomy and space applications.

2. Accuracy matters

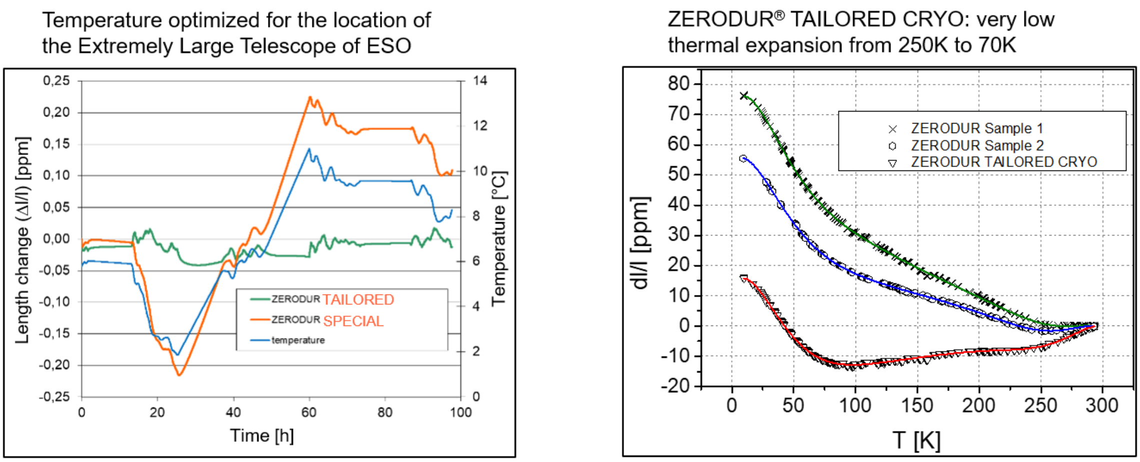
The five standard grades of ZERODUR® feature a CTE of near zero, defined for temperatures from 0°C to 50°C. The grades are distinguished by their CTE tolerances, which range from +/- 100 ppb/K for Class 2 all the way to +/- 7 ppb/K for Expansion Class 0 Extreme (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

For applications requiring specific temperatures, ZERODUR® is also available with a near-zero CTE that can be specifically tailored for an application-specific temperature profile. ZERODUR® TAILORED has a CTE that can be customized for specific temperature ranges experienced at a telescope site. This ZERODUR® variant was used to make the mirror blanks for the Extremely Large Telescope project.

ZERODUR® CTE Grades	$CTE_{(0°C,\ 50°C)}$
Expansion Class 2	± 100 ppb/K
Expansion Class 1	± 50 ppb/K
Expansion Class 0	± 20 ppb/K
Expansion Class 0 **SPECIAL**	± 10 ppb/K
Expansion Class 0 **EXTREME**	± 7 ppb/K
Expansion Class **TAILORED**	Optimized for application T-profile
	[illegible]d for low T [illegible]ons

Figure 4: Available ZERODUR® CTE grades

The ZERODUR® TAILORED CRYO variant has a CTE optimized for the lower temperatures experienced in laboratories or in space applications (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).



Jedamzik, Ralf,et al. "ZERODUR: progress in CTE characterization." UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VI. Vol. 8860. International Society for Optics and Photonics, 2013.

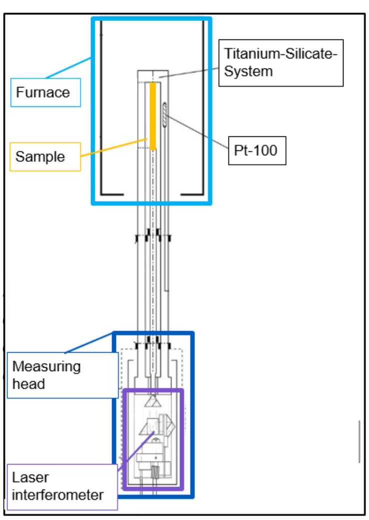
R. Jedamzik, T. Westerhoff, "ZERODUR TAILORED for cryogenic application," Proc. SPIE 9151, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, 91512P (18 July 2014);

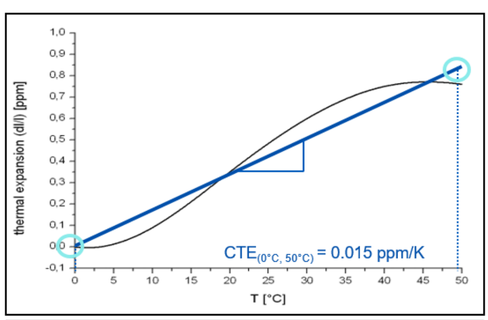
Figure 5: Examples of ZERODUR® TAILORED (left) optimized for the application temperature at the building site of the Extremely Large Telescope and TAILORED CRYO (right) optimized for very low temperature ranges.

Determining the thermal expansion, or the CTE, of a material like ZERODUR® requires a precision instrument known as a CTE dilatometer (see **Fehler! Verweisquelle konnte nicht gefunden werden.** left). This instrument measures how a material's dimensions change as a function of temperature.

To measure CTE, we usually start at room temperature and then heat the sample up to 50°C. After 20 minutes, the material expansion is read and then the sample is cooled in a controlled manner to 0°C. After another 20 minutes, we take another measurement and then repeat the temperature/measurement cycle.

Averaging the data points provides a mean value for each temperature. This, in turn, is used to create a line, the slope of which represents the CTE from 0°C to 50°C (see **Fehler! Verweisquelle konnte nicht gefunden werden.** top right).





$CTE_{(0°C, 50°C)}$	Accuracy [ppb/K]	Reproducibility (95%) [ppb/K]
Standard	± 10	± 5.0
Improved	± 6.2	± 1.2
Advanced	± 3.0	± 1.0
Advanced* II	± 1.0	± 0.5

We check the reproducibility of our CTE dilatometers weekly by acquiring measurements with a reference sample. For our Advanced Dilatometer, the CTE deviation from the mean within 280 days is just +/- 1.0 ppb/K within a confidence level of 95% and an absolute accuracy of +/- 3.0 ppb/K.

SCHOTT is constantly working to improve the accuracy of these measurements and will soon be operating an Advanced II Dilatometer with even better accuracy and reproducibility (see **Fehler! Verweisquelle konnte nicht gefunden werden.** bottom right).

3. Processing and light-weighting

A material with all the right properties for space applications will not do any good if it cannot be easily processed. Here too, ZERODUR® shines. The glass-ceramic can be easily processed into a wide variety shapes and structures with tight specifications. Mirror substrates, optical benches and laser cavities can all be made with dimensions ranging from 10 to 4250 mm (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

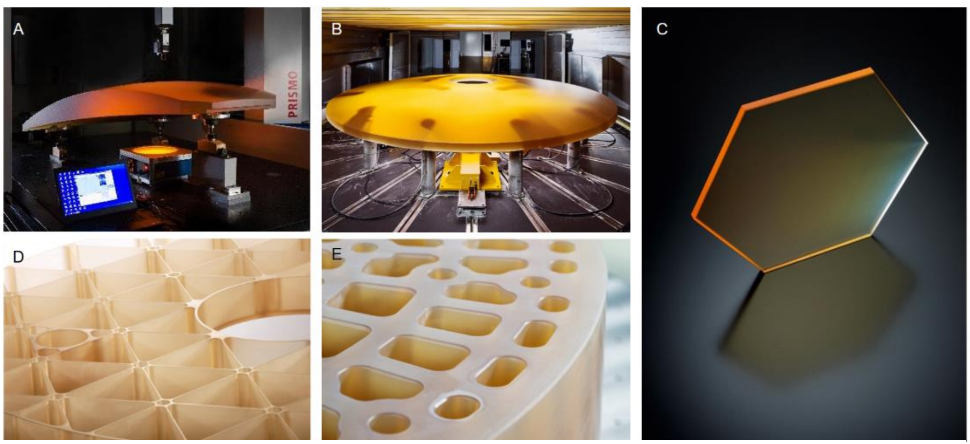
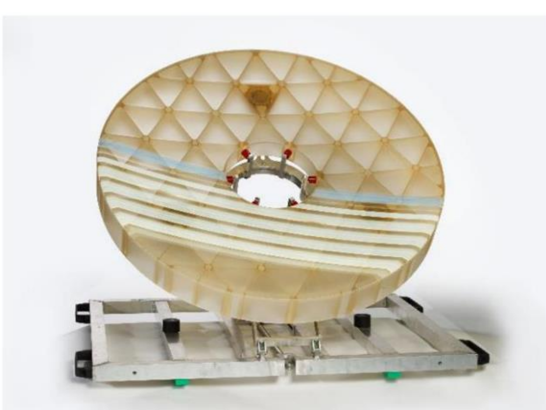


Figure 7: Various shapes such as free-forms (A), spherical mirrors (B), hexagons (C) and light-weighted structures (D,E) are available in dimensions up to 4.25 m.

Thanks to advanced CNC machining, pockets can be introduced into components to reduce mass by up to 90% while maintaining mechanical stability. This is critical for reducing the weight of payloads going into space (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).



Diameter:	1200 mm
Edge Thickness:	125 mm
Rib thickness:	2 mm
Light weighting factor:	88 %
Face sheet thickness:	8 mm
Weight:	45 kg
First Eigenfrequency:	> 200 Hz
Front figure tolerance:	< 15 µm

Passed thermal test confirming
NASA Technical Readiness Level (TRL) 6

Figure 8: ZERODUR® light-weighted mirror substrates ready to be launched in space.

High-precision metrology tools are critical to enabling very tight tolerances. In 2019, we opened a new manufacturing center that added 5000 meters squared of space in a temperature stabilized building that can hold up to 14 CNC machines. The center includes a dedicated temperature-controlled laboratory for a new 3D coordinate measurement machine that can measure pieces up to 5 x 6 x 2 meters in size with exceptional accuracies (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

Manufacturing Center since 2019

- Area ~ 5.000 m²
- T stabilization ± 1K
- Controlled environment: vibration, temperature
- Up to 14 CNC machines (< 4.5 m diameter)

Large 3D CMM ZEISS MMZ-G since 2020

- Room T stabilized to: max. 0.3 K/day
- Maximum measurement range: 5 m x 6 m x 2 m
- Archived accuracy: < 2.0 µm + L/2000 mm

Figure 9: Photos of the new manufacturing center dedicated to ZERODUR® processing (left) and new metrology equipment for blanks up to 4.5 m (right)

An example is the front figure tolerance of 30 microns that is achieved for mirror blanks up to 3000 mm in diameter (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

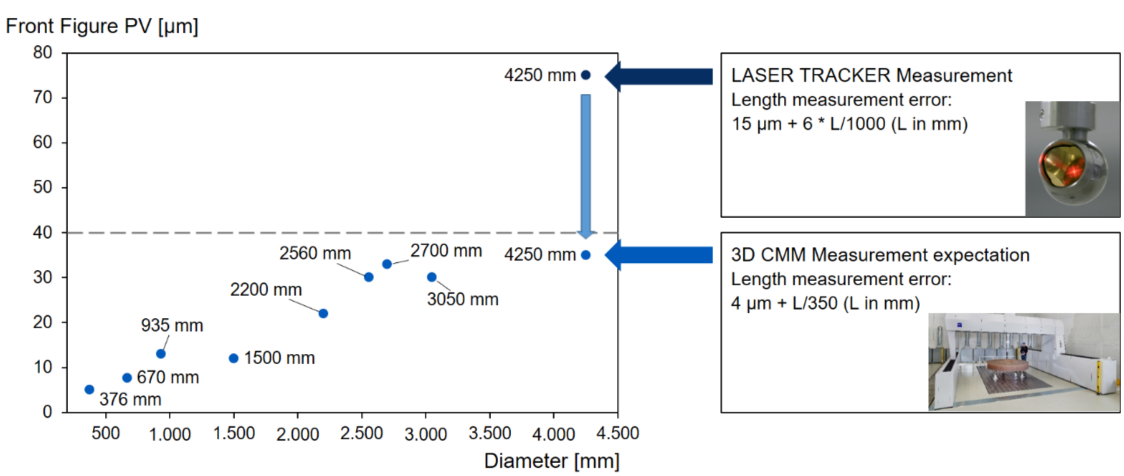


Figure 10: Achieved front figure tolerance peak-to-valley tolerance for several ZERODUR® blanks with diameters up to 4250 mm.

Want to learn more about ZERODUR®?

For more information and resources on ZERODUR® glass-ceramic, visit our website:

www.schott.com/products/zerodur.