Large Stable Mirrors: A Comparison of Glass, Beryllium, and Silicon Carbide

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Abstract

Traditionally, glass has been used for large mirror. Improvements in silicon carbide and analysis of beryllium now allow for other options. This paper goes through the methodology for comparing the three materials.

Analysis

Lightweight Mirror Design Parameters

For every analysis, two different types of basic mirror structures were evaluated: open back or sandwich, shown in Figure 1. The mirror core is described by height (h_c), web thickness (t_w), and cell shape (square, hexagonal or triangular). The face thickness is shown in figure 1 as t_f.

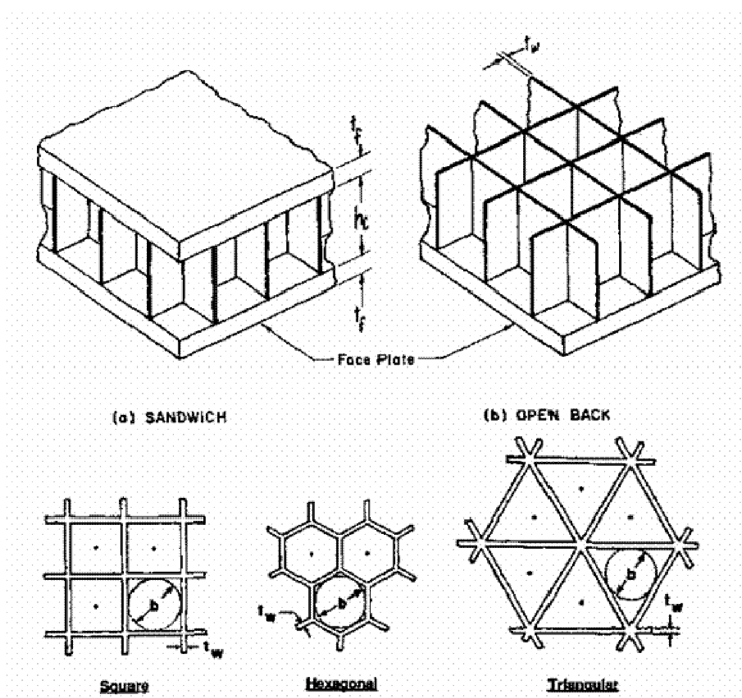

Figure 1: Mirror back construction

Figures of Merit

Certain figures of merit were chosen in order to compare the three materials.

1. Weight
2. Area weight density, which is the weight per area (w/A)
3. Flexural Rigidity, which is a measure of the structural stiffness

$$D = \frac{IE}{1-\upsilon^2}$$

I = Moment of inertia
E = Young's Modulus
ν = Poisson's Ratio

4. Natural Frequency – it is important that the natural frequency is not excited during launch, so a minimum value is usually specified

$$f_o = \left(\frac{\lambda^2}{2\pi}\right)\sqrt{\frac{D}{AW}}$$

D = flexural rigidity
A = mirror area
W = mirror weight
λ = constant that is function of the mirror shape/mounting

5. Characteristic Length, L, which is a measure of the spatial extent of influence, which determines how far apart the actuators can be for an active mirror

$$L = \left(\frac{R^2 D}{t_e E}\right)^{1/4}$$

R = radius of curvature of the mirror
t_e = thickness of a solid mirror having the same weight/area (effective thickness)

Trade Methodology

All analyses looked at both the sandwich and open back designs. An aggressive was compared to a conservative approach for the design of the faceplate and web thickness. The aggressive approach pushed the limits of manufacturability and material, while the conservative approach was low cost and low risk. The core designs were done with adjustable b (the distance between ribs, as shown in Figure 1) to control the quilting to a predetermined limit, which was a cell deflection of λ/80 at 632.8 nm. It is important to note that all core sizes were different because a different pressure was used for the different materials: 2 psi for glass, 1 psi for beryllium (Be), and 2 psi for silicon carbide (SiC). For a fixed t_w, t_f, and b, the core height, h_c, was varied to produce a continuum of point designs having different area weight densities. For weight and f_o, a mirror was chosen with 1.5 m diameter, f/1.5, and 25% obscuration.

Design Parameters

Four material types were compared: Be, ULE, fused quartz (FQ) and SiC. Everything was done at room temperature. Table 1 lists the material properties and design parameters. These values are generic and change for the conservative or aggressive designs.

MATERIAL	YOUNG'S MODULUS E (GPa)	DENSITY (g/cc)	SPECIFIC STIFFNESS E/ρ	FRACTURE TOUGHNESS K_{IC} (MPa $\sqrt{M}$)	POISSON'S RATIO ν
ULE	67	2.21	30.3	<1	0.17
FUSED QUARTZ (FQ)	72	2.19	32.9	<1	0.17
SILICON CARBIDE (SiC)	324	2.93	110.6	≥5	0.20
BERYLLIUM (Be)	287	1.85	155.1	>10	0.07
PREFERRED	HIGH	LOW	HIGH	HIGH	LOW

Table 1: Mirror substrate mechanical properties

Parametric Trades

The first trade varied h_c and compared the flexural rigidity, natural frequency and characteristic length versus the area weight density. Figures 2 and 3 show a linear relationship for the sandwich and open back designs.

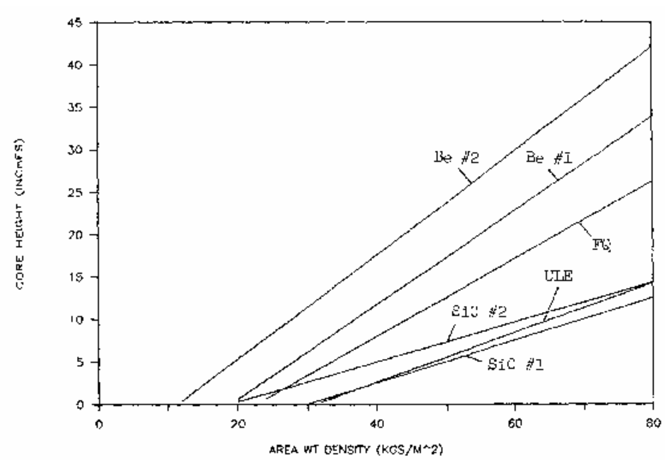

Figure 2: Core height of sandwich back design vs. area weight density

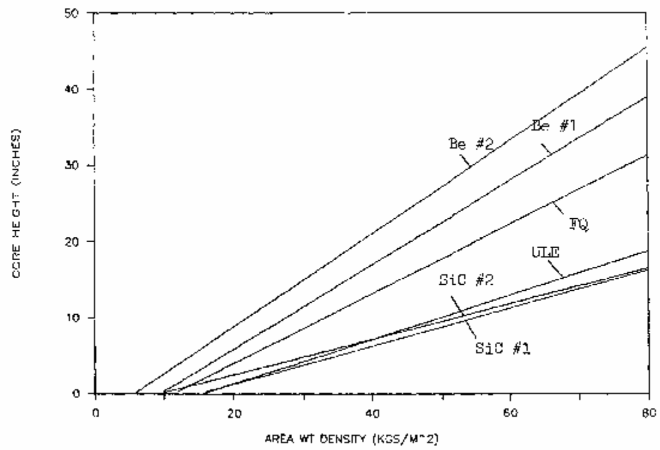

Figure 3: Core height of open back mirrors vs. area weight density

Next, the flexural rigidity was compared. As is seen in Figures 4 and 5, Be has the highest flexural rigidity by at least an order of magnitude. For each class of materials, the more aggressive designs have a higher flexural rigidity than the conservative designs. Also, the open back design dominates for low area weight density, but the closed back designs dominate for higher area weight density.

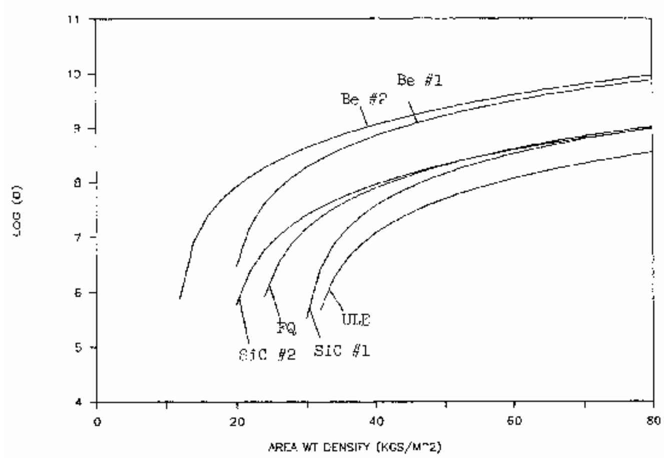

Figure 4: Flexural rigidity of sandwich design vs. area weight density

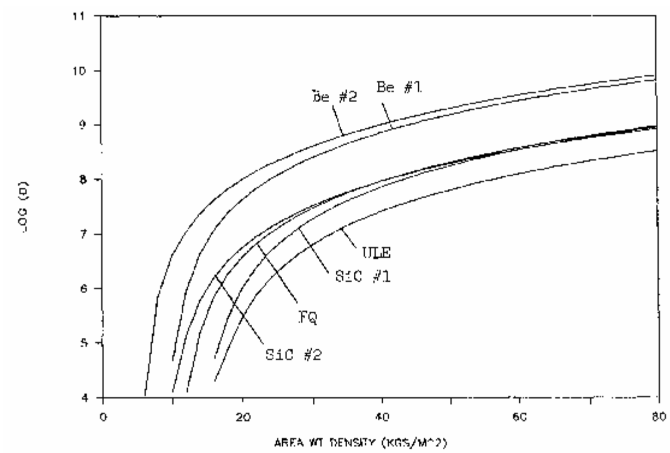

Figure 5: Flexural rigidity of open back design vs. area weight density

The natural frequency is proportional to square root of the ratio of the flexural rigidity to the area weight product. By comparing designs with the same area weight product, the designs with the largest flexural rigidity have the highest natural frequency. Also, for designs with the same natural frequency, the least flexural rigidity gives the lowest weight. Be designs have the largest values of natural frequency with a large margin. FQ and SiC have very similar natural frequency for open back and sandwich designs. See Figures 6 and 7.

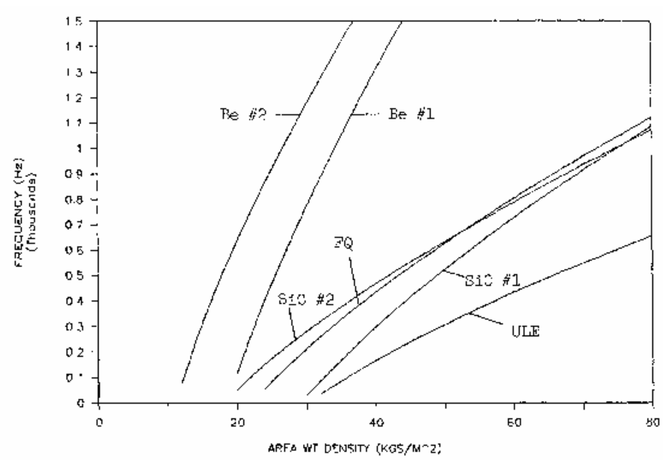

Figure 6: Natural frequency of sandwich designs vs. area weight density

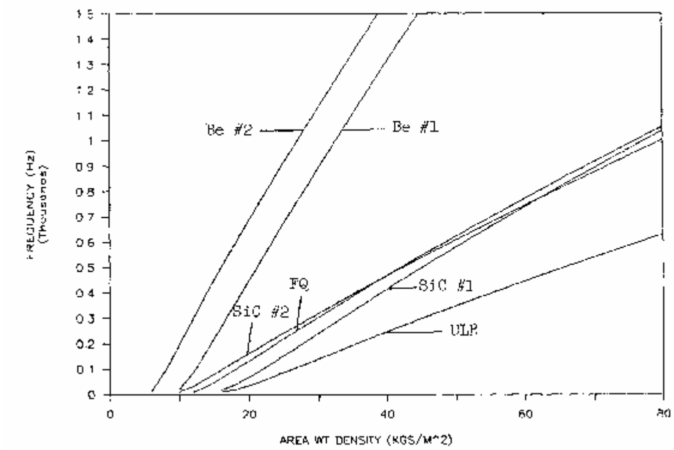

Figure 7: Natural frequency of open back designs vs. area weight density

The weights were then compared for equal natural frequencies, noting the area weight density. For simplicity, only frequencies of 100, 300, and 500 Hz were used. For open back or sandwich designs, Be is the lightest. The conservative ULE design is the heaviest. The aggressive SiC design is lighter than both glass designs, but heavier than Be. The thin web thickness and large core height of FQ makes it structurally sufficient and nearly equal to the aggressive SiC design. However, it is probably not practical to manufacture this type of mirror.

Active Mirrors

Sometimes designs require active motion in order to deform the mirror. This may save weight and add flexibility to improve the errors in the design, but this is done at the cost of complexity. Stiffness must be traded with the actuator spacing. The characteristic length measures the region of influence of the actuator. Be mirrors have the largest characteristic length, which implies it needs the fewest actuator. FQ designs have a higher characteristic length than SiC except at the lowest area weight densities b/c of the low value of E.

Conclusions

SiC is lightweight and has characteristics between glass and Be. It also has very good specific stiffness. Be has the best mechanical properties and makes the lightest mirrors. Open back designs are more efficient than sandwich designs at low area weight densities.

It must be noted that thermal effects were not taken into consideration. For a specific use of these materials, the thermal properties must be evaluated.