



Silicon Carbide Tertiary Mirror for TMT

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1. Introduction

It has been suggested that silicon carbide (SiC) would be a good material to use for the large mirrors of TMT, particularly the tertiary mirror (M3). This technical note discusses the strengths and weaknesses of silicon carbide as a substrate for the TMT M3, and suggests questions that should be answered in order to be able to consider this application.

2. Properties of Silicon Carbide as a Mirror Substrate

Designers of high-performance mirrors have been interested in SiC for some time. It has several properties that are important for high-performance mirror substrates. Of particular interest are its high stiffness-to-density ratio and its low thermal distortion properties. These properties are discussed below.

2.1 Specific Stiffness

Specific stiffness is the stiffness to density ratio of a material.

Specific stiffness = E/ρ

where: E = Young's modulus
 ρ = density

The specific stiffness of a mirror material is important for both static and dynamic performance. The self-weight bending deflection of a thin mirror is inversely proportional to the specific stiffness of its material. The resonant frequencies of mirror bending modes are proportional to the square root of the specific stiffness.

Typical mirror materials have a specific stiffness of about 30×10^3 Nm/g. In comparison, silicon carbide has a specific stiffness higher than 100×10^3 N · m/g. The specific stiffnesses of several mirror materials are listed in Table 1, containing information from Table 2 of reference 1.

Table 1. Specific stiffness of several common mirror materials.

| Material | Young's Modulus (GPa) | Density (g/cm ³) | Specific Stiffness (10 ³ Nm/g) |
|-----------------------------------------------|-----------------------|------------------------------|-------------------------------------------|
| ULE 7971 | 67 | 2.21 | 30 |
| Zerodur | 92 | 2.53 | 36 |
| Silicon carbide (reaction bonded 30% silicon) | 330 | 2.89 | 114 |
| Silicon carbide (chemical vapor deposited) | 465 | 3.21 | 145 |
| Beryllium 1-70 | 287 | 1.85 | 155 |

Silicon carbide is the densest material in the table, but because of its high specific stiffness, SiC mirrors can be made lighter than glass mirrors for the same application, particularly if they are made as lightweight structures. SiC mirrors can often use fewer support points to reach a given limit on gravity-driven deflection than glass mirrors of the same size.

SiC is competitive with beryllium in applications like fast steering mirrors, which need to have high resonant frequency and low gravity deflection on a simple (e.g., 3-point) support.

2.2 Thermal Properties

Because thermal expansion can change the shape of a mirror, precision mirrors are often made of materials having a low coefficient of thermal expansion (CTE). A low CTE makes a mirror less sensitive to differences in temperature.

For many applications, transient thermal effects caused by a changing ambient temperature or localized heat sources are a primary concern. In these cases, high thermal conductivity is helpful.

In transient heat flow conditions, a fundamental property is the thermal diffusivity, defined by the following equation:

$$\text{Thermal diffusivity} = D = K / (C_p \cdot \rho)$$

where: K = thermal conductivity
 Cp = specific heat
 ρ = density

For mirror applications, high thermal diffusivity is advantageous.

Two additional types of thermal distortion coefficient are often defined for mirror materials (see reference 1):

Steady State Thermal Distortion Coefficient = α/K

where: α = coefficient of thermal expansion

Transient Thermal Distortion Coefficient = α/D

For both of these coefficients, smaller numbers are better.

SiC has a relatively low CTE, and a relatively high conductivity, therefore it has excellent combined properties to resist thermal distortion. Table 2 compares thermal properties of several mirror materials (information abstracted from Table 2 of reference 1).

Table 2. Typical thermal properties of several common mirror materials.

| Material | Thermal Conductivity κ (W/mK) | Coefficient of Thermal Expansion α ($10^{-6}/K$) | Specific Heat C_p (J/gK) | Thermal Diffusivity $D=\kappa/C_p\rho$ ($10^{-6}m^2/s$) | Steady State Coefficient α/κ ($10^{-6}m/W$) | Transient Coefficient α/D (s/m^2K) |
|-----------------------------------------------|--------------------------------------|-----------------------------------------------------------|----------------------------|-----------------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------|
| ULE 7971 | 1.3 | 0.03 | 0.77 | 0.8 | 0.023 | 0.039 |
| Zerodur | 1.6 | 0.03 | 0.81 | 0.8 | 0.019 | 0.038 |
| Silicon carbide (reaction bonded 30% silicon) | 155 | 2.4 | 0.67 | 80.0 | 0.015 | 0.030 |
| Silicon carbide (chemical vapor deposited) | 280 | 2.2 | 0.73 | 119.5 | 0.008 | 0.018 |
| Beryllium 1-70 | 216 | 11.3 | 1.92 | 60.8 | 0.052 | 0.186 |

In both of the thermal distortion coefficients, SiC is comparable to zero expansion glasses.

One more factor is important for thermal distortion – the uniformity of CTE in the material. CTE variations in the mirror substrate will cause warping when the temperature changes.

2.3 Forms of Silicon Carbide

Many methods are used commercially to produce SiC mirror blanks. Some products are essentially pure SiC, while others are two-phase mixes of SiC with other materials, usually silicon or carbon. Some of the major fabrication methods include foaming, hot pressing, sintering, reaction bonding, reacted graphite, reacted carbon fibers, chemical vapor deposition, and combinations of these processes. The material properties, including density, stiffness, CTE and CTE uniformity depend on the form of the material and the fabrication process.

The largest SiC mirror known to TMT is the 3.5-m diameter primary mirror for the Herschel telescope. It is an extremely lightweight structured mirror made from 12 sector-shaped pieces of sintered SiC brazed together.

Forming a monolithic mirror 3.5 m across may be beyond the current state of the art. Therefore, in the rest of this document we will assume any proposed SiC tertiary mirror would be a lightweight structured mirror (but perhaps not as aggressively lightweight as the Herschel mirror) made from several pieces joined together.

3. Requirements for the TMT Tertiary Mirror

3.1 General Description and Functions of the TMT M3

The TMT M3 is a flat mirror that reflects the light coming from the secondary mirror to the science instruments through a 90° angle. The shape of the M3 is elliptical, in order to transmit an unvignetted 15 arc minute diameter field of view while minimizing the obscuration of the primary mirror aperture.

The tertiary mirror system (M3S) will be mounted on a structural tower extending upwards from the primary mirror (M1). The center of the M3 optical surface is at the intersection of the telescope azimuth and elevation axes. This is 3.5 meters above the vertex of the M1 surface.

Because science instruments will be mounted in multiple locations along the Nasmyth platforms, the beam from the M3 will not always be aligned with the telescope elevation axis. This means that generally the M3 will have to track in both rotation and tilt as the telescope changes zenith angle. As a result, the lateral support of the M3 will be more complex than for a typical alt-az telescope mirror. In the coordinate system of the mirror, with X and Y axes in the plane of the mirror and the Z axis perpendicular to the mirror surface, there will be gravity components in all three coordinate directions when the mirror addresses the full range of instrument locations.

The optical figure of the M3 will likely be different in the telescope than in the optics shop because of: (1) the change in temperature between the optics shop acceptance test and the observing conditions at the observatory; (2) the effect of stresses in the reflective coating; (3) any imperfections in the metrology mount used during the acceptance test. The coating stresses may change during the life of the observatory, because of advancements in the coating design. Therefore, the M3S must have an active optics capability to make low-order corrections to the figure of the M3.

Given this active optics capability, other corrections are also anticipated. The polishing specification for the mirror has been relaxed for low-order aberrations, including power, astigmatism, trefoil and coma. Manufacturing tolerances for the mirror support system can also be relaxed because of the ability to correct low-order aberrations in situ.

The mirror support forces applied by the active optics system will be controlled using a look-up table, based on measurements made by the facility Alignment and Phasing System. Each actuator force in the look-up table will vary as a function of telescope zenith angle, and possibly as a function of ambient temperature.

The requirements for the tertiary mirror system are contained in the **Requirements Document for Tertiary Mirror System (M3S)**, document number TMT.OPT.DRD.07.006.CCR28. This document is often referred to as the “M3 DRD”, where DRD stands for design requirements document.

3.2 M3 Optical Surface Figure Requirements

The M3 optical surface must be smooth and flat. The allowable surface roughness is specified in the M3 DRD:

[REQ-2-M3-1090] The optical surface of the M3M shall be polished to less than 2 nanometers RMS surface roughness.

To support this requirement, there is also a requirement on the material of the M3 mirror blank:

[REQ-2-M3-0830] The M3 Blank material shall be able to be polished using conventional optical finishing processes and materials to a surface roughness of 1 nanometer RMS or less.

The figure errors of the M3 surface are specified in a structure function that relates the allowable amplitude of an aberration to its spatial frequency:

[REQ-2-M3-1040]* At all separation distances (x), within any beam footprint as defined in [REQ-2-M3-1050], the value of the structure function that describes the surface error of the M3M (normal incidence) shall be less than:

$$D(x) = A \left[10.60 \left(\frac{x}{d} \right)^{5/3} - 13.75 \left(\frac{x}{d} \right)^2 + 3.42 \left(\frac{x}{d} \right)^3 \right] + 2B^2$$

Where:

D(x) is the structure function in nanometers squared

$$A = \cos(45^\circ)^2 \left(\frac{500nm}{2\pi} \right)^2 \left(\frac{30m}{r_0} \right)^{5/3}$$

A = Leading coefficient = 90988

B = High frequency surface error (surface roughness) = 2 nanometers

x = Separation between point pairs

d = Diameter of beam footprint = 1.33 meters

r₀ = Quasi-Fried's parameter = 4.0 meters

The value of r₀ used in this equation was chosen to be consistent with the encircled energy requirement in [REQ-1-OAD-0436].

This structure function is in terms of surface error with piston and tilt subtracted from the phase map, and is in units of squared nanometers. This curve is illustrated in Figure 1.

[REQ-2-M3-1050]* The optical surface figure of the M3M shall not exceed the structure function described in Equation 1 and shown in Figure 1, over any elliptical area with major axis of 1.88 meters and minor axis of 1.33 meters aligned in the same orientation as the clear aperture, when the telescope is zenith pointing.

[REQ-2-M3-1060] When the telescope is pointing away from the zenith, the optical surface figure of the M3M shall not exceed the structure function specifying the optical surface of M3M multiplied by secant(Z), where Z is the zenith angle.

Discussion: The telescope image quality is allowed to degrade with zenith angle by an amount comparable to atmospheric seeing.

[REQ-2-M3-1070] The limits imposed by the structure function shall be for all error sources except look-up table errors. These errors shall include: figuring, optical test measurement uncertainty, thermal distortion, gravitational orientation, passive support, active support, and dynamic support effects.

[REQ-2-M3-1080] During acceptance testing in the optical shop, the M3SS may be used to make active optics corrections of the mirror figure, over the Clear Aperture, using the following low-order aberrations: focus – up to 100 nanometers RMS surface; astigmatism – up to 200 nanometers RMS surface; coma – up to 20 nanometers RMS surface; trefoil – up to 50 nanometers RMS surface. These corrections are defined relative to the nominal mirror support forces. Within these limits, the corrections may be varied with mirror orientation.

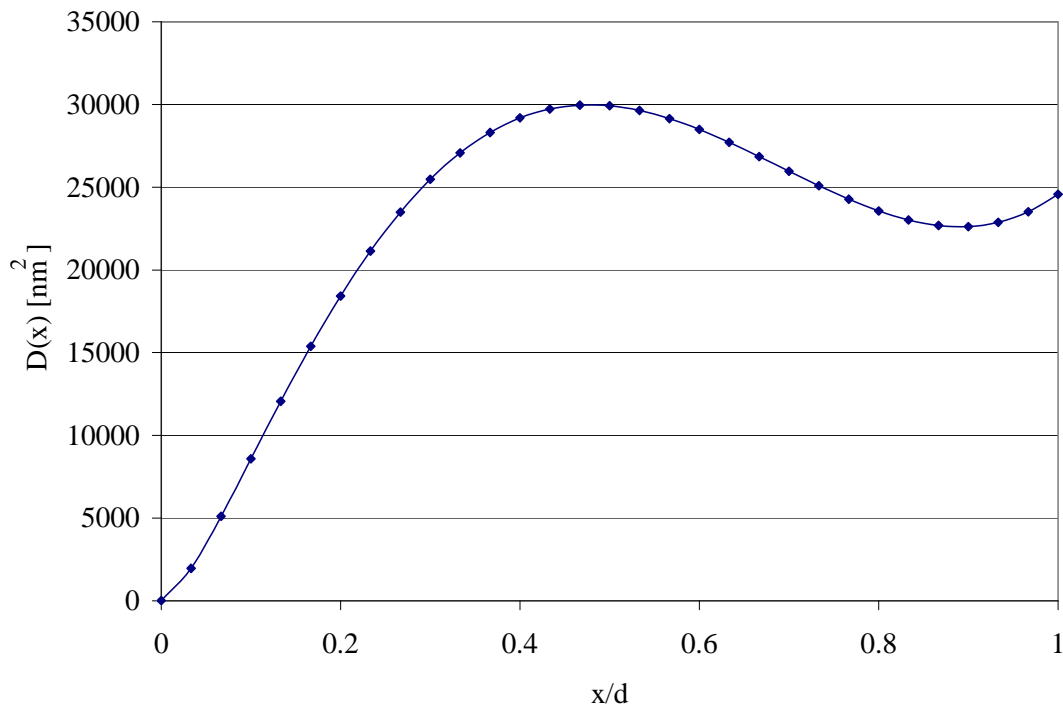


Figure 1: The Structure Function for the M3M surface error.

3.3 M3 Thermal Stability Requirements

The M3 must retain its correct optical surface figure in the changing thermal environment of the observatory. The following requirements are stated in the M3 DRD:

[REQ-2-M3-0170] The M3S shall meet all requirements stated in this document over temporal changes in the ambient air temperature up to and including +/-0.5 Kelvin per hour.

[REQ-2-M3-0180]* The M3S shall meet all requirements stated in this document over spatial ambient air temperature gradients up to and including 0.25 Kelvin per meter in any direction.

[REQ-2-M3-0840] The Average CTE of the M3 Blank over the temperature range involved in optical testing in the polishing shop shall be small enough to ensure that the measurement uncertainty is within the error budget for that testing in the presence of spatial and temporal temperature variations.

[REQ-2-M3-0850] The Average CTE of the M3 Blank over the temperature range of 270 Kelvin to 300 Kelvin shall be small enough to ensure that the M3M shall meet all of its performance requirements over the range of operational temperatures specified in [REQ-1-ORD-1105].

Discussion: Non-zero CTE will cause the figure of the M3M to change between the acceptance test in the optics shop and the use environment at the observatory, and to change over the operational range of temperatures.

[REQ-2-M3-0860] The Average CTE of the M3 Blank over the range of operational temperatures specified in [REQ-1-ORD-1105] shall be small enough to ensure that the M3M shall meet all of its performance requirements when subjected to the operational temperature gradients produced by the ambient air temperature gradients specified in [REQ-2-M3-0180] plus the temperature gradients created by the operation of the M3S.

[REQ-2-M3-0870] The spatial variation of the CTE in the M3 Blank, relative to the average CTE of the M3 Blank, shall be small enough to ensure that the M3M shall meet all of its performance requirements over the range of operational temperatures specified in [REQ-1-ORD-1105].

Discussion: Non-uniform CTE will cause changes in the M3M figure as its temperature changes.

3.4 Other requirements

The requirements on the M3 active optics system include the following:

[REQ-2-M3-1240] The M3SS shall be able to correct the low-order aberrations specified in Table 2 with residual errors less than the amount specified. To verify that the M3SS has the required capacity to apply these corrections simultaneously, the actuator force amplitudes for the six cases may be summed in quadrature.

Table 2: Required active optics correction capability.

| Aberration term | Required Amplitude (nanometers RMS) | Residual Correction (RMS residual / correction) | After (RMS RMS) |
|------------------------|-------------------------------------|-------------------------------------------------|-----------------|
| Focus, Z_{20} | 1000 | 5 percent | |
| Astigmatism, Z_{22} | 2000 | 2 percent | |
| Astigmatism, Z_{2-2} | 2000 | 2 percent | |
| Coma, Z_{31} | 100 | 15 percent | |
| Coma, Z_{3-1} | 100 | 15 percent | |
| Trefoil, Z_{33} | 200 | 5 percent | |
| Trefoil, Z_{3-3} | 200 | 5 percent | |

[REQ-2-M3-1250] The resolution of the active optics force control shall be sufficient to ensure that the figure errors caused by quantization of the forces will comply with an error budget that meets the structure function requirement.

[REQ-2-M3-1260] Any force combination that the M3SS is capable of applying to the mirror shall not be able to damage the mirror or the actuators.

The M3 must survive earthquakes without damage, and without any failure that would damage the M1 segments located below the M3.

[REQ-2-M3-0500] The M3S shall not be able to damage the telescope primary mirror or any other telescope subsystem under any circumstance(s).

[REQ-2-M3-0590]* The M3S shall survive earthquake dynamic accelerations equivalent to a static acceleration of 3 g (TBC), due to a maximum likely earthquake described in [REQ-1-ORD-1500], with no damage to the mirror and only limited damage to the mechanical or electronic components, such that all damages shall be repairable in less than or equal to one week.

To ensure the M3 will be robust to withstand damage from earthquakes or handling, all surfaces should be free from subsurface damage that could promote the growth of cracks. The following requirement was based on the assumption that the M3 would be a zero-expansion glass or glass ceramic.

[REQ-2-M3-1000] The back surface and edges shall receive a commercial polish or etch sufficient to remove subsurface damage.

4. Potential Issues and Concerns about a Silicon Carbide Tertiary Mirror

4.1 Polishability of the surface – effects of cladding

Many forms of SiC mirror substrates are difficult to polish to better than a 2 nm RMS surface roughness, because the surface consists of grains of two materials having significantly different hardness. The typical solution is to clad the optical surface with a homogeneous material that can be polished. The thickness of the cladding layer is normally limited to avoid problems caused by differences in the bulk CTE. This implies that the substrate surface must be machined very accurately to the final surface figure before cladding, so that the polishing and figuring operations don't perforate the cladding and expose the underlying substrate. This also implies that the warping of the blank caused by the cladding operation has to be significantly less than the thickness of the cladding. These will be significant challenges for a 3.5-m flat mirror.

4.2 Print-through

Structured mirrors often suffer from print-through effects, in which the rib structure shows up in the final mirror surface. Print-through can be caused by:

1. Deformation of the facesheet surface between the ribs because of polishing pressure. This results in rebound of the surface to form bumps once the polishing pressure has been removed. Because of its hardness, SiC normally requires high pressures to polish, but perhaps the blank will be coated with a softer cladding material.

2. Thermal expansion effects. Print-through can be caused by thermal gradients through the thickness of the facesheet, or by gradients of the coefficient of thermal expansion of the material, which could be caused, for example, by either the forming process or the cladding material.
3. Changing gravity orientation. The gravitational sag of the facesheet between the ribs will change with the orientation of the telescope.

The allowable print-through of the M3 is limited by the structure function specification. In particular, print-through of a single spatial frequency (because of uniform rib spacing) would not only be likely to violate the specification, it would produce discrete energy concentrations in the point spread function because of diffraction effects.

4.3 Thermal Distortion.

Thermal distortion of a mirror can be caused by:

1. Non-uniform CTE. If the CTE of the material in the mirror substrate isn't uniform, a change in the ambient temperature will cause the mirror to warp. This would particularly be a concern if the mirror substrate is assembled from several different pieces bonded together, and could also be caused by cladding with a different material.
2. Non-uniform temperature. If the CTE of the substrate material isn't close to zero, temperature differences in the substrate will cause warping. SiC has high thermal conductivity, which will help to equilibrate temperature differences. However, in a lightweight structure, the path lengths through the substrate are long, and the cross-sectional area for conduction is small. In a 3.5-m mirror with thin ribs, temperature differences will take some time to equilibrate in spite of the high conductivity of SiC.

It's worth noting that in many applications, a small change in the radius of curvature of a mirror can be accommodated by refocusing the system. However, for a fold flat like the TMT M3, a change in curvature would be problematic.

4.4 Temporal stability.

The design lifetime for TMT is 50 years. The telescope mirrors must remain dimensionally stable over this lifetime, at least within the ability of the active optics system to correct low-order warping. In 50 years the M3 will be subjected to 20 to 30 recoating operations, in which coatings are chemically stripped and new coatings are applied at elevated coating chamber temperatures.

A paper about the Herschel 3.5-m silicon carbide mirror² comments on the characteristics of brazed joints:

"In addition, the brazing combines good mechanical strength (always above 56 MPa) and dismounting possibility by acid attack."

This raises questions about the stability of brazed joints after repeated exposure to stripping chemicals. The chemicals would need to be able to strip a durable reflective coating but not attack the brazing material.

There are also possible concerns with the chemical resistance of any cladding material used to make the optical surface easier to polish. The chemicals used to remove old reflective coatings include strong acids and bases. Pure silicon carbide is resistant to most chemicals, but it will be important to ensure that the cladding material would also be chemically resistant.

Having a substrate material with demonstrated long-term stability is vital.

4.5 Robustness

Although observatory staff members don't like to discuss the subject, most large telescope mirrors have one or more chips in the edge of the glass caused by accidents during fabrication or during handling in the observatory. Even careful people may make mistakes. Secondary mirrors have been broken at existing observatories, and at least one telescope primary mirror was destroyed during shipment to the observatory.

The TMT mirrors must be as robust as possible. In particular, the M2 and M3 would be single point failures – if one of those mirrors were destroyed, the observatory would be out of action for several years while a replacement was manufactured.

There are several potential concerns about the robustness of a SiC M3:

1. How does the fracture toughness of the proposed material compare to other candidate mirror materials, for example, glass ceramics? Some forms of SiC may be tougher, some may be less tough.
2. If the SiC mirror is a lightweight structure, will it be more delicate than a solid mirror because of the thin section thickness?
3. Claims have been made that SiC mirrors are more likely to fail catastrophically, for example, to crack in half, in circumstances where a glass mirror would just lose a chip at the edge. While we don't know of any proof of this theory, it has been claimed that anecdotal evidence bears out this conclusion.

Establishing the toughness of the proposed SiC material will be important, particularly considering the possibility of strong earthquakes on Mauna Kea.

4.6 Manufacturing Feasibility

TMT knows of only one SiC mirror as large as the TMT M3 – the Herschel primary mirror. It apparently wouldn't meet the TMT requirements for surface roughness and surface figure accuracy. Therefore, manufacturing a SiC tertiary mirror for TMT would be at or beyond the state of the art.

Assuming the mirror would be made of several pieces joined together, and assuming it would need to be clad with a coating material that can be polished to a smooth surface roughness, there are several concerns about manufacturing feasibility:

1. Will the pieces have precisely the same CTE?
2. Will the large pieces be free from cracks, voids or other defects, particularly on the back surfaces that won't be polished?
3. Will the cladding be applied before or after joining the pieces?
 - 3.1 If joined before cladding:
 - a. Will the machined substrate hold its shape accurately enough during the cladding operation, to allow the optical surface to be finished by grinding and polishing without wearing a hole in the cladding?

b. Is there a facility that can apply cladding to this large a substrate? Has it ever been done before?

3.2 If joined after cladding:

- a. Will the polished surface at the joints meet TMT requirements?
- b. Will the shape after joining be accurate enough to avoid cutting through the cladding during grinding and polishing?

In the 1990s, the Magellan, Gemini and VLT telescope projects each decided to purchase SiC secondary mirrors, ranging in size from about 70 cm to 1.1 meter in diameter. This size range seemed to be feasible at the time, and three different SiC blank manufacturers entered into contracts to deliver the mirror blanks. All three failed to deliver the blanks, after years of attempts to produce them, and all three projects eventually had to switch to other mirror materials. If TMT were to agree to make the M3 out of SiC, when would the success of the manufacturing process be assured? Would there be time to switch to another material if that became necessary?

4.7 Predictability of properties.

The stiffness properties of the M3 will need to be analyzed for several purposes:

1. To determine the effect of any metrology mount used during the optical test in the optics shop. This is particularly important if the optical test orientation is different than the mirror orientation in the telescope.
2. To calculate active optics influence functions, in order to know how the mirror will bend when you change the support forces.
3. To predict any thermal distortion of the mirror caused by differential expansion of the mounting hardware.

It will be important to understand the uncertainty in finite-element analysis results caused by uncertainty in the material properties and in the dimensions of the structured substrate, e.g., the thickness of the as-built ribs and facesheet.

4.8. Ability to Take Advantage of the Strengths of SiC

The motivation to use SiC would be primarily its superior material properties. For a given size a structured SiC mirror could use fewer supports and could be lighter weight than a solid glass ceramic mirror. Because of its higher conductivity and thinner cross sections, the mirror could follow ambient temperature with less lag. However, questions remain about finding the right balance in taking advantage of these properties.

1. If fewer supports are used, will they be able to bend the mirror smoothly to correct low-order aberrations without introducing large residual errors? What number of support points will provide the best compromise between support simplicity and active optics performance?
2. If the mirror is lightweight, will it be robust enough? What level of lightweighting will provide a mass advantage without making the mirror too fragile?
3. Will faster heat transfer cause the mirror to change shape faster? Will it be necessary to slow down the heat transfer, perhaps by insulating the back side of the mirror?

Before taking on the risk of a SiC M3, we should consider whether we will actually be able to take full advantage of the superiority of the material properties.

5. Path Forward for a SiC M3

Many questions will need to be answered before TMT can consider adopting SiC as the material for the M3. It may be possible to answer some questions immediately, but others will likely require a development program. Here are some of the questions:

1. What form of SiC is proposed for the TMT M3?
2. Will brazing or some other bonding method be required to form the M3 substrate?
3. What must be done to demonstrate the required surface roughness better than 2 nm RMS?
4. Will cladding be required on the optical surface? What type of cladding is proposed?
5. What will be required to demonstrate the capability to successfully clad a surface 3.5 meters across?
6. What will be the required cladding thickness? Will this thickness cause warping of the substrate when the temperature changes?
7. Can print-through from polishing, gravity orientation and temperature changes be minimized to the level required to meet the structure function requirement?
8. Will the mirror be dimensionally stable in a changing temperature environment?
9. Will the mirror figure be stable for the life of the observatory?
10. Will the joints remain stable when exposed to handling, stripping and coating operations?
11. Will a SiC mirror be as robust against handling mistakes and earthquake shocks and accelerations as a glass ceramic mirror?
12. Is it feasible to manufacture the mirror with low programmatic risk?
13. Will the stiffness properties of the mirror blank be predictable enough?
14. Will a design that meets all of TMT's requirements be able to take advantage of SiC's superior properties, to justify the development cost and programmatic risk?
15. Does SiC actually hold the promise of performing better in the TMT M3 than a glass ceramic mirror?
16. Would SiC be less expensive than a glass ceramic for the TMT M3?

These questions should be addressed in any development program for a SiC tertiary mirror for TMT, in order to bring the SiC concept up to the same level of technical readiness as a glass-ceramic mirror.

6. References

1. Paquin, R.A., *Materials for mirror systems: an overview*, Silicon Carbide Materials for Optics and Precision Structures, SPIE Proc. 2543, ed. M. Ealey, San Diego, California, 1995.
2. Gergonne, B. & Rivière, R.. *First SiC Mirror Development*, European Conference on Spacecraft Structures, Materials and Mechanical Testing, ESASP-468, ed. C. Stavrinidis, A. Rolfo and E. Breitbach, ESTEC, Noordwijk, The Netherlands, European Space Agency, pp.69 - 75, 2001.