

# **ZERODUR® Adhesive-Free Fusing Technology for Closed-Back Lightweight Mirror Substrates**

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## **ABSTRACT**

Lightweight mirror substrates that possess high dimensional stability and mechanical rigidity are crucial for advanced optical systems, particularly in astronomical and spaceborne contexts. SCHOTT AG has introduced an innovative ZERODUR® fusing technology, facilitating the fabrication of closed-back lightweight mirror substrates without the utilization of adhesives. This methodology enables the creation of ready-to-polish components while mitigating adhesive-related risks such as outgassing, creep, and differential thermal responses.

The fusing process integrates low mass, elevated stiffness, and superior thermal stability within a quasi-monolithic ZERODUR® framework. When compared to conventional open-back substrate designs, the fused closed-back variants demonstrate substantially enhanced bending stiffness at comparable weight. This advancement is realized by permanently attaching a back plate to the open-back lightweight structure via fusion, resulting in a homogeneous all-glass-ceramic assembly.

Supporting high lightweight ratios, this technology ensures material consistency by removing internal interfaces with disparate properties. Employing a single, well-proven material with a robust legacy in both flight and ground-based optics simplifies qualification and risk assessment processes for precision optical applications.

Successful demonstrations have been conducted on mirror substrates with diameters of 120 mm, 300 mm, and 480 mm. Notably, 480-mm-diameter mirrors achieved approximately 75 % lightweighting and a total mass near 5.1 kg. These substrates exhibited exceptional dimensional stability, absence of visible cracks, and fused areas exceeding 95 %. The first eigenfrequency surpasses 800 Hz, underscoring the high rigidity of the closed-back configuration.

Continued development efforts are geared toward scaling the technology for larger apertures. Results of a 950 mm diameter demonstrator are presented. An update is provided on the current status and plans to advance the Technical Readiness Level (TRL) through environmental testing, encompassing vibration and thermal-vacuum qualification. The fusing technology signifies a promising approach for manufacturing large, lightweight, and thermally stable mirror substrates for next generation optical instruments. The paper also explores the potential adoption of this technique for SCHOTT's new LAS glass ceramic under development, highlighting prospects for high precision applications.

## **1. INTRODUCTION**

Adhesive-free fusing is a SCHOTT technology for producing ZERODUR® structures that cannot be manufactured by CNC grinding alone. A key example is closed-back lightweight mirror substrates for astronomical applications. Adding a backplate to a CNC-machined lightweight core greatly increases stiffness and improves mechanical performance. Conventionally, the backplate is bonded with epoxy, which has several drawbacks. Its high coefficient of thermal expansion (CTE) and its mismatch with the CTE of ZERODUR® can introduce stress at the interface. Epoxies may also outgas, which restricts their use in space applications. In addition, epoxy can age or become embrittled under radiation, altering its elastic properties. The main advantage of SCHOTT's process is that it is completely adhesive-free. As a result, the final structure retains properties close to those of monolithic ZERODUR®. When the process is well controlled, the fused interface is nearly void-free and visually indistinguishable. Fused closed-back mirror substrates can also be post-processed without limitation.

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Closed back mirror substrates produced using this approach have several advantages:

- The technology enables lightweight structures with high mechanical stiffness.
- Adhesive-free closed back structures preserve the excellent CTE properties of ZERODUR®, ensuring high thermal stability.
- Very low stress birefringence further enhances thermal stability.
- Because no adhesives are used, there is no outgassing or adhesive-related degradation at the interface.
- The current process supports structures up to meter scale.

This paper is a continuation of the paper [1] and [2] and summarizes the status of the development.

## 2. CLOSED-BACK MIRROR SUBSTRATE MANUFACTURING PROCESS [1][2]

Adhesive-free closed-back lightweight mirrors are manufactured in several steps. First, a suitable raw ZERODUR® format is selected. Raw, or “glassy” ZERODUR® is coarsely annealed material after melting and hot forming, before ceramization and crystal formation. Parts are then cut from the glassy substrate to produce the CNC-machined lightweight core and the backplate to be fused. Figure 1 summarizes the process flow.

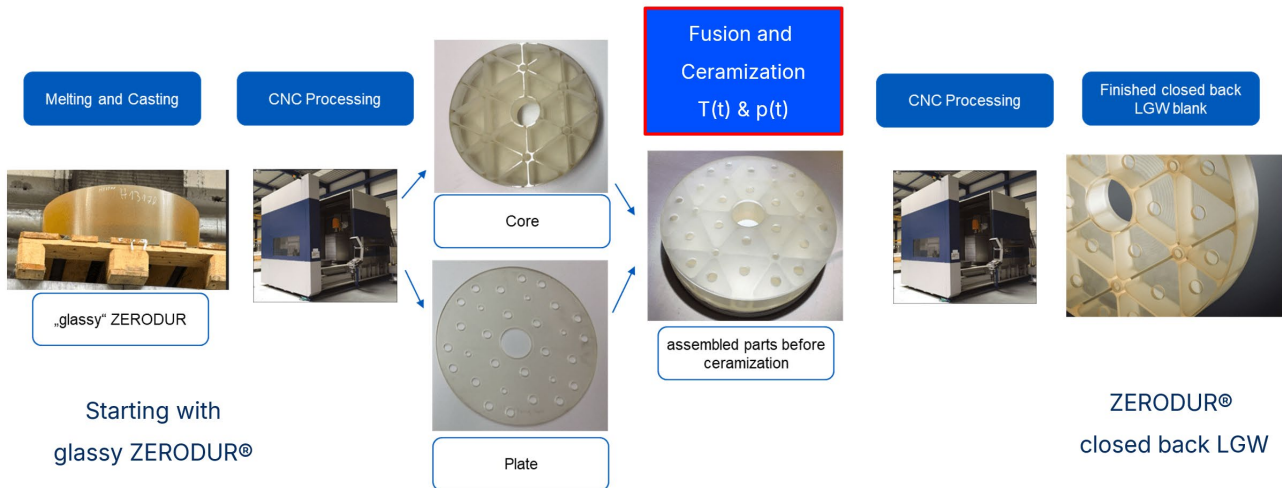


Figure 1: Schematic process flow of manufacturing closed-back lightweight-structured mirror substrates from ZERODUR® [1].

The rib surfaces on the backside of the CNC core are polished. The backplate is machined from a second, thicker plate and polished to the same quality. These polished surfaces form the fusing interface. To minimize dust contamination and ensure reliable fusing, both surfaces are thoroughly cleaned. The parts are then assembled and placed in a dedicated ceramization furnace setup.

Fusing and ceramization are performed in one furnace run using a geometry-specific, time-dependent temperature and pressure profile. The assembled sandwich is heated until the material reaches sufficiently low viscosity. Under controlled temperature and pressure, the contact surfaces slump, fuse, and close remaining geometric gaps. This viscosity range coincides with nucleation and crystal growth during ceramization. Crystal growth across the interface forms a quasi-monolithic bond. At the same time, the proprietary process limits thermomechanical stresses that could damage the parts, which is especially critical for large structures. SCHOTT’s detailed understanding of ZERODUR® ceramization, supported by modeling, enables suitable process parameters to be defined.

The fusing interface must be tightly controlled to maximize component strength. Voids and contaminants reduce strength and must therefore be minimized through careful processing and cleaning. The fusing setup, load uniformity, and temperature profile must be adapted to the part size and geometry. Component-specific design rules also affect process success and should be considered early. Recent hardware and process optimizations have achieved surface bonding above

95 %. Figure 2 shows electron microscopy images of the fusing interface: the left image shows an almost invisible interface, whereas the right image shows small interfacial voids [1].

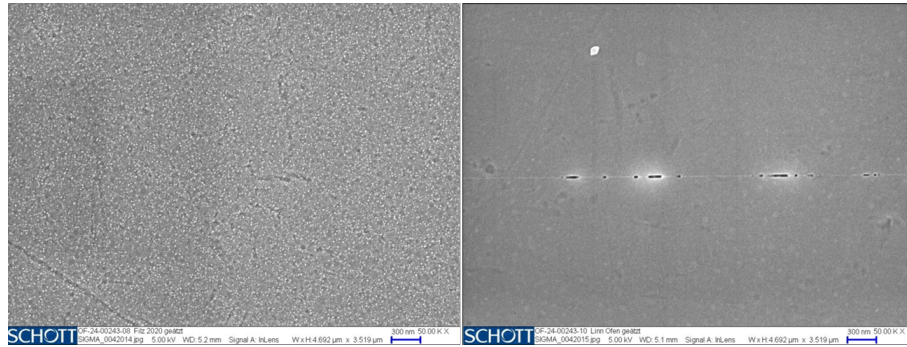


Figure 2: Electron microscope image of fused surfaces, left: no interface visible, right: example of rare interfaces with slight defects visible [2].

Glassy ZERODUR® can be acid-etched to remove subsurface damage and increase component strength. For the demonstrators described below, the lightweight core was acid-etched for this purpose. After fusing, all outer surfaces are CNC-ground to final specification.

### 3. 480 MM AND 950 MM DIAMETER DEMONSTRATORS [1]

All 480 mm demonstrators produced so far have hexagonal pockets with an inscribed circle of about 91 mm. The rib thickness is 2 mm or 4 mm, respectively. For mounting, at least three planar regions with a wall thickness of about 10 mm were included. The areal density is about 33 kg/m<sup>2</sup> with lightweighting ratios up to 78 %. Neither design has been optimized for minimum areal density but could be reduced below 30 kg/m<sup>2</sup>. All demonstrator cores were acid etched before fusing. After fusing, all outer surfaces were machined to their final dimensions to compensate for process-related geometric changes. The parameters of typical 480 mm demonstrators are summarized in table 1.

One of the 480 mm ZERODUR® mirror substrates has been supported by the ESA TB Germany through the ESA Spark Funding initiative. Figure 3 shows a representative example with 4 mm rib thickness.



Figure 3: 480 mm demonstrator with 4 mm rib thickness [1].

Table 1: Properties of 480 mm and 950 mm demonstrators with fused backplate

|                                | <b>480 mm Demonstrators</b> | <b>950 mm Demonstrator</b>                      |
|--------------------------------|-----------------------------|-------------------------------------------------|
| Diameter                       | 480 mm                      | 950 mm                                          |
| Edge Thickness                 | ~ 47 mm                     | 96 mm                                           |
| Center hole                    | ~ 100 mm                    | 130 mm                                          |
| Rib thickness                  | 2 or 4 mm                   | 2 mm                                            |
| Outer edge thickness           | ~ 6 mm                      | 6 mm                                            |
| Inner edge thickness           | ~ 3 or 6 mm                 | 6 mm                                            |
| Inscribed circle               | ~ 91 mm                     | 120 mm                                          |
| Face sheet thickness           | 5 mm                        | 8 mm                                            |
| Backplate thickness            | ~ 5 mm                      | 4.8 mm                                          |
| Radius of curvature            | ~ 1450 mm                   | 3108 mm<br>(~ 30 $\mu\text{m}$ shape tolerance) |
| Weight                         | < 6 kg                      | 32 kg                                           |
| Aerial weight                  | ~ 33 kg/m <sup>2</sup>      | 46 kg/m <sup>2</sup>                            |
| LGW ratio                      | ~ 75%                       | ~ 82%                                           |
| 1 <sup>st</sup> Eigenfrequency | up to ~ 945 Hz              | ~ 528 Hz                                        |

The fusing quality achieved is very high. Overall, more than 99 % of the fused area is void-free, representing a clear improvement over the smaller demonstrators produced a few years ago [1].

The largest demonstrator produced to date has a diameter of 950 mm and was completed in June 2026. Its overall thickness is about 99.5 mm, with a center hole diameter of 130 mm. A hexagonal pocket design with an inscribed circle diameter of about 120 mm was selected. The rib-thickness is 2 mm, the outer and inner edge thickness at the center hole is 6 mm thick.

The three mounting-pad connection areas each separated by 120° are 46 mm thick, substantially thicker than the 6 mm outer wall of the substrate. This design was selected for demonstration purposes; other configurations are possible. Each mounting pad has a 42.7 mm wide flat area.

The mirror surface has a radius of 3108 mm and was finished with a D64 diamond grinding tool. For the 8 mm face sheet, the radius-of-curvature shape tolerance is 30  $\mu\text{m}$ , well within typically achievable limits. Finer grain finishing tools can also be used. To achieve homogeneous face sheet thickness, the pocket-bottom curvature is approximated by stepped machining with an average step height of 0.1 to 0.2 mm.

The solid backplate contains 25 mm diameter venting holes and has a final thickness of 4.8 mm with a flatness of 10  $\mu\text{m}$ . It was finished with a D20 tool to obtain an opaque surface. Pocket cut-outs aligned with the mounting-pad geometry were machined into the backplate. These cut-outs are 6 mm deep and therefore extend 1 mm beyond the backplate thickness into the fusing area. This post-processing step did not compromise the integrity of the fused regions at these locations.

The finished mirror substrate weighs about 32 kg, corresponding to an areal density of 46 kg/m<sup>2</sup>. Its first eigenfrequency is 528 Hz. Further weight reduction is possible by decreasing the backplate thickness to 3 mm, the face sheet thickness to 5 mm, and the outer and inner edge thicknesses to 3 or 4 mm. The final achievable design is governed by the polishing

capability required to meet shape tolerances with low print-through over the large 120 mm inscribed-circle pockets, as well as by the thermomechanical mounting requirements needed for the intended application performance.

After completion of the fusing and ceramization step, the mirror is ready for post-processing. A complete view of the finished 950 mm demonstrator can be seen in Figure 4.

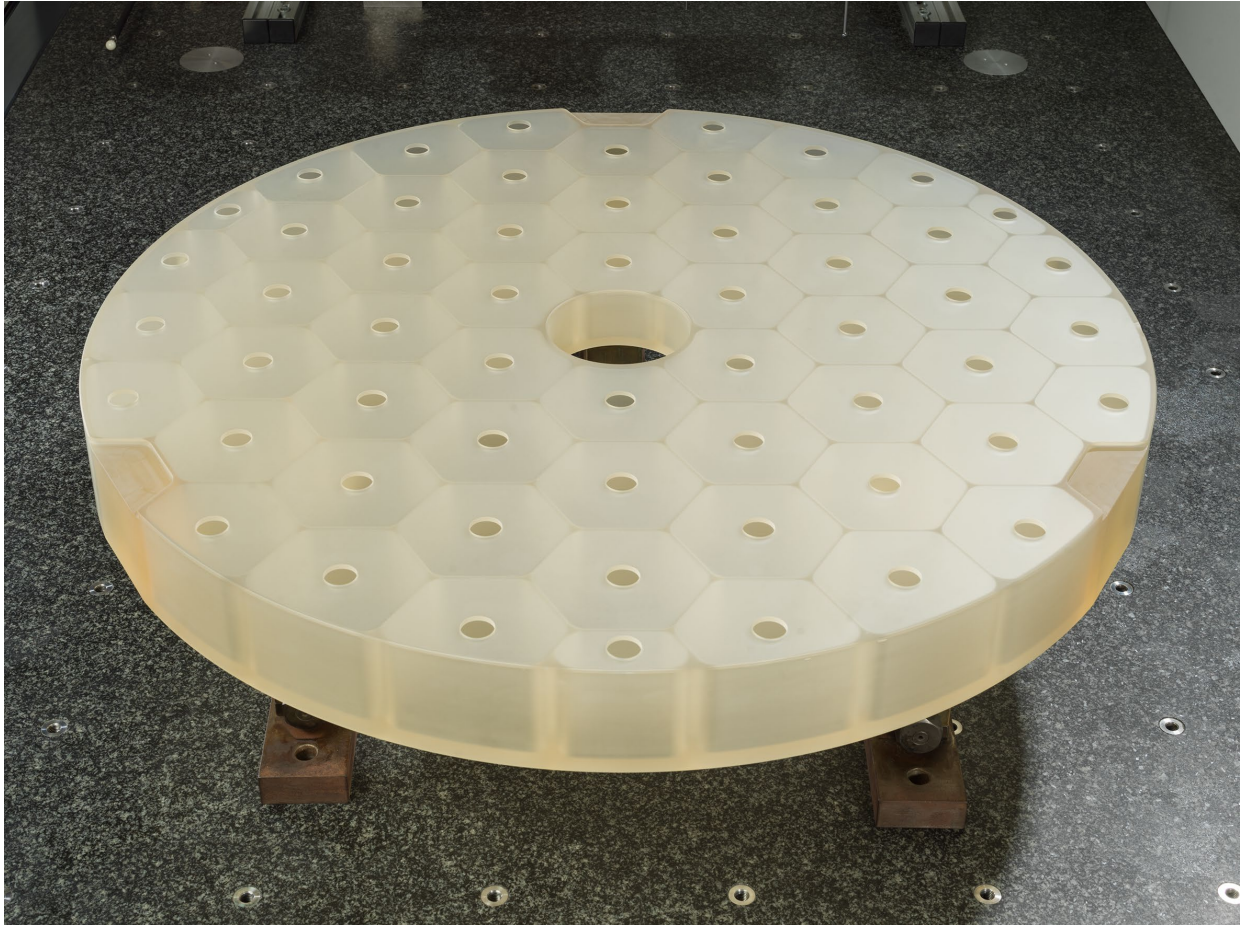


Figure 4: 950 mm Demonstrator backplate view on CMM during measurement [1].

The 950 mm demonstrator shows almost no macroscopic voids ( $\ll 1\%$  of the total area). Around the outer diameter some small single void areas are visible. The central area and the center-hole edge are free of macroscopic voids.

The fusing process has been optimized to achieve very low stress birefringence. Stress-birefringence measurement is a tool for verification of the process. The following measurements have been done after fusing and before finishing the mirror substrates. A maximum stress birefringence of about 6–7 nm/cm on the ribs of the 480 mm demonstrators have been measured. On the outer diameter of the 950 mm demonstrator the stress birefringence was even below 3 nm/cm. Details were presented in [1]. This is within the bulk stress birefringence limits for ZERODUR® parts of up to 1000 mm diameter according to the ZERODUR® catalogue.

#### 4. TENSILE STRENGTH ON RIBS

The previous paper reported shear strength results for two fused samples measuring 10 mm × 20 mm × 1 mm, which were post-processed into test specimens of 8 mm × 20 mm × 3 mm. The measured strength was high, with a threshold value of about 50 MPa in a three-parameter Weibull distribution [2]. Since then, the testing strategy has been revised to better represent closed-back mirror designs in which a backplate is bonded to polished rib surfaces. For this purpose, a new

sample design was defined in cooperation with Thales Alenia Space. Each sample consists of a 26 mm × 40 mm plate with a thickness of 4 mm. A 1 mm deep and 20 mm wide groove is machined into the plate to create a U-shaped geometry. The groove edges represent mirror ribs 3 mm wide and 40 mm long, resulting in a total contact area of about 240 mm<sup>2</sup>. The sample is fused to a slightly wider 30 mm × 40 mm base plate. Figure 5 shows a sample after fusing.



Figure 5: Tensile test sample with two fused 3 mm x 40 mm sized ribs.

Each sample was bonded between mechanically stiff carriers on both flat surfaces. The carriers were connected to the test machine using a fixture designed to compensate for shear motion. A total of 10 samples were prepared and tested on an Instron 5969 universal testing machine. This is a high-precision, servo-hydraulic platform for static and quasi-static mechanical property evaluation. The samples were pulled at a crosshead speed of 0.5 mm/min until fracture.

To interpret results from this more complex test geometry, stress distribution must first be considered. Although the sample fixation and test setup are designed to minimize stress inhomogeneity along the fused area, some non-uniformity is unavoidable because of the sample geometry and stiffness of the materials. Figure 6 shows the simulated stress distribution for an applied load of 1500 N. For infinitely stiff components, this load would generate a uniform stress of about 6.25 MPa over an area of 240 mm<sup>2</sup>. However, in the actual specimen, bending moments cause a non-uniform stress distribution. As shown in Figure 6, stress concentrations develop near the inner edges of each fused area. In this case, the local stress is about 1.6 times higher than the nominal value, reaching approximately 10 MPa. This effect should be taken into account when interpreting the test results.

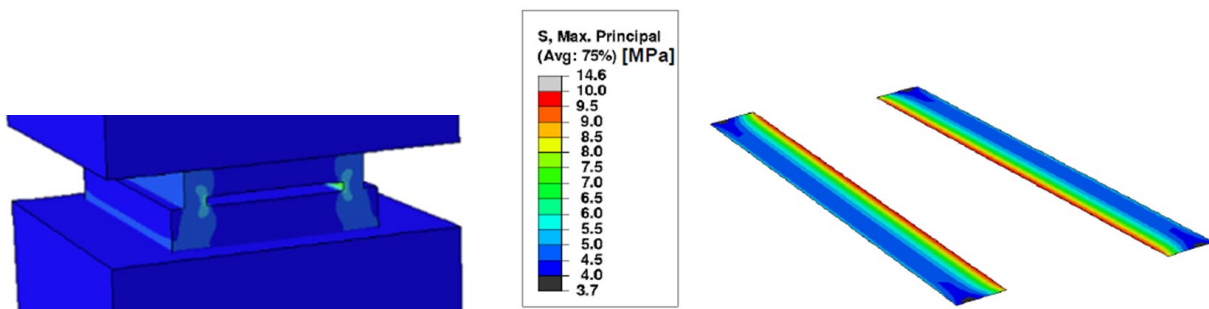


Figure 6: Finite Element Simulation of the load configuration (left) and the stress distribution on the fusing area (right).

The test results are shown in Figure 7. Measured strengths ranged from 9.01 to 10.94 MPa. A two-parameter Weibull fit yields a characteristic strength of 10 MPa and a shape parameter of 17.2, indicating low scatter. After correction based on the finite element simulation, the distribution shifts with values ranging from 14.4 to 17.5 MPa. The corresponding two-parameter Weibull fit gives a characteristic strength of 16 MPa with the same shape parameter. A three-parameter Weibull

analysis of the corrected data yields a threshold value of approximately 14.4 MPa for this test configuration. The concept of a three-parameter Weibull distribution enables to evaluate threshold-strength parameters from suitable distributions [3].

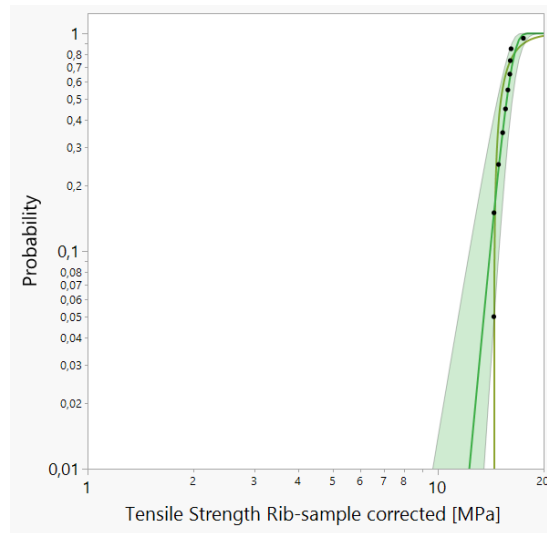


Figure 7: Weibull distribution of corrected tensile test data for the special rib sample geometry.

Examination of the fractured samples clearly shows that failure initiates at the inner rib edge near the bottom of the counterplate. Notably, the cracks do not propagate along the fusing interface but instead deviate from the fusing plane into the rib as shown in Figure 8.

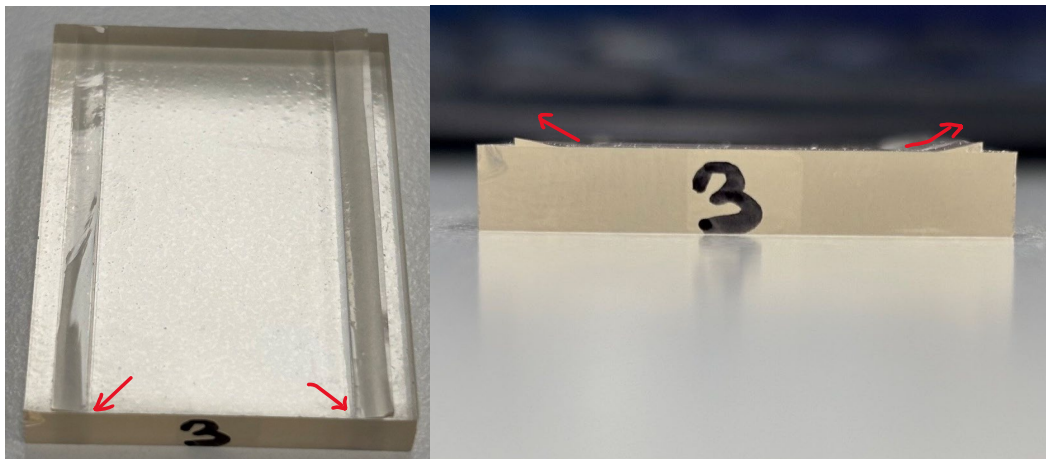


Figure 8: Sample bottom after test. Start of fracture at the inside of the connection between rib and cover plate. Fracture deflects into the rib not into the fusing seam as indicated by the red arrows.

## 5. PERFORMANCE TEST PLAN

One of the main targets of the ongoing work is to achieve a Technological Readiness Level (TRL) for the technology. To achieve this, SCHOTT is partnering with Thales Alenia Space to perform sine vibration testing on one 480 mm demonstrator and further demonstrate the technology readiness of the adhesive-free fusing process.

The mechanical test department at Thales Alenia Space in Cannes operates the electrodynamic shaker, which supports sine and random vibration testing from 5 Hz to 2000 Hz, as well as half-sine shock testing. With a broad range of tools and interfaces, the equipment can test specimens from a few kilograms to several tens of kilograms in both vertical and horizontal configurations. The shaker is controlled by a 128-channel LMS vibration-control and data-acquisition system,

enabling flexible control of acceleration amplitude and frequency spectrum. Numerous notching channels protect the test article by adapting the control parameters and preventing predefined tolerance limits from being exceeded.

The Ø 480 mm mirror substrate demonstrator will be tested in both out-of-plane and in-plane configurations. The campaign starts with a low-level frequency search from 5 Hz to 2000 Hz at 0.1 g to establish the initial dynamic response before higher load levels will be applied.

The sine load sequence is applied from 20 Hz to 50 Hz. Intermediate levels of 10 g and 20 g are each followed by a low-level frequency check. The qualification level of 30 g is then applied over the same frequency range, followed by a final low-level frequency check to identify any change in dynamic response. All sine runs use a sweep rate of 2 octaves per minute.

Accelerometers and strain gauges will monitor the structural response. One tri-axial accelerometer will be mounted on each mirror substrate support, and two uni-axial accelerometers will be attached to the mirror-substrate rim. One pilot accelerometer at the base of each support will control the input signal. Three strain gauges on the backplate will record local strain during vibration loading.

The test will be successful if all measurement channels are acquired and recorded, visual inspection shows no cracks, fractures, delamination, or other visible degradation, and the frequency shift between the initial search and subsequent checks remains below 5 %. In addition, no loosening or relative movement at the mounting interface shall occur, and all specified test levels must be completed without interruption or anomaly.

## **6. ADOPTION OF THE TECHNOLOGY TO NEW ZERODUR® FOR PICOMETER STABILITY [4]**

ZERODUR® has a long heritage as a mirror substrate and structural material for precision astronomy because of its ultra-low CTE, excellent CTE homogeneity, and demonstrated scalability to meter-class optics. However, future observatories require even higher up to picometer-range stability over long mission lifetimes.

Therefore, SCHOTT developed a new ZERODUR® composition that preserves the established advantages of conventional ZERODUR® but significantly improving the temperature application range and the stability over time.

The CTE of the new ZERODUR® composition remains within approximately  $\pm 10$  ppb/K over a wide temperature range from about 15°C to 90°C. This reduces sensitivity to operating temperature, thermal gradients, and thermal transients, providing larger margins during launch, commissioning, and science operation (figure 9).

A further advantage is the significantly reduced sensitivity to thermal loads encountered during the manufacturing and integration of precision optical components. Typical examples include localized heating during polishing, ion beam figuring, coating deposition, and related processing steps. The new ZERODUR® grade exhibits no measurable CTE change following thermal exposure up to 200°C, while maintaining only a small response at higher temperatures. Consequently, process-related uncertainties are minimized, leading to improved manufacturing robustness and reproducibility for large-aperture precision optics.

The new ZERODUR® composition retains this manufacturing heritage while adding the improved ultra-stability properties required for future missions. The material has already been produced in our large industrial-scale melting tanks. More information can be found in [4].

Currently the adhesive free closed-back fusing technology is also applied to the new ZERODUR® composition.

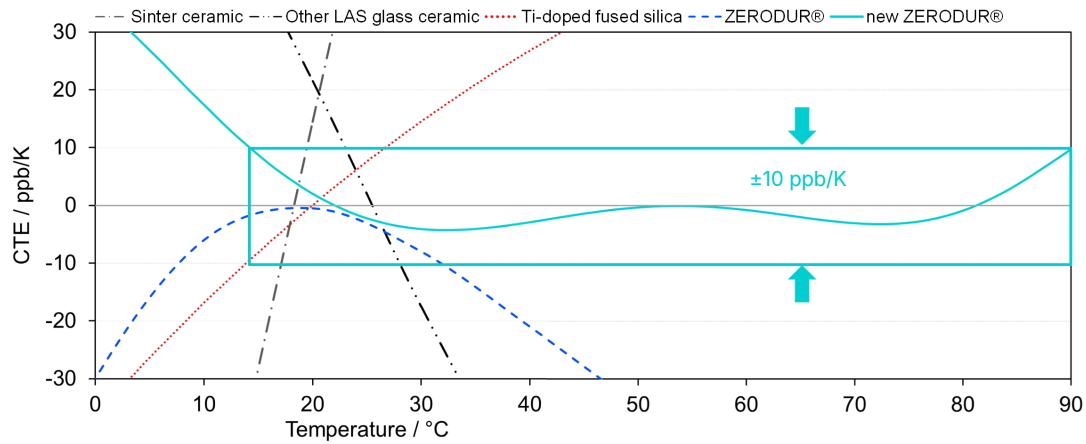


Figure 9: New ZERODUR® composition application temperature range from 15°C to 90°C with CTE smaller  $\pm 10$  ppb/K in comparison to other low thermal expansion materials [4].

## 7. SUMMARY

SCHOTT has demonstrated the reproducible manufacturing of adhesive-free fused closed-back mirror substrates in the 480 mm diameter class. The largest demonstrator manufactured to date has a diameter of 950 mm. This technology enables the realization of closed-back ZERODUR® mirror designs without the thermomechanical limitations associated with adhesive bonding.

As with any emerging technology, further maturation is required, particularly regarding space applications. In this context, achieving an appropriate Technology Readiness Level is essential. The current generation of 480 mm closed-back mirror substrates is scheduled to undergo shaker testing with Thales Alenia Space. The test campaign will include sine-vibration loads over a broad frequency range and at elevated g levels.

## 8. ACKNOWLEDGEMENT

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## 9. REFERENCES

- [1] R. Jedamzik, M. Kurz, C. Kunisch, H. Esemann, C. Stolz, V. A. Amasifuen, Axel Ohlinger, Janina Krieg: "Progress and upscaling of adhesive-free fused closed back ZERODUR light weight structures", SPIE Proc. 14145 (2026)
- [2] R. Jedamzik, M. Kurz, C. Kunisch, H. Esemann, C. Stolz, V. A. Amasifuen, T. Westerhoff: "Closed back lightweight ZERODUR® mirrors with adhesive-free fusing", SPIE Proc. 13624 (2025)
- [3] P. Hartmann: "Minimum Lifetime of ZERODUR® structures based on the breakage stress threshold model: a review", Optical Engineering, Vol. 58, Issue 2, 020902 (2019)
- [4] F. Kanal, R. Jedamzik, I. Mitra, C. Kunisch, M. Kurz, A. Carre, J. Krieg: „Progress on a new ZERODUR composition for picometer-stability requirements in astronomy", SPIE Proc. 14154 (2026)