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# Material attributes that define performance and efficiency of spaceborne mirrors

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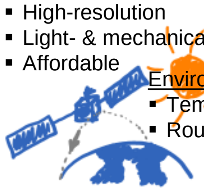
## Abstract

In addition to the classical parameters used for mirror substrate material selection, we discuss several other attributes critical to implementation of spaceborne mirrors for various environments. Often trades are either limited to the material and approach the designer has used in the past, or are based on primary factors like specific stiffness and transient response. We look further at mission-critical attributes, including fracture mechanics, temporal drifts, deterministic implementation to design, inhomogeneity, anisotropy, polishability, compatibility with advanced coatings, and space heritage.

## Scope and context

Space optics specifications:

- High-resolution
- Light- & mechanically stable
- Affordable



Environmental challenges:

- Temperature changes
- Rough launch conditions

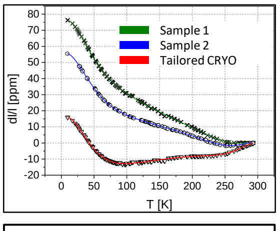
Space optics architectures:

1. Science flow down and orbit selection
2. Material choice based on support data
3. Cost, schedule, TRL/risk, performance and error budgets

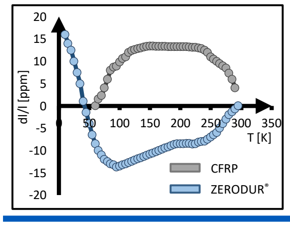
**Detailed know-how of material required**

## CTE Tailored to application

The near-zero thermal expansion of ZERODUR® is tailored to the temperature range of interest: operating T environment or subsequent structural materials.



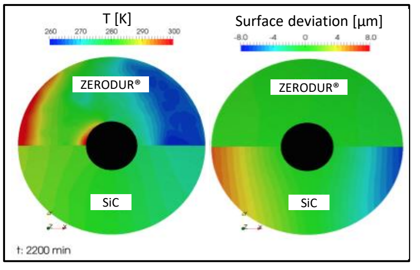

ZERODUR® TAILORED CRYO: very low thermal expansion especially achieved from 250K to 70K [1]




ZERODUR® TAILORED to compensate for the CTE of CFRP, a potential material used as support for the optical alignment of the mirrors [1]

## CTE vs. diffusivity

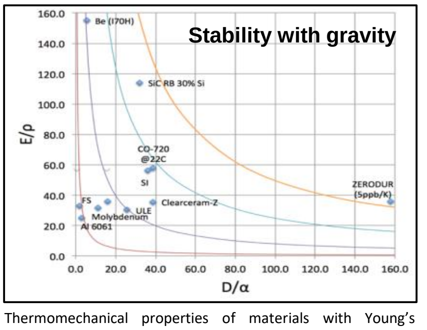
Simulations of the surface deviation under a 40K T-gradients are conducted to compare high CTE and high diffusivity materials. The former exhibits a surface deviation of at least 16 µm, while this is negligible for ZERODUR®.




Relative response of ZERODUR® and SiC primary mirrors: (left) temperature smoother for SiC; (right) ZERODUR® shows smoother surface deviation. high diffusivity fails to compensate for low CTE in terms of surface deviation [2].

## Thermomechanical properties

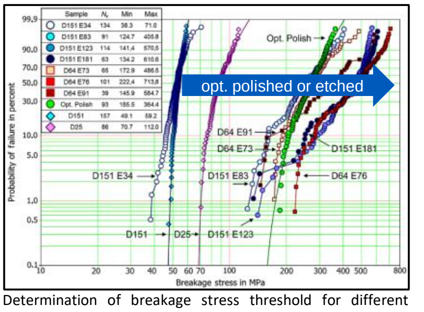
The representative value of 5 ppb/K gives the best thermal performance for ZERODUR®, while the mechanical figure-of-merit is similar to those of most comparable materials for mirror substrates




Thermomechanical properties of materials with Young's modulus E, density ρ, thermal diffusivity D and expansion α.

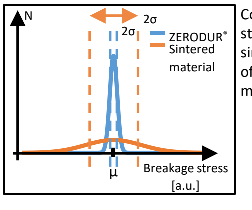
## Bending strength

The bending strength is analyzed from ZERODUR® samples of different surface conditions (ground, etched and polished). The threshold stress of ~42 MPa (D151 ground surface) is determined by a 3-parameter Weibull statistics. It triples for polished surfaces [3,4].




Determination of breakage stress threshold for different surface conditions by fitting the 3-parameter Weibull statistics

The distribution of the breakage stress around the mean value µ is recorded by 3-point flexural tests on ground surfaces. ZERODUR® exhibits a much tighter dispersion resulting in a smaller safety margin necessary compared to sintered materials.




Comparing the breakage stress dispersion of a sintered material to that of ZERODUR®, a cast material.

## Material properties comparison

A number of mirror materials, compared below, have been used in spaceborne telescopes, each with strengths and weaknesses. Maximal dimensions, CTE values and inspection techniques as well as CTE homogeneity and zero-crossing are considered.

Material properties: Glass ceramics, glass, cordierites and metals. Bold designates favored

| Attribute / Material | Maximum monolithic diameter | CTE Value | CTE Homogeneity | CTE 0 at some Temp. | $\frac{\partial CTE}{\partial T}$ | Inspect volume |
|---|---|---|---|---|---|---|
| ZERODUR® | **4.3 m** | **Extremely Low 5 ppb/K** | **Superb** | **Yes, most cases** | **Low** | **Visible high resolution** |
| ULE | ~1.5 m / fuse larger | Low 30 ppb/K | Not published | **Yes** | **Low** | **Visible high resolution** |
| Fused Silica | ~1.5 m | 550 ppb/K | Good | No | **Low** | **Visible high resolution** |
| Cordierite 720 | ~1.5 m | Moderate Variable | Not published | **Yes** | High | X-ray low resolution |
| SiC | ~1.5 m / fuse larger | 2 500 ppb/K | Variable | No | **Low** | X-ray low resolution |
| Al | ~0.4 m | 23 000 ppb/K | Variable | No | **Low** | X-ray low resolution |
| Be | ~1.6 m | 12 000 ppb/K | Variable | No | **Low** | S-ray low resolution |

## Conclusion

The implementation of a successful spaceborne telescope must address controlling dimensional instabilities into orders-of-magnitude smaller regimes than traditional engineering applications. Every design decision is critical, and the choice of mirror material is especially critical. The best design must look beyond the first order characteristics of a material and consider CTE homogeneity and tailoring, breakage behavior, inspection possibilities and TRL. Extensive ZERODUR® data address these questions and is continuously extended.

## References

[1] Jedamzik, R., and T. Westerhoff, Proc. SPIE 9151 (2014)
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[3] P. Hartmann, Proc. SPIE 10706-25 (2018 & references )
[4] P. Hartmann, Optical Engineering Vol. 58, Issue 2 ( 2019)

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