Goodman Technologies, LLC

NASA

3D PRINTED SILICON CARBIDE SCALABLE TO METER-CLASS SEGMENTS FOR FAR-INFRARED SURVEYOR

2018 Mirror Technology Days

NASA Phase II Results

Contract #80NSSC18C0077

An ACTIVE Participant in STEM
"You have to give it away to keep it"

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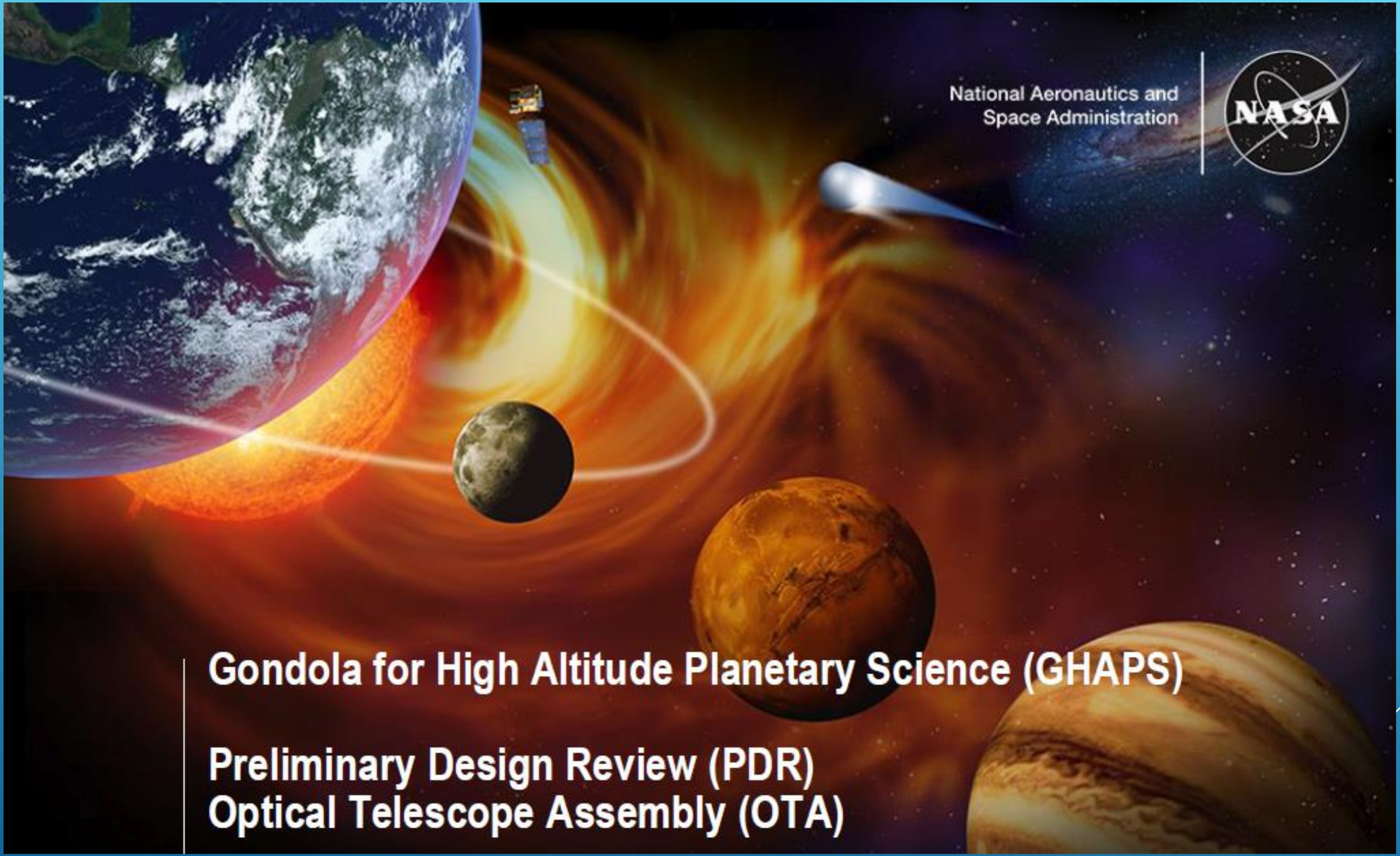

Courtesy of Monica Hoffman (TPOC) and Roy Young (Deputy)

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OVERVIEW

- NASA Priority Technology Gaps
- GHAPS Requirements
  - GHAPS OTA Overview
  - OTA Characteristics
  - Primary Mirror Mechanical Requirements
  - Primary Mirror Design
- Phase II Goals
- Phase II Progress Report
- Full-Scale Mirror Analysis Results
- 1/4th scale mirror design
- 1/4th scale mirror analysis
- Alternate design for 1/4th scale mirror

NASA PRIORITY TECHNOLOGY GAPS

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- **Phase II Addresses Technology Development/Demonstration of Segments Traceable to Origins Space Telescope (OST)**

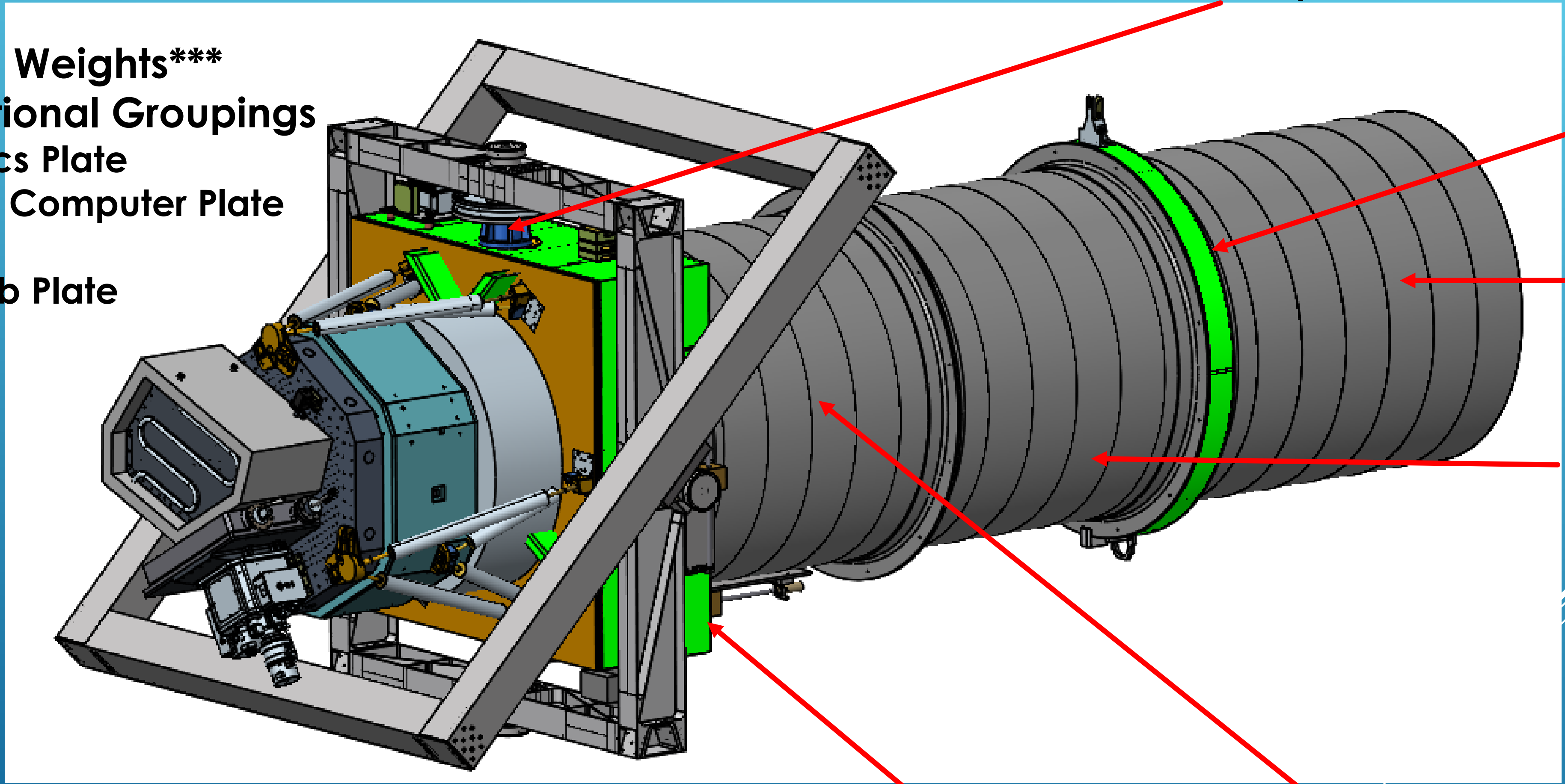
Cosmic Origins (COR) Program Annual Technology Report (PATR)

2017 Priority	Technology Gap Name	Science Addressed	Submitted By
Priority 1	Heterodyne Far-IR detector arrays and related technologies	Far-IR	OST STDT
	Cryogenic readouts for large-format Far-IR detectors	Far-IR	OST STDT
	Warm readout electronics for large-format Far-IR detectors	Far-IR	OST STDT
	Large cryogenic optics for the Far IR	Far-IR	OST STDT
	Large-format, low-noise and ultralow-noise Far-IR direct detectors	Far-IR	OST STDT
	High-performance, sub-Kelvin coolers	Far-IR/X Ray	OST STDT
	Large-format, high-dynamic-range UV detectors	UV/Far-UV	LUVOIR STDT
	High-reflectivity broadband Far-UV-to-Near-IR mirror coatings	UVOIR	LUVOIR STDT
Priority 2	Lightweight, large-aperture, high-performance telescope mirror systems for Far-IR	Far-IR	General Community
	Compact, integrated spectrometers for 100 to 1000 μm	Far-IR	OST STDT
	Advanced cryocoolers	Far-IR/X Ray	OST STDT
	Mid-IR detectors	Mid-IR	OST STDT
	Cryogenic deformable mirror	Mid-IR	OST STDT
	High-efficiency UV multi-object spectrometers	UV	General Community
	Lightweight, large-aperture, high-performance telescope mirror systems for UVOIR	UVOIR	General Community

GHAPS REQUIREMENTS

GHAPS OTA Overview

BIRC-IR
UV-VIS
Motorized Trim Weights***
Avionics Functional Groupings
- OTA Avionics Plate
- WASP Flight Computer Plate
- LN251Plate
- Ethernet Hub Plate



OTA Characteristics

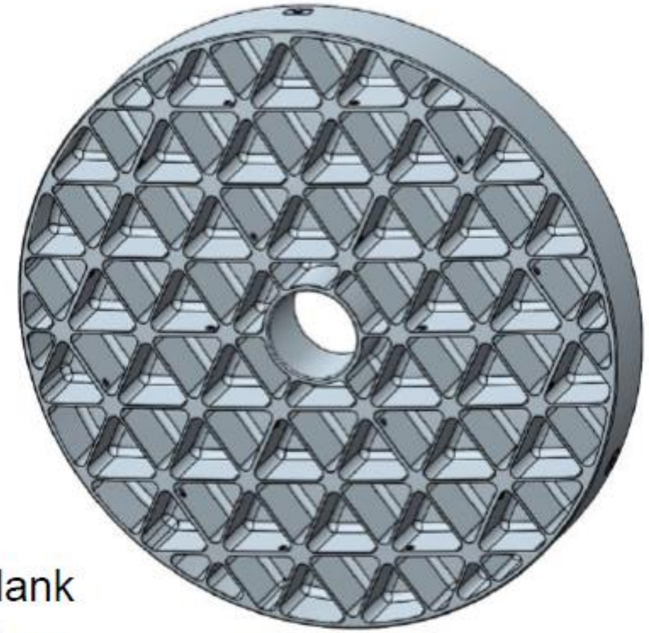
- Key Features of OTA
  - 14.052-m effective focal length (EFL) Ritchey-Chretien (RC) design
  - Hyperbolic primary and secondary
    - Primary will be a contracted item – size exceeds in-house fabrication capabilities
    - Secondary will be fabricated in-house
  - Design influenced by existing legacy UV-visible and IR instruments
    - OTA focal length is a compromise between short focal length desired for IR instrument and long focal desired by UV-visible instrument
  - 1.0-m clear aperture, F/2.5 focal ratio
    - Physical diameter of mirror 1030-mm to include rolled bevel edges
    - Edge thickness 125 mm
  - Mirror Material: Zerodur Tailored CTE
  - Open back configuration with isogrid light weighing pattern
    - Current weight 78.7 kg, Light weighting fraction ~ 68%
    - Compromise between weight reduction and mirror robustness (i. e., crash survival)

PRIMARY MIRROR MECHANICAL REQUIREMENTS

- Optical System Performance:
  - Operating Temperature Range: -50C to 20C
  - Gravity release
- Fundamental Frequency:
  - 10 Hz Minimum for Optical Telescope Assembly.
  - Zerodur Primary Mirror estimated 378.5 hz
- Adequate Strength
  - +/-10g (X,Y, and Z directions, independently)
- Drawing Requirements
  - Aspheric Optical Surface
  - 1080 Diameter, Center Hole
  - Whiffletree and Tangent bar Mounting Interfaces

(M1) Primary Mirror

- **Primary Mirror**
  - 1030 mm OD
  - 125 mm Thick
  - Schott Zerodur (0±0.02 PPM/K CTE)
  - 65% Light-Weighted Open Back
- **Support Bond Pads**
  - 3 Tangent Bar Mirror Mount
  - 18-Point Whiffle Tree Axial Mount
- **Drawings**
  - MEE00532: Pre-Polished, Light-Weight Blank
  - MEE00531: Bonded/Polished, Primary Mirror



- **Total Weight: 171.5 lbs (77.8 kg)**
- **Potential Weight Savings**
  - No Opportunity

40.55 inch OD
4.92 inch thick

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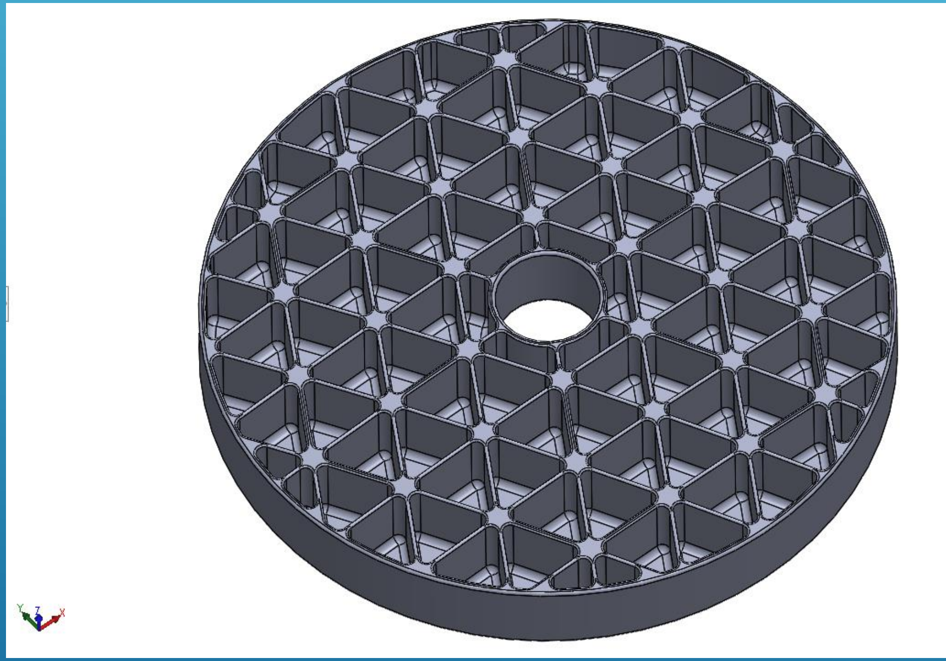
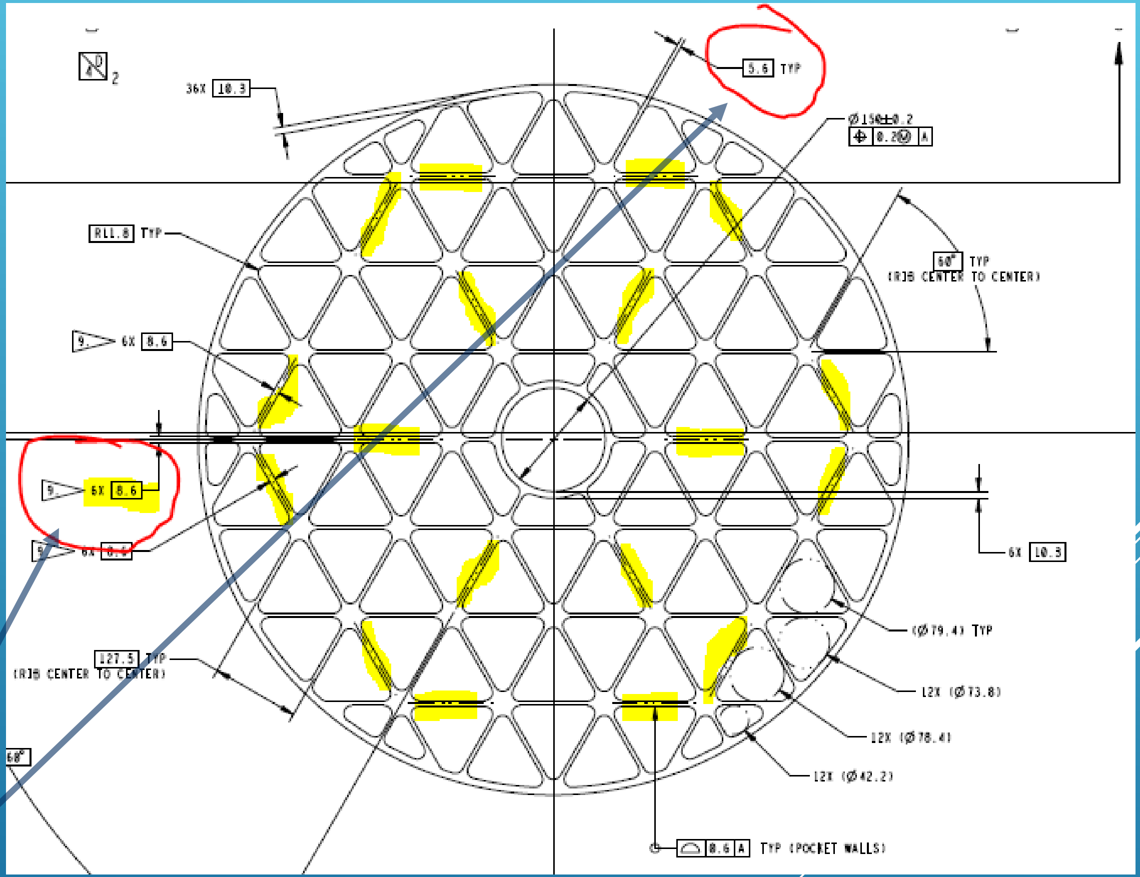
MEE00532-001, REV C. GHAPS PRIMARY MIRROR PREPOLISHED BLANK



STEP File Model

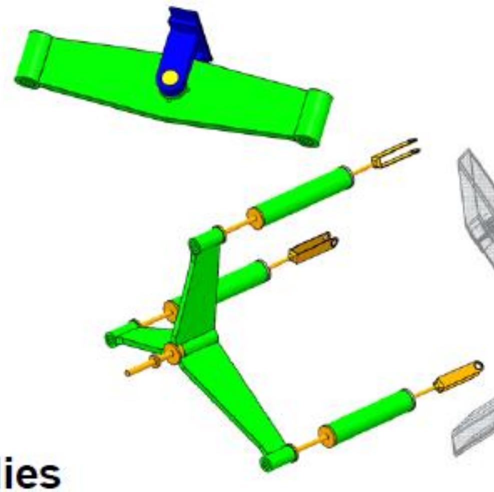


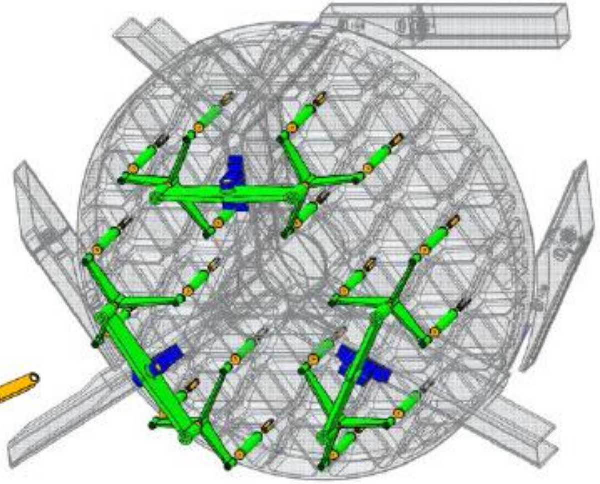
GSFC Drawing

Note 2 different Rib Thicknesses 8.6 (0.34 –in) and 5.6 mm (0.22-in)

(M1) Whiffle-Tree & Tangent Bar Mirror Mount

- **6X Rockers**
- **3X Yokes**
- **Simultaneous 1D Athermal**
  - Inner Bond Path
  - Outer Bond Path

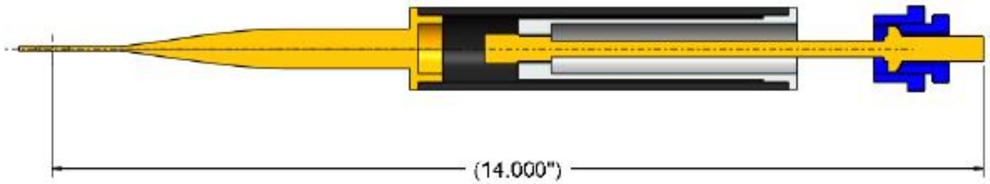


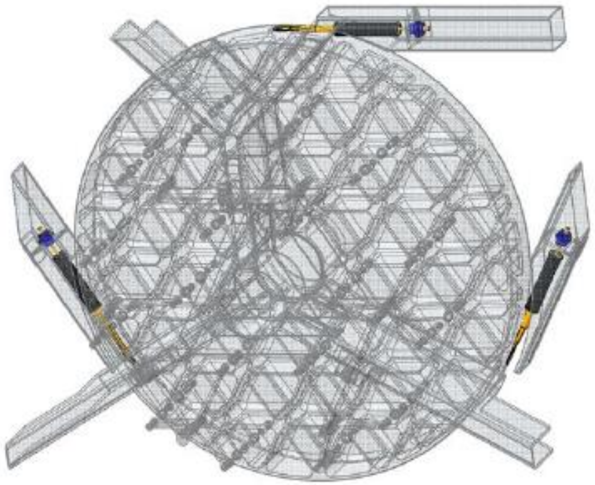


- **3X Tangent Bar Assemblies**
  - Bond Pad Flexure (Titanium)
  - Composite Tubes (IM7/8552)
  - Switch Back (6061 Aluminum)
  - Expendable Flexure (Titanium)
  - Differential Screw (Inner, Outer)
- **1D Athermal**

  Axial Position Datum A

  Tangential Line of Action





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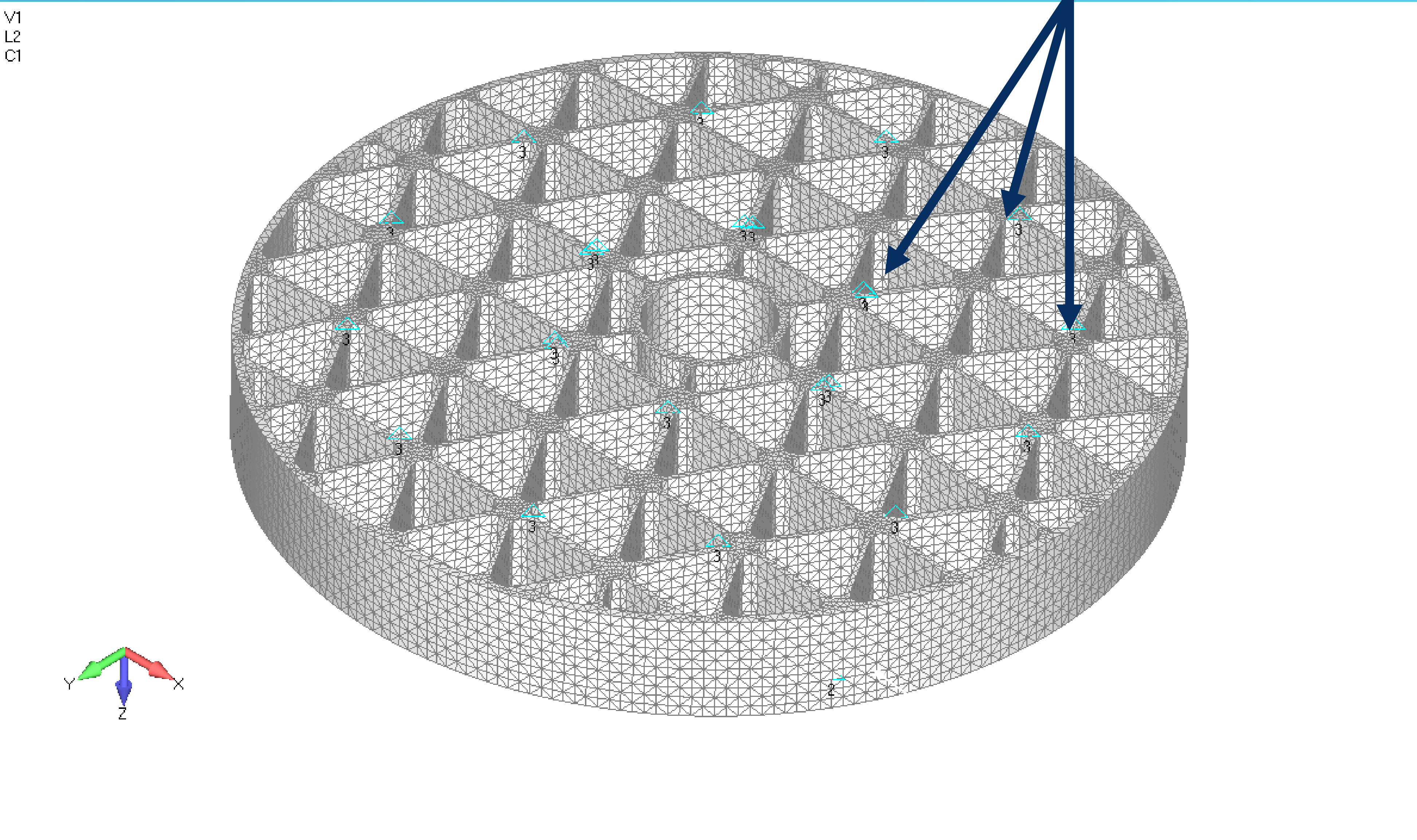
FULL SIZE GHAPS PRIMARY LEGACY ISOGRID DESIGN FINITE ELEMENT MODEL DESCRIPTION

18 Whiffle Tree Support Areas



PHASE II GOALS

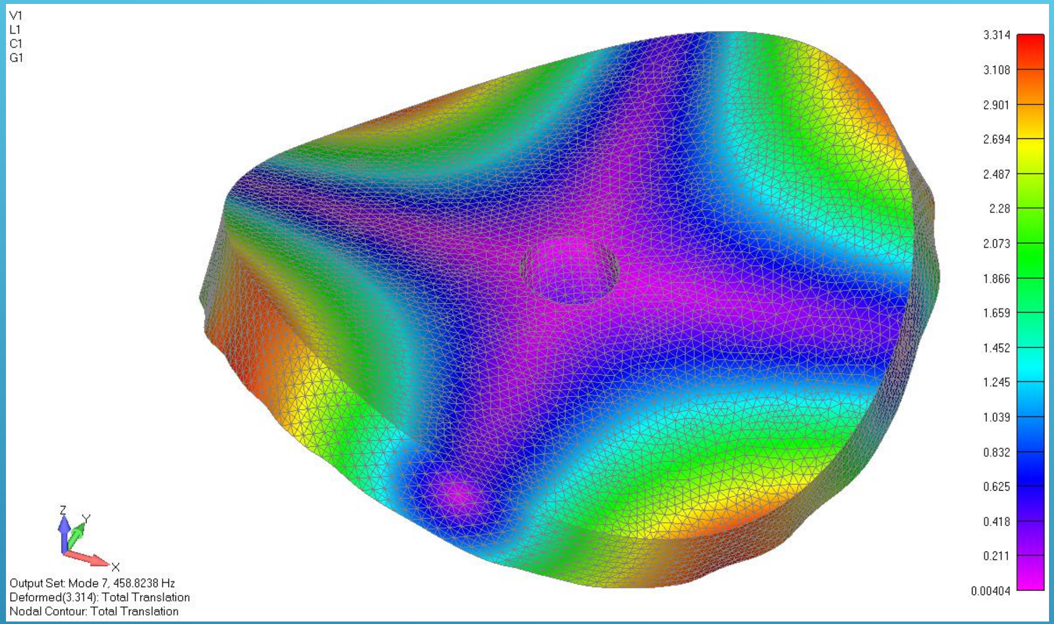
- Use 3D printing and additive manufacturing processes to produce the greenbody components, that when assembled and ceramized, will yield a large meter-class silicon carbide primary mirror substrate suitable for GHAPS, and is traceability to future missions that require large mirrors.
- Print four OAP parts and then AM to make a monolith primary mirror at quarter scale.

PHASE II PROGRESS REPORT

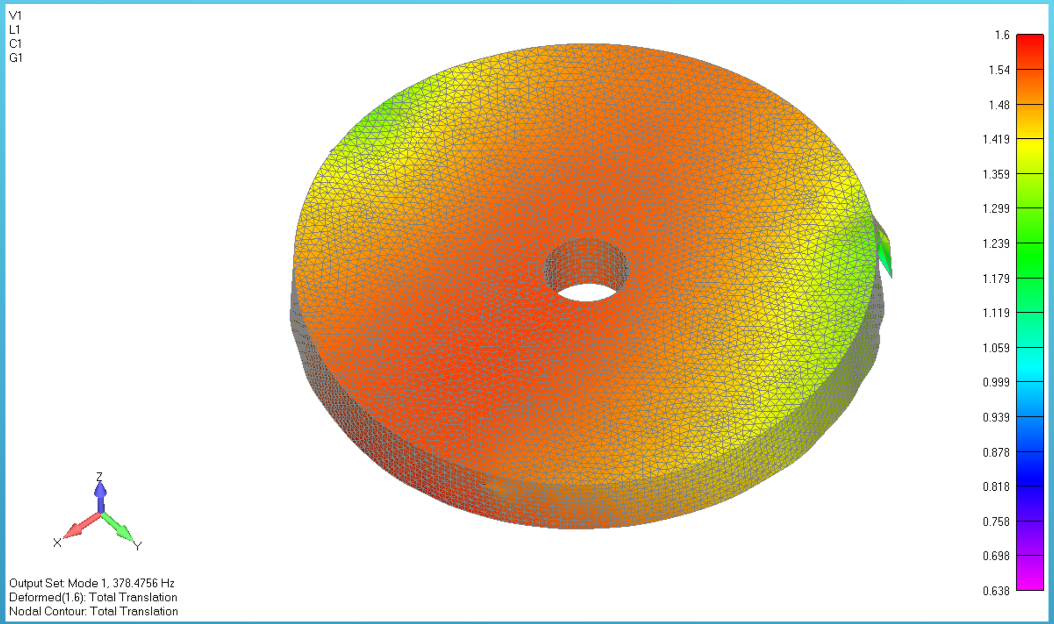
- Reviewed NASA GHAPS Requirements
  - Requirements Document
  - Primary Mirror Drawings and STEP file model
- Performed Full Size Isogrid Primary Mirror Analysis, Zerodur® vs RoboSiC™
  - Fundamental Modes
  - Gravity Sag (X,Y, and Z directions)
  - Thermal Soak (20C to -50 C)
- Created 1/4 "Scale" Primary Mirror Design, Isogrid (legacy)
  - Design Model and Drawing
- RoboSiC™ design and manufacturability for ¼-Scale Pathfinder

FULL SCALE MIRROR ANALYSIS RESULTS

FULL SIZE GHAPS PRIMARY **DESIGN:** LEGACY ISOGRID **RESULTS:** FIRST MODE



Boundary Condition: Free-Free
Shape: Saddle



Boundary Condition: Whiffletree/Tangent Bars
Shape: Bending

Design	Material	Weight		Free-Free 1st Mode	WT/TB BC 1st mode
		lbs	Kg	hz	hz
Ghaps Primary Ø1030	Zerodur	175.3	79.5	458.8	378.5
Ghaps Primary Ø1030	RoboSiC-Optical	222.5	100.9	921.0	760.0

100% improvement with RoboSiC™ at Constant Volume

The superior specific stiffness to weight ratio of RoboSiC™ will allow a thinner, lighter mirror. But how much thinner Dr. Bill?

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POTENTIAL WEIGHT IMPROVEMENT AT CONSTANT 1ST MODE

	ρ	E	E/ρ	σ_t	σ_t/ρ	α	k	C_p	$D=k/\rho C_p$	k/α	D/α	ν
Room Temperature Property:	Density	Young's Modulus	Specific Stiffness	Tensile Strength	Specific Strength	Thermal Expansion	Thermal Conductivity	Specific Heat	Thermal Diffusivity	Steady State Stability	Transient Stability	Poisson's Ratio
Units:	kg/m^3	GPa	$MPa\text{-}m^3/kg$	Mpa	$MPa\text{-}m^3/kg$	$10^{-6}/K$	W/m-K	j/kg-K	$10^{-6}/m^2/s$	W/µm	$m^2\text{-}K/s$	arbitrary
Preferred Value:	Small	Large	Large	Large	Large	Small	Large	Large	Large	Large	Large	
Zerodur	2530	90.3	36	variable	variable	-0.09	1.46	800	0.72	-16.22	-8.01	0.24
SiC: Sintered (alpha)	3100	410	132		0.00	4.02	125	670	60.18	31.09	14.97	0.14
SiC: Reaction Bonded	2950	364	123	300	0.10	2.44	172	670	87.02	70.49	35.66	0.18
RoboSiC-Optical	3210	460	143	470	0.15	2.2	380	640	184.97	172.73	84.08	0.21
IMPROVEMENT:		5.09	4.02						256.42	10.65	10.49	

	Thickness for Equivalent Stiffness	Relative Areal Density
	cm	kg/m^2
Zerodur	3.66	93
SiC: Sintered (alpha)	0.81	25
SiC: Reaction Bonded	0.91	27
RoboSiC-Optical	0.72	23
IMPROVEMENT:	5.09	4.02

- If the mirror were a solid “Hockey Puck” the RoboSiC would be 1/5 the thickness.
- It can be ¼ the areal density (mass 19.875 kg)
- Print in microgravity and you only need a facesheet with attach points (2-3 kg)
- Also get 10X BETTER Thermal Stability with RoboSiC™

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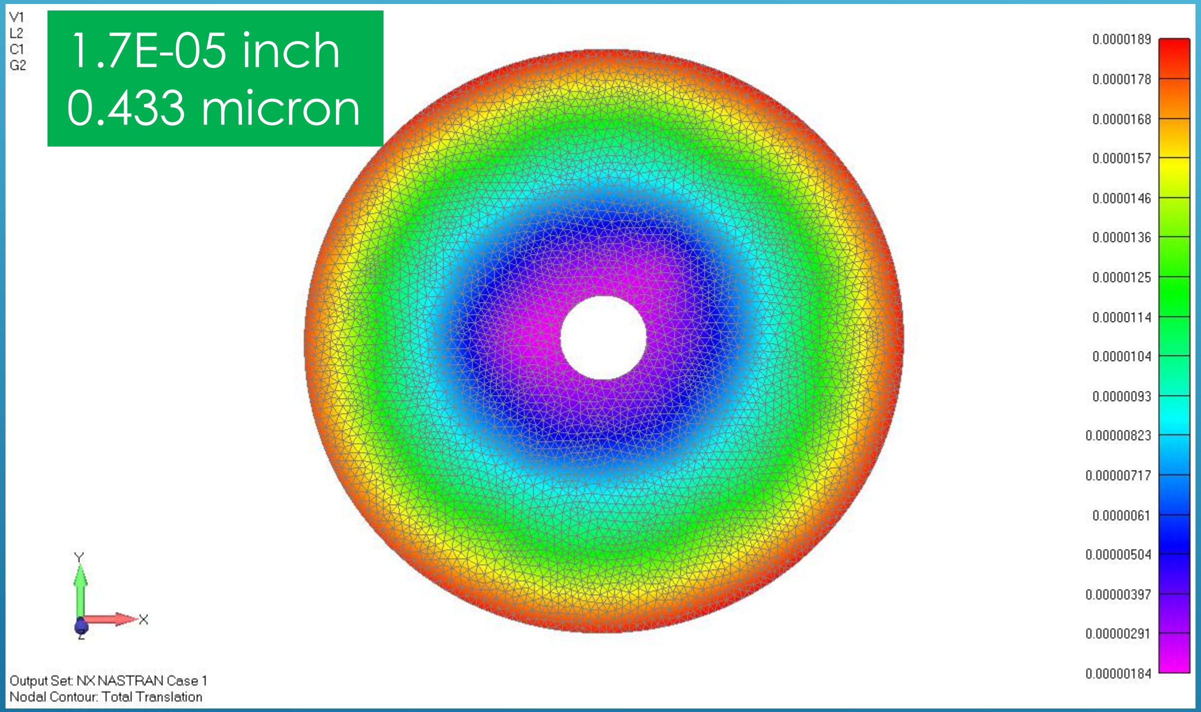
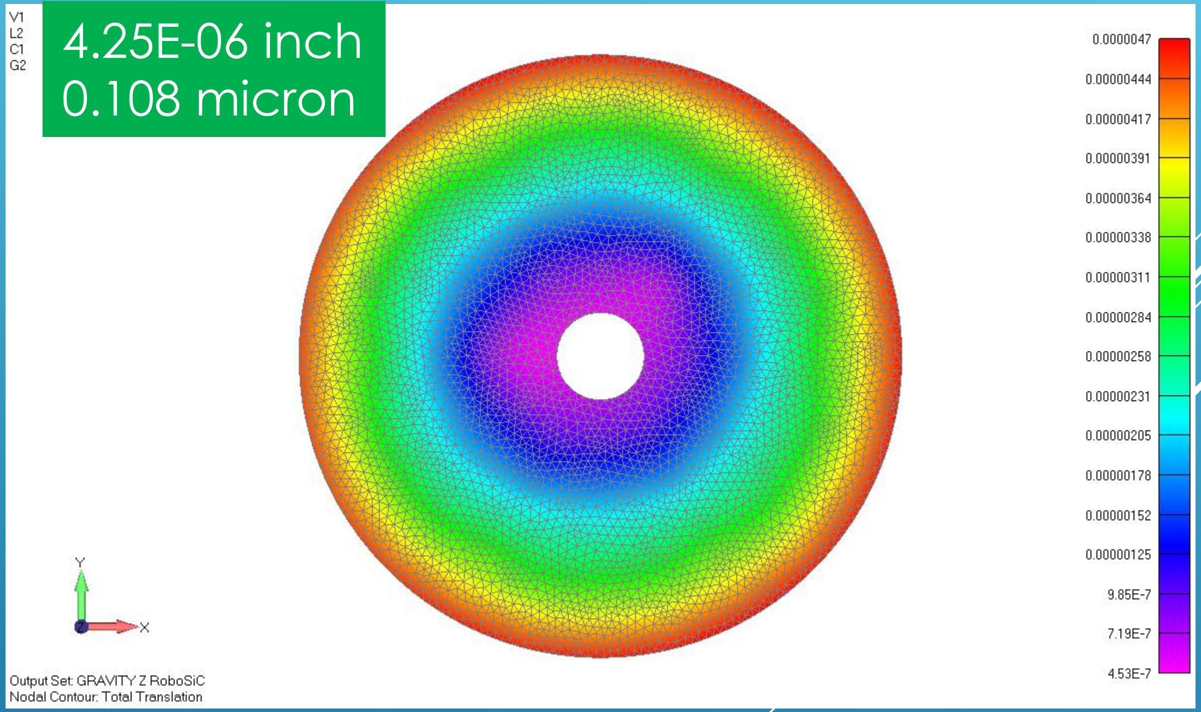
FULL SIZE GHAPS PRIMARY
DESIGN: LEGACY ISOGRID
LOAD: 1G GRAVITY, **Z DIRECTION**
RESULTS: TOTAL DISPLACEMENT (PV IN INCHES, MICRONS)



Material: Zerodur®



Material: RoboSiC™

1/4 Sag with RoboSiC™, 75% Improvement

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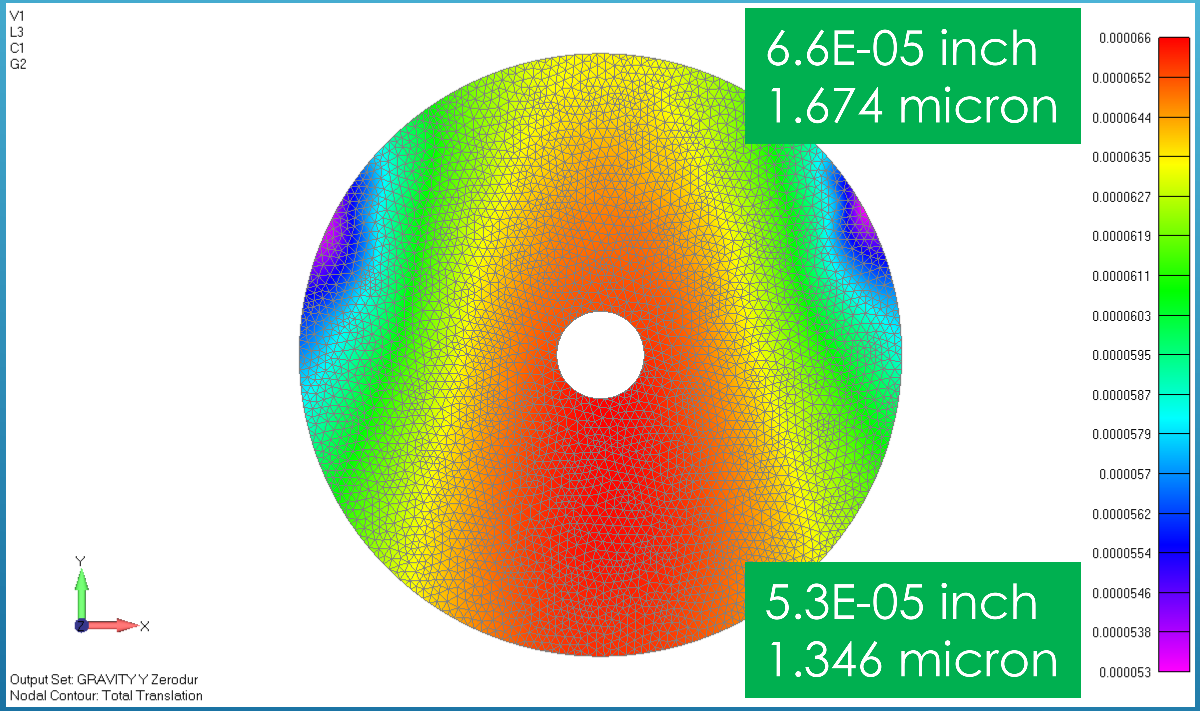
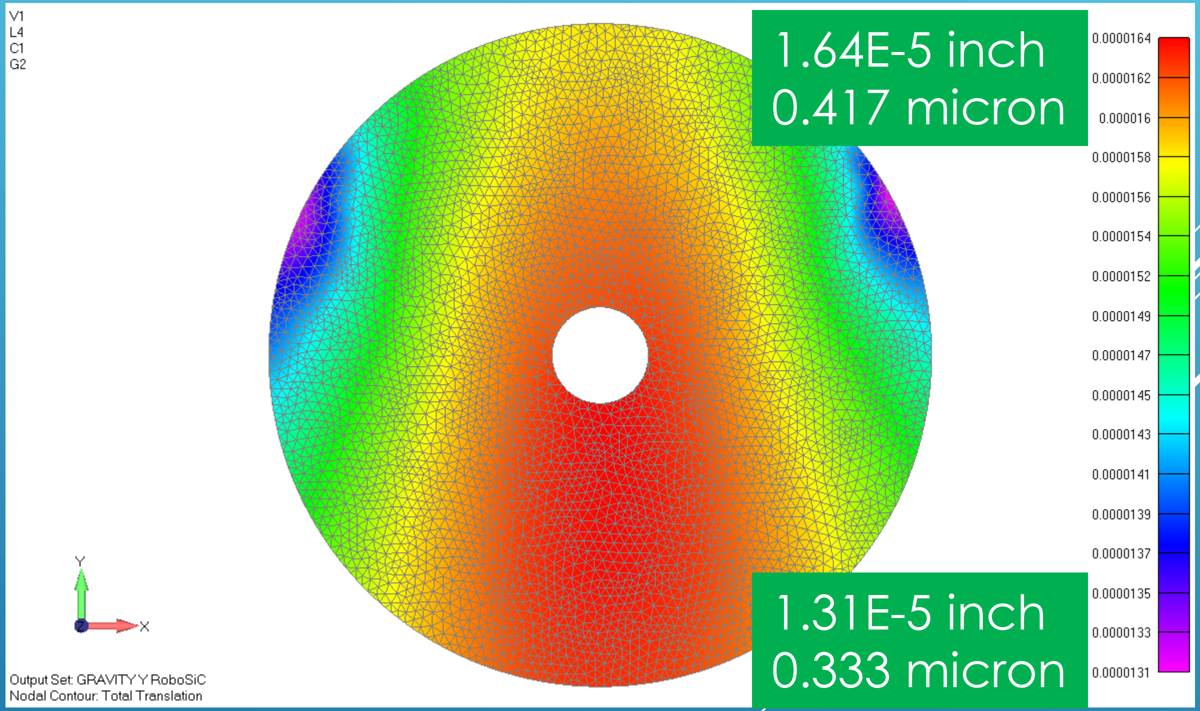
FULL SIZE GHAPS PRIMARY
DESIGN: LEGACY ISOGRID
LOAD: 1G GRAVITY, **Y DIRECTION**
RESULTS: TOTAL DISPLACEMENT (INCHES, MICRONS)



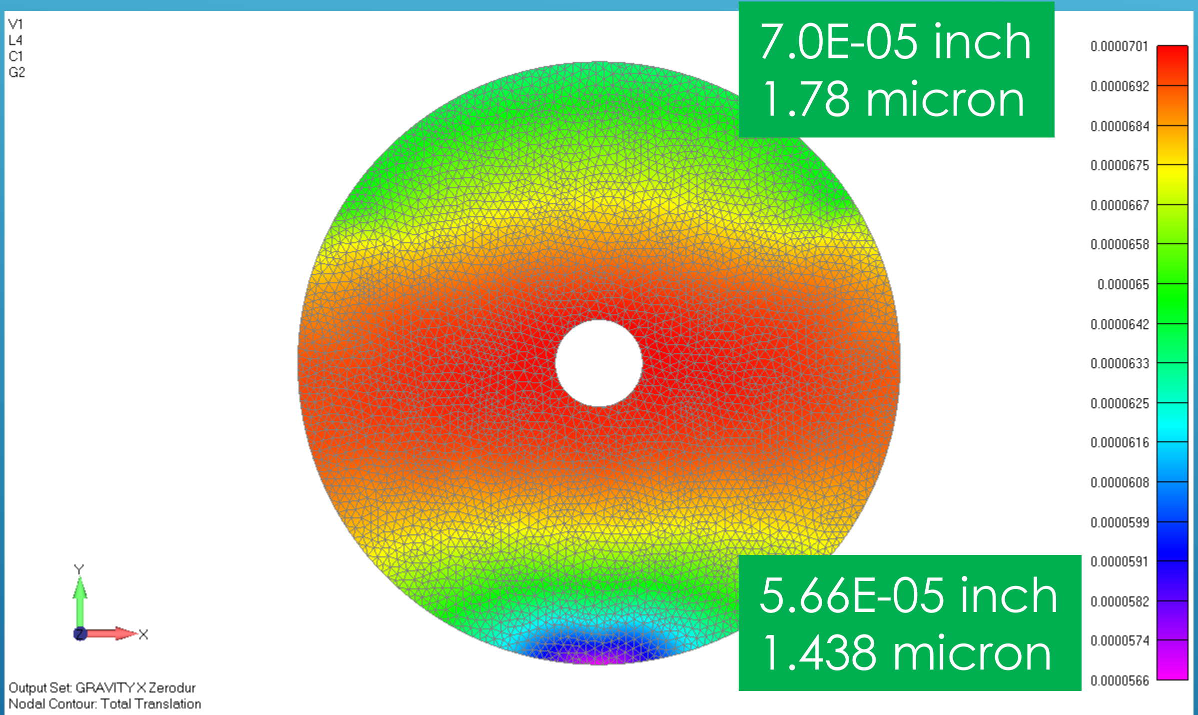
Material: Zerodur®



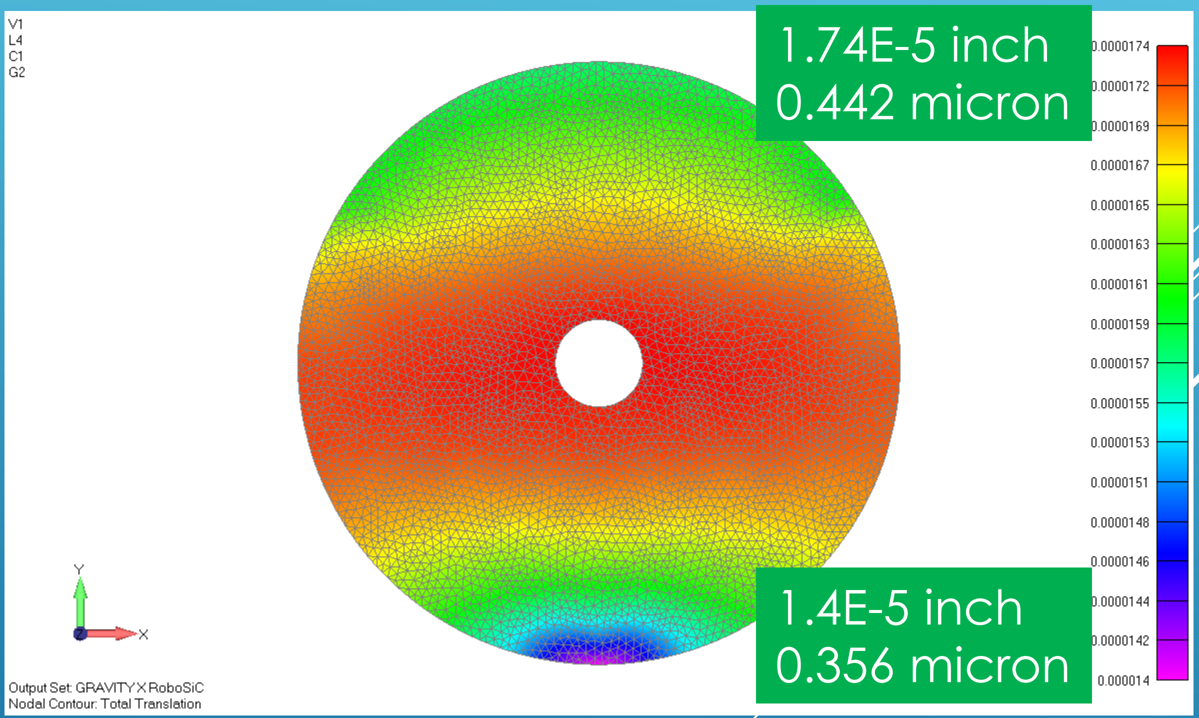
Material: RoboSiC™

1/4th deflection with RoboSiC™, 75% Improvement

FULL SIZE GHAPS PRIMARY
DESIGN: LEGACY ISOGRID
LOAD: 1G GRAVITY, **X DIRECTION**
RESULTS: TOTAL DISPLACEMENT (INCHES, MICRONS)



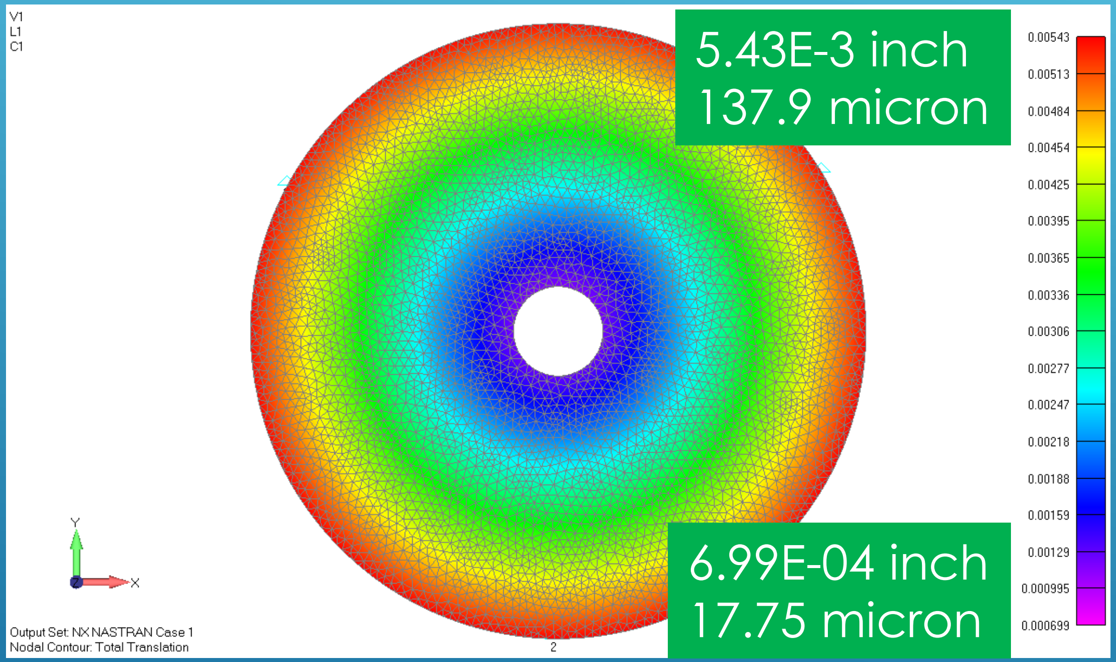
Material: Zerodur®



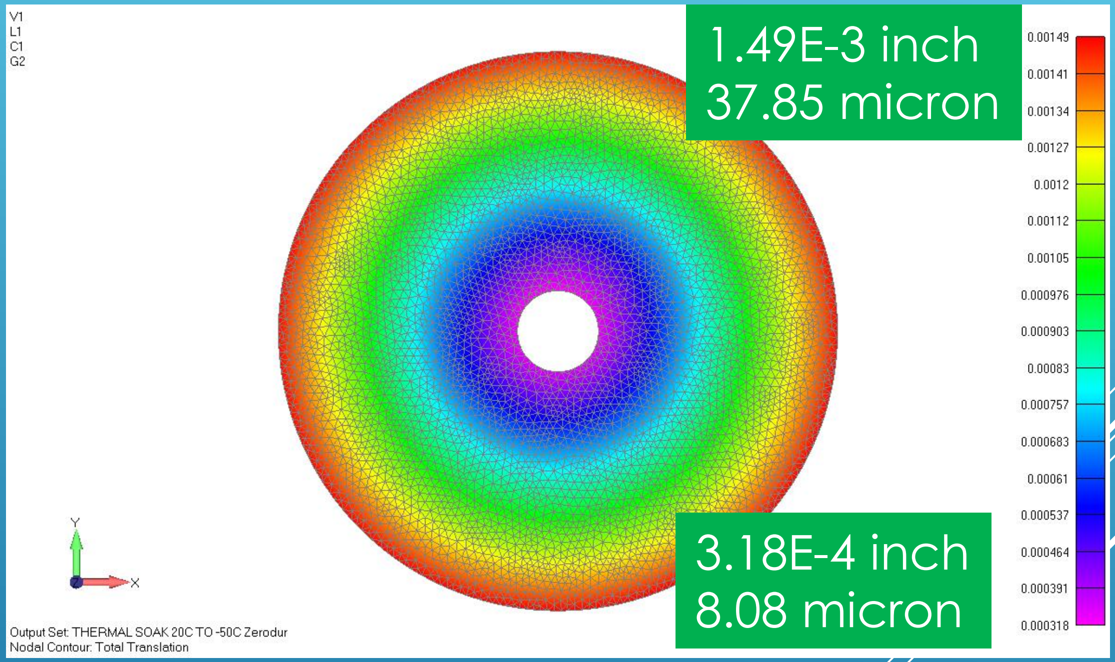
Material: RoboSiC™

1/4th deflection with RoboSiC™, 75% Improvement

FULL SIZE GHAPS PRIMARY
DESIGN: LEGACY ISOGRID
LOAD: 20C TO -50C THERMAL SOAK
RESULTS: TOTAL DISPLACEMENT (INCHES, MICRONS)



Material: Zerodur®

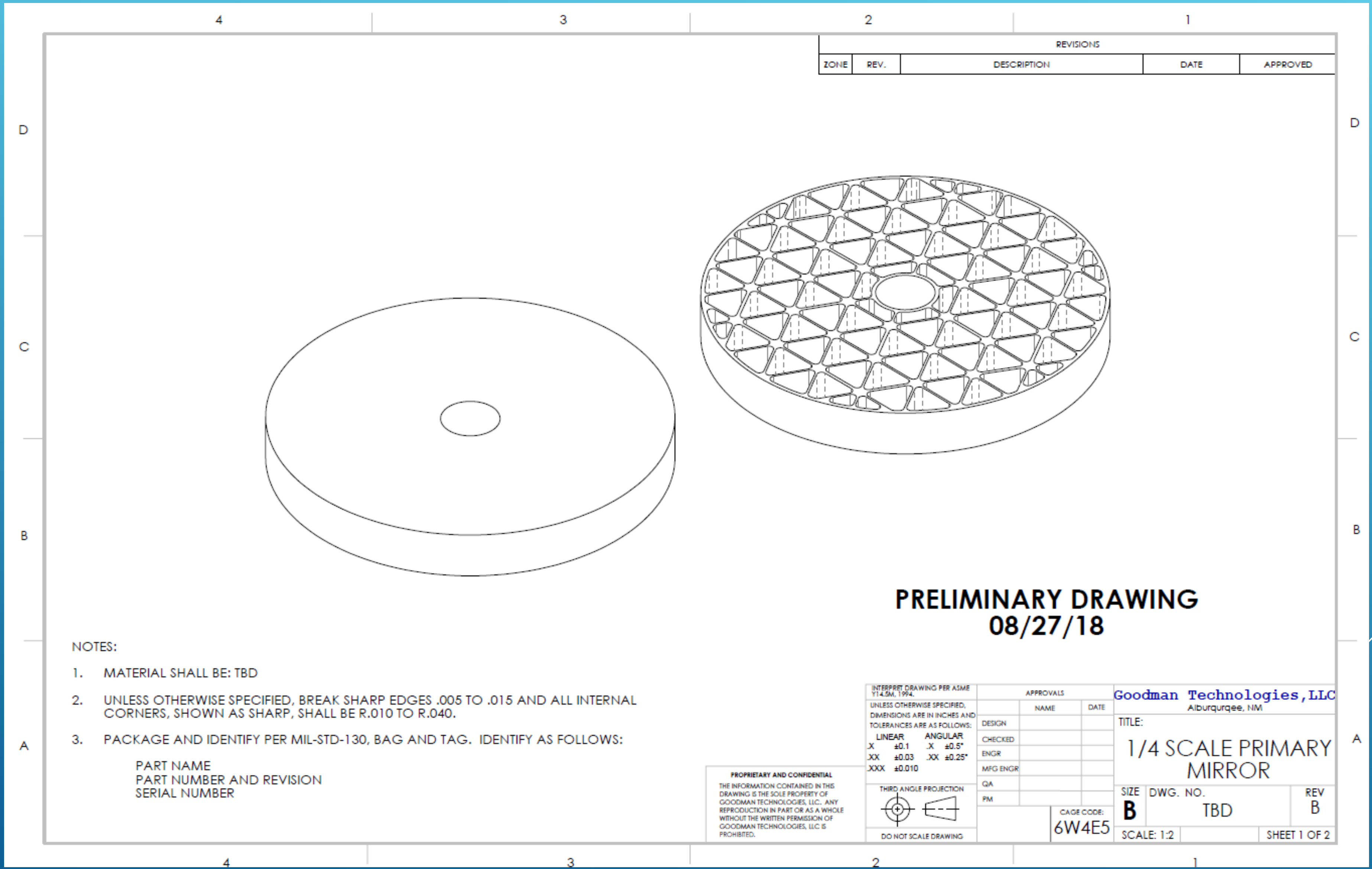


Material: RoboSiC™

Thermal Soak Optical Surface Deformation (72% Improvement with RoboSiC™)

1/4TH SCALE MIRROR DESIGN

1/4 SCALE PRIMARY MIRROR – LEGACY DESIGN



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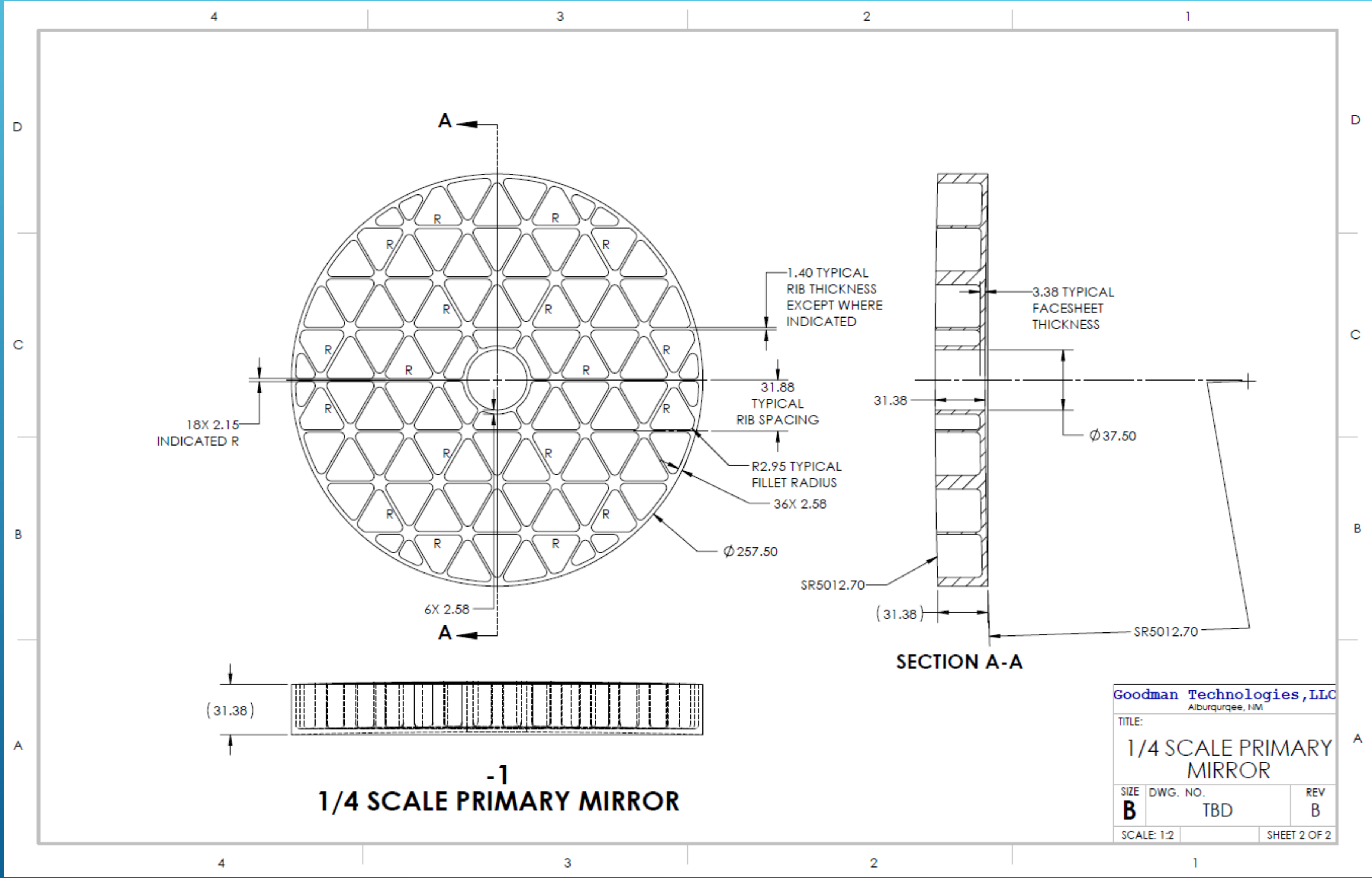
1/4 SCALE PRIMARY MIRROR – LEGACY DESIGN



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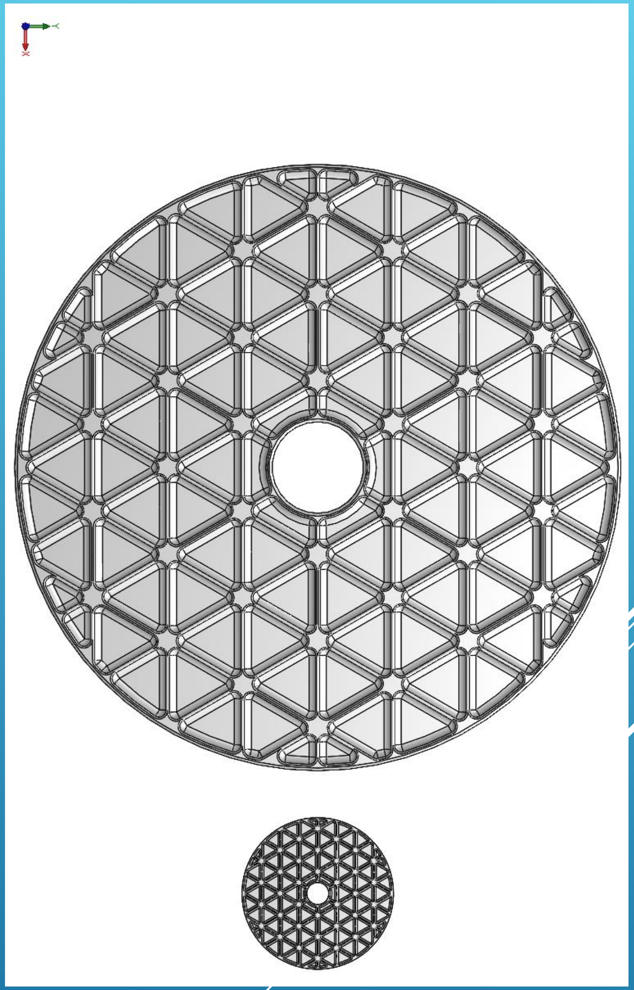
1/4 SCALE PRIMARY MIRROR - DIMENSIONS COMPARISON

Description	Full Size PM	1/4 Scale PM
	mm	mm
Optical Surface Spherical Radius	5012.7	5012.7
Physical Diameter	1030	257.5
Mirror Depth	125.5	31.375
Faceskin Thickness	13.5	3.375
Rib Spacing	127.5	31.875
Rib Thickness	5.6	1.4
Thicker Rib Thickness	8.6	2.15
Fillet Radius	11.8	2.95
	Kg	Kg
Mass (ULE)	75.2	1.2136



Areal Density = 90.25 kg/m²

Areal Density = 23.30 kg/m²

1/4TH SCALE MIRROR ANALYSIS

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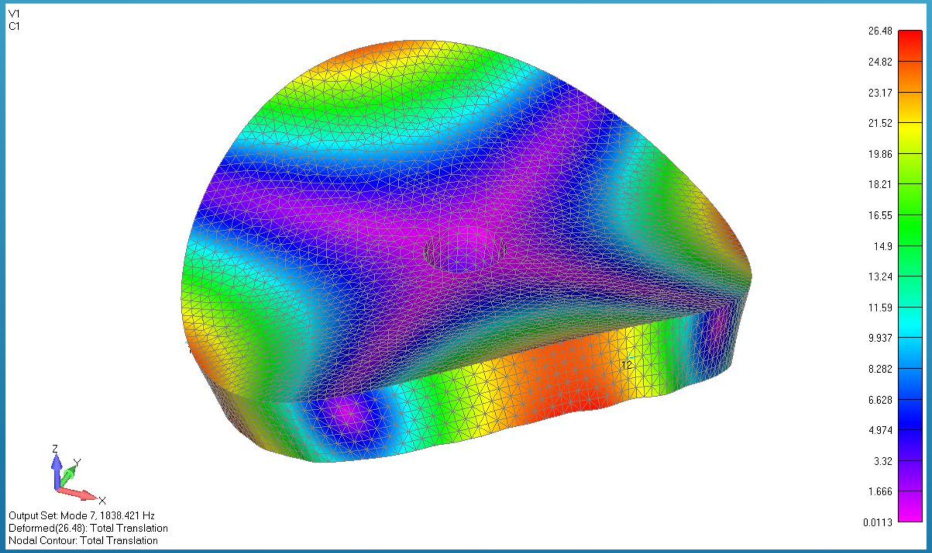
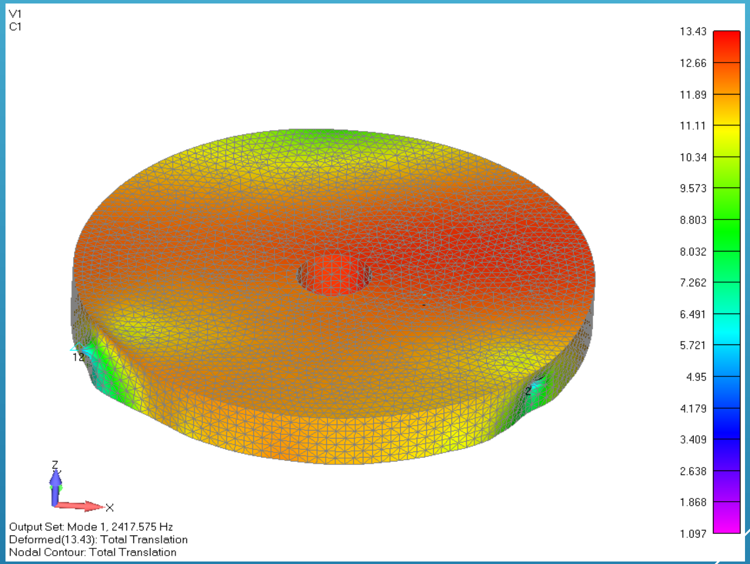
QUARTER SIZE GHAPS PRIMARY DESIGN: 1/4 LEGACY ISOGRID RESULTS: FIRST MODE

Design	Material	Weight		Free-Free 1st Mode	WT/TB BC 1st mode
		lbs	Kg	hz	hz
1/4 GHAPS Primary Ø257	Zerodur	2.7	1.2	1838.6	2417.6
1/4 GHAPS Primary Ø257	RoboSiC-Optical	3.5	1.6	3689.6	4856.7

100% improvement with RoboSiC



Boundary Condition: Free-Free
Shape: Saddle



Boundary Condition: Whiffletree/Tangent Bars
Shape: Perimeter Wall Bending

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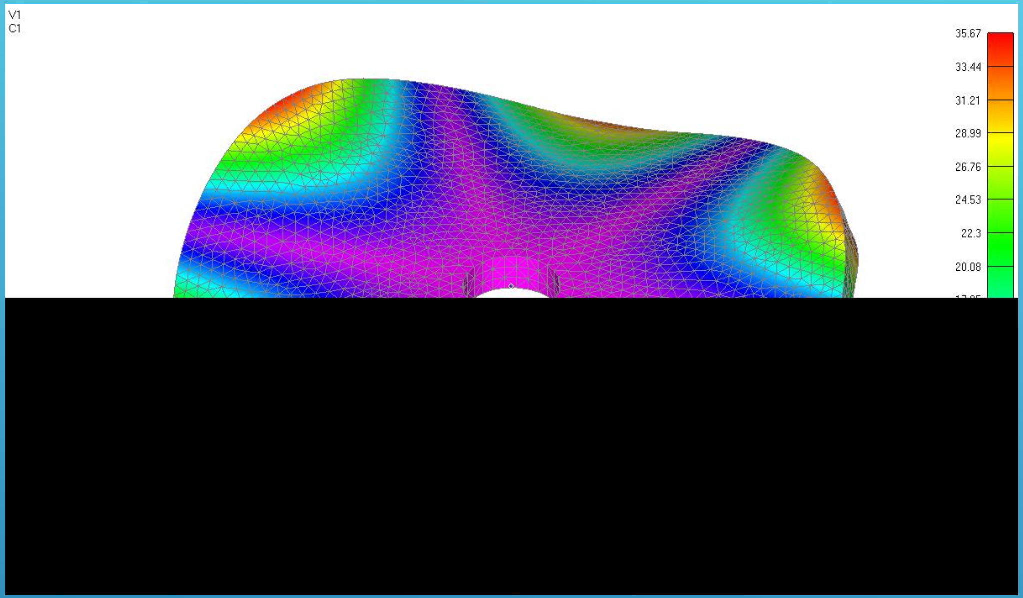
QUARTER SIZE GHAPS PRIMARY – STIFFNESS EQUIVALENT ROBOSIC ISOGRID DESIGN: 1/4 LEGACY ISOGRID, HALF HEIGHT RIBS (15MM), 2.4MM FACESHEET RESULTS: FIRST MODE



Boundary Condition: Free-Free
Shape: Saddle

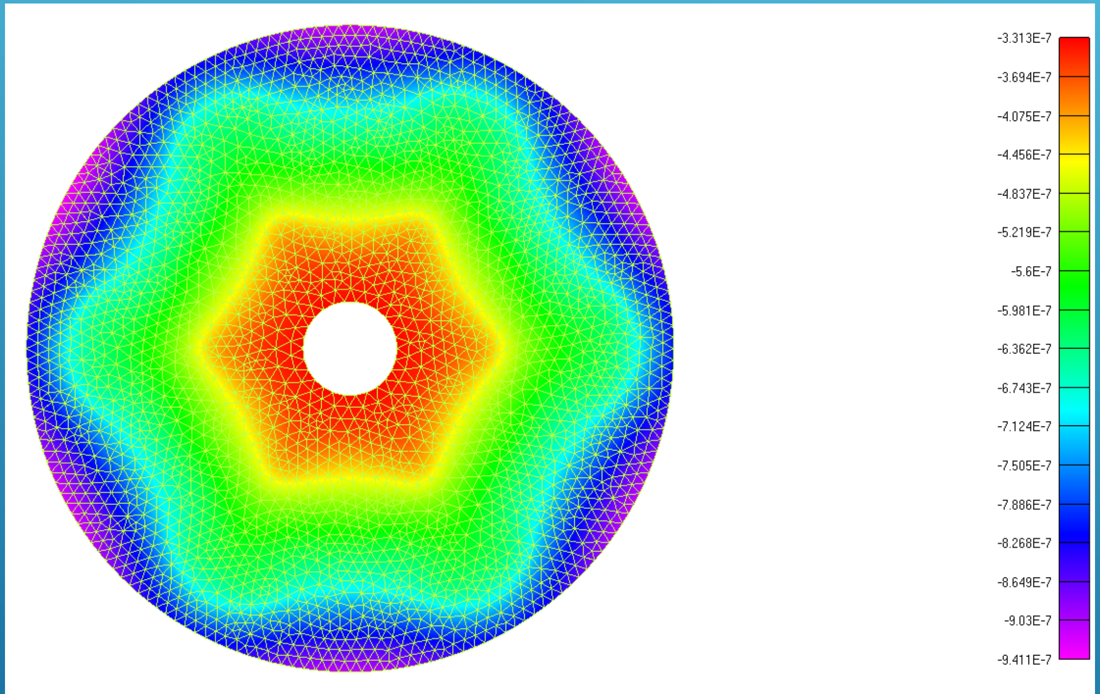
Boundary Condition: Whiffletree/Tangent Bars
Shape: Bending

Design	Material	Weight		Free-Free 1st Mode	WT/TB BC 1st mode
		lbs	Kg	hz	hz
1/4 Ghaps Primary Ø257	Zerodur	2.7	1.2	1838.6	2417.6
1/4 Ghaps Primary Ø257	RoboSiC-Optical	2.0	0.9	1799.0	4858.0

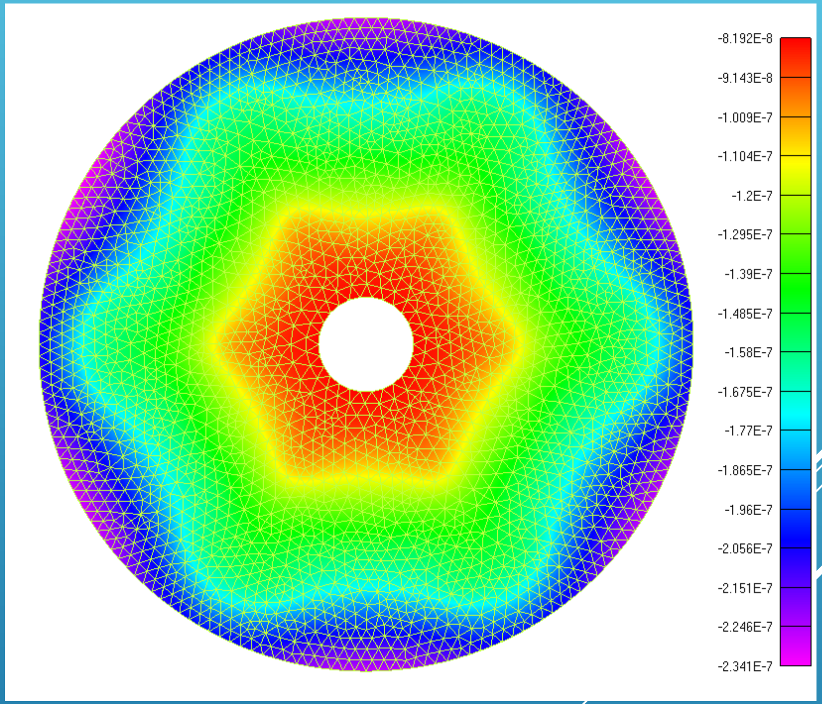
25% lower mass for equivalent Free-Free 1st mode with RoboSiC
25% lower mass and 2X Whiffle Tree Support 1st mode with RoboSiC

FULL SIZE GHAPS PRIMARY
DESIGN: 1/4 LEGACY ISOGRID
LOAD: 1G GRAVITY, Z DIRECTION
RESULTS: TOTAL DISPLACEMENT (INCHES)

75% improvement with RoboSiC



Material: Zerodur



Material: RoboSiC

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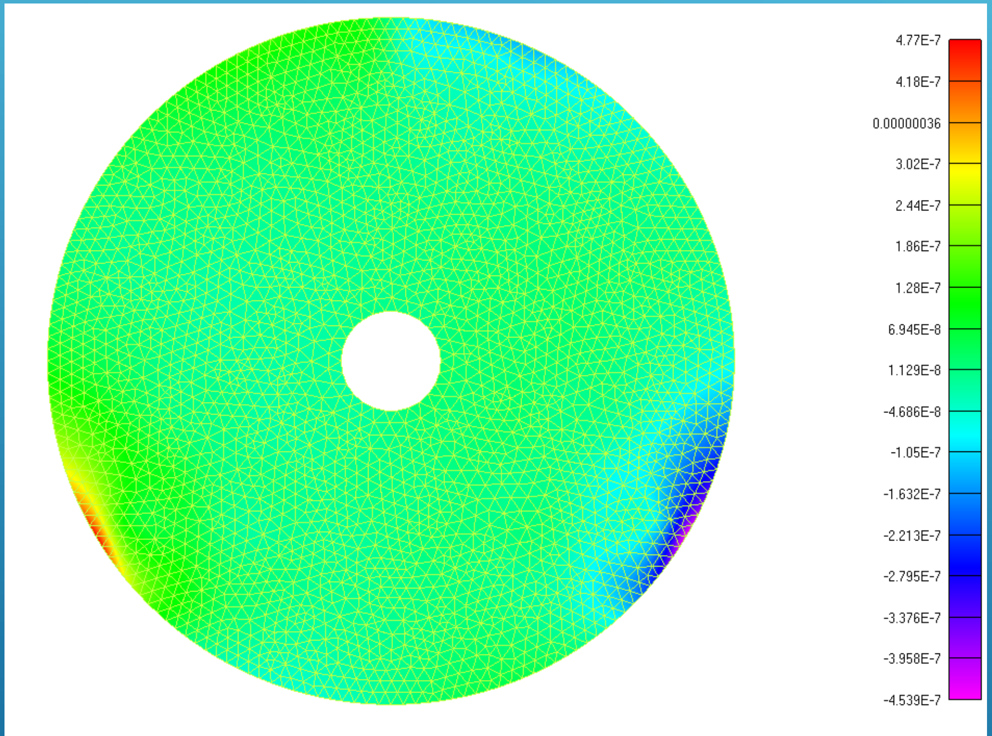
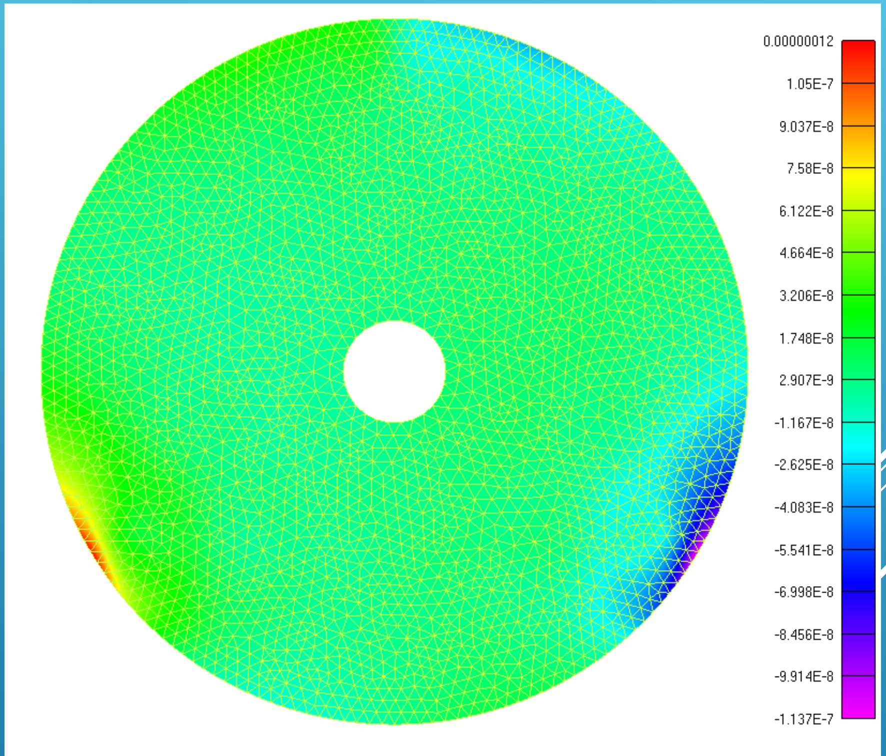
FULL SIZE GHAPS PRIMARY DESIGN: 1/4 LEGACY ISOGRID LOAD: 1G GRAVITY, Y DIRECTION RESULTS: TOTAL DISPLACEMENT (INCHES)

75% improvement with RoboSiC



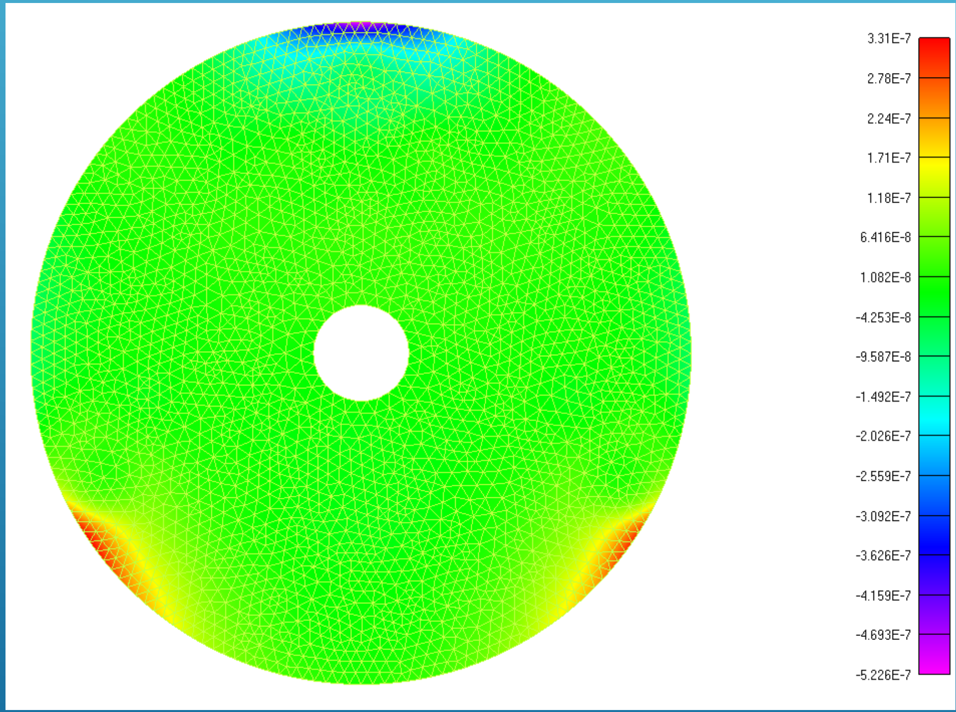
Material: Zerodur



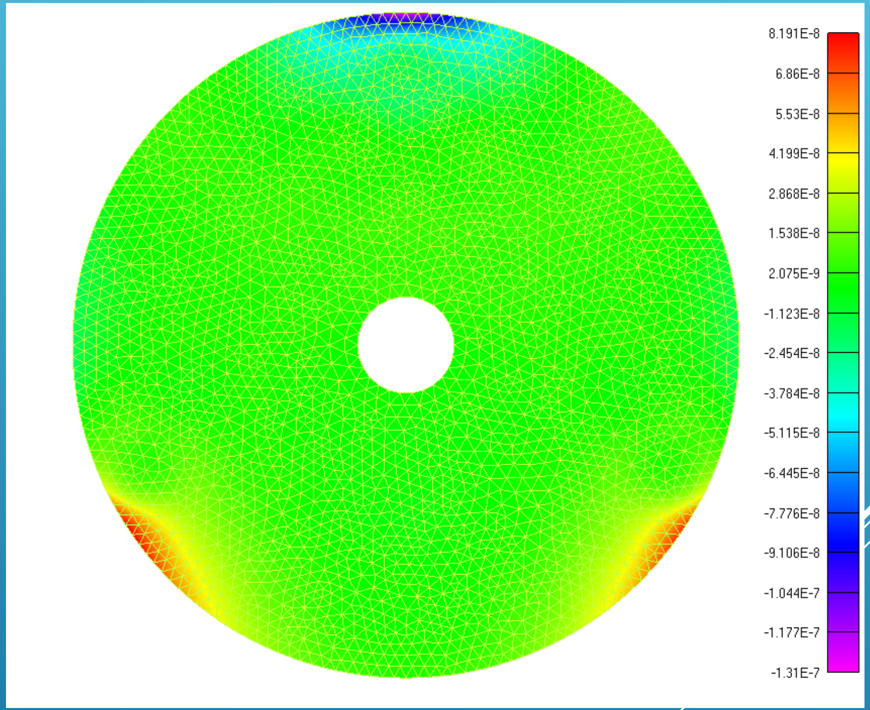
Material: RoboSiC

FULL SIZE GHAPS PRIMARY
DESIGN: 1/4 LEGACY ISOGRID
LOAD: 1G GRAVITY, X DIRECTION
RESULTS: TOTAL DISPLACEMENT (INCHES)

75% improvement with RoboSiC



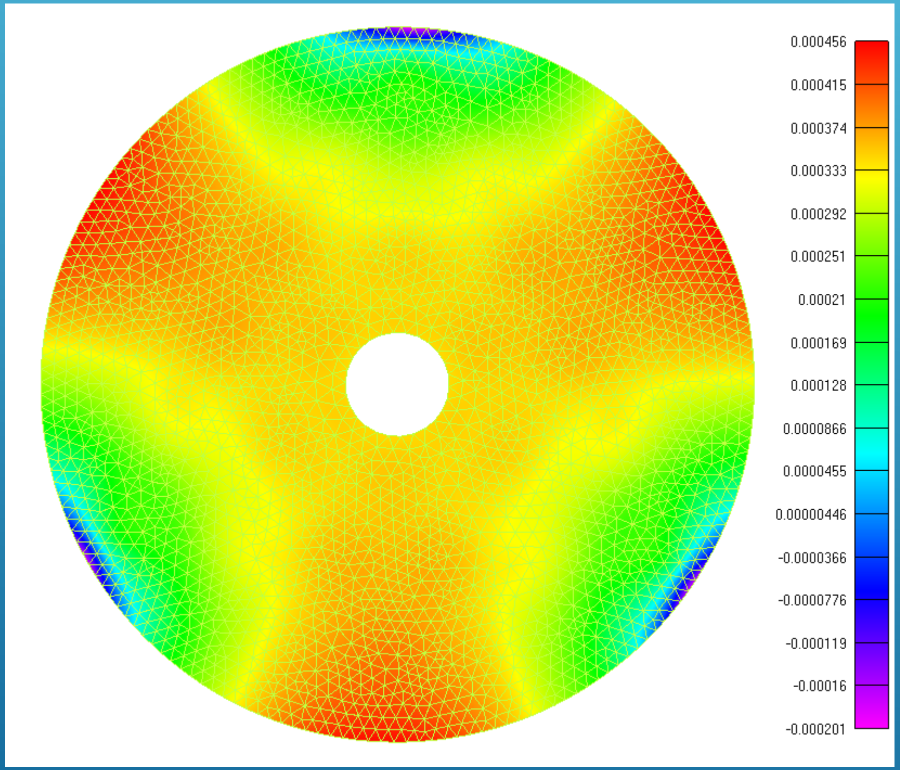
Material: Zerodur



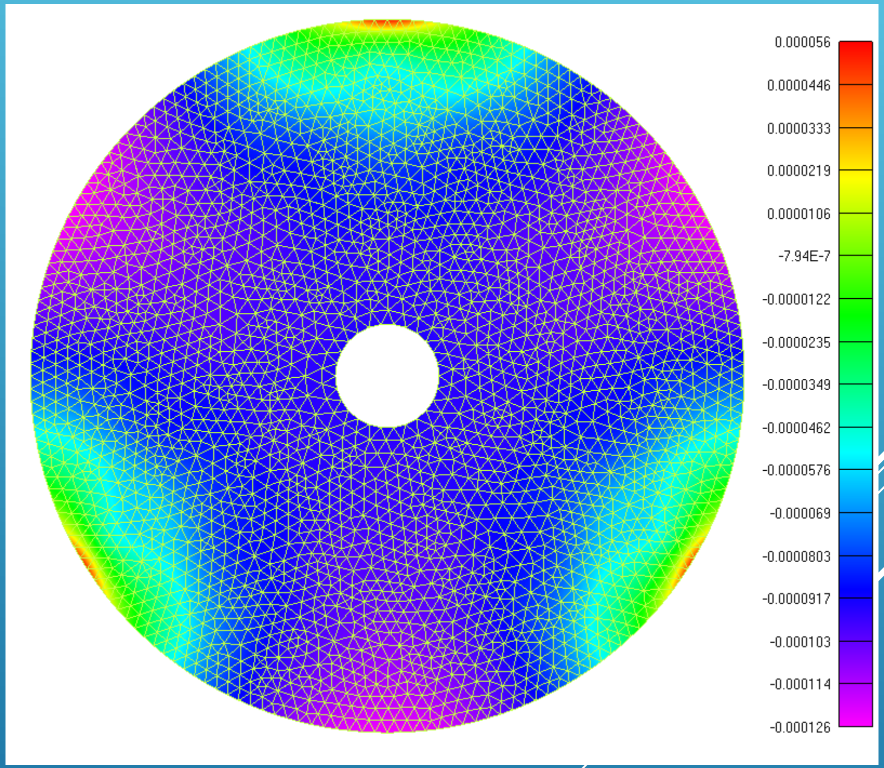
Material: RoboSiC

FULL SIZE GHAPS PRIMARY DESIGN: 1/4 LEGACY ISOGRID LOAD: 20C TO -50C THERMAL SOAK RESULTS: TOTAL DISPLACEMENT (INCHES)

72% improvement with RoboSiC



Material: Zerodur



Material: RoboSiC

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1/4 GHAPS PRIMARY, LEGACY ISOGRID ZERODUR VS ROBOSIC ANALYSIS SUMMARY

Mass and Fundamental Modes (2x Stiffness Improvement with RoboSiC)

Design	Material	Weight		Free-Free 1st Mode	WT/TB BC 1st mode
		lbs	Kg	hz	hz
1/4 Ghaps Primary Ø257	Zerodur	2.7	1.2	1838.6	2417.6
1/4 Ghaps Primary Ø257	RoboSiC-Optical	3.5	1.6	3689.6	4856.7

Gravity Sag (4x Improvement with RoboSiC)

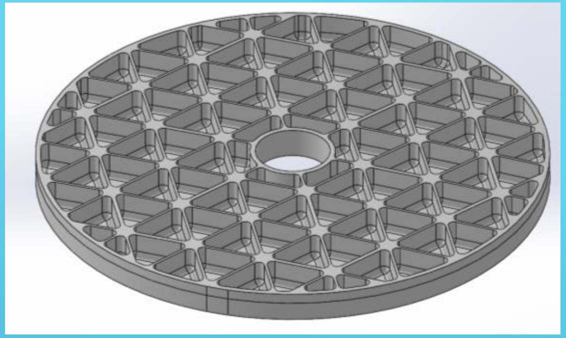
Design	Material	Gravity Z Sag				Gravity X Sag				Gravity Y Sag			
		Max Total Displacement		Max Z Direction Displacement		Max Total Displacement		Max Z Direction Displacement		Max Total Displacement		Max Z Direction Displacement	
		in	micron	in	micron	in	micron	in	micron	in	micron	in	micron
1/4 Ghaps Primary Ø257	Zerodur	0.00000007	0.002	0.00000094	0.024	0.00000181	0.046	0.00000048	0.012	0.00000024	0.006	0.00000052	0.013
1/4 Ghaps Primary Ø257	RoboSiC-Optical	0.00000002	0.000	0.00000023	0.006	0.00000045	0.011	0.00000012	0.003	0.00000006	0.002	0.00000013	0.003

Thermal Soak Optical Surface Deformation (8x Improvement with RoboSiC)

Design	Material	20C to -50C Thermal Soak			
		Max Total Displacement		Max Z Direction Displacement	
		in	micron	in	micron
1/4 Ghaps Primary Ø257	Zerodur	0.00132000	33.528	0.00045600	11.582
1/4 Ghaps Primary Ø257	RoboSiC-Optical	0.00035300	8.966	0.00005600	1.422

Goodman Technologies, LLC

QUARTER SIZE GHAPS PRIMARY MODAL STUDY



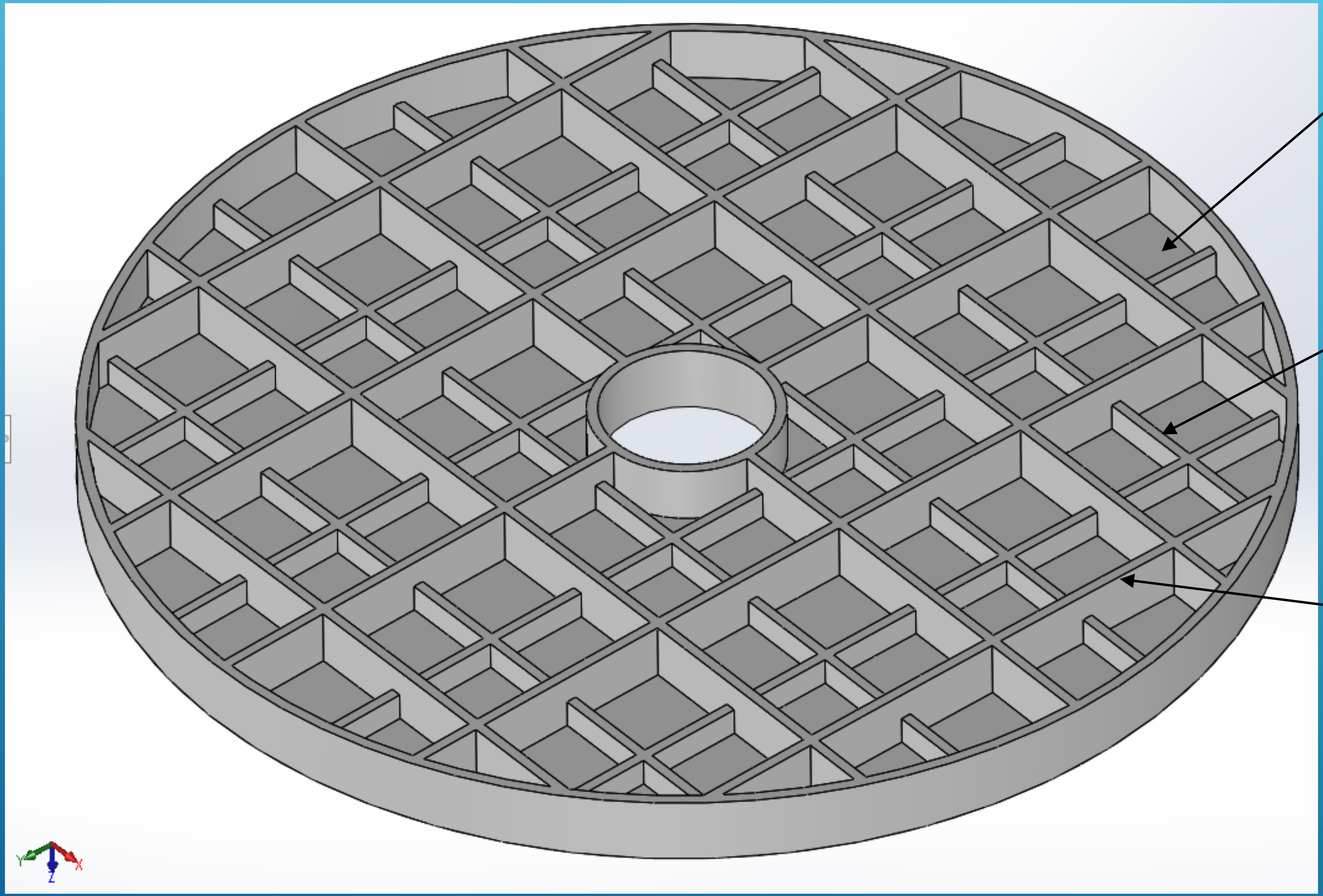
No.	Description	Facxeskin Thickness	Edge Thickness	Material	Mass		Free-Free 1st mode	Whiffle-Tree 1st mode
		mm	mm		lbs	kg	hz	hz
1a	1/4 GHAPS Isogrid Design	3.375	31.38	Zerodur	2.68	1.22	1863	2305
1b	1/4 GHAPS Isogrid Design	3.375	31.38	RoboSiC	3.40	1.54	3704	4595
2a	Reduced Facesheet thk	2.4	31.38	Zerodur	2.46	1.12	1894	2312
2b	Reduced Facesheet thk	2.4	31.38	RoboSiC	3.12	1.42	3767	4608
3a	Reduced Facesheet thk and rib depth	2.4	15	Zerodur	1.50	0.68	908	2442
3b	Reduced Facesheet thk and rib depth	2.4	15	RoboSiC	1.90	0.86	1799	4858

- **Reducing facesheet thickness from 3.375 to 2.4 does not reduce first mode stiffness (No. 2a/b compared to No.1a/b)**
- **RoboSiC with 1/2 height ribs and reduced face sheet:**
  - **Nearly equivalent free-free mode stiffness to 1/4 GHAPS Isogrid Zerodur**
  - **More than 2X whiffle tree supported 1st mode**

Note: Trade study for relative comparison. Results shown may not match final `Nastran model results exactly because different element formulation and solver were used.

ALTERNATE DESIGN FOR 1/4TH SCALE MIRROR

GOODBYE ISOGRID: QUARTER SIZE PRIMARY ROBOSIC DESIGN CONCEPT 1



FACE SHEET
- 2.4 mm THICK
- 3 BEADS *.8 mm/BEAD

MINOR RIBS
- 25 mm SPACING
- 2.4 mm THICK(3 BEADS)
- +6.4 mm DEEP (8 BEADS)

MINOR RIBS AND PERIMETER
- 50 mm SPACING
- 2.4 mm THICK (3 BEADS)
- +6.4 mm DEEP (8 BEADS)

TOTAL DEPTH = 2.4+6.4+6.4 = 15.2 mm
MASS: .76 Kg(1.67 LBS)