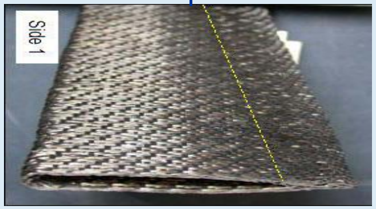
# Additive Manufacturing 2.0

Ajay Misra, David Ellis, Chantal Sudbrack,
Robert Carter, Michael C. Halbig,
Mrityunjay Singh, Valerie L. Wiesner,
Joseph E. Grady, William Marshall

# Materials and Structures Research and Development

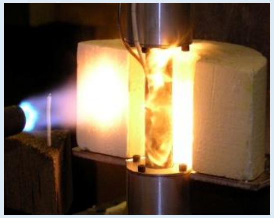
## High Temperature Materials

Ceramic Matrix Composite

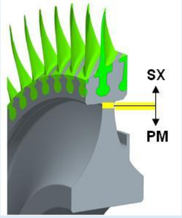


Protective Coatings

Thermal Protection Seal



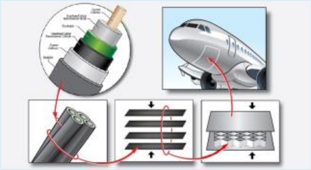
Hybrid Disk



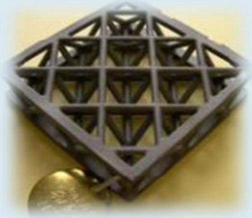

## Lightweight Concepts

Hybrid Composite Gear

Multifunctional Structures



Lattice Block



Flexible Aerogel

## Power System Materials

Materials for High Power Density Electric Motors

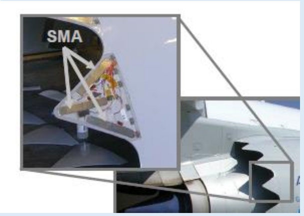

Lightweight Power Transmission Cable

Solid Oxide Fuel Cell Material

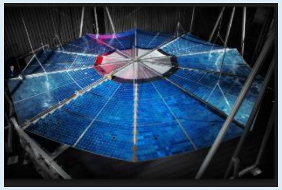
## Mechanisms and Drive Systems

High Efficiency Gear

Shape Memory Alloy-Based Actuation

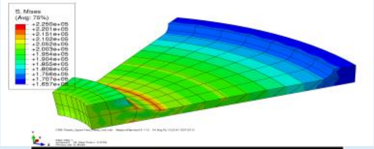


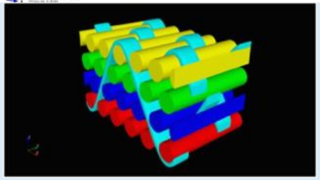

Deployable Structure

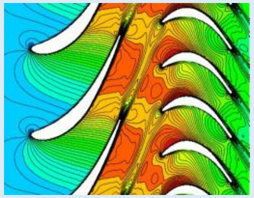


Spring Tire

## Computational Modeling

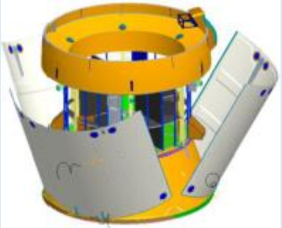






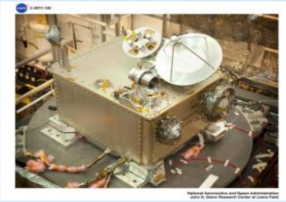
## Flight Structures

Orion Fairing Jettison



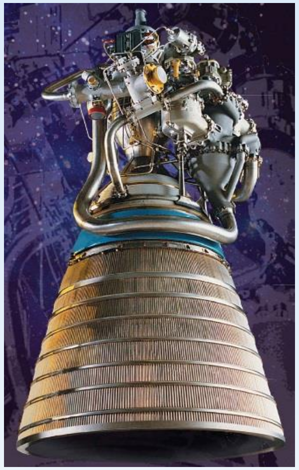
EFT-1

Vibration Testing



Large Composite Structures

# Role of Additive Manufacturing in Aerospace Propulsion and Power



Large Rocket Propulsion

- Reduced complexity
- Faster cycle time
- Complex design features
- New design concepts and material/structural architectures enabled by additive manufacturing

Aircraft Gas Turbine Engine

Solar Electric Propulsion for Space Exploration

Small Propulsion for Cubesat

Hybrid Electric Propulsion for Aircraft

# Current GRC Focus in Additive Manufacturing

- Additive manufacturing of space propulsion components
- Testing and characterization related to certification of additively manufactured components
- Location-specific properties in high temperature components enabled by additive manufacturing
- Additive manufacturing of multimaterial/multifunctional systems related to electrical machines and electric propulsion
- Additive manufacturing process for fabrication of continuous fiber reinforced composites
- Understanding and modeling processing-microstructure-property relationship for additive manufactured components

# Additive Manufacturing Of Metals At NASA GRC

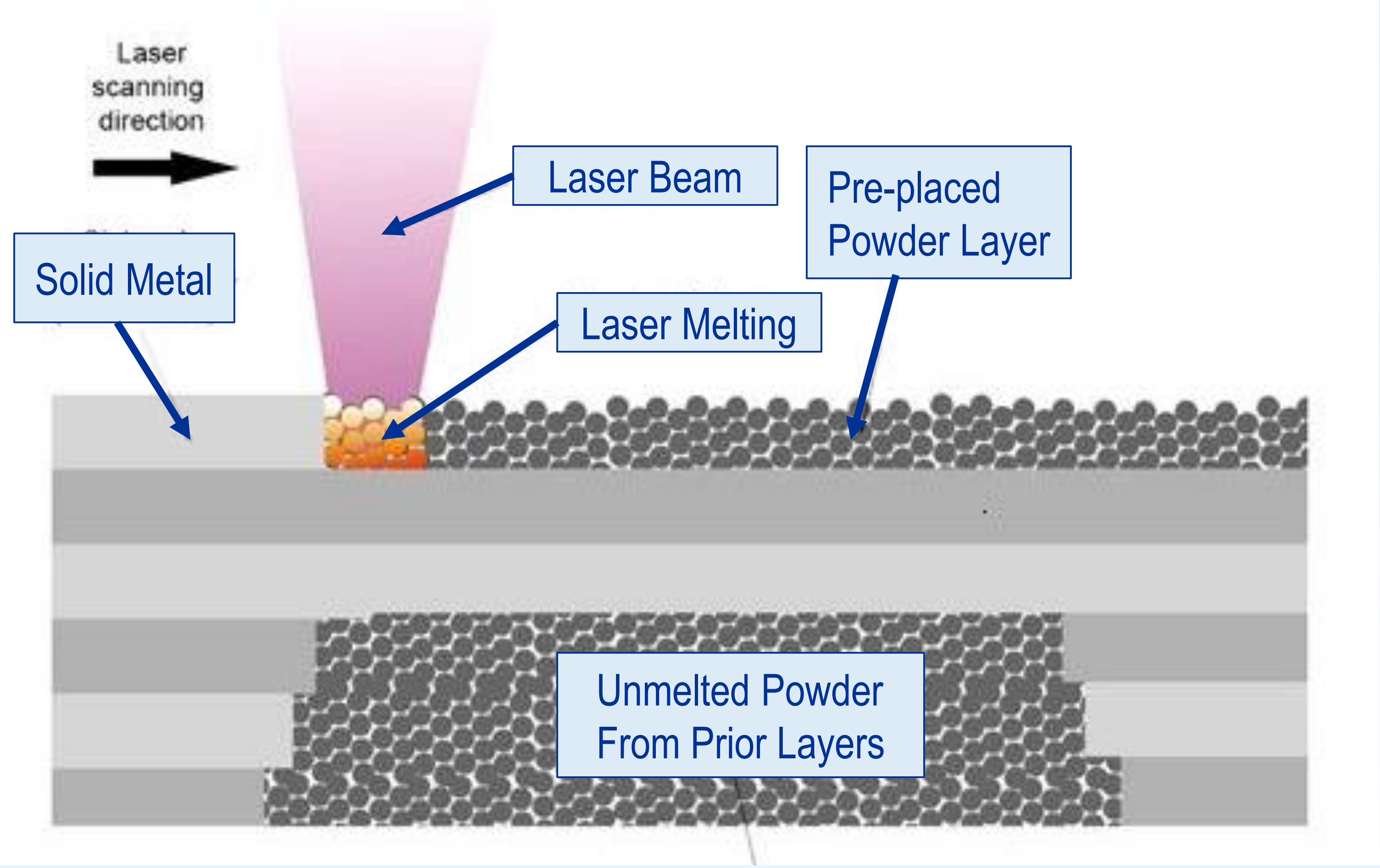
David Ellis, Chantal Sudbrack, Robert Carter

# Low Cost Upper Stage Program (LCUSP)

- **GOAL:** Additively manufacture a 30,000 to 40,000 lbf thrust rocket chamber at a lower cost and faster production time than conventional rocket chamber fabrication methods
- Liner is made of GRCop-84, a NASA Glenn Research Center developed Cu-Cr-Nb alloy, and was manufactured using Selective Laser Melting (SLM)
- The jacket is made from IN-625 and was manufactured using Electron Beam Freeform Fabrication (EBF3)

# NASA MSFC Concept Laser M2 Machine


# Selective Laser Melting (SLM)

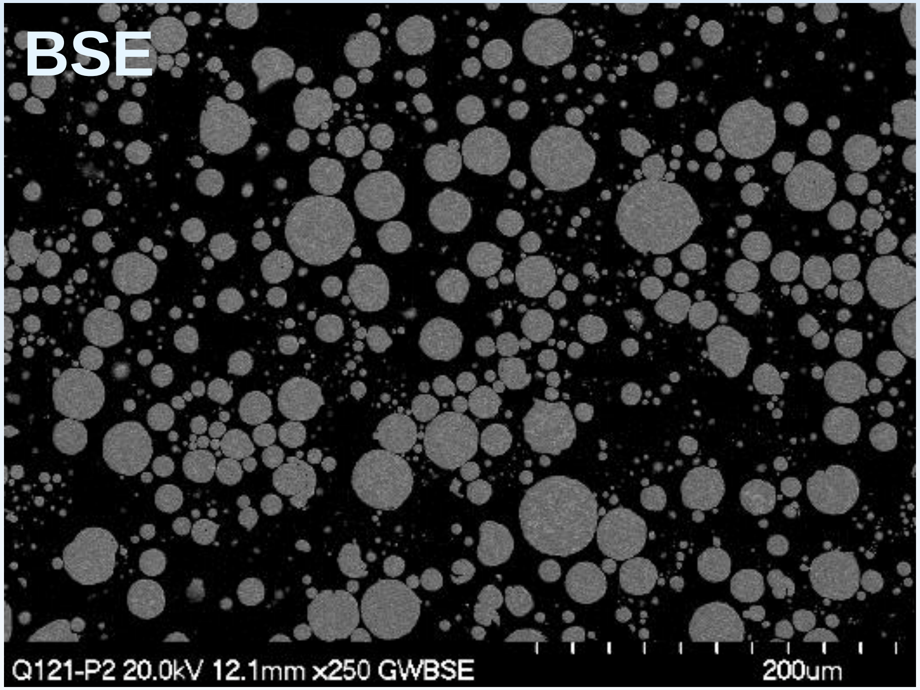


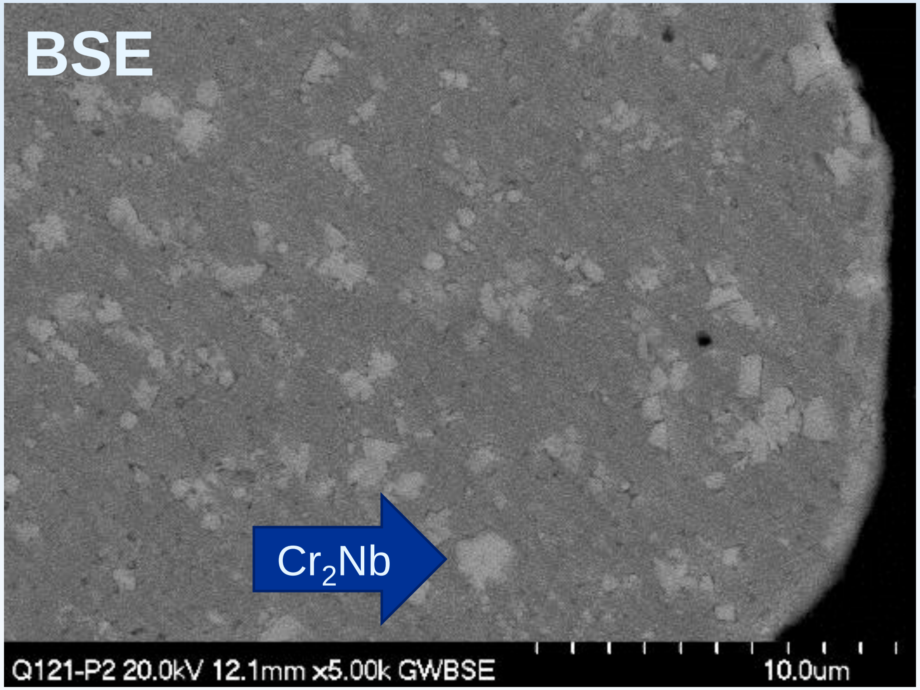

**Unlike Selective Laser Sintering (SLS), SLM involves melting and resolidifying the powder**

# Potential Obstacles To SLM GRCop-84

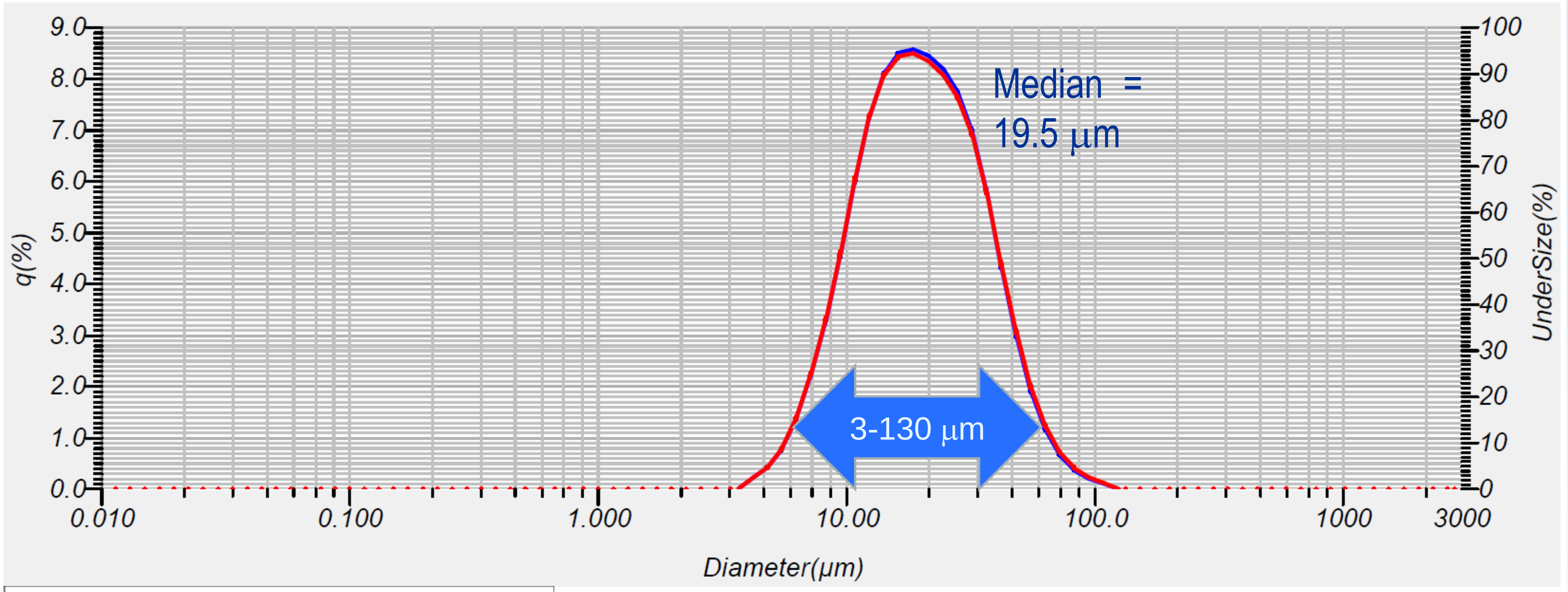
- High reflectance may limit power that can be put into powder to melt it
  - Copper reflectance is about 0.75 at laser wavelength
- High thermal conductivity may limit maximum temperature that can be attained
- Lower density $Cr_2Nb$ phase used for strengthening may float to surface of melt pool
- Shrinkage porosity may be excessive
  - Copper shrinks about 4% upon solidification
- Surface finish may be too rough
  - A rough surface could be beneficial if it improves heat transfer in the cooling channels

# GRCop-84 Powder Microstructure



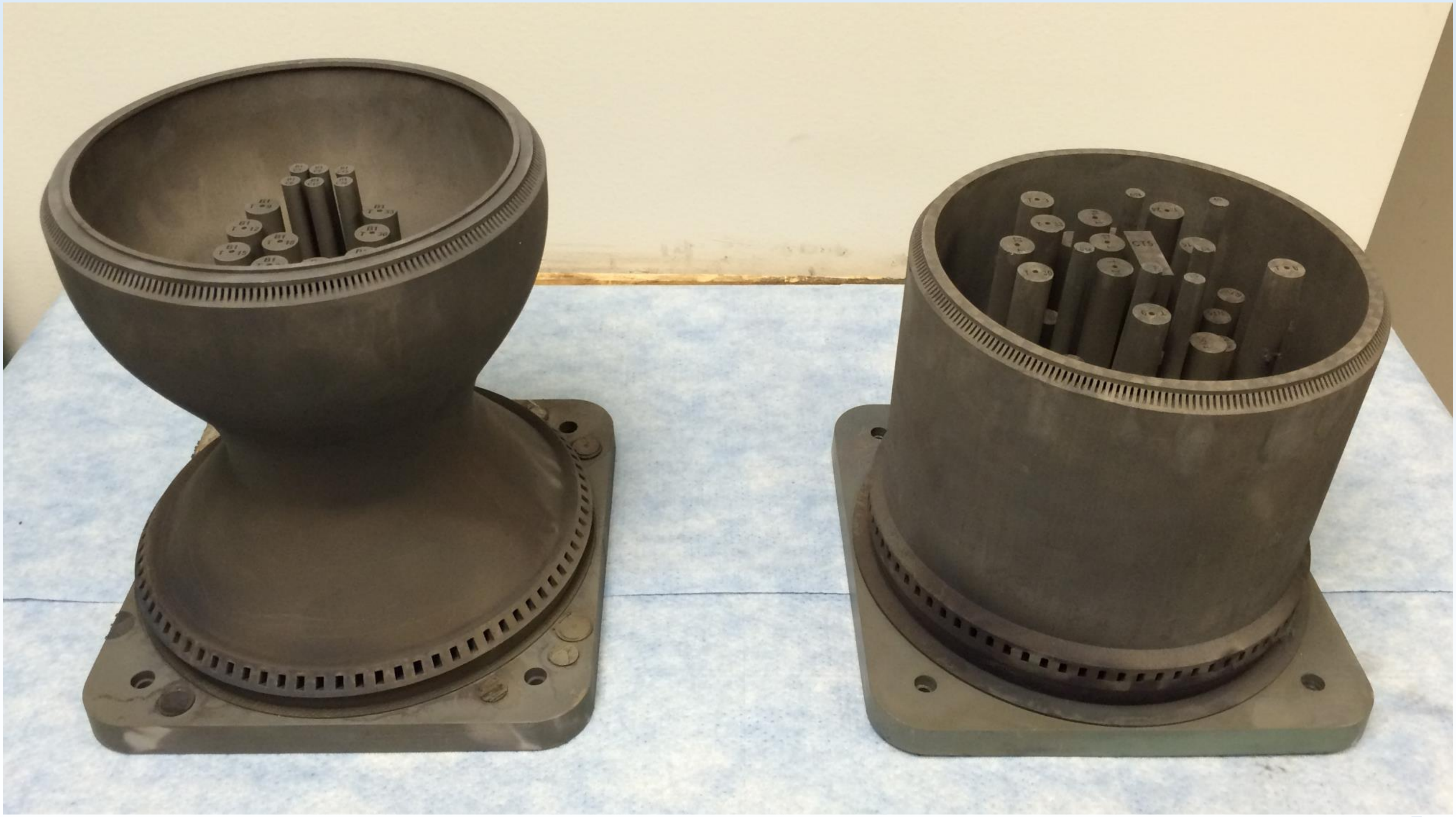



# Typical GRCop-84 Powder Size Distribution

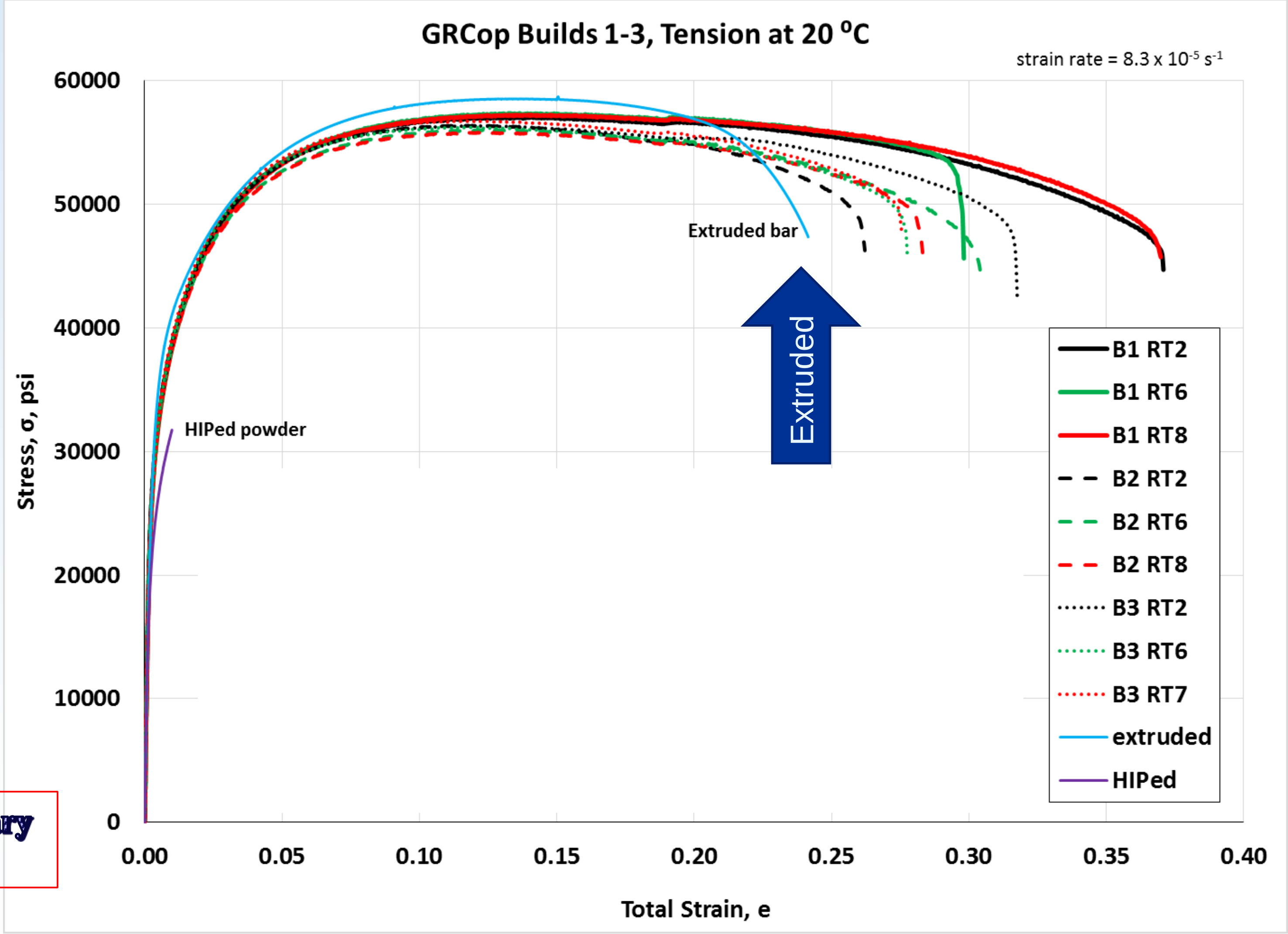



| Data Name | Graph Type | Median Size |
|---|---|---|
| 201502241543055 | (blue) | 19.52085(µm) |
| 201502241540054 | (red) | 19.52655(µm) |

# Liner Sections And Mechanical Test Samples

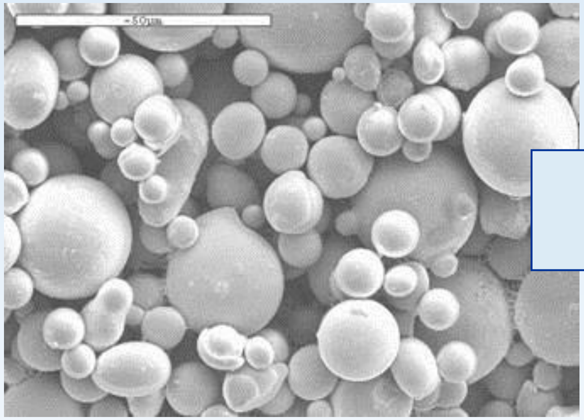


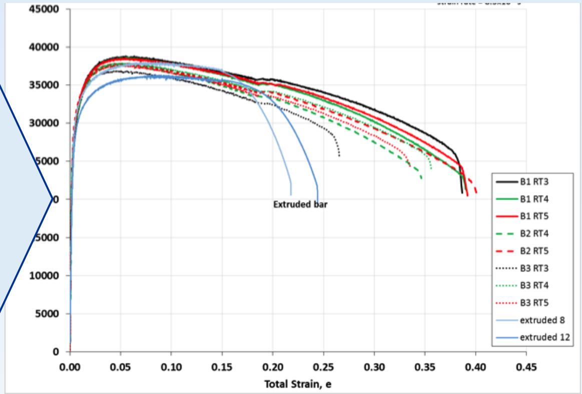
# Room Temperature Tensile Strength




Preliminary Results

# Additive Manufacturing Structural Integrity Initiative (AMSII)




## AMSII is taking a holistic approach to additive manufacturing from powder to processing to properties

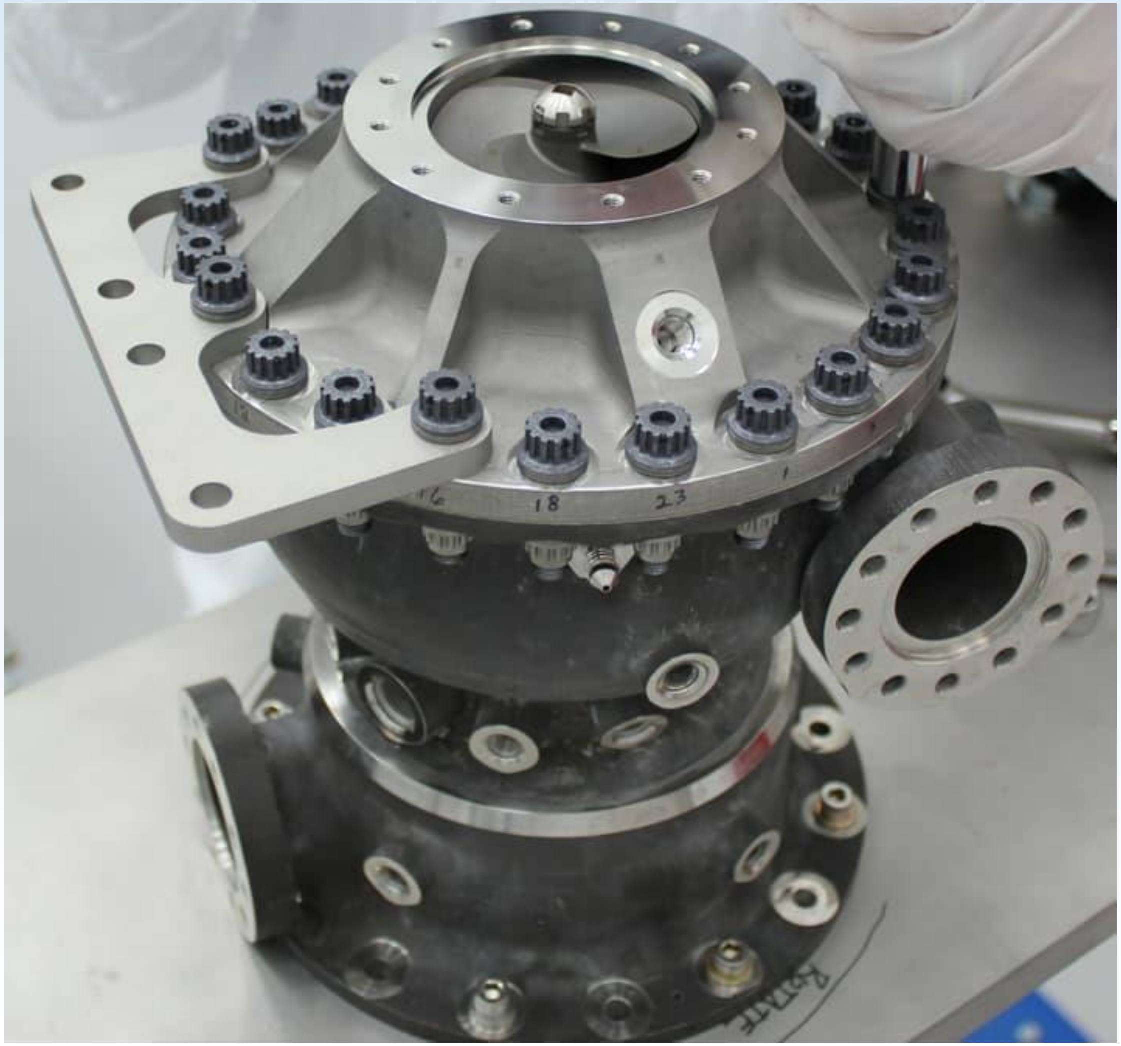
**Major Goals:**

- Develop feedstock controls and maximum recyclability limits
- Identify powder control and heat treatment metrics for inclusion in standard for RS-25E Engine

# Overview Research Plan For AMSII

1. **Powder Characterization**
   A. Size distribution
   B. Morphology
   C. Rheological properties
   D. Post-use changes / reusability
2. **Manufacturing**
   A. Powder bed characterization
   B. SLM parameters
   C. Melt pool modeling
   D. HIP parameters
   E. Microstructural modeling
3. **Consolidated Properties**
   A. Microstructure
   B. Mechanical properties such as tensile, creep and fatigue strengths
   C. Flammability

# 3D Printed Rocket Components Are Already A Reality

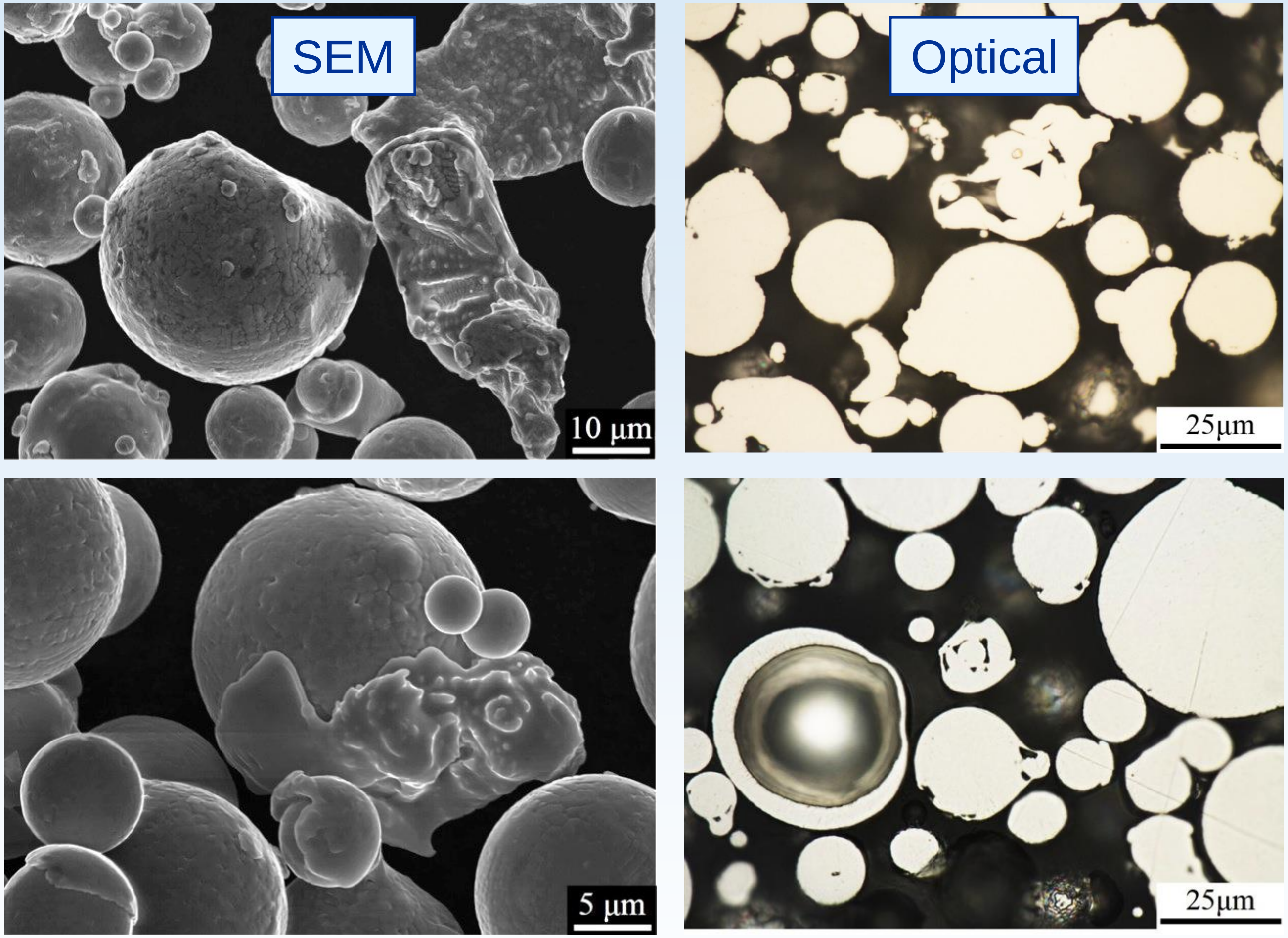


- Fuel Turbopump (FTP) for 30,000 $lb_f$ class rocket engine
  - Suitable for upper stage engine
- 90,000 RPM disk speed
- 45% fewer parts than Space Shuttle Main Engine (SSME) FTP
- Tested under actual service conditions in July 2015 at NASA MSFC

# IN-718 Powder Lots 1 and 2

Powder Lot 1

Powder Lot 2




- Differences already observed in commercial powders
  - Lot 1 – More agglomerations,  less porosity and inclusions
  - Lot 2 – More spherical, large porosity, many inclusions

# Near Term Work

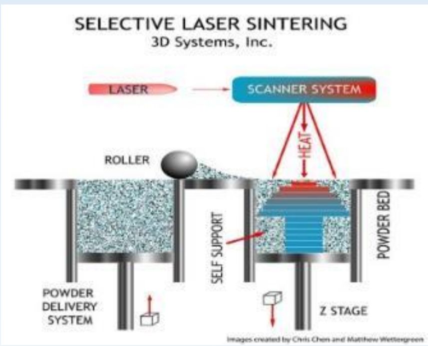
- Characterize 10 to 12 commercially available IN-718 powders
- Determine the strength and fatigue properties of AM IN-718 as a screening test
- Correlate measured powder properties with mechanical properties to determine primary factors affecting mechanical properties
- Begin modeling microstructural evolution

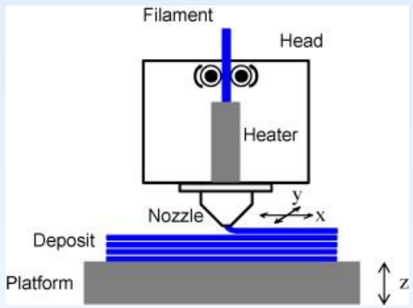
# Additive Manufacturing of Non-Metallics and Multi-materials

Michael C. Halbig, Mrityunjay Singh,
Valerie L. Wiesner, and Joseph E. Grady

# Overview of Additive Manufacturing Technologies

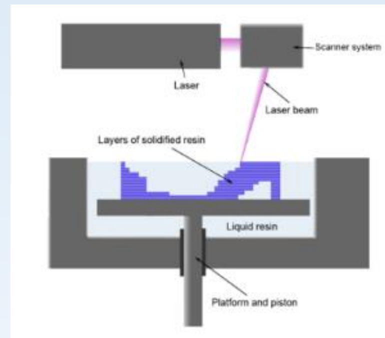
## Selective Laser Sintering
**High powered laser fuses plastic, metal, or ceramic powders.**

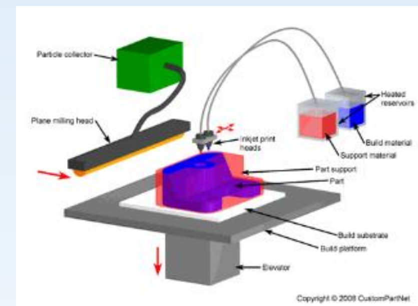



## Fused Deposition Modeling
**Plastic or metal is heated and supplied through an extrusion nozzle and deposited.**

## Stereolithography
**A beam of ultraviolet light is directed onto a vat filled with a liquid ultraviolet curable photopolymer.**



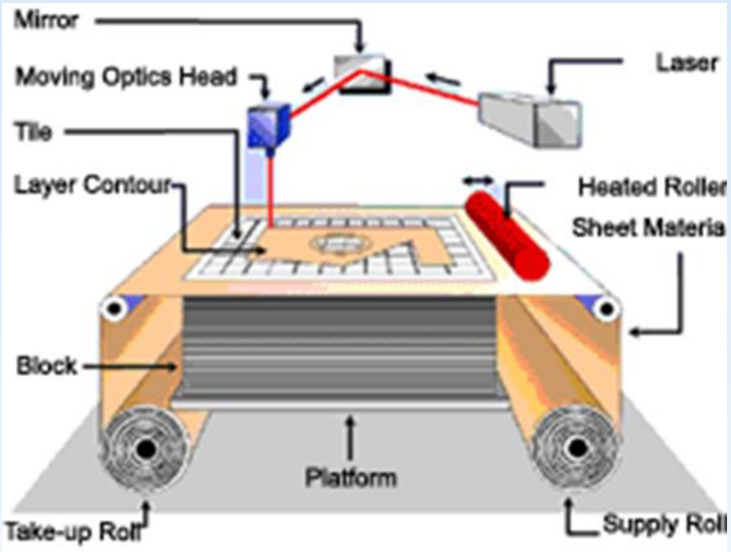




## Binder Jet 3D Printing
**An inkjet-like printing head moves across a bed of powder and deposits a liquid binding material.**

***Material choices are limited by the machine's manufacturers***
***Fabrication of continuous fiber composites is not possible***

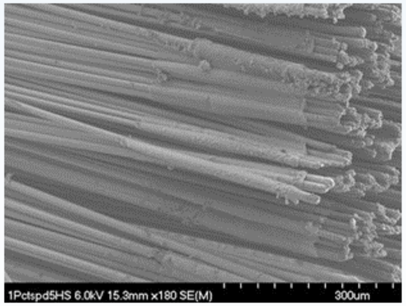
**Objective:** **Utilize additive manufacturing technologies as alternative processing approaches for fabricating advanced ceramics and CMC components**

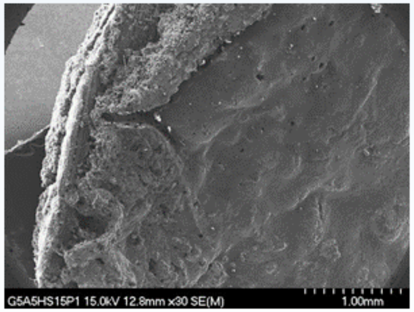
# Laminated Objective Manufacturing For Silicon Carbide-Based Composites



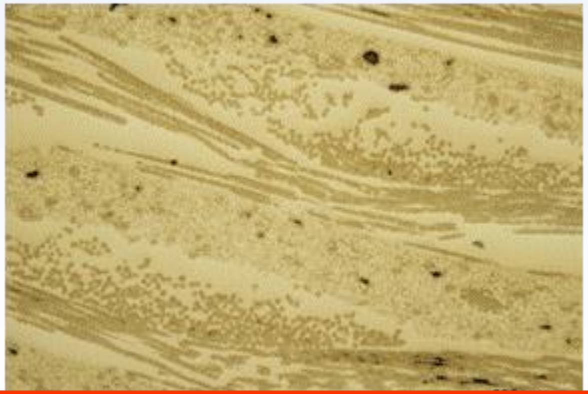

**LOM allows for continuous fiber reinforced CMCs.**

Universal Laser System (Two 60 watt laser heads and a work area of 32”x18”)




**Fabrics and Prepregs cut at different laser powers/speeds**



**Silicon Infiltration:**
1475 C, 30 minutes in vacuum

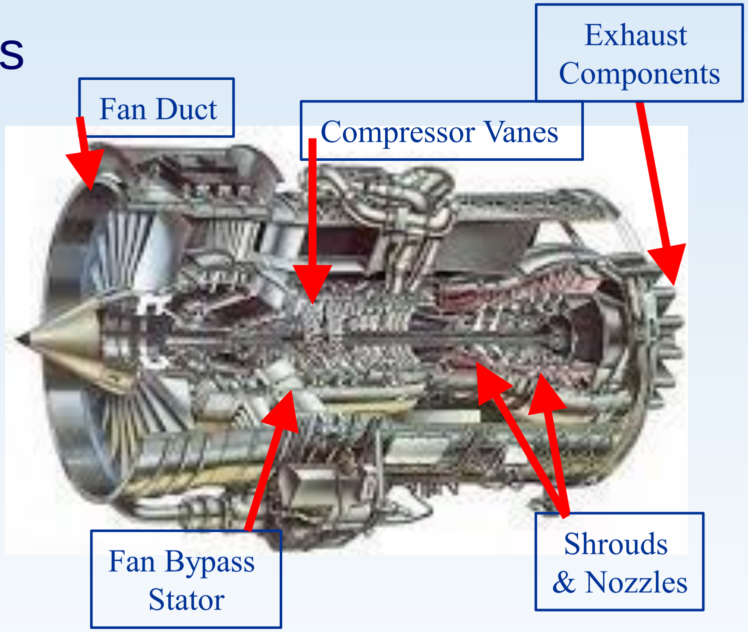
# Non-Metallic Turbine Engine Project (NARI)

## TEAM: NASA GRC, OAI, Honeywell Aerospace, RP+M, NASA LRC

**Project Objective:** Conduct the first comprehensive evaluation of emerging materials and manufacturing technologies that will enable non-metallic gas turbine engines.

- Assess the feasibility of using additive manufacturing technologies to fabricate gas turbine engine components from polymer and ceramic matrix composites.
  - Fabricate and test prototype components in engine operating conditions
- Conduct engine system studies to estimate the benefits of a fully non-metallic gas turbine engine design in terms of reduced emissions, fuel burn and cost

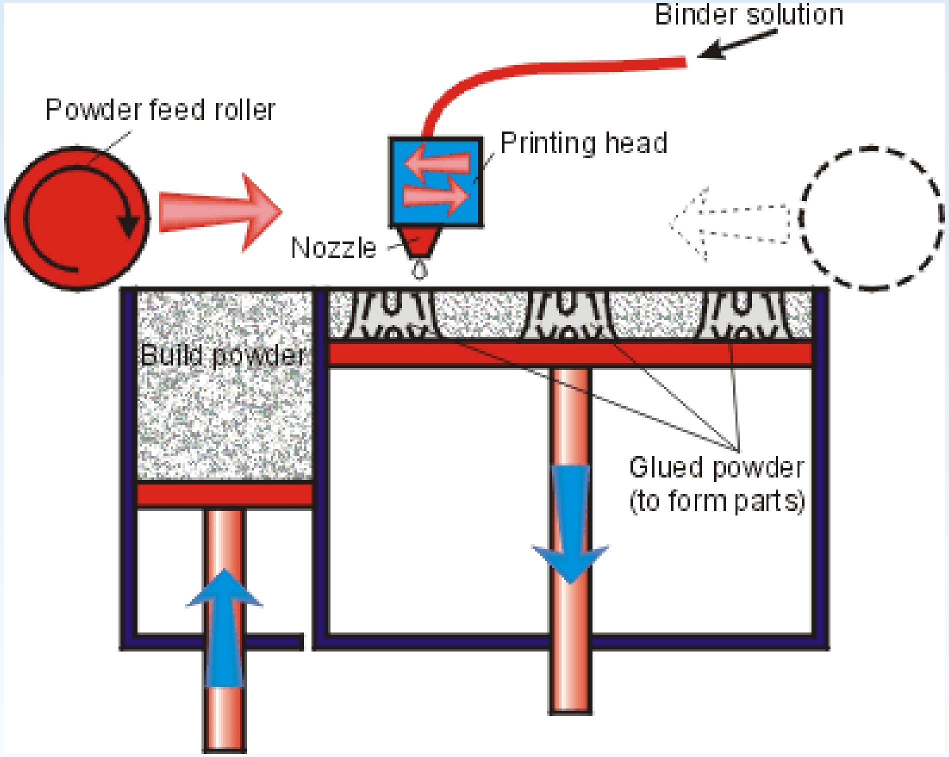
Targeted Components

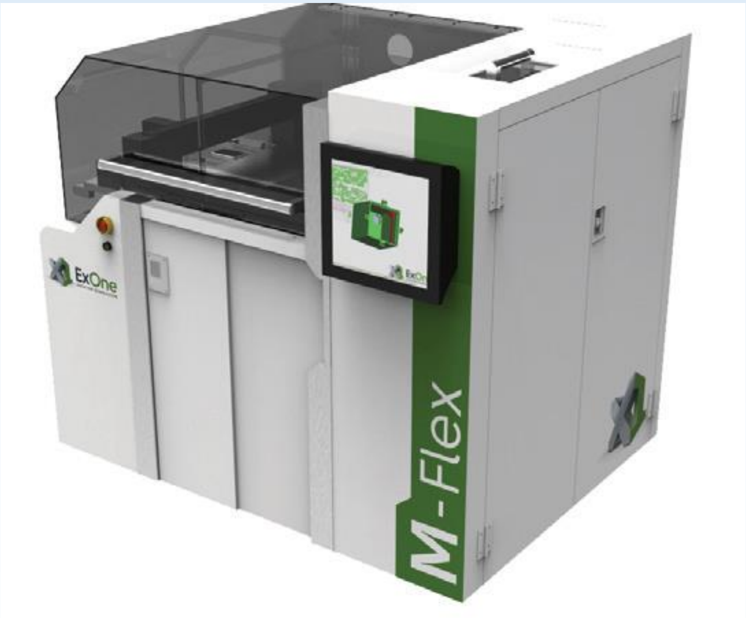



Business Jet size turbofan engine

# Additive Manufacturing of Ceramics using the Binder Jet Process

**In collaboration with rp+m**




ExOne's M-Flex print machine

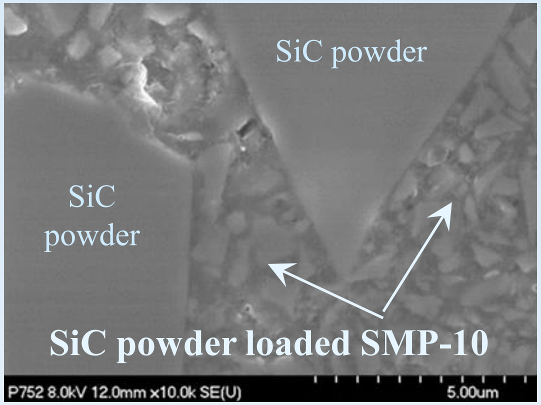
## Binder Jet printing

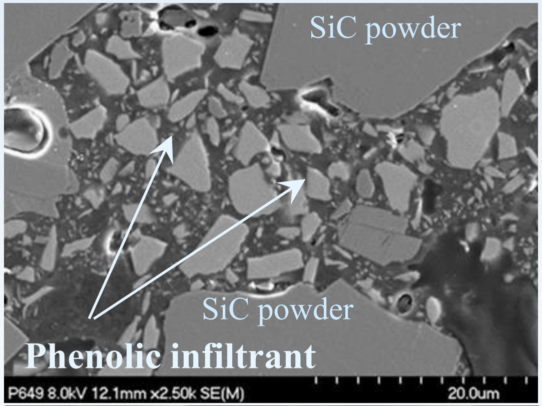
An inkjet-like printing head moves across a bed of powder and deposits a liquid binding material in the shape of the object's cross section

***Binder jet printing capability will allow for powder bed processing with tailored binders and chopped fiber reinforcements for advanced ceramics.***

# Fabrication and Microstructure of SiC Fiber Reinforced CMCs

## Constituents

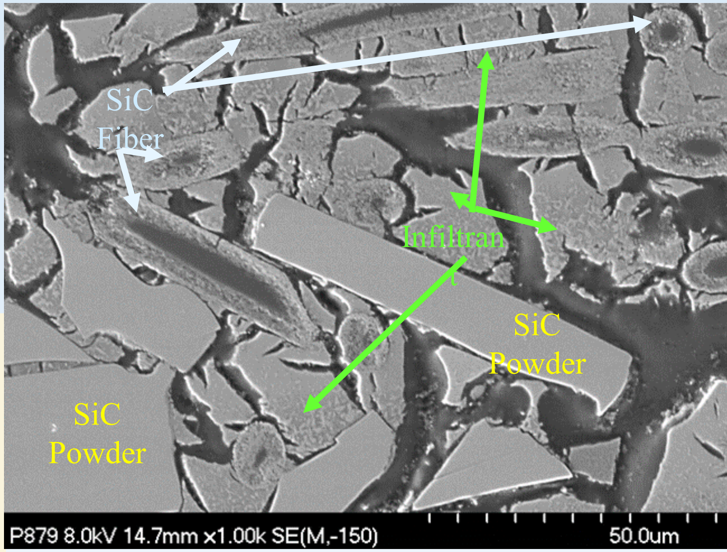


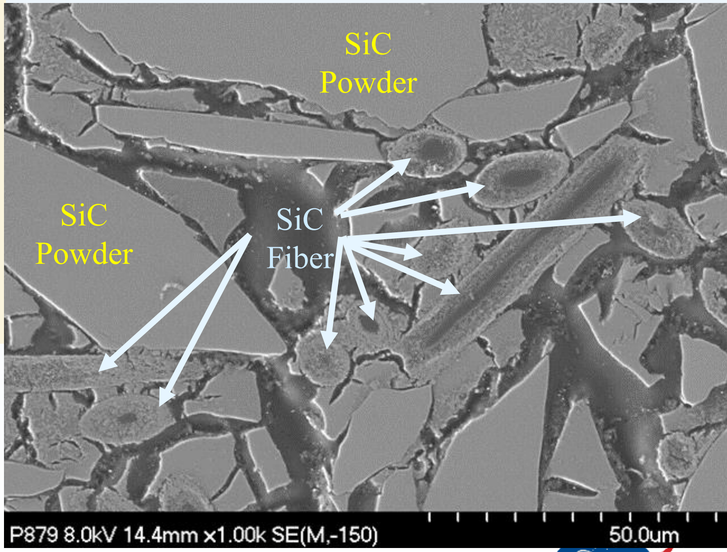





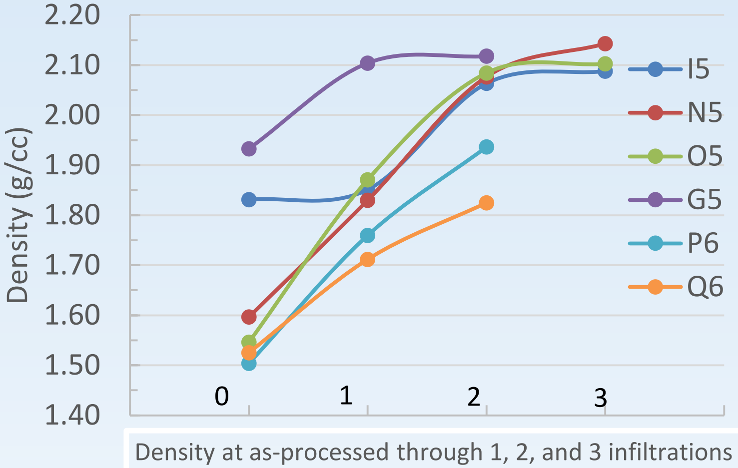
**CMC coupon with 35 vol% SiC fiber loading and infiltrant with smaller SiC powders.**

- ***Higher density observed due to powder loaded infiltrant***
- ***Good distribution and non-preferred orientation of SiC fibers is observed.***

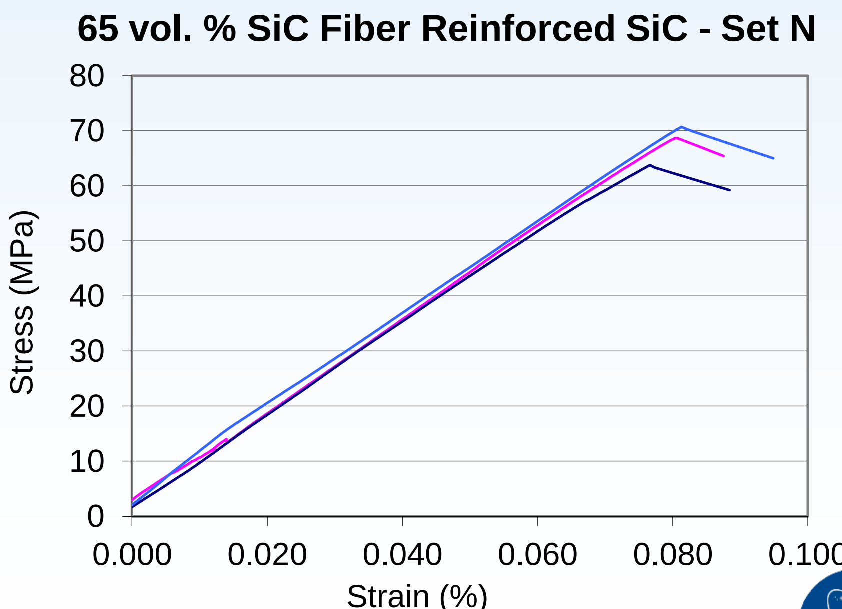


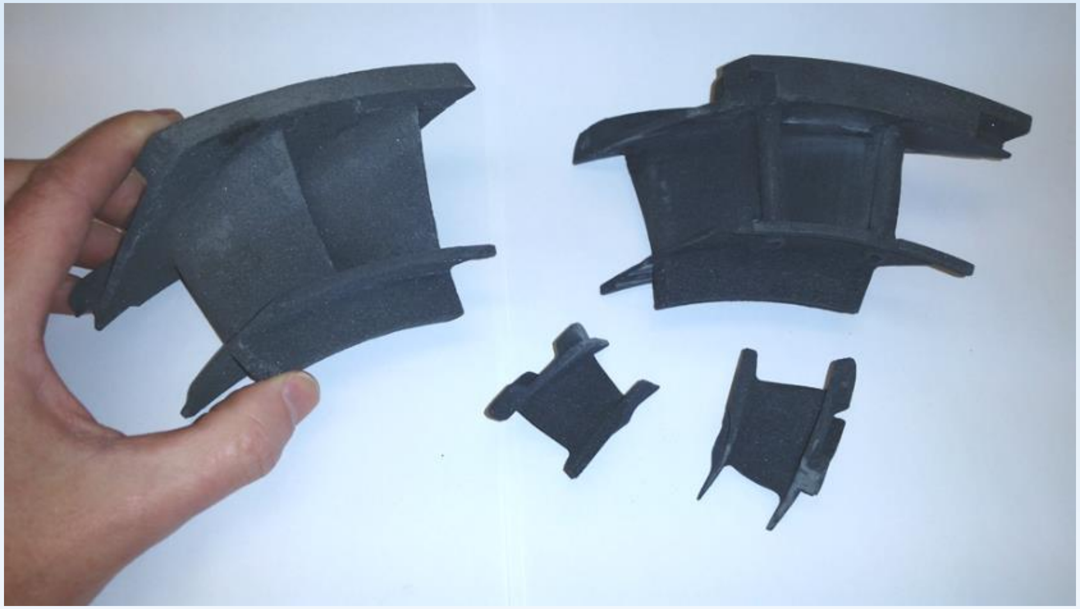
# 4 Point Flexure Tests of the Monolithic SiC and CMC materials - at room temperature and 1200°C




**The fiber loaded SiC materials had significantly higher stresses and higher strains to failure.**

# Demonstration of the Additive Manufacturing of Turbine Engine CMC Components (20 vol.% SiC Fiber)

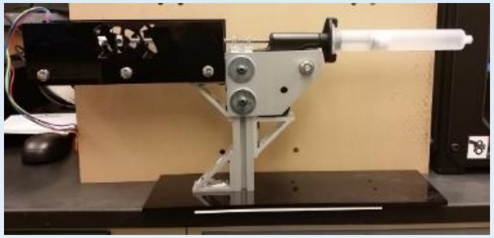


First stage nozzle segments.

**High pressure turbine nozzle segments: cooled doublet vane sections.**

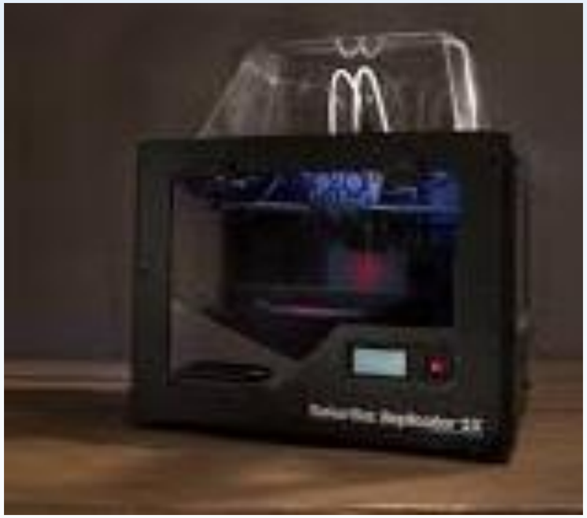
# Additive Manufacturing of Ceramics using 3-D Printing Technologies

**Objective:** **To develop and characterize feed materials for 3-D printing of silicon carbide (SiC)-based ceramics.**

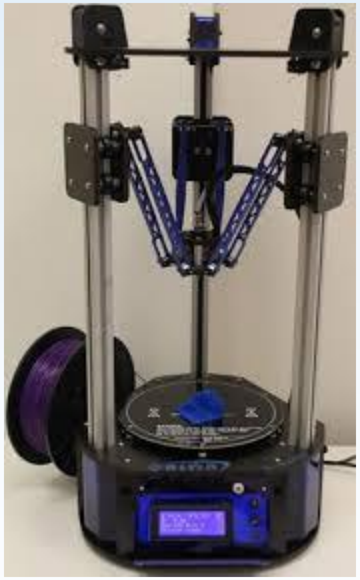


**3-D Printing Efforts**

- Powder Loaded Filament - direct printing of ceramic parts
- Wood Containing Filament - provide preforms for densification
- Slurry Dispensing of Pastes - evaluate pastes for full conversion to dense SiC



MakerBot Replicator 2X

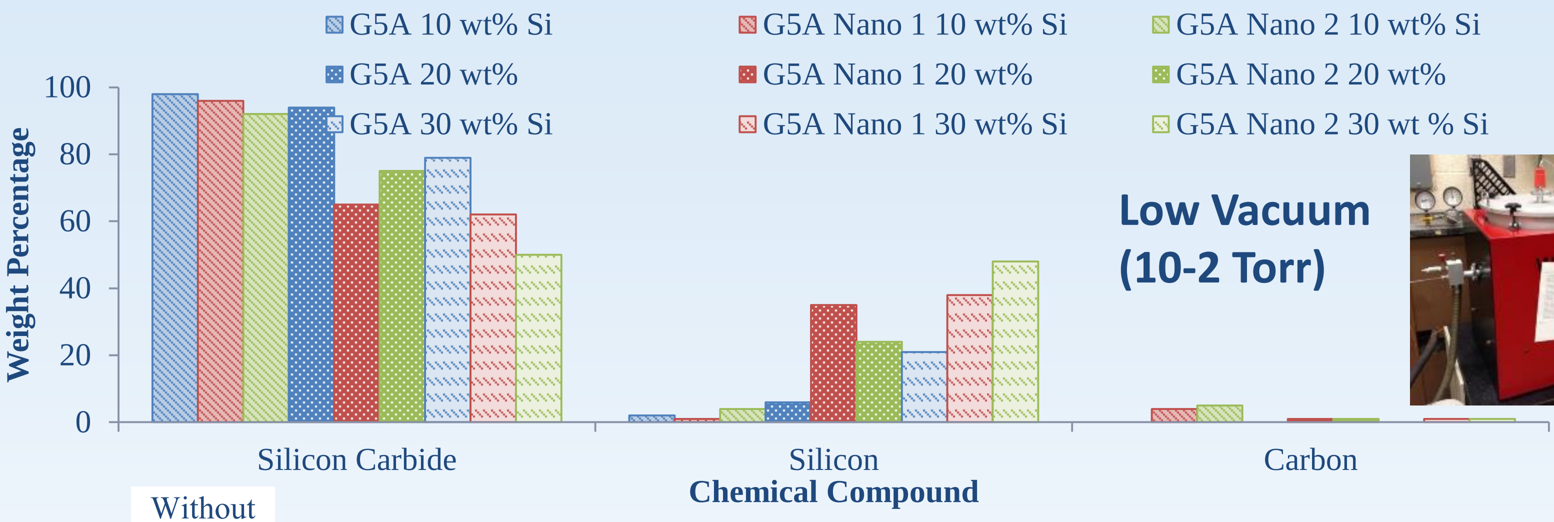


Orion Delta 3D Printer

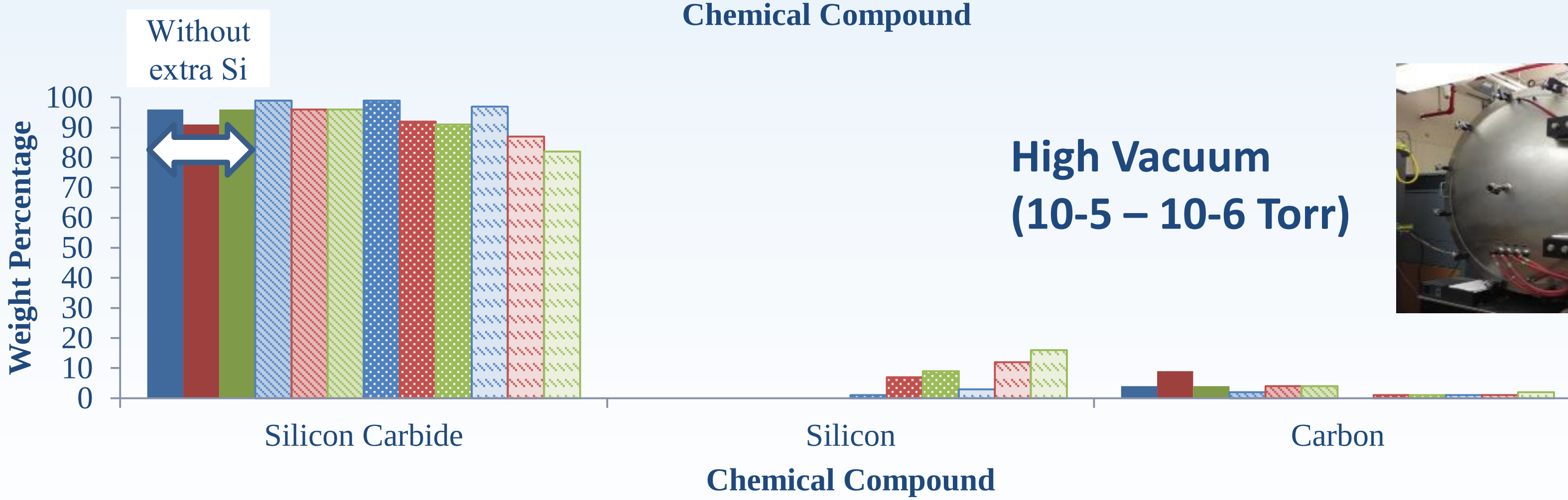
Rostock 3D Printer

***These printers can print polymers with specific filaments***
***Ability to fabricate ceramics is being investigated***

# Chemical Composition of Heat-treated Pastes at 1450°C (from X-Ray Diffraction Analysis)




**Low Vacuum (10-2 Torr)**




**High Vacuum (10-5 – 10-6 Torr)**

- **All compositions after pyrolysis show a high yield of SiC.**
- **Vaporization of Si occurs in vacuum due to its high vapor pressure**

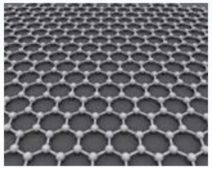
# NScrypt Capabilities and Applications

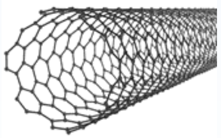
- Ability to host four separate materials and print on curved surfaces.
- Precise control of motion and micro-dispensing pump.
- Variety of print materials: ceramic pastes, electronic pastes, adhesives, solders, bio-materials, plastics.
- Direct writing with clean starts and stops

**Direct Printing for Multi-Material Systems**

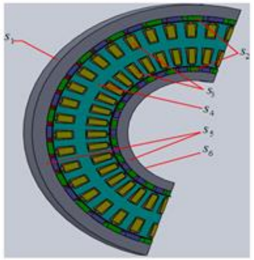
**AM for Innovative Electric Motor Designs**

**Highly Conductive Copper Pastes**

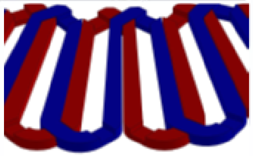




Additions of graphene and carbon nanotubes



Multi-material components

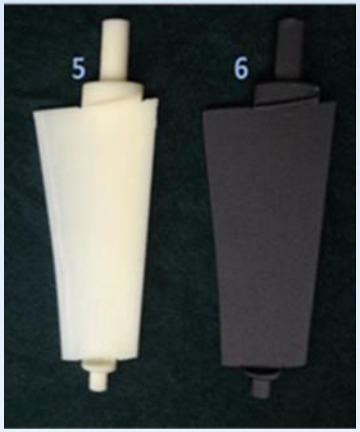


Overlapping direct printed coils.

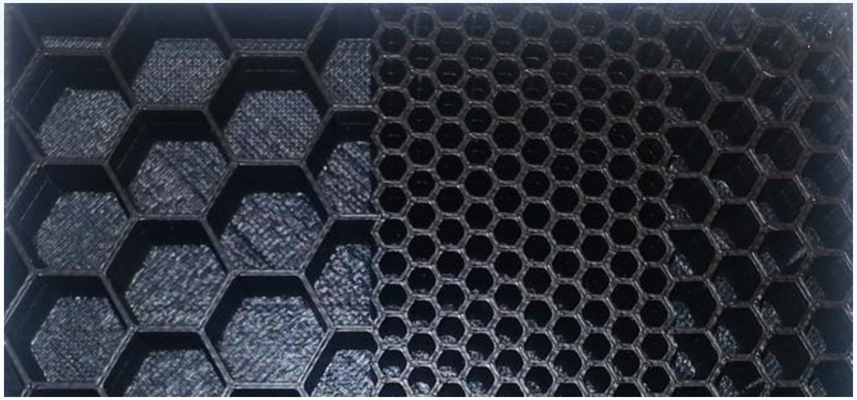
# 3-D Printing Capability of Various Components Demonstrated in Polymers at NASA GRC

Engine Panel Access Door

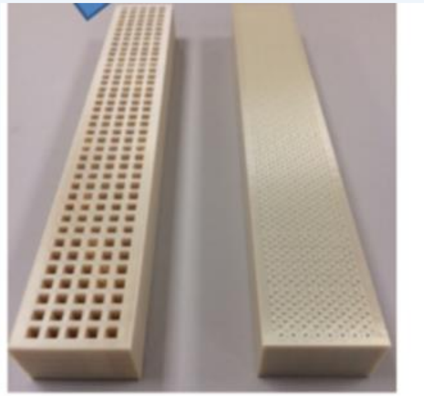
Lightweight Structures




Engine Inlet Guide Vanes from ABS and Ultem 1000



Variable Geometry Panels for Acoustic Treatment



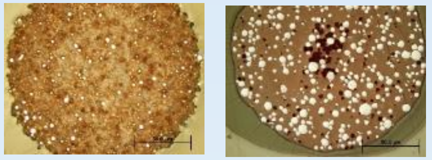
Acoustic Liner Test Articles

Turbine Blade Shape Demo

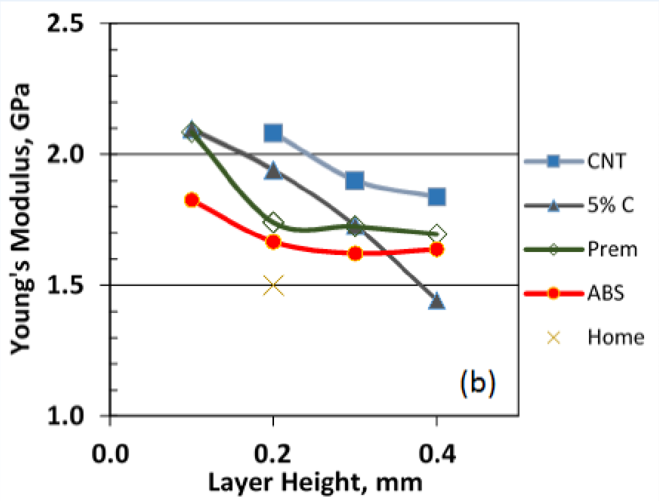
# Additive Manufacturing of Polymer Composites for Multifunctional Applications

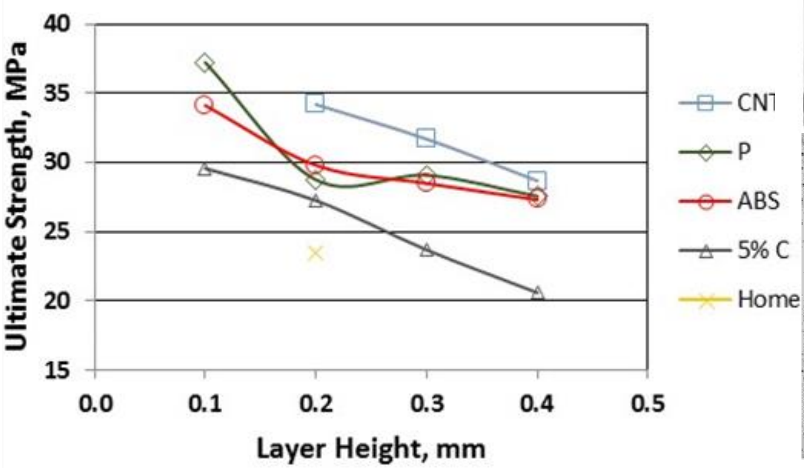
## Potential Missions/Benefits:

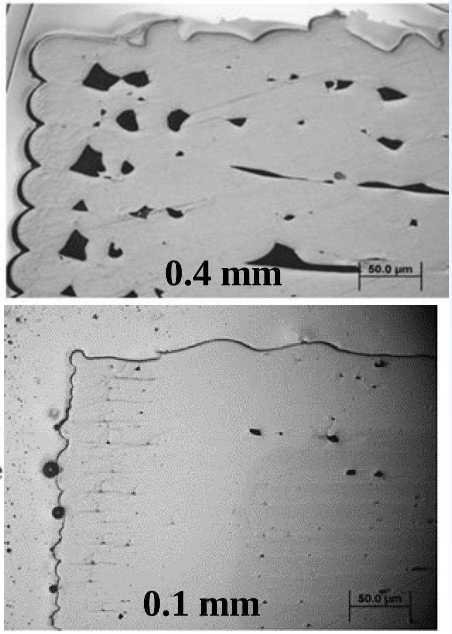
- Tailored, high strength, lightweight support structures
- Tailored facesheets for functional properties, i.e. *wear resistance, vibration dampening, radiation shielding, acoustic attenuation, and thermal management*



Copper filled PLA and bismuth filled ABS




Effect of print layer height

**Highest strength and modulus in CNT reinforced coupons**
**Pure ABS Coupons – less porosity for lower print heights**

# Summary/Conclusions

- Additive manufacturing can offer significant advantages in fabricating preforms, ceramics and CMCs.
- They will have to be selectively applied to “traditional” components but can also enable new applications.
- Good progress in binder jet printing and LOM for fiber reinforced SiC-based ceramics.
- AM and 3-D printing of ceramics has the potential to be game changing.
- New opportunities for multi-functional plastic components and multi-material systems.

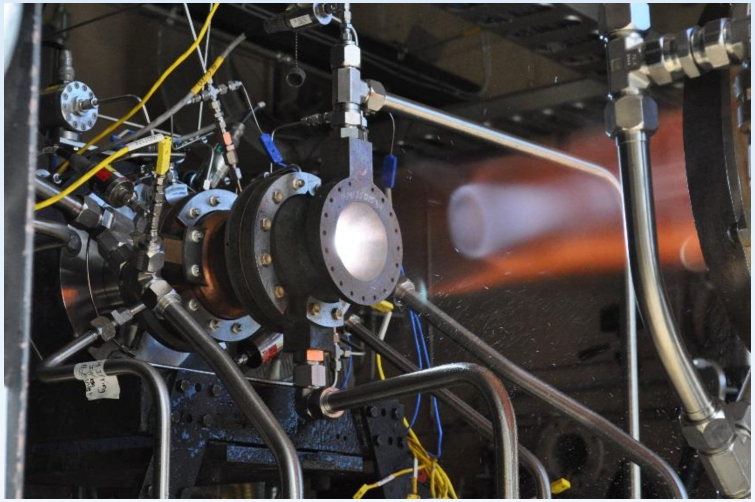
# Materials Testing Capabilities

## NASA GRC Rocket Engine Test Stands for Realistic Extreme Pressure and Temperature Environments

Dr. William Marshall

# 3-D Printed Rocket Engine Parts Withstand Hot-Fire Tests

- NASA and Aerojet Rocketdyne conducted 19 hot-fire tests on four additively manufactured rocket injector and thrust chamber assembly configurations
  - Used copper alloy additive manufacturing (AM) technology
  - Explored various mixture ratios and injector operability points and were deemed fully successful against the planned test program
  - **The work is a major milestone in the development and certification of different materials used in this manufacturing process**



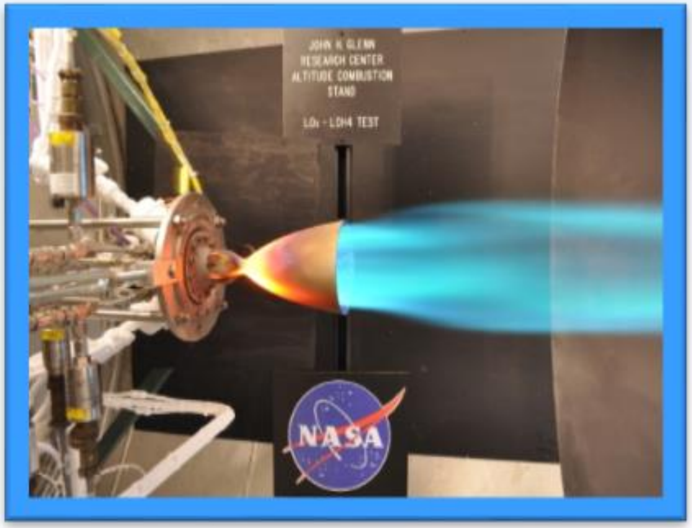
**Significance:**

- First ever hot fire test of an AM copper component
- Potential for improved engine performance and significant cost savings
- **Enables verification of AM component functional requirements, validates AM design tools and paves the way for full scale infusion**

"The successful hot fire test of subscale engine components provides confidence in the additive manufacturing process and paves the way for full scale development"
– Tyler Hickman, NASA

# NASA GRC
# Chemical Propulsion Research Complex

- NASA GRC has several rocket engine test stands to provide a realistic hot-engine environment for testing additively manufactured materials at extreme temperatures and pressures
  - Include sea-level and altitude (100,000 ft.) capable test stands
  - Thrust levels up to 2000 lbf (8.8 kN), Chamber pressures up to 1000 psia (6.9 MPa).
  - Hydrogen, methane, hydrocarbon fuels, and oxygen propellants capability
- For more information: http://facilities.grc.nasa.gov/rcl/index.html or contact Lori Arnett (216.433.2947 or lori.arnett@nasa.gov)

# Questions / Discussion