Polymer Material and Casting Process Development for Reduced Manufacturing Cost of Spaceborne Optics

Brian Patrick – SRS Technologies
Dan Marker – AFRL
Jim Rotge - Boeing

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AIR FORCE RESEARCH LABORATORY

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Overview

- Research Objectives
- Polymer Material Capabilities
- Initial Experiment Description and Results
- Additional Required Research
- Conclusions

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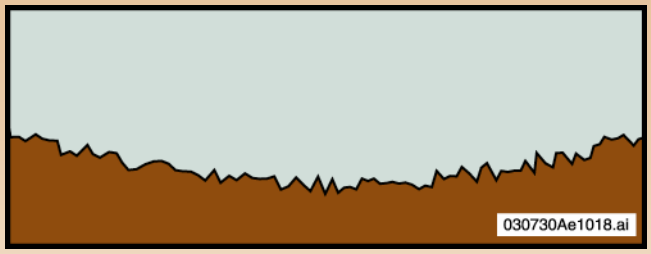
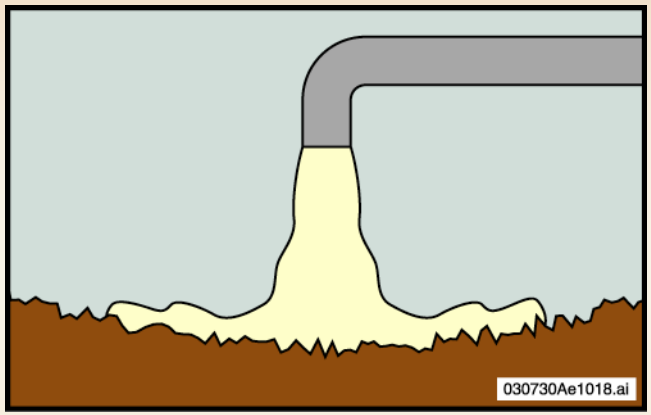
Objectives

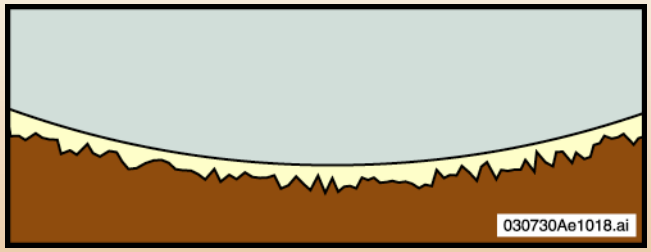
- **Demonstrate Feasibility of Depositing a Thin Layer of Polymer onto the Surface of a Mirror Still in a Rough-Polished State to Eliminate the Need for Time Consuming Final Surface Finishing.**
- **By Flow Casting a Polymer onto the Surface, Remaining Peaks and Valleys Are Filled In Resulting in a First-Surface Quality Finish**
- **This Process Would Be Ideal for Many Emerging Mirror Technologies Such as Nanocomposite and SiC Mirrors**



Initially Rough Surface



Addition of Polymer Layer



Deposition Process Results in In-Spec Surface Roughness

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Membrane Material for Optical Applications

CP1™ (Clear Polyimide)

- Developed by NASA Langley specifically for Space Applications
- Material Synthesized by SRS Under Exclusive License from NASA. (End to End Quality Control)
- Film Manufacturing Process Results in Very Homogenous Film Properties
- Wide Range of Operating Temperatures (Cryogenic – 250°C)
- Resistant to UV Radiation
- Film Solubility Enables Advanced Casting and Surface Replication Manufacturing Techniques

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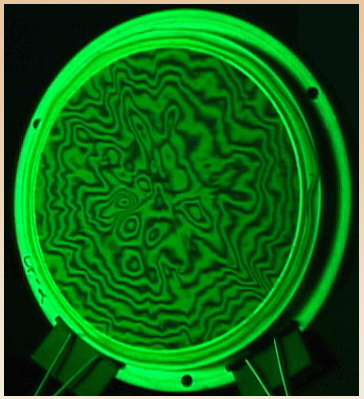
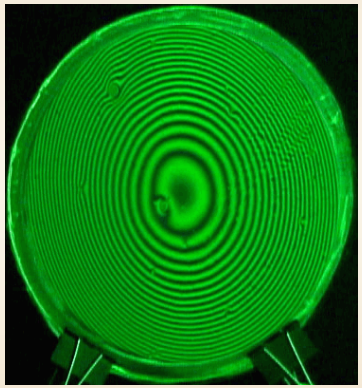
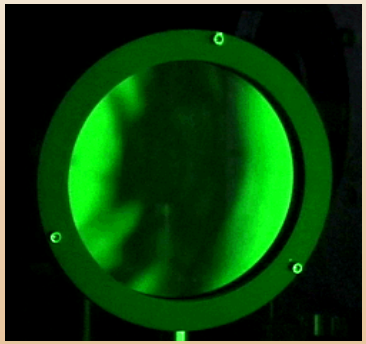
CP1 Material Development at SRS



Typical Membrane Material



Uniform Thickness Variation



Minimized Thickness Variation

(Monochromatic light reveals Fizeau fringes due to thickness variation)

- Proprietary Manufacturing Process Has Resulted in Drastic Improvement in Thickness Variation Present on Both Flat and Curved Substrates.
- Sub-Wavelength Thickness Variation Demonstrated on Apertures Up To 1.5-Meters.
- Low RMS Surface Roughness.
- Research has focused on development of lightweight optical quality mirrors for visible imaging and high energy laser applications.

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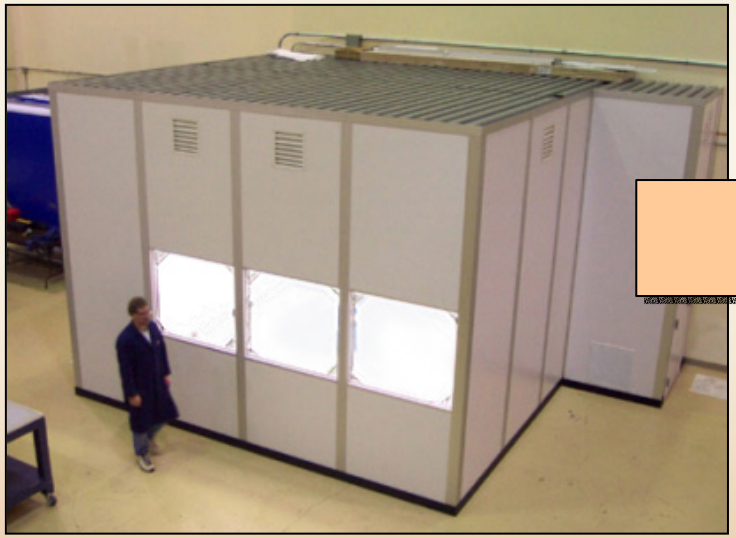
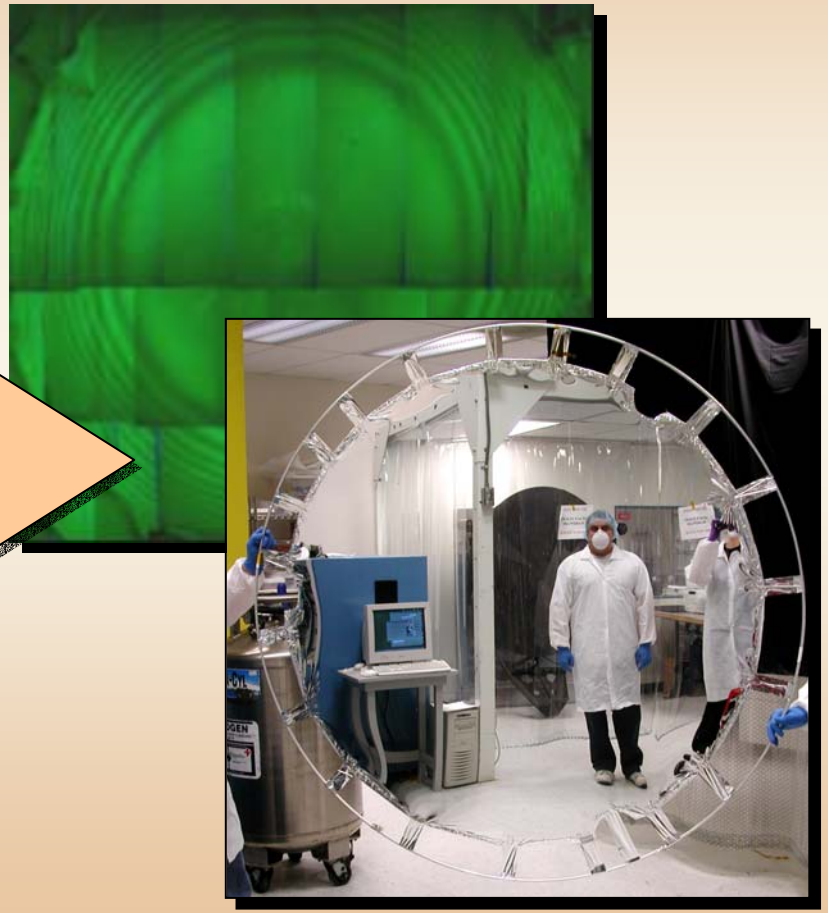
Scale-Up Potential

SRS Has Shown Precision Membrane Production Using Custom Manufactured Large-scale Polymer Film Casting Systems.

- 1.5-Meter Membrane Flats have been Successfully Manufactured and Coated.
- This can be expanded up to 3m.
- Roll to roll production also available.



SRS Clean Room Casting Facility



1.5m CP1-Film Coated with Aluminum

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Initial Surface Roughness Improvement

- **Initial Research Showed an Order of Magnitude Improvement on the RMS Surface Roughness of CP1 Airside Cast on a Teflon Substrate.**
- **The Tool Side of the CP1 Closely Matched the Substrate Measurement As Expected.**
- **Based on These Results Additional Research Was Proposed to Determine If This Process Could Be Used to Deposit a Very Thin Layer of CP1 Onto the Surface of a Rough-polished Mirror Substrate.**
- **The CP1 Layer Would Provide the Required Surface Finish, Eliminating the Need for Final Polishing of the Substrate.**

Sample	RMS Surface Roughness (nm)		
	Trial 1	Trial 2	Avg.
Teflon Casting Surface	21.3	13.9	17.6
CP1 Film – Tool Side	17.8	28.8	23.3
CP1 Film – Air Side	1.84	1.86	1.85

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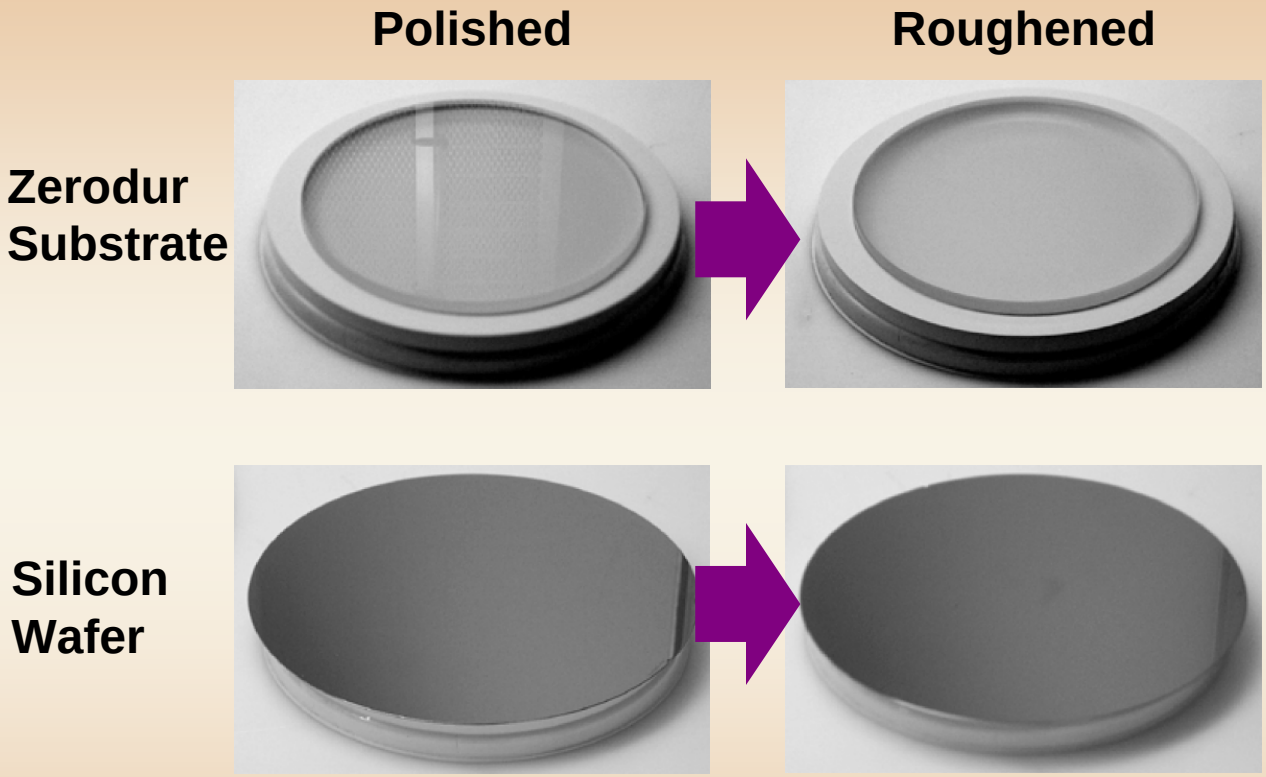
Substrate Selection and Preparation

- A 15cm Diameter Zerodur Flat and a 20cm Diameter Silicon Wafer Were Used As Test Articles for Additional Research.
- Both Substrates Were Initially in a Highly Polished State (Rq < 10Å)
  - One Side of Each Substrate Was Then Refinished to Increase the Roughness.



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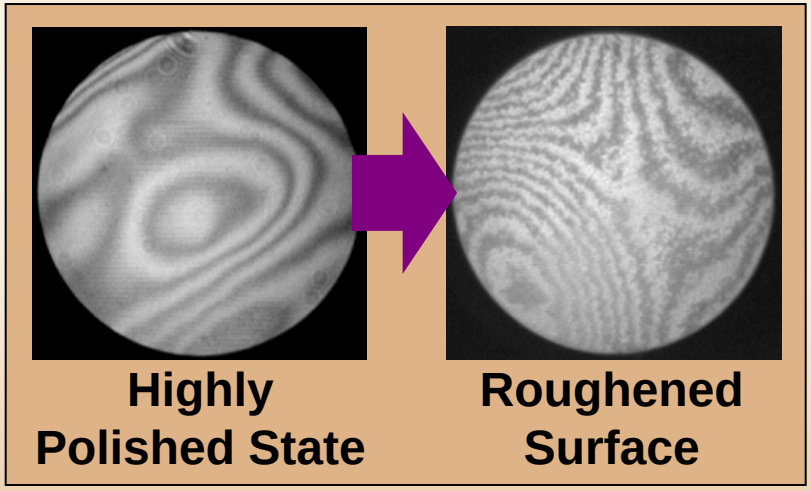
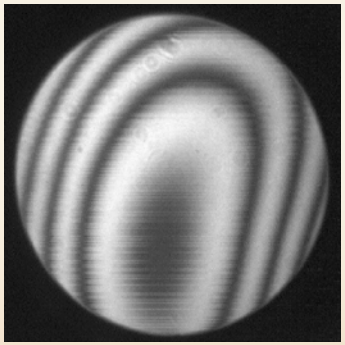
Substrate Selection and Preparation

- Interferograms Were Also Taken of Each Surface Prior to and After Surface Modification.
- This Easily Shows the Increased Diffusion of the Silicon Surface.
- The Zerodur Surface Was Too Diffuse to Obtain an Interferogram After Surface Refinishing.





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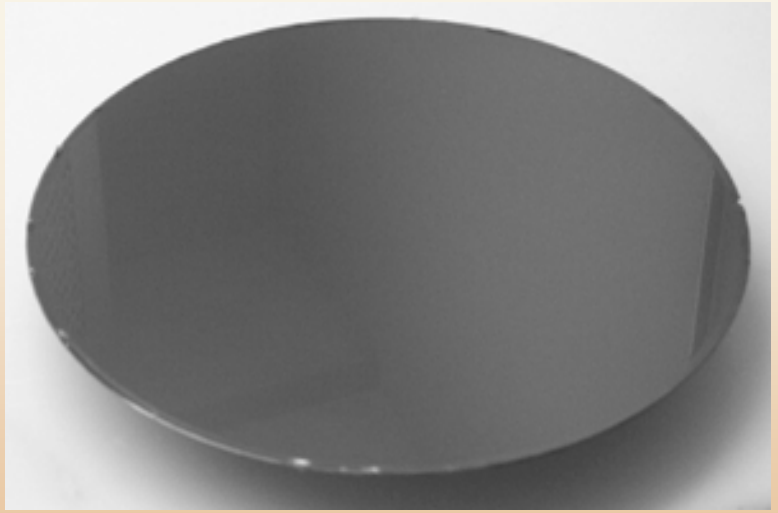
Polymer Application

- Typical Optical Quality CP1 Castings Are Between 7–9μm in Thickness.
- For This Experiment the Thickness Was Increased to Approximately 12μm to Attempt to Completely Smooth the Surface in a Single Coating.
- Other Than Adjusting the Viscosity of the Polymer Resin to Increase the Thickness, Standard Procedures for Optical Quality Membrane (CP1-DE) Production Were Used.

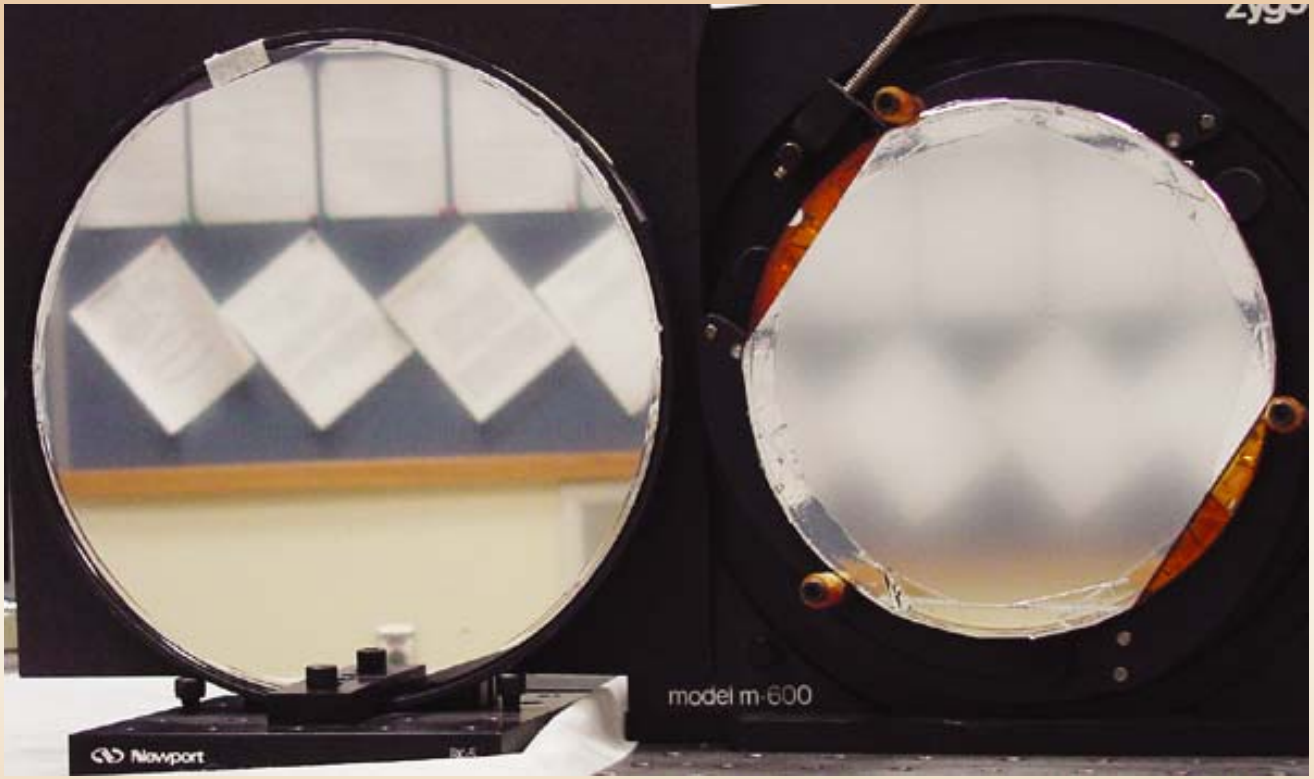
Zerodur Substrate



Silicon Wafer

Addition of Reflective Coating

- A reflective Coating of Aluminum Was Added to the CP1 Layer by Vapor Deposition.
- The Aluminum Is Required Since the CP1 Is Clear and Focusing on the Correct Surface Using an Interferometric Microscope Can Be Difficult.



Silicon Wafer Zerodur Substrate

Test Data

- **For the Roughened Surfaces the Addition of the Polymer Introduced an Approximate Factor of Three Reduction in RMS Surface Roughness for Both Substrates.**
- **The Polished Side of the Si Wafer That Was Coated Produced the Standard 1-1.5nm RMS Roughness Value Typically Produced by CP1 Membranes.**
- **While the Polymer Did Not Return the Material Back to Its Initial Quality, This Is a Significant Result That Demonstrates the Concept. Work Can Now Be Conducted to Improve This Result by Varying the Polymer Thickness and Application Processes.**

Substrate	Initial Polished Surface (RMS) (Å)			Roughened Surface (RMS) (Å)			Polymerized / Al Surface (RMS) (Å)					
Zerodur	3.5	4.9	6.3	2,641.6	2,692.4	2,641.6	850		766		796	
Silicon Wafer	9.1	9.4	10.4	838.2	787.4	914.4	Polished Side			Rough Side		
							10.8	14.8	10.7	290	195	242

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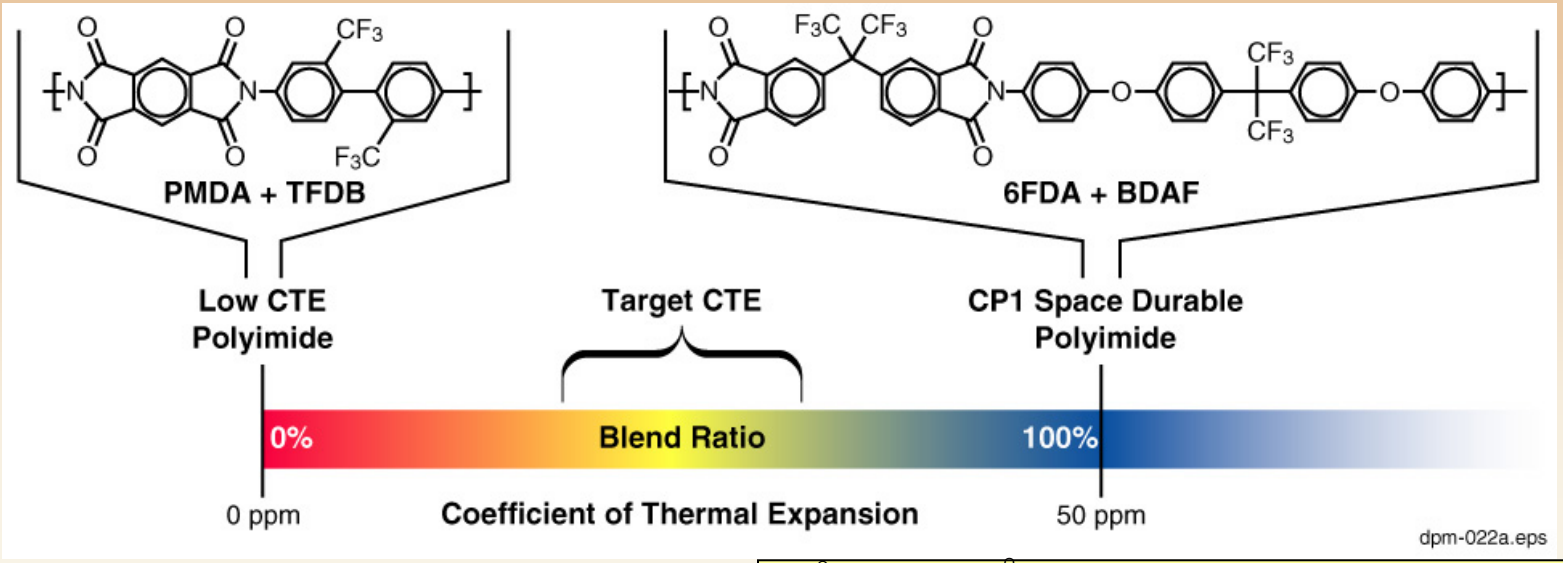
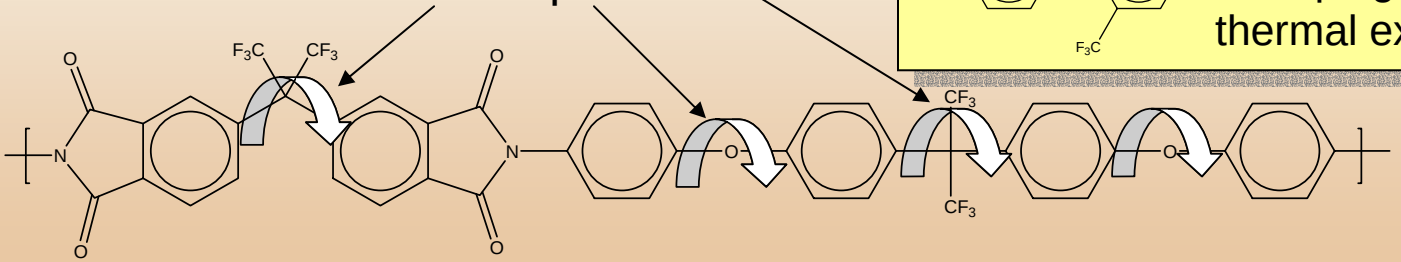
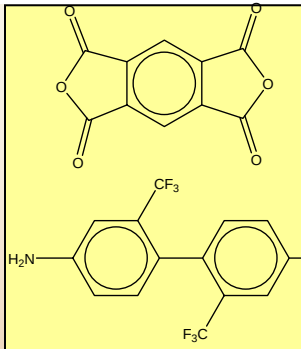
Tunable CTE Reduction
Crankshaft Mobility Reduction



Thermally-induced crankshaft rotations about flexible covalent bonds sweep out free volume and increase thermal expansion





Crankshaft Reduction

Conformationally restricted monomers reduce crankshaft sweeping motion and reduce thermal expansion.

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Reduced-CTE High Temperature Polyimide Films

Current Polymers Tested

- CTE = 28 ppm/°C
- CTE = 38 ppm/°C
- CTE = 39 ppm/°C
- CTE = 43 ppm/°C

Synthesized and fabricated at SRS

Reduction of CTE and low modulus of CP1 will allow negligible shape distortions when thermally cycled on a substrate.

1. **Synthesized reduced CTE polyimides to provide broad overview of CTE-reduction**
2. **Characterized thermal, solubility, and casting behavior**
3. **Obtained clear, flexible films similar to CP1**

CP-1 Reference
51 ppm/°C Reported

Common Materials
Aluminum – 25 ppm/°C
Copper – 17 ppm/°C
Ceramics – 5-10 ppm/°C
Graphite – 0 ppm/°C

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Additional Research Required

- **Additional Studies to Test the Effect of Increasing the Thickness of the CP1 Layer to Further Reduce the Substrate Surface Roughness Must Be Completed.**
  - **Maintaining a Minimized Thickness Variation Film Is Important to Maintain the Substrate Shape, but There**
- **Additional Separately Deposited Layers of Polymer Can Be Added to Provide an Overall Increase in Thickness. The Thicker Multilayer Surface Could Be Used for Finishing Rougher Surfaces.**
- **The Allowable Initial Roughness of the Substrate Needs to Be Defined and Weighed Against Process Improvements for Casting Thicker or Multilayer Polymer Membranes.**

Conclusions

- Tests Were Conducted to Determine the Surface Finish Improvement Introduced by Depositing a Layer of Precision Polymer on Two Substrates With an Initially High Surface Roughness
- With a Polymer Layer Thickness of Approximately 12μm, a Factor of Three Surface Roughness Reduction Was Achieved on Both Test Articles.
- This Demonstrates the Feasibility of the Process and Additional Research Must Now Be Conducted in Order to Improve on This Promising Result.
- This Process Could Significantly Reduce the Manufacturing Costs and Time for Lightweight Mirror Production Using Materials Such As SiC and Nanocomposite Technologies.