Silicon Carbide Technologies for Lightweighted Aerospace Mirrors

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Abstract: The use of monolithic glass and beryllium to produce lightweighted aerospace mirror systems has reached its limits due to the long lead times, high processing costs, environmental effects and launch load/weight requirements. New material solutions and manufacturing processes are required to meet DoD's directed energy weapons, reconnaissance/surveillance, and secured communications needs. Over the past several years the Air Force, MDA, and NASA has focused their efforts on the fabrication, lightweighting, and scale-up of numerous silicon carbide (SiC) based materials. It is anticipated that SiC can be utilized for most applications from cryogenic to high temperatures. This talk will focus on describing the SOA for these (near term) SiC technology solutions for making mirror structural substrates, figuring and finishing technologies being investigated to reduce cost time and cost, and non-destructive evaluation methods being investigated to help eliminate risk. Mirror structural substrates made out of advanced engineered materials (far term solutions) such as composites, foams, and microsphere arrays for ultra lightweighting will also be briefly discussed.

Keywords: large lightweight mirrors, space based mirrors, materials and processes, SiC mirrors

1. The Need for Advanced Materials for Aerospace Mirrors

Aerospace mirrors are pervasive in current and future government systems. Agencies of the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) have identified airborne and space based systems that will require mirrors ranging in size from 0.1 to 100 meters in diameter. Large, lightweight, high precision mirrors are critical for enhanced surveillance/reconnaissance missions, directed energy weapons and communication systems, laser radar systems, X-ray and UV telescopes, as well as large astronomical telescopes. Mass, size, first modal frequency, and reliability are major issues that are affected in these applications due to flight/launch constraints and anticipated life times. Cost, production infrastructure, and scheduling are important technology drivers in some missions where high acreage is required. In all these applications, lightweighting of the mirror is crucial because the weight of the mirror affects the size and weight of the support and slewing structures (a cascading effort). Unfortunately, it appears that current glass mirror materials have reached their lightweighting limit, so additional weight reduction is only possible through new material considerations and/or optimized hybrid material designs.

The requirement for large lightweight telescopes continually increases for space borne missions (Fig. 1). There is need for larger aperture, lower areal density, and increased durability in space environments. For instance, the primary mirror for a current telescope systems consist of a monolithic design with a diameter of up to 1.5 meters to fit inside shrouds. The mirror is shielded or encased within the shroud so fracture toughness of the mirror may not be a major issue. However, future space based surveillance/reconnaissance systems would require very large mirrors, 10 to 15 meters in diameter. Segmented design with segments no larger than about 3.25 meters will be required so that they could be stowed in the Space Shuttle cargo bay or some other launch vehicle shroud. Once launched to proper orbit these segments would then be assembled or deployed. To meet the launch payload weight constraints, the mirror would also have to be substantially lightweighted to an aerial density well below 15 kg/m^2. Their reliability and robustness is a major concern because they will be un-shielded and exposed to the high launch loads, in-space assembly damage, and micrometer impacts. The successful development of the James Webb Space Telescope (JWST) by NASA will

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14. ABSTRACT
The use of monolithic glass and beryllium to produce lightweighted aerospace mirror systems has reached its limits due to the long lead times, high processing costs, environmental effects and launch load/weight requirements. New material solutions and manufacturing processes are required to meet DoD?s directed energy weapons, reconnaissance/surveillance, and secured communications needs. Over the past several years the Air Force, MDA, and NASA has focused their efforts on the fabrication, lightweighting, and scale-up of numerous silicon carbide (SiC) based materials. It is anticipated that SiC can be utilized for most applications from cryogenic to high temperatures. This talk will focus on describing the SOA for these (near term) SiC technology solutions for making mirror structural substrates, figuring and finishing technologies being investigated to reduce cost time and cost, and non-destructive evaluation methods being investigated to help eliminate risk. Mirror structural substrates made out of advanced engineered materials (far term solutions) such as composites, foams, and microsphere arrays for ultra lightweighting will also be briefly discussed.

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incorporated these types of concepts using cryo-cooled beryllium mirrors that have a projected areal density requirement at the 20-25 kg/m^2 [1]. The Webb telescope is scheduled to be launched in the 2013 timeframe with capability far exceeding the current Hubble Space Telescope, which has an areal density of the primary mirror of ~180 kg/m^2.

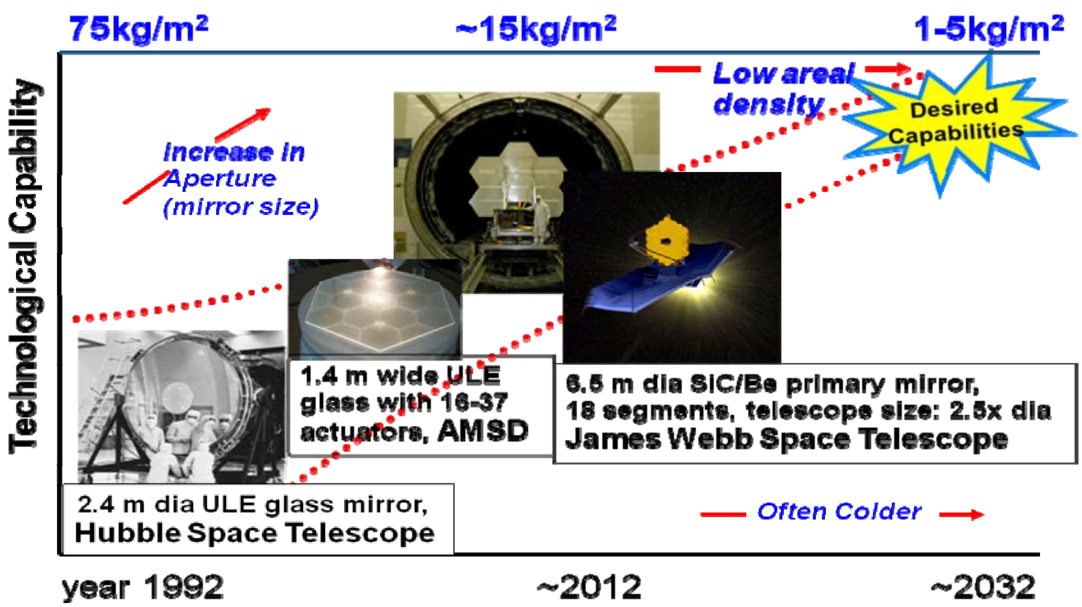


Fig. 1. Historical and projected technological capabilities in large space mirrors.

2. Current Monolithic Mirror Substrate Materials

For hundreds of years silica-based glasses have been used as both the optical and structural substrate for mirrors. They make a good optical substrate due to their low softening point, low hardness, and the absence of a grain structure. This amorphous microstructure, allows for a wide variation in chemistries, which is used to tailor the coefficient of thermal expansion (CTE) to values approaching zero at various use temperatures. These mirror glasses provide dimensional stability of the mirror figure with respect to the thermal variations of the environment. Unfortunately, glass makes a poor structural substrate due to it low modulus, tensile strength, thermal conductivity and fracture toughness. To overcome these shortcomings, thick and heavy mirror designs have been used along with good handling and mounting practices. Reliability and robustness was assured in space-based systems by encasement of the mirror system into metallic tube structures. However, in future airborne and space-based mirror systems where weight and size are constrained by the payload requirements; this shielded approach is not feasible. In these new systems robustness will have to be provided by either new structural substrate materials with high modulus, strength, and fracture toughness or with new hybrid materials designs.

A brief review of the glass chemistry and its effects on mirror performance is included as follows. Silica-based glass is an inorganic material with a metastable amorphous structure. Most glasses are produced by supercooling their liquids to a rigid condition without crystallization, however, some glasses are prepared without cooling from the liquid state such as vapor grown or solution grown glasses. In either case, the atoms of a silicate glass form a continuous framework of silicon oxygen tetrahedral bonded together at their corners (Fig. 2). The bonds are strong but they have a large variation in the Si-O-Si bond angle. Such a random network is not necessarily uniform and local variations in density and structure are to be expected. This variability allows the absorption of thermally inducted vibrational energy through transverse modes of vibration and the adjustment of bond angles.

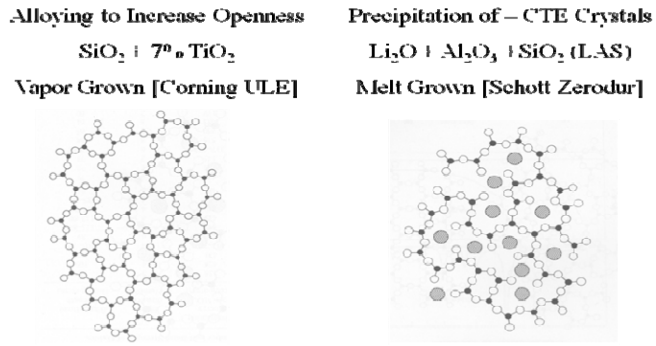


Fig. 2. Structural framework of a silicate glass and methods to modify it to tailor its CTE

The coefficient of thermal expansion (CTE) of a glass can be tailored by modifying its structure through alloying to open up its structure, like with Ultra Low Expansion (ULE) glass from Corning or by homogeneous precipitation of negative CTE crystalline phase, like with Zerodur from Schott Glass [2], (Table 1). ULE and Zerodur both can show dimensional instability if segregation of the elements occurs during processing of large boules, resulting in non-homogeneous dispersion of the alloying elements or the negative CTE phase. Polishing and print-through distortions may also become a problem for high-resolution mirrors if the crystalline phase is allowed to grow much larger than 200nm.

Table 1. Properties of several different materials

Properties:	Density (ρ)	Young's Modulus (E)	CTE @ RT (α)	RT Thermal Conductivity (k)	RT Fast Fracture Tensile Strength	RT Bending Strength	RT Fracture Toughness	Hardness Knoop	Typical Surface Finish
Units:	Kg/m^3 x 10^{-3}	GPa	ppm / K	W/m K	MPa	MPa	MPa-m$^{1.5}$	kg/mm2	
mirror #1 DESIRED:	LOW	HIGH	LOW	HIGH	HIGH	HIGH	HIGH		
Silicon (Si) (Single Crystal)	2.33	147.00	2.60	150.00					2
Silicon (Polycrystalline)	2.33	130.00	2.74	150.00			15	1150	3
Graphite fiber-T300	1.75	500.00	-0.10						
C nanofibers-Pyrograph 3 (as-grown)	1.8	400		20	2700				
C nanofibers-Pyrograph 3 (heat treated)	2.1	600	-1	1950	7000				
Alpha Silicon Carbide by Sintering	3.20	450.00	2.20	180.00		374	2.8	2740	30
Beta Silicon Carbide by CVD	3.21	466.00	2.20	300.00			3	2450	3.4
Beta Silicon Carbide by Vap. Rx, 80%dense	2.55	214.00	4.60	143.00	129	147	2.3	1992	
Nicalon SiC Continuous Fiber	2.55	220.00	3.90	1.40	3000				
Rx. Bonded Silicon Carbide@80%SiC+20%Si	3	380	2.9	150		280	4		20
Carbon/SiC discontinuous	2.70	250.00	2.00	125.00					
Si - SiC/SiC (continous reinforcement)	2.80	320.00	4.50	210.00			10		
Fused Silica	2.20	73.00	0.55	1.50					
ULE (Corning)	2.20	67.00	0.02	1.30			1.8		3
Zerodur (Schott)	2.53	91.00	0.05	1.67		10	0.9		3

Significant effort has been made over the past twenty years to reduce the weight of airborne and space-based glass mirrors. These efforts were driven by needs to reduce launch costs, to decrease the thermal mass in order to equilibrate temperatures in shorter times, and to minimize the weight and complexity of the support and handling equipment. The Hubble Space Telescope mirror was a lightweight design [3] and produced using a frit bonding process to join individual ULE glass plates to create an open-faced honeycombed core structure. The core was then frit bonded between two ULE glass face-sheets to produce a lightweight mirror blank. This mirror was ground, polished, and vapor coated with aluminum to create a visible light reflective surface. The major problems encountered in this process were thermal distortions and uneven stresses in the plates and joints. In addition, the method was extremely labor intensive, time consuming, and expensive.

In the late 1990s the DoD and NASA ran the Advanced Mirror Systems Demonstrator (AMSD) program to help define the limits of lightweighting meter sized mirror segments for both ambient and cryogenic space thermal conditions [3, 4]. Glass mirrors were fabricated by teams lead by Kodak and Goodrich (Fig. 3). Both showed that areal densities for lightweighted glass could be reduced to the 15 kg/m^2 range and the cost and fabrication time could be reduced to half that of a comparable Hubble mirror. Similar results were found by the Ball Aerospace for beryllium substrates and this material was selected for the Webb telescope. SiC substrates where dropped from consideration due to the lack of scale-up infrastructure and processing maturity issues.

Fig. 3. Kodak's lightweighted glass mirror segment with ULE honeycomb core produced in the AMSD program. (1.4 m)

3. New Materials and Processes

Advances in various materials and processes have evolved over the past several years for large lightweight mirrors. Mirror substrate can be notionally sub-divided into optical, structural, and mechanical substrates (Fig. 4). The requirements for the new materials depend on which sub-category it will be placed in. The mechanical substrate consists of the stiff backplate which is actuated and fastened to the underlying reaction structure. The structural substrate consists of facesheet, which meets the surface figure, finish and scattering requirements as well as a core rib structure which provides structural stiffness and the backplate. Finally, the optical substrate consists of mainly the cladding and coatings on the facesheet which provide the reflectivity needed for the specific application. All of these substrates need to be designed and processed with a stress balanced or stress free configuration

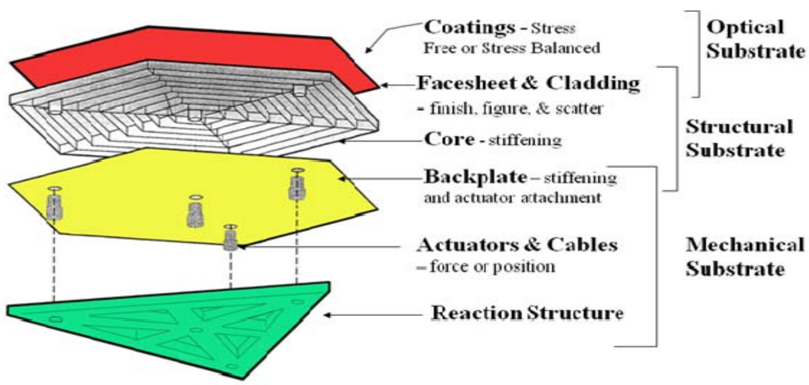


Fig. 4 Schematic of lightweighted linear actuated mirror.

3.1 Lightweight Glass Mirrors

Over the past five years the Air Force Research Laboratory (AFRL/RX) has sponsored research to create a tool kit for the glass industry which contains near zero CTE glass sols and geo-polymers for use as bonding and repair agents and surface claddings to help eliminate figure and finish distortions as well as glass micro-spheres and balloons for fillers to produce glass foam type structural substrates (Ref 5).

Foam based substrate designs should result in low areal density mirrors that may be more robust than current honeycomb web designs. A micro-sphere array mirror should eliminates the quilting distortions due to the large web spacing needed for AWJ machining in current monolithic glass mirrors discussed previously. Additionally, a micro-sphere array mirror eliminates the continuous crack path at the web-factsheet joints. The sol-gel chemistry approaches also allow for the incorporation of nano-particles or nano-fibers to tailor the tensile strength, modulus, thermal conductivity and fracture toughness of the mirror substrate. As an example, AFRL and some of its contractors have produce small replicated mirrors which used a combination of either organic or inorganic polymers to bind glass micro balloon together in arrays (called syntactic foams). Some of these systems are CTE tailored with negative CTE nano-dispersoid for CTE control and carbon nano fibers added for increase in strength and thermal conductivity (Fig. 5). Future work in this area will be directed toward scale-up, optimization for specific applications and characterization in air and space environments.

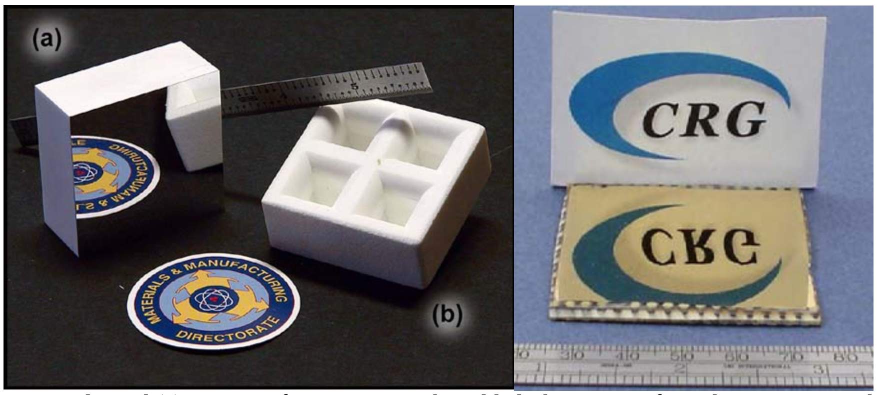
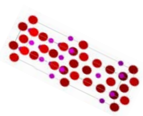
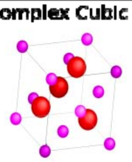
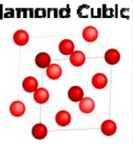


Fig. 5 Replicated (a) syntactic foam mirror with molded rib-structure for reducing part weight.
(b) Cornerstone Research Group polymer composite replica mirrors [6].

3.2 Silicon Carbide-Based Mirrors

Following the AMSD program, the DoD and NASA has invested heavily in Silicon Carbide (SiC) optics. SiC is a promising materials for use as structural substrates because of its high specific stiffness (high modulus and low density), low thermal distortion susceptibility (low thermal expansion and high thermal conductivity) and capability to be used at high, ambient and cryogenic thermal conditions. There are many types of SiC-based materials shown in Table 2 and each has a little different thermal physical and mechanical properties. Additionally each has a different cost and schedule associated with it.

Table 2. Common SiC types and crystalline forms of SiC and Si.

Type	Structure	Details	
Alpha (α - SiC)	Rhombohedral/ Hexagonal 	Produced when Processing Temperatures Exceed 2000° C Hexagonal Crystal Structure	Sintering [Astrium/Boostec/CoorsTec] Anisotropic Properties Acicular Morphology
Beta (β- SiC)	Complex Cubic 	Produced When Processing Temperatures are Below 2000° C Cubic Crystal Structure	Gas Phase Reactions [Poco], CVD/CVI [many companies], and PIP [Starfire] Isotropic Properties Equiaxed Morphology
Silicon (Si)	Diamond Cubic 	Used as a Cladding, Foam, and Infiltrant. Cubic Crystal Structure	Similar Density, CTE, and Conductivity to SiC Isotropic Properties Equiaxed Morphology

1) Alpha (α-SiC), has a rhombohedal or hexagonal structure and is produced by processes that exceed temperatures greater than 2000°C. Sintered alpha SiC is produced in the US by CoorTek and in Europe by Boostec (Fig. 6) [7]. Sintering of pure alpha (α -SiC) mirror substrates to full density is difficult and only achievable using both sub-micron powders and sintering aids. The oversized, machined green body part is sintered above 2100°C with approximately 17% linear shrinkage. The sintered SiC component is approximately 97% dense and contains 98 to 99% α-SiC depending upon the amount of sintering aids used.

Fig. 6 Herschel Space Telescope--All SiC infrared telescope 3500 mm aperture [7].

Fig. 7. CoorsTec 12" hexagonal flat to flat concave spherical mirror segments [8]

2) Beta (β-SiC) has a face-centered cubic structure and is produced in bulk by processes that operate below 2000°C, like chemical vapor deposition and infiltration (practiced by Trex and others), SiO gas phase reaction with graphite and polymer pyrolysis. The highest strength, highest density, smallest grain size, single-phase β-SiC is produced by controlled re-nucleation in a Chemical Vapor Deposition (CVC) process used by Trex (Fig. 7). In their process, SiC particles are added to the CVD gas stream to promote re-nucleation at the surface and the growth of equiaxial grains [9] (Fig. 8). The process offers the advantage of a five-fold increase in deposition rate than traditional CVD, including high yields but is limited to simple structures like plato structures. This process produces the highest values of modulus (460 GPa), flexural strength (400 MPa), and hardness (2850 kg/mm^2) that have been achieved in SiC. Poco Graphite produces lightweighted, near net shaped β-SiC mirrors by taking a special grade of graphite and machining it to the desired lightweighted structure followed by conversion of the graphite to silicon carbide through a gas phase reaction with SiO vapor [10]. This reaction process has a very small but predictable dimensional change. The as-converted β-SiC structure has approximately 20% porosity but this can be reduced to near zero by CVI or siliconizing. Property data for Poco's β-SiC material is lower than that of the Trex materials. Poco mirror substrates are cladded with CVD β-SiC or PVD Si to make a 100% dense mirror surface which is polishable.

3. Siliconized SiC used to avoid the shrinkage problems associated with fully sintered SiC. Two approaches are commonly used to produce this material. The first approach, slip cast α-SiC powders into molds and sinters it to a near net shaped perform with 50-60% density. This preform is then infiltrated with silicon metal by either gas phase deposition or liquid infiltration to fill the open porosity and form two-phased, silconized-SiC (Si-SiC) component. This produces a fully dense, two-phased continuous structure that is intertwined. The second approach involves slip casting SiC with carbon particulates in a polymer binder that decomposes to a carbon network upon vacuum calcination. The calcined SiC/C body is then exposed to either Si vapor or molten Si to convert the carbon phase to SiC through a reaction bonding process. Any remaining porosity is then filled with silicon metal. For visible quality optics these

materials need to be cladded with either beta SiC by CVD or PVD Si and then polished. Major produces for Siliconized-SiC is Northrop Grumman-Xinetics, L3-SSG, and M- Cubed Technologies.

Fig. 8. Trex CVC SiC

Fig. 9(a) Microstructure of CVD SiC

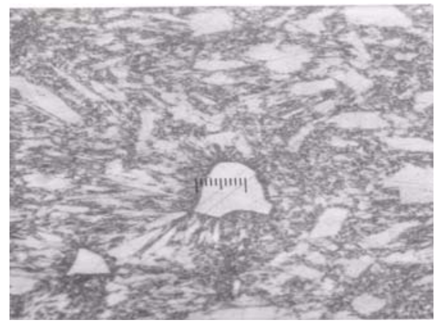


Fig. 9(b) Microstructure of Trex CVC SiC

4. Discontinuous Fiberous SiC Composite consisting of (Chopped C fiber /C interface layer /SiC matrix) can be fabricated by many processes. For example, ECM from Germany and GE from the USA, molds a mixture of SiC and C particles, polymer binder, and chopped carbon fibers (with and without an interfacial coating) into blank. These are heat treated under vacuum to form a porous graphitized green body. The green body is easily machined into a lightweighted shape using standard CNC milling equipment. Next, application of a melt infiltration with Si in a vacuum to form a near net shaped C/SiC composite structure [5, 11, 12]. Polishability of the structural substrate is improved by adding a thick cladding of dense CVD β-SiC or PVD Si to form an optical substrate.

In the past few years, many of these companies have scaled their processes to around AMSD size of over one meter in diameter. If segments large than this is required for an application then either advanced brazing techniques like those demonstrated on the 3.5 m Herschel Space Telescope primary mirror by Boostec could be employed or individual segment control like on the Webb telescope could be utilized. Government focus in SiC is now on the development non–destructive evaluation NDE techniques to quantify internal damage/defects and internal stress during the various processing stages. Additionally, we are looking at advanced figuring/finishing technologies which could be faster than conventional grind and polish methodologies. Most of these material vendors are also ready for some type of manufacturing science type program or component development efforts where many parts can be produced and their processes optimized.

3. 4 Advanced Foam Mirror Materials

The next major advancement in lightweighting will have to coming in the form of foams, fiberous composites, and hybrid material designs. Over the past several years small foam based mirrors have been produced from carbon (Touchstone), silicon and SiC (Shaffer) as well as glass syntactics both organic and inorganic based (Cornerstone RG and AFRL). The advantageous to these ultra lightweight designs is their ability to prevent quilting distortions from occurring during mirrors figuring and finishing operation. The disadvantages have been in scale-up and elimination of moisture absorption due to the increased surface area. The most advanced foam based mirror is made from silicon foam by Schaffer Corp. which utilizes a displacement reaction between C foam and SiO vapor. This occurs when SiOg + Cfoam = Sifoam + COg or when C diffusion through a CVI-Si surface coating that has been deposited onto C foam. This has enabled them to create net-shaped Si foam performs using machined C foam performs. The surface of the foam core is then closed off with either sintered Si particulate slurry or with CVD and then polished. (Fig 10) [5].

Fig. 10. SLMS™ six-inch diameter foam mirror developed by Shaffer Inc.

Continuous and discontinuous composites made from metals, ceramics and polymers have also been screened for their applicability. Most of these have issues with thermal stability that is due to high temperature processing, fiber packing irregularities, CTE mismatches, and fiber print through distortions. The incorporation of nano fibers instead of tow based fibers could possible improve on some of these problems. Additionally organic polymer matrix composites often have issues with space environmental degradation, microcracking, absorption of moisture, residual stresses, low thermal conductivity, and creep.
Polymer membrane and inflatable mirror systems appear promising because they can be made in sizes greater than 10s of meters in diameter while maintaining low weight and deployability. They are limited by their survival time in space, shape formation and retention.

4.0 Conclusions

The state-of-the-art material of choice for mirrors is monolithic glass and beryllium (for cryo-cooled optic). The AMSD program has shown that both mirror designs can be lightweighted to around 15kg/m2 and its cost reduced substantially compared to Hubble based technology. However, both technology are fast approaching their lightweighting limit and that any further reductions in the areal density will require new materials such as SiC and Si foam optics (in the near term) and hybrid/composite optics (in the far term).

With the retirement of the space shuttle and the deployment of larger and more powerful launch system in the future, reductions in lead times and processing costs will become important drivers. Mirror structural substrates made out of advanced composite materials (metal, ceramic, and polymer), foams, and microsphere arrays do allow for CTE and modulus tailorability, low-density, and high strength, stiffness, and toughness. Small sized structural substrates have been fabricated from these new emerging materials but scaling to the 1 meter size and assuring stability will be challenging. Producing the surface figure and finishes required for visible quality optics from these multi-phase complex systems will be difficult. New methods for figuring and finishing, replication, and film spinning will need to be advanced in order to produce quality optical substrate. Nondestructive evaluation and thermal-mechanical qualification will be required. Finally, research will be required to produce uniform stress free reflective coatings and dielectric stacks on such large mirror systems.

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