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SBIR Phase II for Contract No. NNX17CM08C

"Ultra-stable Zero-CTE HoneySiC™ and H^2CMN Mirror Support Structures"

Contract Brief

Dr. William Fischer
Principal Investigator
Ph: (808) 245-6465
wfischer@ascmtech.com

Introduction

- HoneySiC™: Fantom's innovative, additively manufactured, ceramic matrix composites
    - HoneySiC (HCMC) – T300 carbon fiber reinforced SiC CMC
    - H^2CMN – hybrid hierarchical ceramic matrix nanocomposite with CNTs
- Program effort addresses the need for stable, strain-free, precision optical structures under the influence of dynamic and thermal stimuli, specifically whiffle plates, delta frames and backplane
- Traceable to the needs of Cosmic Origins for UVOIR, Exo and FIR telescopes
- Technology gaps requiring precision optical structures:
    - Starshade Precision Deployment
    - Starshade Precision Deployment Petal Prototypes
- Maturation of this technology will allow NASA and Fantom to develop a method to create large aperture optical support structures and assemblies via deployment, assembly or active control
- HoneySiC additive manufacturing process significantly minimizes cost and schedule associated with post-production fabrication steps (machining, polishing, metrology).

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Background & Technology Gaps

- **NASA Strategic Plan 2014, New Worlds, New Horizons, seeks cost-effective, high performance advanced space telescopes for Astrophysics and Earth Science**
- **2015 NASA Technology Roadmap (TA 8: Science Instruments, Observatories and Sensor Systems, part 8.2 Observatories) sub-goal for structures:**
  - The ability of the structure to hold mirrors in a stable, strain-free state under the influence of anticipated dynamic and thermal stimuli
  - For extra-large apertures, a method to create the aperture via deployment, assembly, or formation flying
- **NASA MSFC, GSFC and JPL interested in Ultra-Stable Mirror Support Structures for Exoplanet Missions**
  - Telescopes with apertures of 4-meters or larger and using an internal coronagraph require a telescope wavefront stability that is on the order of 10 pico-meters RMS per 10 minute
  - IR/FIR missions requiring 8-meter or larger diameter mirrors with cryogenic deformations <100 nm RMS

Technical Solution: HoneySiC™

- **HoneySiC™: Fantom's innovative, additively manufactured, ceramic matrix composites**
  - HoneySiC – T300 carbon fiber reinforced SiC CMC
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HoneySiC™ Features

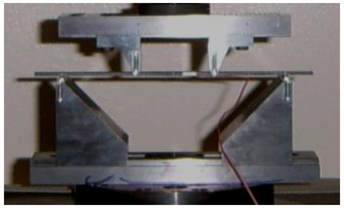
- **Rapid Prototyping** - Extremely rapid additive manufacturing process with all assets under a single roof.
  - Large complex mirrors/structures could be produced in a matter of weeks.
  - Web thickness < 1mm, core geometries (pocket depth, pocket size) easily tailored.
  - Minimizes machining, recurring/non-recurring costs; cost is 100X < beryllium.
- **Ultra-low areal cost** - Cost of raw materials ~$38K/m^2 for unpolished HoneySiC, which already meets NASA's goal of $100K/m^2 -> ~100X reduction in mirror cost based on current cost of $4-$6 million/m^2.
- **Ultra-low areal density**
  - Facesheet density same as beryllium; sandwich constructions are a fraction of Be density.
  - Void space in cells of honeycomb enables maximum lightweighting and stiffness.
  - 95% lightweighting w.r.t. bulk silicon carbide.
  - Areal density of first panel made: 5.86 kg/m^2.
  - Estimated weight and areal density of a 255-mm mirror: 0.35 kg and 7.0 kg/m^2, respectively.
  - Estimated mass of 305-mm optical bench with inserts: 0.94 kg.
- **Extreme dimensional stability** - CTE of HoneySiC confirmed to be near-zero with a variation of only -91 to -146 ppb/°C from -196°C to 0°C in testing at Southern Research Institute.
- **Carbon fiber or SiC reinforced SiC structure**
  - Thermal conductivity "supercharged" by addition of CNT
  - No coefficient of moisture expansion (CME)
  - Low Z for nuclear survivability
  - Electrically conductive for dissipating static charge build-up
  - ~2X higher fracture toughness than pure SiC, estimated ~4.6 MPa-m$^{0.5}$
- **Nuclear and Space Survivable** - Precursor carbon-carbon honeycomb is flying on >100 spacecrafts.

Phase I Objectives

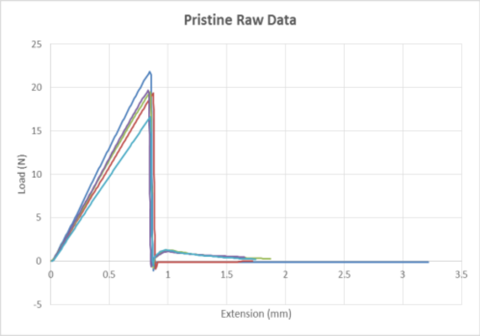
- Fantom would produce HCMC and H^2CMN coupons for flexural strength and CTE measurements.
- Flexure testing would be performed by Professor Nejhad at the University of Hawaii using a 4-point flexure test set up. Properties to be determined: strength, strain/deflection, stiffness and toughness.
- In-plane coefficient of thermal expansion (CTE) testing would be performed at Southern Research Institute (SoRI) at the University of Alabama using a linear variable differential transformer (LVDT). Test temperature range: -196°C to RT.
    - LVDT measures change in length as a function of temperature
    - A dial gauge would be used to provide additional expansion data and validate the LVDT measurements.

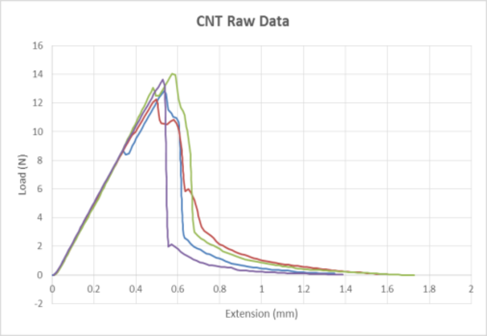
Phase I Results – Flexure Testing

- Flexure testing was performed by Professor Nejhad. Specimens are shown on the left, test fixture is shown on the right.



- Raw load-deflection curves for Pristine (HCMC) and CNT (H^2CMN) samples are shown below.



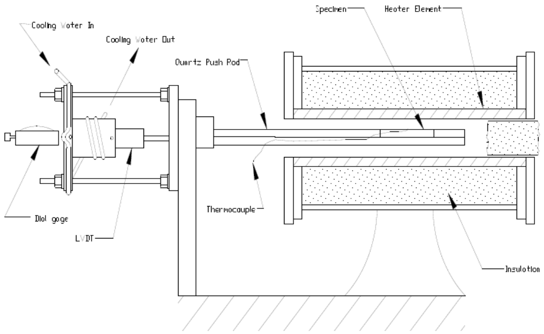


- The generated stress-strain data was used to deduce strength, toughness, modulus/stiffness and strain-at-failure.

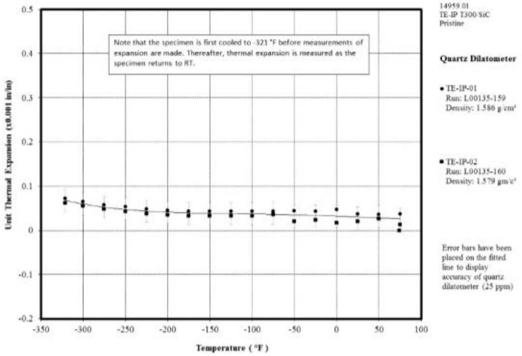
Sample	Avg. Flexure Strength (MPa)	Avg. Real Toughness (KJ/m³)	Avg. E Modulus (MPa)	Avg. Flexure Strain at Failure (mm/mm)
HoneySiC™	63.96	44.55	53,116.96	0.00139
H^2CMN	40.87	18.49	54,281.89	0.00090
Notes	CNT had ~36% less strength	CNT had ~59% less toughness	CNT had ~2% higher stiffness	CNT had ~35% less strain at failure

Phase I Results – CTE Testing

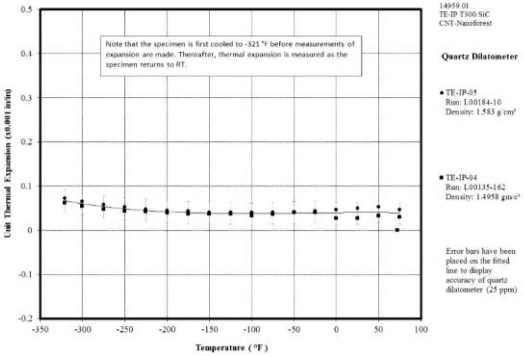
- LVDT test set up for in-plane CTE measurements shown below.



- Tabulated data is shown below for Pristine (HCMC, left) and CNT samples (H^2CMN, right). Error bars represent the accuracy of the quartz dilatometer (25 ppm)


Note that the specimen is first cooled to -321 °F before measurements of expansion are made. Thereafter, thermal expansion is measured as the specimen returns to RT.

Error bars have been placed on the fitted line to display accuracy of quartz dilatometer (25 ppm)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Error bars have been placed on the fitted line to display accuracy of quartz dilatometer (25 ppm)

Phase I Conclusions

- **Mechanical Measurements**
    - The powder impregnation process during SMP-730 prepregging allowed sufficient infiltration into HCMC samples, but ineffective for H2CMN since the CNT growth requires a viscous matrix to penetrate the nanoforest.
    - It is believed the CNT matrix wet-outs were incomplete and interlaminar bonding was relatively weak, leading to reduced mechanical performance in strength, toughness and strain-at-failure.
    - H^2CMN elastic modulus increased slightly due to the sandwich-type structure.
    - It is believed that the advantages of CNTs will be realized if a less viscous prepregging matrix (SMP-10) is used as the initial prepregging matrix. This will be explored in Phase II.
- **CTE Measurements**
    - Both HoneySiC materials exhibited relatively zero expansion in the in-plane direction from -196°C to RT.
    - Negative expansion was observed between -196°C and -128°C.

Phase II Proposed Effort

- Collaborate with NASA MSFC, GSFC, JPL and Northrop Grumman Aerospace Systems (NGAS) to design a prototype whiffle plate, delta frame or tube structure to be made using HoneySiC or H^{2}CMN materials that will support space-based telescope applications.
- Supplement the suite of HCMC and H^{2}CMN material properties measurements as requested by NASA and NGAS.
- Produce HCMC and H^{2}CMN prototype(s) for demonstration of the technology.
- Characterize the prototype via mechanical property testing.
- Demonstrate superior performance to the incumbent material (M55J cyanate ester), which is an organic material and subject to outgassing, dimensional instability under temperature and environmental fluctuations.

Phase II Progress

- Material procurement for technology demonstration prototypes HCMC and H^2CMN prototype(s)
- Planning for manufacturing of one of the following:

Figure 1. Latch, mounting bracket, struts, whiffle plate, delta frame

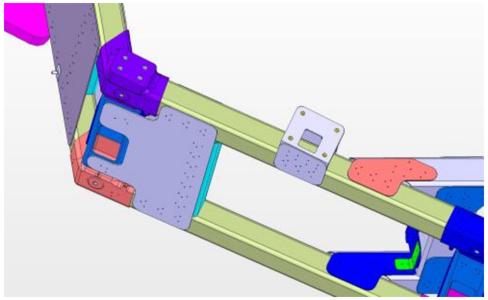

Figure 2. Composite tube structure (yellow)

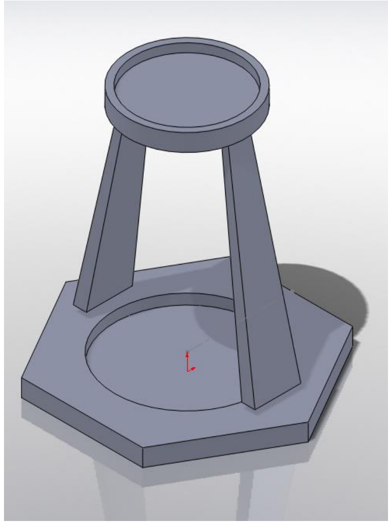

Figure 3. Cassegrain telescope structure

NASA Applications

- **NASA sees potential for HoneySiC™ as an affordable technology for large observatories and future astrophysics missions[5] for:**
  - The Formative Era, answering such questions as “What are exoplanets like?”
    - Characterizing planet forming disks and planetary atmospheres with the LUVOIR Surveyor.
    - Searching for life using the LUVOIR Surveyor to obtain full-disk images and spectra of pale blue dots.
    - Making longitudinal maps and detecting seasonal variations on exoEarths.
    - Searching for signs of habitability and evidence of biological activity on exoEarths.
  - The Visionary ERA, searching for life using an ExoEarth Mapper to produce resolved maps and spectra of “New Earth”, confirming surface water and identifying possible life.

Gov't & Commercial Markets

SECTOR	Market	# Units	Value	Comments
Government	Airborne & Space-Based EO Systems	>23K units total ~2-3K/year	$35B total, $2.9-$5.1B/year	POD based, Programs include airborne pilot visual navigation and weapon delivery aids; airborne IR/EO countermeasures; automatic target acquisition
	Land & Sea Based EO Systems	>560K units total, ~50,000/year	$8.1B, $500M-$1B/year	Primarily thermal weapon sites and night vision
	UAV Recon Systems	1600 units total >80 Programs	$16B total, $1-2B/year	Military Uses
	Surface to Air Missiles	>82K units total, 30 manufacturers, >70 systems	$21B	Man portable to Theater Ballistic Defense
	NASA/JPL Missions	20 missions total, 1-3 missions/year, 3-4 small instruments/mission	$480M total instruments, $24-72M/year	5 year development lead time
Commercial & Civil	Remote Sensing	139 spacecraft total, 10-25 spacecraft/year, 3-4 instruments/SC	$16.3B total, $60-100M/year for instruments	Imaging, Surveillance, Reconnaissance
	Solar Power Generation	100s of Acres Low-Tech Mirrors, Dozens of Hi-Tech per Plant	$500M total, $50$150M/year	Green Power for Grid
	UAV Civil	100's units, 10-50 /year ramp up	$1.8B	Numerous Civil & commercial Applications
	Semi-conductor	1,000's units, cyclical investment	$100M	Beam Steeering, Laser Cuttting and Welding, Lithography
	Communications	100,000's units, 1000s per year	$2B	Fibers, gratings, windows

Summary of Tasks

- **Task 1: Kick-off and Requirements Review**
  - Telecon with Ron Eng (NASA), Dr. Bill Fischer (Fantom), Professor Mehrdad Nejhad (UH), Jon Arenberg (Northrop Grumman)
- **Task 2: TIMs**
  - Monthly technical interchange meetings will establish program status, action items and technical progress.
- **Task 3: H^2CMN Validation (19 weeks)**
  - Prepare coupons using SMP-10 as the initial prepregging matrix.
- **Task 4: HCMC and H^2CMN Prototype Definition (10 weeks)**
  - A prototype design will be collaboratively designed by Fantom, NASA, NGAS and Professor Nejhad
- **Task 5: Prototype Design and Engineering (16 weeks)**
  - FEM will be used to define design and performance requirements.
  - Design concepts will be refined and optimized for HoneySiC™; not a redesign of the original component.
  - ICDs, preliminary and final manufacturing drawings will be generated.

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Summary of Tasks

- **Task 6: Joint Specimen Production (22 weeks)**
    - Full scale specimens of the intended prototype joint will be produced to replicate the design, application and use of fasteners/hardware for mechanical testing (or other testing deemed appropriate by NGAS and NASA).
    - We anticipate there will be several candidate designs.
- **Task 7: Joint Specimen Testing (5 weeks)**
    - Fantom will test the strength of at least one joint specimen design.
    - Final selection will be based on manufacturability, cost effectiveness and strength test results.
- **Task 8: Prototype Definition (28 weeks)**
    - An HCMC or H^2CMN prototype will be produced based on the D&E and joint specimen testing in Tasks 5 and 7.
    - Tentative plan is to make a scaled-down version of whiffle plate, delta frame or tube structure. Scaling ratio will depend on the selected component relative to UH’s furnace workspace (13”x13”x14”).
    - Estimated task time includes procurement of materials.

Summary of Tasks

- **Task 9: Prototype Testing (5 weeks)**
    - Mechanical testing will be performed at UH.
- **Task 10: Phase II-E Application and Plan (12 months into POP)**
    - Fantom, with financial investment from MDA, intends to apply for a P2-E.
    - The proposed scope of work is as follows:
        - Additional material characterization of HoneySiC™ materials. Specifically:
            - Thru-thickness CTE
            - In-plane CTE at ppb level (optional)
            - Thermal conductivity
            - Volume resistivity
            - BRDF using visible and single line laser sources
        - Development of 3D printing processes for HoneySiC™ material systems
        - Design and fabricate a meter-class telescope front structure
- **Task 11: Phase III Plan**
    - Fantom, NASA, NGAS and UH will develop a preliminary and strategic plan for Phase III and transition to commercial production.

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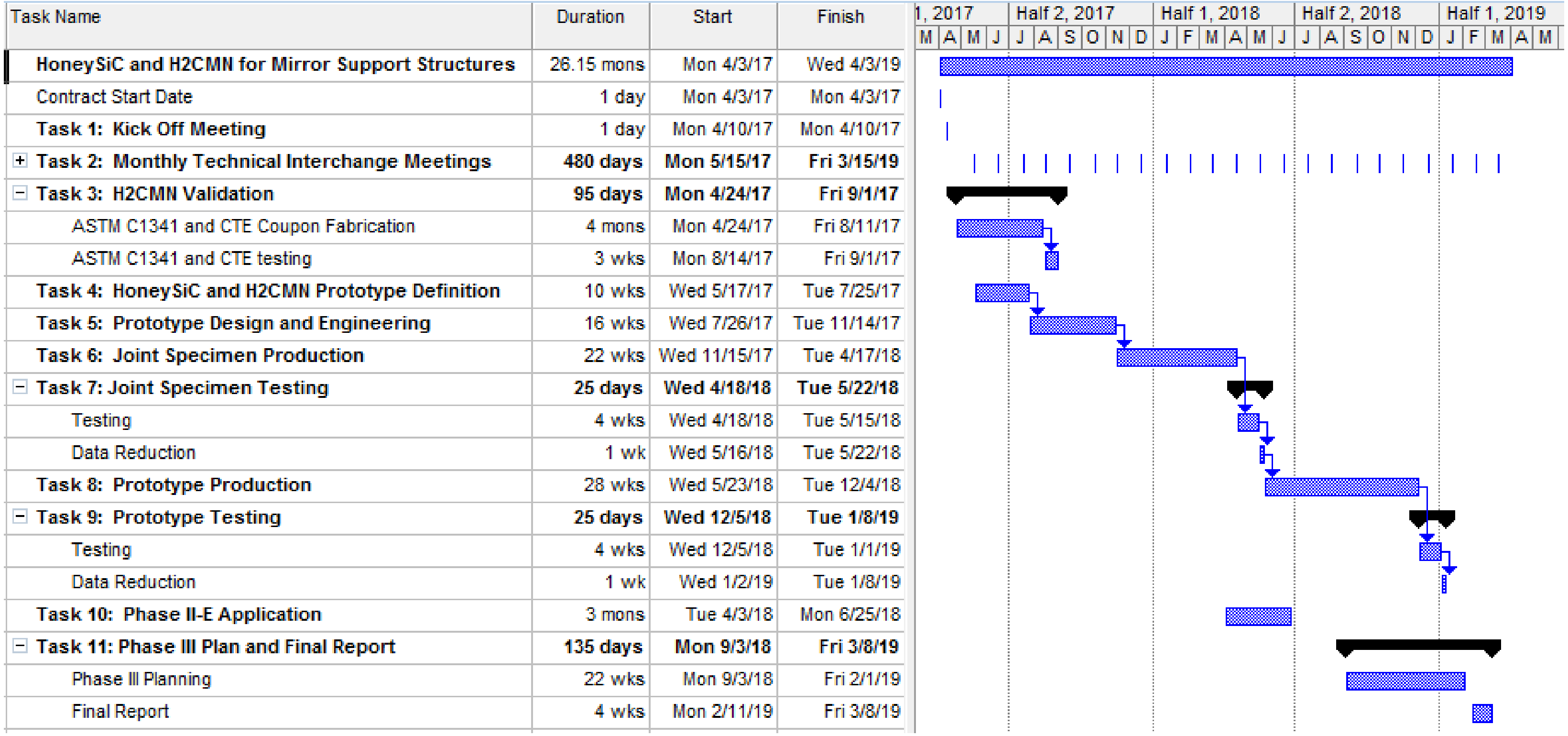
Project Schedule

- Period of Performance: 1 May 2017 – 30 April 2019
- Project schedule defined to complete all tasks by March 8, 2019



Task Name	Duration	Start	Finish
HoneySiC and H2CMN for Mirror Support Structures	26.15 mons	Mon 4/3/17	Wed 4/3/19
Contract Start Date	1 day	Mon 4/3/17	Mon 4/3/17
Task 1: Kick Off Meeting	1 day	Mon 4/10/17	Mon 4/10/17
+ Task 2: Monthly Technical Interchange Meetings	**480 days**	**Mon 5/15/17**	**Fri 3/15/19**
− Task 3: H2CMN Validation	**95 days**	**Mon 4/24/17**	**Fri 9/1/17**
ASTM C1341 and CTE Coupon Fabrication	4 mons	Mon 4/24/17	Fri 8/11/17
ASTM C1341 and CTE testing	3 wks	Mon 8/14/17	Fri 9/1/17
Task 4: HoneySiC and H2CMN Prototype Definition	10 wks	Wed 5/17/17	Tue 7/25/17
Task 5: Prototype Design and Engineering	16 wks	Wed 7/26/17	Tue 11/14/17
Task 6: Joint Specimen Production	22 wks	Wed 11/15/17	Tue 4/17/18
− Task 7: Joint Specimen Testing	**25 days**	**Wed 4/18/18**	**Tue 5/22/18**
Testing	4 wks	Wed 4/18/18	Tue 5/15/18
Data Reduction	1 wk	Wed 5/16/18	Tue 5/22/18
Task 8: Prototype Production	28 wks	Wed 5/23/18	Tue 12/4/18
− Task 9: Prototype Testing	**25 days**	**Wed 12/5/18**	**Tue 1/8/19**
Testing	4 wks	Wed 12/5/18	Tue 1/1/19
Data Reduction	1 wk	Wed 1/2/19	Tue 1/8/19
Task 10: Phase II-E Application	3 mons	Tue 4/3/18	Mon 6/25/18
− Task 11: Phase III Plan and Final Report	**135 days**	**Mon 9/3/18**	**Fri 3/8/19**
Phase III Planning	22 wks	Mon 9/3/18	Fri 2/1/19
Final Report	4 wks	Mon 2/11/19	Fri 3/8/19