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ABSTRACT

Demanding new environmental requirements for earth observation, and for astrophysics, may impose ultrastability requirements on telescope mirrors. Dimensional stability of the mirror material under environmental boundary conditions is as important to the success of a mission, if not more so, than considerations of strength and stiffness. Among these characteristics is the response of the mirror material to variable thermal stimulus. It is found that not only the mirror material's coefficient of thermal expansion (CTE) is important, but also the homogeneity of the material characteristics. Furthermore the match of thermal characteristics between the mirror material and those of metering structure contributes to maintaining a manageable error budget for operations under various view factors to sun and earth.

Keywords: Spaceborne mirror materials, ZERODUR®, Coefficient of thermal expansion, CTE homogeneity, Ultrastability, Parametric mirror selection, Lightweight mirrors

1. INTRODUCTION

Many factors go into mirror material selection for a spaceborne mission, including familiarity of the material within the design institution's engineering culture. Yet the choice of mirror material may have profound effects on many aspects of the system, including complexity, cost, schedule, reliability and system error budget. In the past, emphasis for large telescope mirrors has been on low mass, often represented as percent lightweighting or areal density. While mass remains important, launch vehicles capable of lifting to orbit larger masses are increasingly becoming available, and simultaneously considerations of thermal stability and cost are increasingly emphasized. While ZERODUR® has been used for spaceborne mirror substrates for four decades [1], even for NASA Flagship Missions like Chandra and Hubble Secondary Mirror, only in the last decade has it been available in attractively lightweighted form directly from SCHOTT. Lightweighting, even approaching 90%, is currently available on ZERODUR® substrates as large as 4 meters in diameter [2]. Unlike most materials, this lightweighting is from a single, homogeneous [4,5,6,7] melt, and is free of any form of fusing or bonding. Furthermore, the thermal expansion characteristics can be tailored to be optimal over specific thermal ranges. We will discuss first parametric trades involving several candidate mirror materials, especially those for the Ultraviolet, Visible and Near Infrared bands, and examine factors indicative of the thermal stability performance of the optical system under these parameters.

2. MATERIAL CHARACTERISTICS AND PARAMETRIC TRADES

Michael Ashby notes that design process requires detailed information both about the materials from which the product will be made, as well as about the environments the product will experience [1]. Furthermore, the choice of material is dependent on the choice of processes available to form the structure, and finish to optical form. Ashby continues to discuss that cost too is an important parameter. Cost may manifest not only as that of the mirror alone, but also through the implications that selection imposes on the rest of the system. For example, if a mirror is very sensitive to thermal perturbations, to achieve stable operation the system design must rely upon a complex array of sensors, heaters, cabling and power, and the associated risks of failure modes thus introduced. Ashby proceeds to express the utility of parametric evaluation to narrow and optimize choices of material for an application and environment, recognizing that cost and manufacturability are also included in the parameters worthy of consideration. Usually we start first with the environmental response, and then take a short list of materials to optimize for other factors.

To first order, deflection under gravity has a dependence $\delta \sim \rho/E$ where E is Young's Modulus and ρ the material's density. Then the ratio E/ρ is customarily used as it relates to both the making of the mirror, with a surface accuracy measured in nanometers, and to the AI&T of the telescope or instrument in a 1-g environment. For lightweight mirrors, this includes quilting at the cellular level, which may cause added error during optical fabrication metrology. E/ρ is also one of the constraints on the amount of mass that can be removed from a lightweighted mirror. Thus this is one of the critical parameters for mirror design.

Similarly, as we review candidate mirror materials in environment with thermal gradients and transients, most fall in a domain of low coefficient of thermal expansion CTE, or high thermal diffusivity $D = k/(\rho*c_p)$, where k is thermal conductivity, but in most cases not both. For example,

Table-2.1: Thermal categories of mirror materials. Traditional mirror materials neither lie in the best or worst positions. Thus a combined metric D/CTE may be thought of as an initial figure of merit. Here we will focus on ZERODUR® and direct trades with competing materials.

	High CTE	Intermediate CTE	Low CTE
High D	Al, Be	SiC	BEST↑
Low D	WORST↓		glass ceramics ~ZERODUR® low expansion glass ~ULE®

Traditionally, the structural and thermal figures-of-merit are expressed on a plane as orthogonal variables, one plotted against the other, as in Figure 2-1. In this case, room temperature values are used as published either in product brochures, or in the literature. It should be emphasized that this structural figure-of-merit relates to deflection in gravity, and that this expresses the extent methods need to be developed for optical fabrication and test. Also, it is customary in catalogs and the literature, to address α as the secant of the change in length of a sample between two temperatures. In the case of ZERODUR® made by SCHOTT, the expressed value of α is the fractional change length between 0C and 50C. Later the instantaneous coefficient of thermal expansion will be discussed. We note that measurement of α to the parts per billion (PPB) levels is difficult. For example, ZERODUR® was introduced 50 years ago, and today α can be measured much more reliably at very low levels, even to 1 ppb. Older textbooks list ZERODUR's® CTE at 50ppb/C, while SCHOTT frequently is delivering ZERODUR® at $\alpha < 5\text{ppb/C}$ level. This factor of 10 in the denominator moves ZERODUR's® thermal figure-of-merit to the highly favorable side [5].

Contours of equal weight are shown on the plot of E/ρ vs. D/α in Figure 2.1, which allows comparison of materials strongest on the structural efficiency coordinate to those strongest on the thermal efficiency coordinate. However, rarely are these figures-of-merit equal in importance to a mission. Factors to be considered include the cost of launch of a mass to a given orbit. At this time there is an increase in heavy lift capacity. Thermal stability, which can be achieved from various combinations of materials with low passive response, and application of thermal control coatings and heater networks. At this time, we are seeing increasing emphasis on thermal stability.

Another consideration, especially important for lightweighted mirror substrates, is the homogeneity of CTE. While in flight telescopes, many times a change in curvature or power of the mirror can be accommodated by refocus, inhomogeneity introduces effects which may vary rapidly across the mirror surface as the temperature changes, or gradients imposed.

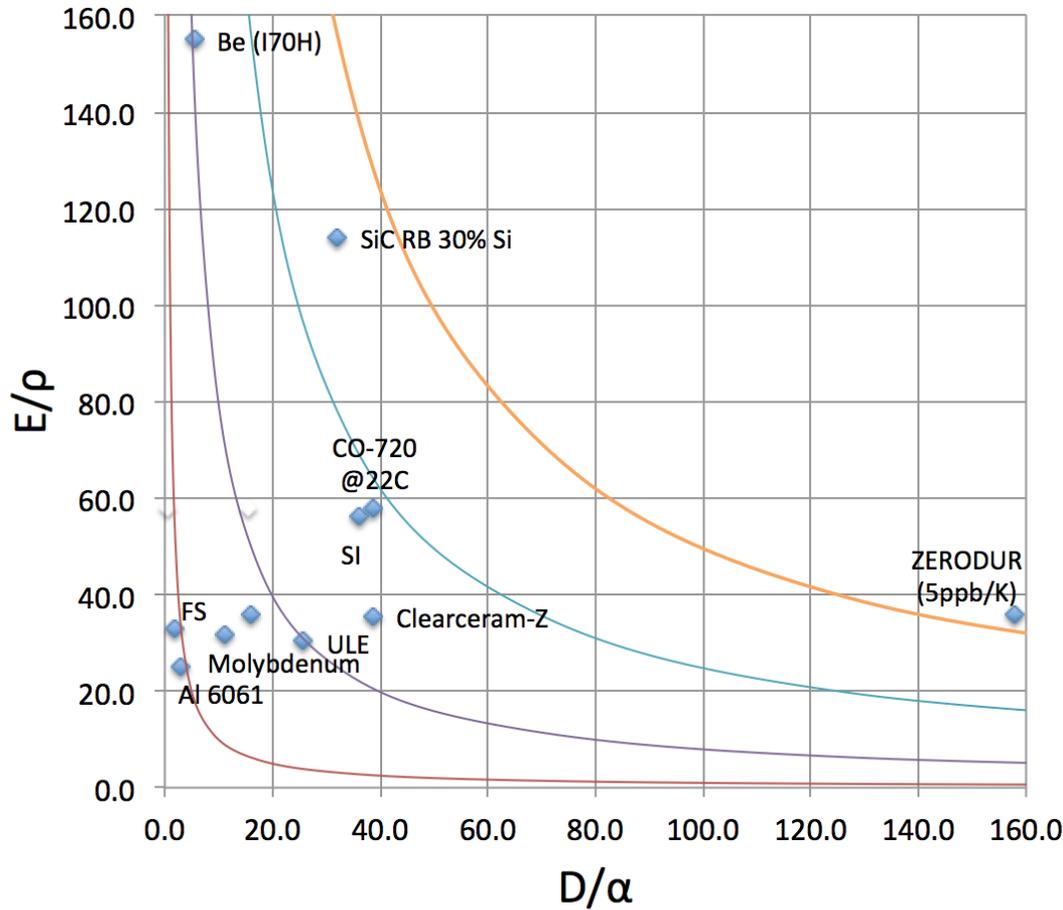


Figure 2-1: Here $\alpha = \text{CTE}$. The relationship between E/ρ (structural efficiency figure-of-merit) and D/α (thermal efficiency figure-of-merit) is “best” at the upper right, and “worst” at the lower left. All the materials here have been considered for substrates of flight mirrors, and most have flown in space.

Table 2-2: Units used in Figure 2-1

ρ	E	$\alpha = \text{CTE}$	K = conductivity	Cp	D
g/cm ³	Gpa	ppm/K	W/mK	W sec/kg-K	10 ⁻⁶ m ² /sec

Short of going to the complexity of a high authority deformable mirror at a reimaged pupil plane, there is very little that can be done to mitigate the effects of this irregularity of optical figure, and associated significant contributions need to be included into the error budget. Cordierite-720 is a special case, and we have used the catalog value **CTE** at 22C in Figures 2-1 and 2-2.

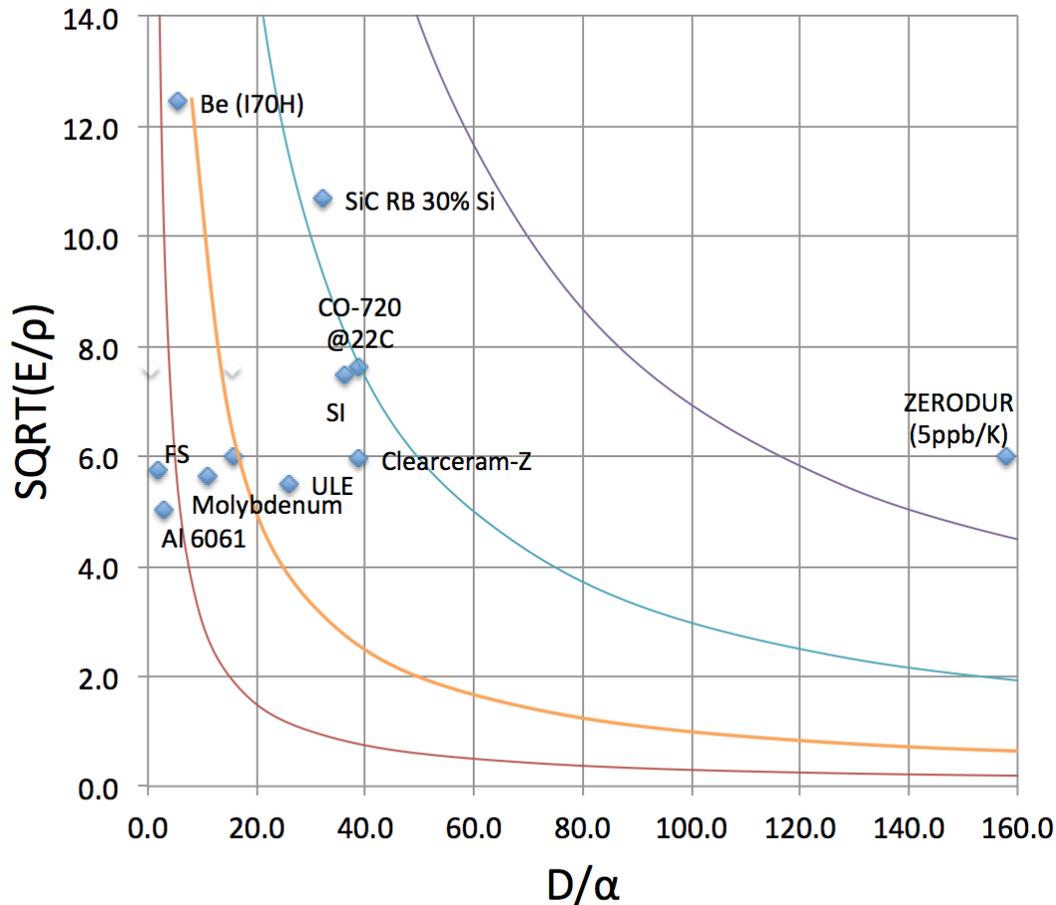


Figure 2-2: Here $\alpha = \text{CTE}$. Again the relationship between $\sqrt{E/\rho}$ (structural efficiency figure-of-merit) and D/α (thermal efficiency figure-of-merit) is “best” at the upper right, and “worst” at the lower left. Structural efficiency is described in terms of higher Eigenfrequency f_0 since $f_0 \sim \text{thickness} * \sqrt{E/\rho}$.

Thus in launch and operations considerations, differences in E/ρ are not as important as they are for Fabrication and Assembly, Integration & Test (AI&T) considerations. And there are multiple effective methods to address gravity back-out in Fabrication and AI&T.

3. TAILORED THERMAL EXPANSION AND INSTANTANEOUS CTE

While it is useful for preliminary trades to use the secant CTE described in Section 2, additional metrics need to be considered at the next level of trades. Furthermore, spaceborne operation may favor temperatures from room temperature down to much colder temperatures. Our discussion is mostly addressing operation in the UV, Visible and Near Infrared parts of the spectrum. For operations approaching the thermal infrared, those mirrors must be driven to cold temperatures to avoid introduction of background noise from the heat of the mirrors. Thermal infrared cryogenic operation introduces considerations that we do not evaluate here.

Schott has published extensively on the thermal characteristics of ZERODUR®. The formulation to make ZERODUR® has remained unchanged since its introduction to the market in 1968. Meticulous records have been maintained, and experiments with the ceramization time-temperature profile has shown that the thermal expansion characteristics of ZERODUR® can be optimized for a given thermal environment. This is called tailored ZERODUR®, which addresses

not just the secant CTE, but also the instantaneous CTE's dependence on Temperature or CTE(T). Figure 3-1 shows the secant definition.

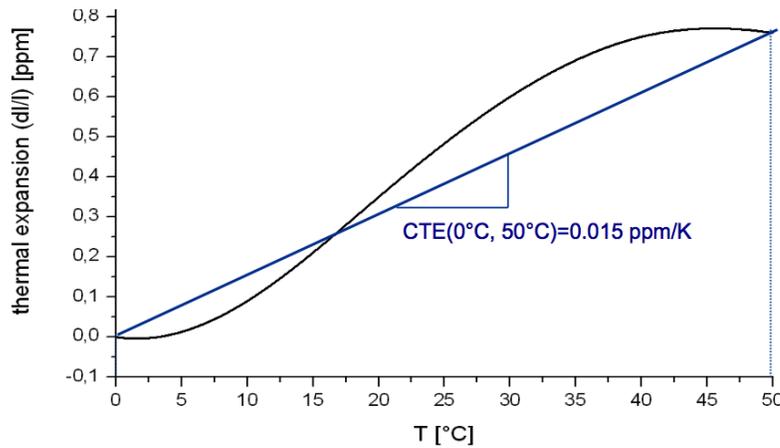


Figure 3-1: Schematic of calculation describing the secant CTE (0, 50C) used in many catalogs and text books. For example, ZERODUR® is often described by its CTE between 0C and 50C, though instantaneous values of CTE are available from SCHOTT

However, there are many instances where requirements for ZERODUR® are not addressed by the secant behavior over this entire range. One example would be semiconductor equipment, typically operated at room temperature +/- a fraction of a degree C. Or ground astronomy, where optical telescopes at night go from room temperature to well below freezing.

Figure 3-2 illustrates four examples of fractional change of length dl/l as a function of temperature by SCHOTT deliberately tailoring the thermal expansion characteristics of ZERODUR®. These are custom optimizations to specific applications, and as we will show, are especially relevant to optimal spaceborne telescope operations.

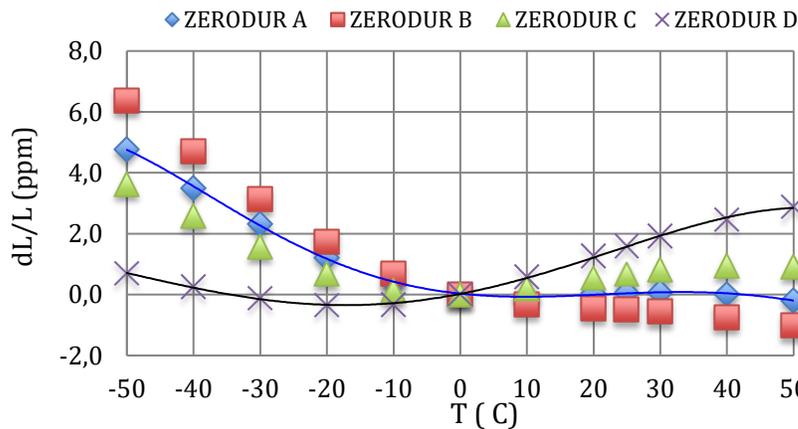


Figure 3-2 shows for examples of SCHOTT tailored thermal expansion for ZERODUR®. Note that each pivots around the 0C temperature point. The designations A, B, C and D represent four examples for the convenience of this discussion, and are not SCHOTT product names. Other optimizations may be requested from SCHOTT. The rate of change for A is very small around room temperature, for example, and D low between +10C and -50C.

The coefficient of thermal expansion, CTE, is found by differentiating whichever curve is selected. Figure 3-3 represents the CTE associated with each of the dl/l curves in Figure 3-2.

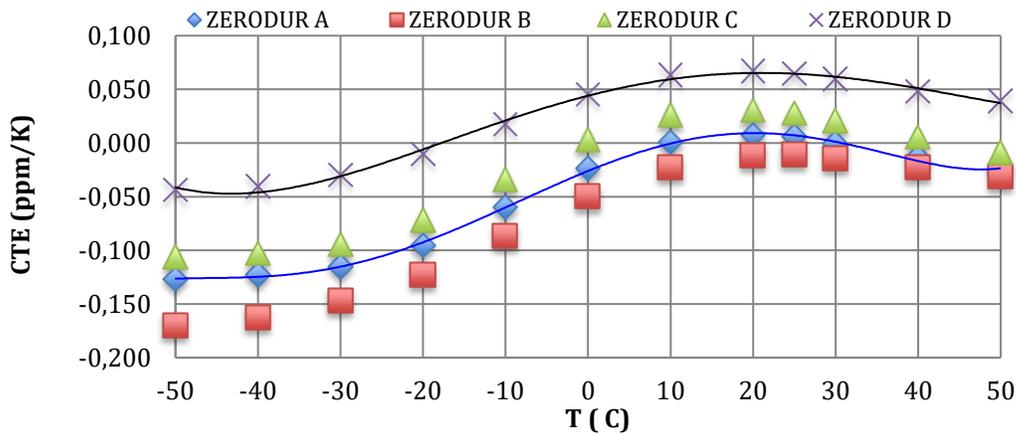


Figure 3-3: Four cases are examples of tailoring CTE of ZERODUR®. Selection may be made to optimize for the desired temperature range. The designations A, B, C and D represent four examples for the convenience of this discussion, and are not SCHOTT product names. Other optimizations may be requested from SCHOTT.

Thus the precise α characteristic over the operational temperature range may be considered. Thus if the operational temperature range is narrow, or deviates from the definition range of temperatures, a material's thermal stability may be very different than that predicted by Figures 2-1 and 2-2.

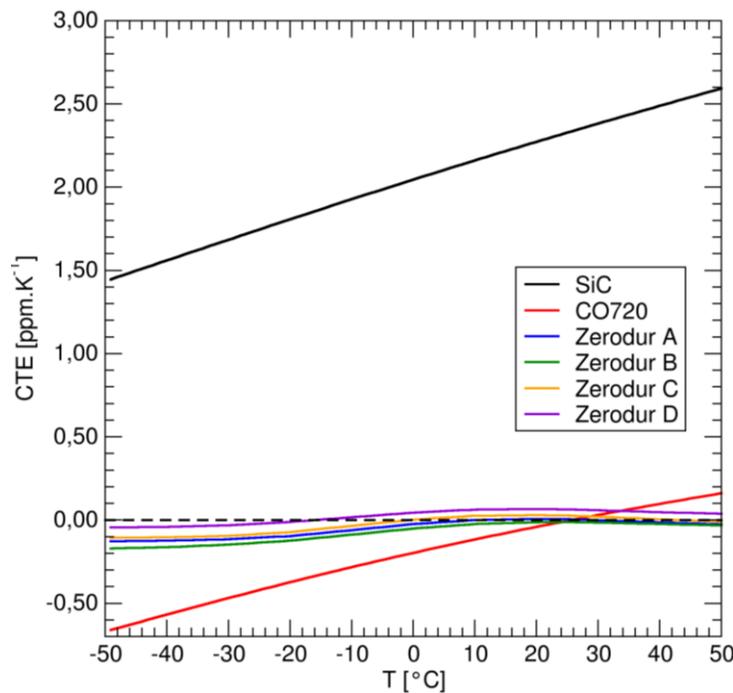


Figure 3-4: CTE(T) dependence of SiC, CO720, and the reference ZERODURs® A, B, C and D. Two things differentiate these curves. A) The CTE of SiC is orders of magnitude larger than the other materials considered here, and B) Cordierite exhibits a zero-CTE crossing and a steep slope. In fact three of the ZERODURs® also exhibit a zero-CTE crossing in this diagram.

For example, a recently introduced Cordierite material for spaceborne mirrors from Japan, CO-720, exhibits a low CTE near room temperature, yet CTE increases rapidly at small deviations from room temperature. Figures 3-4 and 3-5 show its dependence with temperature.

Figure 3-5 expands the CTE scale allowing consideration of the differences between CO720 and the four ZERODURs®.

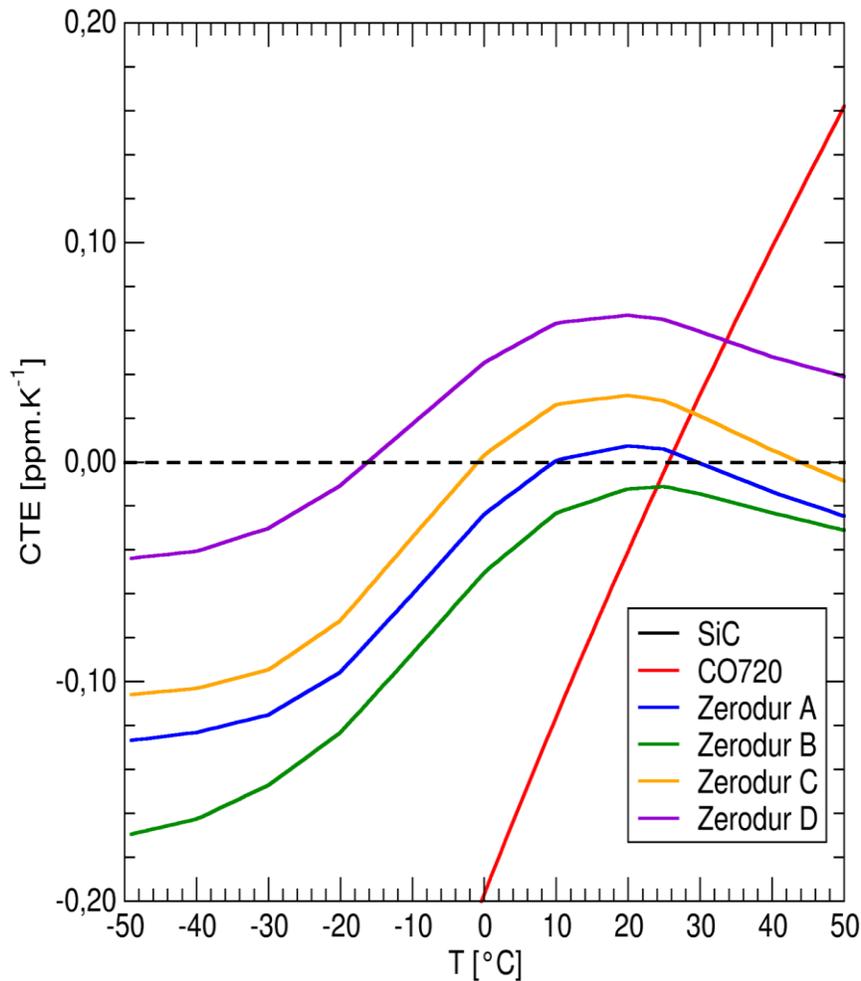


Figure 3-5: Zero crossings are shown, and the steep slope of CO720 is notable.

The thermal distortion for these materials scales as $1/(\rho \cdot c_p \cdot \text{CTE})$. Since we see that $\text{CTE}(T)$ passes through 0 for these materials at locations which may be over the operational temperature range, there are singularities of infinite merit caused by division by 0. However these singularities are infinitesimally narrow. Immediately at either side of the singularity are regions with very high, but not infinite figures of merit. This is expressed in Figure 4-6.

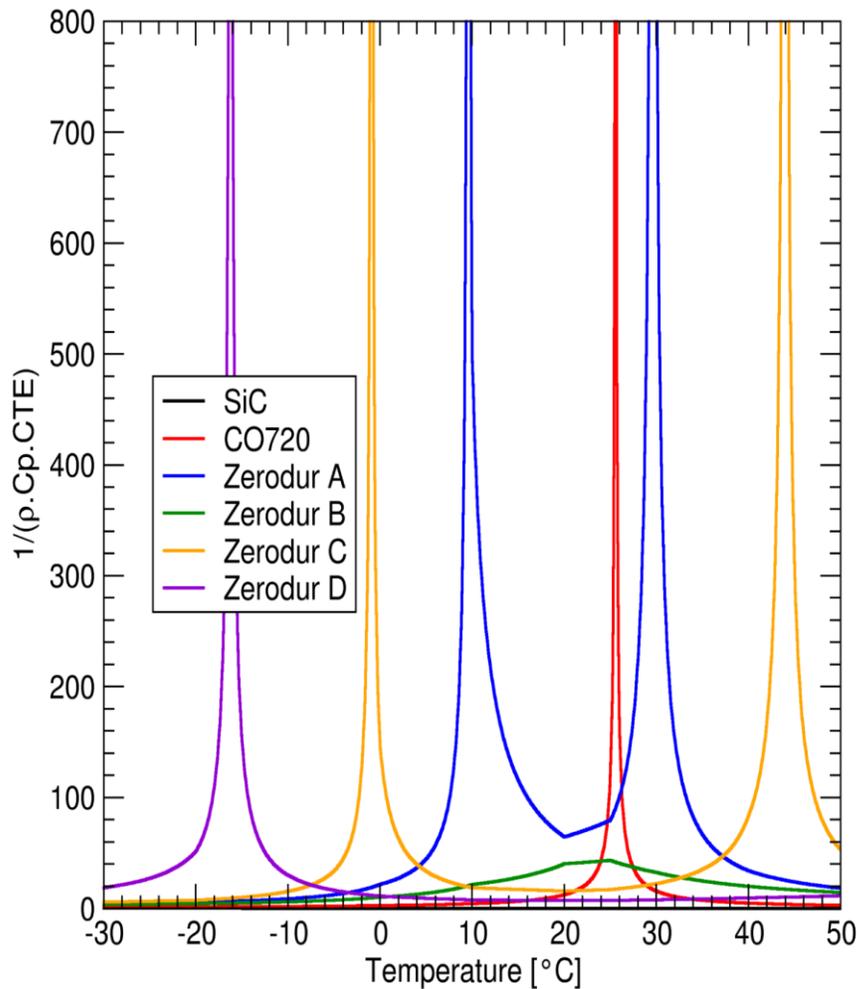


Figure 3-6: The area under each curve, and the feature width, are indications of the stability of the material against transients. The higher the curve, the better the resilience to thermal transients. SiC is seen near the bottom of this chart since its CTE never approaches zero. The extremely narrow profile of CO720 compared to the breadth the profiles of all ZERODUR® cases considered, suggests that solutions with ZERODUR® are more stable against thermal disturbances than are solutions with CO720.

The result in Figure 4-6, together with the possibility of tailoring the zero crossing of ZERODUR® at optimum operation temperatures, suggest a broader and more robust set of solutions for tailored ZERODUR® than for Cordierite CO720.

Another feature of tailored CTE ZERODUR® is the excellent thermal match possible with Carbon Fiber Reinforced Polymers (CFRPs) used to create the metering structure carrying the solid body alignment between mirrors in the OTA. CFRPs are widely used in space for this purpose from the implementation of Hubble on to the future. Figure 4-7 illustrates that tailored ZERODUR® can be matched to the dI/I of CFRP to have the same strain at room temperature, where most AI&T takes place, and at operational temperature.

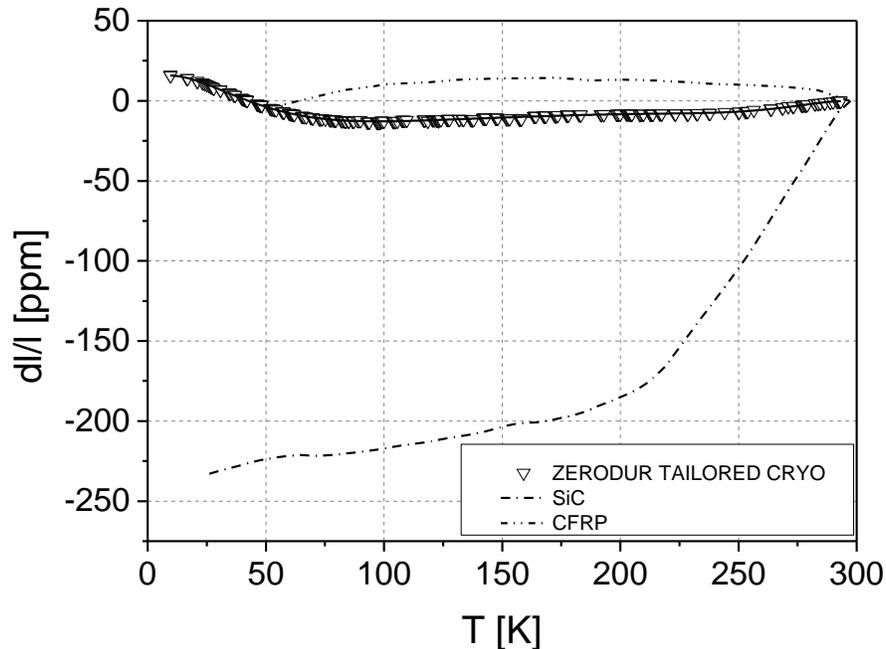


Figure 4-7: Tailored ZERODUR®, with thermal strain measured at PTB in Germany, is made to closely match at $d/l = 0$ at both room temperature, and near LN2 temperature. This is but an example. Since both CFRP and ZERODUR® can have their expansion characteristics tailored, they can be made to match at a given temperature, or now have near zero differential strain between room temperature and typical cooler temperatures for a UV-VIS-NIR OTA, perhaps 230C to room temperature. One would not expect to match SiC to CFRP for metering purposes. Obviously significant differential strain would occur and optical alignment compromised.

4. CONCLUSION

Figures-of-merit for several presently considered mirror substrate materials have been considered. We reference ZERODUR®, a heritage low expansion glass-ceramic made by SCHOTT and enjoying its 50 year anniversary in 2018. Due to its low CTE, small inhomogeneity and ability to take an excellent optical finish, it has been used extensively in space as mirror substrates on space telescopes for over four decades.

A decade ago, SCHOTT extended the applications for ZERODUR® in space by offering aggressively lightweighted substrates of ZERODUR®, and have recently extended offerings with fabrication facilities that can lightweight monolithic cast ZERODUR® mirror blanks as large as 4m in diameter [8,9,10]. Even in these large sizes, homogeneity of CTE is maintained at an unparalleled 5 parts per billion level or better.

We have addressed the parametric regime addressing both structural efficiency and dimensional efficiency under varying thermal boundary conditions. It has been demonstrated the stability advantages of tailoring the CTE to operational temperatures. ZERODUR® is among the materials have the CTE cross from positive to negative or vice versa as temperature is varied. Cordierite CO720 is another example of a material with a zero CTE crossing, and would be expected to exhibit very good performance at that singular temperature. However Cordierite CO720 is among the materials with a steep CTE(T) slope of the crossing temperature. Thus, with only small deviations from that optimum temperature, resilience to dimensional changes from thermal transients will not be as good. ZERODUR® exhibits both a CTE(T) that has several degrees of freedom to be tailored to the temperatures of interest, and the slope of ZERODUR's® is much gradual. Thus good optical performance, associated with mirror perturbation response to temperature changes, is sustained over a wider temperature range. This in turn simplifies (or eliminates) imposed temperature controls.

ZERODUR's® tailored low CTE, and high degree of homogeneity, together with the ability to make large monolithic mirrors without fusing or bonding, suggests that this material belongs in trade space for optimal architectures both for earth observing missions and for astrophysics missions.

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