CVC Silicon Carbide Optical Programs

William F. Fischer III
Trex Advanced Materials Group
3038 Aukele Street
Lihue, Hawaii 96766

(808)-245-6465 extension 21
(808) 250-1958 (cell)
bfischer@trexenterprises.com

Outline

- **Why SiC for High Performance Optics**
- **SMDC: Large Aperture SiC Chemical Vapor Composites for High Performance Mirrors**
  - TPOC: Douglas Deason of SMDC
- **NASA: High Volume, Low Cost Production Process for High Grade Silicon Carbide Optics**
  - TPOC: David Content of GSFC
- **AF: CVC SiC Mirrors Designed for High Energy Laser Applications**
  - TPOC: Lewis DeSandre of AFRL-DE Kirtland
- **MDA: CVC SiC to Replace Beryllium Mirrors**
  - TPOC: Lawrence Matson of MDA/ML Wright-Pat
- **MDA: CVC SiC: The Low Cost Manufacturing Pathway to High Performance Lightweight Mirror Systems**
  - TPOC: Brett deBlonk of AFRL-VS Kirtland

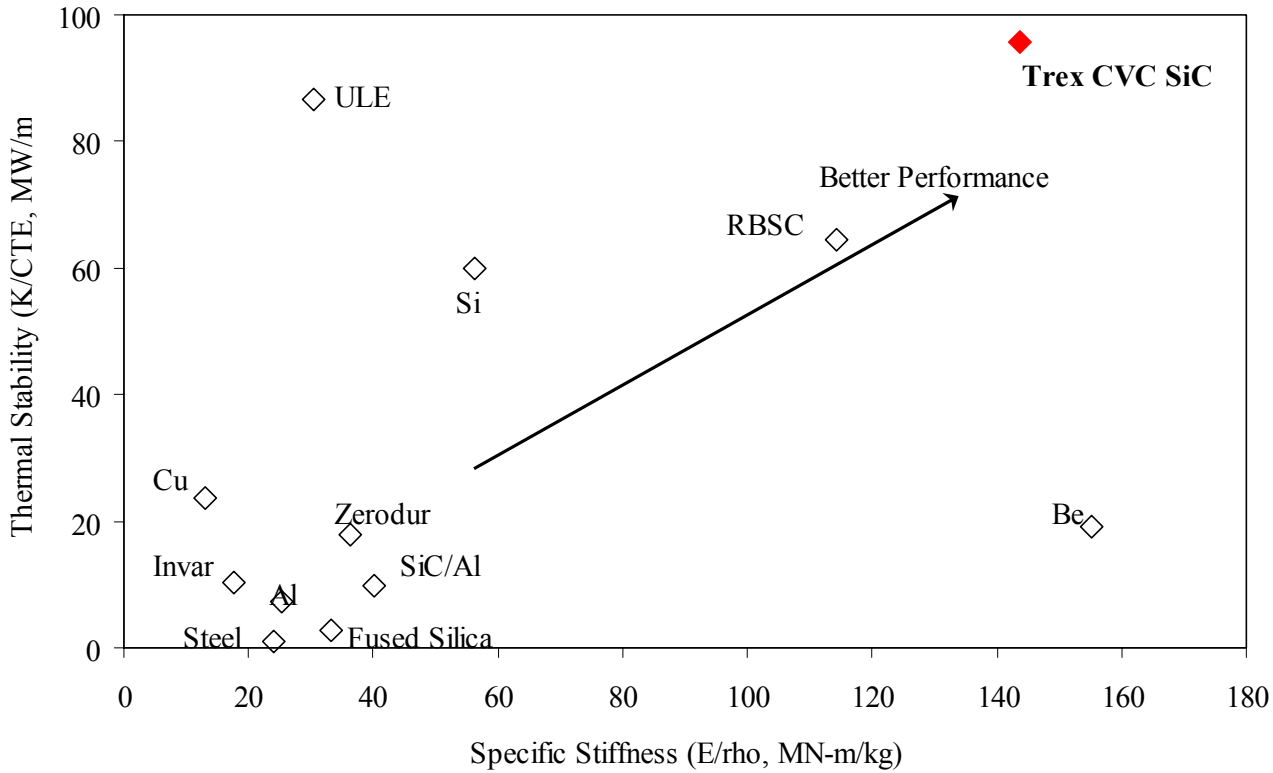
Outline

- **Why SiC for High Performance Optics**
- **SMDC**
  - TPOC: Douglas Deason of SMDC
- **NASA STTR**
  - TPOC: David Content of GSFC
- **AF-008**
  - TPOC: Lewis DeSandre of AFRL-DE Kirtland
- **MDA-59**
  - TPOC: Lawrence Matson of MDA/ML Wright-Pat
- **MDA-86**
  - TPOC: Brett deBlonk of AFRL-VS Kirtland
- **DARPA BAA**
  - TPOC: Leo Christodoulou of DARPA

Why SiC for Mirror Applications?

Why SiC for Mirror Applications

Comparison of mirror material performance parameters

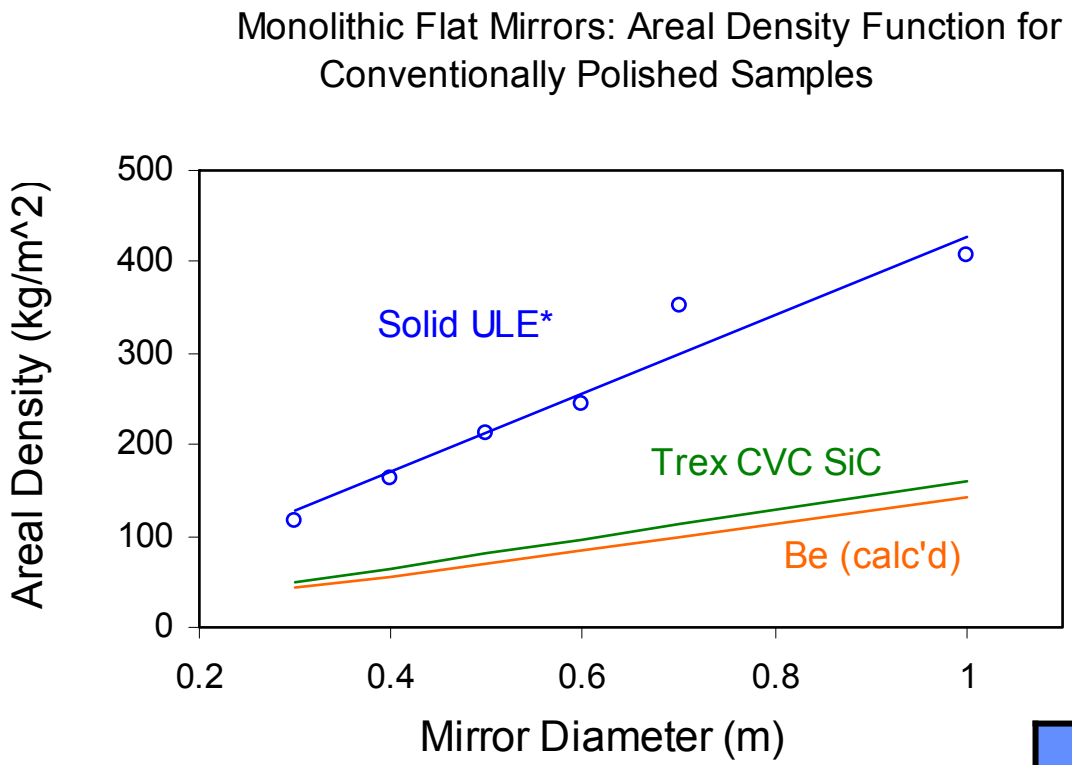


Additional Advantages:

1. Fine polish possible with CVC SiC
2. Near net shape deposition
3. Highly reflective in vac. UV and X-ray regions of EM spectrum.

*Ealey, M.A.; Wellman, J.A.; Weaver, G. "CERAFORM SiC: Roadmap to 2 Meters and 2 kg/m^2 Areal Density", in *Advanced Materials for Optics and Precision Structures*, M.A. Ealey, R.A. Paquin, and T.B. Parsonage, Eds., SPIE: Bellingham, WA, 1997.

Why Trex SiC for Mirror Applications



$$AD = \rho t$$

$$AR_{max} = (D/t)^*$$

$$AD_{min} = D\,(\rho/AR_{max})$$

*http://www.hextek.com/hitek.html

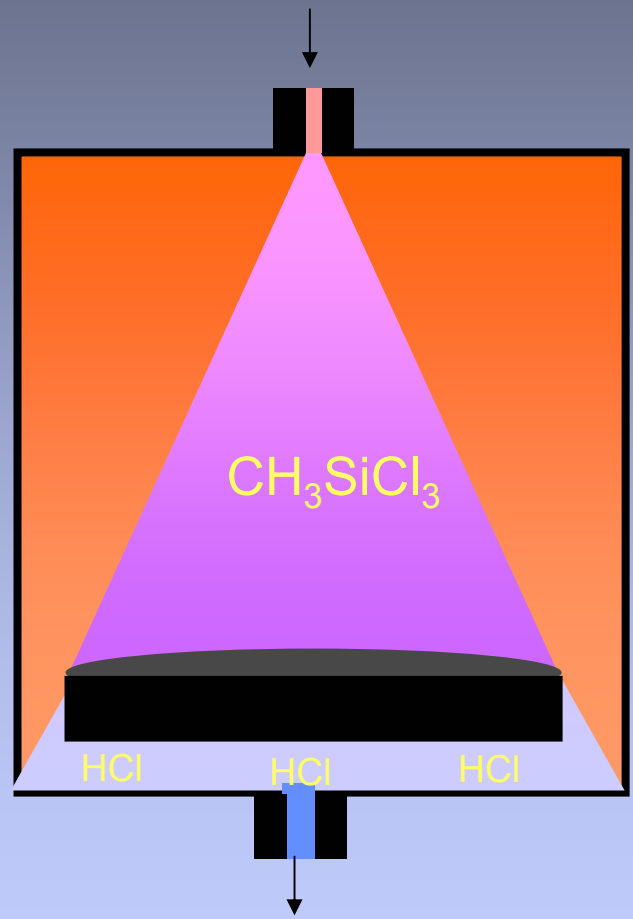
Material	E (GPa)	AR_{max}	ρ/AR_{max}
ULE	67	5.1	431
SiC	460	20	160.5
Be	303	13	141

“Issues” Associated with SiC Optics

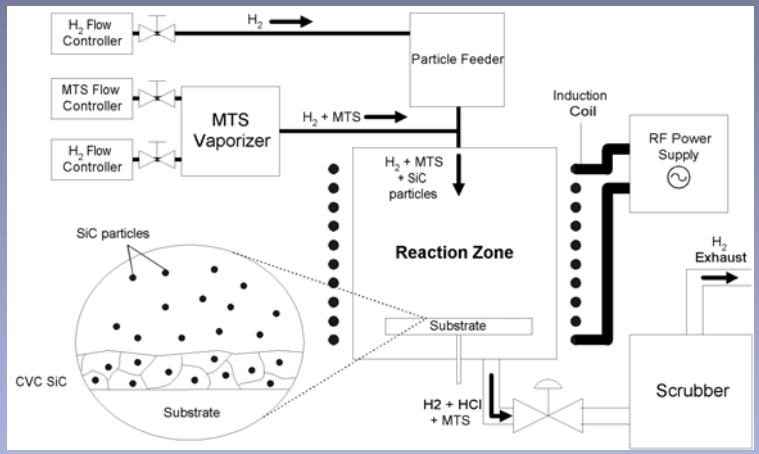
- Manufacturability
- Internal Stress
- Optical Performance
- Aperture Limitations
- Lead Time

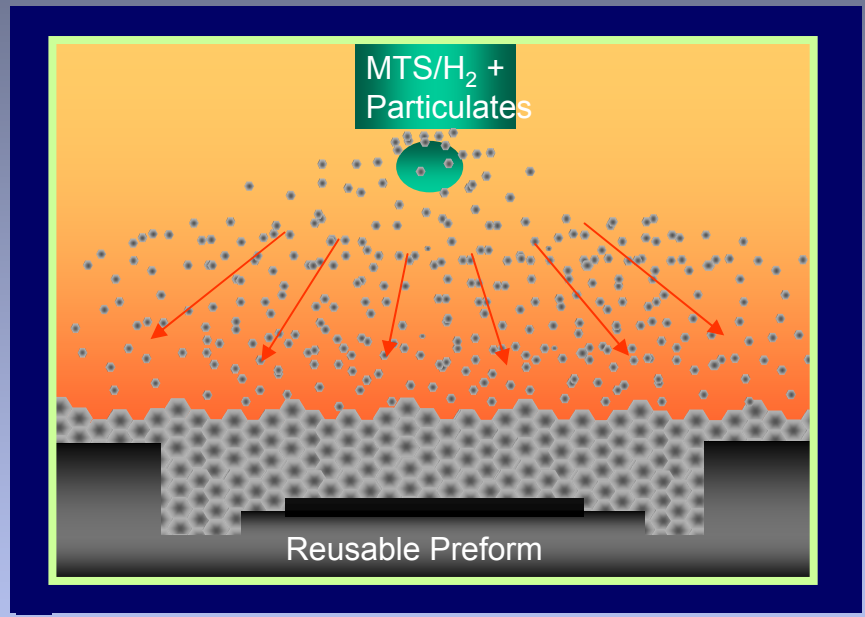
Conventional Chemical Vapor Deposition

$$CH_3SiCl_{3\,(g)} \rightarrow SiC_{(s)} + 3\,HCl_{(g)}$$



The Trex Chemical Vapor Composites Process





$$CH_3SiCl_{3(g)} \rightarrow SiC_{(s)} + 3HCl_{(g)}$$

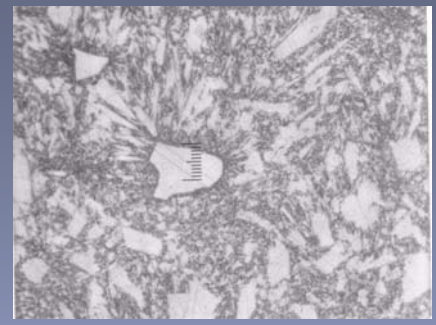
- Particles added to CVD stream promotes equiaxial grain growth and low intrinsic stress

  US Patent No. 5,348,765

CVD and CVC Silicon Carbide: Grain Structure

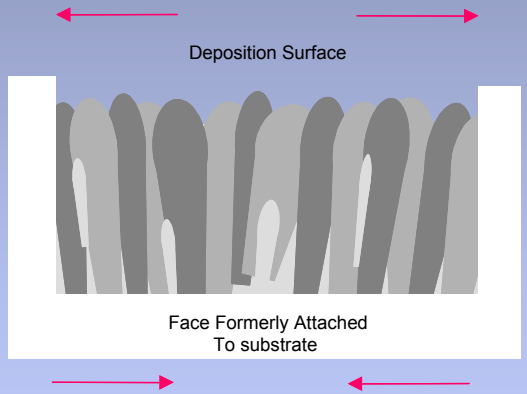
Conventional CVD

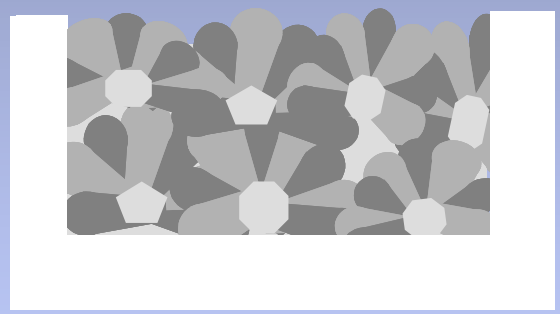
scale bar = 15 μm



Trex CVC

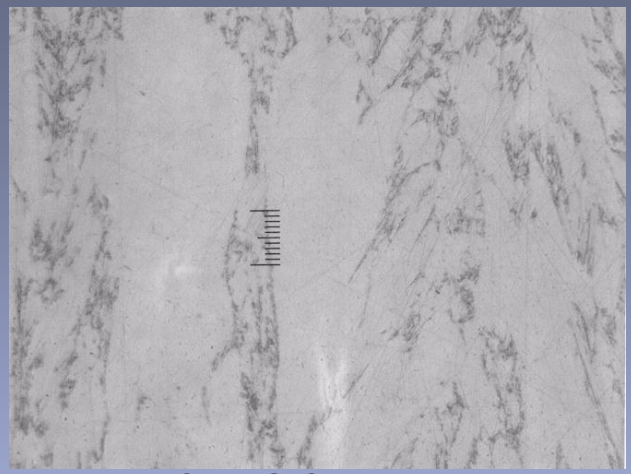
scale bar = 15 μm





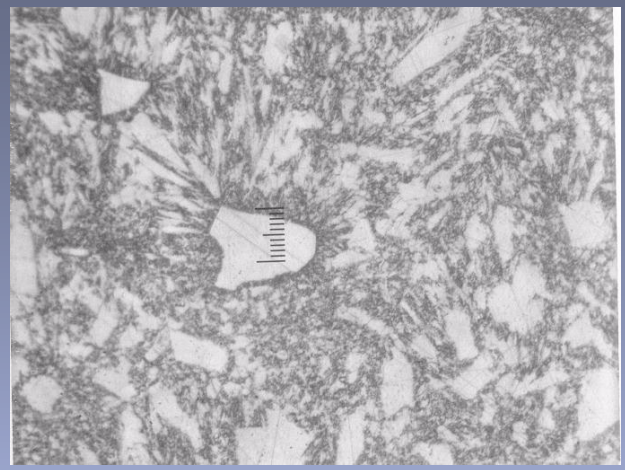
SiC Particulates added to CVD reaction stream relieve intrinsic stress, reduce average grain size and allow for faster growth rates.

Grain Structure (cont.)



CVD SiC

scale bar = 15 μm



Trex CVC SiC

scale bar = 15 μm

Powder Addition Relieves Intrinsic Stress

- Uniform Microstructure
- Faster growth rate (>5x CVD)
- High Yields (Nearly 100%)
- Near net shape
- Large Size and Thick Parts

Why Trex CVC SiC for Mirror Applications (cont.)

Property	Units	CVC SiC	Be S-65H HIP	Al 6061-T6	Zerodur	ULE 7971	Pyrex
Density	kg/cc	3200	1860	2710	2530	2205	2230
Elastic Modulus	GPa	460	303	68	90.6	67	63
Poisson's Ratio		0.21	0.12	0.33	0.24	0.17	0.20
Strength	MPa	450	217	310	57	50	60
Hardness (Vickers)	kg/mm^2	2850	1670	170	630	500	500
CTE (@ 273 K)	10^{-6} /K	2.2	11.5	23.9	0.05	0.015	3.25
Specific Heat Capacity	J/kg K	640	1925	896	821	741	1050
Thermal Conductivity	W/m K	205+	210	167	1.64	1.37	1.13
Specific Stiffness	$E/\rho \times 10^3$	144	163	26	37	30	29
Resonant Frequency	$(E/\rho)^{0.5}$	0.37	0.41	0.16	0.19	0.17	0.17
Thermal Diffusivity (D)	$m^2/s \times 10^{-6}$	100.1	58.65	68.78	0.79	0.84	0.48
Steady State Distortion	α/κ	0.011	0.055	0.143	0.030	0.011	2.876
Transient Distortion	α/D	0.022	0.196	0.348	0.063	0.018	6.734

Outline

- **Why SiC for High Performance Optics**
- **SMDC**
  - TPOC: Douglas Deason of SMDC
- **NASA STTR**
  - TPOC: David Content of GSFC
- **AF-008**
  - TPOC: Lewis DeSandre of AFRL-DE Kirtland
- **MDA-59**
  - TPOC: Lawrence Matson of MDA/ML Wright-Pat
- **MDA-86**
  - TPOC: Brett deBlonk of AFRL-VS Kirtland
- **DARPA BAA**
  - TPOC: Leo Christodoulou of DARPA

Pre-Program State of the Art Trex CVC SiC Mirrors

- **Reactors: Two 7” Quartz Reactors**
- **Material highly porous – 2-5% common**
- **CVC Patent in place**
- **Poor uniformity within each run and especially between runs**
- **Process Scaling Unknown**
- **Aperture limitations excluded most applications**
- **Best mirror properties**
  - 2.54 cm Square mirror
  - Surface Figure 0.1 wavelength
  - Extremely poor Scratch – Dig (due to porosity)

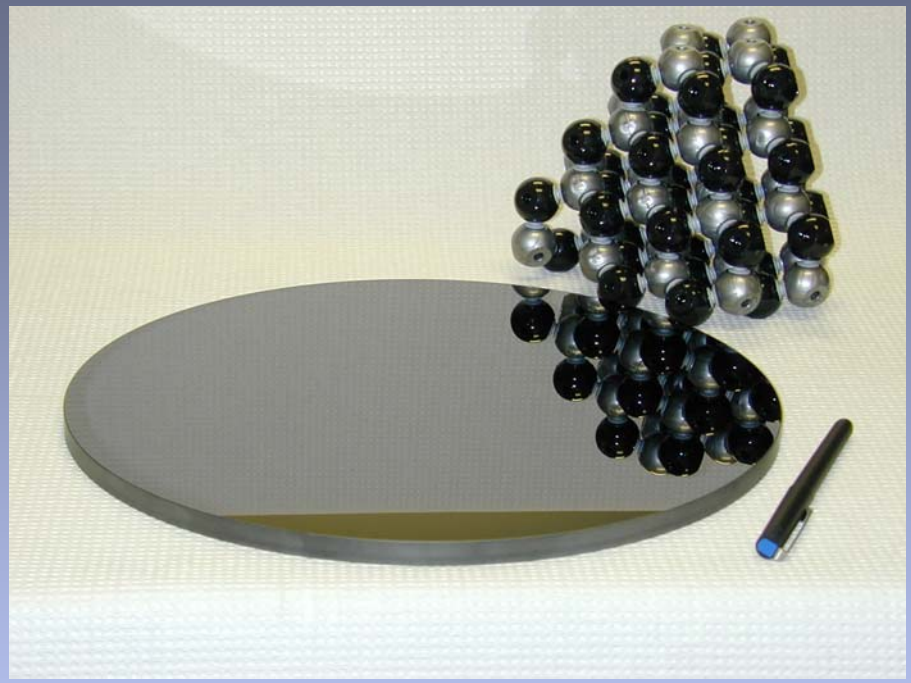
Program Review

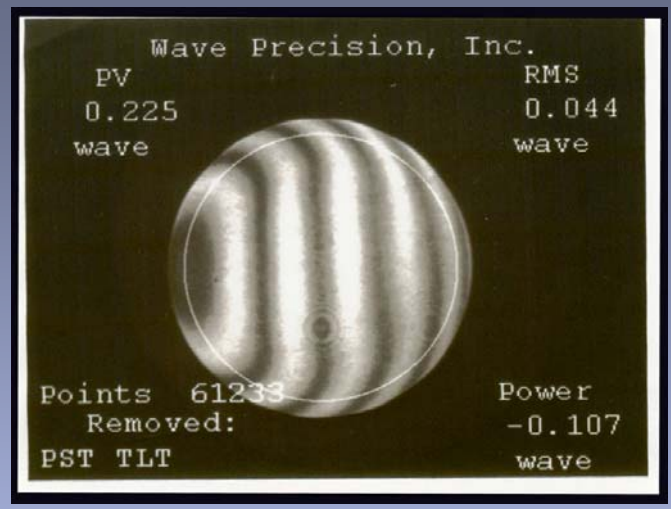
Current State of the Art Trex CVC SiC Mirrors

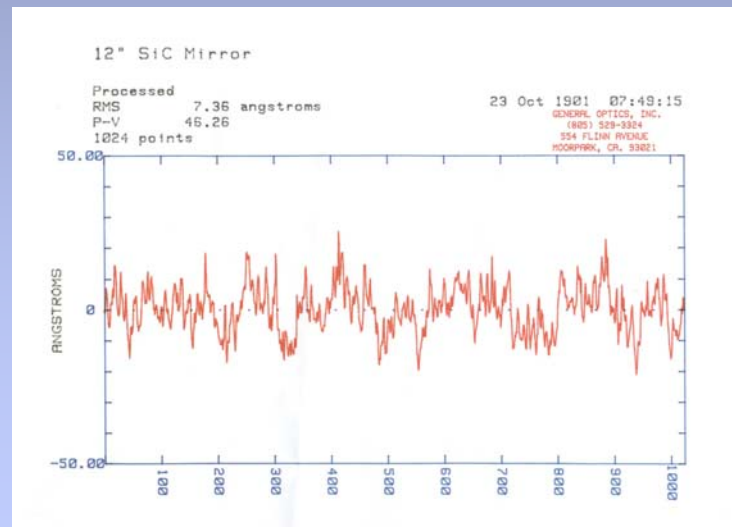
- **Reactors: 18", 16", 14" and Tube Reactors**
- **Material Density at 3.2 g/cc (99+% theoretical density**
- **Near net shape deposition**
- **4 types of light weight structures explored**
  - Carbon foam Backed
  - SiC Foam Backed
  - Very Thin monolithic structures (25.4 cm aperture x 3mm thickness)
  - Working on monolithic near net shaped Ribbed structures

- **Best mirror properties**
  - 36 cm round plano mirrors
  - 25.4 cm powered mirror (f/4)
  - Surface Figure 0.037 λ P-V and 0.004 λ rms
  - Surface Flatness 1.64 Angstroms rms

Mirror Fabrication
Interference and Profile Analysis on 304 mm Monolithic Mirror







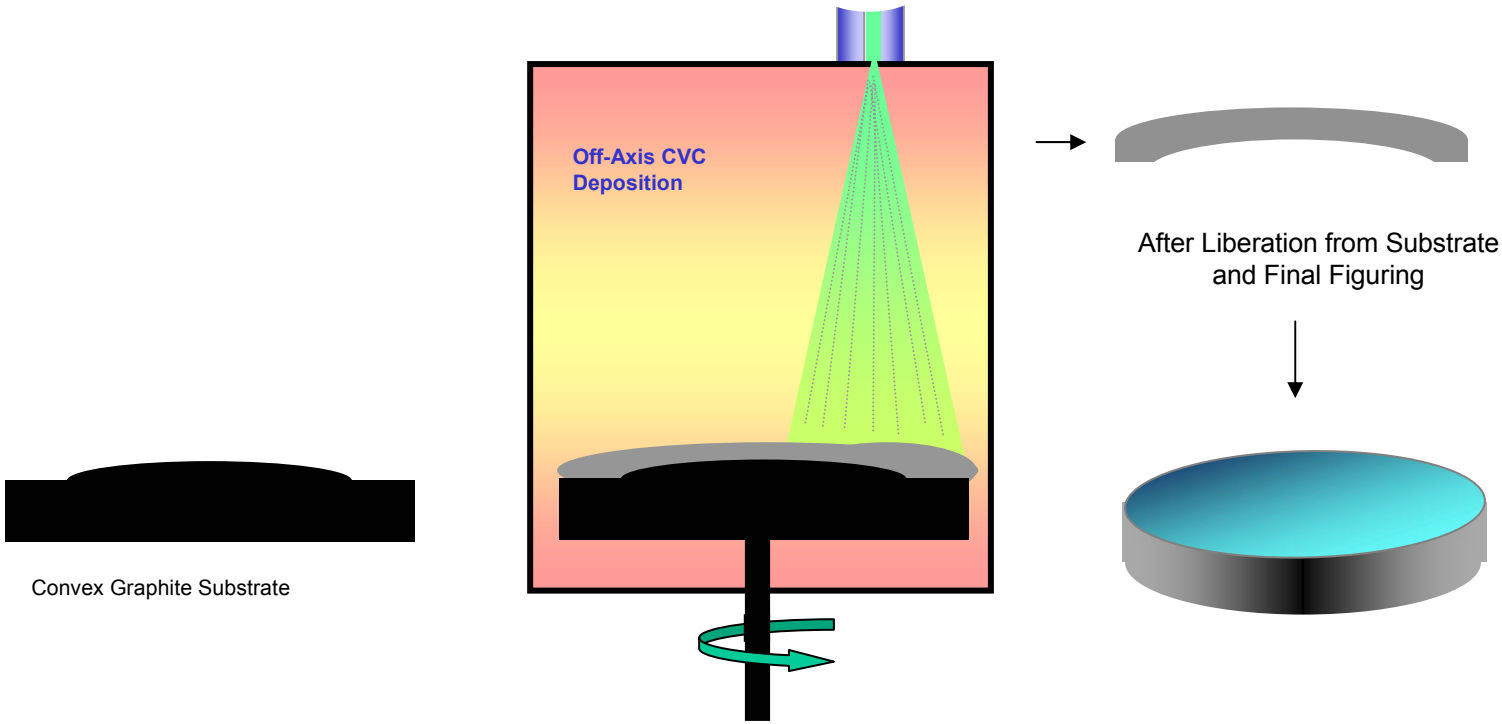
304 mm diameter 10 mm thick flat.

Areal density 32 kg/m^{-2}

Flatness 0.225 λ

RMS Roughness 7.36 Å

Net Shaped Deposition of Powered Silicon Carbide Mirrors

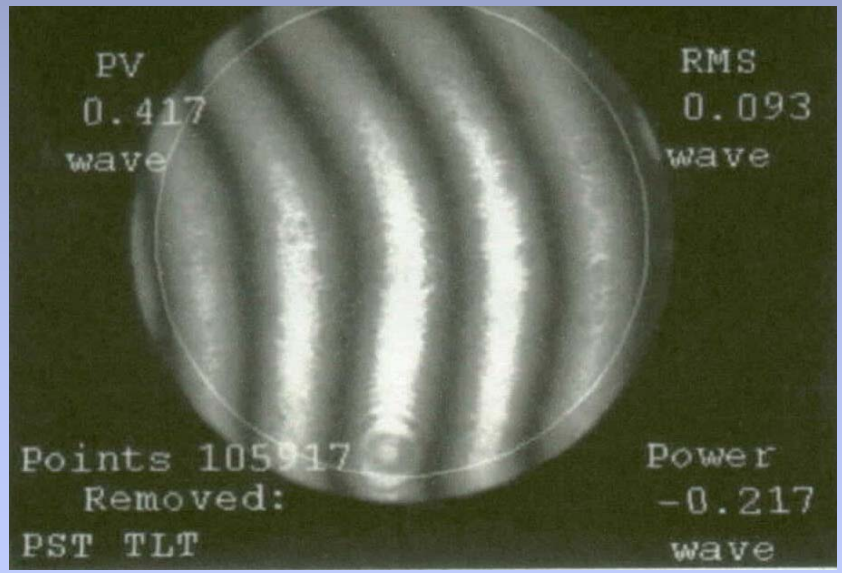


Near Net Shape Deposition

254 mm diameter mirror. 1 m radius
1 meter radius of curvature, 3 mm thick

254 mm diameter mirror, side view.

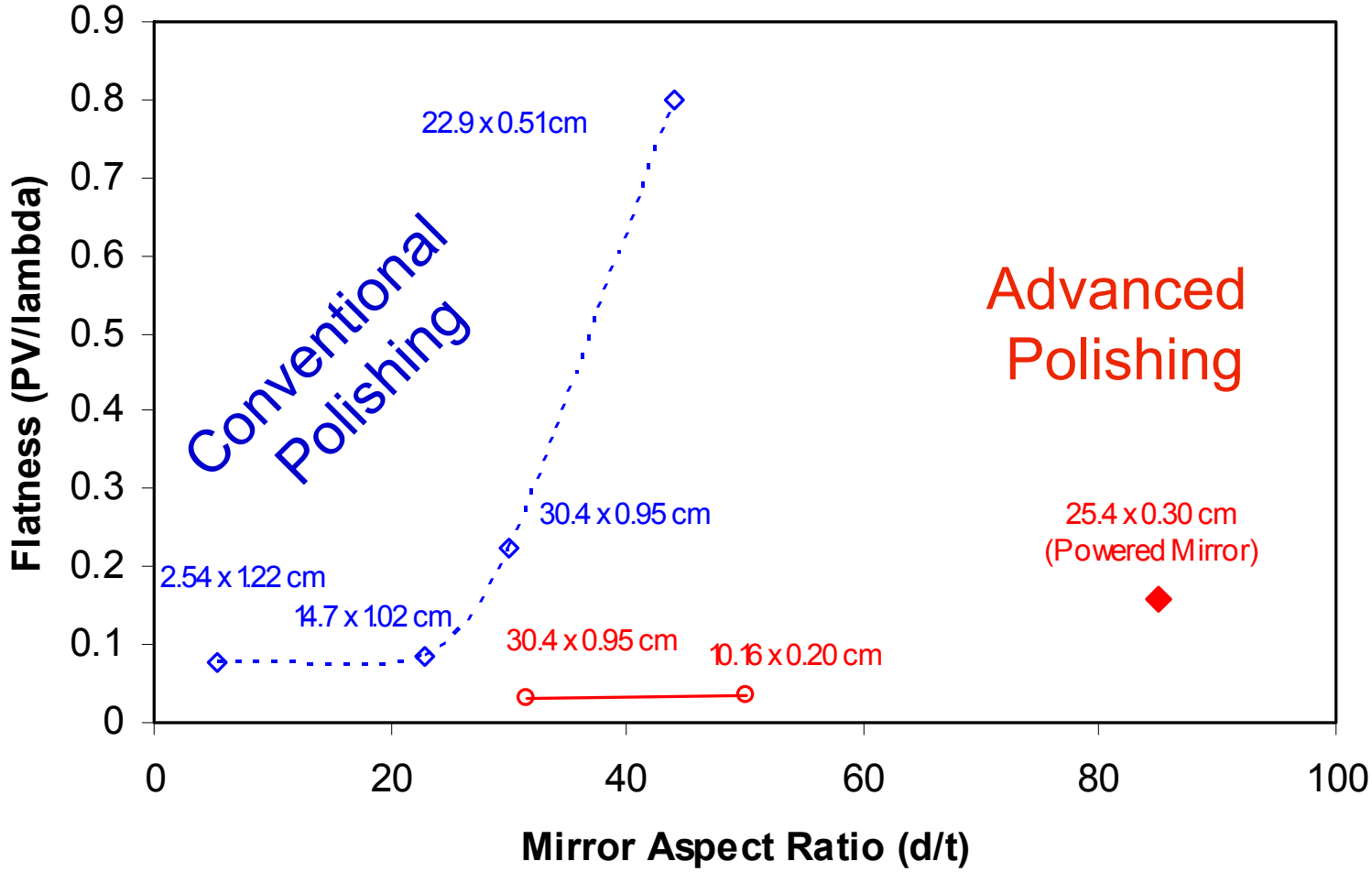
CVC SiC Foam Backed Mirror
Carbon and SiC Foams



Quickly and Easily Polished

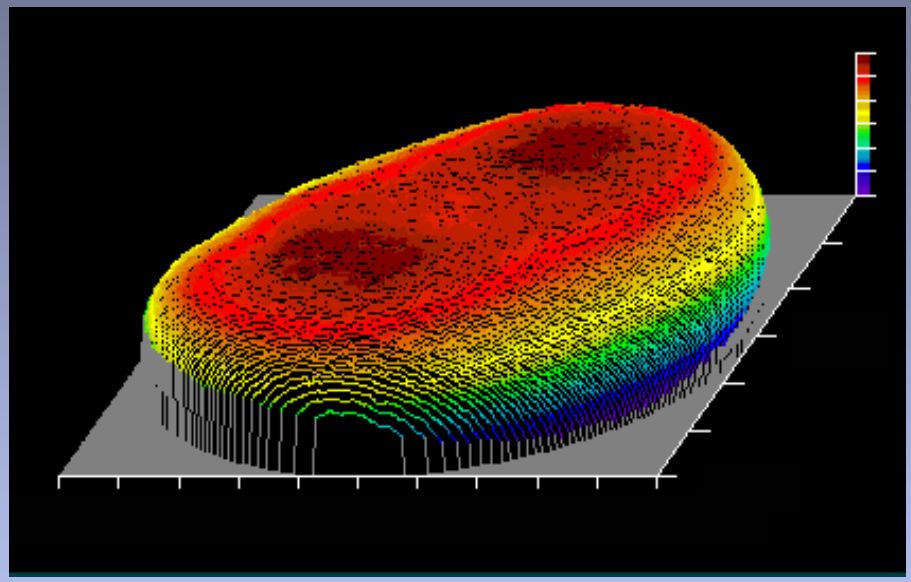
- Time/Schedule
- Surface Figure Achieved
- Surface Roughness Achieved

Trex CVC SiC is a Lightweight Material



Trex CVC SiC Optical Properties

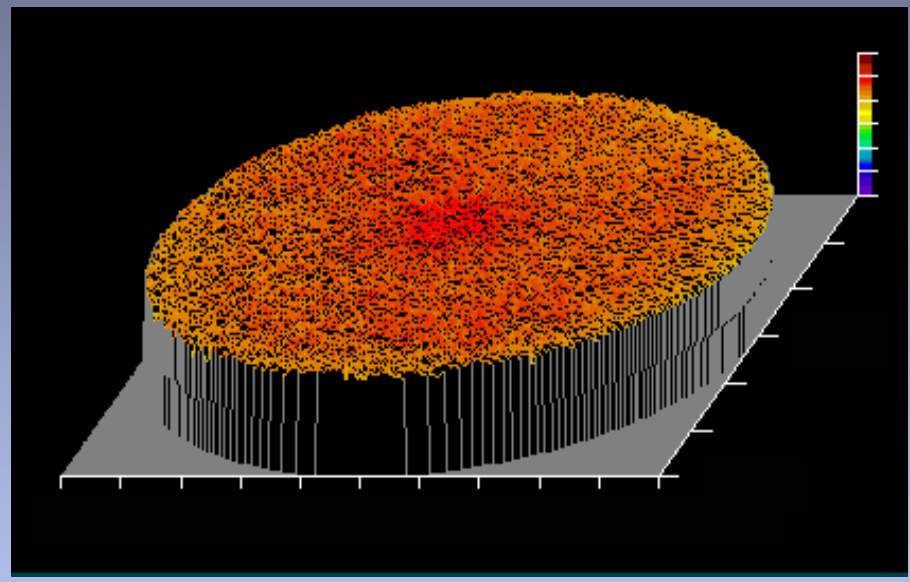
Initial Condition



0.122 λ P-V

0.022 λ rms

Single 11.3 minute Correction

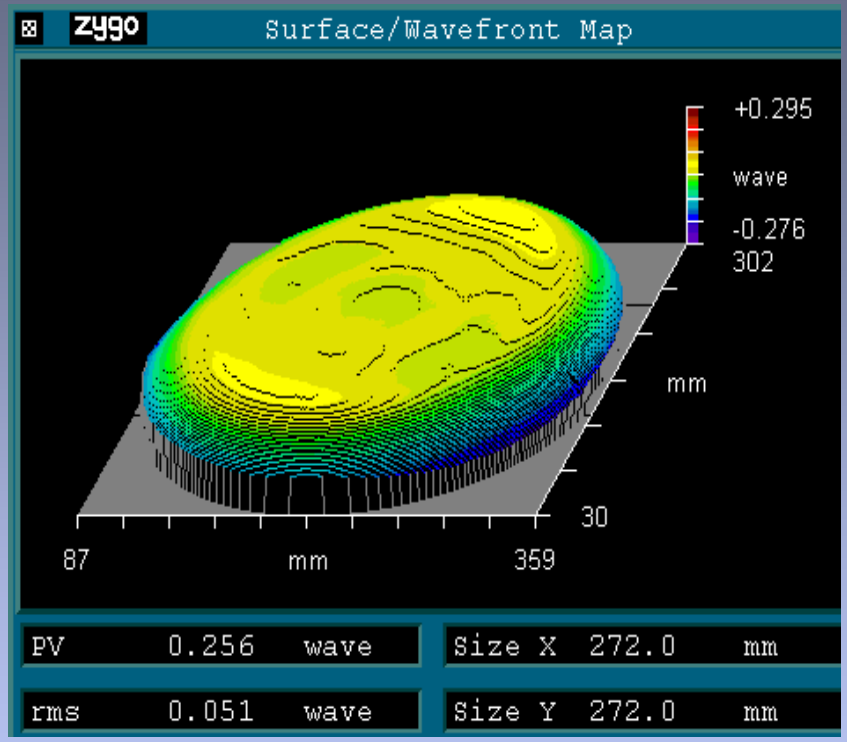


0.042 λ P-V

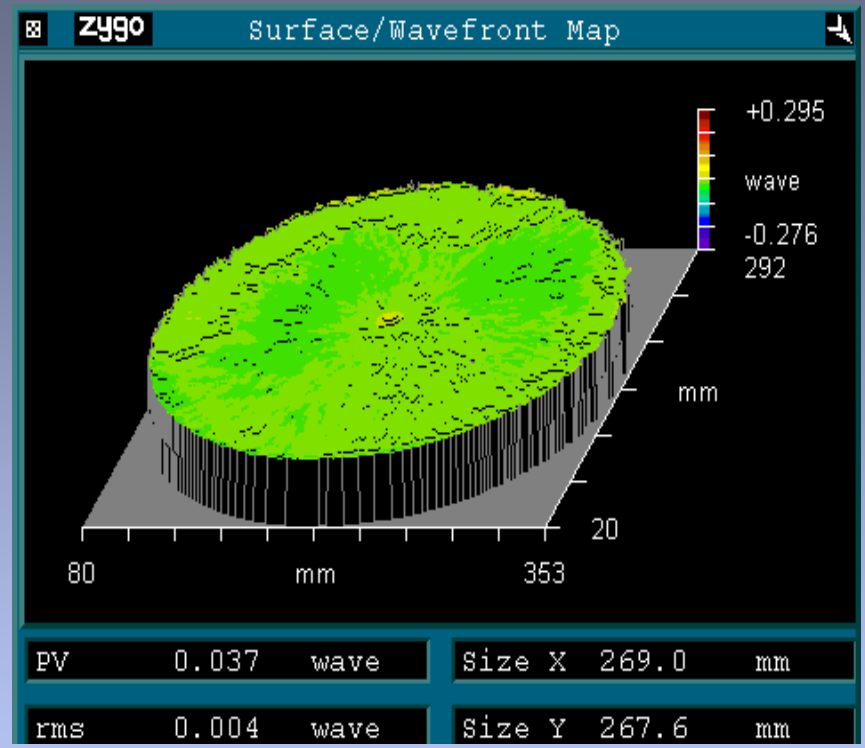
0.003 λ rms

304 mm Monolithic Mirror
Super Polished

Before



After

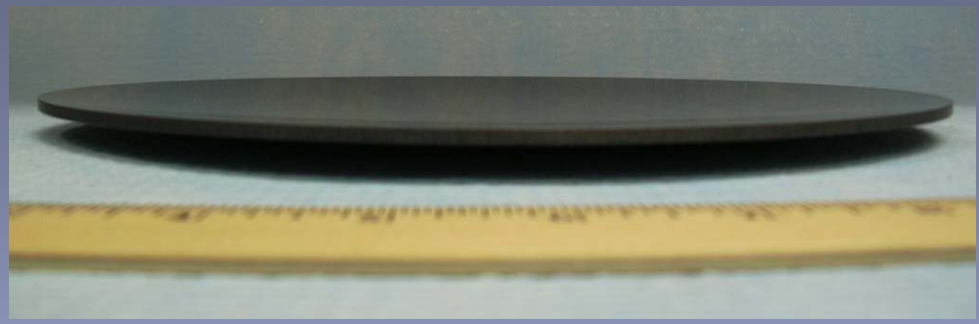


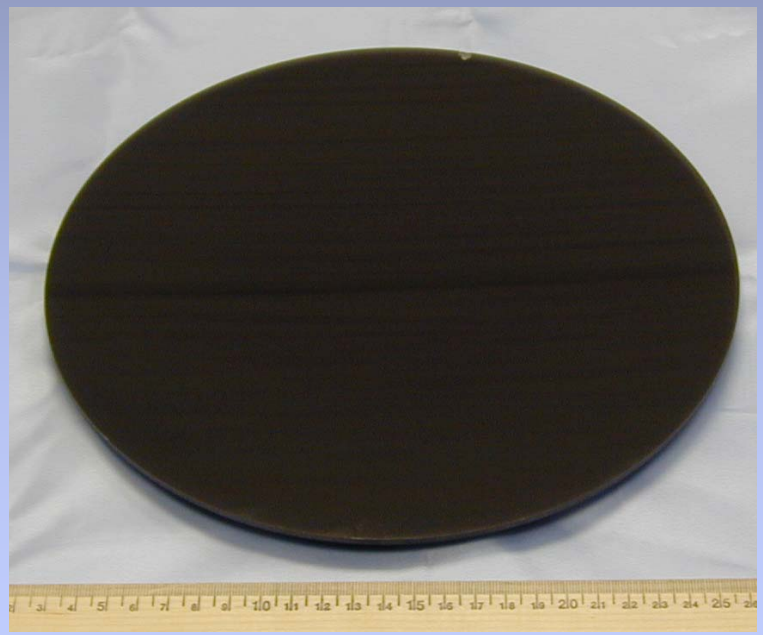
304 mm diameter 10 mm thick flat

Areal density 32 kg m^{-2}

Flatness 0.037 λ P-V and 0.004 λ at 632.6 nm

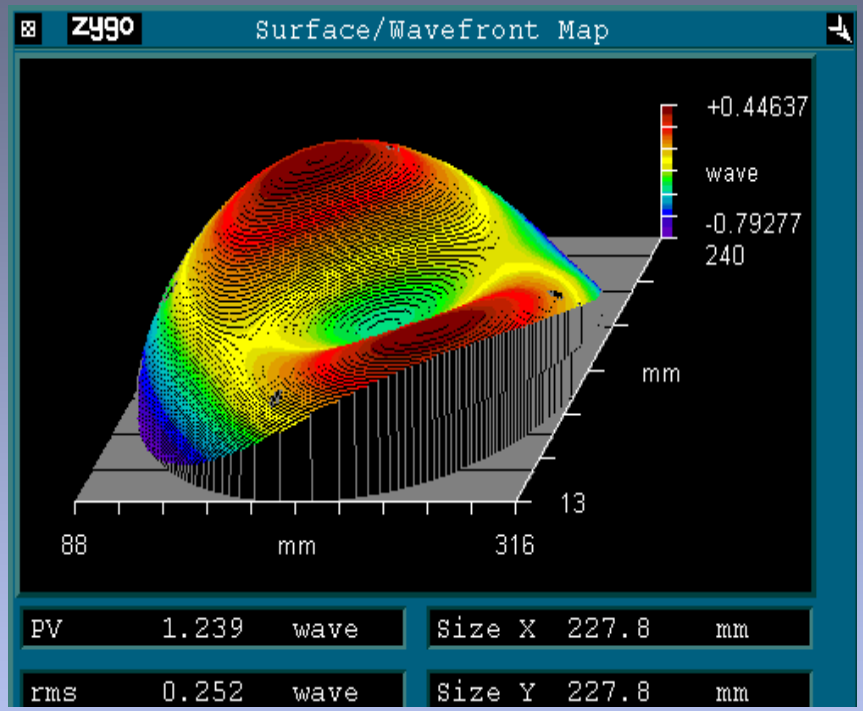
254 mm Curved mirror (1m r.o.c.) thickness of 3mm Areal Density 8.1 kg/m^2





Optical Properties of 3mm thick Powered Mirror (Advanced Polishing)

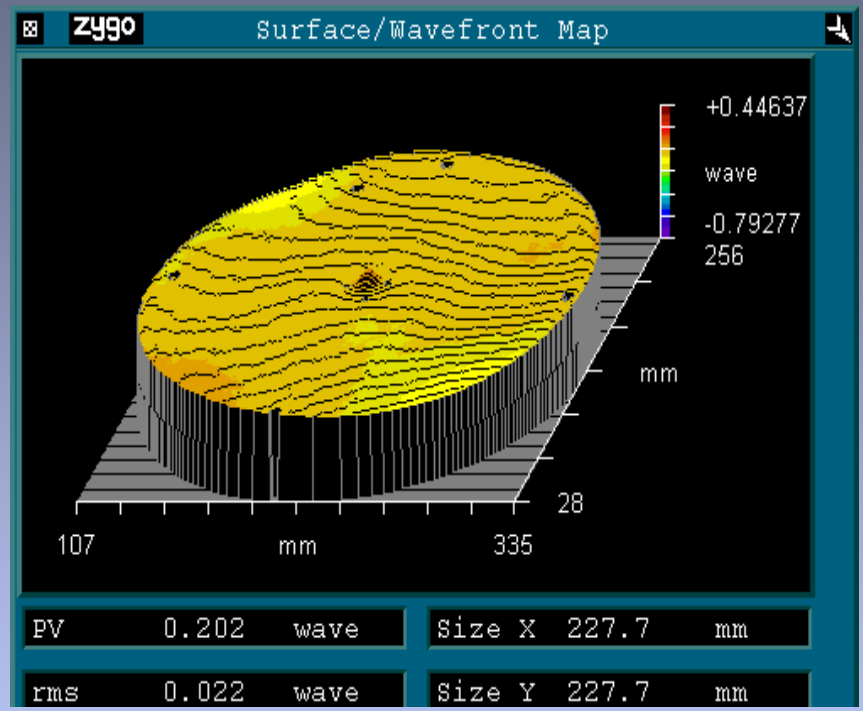
Before



126 nm rms

(1/5 λ)

After



11 nm rms

(1/58 λ)

Accomplishments to Date

- **Scientific and Technically Robust Process**
- **Reliable and Repeatable Process: Capable of producing components of various sizes, shapes, and configurations**
- **Superior Material Properties Demonstrated and Measured**
  - Exceptional Optical Performance (1/35 λ P-V figure; < 2 Å rms roughness)
  - Stress Free Material: Low cost, High yields, Geometric flexibility

Current Focus

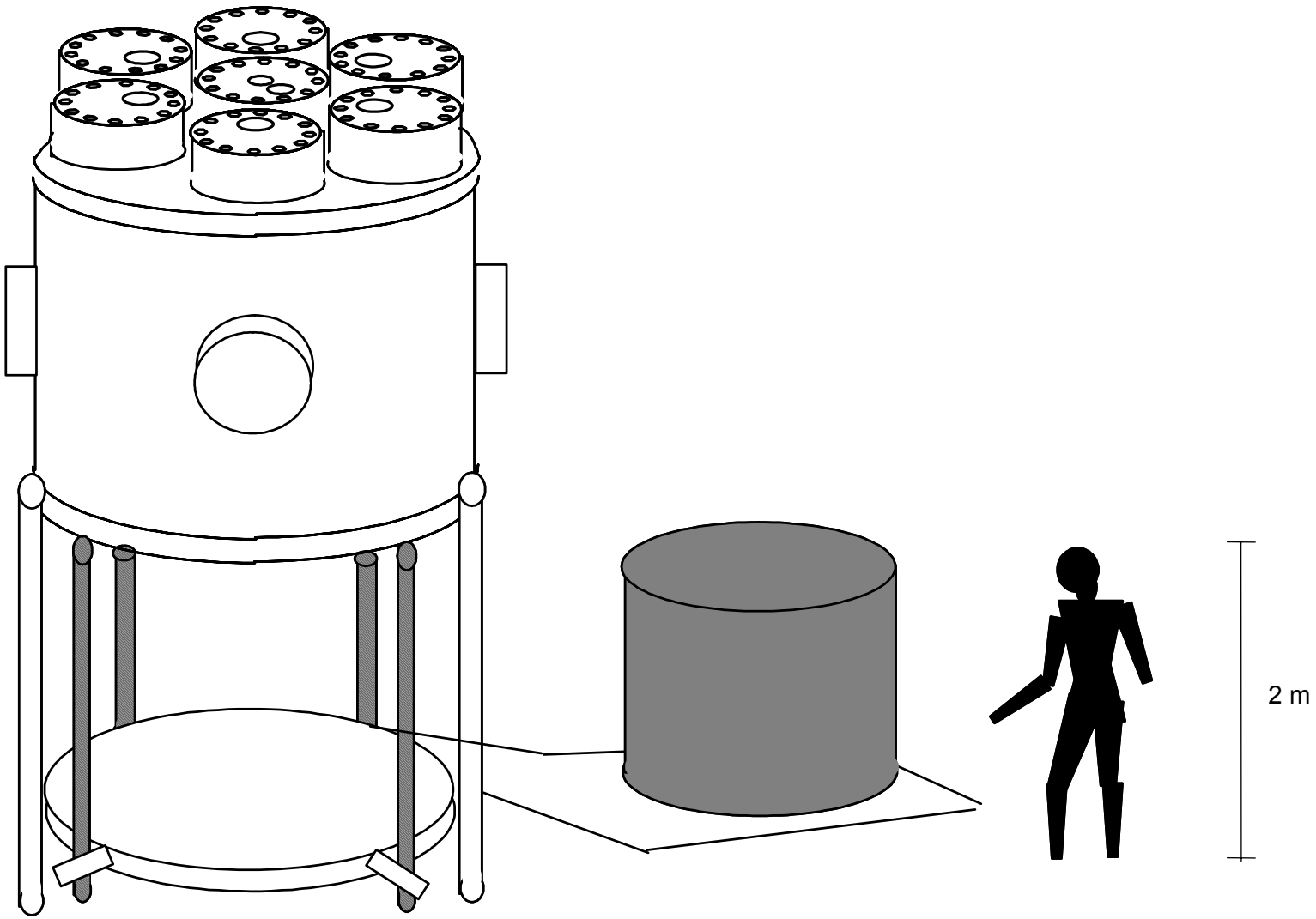
Program Goals

- **Design & Installation of 1.625 m Reactor**
  - Reactor and Graphite Structures
- **Scaling CVC Process to Fabrication of 1.5 Meter Optics**
  - Define process parameters for rapid fabrication of 1.5 m optics
- **Lightweight Mirror Designs**
  - Single Deposition of Ribbed Structures
  - Alternative Backing Structures/Materials
- **Near Net shape Deposition of 1.5 Meter Class Mirrors**

1.5 Meter Program Schedule

- **Schedule**
  - Reactor Design Q3 2004
  - Reactor Delivery Q1/Q2 2005
  - Reactor Installation Complete Q2/Q3 2005
  - Process Scaling to 1.5 meter scale Q4 2005/Q1 2006
  - Lightweight Ribbed Designs
    - 300 mm aperture
    - 1.5 meter aperture
  - Optimize Surface Replication/Preparation

Scale Up to 1.625 Meter Reactor



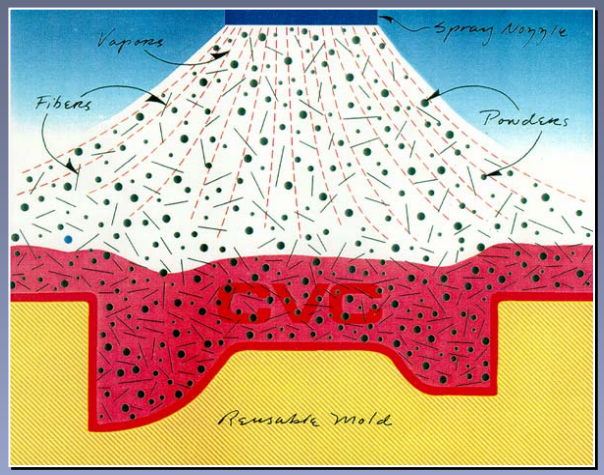
Current Work within CVC SiC Mirrors

- **1.5 Meter Class Reactor and Related Process Scaling Work**
- **Continued Work on Lightweighting, esp. Monolithic Ribbed Structures**
- **Improved Polishing Performance**
  - Targeting Surface Figure 1/100 λ P-V and Roughness <1 Angstrom rms
  - Meter Class Aperture Mirrors
  - Aspherical and Spherical Powered Mirrors

OPTICAL PROPERTIES
CVC SILICON CARBIDE

	Current	Future (<1 yr)	Potential
Surface Figure (P-V & rms)	23.4 & 2.5 nm ($^1/_{37}$ λ & $^1/_{253}$ λ)	6 nm P-V ($^1/_{106}$ λ)	2-3 nm P-V ($^1/_{211}$ - $^1/_{316}$ λ)
Surface Roughness (rms)	1.64 Å	1 Å	<1 Å
Areal Density (@ 300 mm)	8 kg/m^2	3-7 kg/m^2	2-3 kg/m^2
Areal Density (@ 1m)	N/A	10-15 kg/m^2	3-7 kg/m^2

Chemical Vapor Composites for Advanced Optics



Concept

- Patented ceramics manufacturing process
- Fabrication of very high quality light weight SiC optics
- Development of MRF polishing technique for short delivery times.
- Optics up to 1.5 m with <0.05 λ figure, Surface roughness <7 Å and areal density <10 Kg/m^2

MDA Benefit

- Rapid delivery of very high quality optics for missiles and sensors
- Large reactor fabricates parts up to 1.5 m and reduced cost for smaller parts.
- Be mirror replacement technology

Insertion Opportunities

- MDA missiles including EKV, SM3, KEI
- Sensors such as STSS

Current Status

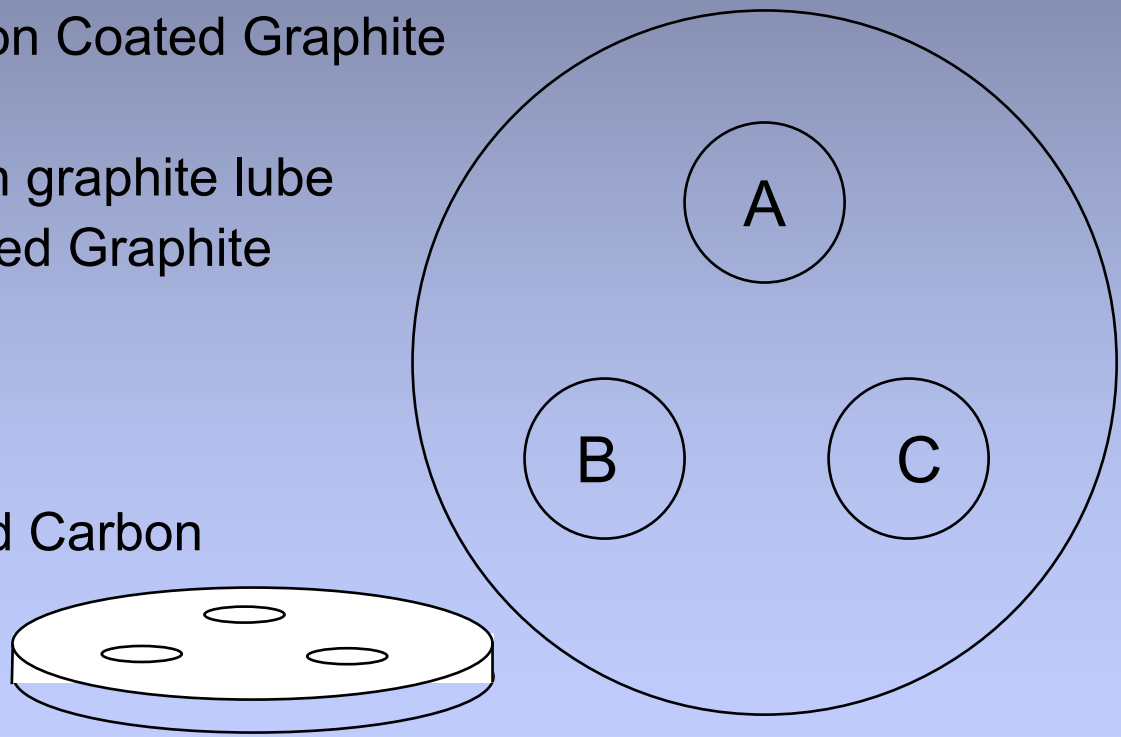
- Demonstration optics up to 40 cm. 1.5m reactor completion in Mar. 05.
- Preparing designs for Raytheon EKV and STSS
- Preparing designs for ARMS with Boeing SVS
- Erwin Myrick MDA TPOC

Outline

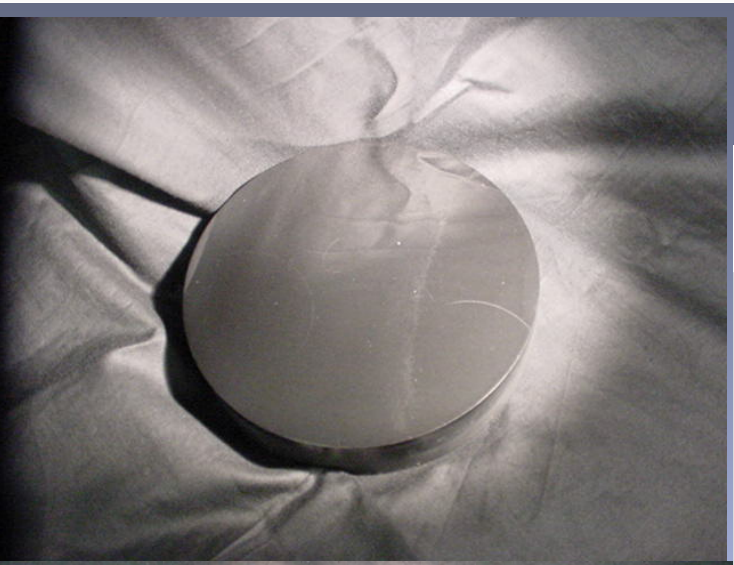
- **Why SiC for High Performance Optics**
- **SMDC**
  - TPOC: Douglas Deason of SMDC
- **NASA STTR**
  - TPOC: David Content of GSFC
- **AF-008**
  - TPOC: Lewis DeSandre of AFRL-DE Kirtland
- **MDA-59**
  - TPOC: Lawrence Matson of MDA/ML Wright-Pat
- **MDA-86**
  - TPOC: Brett deBlonk of AFRL-VS Kirtland
- **DARPA BAA**
  - TPOC: Leo Christodoulou of DARPA

NASA STTR Program

- **NASA STTR**
  - Surface Replication
  - Going to test highly polished surfaces of:
    - Glassy Carbon Coated Graphite
    - CVC SiC
    - CVC SiC with graphite lube
    - NASA Polished Graphite
    - Molybdenum
    - Tungsten
  - Others
    - Finer Grained Carbon
    - etc



Polished Graphite Mandrel



Veeco

Measurement Parameters

File:	WYK7F8
Wavelength	632.80 nm
Wedge	0.50
X/YSize	459 X 392
Pixel size	282.31 um
Date	03/03/2004
Time	08:29:50
Averages	4

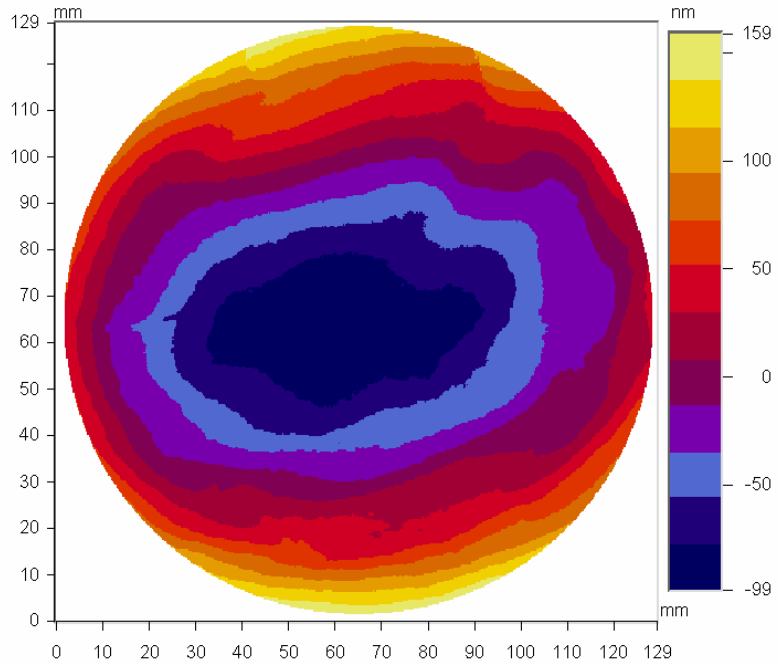
Analysis Results

Ra	47.790 nm
Rms	57.785 nm
20 Pt. PV	253.676 nm
2 Pt. PV	257.73 nm

Analysis Parameters

Terms	Tilt
Masks:	
Filtering	None
Data Restore	No
Valid Points	136198

Contour Plot



TREX ENTERPRISES
HAWAIIAN OPERATIONS

NASA STTR

Phase II Strategy

- Work towards insertion into Space Programs
  - X-Ray Optics
  - TPF, etc
- Technology applies to all optical programs

Outline

- **Why SiC for High Performance Optics Why SiC for High Performance Optics**
- **SMDC**
  - TPOC: Douglas Deason of SMDC
- **NASA STTR**
  - TPOC: David Content of GSFC
- **AF-008**
  - TPOC: Lewis DeSandre of AFRL-DE Kirtland
- **MDA-59**
  - TPOC: Lawrence Matson of MDA/ML Wright-Pat
- **MDA-86**
  - TPOC: Brett deBlonk of AFRL-VS Kirtland
- **DARPA BAA**
  - TPOC: Leo Christodoulou of DARPA

AF 04-008

- **Plan**
  - Partnership with DoD Prime
    - Fabricate and polish 5-6” mirrors
    - Model and Test Performance
    - Manufacturing plan for scaling to larger systems

AF 04-008

- **Phase II Strategy**
  - Phase II: Deliver and test two 750 mm mirrors to DE
  - Phase III: Build 1.3 meter mirrors according to Prime design specs
  - Insertion into ARMS program utilizing HAA
  - Expansion into ATL, ABL and/or SBL

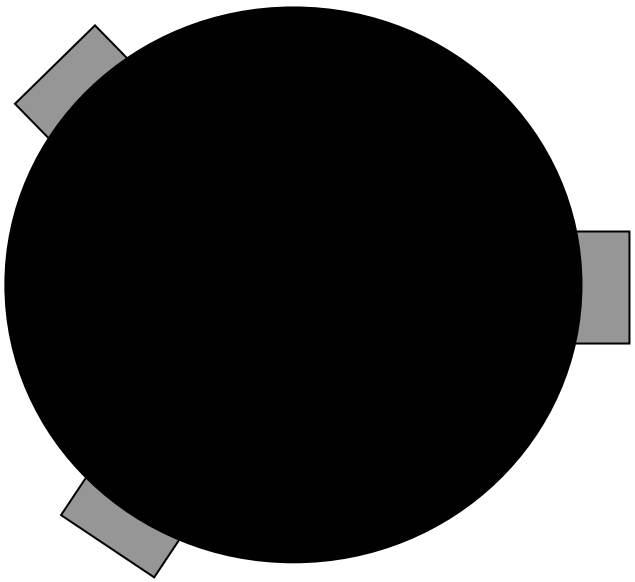
Outline

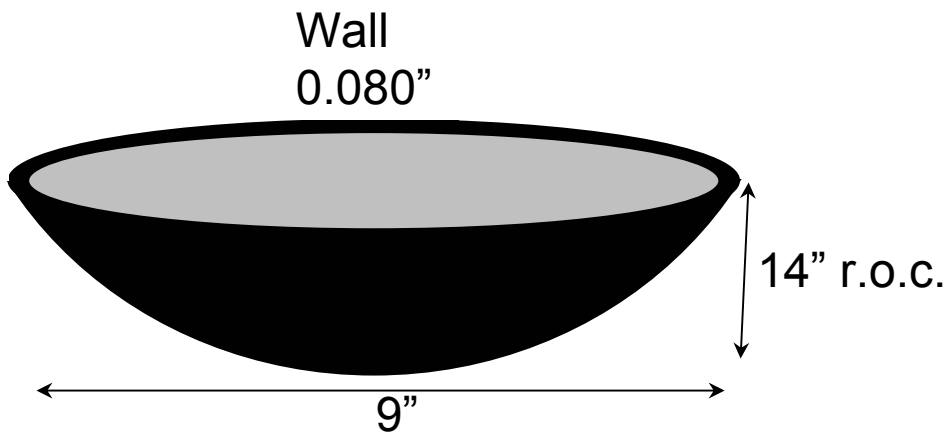
- **Why SiC for High Performance Optics**
- **SMDC**
  - TPOC: Douglas Deason of SMDC
- **NASA STTR**
  - TPOC: David Content of GSFC
- **AF-008**
  - TPOC: Lewis DeSandre of AFRL-DE Kirtland
- **MDA-59**
  - TPOC: Lawrence Matson of MDA/ML Wright-Pat
- **MDA-86**
  - TPOC: Brett deBlonk of AFRL-VS Kirtland
- **DARPA BAA**
  - TPOC: Leo Christodoulou of DARPA

Phase I Strategy

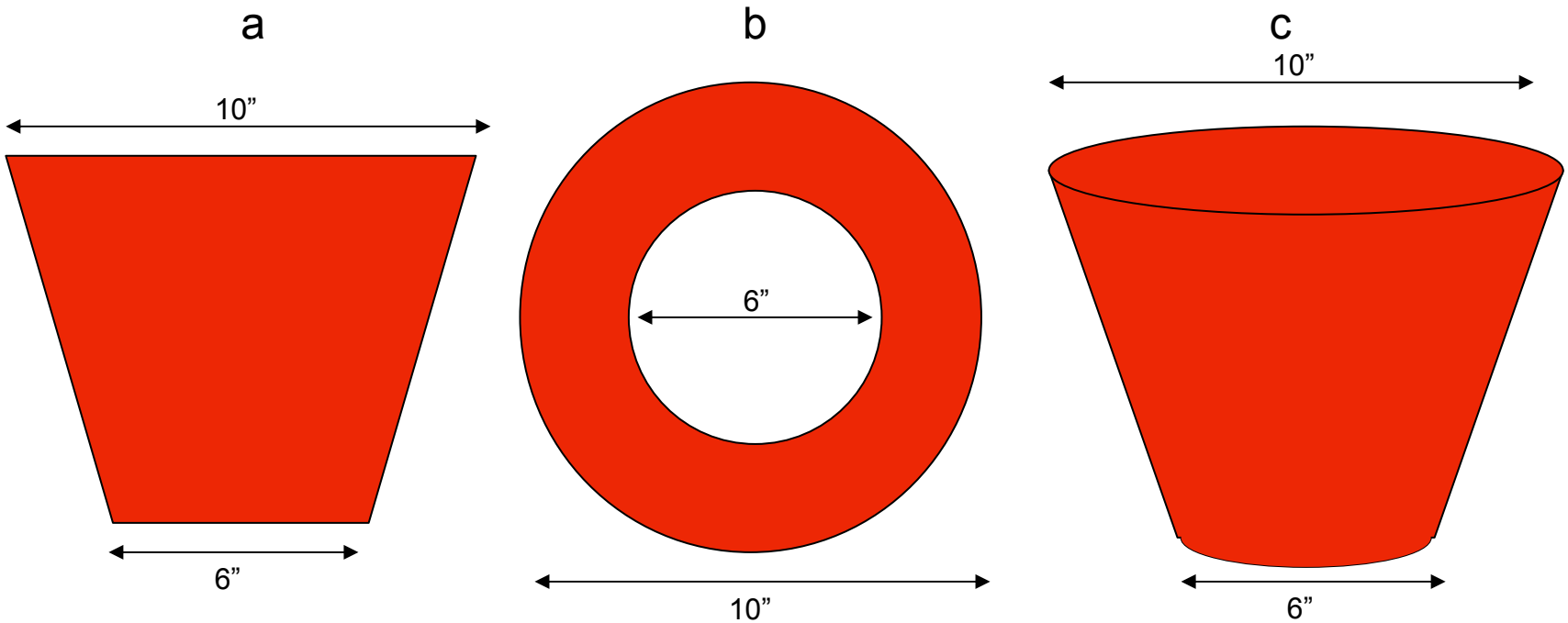
- Fabricate lightweight CVC SiC mirror for EKV
- Fabricate CVC SiC Mounting Structure
- Model and test performance of designs

Powered Mirror





CVC SiC Mounting Structures



MDA 04-59

- **Phase II Strategy**
  - Introduce design and mounting strategy as appropriate towards EKV mirror and telescopic system
  - Deliver system for flight qualification testing
  - Work with DoD Prime

Outline

- **Why SiC for High Performance Optics**
- **SMDC**
  - TPOC: Douglas Deason of SMDC
- **NASA STTR**
  - TPOC: David Content of GSFC
- **AF-008**
  - TPOC: Lewis DeSandre of AFRL-DE Kirtland
- **MDA-59**
  - TPOC: Lawrence Matson of MDA/ML Wright-Pat
- **MDA-86**
  - TPOC: Brett deBlonk of AFRL-VS Kirtland
- **DARPA BAA**
  - TPOC: Leo Christodoulou of DARPA

MDA 04-86

- **Tasks**
  - Reduce cost of 0.5 m class optics from $500k+ to $200k
- **Plan**
  - Polish Ultra Thin CVC SiC Mirrors
    - Aperture 10”
    - Areal Density 1.8 kg/m^2
  - Cryogenic Performance of CVC SiC mirror
  - Optimize Process steps of most attractive geometries and manufacture two 500 mm mirrors for Phase II

Phase II Strategy

- Work towards insertion into DoD Programs with partnering prime