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# *ZERODUR® characteristics that enable ultrastability for landmark future European and US Space Missions*

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# ZERODUR® characteristics that enable ultrastability for landmark future European and US Space Missions

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## ABSTRACT

Planning for 21st Century Astrophysics endeavors (Voyage 2050, LISA and IR/O/UV) imposes uncommon systems requirements for opto-mechanical dimensional stability. Material characteristics are key to discriminating between strategies and enabling these missions. Substantial SCHOTT IR&D and facilities investments over the last decade support use of ZERODUR® on critical missions with specific demands like those of the IR/O/UV Mission. IR&D includes published comprehensive studies of material strength and lifetime, process control and metrology ensuring homogeneity at the part-per-billion level, the ability to prescribe and tailor minimum CTE to desired operational temperature range.

Lightweighting up to as much as 90% is now available, plus aspheric surfaces can be generated with low and controlled subsurface damage, including off-axis forms and even free-forms. SCHOTT is producing 949 mirror segments for ESO's ELT M1, plus secondary and tertiary mirror blanks over 4-m in diameter and still has significant capacity. We discuss monolithic mirror substrates from a single cast piece of ZERODUR®, free of methods to fuse, bond or braze separate pieces to make a lightweighted mirror substrate.

While IR/O/UV 6-m blanks constitute an extension in ZERODUR® production, the pathway is illuminated by direct ZERODUR® experience in the 4-m to 8-m monolith range.

**Keywords:** dimensional stability, ultra-stability, glass-ceramic mirrors, ZERODUR®, radiation compaction

## 1. INTRODUCTION

Large space missions requiring exceptional dimensional stability are presently being considered by ESA and by NASA. In November 2021, the US National Academy of Sciences issued a report [1] of its Decadal Survey results following consideration of the most productive use of NASA and NSF funds for the ensuing decade, including defining the next Great Observatory to be led by NASA. Their selection was informed by GSFC's LUVOIR study and JPL's HABEX study and is temporarily called IR/O/UV. Europe initiated its Voyage 2050 study in March 2019 [2] and is addressing three large-class mission concepts. As with NASA, Voyage 2050 was informed by input from the European community. Concurrently, LISA, led by ESA, has been selected in Europe [3] as a present large-class mission in 2017 and is advancing with NASA contributions. Each is looking to sophisticated opto-mechanics and dimensional ultra-stability. While many of the considerations discussed here are relevant to LISA, our focus will be on Great Observatories requiring large spaceborne telescopes, while LISA is based on three small but ultraprecise payloads.

### 1.1 Future Relative Importance of Mass Efficiency and Thermal Transient Resilience

As it was for the Webb Telescope, basic to mission architecture will be early mirror material selection for future great spaceborne observatories. This is especially true for large apertures in the domain being called for of monolithic or segmented apertures 4 meters diameter through 6 meters diameter or larger. With the advent of heavy lift vehicles available for the next generation of great observatories, there will be less emphasis on lightweighting of the telescope mirrors. Thus, the mass/stiffness efficiency, a classic predictor of gravitational deformation

$$\eta \sim E/\rho \text{ (Elastic Modulus/density)}$$

is of less importance for launch. The main structural stability driver may be Eigenfrequency resonance to launch loads and to gyros, reaction wheels and cryo-coolers during operations. And the first Eigenfrequency is given by

$$f_o \sim \sqrt{(E/\rho)}$$

Since this is a square root function, the differences in Young's Modulus between very stiff materials and materials with excellent optical properties is less pronounced than in the gravitational deflection case $\eta$.

For these missions, perhaps even more crucial than mirror eigenfrequency response and mass considerations are the effects that define optical figure stability. While operational vibrational resonance is a factor in optical stability, technologies are advancing to decouple spacecraft vibration disturbance sources from the optical system. In Figure 1 below, we plot eigenfrequency response vs. the Thermal Transient Resilience Parameter. This is an expression of balance relating how rapidly the equalization of temperature field occurs after the introduction of a thermal transient, divided by the coefficient of thermal expansion (CTE) of the material. Later, we will discuss second order effects including how homogeneity of CTE($x_i$ Cartesian Tensor notation) throughout the volume affects stability, and also including how the variation of CTE with temperature $\partial CTE/\partial T$ also affects stability. Special problematic cases include:

- Mirrors that needed to be fused/bonded/brazed from different castings due to limit of casting size
- Mirrors that need to be clad with a somewhat dissimilar material to achieve the requisite optical surface, thus introducing some level of bimetallic bending moments.

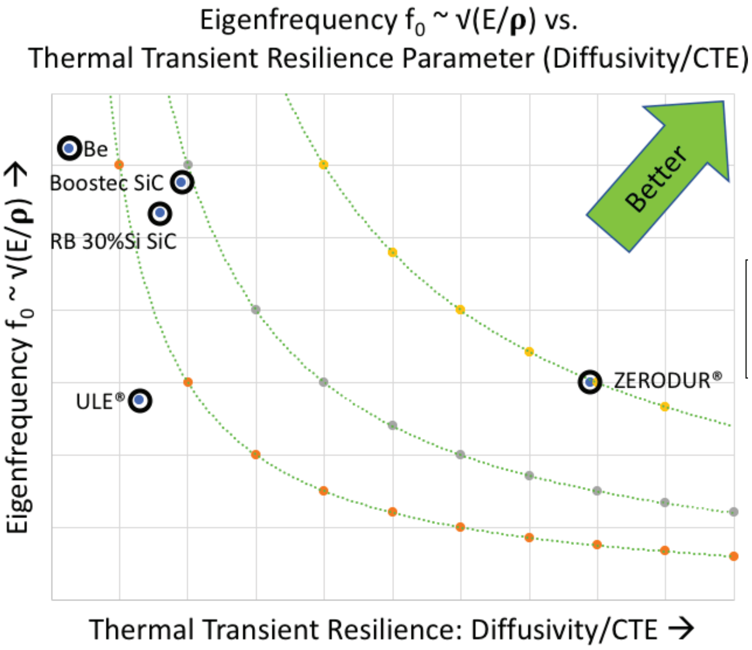

Figure 1. Both Specific Stiffness (E/ρ where E is Young's Modulus and ρ material mass density) and Thermal Transient Resilience (Diffusivity = k/(ρ*cp where k is thermal conductivity) are commonly used in initial considerations of mirror material. They are expressed, one against the other, in this LINEAR-LINEAR room-temperature diagram. Contour hyperbolae denote constant utility as the product of the two axes. ZERODUR® performs favorably on this 2-dimensional metric. It may be argued that for ultrastability as required in the subject future great observatories that thermal transient resilience is the most important parameter. At presently expected operating temperatures of these missions (In contrast to InfraRed Webb, the likely operational range is expected to fall at temperatures of 250K to room temperature), the extremely low CTE of ZERODUR® is highly favorable to consideration. Later other thermal factors will be discussed.

## 1.2 Mission Characteristics will drive Mirror Material Considerations

For the large perspective missions of ESA and NASA, contemporary high performance mirror material considerations are summarized in Table 1. Wavelengths far shorter than those of Webb are being called for in the future of both ESA and NASA great observatory telescopes. Exoplanet coronagraphy is a highly desirable future tool for characterizing "Worlds around other Suns". When this is a science flow-down, both wavelength and coronagraphy operations put a premium on the mirror's ability to be polished to an extremely high smoothness and, perhaps more important to accurately maintain its figure over an operational temperature range. Since Webb was optimized to be "The First Telescope to see the First Light in the Emerging Universe", This implies very large redshifts of light from early universe objects with the associated requirement to operate in the infrared. The infrared requirement in turn required the reduction of thermal noise from the telescope optics, necessitating very cold telescope operation at about 35K. The situation is different for next flagships of both ESA and NASA.

Table 1. While future large observatory attributes are far from settled, we consider candidate operating environments and observational wavelengths. This Table is a top-level look at how suitable materials map into the underlying requirements, and a starting point for this discussion. Manifestations of the Coefficient of Thermal Expansion (CTE) ultimately include second level material requirements including homogeneity $\partial CTE/\partial xi$, CTE = f(T), $\partial CTE/\partial T = f(T)$, radiation compacting stability will be considered together with heritage, TRL and infrastructure.

| *Mission* | *Temperature* | *Diffraction Limited $\lambda$* | *Mirror/Segment Finish & Stability* | *Largest Size without fusing* | *Suitable Material* |
|---|---|---|---|---|---|
| Webb (Ref.) | Operating T ~ 35K | $\lambda_{DL} \sim 2um$ | ~20nm RMS figure, 4nm RMS micro finish | 1.5m segment p-p | Unclad Be |
| Voyage2050 VLST | $T_{OP}$* ~ 270K-300K | $\lambda_{DL} \sim 0.5um$* | ~5nm* RMS figure, 1nm* RMS micro finish | 4m | ZERODUR®<br>(SiC needs to be fused and clad) |
| Voyage2050 Distributed Ap/ | $T_{OP}$* ~ 270K-300K | $\lambda_{DL} \sim 0.5um$* | ~5nm* RMS figure, 1nm* RMS micro finish | 1.5m rondels | ZERODUR®<br>SiC |
| IR/O/UV segmented | $T_{OP}$* ~ 270K-300K | $\lambda_{DL} \sim 0.2um$* | ~2nm* RMS figure, .0.3nm* RMS micro finish | 1.4m segment p-p | ZERODUR®<br>ULE |
| IR/O/UV monolithic | $T_{OP}$* ~ 270K-300K | $\lambda_{DL} \sim 0.2um$* | ~2nm* RMS figure, 0.3nm* RMS micro finish | 6m off-axis | ZERODUR®<br>(ULE needs to be fused for size) |

For mirrors of new large observatories working in Near InfraRed (NIR), Optical Ultraviolet (UV) domain, dimensional stability is crucial. Not only will the diffraction limited wavelength be much shorter than for Webb, in some cases, stabilities as challenging as 10 picometers (pm) over $10^4$ seconds may be required. The principal mechanisms driving such short-term optical surface perturbations usually relate to thermal transients. These may result from orbit and pointing driven solar view-factor changes, heat transfer from electronics and active devices, and any mixture of these effects.

## 2.0 Material Stability

The introduction establishes the domain of stability of the optical surfaces. Stability of these surfaces is established with a detailed look at factors enumerated in Table 2. We reference ZERODUR®, a heritage mirror material developed and manufactured by SCHOTT expressly for mirrors in astronomical telescopes. ZERODUR® has been in stable formulation and production since 1969 with comprehensive technical reports available on its detailed attributes [4]. It has also flown and performed flawlessly on many ESA and NASA missions [5,6], including the Wolter II mirror suite in NASA's Chandra Great Observatory and Hubble's secondary mirror. ZERODUR® is a glass-ceramic matrix, the ceramization process creating on a microscopic scale a negative CTE ceramic counterbalancing the positive expansivity of glass. ZERODUR® is regarded to assume an excellent optical surface both with traditional optical polishing methods and alternate methods including but not limited to Magneto-Rheological Finishing (MRF) and Ion Beam Figuring (IBF)

Table 2. Mirror surface stability may be addressed by multiple methods, and when ultimate surface stability is needed, by combination of these methods. Critical imaging and spectroscopy extending into the optical and ultraviolet part of the spectrum impose demands on mirror stability, and this may be even more critical for coronagraphy where images exo-earths around other suns (Contrast between the exo-sun and exo-earth may be $10^{10}$ or higher). Analyses have suggested stability of 10 picometers over $10^4$ seconds may be required [7]. Topics D2.-D6 will be discussed in the following section. Even with optimal isolation, optimal design and active thermal control, we propose that the most robust, lowest risk approaches begin with the qualified mirror material with the greatest passive stability!

| *Method* | *Implementation* |
|---|---|
| A. Thermal Isolation; sources/sinks | Insulation from exterior and interior sources |
| B. Active Thermal Control | Networks of closed loop heaters and thermistors |
| C. Design Detail | Proper use of epoxies and mounting techniques, stable structures, eigenfrequencies away from excitation |
| D. Favorable Passive Attributes of mirror materials selected | 1. High heritage, high TRL made with stable process |
| | 2. Ratio of (Thermal Diffusivity)/CTE large (See Fig. 1) |
| | 3. Homogeneity and Isotropy of CTE |
| | 4. Avoid cladding to make optical surface. Cladding introduces bimetallic effects evident at mirror precision |
| | 5. Avoid bonding, fusing or brazing materials from different melt batches together to make a mirror |
| | 6. Tailor the CTE for operational temperature range<br>☐ Very low average CTE over range<br>☐ Gentle slope: $\partial$CTE/$\partial$T is small |

### 2.1 Thermal Stability of ZERODUR®

ZERODUR®, in continuous production since 1968, exhibits the heritage and high TRL suitable for consideration for future extremely high performance spaceborne telescopes. The formulation is unchanged since inception. Since Ultrastable Materials have become critical enabling many dimensionally critical applications, including extensive applications in the semiconductor industry, production has been continuous, not only responsive to episodic astronomical demand, and accordingly, investment in IR&D and infrastructure ongoing. Presently ZERODUR® is made in monolithic single melt pours up to 4m. In the past, the VLT 8m mirror blanks were made at SCHOTT, and some of this large infrastructure remains as well as the methods.

### 2.2 Passive Stability (Topic D2) Ratio of (Thermal Diffusivity)/CTE should be large for low Transient Respose

Textbook material selection often describes plotting orthogonal material attributes, one-against-another [8]. Figure 1 is an example of this where the selection factors First Eigenfrequency Parameter and Resilience to Thermal Transients are treated. With the advent of heavy lift vehicles, mirror material selection is somewhat relieved from extreme lightweighting and now gives special emphasis on thermal stability. There are two classes of materials most commonly considered for mirror substrates:

- ☐ Those materials exhibiting high thermal diffusivity and high CTE. It is argued that with high diffusivity, temperature gradients resulting from transients will be supported only for short intervals and nearly instantaneously relax to an isothermal material. Such materials in common use are Beryllium (Be) and Silicon Carbide (SiC). However, if a source and sink boundaries to the mirror, there will be a through thickness gradient. A front-to-back through-thickness gradient will alter the mirror radius-of-curvature (ROC). Thus, low CTE is still important to form stability.

☐ Those materials exhibiting lower thermal diffusivity and very low CTE. It is argued that CTE, the direct expression of how an element of material will respond to a change in temperature, if minimum will result in minimum change of shape. Such materials in common use are ZERODUR® by SCHOTT and ULE by Corning. With recent improvements in dilatometry, ZERODUR® is realizing CTE levels of the order of 5ppb/K, a reason for its favorable placement seen in Figure 1 and Figure 2.

There is no mirror-appropriate material that both has high thermal diffusivity and low CTE over a reasonable range of temperatures for space applications. Therefore, the telescope architect must choose from the above options. If the distinction in eigenfrequency is less important, the choice falls between the thermal attributes of heritage materials. Figure 2 addresses the trade between these materials room temperature to moderately cold (~260K to 290K). Webb was able to use Beryllium since at its very low temperatures (~35K), the CTE of Beryllium is nearly zero. However, at near room temperature, where the CTE of ZERODUR® is routinely less than 5ppb/K, or a factor of over 2000x smaller than that of Beryllium at 11400ppb/K and a factor of over 400x smaller than SiC at over 2200ppb/K. Figure 2 illustrates the differences between relevant mirror materials on the log-log plane.

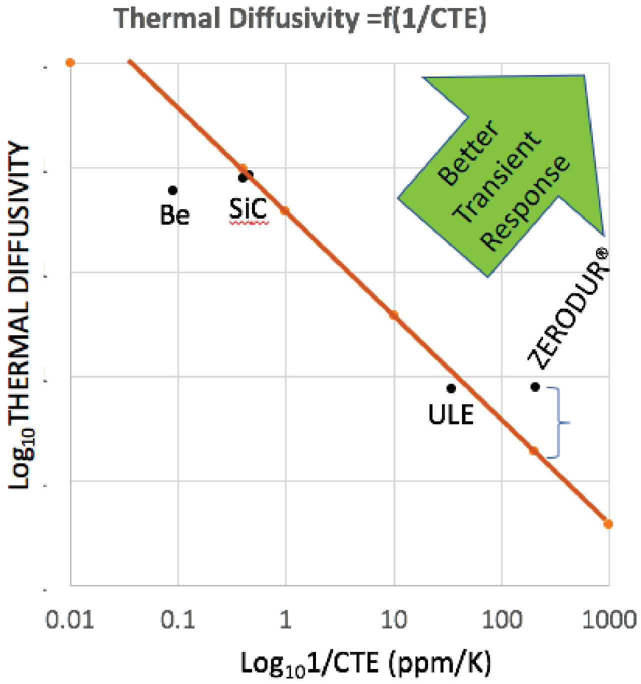

Figure 2. In this Log$_{10}$-Log$_{10}$ plot, the solid curve represents equal merit between the two axes. This assumes transient stability merit equally values thermal diffusivity and inverse Coefficient of Thermal Expansion (1/CTE). At operating temperatures of room temperature to perhaps 250K expected for a Visible/InfraRed mission, the extremely low CTE of ZERODUR® establishes this as the preferred material based on the thermal transient criterion.

We have considered a worst-case analysis as an illustration comparing the transient response of two mirrors:

☐ A high CTE, high Thermal Diffusivity material…Boostec SiC

Versus…

☐ A very low CTE, moderate Thermal Diffusivity material…ZERODUR®

Both were subject to the same telescope geometry; both were Low Earth nadir-looking telescopes. And both passed through the Earth's umbra. As such, the telescope and mirror would see continuous change of solar view factor, continuous thermal transients. The result of this analysis is illustrative. To the left, the mirror of Boostec SiC exhibits nearly imperceptible temperature gradients to the full-scale resolution seen here at the moment in orbit this frame was taken while that of ZERODUR® shows apparent transient-induced temperature gradients across the mirror, also at full scale. However, to the right as we look at surface deformation across the mirror, Boostec SiC shows notable surface errors while surface errors are nearly imperceptible in ZERODUR® at the same scale. This illustrates in another manner the thermal advantage of ZERODUR®, a very low CTE, moderate Thermal Diffusivity material.

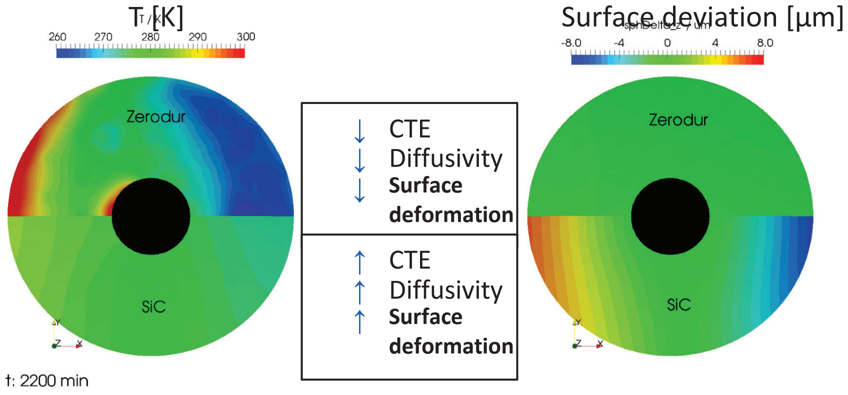

Figure 3. This simulates the relative response of a ZERODUR® and a SiC primary mirror in telescopes, identical except for the material [9]. After 22 orbits, the temperature distribution on the primary mirror of each telescope is examined (Left), and as expected, temperature is notably smoother for SiC. However, the opposite is true for surface deviation (Right). This demonstrates that in comparison with an extremely low expansion material like ZERODUR®, high diffusivity fails to compensate for ZERODUR®'s low CTE in terms of surface deviation

### 2.3 Homogeneity and Isotropy of CTE (Topic D3)

ZERODUR® is highly isotropic in thermal qualities. This is not necessarily true of other materials. For example, the beryllium crystal is anisotropic and there is some residual anisotropy in packing the powder and solidifying it. Improvements have been made by introducing quasi-spherical particles, and consolidation of the powder by hot-isotropic pressing (HIP). Nevertheless, some anisotropy remains. Isotropy is a valid consideration in material selection.

For ultrastability, the next incisive consideration is homogeneity. Comprehensive studies have been conducted at SCHOTT over the last decade demonstrating the extremely low inhomogeneity of ZERODUR® [10,11, 12]. Recently the 4.3m diameter mirror blank for the next generation solar telescope (DKIST) was produced by SCHOTT from a single casting for which perimeter readings determined that the CTE throughout the mirror (Secant 0C to 50C) averaged 0ppb/K +/-5ppb/K. SCHOTT has done frequent destructive testing exploring homogeneity on scales from 1cm to meter spatial frequencies. Unlike other materials, comprehensive ZERODUR® results are published.

ESA's and NASA's next generation large observatories will require ultrastability, even to the 10 picometer level! In 2015, a study was presented by Eisenhower et al: "ATLAST ULE mirror segment performance analytical predictions based on thermally induced distortions" [13]. SCHOTT has conducted a parallel study for ZERODUR®, using the well-established values for homogeneity of ZERODUR® [14, 15].

- ☐ Both perfectly homogeneous CTE material and representative CTE values for each material (ZERODUR® and ULE) were evaluated
- ☐ Little differences between the surface response of the materials were found when perfect CTE homogeneity was the basis of the calculation

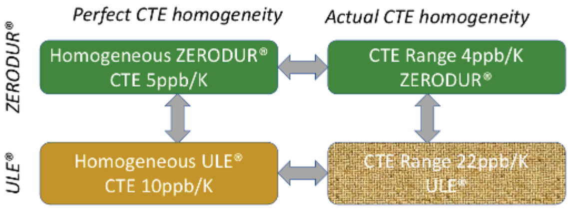

Figure 4. The confirming study between ZERODUR® and ULE addressed first the assumption of perfect homogeneity, then actual measured inhomogeneity. Since Corning has not released homogeneity data, based on data at hand an inhomogeneity of 22 ppb/K was used for ULE. ULE, produced by deposition on a rotating platform, has been found to display a systematic CTE variation from the center to edge.

☐ However, when representative CTE inhomogeneity for each material was evoked, significant differences in surface response thermally induced distortions became apparent. (Figure 5).

☐ Nevertheless, either material will deliver the required 10 picometer stability result if thermal impulses are limited to 10 mK. ZERODUR® meets the 10 picometer stability result even with 100 mK thermal impulses.

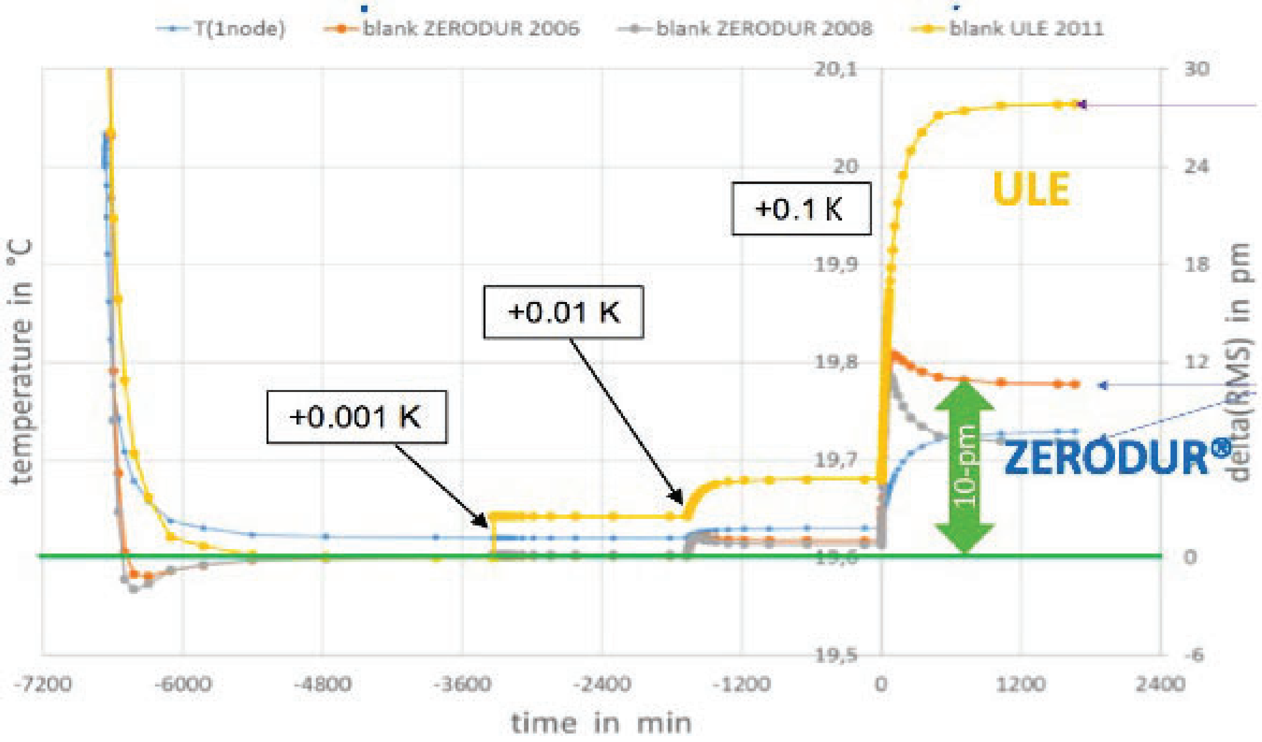

Figure 5. Homogeneity drives achieving a 10-picometer rms surface in response to 1-mK, 10-mK and 100-mK. Measured inhomogeneities of several different batches of ZERODUR® were used, and all satisfied 10-picometer surface stability to up to a 100-mK perturbation. Thus, the superior homogeneity of ZERODUR® resulted in superior dimensional stability of ZERODUR® mirrors.

### 2.4 Cladding Mirror Substrate for Optical Finishing & a Mirror Substrate of Multiple Pieces (Topics D4, D5)

For smoothness of optical surfaces required for Optical and Ultraviolet wavelength observation, ZERODUR® is regarded as highly satisfactory. It polishes well with an extremely smooth microroughness, even to the Angstrom level.

If either beryllium or silicon carbide is to be used for telescope mirrors operating in the Optical and Ultraviolet wavelength regions, the natural microroughness of the polished surface is too large and will induce significant scattered light. Total Integrated Scatter is proportional to $(\text{microroughness/wavelength})^2$. The specular surface must be clad with a material that polishes to a high smoothness. Webb mirrors are of bare polished beryllium which can only achieve a microroughness of the order of 4 nanometers rms. Thus, if beryllium was to be used, it would need to be clad with autocatalytic nickel, perhaps between 25 microns and 100 microns thick. ULE is polished to an order of magnitude better microroughness, and ZERODUR® up to another order of magnitude smaller. The same is true for SiC. To have a mirror surface clad in a manner it does not affect the optical figure, three conditions need to be addressed. Table 3 summarizes these considerations.

Another potential instability is the fabrication of mirrors out of many roundels of material. In 2003, NASA's 1.8m diameter Technology Demonstration Mirror (TDM) was being constructed out of ULE [16, 17]. At that time, the TDM substrate was to be fabricated by low temperature fusion out of 9 separate selected pieces of ULE. At the level of ultraprecision, it must be asked how the slightly differing characteristics of each piece affects the overall stability of the mirror. Similarly, ESA built the 3.5m Hershel Primary Mirror out of 9 pieces of Boostec SiC, brazed together in pie shaped segments. While Herschel has been highly successful, it operates in he sub-millimeter wavelength regime, 80 microns to 640 microns. There is little resemblance to the stability that will be needed for the upcoming large observatories.

Table 3: When ultraprecision is needed, what are the criteria for cladding a mirror surface to induce an acceptable instability. Often notional approaches of no-impact cladding are stated. Each of these requires detailed examination. Cladding materials typically exhibit a significant Modulus of Elasticity ( E ) and thus, the ability to impose a bending moment on the substrate in the presence of thermal transients and gradients. Furthermore, cladding induces a stress balance opposing the substrate material. Does this induce the propensity for microcreep and other temporal effects? Comprehensive studies are necessary if cladding is to be used for Ultrastable mirrors taking into account the entire thermal history of the mirror through optical fabrication, coating and operation.

| | *No impact cladding criteria for ultraprecision* | *Ultrastability Factors* | *Go/No* |
|---|---|---|---|
| 1 | The CTE(T) of the cladding must be exactly the CTE(T) of the substrate over operational temperature range | ✓ Be clad with Electroless Nickel only crudely achieved<br>✓ SiC clad with Si imperfect match<br>✓ SiC clad with CVD SiC better but imperfect match | **No** |
| 2 | The cladding is infinitesimally thin | ✓ While the bimetallic moment → zero at extreme thinness, the propensity of the cladding to polish-through is large. Then stripping of the cladding is needed and starting over. Thus, thin claddings induce high technical, cost and schedule risk<br>✓ Cannot be thin enough with the E of cladding materials | **No** |
| 3 | The neutral axis of the cladded shell exactly matches that of the lightweighted substrate | ✓ Not true if there is even a small temperature gradient<br>✓ While neutral axis matching can be done for slab mirrors, this would be extremely difficult for an open-back lightweighted mirror and impossible for a closed back lightweighted mirror<br>✓ Polishing will perturb the neutral axis match, and also remove some of the initial stress of the cladding on the substrate | **No** |

### 2.5 Optimizing Mirror Transient Response by Tailoring CTE to Operational Temperature Range (Topic D6)

The ability to tailor the thermal expansion characteristics of ZERODUR® to various operational environment conditions simplifies the design requirements imposed on an Optical Telescope Assembly (OTA). The CTE of ZERODUR® may be optimally tailored over the relevant thermal range. There are three ways tailoring can help minimize thermally induced perturbations on the mirror optical surface. Four examples of many SCHOTT tailored ZERODUR® CTEs are shown as examples in Figure 4. Notice that there may be ZERO-CTE crossings at specific temperatures. If the operational temperature range that the mirror assembly will experience is:

1. Small → for example, maintained in a tight temperature range with closed-loop heater/thermistor arrays, the mirror may be actively driven to near a ZERO-CTE crossing. Some materials with ZERO-CTE crossings (for example cordierite) show high slope ∂CTE/∂T around these crossings while ZERODUR® exhibits low slope ∂CTE/∂T.
2. Moderate → a regime of low CTE may be established around these temperatures
3. Larger → a mirror will be least sensitive to gradients ∂CTE/∂T in domains where changes of CTE with temperature are small

Tailoring is done in the production process and does not alter the composition or Technology Readiness Level (TRL) of the material. Thus, the material itself may largely support required dimensional stability over orbital varying thermal boundary conditions. While this tailoring of ZERODUR® may be applied to optimally match operating conditions, in Figures we express four examples of CTE as a function of temperature for different factory applied tailoring, suggesting that a variety of thermal environments may be met with a high degree of passive stability.

A gradual slope of CTE with temperature is important. The larger the slope, the more homogeneous the material must be in CTE. Tailoring of ZERODUR®'s CTE provides a powerful tool to support optimization of ultrastability [11].

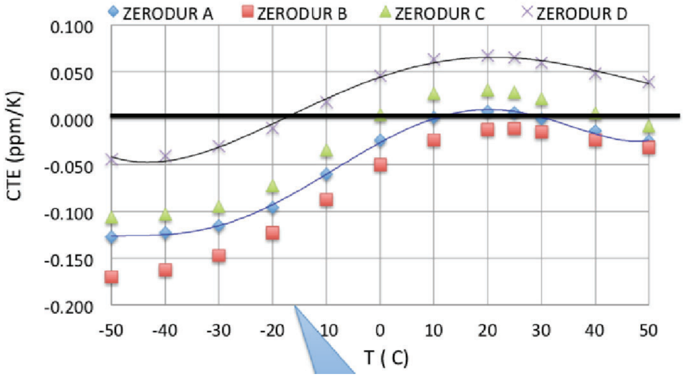

Figure 6. Designations A,B,C,D are examples of actual CTE(T) tailoring. CTE can be both positive and negative, and that there are ZERO Crossings of CTE, as designated at -17°C for case D.

## 2.6 Evaluation of the Effect of Space Ionizing Radiation on Mirror Stability

While radiation compaction has been reported via laboratory testing of ZERODUR®, there is no evidence of any radiation induced dimensional instability on ZERODUR® experienced in telescopes at a variety of orbits. Well over 30 spaceborne missions have partially or totally depended on ZERODUR® mirrors [5, 6] and none have exhibited changes due to radiation. These include two NASA Great Observatories with enduring timelines…

- ✓ The secondary mirror of Hubble now in its 32nd year in space
- ✓ The entire Wolter II mirror suite of Chandra, the front-most mirrors seeing nearly a hemisphere of sky

While other parts of these systems have endured radiation damage, none is evident in the ZERODUR® mirrors. In an effort to close this ambiguity and provide actual data that can be used in error budgets, SCHOTT initiated a study under the direction of Dr. Antoine Carre. A comprehensive article is presently being prepared by Dr. Carre for JATIS. Figure 7 is a result of that study

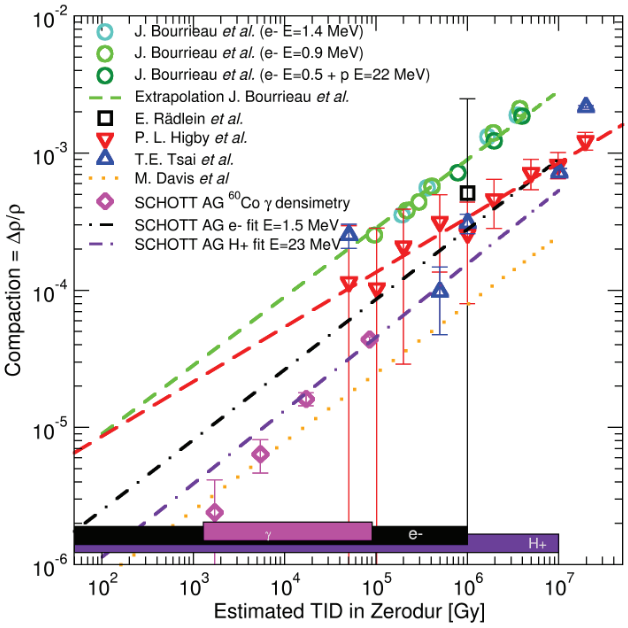

Figure 7 gives one result of Dr. Carre's study that begins to explain the dichotomy between actual flight experience and prior laboratory results. Literature extrapolations to realistic (lower TID) dosages far overestimate the measured values using the precision methods of the current study

## 3.0 Segmented or even Large Monolithic Mirror Substrates are Viable

We have addressed factors centered on the mirror material selection that are essential to dimensional stability. Arguably, for the most immediate of the pending large missions of ESA under Voyage2050 and NASA under Astro2020 will have science traceability matrices (STMs) that will flowdown unusually high optical stability requirements, even ULTRASTABILITY (values like 10-picometer surface distortion in $10^4$-seconds are discussed). ULTRASTABILITY is implicit both in the short wavelength regimes to be explored and also the challenging technologies including exoearth coronagraphy. ZERODUR® is a favorable material in terms of stability under realistic spaceborne thermal transients and radiation environments. The next questions and answers are expected to be:

Table 4: In addition to stability, factors of producibility also influence selection. Lightweighted ZERODUR® infrastructure is fully in place at SCHOTT and has been demonstrated. The only exception is the 6-meter unobscured monolithic that Astro2020 included in its trades. Schott has manufactured 8-meter monolithic mirrors in the past for ESO's VLT. While the full infrastructure has not been maintained, processes have been vetted, and viable approaches may be available with facilitization.

| | *1st Tier Question* | *2nd Tier Question* | *3rd Tier Question* | *ZERODUR®'s response* |
|---|---|---|---|---|
| 1. | Material manufactured from a single casting | | | |
| 1.1 | | Voyage2050/monolithic 4-m class | | Ready |
| 1.2 | | Astro2020/segmented or monolith | | |
| 1.2.1 | | | Segments in 1.2-m class | Ready |
| 1.2.2 | | | Monolith in 6-m class | Methods exist but facility adds |
| 2. | Lightweighted to preserve high eigenfrequency in response to… | | | |
| 2.1 | | Ground testing deflections | | Yes |
| 2.2 | | Launch loads | | Yes |
| 2.3 | | Space element response to gyros, reaction wheels and cryocoolers | Requirements and isolation definitions? | Probably yes |

A decade ago, SCHOTT introduced lightweighting methods in the 90% domain [18,19, 20,21, 22] (see Figure 8).

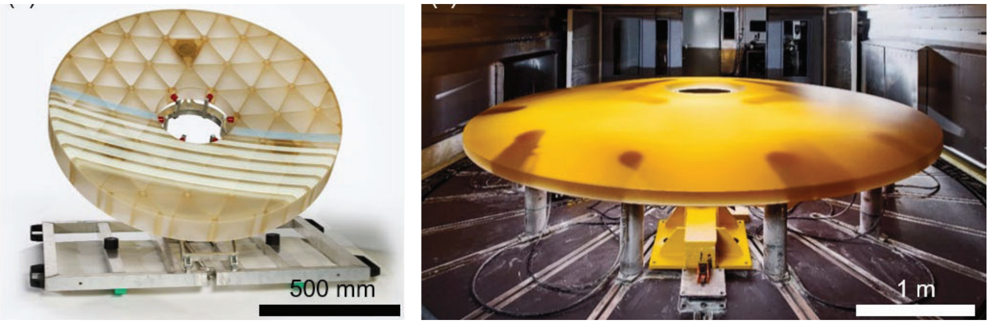

Figure 8: The left side illustrates aggressive lightweighting of ZERODUR® at the 88% level on a 1.2-meter diameter mirror. Deep isogrid pockets with 2mm thick ribs are routine and the first Eigenfrequency is >200Hz. This mirror has been tested at NASA's XRCF facility and proven to match the expectations for ZERODUR® CTE homogeneity at no more than 5ppb/K [23]. The right side illustrates the largest convex secondary mirror ever made at over 4-meters diameter, that for ESO's ELT, as monolithically cast and machined at SCHOTT [24]. Recently, SCHOTT has produced several 4-meter mirror blanks for critical astronomical applications.

In 2019, requirements for machining ZERODUR® had expanded to the extent that SCHOTT implemented and dedicated a new 5000-meter$^2$ Center of Excellence with CNC machines and Coordinate Measuring Machines enabling high accuracy lightweighting and even generation of aspheric forms with low subsurface damage. Vibration isolation and temperature control are similar to those in a precision optical fabrication shop. SCHOTT has the methods, abrasive schedule, ability to define fiducials and metrology to generate not only to the nearest sphere, but also generate general aspherical surfaces, off-axis aspheric forms and even free-form optical surfaces.

Figure 9: SCHOTT's Center of Excellence offers powerful abilities to not only lightweight, but also to address Design-To-Cost (DTC) in support of minimizing unnecessary work at the subsequent optical fabrication stage.

## 4.0 Conclusion

Via extensive published research and development, SCHOTT has characterized ZERODUR® into the special position being able to answer yes to each of the questions that flow from creating the imminent large observatories envisioned by Voyage 2050 and Astro2020. ZERODUR® has over a half-century heritage as a very low CTE, stable material optimized for astronomical telescopes. Employed in space telescopes for decades, it is now available from SCHOTT in stiff, highly lightweighted mirror substrates. Full scale production is being demonstrated by present production over half of the 949 mirror segment substrates needed for ESO's 39-meter Extremely Large Telescope.

Infrastructure is fully in place to routinely manufacture, characterize and lightweight mirror substrates to just over 4-meters in diameter. Since SCHOTT has manufactured multiple 8-meter ZERODUR® mirror substrates for ESO's VLT, processes are in place, although all the infrastructure has not been maintained due to hiatus in demand. Facilitization would be needed to address mirrors larger than 4-meters if large monoliths are needed. One advantage of ZERODUR® over competing potential substrate materials is that only ZERODUR® has been demonstrated to be made from a single homogeneous casting in sizes of 1.5-meters and larger. For alternative materials, the homogeneity of multi-piece fused or bonded substrates (as needed in larger sizes) has not been studied in the context of "ultrastability" requirements as exacting as 10-picometers over $10^4$ seconds. In contrast, a ZERODUR® mirror is presently made from a single casting as large as 4-meters, and larger mirrors have been made. Fused or bonded multi-piece inhomogeneity is not a factor with ZERODUR®. As exhibiting the lowest CTE of materials in this menu and also the most homogeneous CTE distribution, technology for ZERODUR® has the greatest likelihood of satisfying pending Ultrastability requirements for upcoming Large Observatories.

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