

## Executive Summary

### Pictorial of Mirror Segments

The “Fabrication of Silicon Carbide Prototype Mirror Segments for Thirty-Meter Telescope” represents the first step forward of an integrated AURA program to produce cost effective spherical mirror segments. Poco Graphite, Inc. is pleased to support the AURA-NIO initiatives to develop the Thirty Meter Telescope. POCO has produced two 30-cm prototype silicon carbide segments as being representative of the POCO Chemical Vapor Conversion (CVC) process to create larger mirror segments.

The design for the two Prototype Mirror Segments produced by POCO are shown in Figures 1-3.

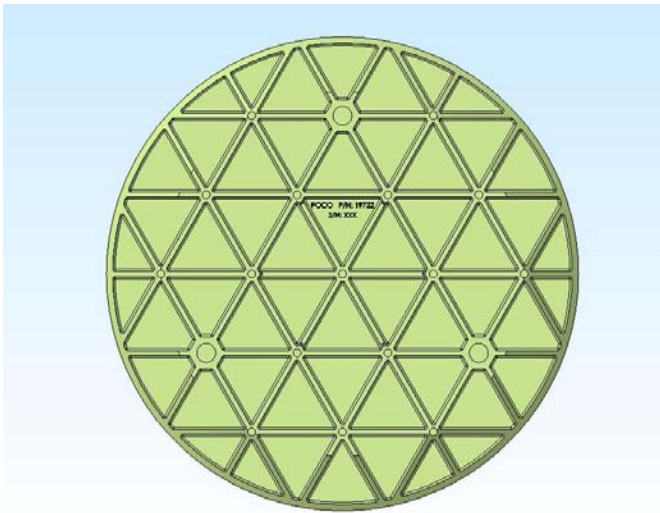


Figure 1. Back View of POCO Prototype Mirror Segment Model

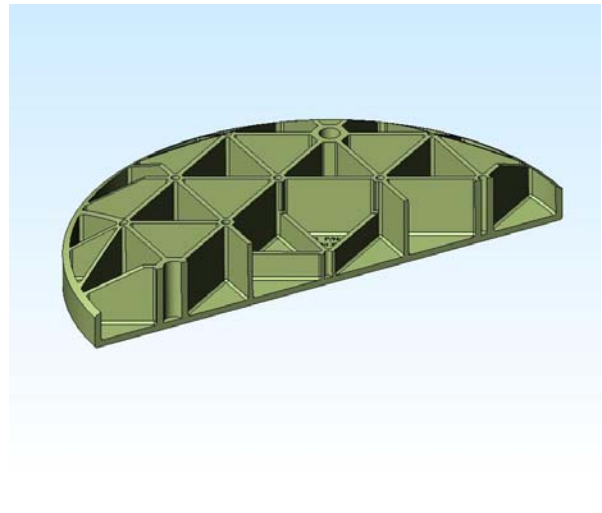


Figure 2. Cutaway view of POCO Design for AURA Prototype Segment Model

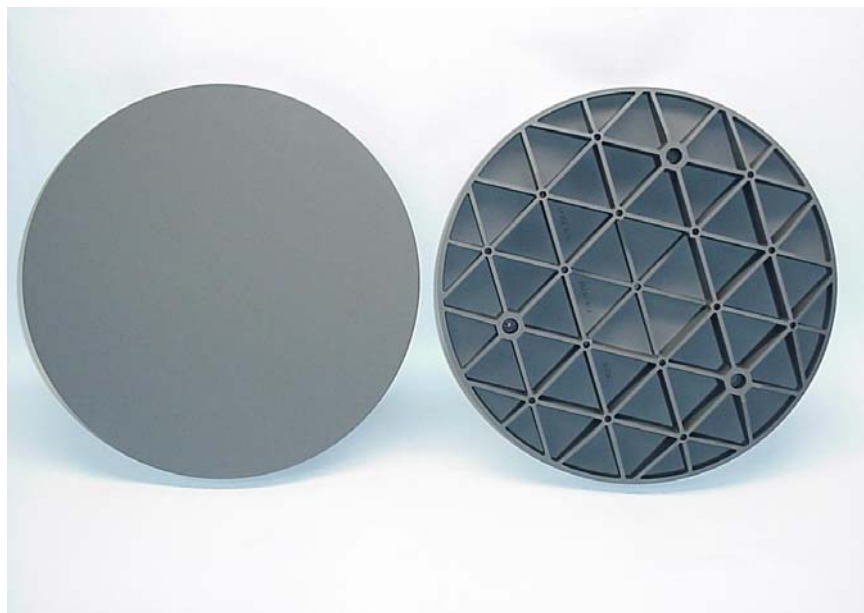


Figure 3. Photograph of two completed Prototype Segment Substrates.

### General Description of Manufacturing Process

POCO has developed a low-cost method to fabricate silicon carbide mirrors with low areal density. Silicon carbide has many of the attributes required for a TMT mirror segment. POCO's process for manufacturing net-shape SiC parts takes advantage of the ease of graphite machining. The POCO Chemical Vapor Conversion process (CVC) represented in Figure 4 eliminates the majority of the fabrication problems of conventional silicon carbide manufacturing. A special grade of graphite has been developed by POCO for conversion to SiC in a controlled fashion. The graphite block or billet is made from petroleum coke, a carbonaceous material that is readily available from petroleum refineries. These billets are produced using POCO proprietary batch process for graphite manufacture (batches are typically on the order of 100 billets). The billets produced for SiC conversion are nominally 6" thick by 24" wide x 60" long (155mm x 610mm x 1530mm). A graphite block is machined to produce the desired net-shape. Complex graphite components are routinely machined to tolerances of  $\pm 0.001$ " using CNC milling and grinding equipment. A machined finish of lower than 63 micro-inch Ra (arithmetic mean roughness) is achievable. The machined mirror substrate is subsequently converted to silicon carbide without any significant dimensional change in a high temperature reaction using a vapor phase Si-carrying species. The converted SiC contains about 20% total residual porosity. POCO has designated the material produced by the CVC process as SuperSiC<sup>®</sup>-1 (SiC-1). The SiC-1 material is coated with a CVD layer of silicon carbide to seal off the outer porosity and provide a surface that can be polished to a high accuracy finish for optical applications. This CVD coated SiC-1 material is designated SuperSiC<sup>®</sup>-2 (SiC-2).

The manufacturing path flow chart illustrated in Figure 4 is typical of SiC parts manufactured at POCO. Within the capability for machining and measuring precision parts, the manufacturing path is not strongly influenced by the mirror size.

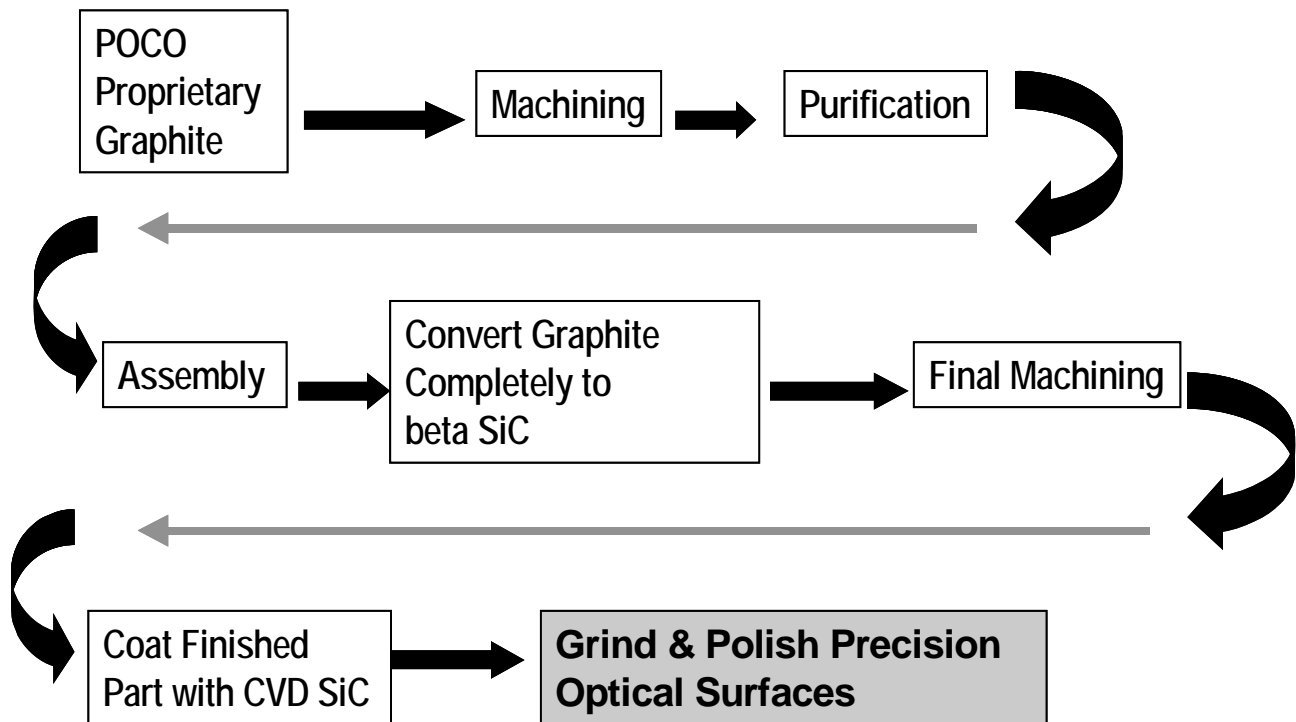


Figure 4. A Flowchart of POCO's CVC Process for the Manufacturing of Near-Net Shape SiC Products.

## Material Properties in Prototype Segments

The property development of POCO's SuperSiC<sup>®</sup> has historically been geared towards the needs of the semiconductor industry. More recently, POCO has been working with others to generate data pertinent to the optics field. The properties are summarized in Table 1.

Table 1. Properties of POCO's SuperSiC<sup>®</sup>-1 Materials

Property & Units		Value	Comments
Apparent Density, $\rho_a$ (g/cm <sup>3</sup> )		3.13	ASTM C-373 Standard Method (POCO Materials Testing Lab.)
Bulk Density, $\rho_b$ (g/cm <sup>3</sup> )		2.53	
Total Porosity, $P_t$ (%)		20	
Open Porosity, $P_{op}$ (%)		19	
Flexural Strength (MPa/ksi) (m is Weibull modulus)	at RT	147/21.3 (m=17)	ASTM C-1161, 4-Point (ORNL/HTML)
	1000°C	146/21.2 (m=16)	ASTM C-1211, 4-Point
	1300°C	148/21.5 (m=19)	(ORNL/HTML)
Tensile Strength (MPa/ksi)		129/18.7 (m=16)	ASTM C-1273 (ORNL/HTML)
Young's Modulus, $E$ (GPa/msi)		218/32	Tensile test, extensometer (ORNL/HTML)
Specific Stiffness, $E/\rho_b$ (kN-m/g)		85	Calculated
Poisson's Ratio, $\nu$		0.17	ASTM C-1259
Dynamic Shear Modulus, $G$ (GPa/msi)		96/14	(Grindosonic, J.W. Lemmens)
Fracture Toughness, $K_{Ic}$ (MPa·m <sup>0.5</sup> )		2.3	SENB(CoorsTek Analytical Lab)
Thermal Diffusivity, $D$ (10 <sup>-6</sup> m <sup>2</sup> /s)		102	Laser flash method (POCO MTL)
Thermal Conductivity, $\kappa$ (W/m·K) (RT)		170	Laser flash method (POCO MTL)
Coefficient of Thermal Expansion, $\alpha$ (10 <sup>-6</sup> /K)	at 25 <sup>(1)</sup>	2.0	ASTM E-228 (POCO Materials Testing Lab. and ORNL)
	20-500°C <sup>(1)</sup>	4.0	
	20-1000°C <sup>(1)</sup>	4.4	
	Cryogenic <sup>(2)</sup>	See Note (1)	ASTM E-289 (COI)
Thermal Distortion Coefficients	Steady, $\alpha/\kappa$ ( $\mu\text{m}/\text{W}$ )	0.012	Calculated
	Transient, $\alpha/D$ (s/m <sup>2</sup> ·K)	0.020	Calculated
Thermal Stress, $\kappa/\alpha \cdot E$ (10 <sup>6</sup> W·m/N)		390	Calculated

1) Mean CTE ( $\alpha_m$ ) =  $-5.225 \times 10^{-12} T^4 + 1.671 \times 10^{-8} T^3 - 1.961 \times 10^{-5} T^2 + 1.087 \times 10^{-2} T + 1.706$  (20°C < T < 1050°C, T<sub>0</sub> = 20°C)

2) Instantaneous CTE ( $\alpha_T$ ) =  $8.355 \times 10^{-6} T^2 + 8.001 \times 10^{-3} T - 0.688$  (90K < T < 400K)

As part of this sub-award effort, POCO pursued additional testing to characterize the thermal expansion behavior of POCO's SiC-1 in a broad temperature range (25 – 330K) and within the specified operation temperature range (248 – 300K) that the final components would be exposed to. Figure 5 illustrates the Thermal Expansion between two samples of SiC-1. Figure 6 Illustrates the Thermal Expansion between a sample of SiC-1 and SiC-2

Thermal Expansion of POCO SiC-1  
Tested between 22 - 330K

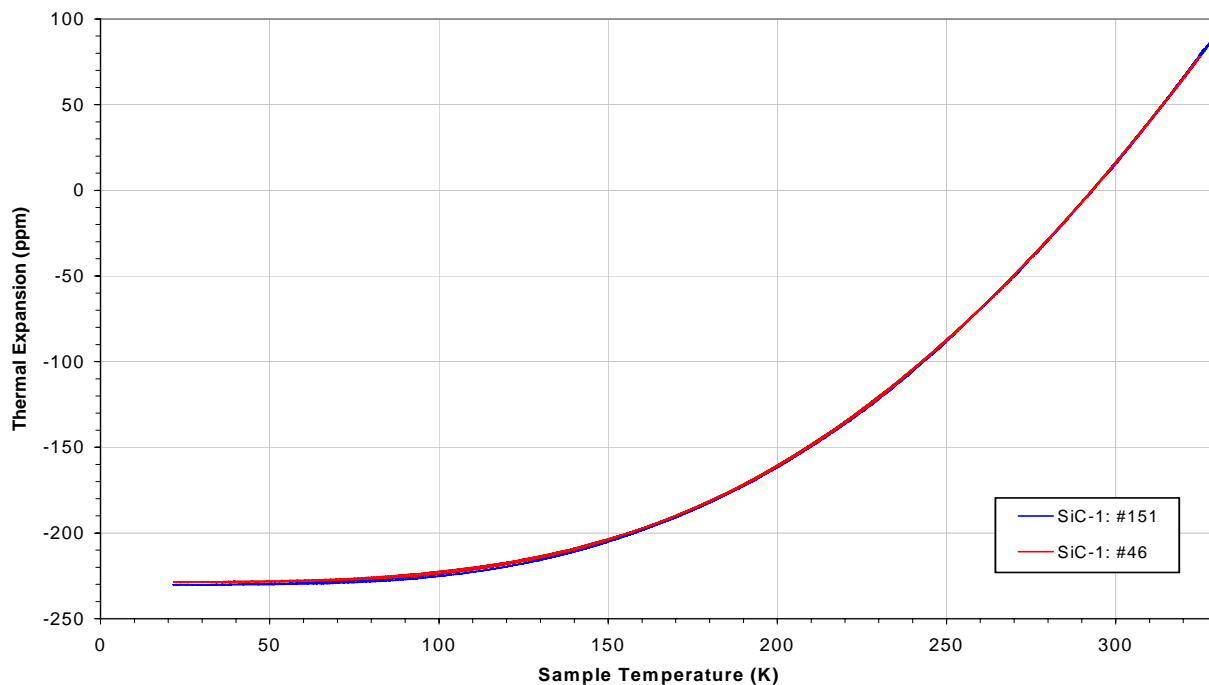


Figure 5. Thermal Expansion of two SiC-1 samples between 25-330K

Thermal Expansion of POCO SiC-1 (Base SiC) and SiC-2 (Base SiC with CVD SiC Coating),  
Tested between 243 - 305K

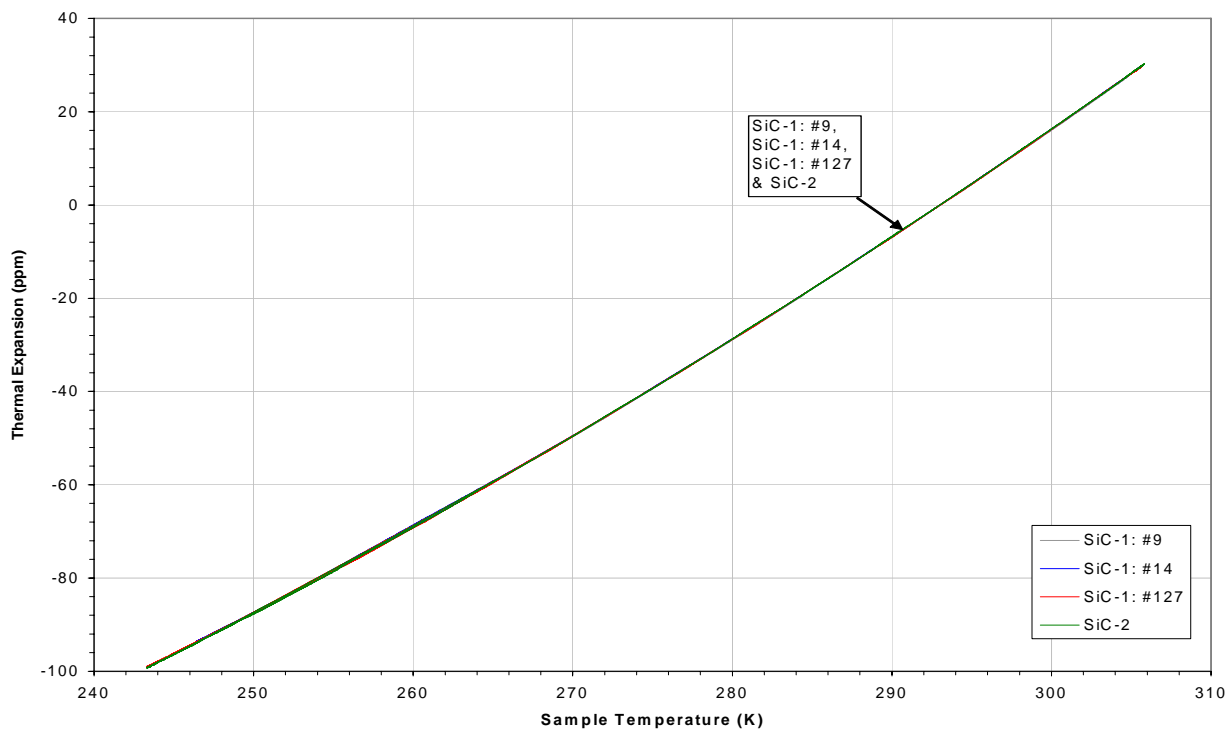


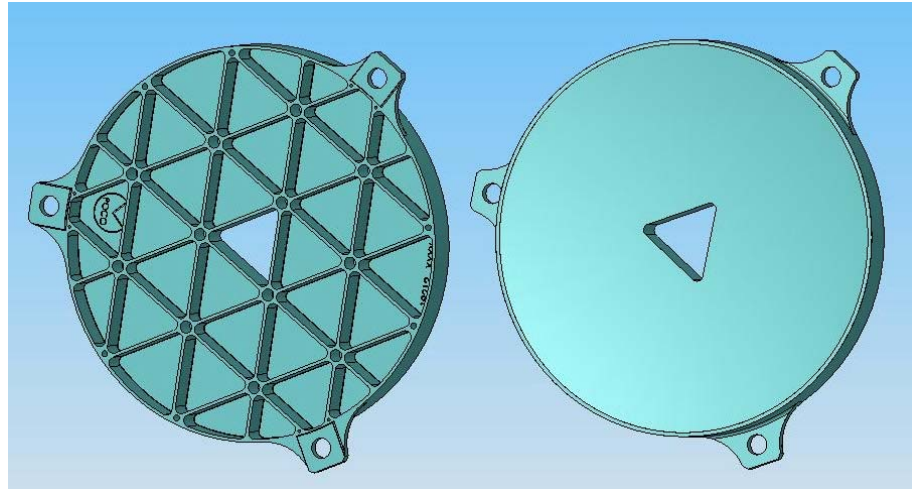
Figure 6. Thermal Expansion comparison of SiC-1 & SiC-2 samples between 243-305K

## POCO Relevant Experience

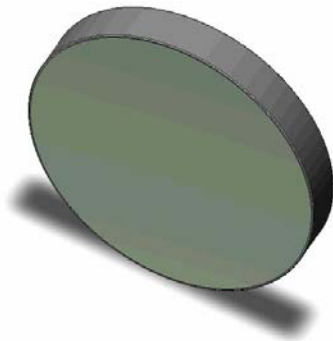
POCO currently supplies various industries with graphite and SiC products. Wafer carriers, of high purity, with excellent mechanical and thermal properties, are one example product line.

POCO has more recently focused the attributes of the SuperSiC<sup>®</sup> technology to the optics marketplace. Below are examples of some of the optics applications where POCO is currently working.

**Mirror for TNO/TPD.** As part of the European Astronomy Telescope program, POCO has fabricated a 0.25-meter mirror for the TNO/TPD Delay Line Demonstrator (Figure 7). This is a off-axis aspheric mirror that demonstrates the ability to fabricate a complex mirror substrate- including a center hole- using the POCO process.



**Figure 7. TNO/TPD Delay Line Demonstrator Mirror Substrates**



**Figure 8. Spherical Mirror for Evaluation at MSFC**

**Cryogenic Test Mirror for MSFC.** POCO designed and manufactured a SuperSiC<sup>®</sup> mirror substrate for a test program at Marshall Space Flight Center (Figure 8). The substrate was polished at Dallas Optical Systems to the specifications below.

- ☑ Circular periphery 0.25 meter diameter (9.75 inches)
- ☑ 50-100 mm(1–2 inch) depth
- ☑ with a radius of curvature of 3 meters. (118 inches)
- ☑ This mirror demonstrated a low areal density configuration.
- ☑ Polished to optical figure error of less than 0.25 wave RMS and surface roughness of approximately 10 angstroms RMS.

The mirror was delivered to Marshall Space Flight Center and cryotesting was carried out in November 2003. The preliminary POCO SiC optical test data reduction indicates there is only 7 nanometers RMS change between 30 and 290 degrees Kelvin. The mirror radius of curvature change is less than the noise of the test instrument. The reported deformation was the lowest observed of any SiC mirror tested so far.

**Cryogenic Test Mirror for Raytheon.** In a collaborative effort, POCO manufactured a test mirror for Raytheon to demonstrate the cryogenic behavior of a POCO SiC mirror. This elliptical 300mm x 200mm x 45mm thick light-weighted mirror has an areal density of approximately 16 kg. Per sq. meter. Approximately 125-micrometer thick CVD silicon carbide coating was deposited on the mirror face. It was polished to flatness of less than 0.5 wave p-v (0.2 wave RMS) and surface roughness less than 10 angstroms RMS. This mirror is shown in Figure 9. It was also cryogenically tested at Raytheon and found to have no significant distortion.

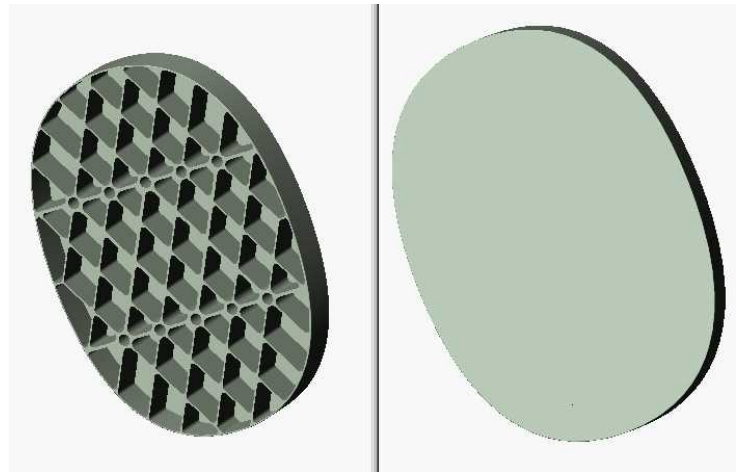


Figure 9. Isometric view of 300mm X 200mm X 45mm Elliptical Flat

**Laser Galvo System Scan Mirror.** X-Mirror, Y-Mirror - 50mm Galvo Sys lightweight scan mirrors. (Figure 10) With approximately 125 micrometer thick CVD silicon carbide coating on mirror faces. Polished to a surface roughness less than 5 angstroms RMS before coating. This scan mirror pair was designed for matched inertia and takes advantage of a unique manufacturing feature of the POCO SiC process to provide additional stiffness without paying a significant weight penalty. The plates on the back side are bonded by fusing graphite to graphite during the SiC conversion process step.

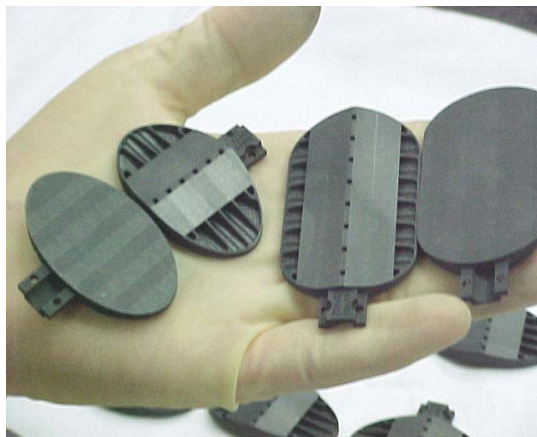


Figure 10. Graphite Scan Mirror Pairs with back plate before Conversion

**Specifications:**

- Clear Aperture: **31.1 mm**
- Wavelength: **10.6  $\mu$ m**
- Reflective Coating: **99.5% minimum S and P**
- Flatness: **1/4 wave or better at .5 Nm torque**
- Distance between mirror centers: **Designed for 46.4 mm**

Poco Graphite, Inc. has recently completed two Phase I SBIR research programs to demonstrate an SiC mirror and optical bench for the STSS cryogenically cooled infrared Track Sensor.

- SBIR MDA 03-048 Phase I: **Low-Cost Approach for the Fabrication of Net Shape Dense SiC for Mirrors:** This program developed a densified SiC material that has applicability for increased stiffness for mirrors that will be used in a SiC Test Telescope (based on the existing FDS mirror and telescope designs). The emphasis and innovative engineering is on new materials for mirrors, and focused on the design requirements of as individual mirror components. Optical issues include surface finish, figure, thermal properties and the changes in wave front error over the operating temperature range.
- SBIR MDA 03-026 Phase I: **SiC Optical Bench and Telescope Assembly for SBIRS Low:** This program developed a SiC optical bench design. The focus is on utilizing the same material as the

mirrors to achieve superior system performance during cryogenic testing. The emphasis and innovative engineering is on mounting interfaces, mechanical assembly and alignment of the assembly of components and interfaces. The proposed follow-on effort is to build the optical bench using the POCO SiC process and integrate the SiC Mirrors into the telescope assembly and perform ambient temperature and cryogenic performance testing, as well as environmental testing of the integrated telescope.

In addition, POCO has the following SBIR contracts underway:

- SBIR MDA 04-086 Phase I: **Low-Cost Manufacture of Lightweight Mirrors:** this Phase I program will survey and evaluate the various processes for finishing a POCO SuperSiC<sup>®</sup> mirror. The objective is to determine the alternatives to fabricating a completed mirror that offer the potential to reduce the cost and manufacturing time.
- SBIR MDA 03-026 Phase II contract number FA9453-04-C-0323. **Converted SiC for Precision Optics.** This Phase II project will provide the materials property foundation for the broad development and use of silicon carbide for precision optics applications. The project will also be aimed at development and scale-up of this unique process for silicon carbide.



**Front surface of a SiC blank manufactured by POCO**



**Back surface of a SiC blank manufactured by POCO**