

# **ZERODUR<sup>®</sup> heritage solutions and new paradigms for high-performance spaceborne mirror substates, small to large**

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## **ABSTRACT**

Introduced nearly 6 decades ago with extensive use in space, ZERODUR<sup>®</sup> has defined the mirror substrate standard for minimal passive response to thermal transients common in most spaceborne missions. ZERODUR<sup>®</sup>'s first- and second-order thermal characteristics are unmatched for dimensional stability, especially when operating in the domain of room temperature  $\pm 30^\circ\text{C}$ , and even for many colder applications. Evidence-based design is possible referencing SCHOTT comprehensive published data on all material characteristics including strength and radiation compaction resilience. We summarize several key characteristics of ZERODUR<sup>®</sup> in the context of those of other materials, then describe recent SCHOTT advancements in lightweighting appropriate for each mirror size, including backside-shaping for small telescopes, isogrid open-back lightweighting for intermediate sizes and for larger mirrors and highest eigenfrequency, now fused closed-back mirror architecture. ZERODUR<sup>®</sup> mirrors and structures are presently available from monolithic, extremely homogeneous blanks in sizes up to 4 meters plus in diameter. We discuss SCHOTT aspheric generation, tailoring of CTE(T), structures of ZERODUR<sup>®</sup> and other attributes consistent with Design-to-Cost in production programs.

**Keywords:** ZERODUR<sup>®</sup>, first- and second-order material characteristics, thermal transient resilience, eigenfrequencies, mirror lightweighting options, fused closed-back development, mirror design-to-cost methods.

## **1. INTRODUCTION**

ZERODUR<sup>®</sup> is both a heritage material for advanced spaceborne telescopes, and the subject of approximately 100 papers on studies of the material recognizing the evolving requirements of upcoming space missions [1,2]. As new requirements are being considered, the mission architect can rely on evidence supporting evaluation virtually all aspects of production of mirror substrates to address these requirements. Evidence-Based Design is a feature of ZERODUR<sup>®</sup> both in comparison to other materials, and optimum use of ZERODUR<sup>®</sup> for the mission requirement. For many of the evolving space mirror and structure requirements, whether a mirror or structure is 10cm in size, or 4m in size, ZERODUR<sup>®</sup> offers a passive design deterministic approach to simplest, most cost-effective and highest optical performing reflective optical assembly.

Over the last two decades, SCHOTT production advances for ZERODUR<sup>®</sup> include

1. ZERODUR<sup>®</sup> is monolithic: Mirrors up to 4m in diameter can be made from a single homogeneous boule [3].
2. Aggressive lightweighting of mirrors and structures compatible with launch mass budgets
3. Appropriate lightweighting of mirror blanks and structures compatible with mirrors that are small, intermediate or large yielding sufficient eigenfrequencies that will survive launch loads and minimize response to on-board stimuli [4].
4. Comprehensive published studies on blank preparation [5,6] compatible with optimal strength and lifetime
5. Tailoring of the Coefficient of Thermal Expansion and its dependence on temperature (CTE(T)) to optimally address environmentally induced temperatures and thermal transients [7]
6. High precision defining radiation compaction response due to solar and cosmic  $\alpha$ ,  $\beta$  and  $\gamma$  irradiation. These results are consistent with the absence of any known flight change in ZERODUR<sup>®</sup>'s dimensions [8,9]
7. Evolving offerings in fused closed back ZERODUR<sup>®</sup> mirrors offering highest eigenfrequency on intermediate to large spaceborne mirrors. [10]
8. SCHOTT has demonstrated ability to satisfy stable supply chain requirements even for large mirrors. SCHOTT recently provided 949 ZERODUR<sup>®</sup> mirror blanks, each 1.5m in diameter, for the European Extremely Large

Telescope. This was accomplished on time, meeting all requirements, and without disruption of requirements of other customers [11].

9. Deterministic precision aspheric generation in machining of mirror optical surfaces (with datums) significantly shortening optical fabrication time and minimizing large-tool induced sub-structure print through inducing Mid-Spatial Frequency (MSF) surface errors, typically 4 to 40 cycles per aperture. Such MSF frequency errors may substantially affect image contrast [12].

## 2. COMPARISON OF THERMAL/STRUCTURAL/OPTICAL CHARACTERISTICS BETWEEN MATERIALS

Ashby has identified a useful method to do initial assessment of material selection [13,14]. “Material properties limit performance. But it is seldom that the performance of a component depends on just one property. Almost always it is a combination (or several combinations) of properties that matter.” In the case of selecting optimum performance of a spaceborne mirror, it is common to consider a) how the material influences resulting first eigenfrequency  $f_0$  and dimensional stability under infliction of thermal transients, or Thermal Transient Resilience. In turn,

$$f_0 \sim \sqrt{(E/\rho)} \text{ where } E \text{ is Young's Modulus and } \rho \text{ is density}$$

$$\text{Thermal Transient Resilience} = (\text{Thermal Diffusivity})/\text{CTE}$$

and

$$\text{Thermal Diffusivity} = \text{Thermal Conductivity}/(\rho * c_p)$$

Thus, critical first order structural and thermal material characteristics that will affect the passive response of the system to dynamic and thermal perturbations is collected in these properties. Figure 1 considers this collection of factors together.

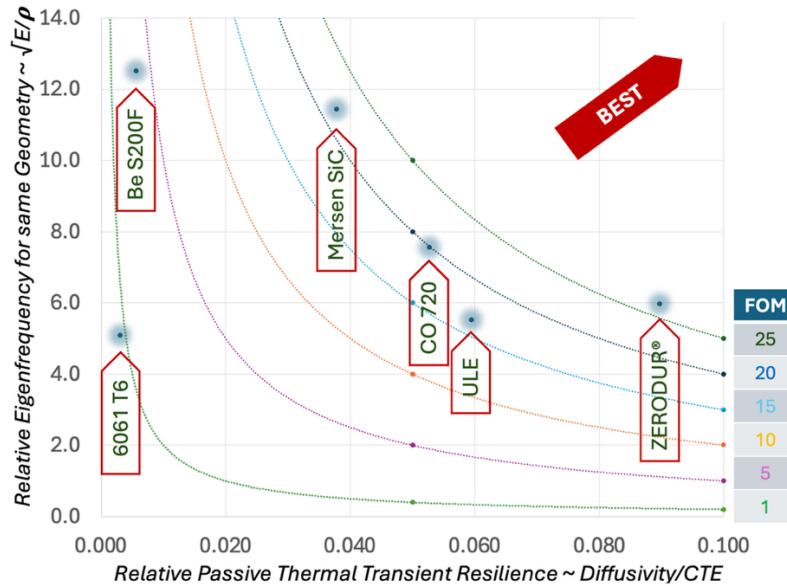


Figure 1. Figure of Merit (FOM) contours equally weight eigenfrequency and thermal-transient resilience, both factors for optical stability and thus performance. No known material occupies the ideal upper-right domain. ZERODUR® occupies the highest contour; while Mersen SiC (SiC 100), a ceramic, falls on the contour down just one level. However, often these parameters are not equally weighted. For example, eigenfrequency may be most important in launch, while addressing thermal transients may be key throughout the orbital lifetime of the mission.

In most thermal analysis codes, CTE is treated as a simple constant. Though in reality, for all materials including SiC 100 and ZERODUR®, CTE is a function of Temperature and the variation from constant may be as important as the CTE and Diffusivity values. The resulting strain therefore is

$$\Delta L/L = T * CTE(T) \quad (1)$$

And if there is a temperature gradient, temperature is a function of position in the material  $x_i$  where the subscript “i” is cartesian tensor notation for position in the material. Thus,

$$\Delta L/L = T(x_i) * CTE(T(x_i)) \quad (2)$$

Furthermore, if the material exhibits inhomogeneity, CTE also depends on the position in the material element.

$$\Delta L/L = T(x_i) * CTE(T(x_i), x_i) \quad (3)$$

ZERODUR®, with superior polishing attributes, is used unclad while SiC is generally clad with another formulation of SiC, presenting a bimetallic like response. ZERODUR®, even in largest sizes (presently 4.3m in diameter) can be made from an extremely homogeneous single melt of material and thus yields the highest homogeneity [15]. Large examples of SiC 100 mirrors (for example the 3.5m diameter Herschel primary) is brazed together from many pieces of material and thus expected to have a reduction in homogeneity due to this being a multi-piece assembly. CTE(T) and CTE(T,x) are second order properties that if not managed, may considerably reduce the dimensional stability and thus performance of a spaceborne telescope experiencing variable solar heating due to orbit and Concept of Operations (CONOPS).

While Figure 1 expresses that ZERODUR®’s response to a thermal transient is expected to be on average 2.5 times better than that of SiC 100 to a thermal transient, additional effects happen due not only the great difference of CTE between these materials, but also due to the slope. Figure 2 displays that difference.

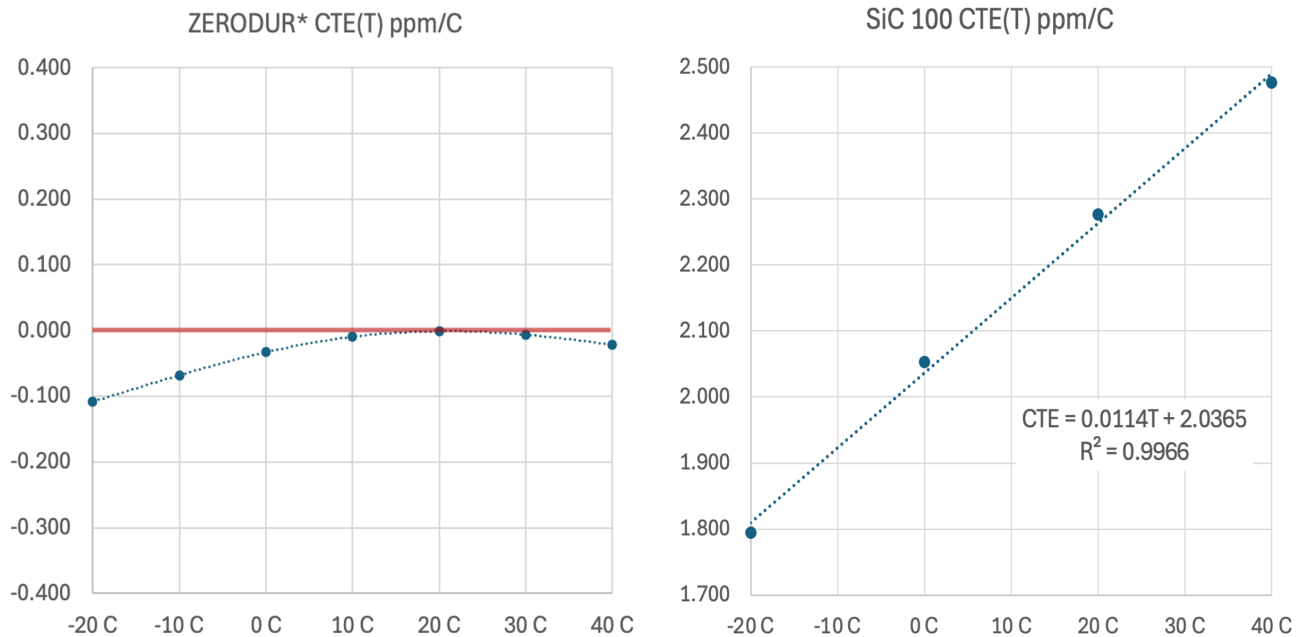


Figure 2. Both charts use the same ordinate and abscissa ranges yet express the difference in both the typical CTE(T) range of each material, and the slope that can magnify the effect of transient induced gradients on the optical stability of an optical system. \*Note that for ZERODUR®, CTE(T) can be tailored to be optimum for operating conditions. The CTE(T) of this example of ZERODUR® is intentionally extremely flat and near zero over an operating range around Room Temperature of 10C to 30C. In this range, the average ZERODUR® CTE = -0.006 ppm/C, while SiC 100 is 2.2ppm/C, of the order of 4000 times larger.

The large value of SiC 100's CTE around room temperature is mitigated by large value of SiC 100's thermal diffusivity, a measure of how efficiently (quickly) thermal transients can dissolve the resulting gradients. Systemic isothermal changes have very little effect on the overall thermal influence on performance. However, as expressed in Figure 1, SiC 100's thermal diffusivity is insufficient to overcome the massively larger CTE of SiC compared to that of ZERODUR®. Thus, around room temperatures, ZERODUR® is clearly preferred to SiC 100 based on thermal transient resilience. The added influence of the slope of the CTE curve will be discussed in Section 3.

In Table 1, we summarize additional material attributes that that a spaceborne telescope or optical system architect will want to consider in selecting materials.

Table 1. Comparison of additional characteristics of ZERODUR® and SiC 100 for spaceborne mirror consideration

| Characteristic                                                              | ZERODUR®                                                                                                                                                                                                                                                                                                                                                   | SiC 100 [16]                                                                               | Favored Solution |
|-----------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|------------------|
| Satisfactory Optical Surface for wavelengths < 1µm                          | YES: Superior                                                                                                                                                                                                                                                                                                                                              | NO: High scatter unless a cladding layer of different material is added.                   | ZERODUR®         |
| Cladding & bi-material bending (undesirable)                                | NO: Unnecessary...ZERODUR® can be                                                                                                                                                                                                                                                                                                                          | YES: CVD SiC not perfect CTE match to SiC 100                                              | ZERODUR®         |
| Single Boule Homogeneity at sizes > 1.5m                                    | YES: Monolithic boules presently available in Diameters up to 4.3m [17]<br><i>Closed-Back fused from Open-Back Cellular Mirror + Back Sheet (2 pieces)</i><br><i>Potential for Closed-Back from Facesheet + Core + Backsheet (3 pieces)</i>                                                                                                                | NO: 1.5m & Larger mirrors joined from multiple pieces. <i>EUCLID (1.25m) is a monolith</i> | ZERODUR®         |
| Constructed Mirror by multi-boule edge-bonding                              | Multiple pieces unnecessary for Open Back. One or two additional pieces (from same boule) needed for fused closed back sandwich                                                                                                                                                                                                                            | YES: 3.5m Herschel mirror edge brazed 12 pieces of SiC, acceptable since λλ 80-640µm       | ZERODUR®         |
| Material Strength                                                           | Evidence based comprehensive Strength data is available enabling informed design. With structural forms introduced by emerging technology for Fused Closed-Back mirror substrates, eigenfrequencies needed for launch can be realized, even to 4 meter diameter. With full design data, most requirements can be safely realized. See [5,6] and Section 5. | Superior                                                                                   | SiC 100          |
| Small thermal transient response near room temperature: essential for Space | YES: room temperature (See Figure 1). Diffusivity is also a factor<br>CTE(22C) ~10ppb/C                                                                                                                                                                                                                                                                    | CTE(22C)=2340 ppb/C<br>>200x ZERODUR                                                       | ZERODUR®         |
|                                                                             | YES: dCTE(T)/dT ~ 1.4ppb/C variable                                                                                                                                                                                                                                                                                                                        | dCTE(T)/dT=11.4ppb/C                                                                       |                  |
|                                                                             | YES: CTE(xyz) for a single boule is extremely homogeneous                                                                                                                                                                                                                                                                                                  | CTE(xyz) >> ZERODUR due to multi-piece fabrication                                         |                  |

### 3. RESPONSE OF SiC 100 & ZERODUR® TO A THERMAL GRADIENT

Figure 2 (above) illustrates the two different CTE(T) gradients, one for ZERODUR® and one for SiC 100, observed over the temperature range of -20C to +40C, commonly containing the desired temperature range of many spaceborne optical telescopes operating in the wavelengths of Ultraviolet, Visible and Near Infrared. The significance of the slopes is explored schematically in Figure 3.

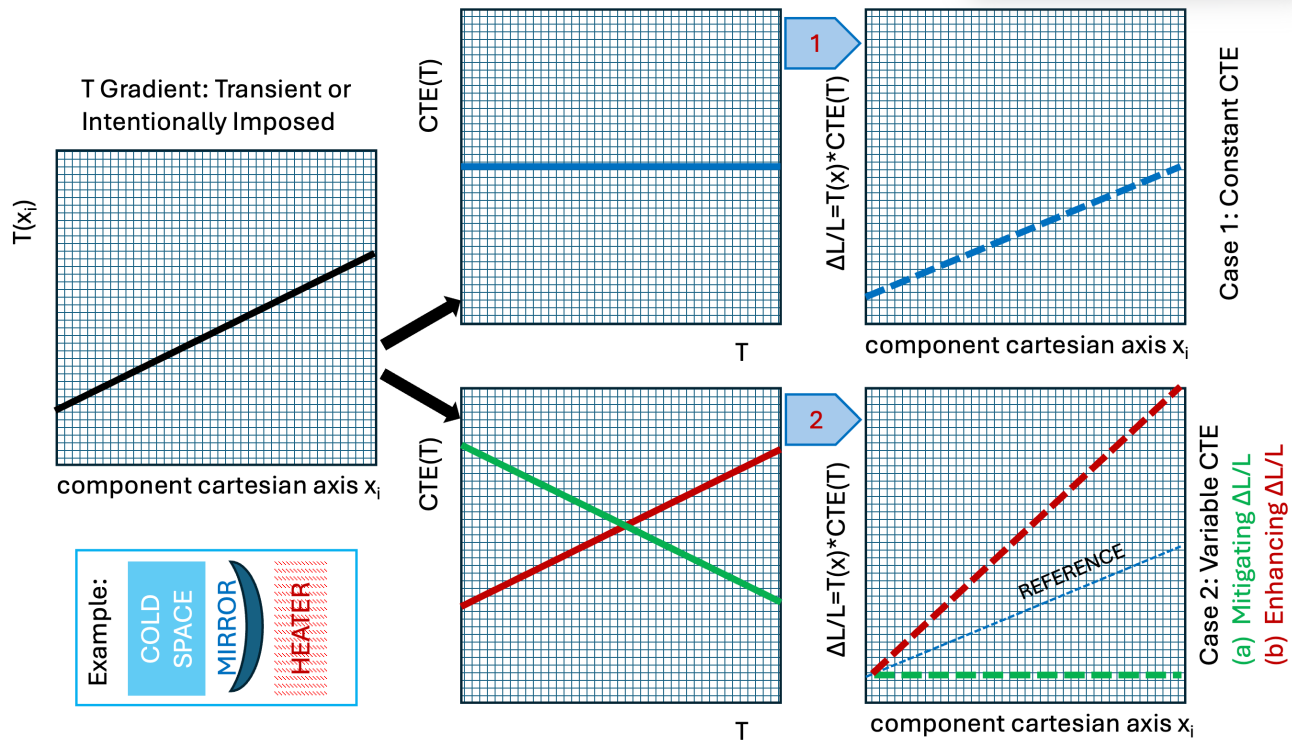


Figure 3. Three CTE(T) cases are examined in the presence of a thermal transient. An intentional example would be the case of backside heating a mirror looking at cold space (2.7K) to prevent the mirror surface from being a better attracting contamination. This would impose a thermal gradient from back to front which would respond to CTE(T). As seen, if CTE varies with Temperature, (T), this could either enhance or reduce the dimensional perturbation on the mirror, reducing its performance. The RED case is worst, while the GREEN case is best. A quality SCHOTT can achieve with ZERODUR® is tailoring the CTE(T) for the operational range, and potential gradient mitigation. While this is an imposed gradient, the same amplification of mitigation occurs from random gradients induced by solar view factors changing due to either orbit or Concept of Operations (CONOPS). Adjusting the slope of CTE(T) is a tool in ZERODUR® but not in SiC.

These cases illustrate schematically the importance of thermal gradients on thermos-optical stability of an assembly. We note that in the case of SiC 100, as in the First-Order Thermal Response defined in Section 2, both the magnitude of CTE(T) gradient is also mitigated by thermal diffusivity.

### 4. ZERODUR®: SMALL, INTERMEDIATE & LARGE MIRRORS FOR SPACE

ZERODUR® mirrors and structures have been made in single boule in scales ranging from less than 10cm to over 4m [17]. Monolithic mirrors, also made from a single boule, have been made as large as 8m for ground astronomy, though not suitable for the rigors of launch. Multiple approaches are available to lightweight a spaceborne mirror, and the optimal choice of lightweighting depends on mirror size (see Table 2). These approaches are principally driven by aperture, though other factors may enter including space element acceleration, slew and settle requirements as well as vibration or shock. Such vibrations may be induced by reaction wheel assemblies (RWAs), instrument cryo-pumping, and the like.

Table 2. Roadmap involving typical lightweighting mode for high-performance spaceborne mirrors or structures responding to both operational performance and launch loads. SCHOTT either offers ZERODUR® substrates in each of these modes or , in the larger sizes, will respond to demand and extend facilities using methods under development.

| Size               | Production Pace* | Backside Shaped     | Pocket Form | Present TRL | Production Readiness      |
|--------------------|------------------|---------------------|-------------|-------------|---------------------------|
| ≤20cm              | >30/mo.          | Yes                 | No          | 7-9         | Demand Driven             |
| ≤50cm              | ~5/mo.           | Yes                 | OB          | 7-9         | Ready                     |
| ≤50cm              | >5/mo.           | Yes                 | OB          | 7-9         | Demand Driven             |
| 0.6 ≤1.2m          | ~1 per 2mo.      | If desired          | OB, PCB     | 6           | Ready                     |
| 0.6 ≤1.2m<br>x-ray | ~1 per 2mo.      | Wolter 2<br>Grazing | Shell       | 9           | Ready                     |
| 1.2m-2m            | ~1 per 4mo       | If desired          | PCB         | 6           | Ready                     |
| 1.2m-2m            | ~1 per 6mo       | Flat                | CB          | 3           | Actively<br>Elevating TRL |
| 2m-4m              | ~1 per year      | Flat                | CB          | 3           | Demand Driven             |

In Table 2, pocket form refers to Open Back Cells (OB), Partially Closed Back (PCB) or Fused Closed Back (CB) depending on the eigenfrequency needed. Note that “Pace\*” is notional and driven by business considerations. Closed Back mirrors are further discussed below. Technology Readiness Level (TRL) is a current assessment. SCHOTT is in the process of elevating TRL to a level viable for selection for spaceborne missions.

## 5. EMERGING ZERODUR® TECHNOLOGY: CLOSED BACK MIRRORS

In addition to advanced lightweighting by open-back isogrid pocketing (88% lightweighting demonstrated on a 1.2m diameter mirror with safe thicknesses for manufacture), SCHOTT is presently producing fused, closed back mirrors capable of very high eigenfrequencies. A recently produced fused mirror 0.95 meters in diameter was exhibited [10]. SCHOTT is actively pursuing advancing the TRL of Fused ZERODUR® lightweight mirrors to a flight-ready level.

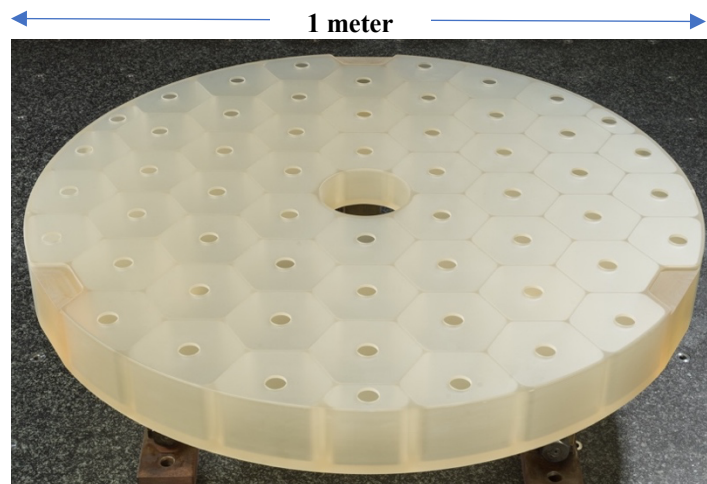


Figure 4. A recently fused Closed back 95 cm ZERODUR® with a 10:1 aspect ratio mirror demonstrates enhanced first eigenfrequency  $f_0 \sim 528$  Hz. This is configured for 3-point edge mounting rather than at the radius of percussion and neutral axis, a viable trade in this size mirror.

This is developmental though highly encouraging and leading to larger size closed back mirrors. For launch of a spaceborne optical assembly, vibration and shock survival, is crucial. Closed Back (CB) mirrors and structures elevate the mirror vibration response or eigenfrequency over that possible in Open Back mirrors and structures. This becomes increasingly important as mirrors tend to diameters of 1.5 meters or larger. While the eigenfrequency of any cellular lightweighted mirror depends on several factors (including material characteristics, diameter-to-thickness ratio, sheet thickness, rib thickness, cell inscribed diameter and support condition), for a homogeneous set of these parameters,

$$\text{eigenfrequency } f_0 \sim 1/\text{Diameter}$$

While the exact eigenfrequency decay depends on numerous design parameters, larger mirrors typically are closed back because Open Back mirrors often have less than half the eigenfrequency of closed back at diameters of 1.5m and larger. By analogy, the I beam is much stiffer than the T-beam. It is desirable to maintain eigenfrequency of mirrors to be greater than 200Hz and essential to keep this above 80Hz. Lower eigenfrequencies typically have auxiliary launch locks, an added complication and risk. Also, the lower the thickness ratio (diameter/thickness), the higher the eigenfrequency.

The process of making Closed Back (CB) has added complexity over that to make Open Back (OB) or Partially Closed Back (PCB) mirrors. This flow is described in Figure 5. The added complexity is warranted to get the requisite stability.

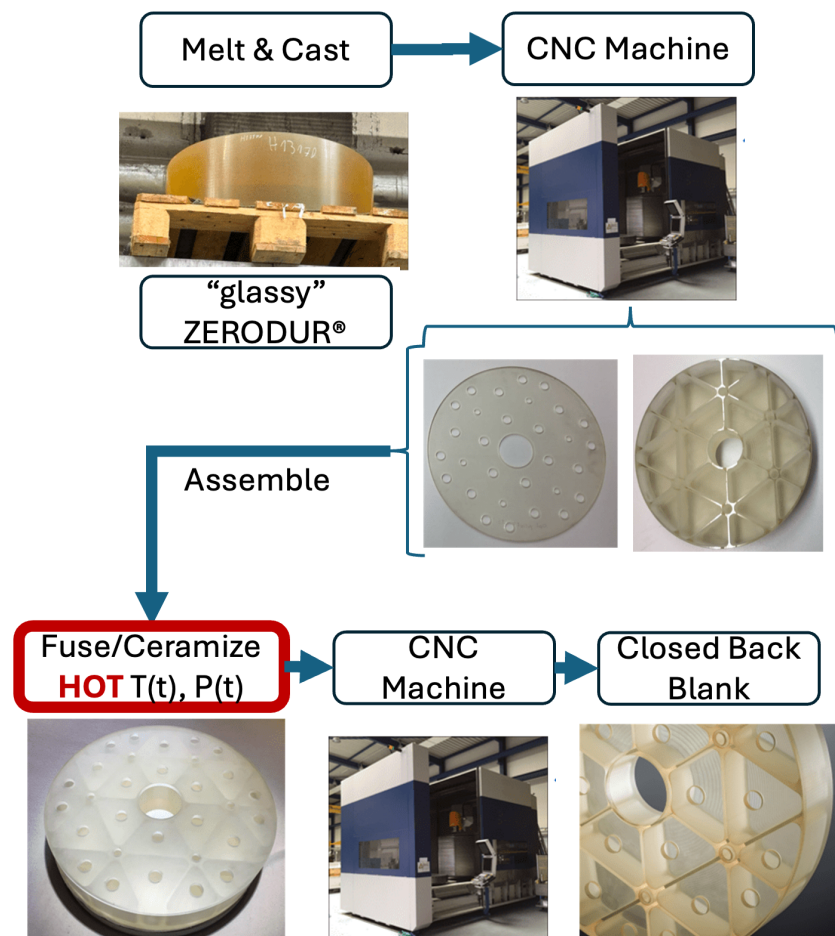


Figure 5. The ZERODUR® fusing process developed at SCHOTT is done without binder or adhesive, directly merging pieces of “glassy” state ZERODUR® together under a prescribed temperature and pressure profile. The glass-to-glass contact becomes one piece of glass including lightweighting. This achieves the highest eigenfrequencies especially needed for mirrors in the 1.5m domain and larger.

## 6. CONCLUSION

ZERODUR® has decades of flawless spaceflight experience in apertures up to a little over one meter. This size limitation is an artifact that at the time that mass was a dominant consideration in going to space, SCHOTT did not offer state-of-the-art lightweighting. Fifteen years ago, this changed, with SCHOTT offering aggressive Open Back lightweighting of ZERODUR® appropriate for most applications up to 1.5m in diameter (see Figure 6). As size requirements of several space missions are going larger, high-eigenfrequency fused Closed Back mirrors are now in rapid development at SCHOTT and will establish flight-suitable TRLs.



Figure 6. Open Back ZERODUR® mirror substrate, lightweighted 88%, introduced in January 2013 at the American Astronomical Society Annual Meeting.

ZERODUR® is an exceptional material for spaceborne mirrors and precision structures [18,19], offering many thermal stability and optical finish advantages over other mirror substrate options, including SiC 100 mirrors. Evidence Based design is possible with ZERODUR® through numerous technical studies. ZERODUR® exhibits appropriate strength and space-effects characteristics to qualify as a strong option for most spaceborne missions, with small or large mirrors. With Closed Back ZERODUR® technology development, SCHOTT is responding to the present and future of new spaceborne missions, both astronomical and surveillance, with all the optical advantages of ZERODUR® for mirrors, optical benches and even metering structures (for the smaller sizes).

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