Zerodur

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Introduction

Zerodur is the trade name of a low thermal expansion glass-ceramic composite material made by Schott Glass. This report summarizes the chemical, physical and optical properties of Zerodur and discusses the applications for which this material is suited.

History

Borosilicate glasses $\alpha \sim 3$ ppm/°C were developed in the late 1800s. These glasses had poor optical properties but found use in commercial cookware (Pyrex©, for example). The next major advance in low CTE glasses came with the accidental discovery of glass-ceramic composites by Dr. S. D. Stookey at Corning glass in 1952. The material discovered at Corning was not transparent, and was commercialized as as Corningware, a cookware product, in 1957.

Schott Glass initially pursued research on glass-ceramic composites for the same reason. The development of a glass-ceramic composite for scientific use began in 1966 as a collaboration between Schott and the Max Planck Institute for Astronomy, which was interested in using an ultra-low CTE material mirror blank. The requirements were:

- CTE ~ 50 ppb
- E ~ 70 GPa
- Homogeneity comparable to standard optical glasses
- Sufficient transparency to test for striae
- Shapeable to ~ $\lambda/10$ at 546nm
- Aluminum adhesion comparable to standard glasses

After two years of intensive research, a material was found which met all of these requirements - Zerodur.

Structure and Composition

The distinguishing property of Zerodur, its ultra-low CTE, is the result of its glass-ceramic composite structure. This means that both amorphous and crystalline phases are present in the material. In Zerodur, crystals about 50nm in diameter are suspended in the amorphous material. The amorphous phase has a positive CTE, but the crystalline phase has a negative CTE. Careful control during the manufacturing process adjusts the two phases to a ratio of 70%

crystals 30 - 50 nm in diameter and 30% amorphous glass. At this ratio the net CTE of the material is essentially zero.

The chemical composition is given in table 1 below:

Material	**% by weight**
SiO_2	57.2
Al_2O_3	25.3
P_2O_5	6.5
Li_2O	3.4
TiO_2	2.3
ZrO_2	1.8
ZnO	1.4
MgO	1.0
As_2O_3	0.5
K_2O	0.4
Na_2O	0.2

Table 1: The chemical composition of Zerodur.

The crystalline phase of the primary constituents, SiO_2, Al_2O_3 and Li_2O exhibit the negative CTE behavior. The remaining constituents are present to help control the crystallization process and give the material its desired mechanical and optical properties.

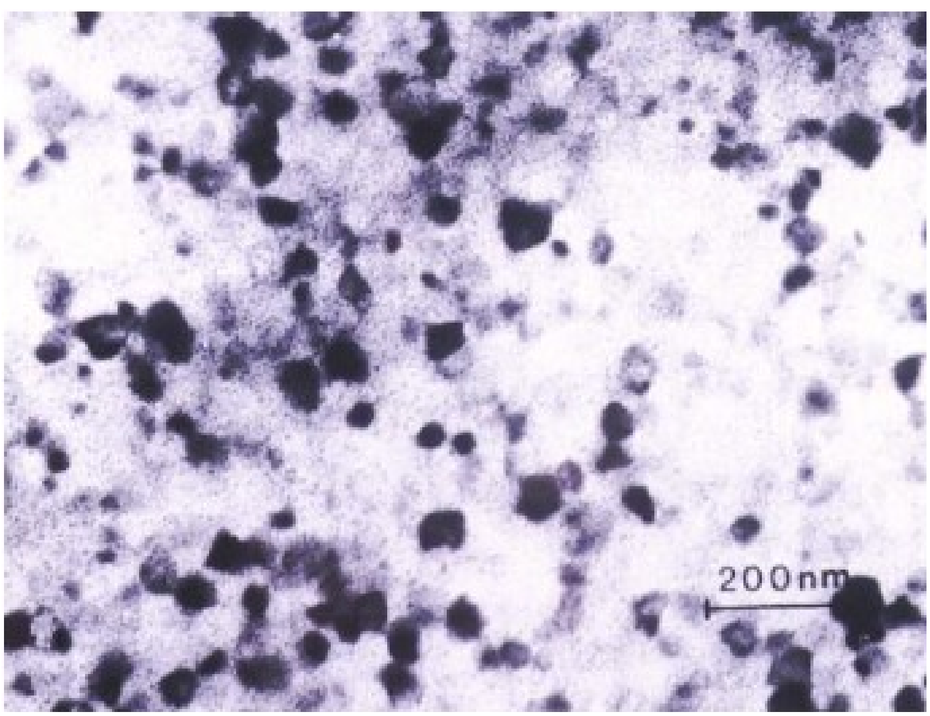

Figure 1: The microstructure of Zerodur

Optical Properties

The optical properties of Zerodur are fiven in table 2 and in figures 1 and 2. Zerodur has a low transmittance relative to most glasses. This is due to the two-phase structure of Zerodur; light undergoes Rayleigh scattering by the embedded crystals. However, it does have relatively high transmittance in the 3 - 4 μm range (the L band in infrared astronomy), which could make it a candidate for certain IR applications. It is useful that Zerodur have <u>some</u> transmittance, however, because this allows the material to be examined for striae and stress birefringence, both of which cause inhomogeneities in the CTE.

Index of refraction	1.5424
Abbe number	56.1
dn/dT	$14.3\times10^{-6}/°C$
Stress optic coefficient	3.0×10^{-6}/MPa

A large Zerodur blank. This picture shows the consequences of Zerodur's unusual transmittance properties.

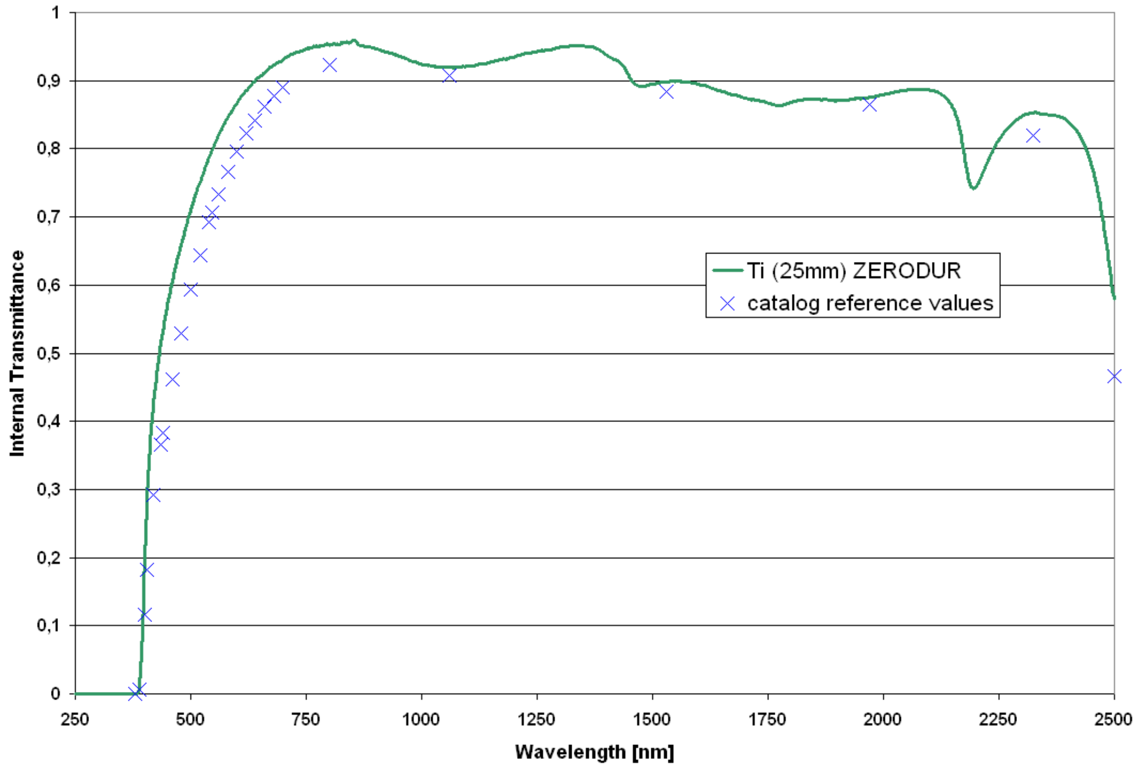

Figure 2: The transmission curve of a 25mm thick sample of Zerodur. The measured values for the measured batch (green line) are slightly larger than the catalog reference values due to normal batch-to-batch variations.

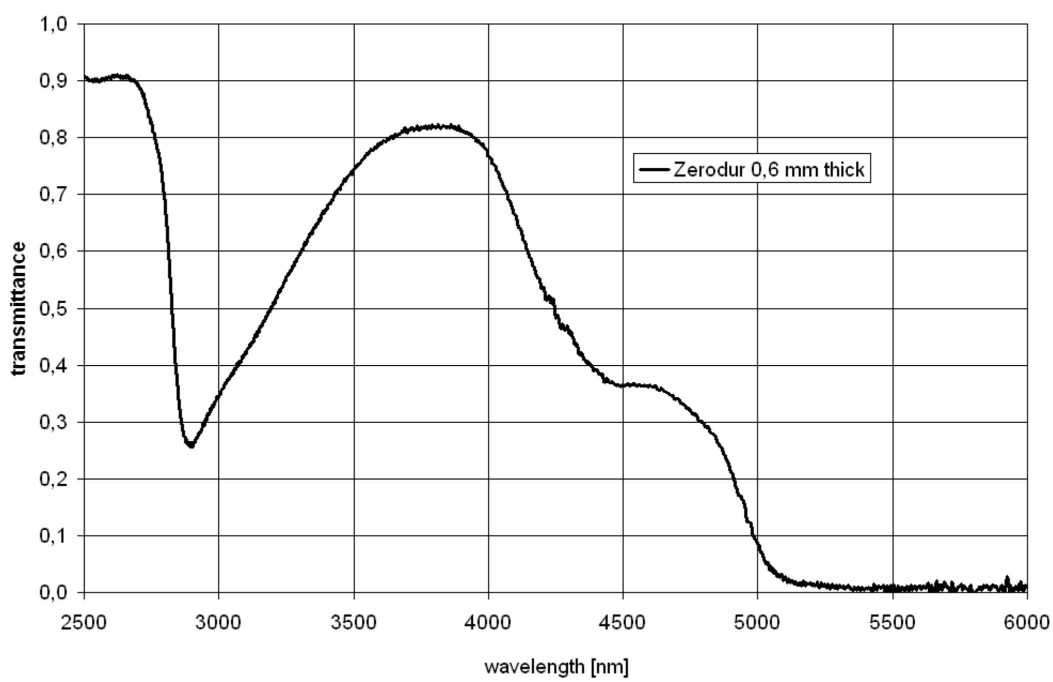

Figure 3: The transmission curve of a 0.6mm sample of Zerodur in the infrared.

Thermal and Physical Properties

The behavior of the CTE of Zerodur is summarized in table 3 and figure 4:

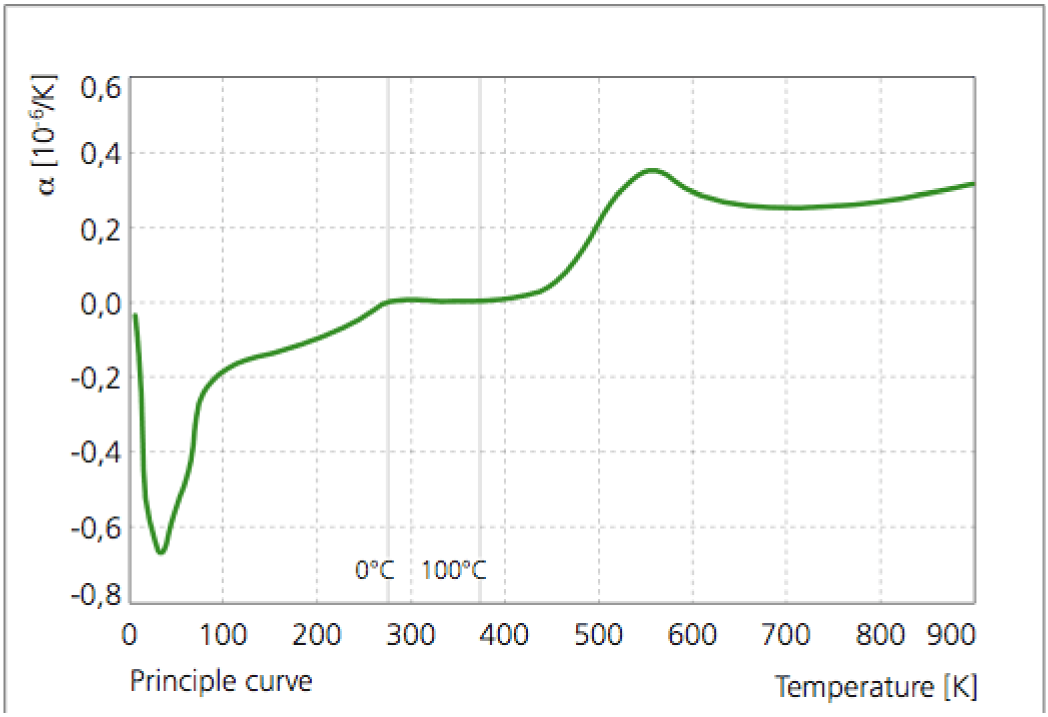

Figure 4: The CTE of Zerodur as a function of temperature. Batches of Zerodur have been produced with a CTE as low as ±1.2 x 10^{-9}/°C.

CTE (0°C; 50°C) Specification tolerances	
Expansion Class 0	$0 \pm 0.02 \cdot 10^{-6}$/K
Expansion Class 1	$0 \pm 0.05 \cdot 10^{-6}$/K
Expansion Class 2	$0 \pm 0.10 \cdot 10^{-6}$/K
Tighter tolerance available upon request.	

Table 3: This table describes the CTE for standard classes of Zerodur sold by Schott.

In practical terms this means that the diameter of an 8 meter mirror blank made of expansion class 1 Zerodur would undergo a change of only 0.4µm/°C.

Additional physical properties of Zerodur are given in table 4.

Young's modulus E @20°C	90.3 GPa
Poisson ratio ν	0.24
Density	2.53 g/cm^3
Thermal conductivity λ @20°C	1.46 W/m/°C
Knoop hardness	620
Maximum application temperature	600°C
Residual surface roughness	as low as 1nm

Table 4: Physical and thermal properties of Zerodur.

These numbers are typical of an ordinary glass. In addition, Zerodur is not measurably affected by most acids an alkali. This is an important consideration for telescope mirrors that may undergo repeated recoating.

Applications

Extreme thermal stability is not necessarily a desirable quality in a glass; for example, it makes mounting difficult. In addition the extremely high cost of Zerodur makes it an impractical choice in most cases. There several applications, however, where the special properties of Zerodur make it the glass of choice.

The most visible of these is in astronomy. A large telescope mirror inevitably contains thermal gradients. In ordinary glass these will induce figure irregularities that degrade the final image. This problem is especially acute if the mirror is to be used in space. A mirror made of Zerodur eliminates this problem completely. For this reason a substantial number of large modern ground-based and satellite telescopes use Zerodur:

- The Keck I and Keck II telescopes, Mauna Kea, Hawaii (segmented mirrors)
- Very Large Telescope (VLT) 8.2m mirror, European Southern Observatory
- SOFIA airborne infrared telescope 2.7m mirror
- CHANDRA X-ray Observatory grazing incidence mirrors

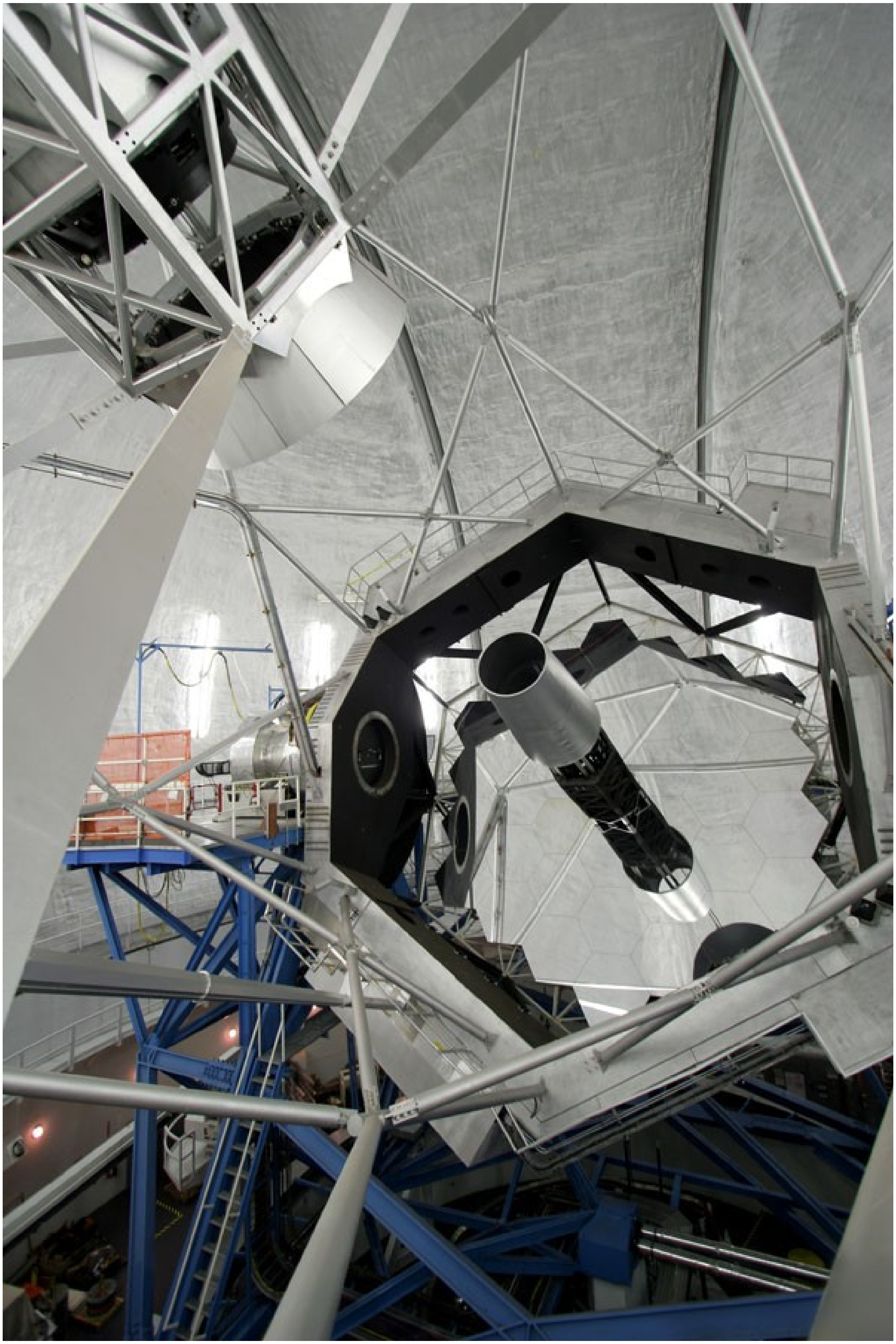

Figure 5: The Keck II primary mirror.

A less dramatic but far more common use of Zerodur is in industrial applications. Many manufacturing processes require extreme dimensional stability. A prime example is photolithography, where a beam of light must be guided reliably to submicron accuracy. Figure 6 shows a schematic of a photolithography system used by Canon to make LCD displays. All of the optical elements in this system are made of Zerodur.

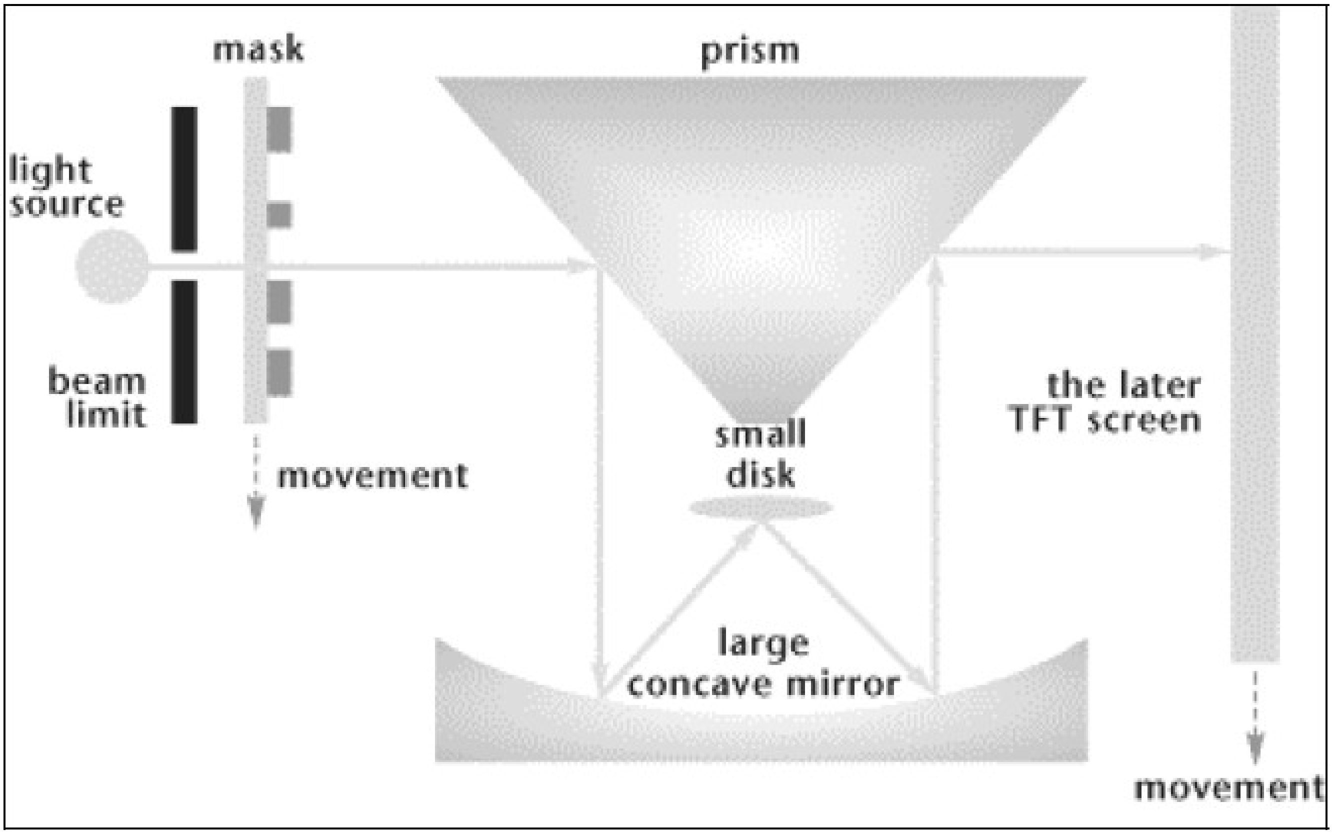

Figure 6: All of the optical components in this photolithographic system are made of Zerodur.

Another industrial use of Zerodur is as a structural material in assemblies where extreme dimensional stability is required. Zerodur can be shaped diamond grinding using CNC milling machines, so the fabrication of complex parts is possible. (Bulk removal is also possible using water jetting). Figure 7 shows some examples of parts made with Zerodur.

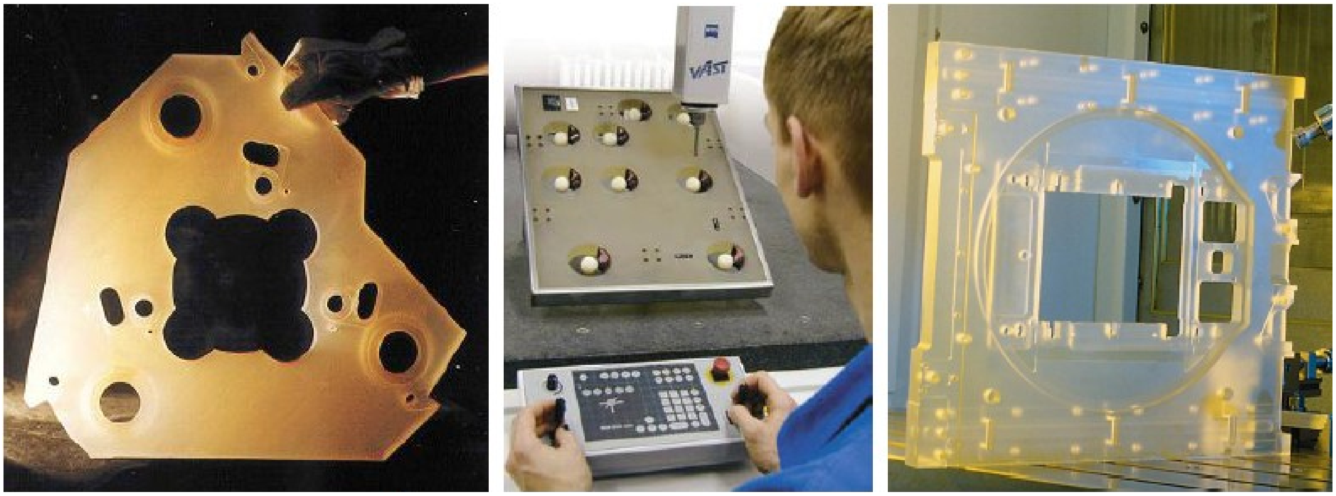
Figure 7: Structural parts made of zerodur.

Zerodur is also used as a material for measuring guages. The length stability of Zerodur has been measured at better than 10^{-7}/yr, which generally superior to a metal gauge by a factor of ten or so.

Other Materials

Two alternatives to Zerodur are ULE, made by Corning Glass, and Clearceram, made by Ohara. ULE has ben used in several major telescopes, including the Hubble Space Telescope and the Subaru Telescope on Mauna Kea in Hawaii. Clearceram has been used primarily in industrial applications.

Zerodur has been shown to exhibit a small amount of thermal hysteresis at temperatures between -70°C and +40°C. The hysteresis effect reverses over a "relatively short time" (Schott). ULE does not exhibit this effect. In applications where rapid temperature changes occur within this temperature range, ULE may be the better choice.

Summary

Zerodur is a glass-ceramic material with an extremely low CTE ($\alpha \sim 0.05 \times 10^{-6}$), but otherwise exhibits most of the properties of a mormal glass, with the exception of its transmittance. It is extremely homogeneous and temporally stable. It is capable of taking an extremely smooth (~ 1nm) polish and is essentially unaffected by most chemicals, which makes it suitable for mirrors that require repeated recoating. It is also suitable for many industrial uses requiring extreme dimensional stability because of its ease of shaping with diamond grinding.