



# Additive Manufacturing: Ensuring Quality for Spacecraft Applications

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Earth rising above Moon, from LRO Spacecraft

# Abstract

- Reliable manufacturing requires that material properties and fabrication processes be well defined in order to insure that the manufactured parts meet specified requirements. While this issue is now relatively straightforward for traditional processes such as subtractive manufacturing and injection molding, this capability is still evolving for AM products. *Hence, one of the principal challenges within AM is in qualifying and verifying source material properties and process control.* This issue is particularly critical for applications in harsh environments and demanding applications, such as spacecraft.

# Background

- Additive Manufacturing is rapidly developing and, like any such technology, has numerous developmental issues.
- Demanding engineering applications, such as aerospace, have traditionally required higher levels of process control, inspection, standards, qualification test criteria, materials properties knowledge, certification, communication, and related issues.
  - This is driven by tighter design tolerances, need for minimal mass, exposure to severe environments, safety concerns, impact of failures, etc.
- The potential of AM for addressing classic aerospace design issues is well recognized, but significant improvements are needed in a variety of areas.

# Suitability of AM for Aerospace

- **AM offers unrivaled design flexibility.** Parts that are *impractical or impossible* to make with traditional methods are feasible with AM. Complex geometry not an issue.
- **Engineers are challenged to think anew.** A whole new design paradigm.
- With the \$Ms being spent on technology development by industry, **NASA is not going to drive this technology** but needs to make good use of it.
  - Where possible, use what's available as-is
  - **Adapt technology to space environment** and hardware as appropriate

# Suitability, continued

- AM is **ideal for prototyping** and small volume fabrication; fits aerospace environment very well.
  - Easily customizable, much shorter lead times
  - Additive manufacturing not likely to replace existing high volume manufacturing processes (e.g., injection molds)
- The **technology is very rapidly evolving**: in machines, materials, applications, integrated design software, etc.
  - Costs dropping rapidly
- **Developing” standards” is very difficult** due to the rapidly developing technology and immaturity of the industry
  - Proprietary nature of many processes
  - Uniformity and quality of feedstock materials
  - Calibration of equipment
  - Potential QA problem, etc.

# Some Specific Design Concerns

- Tension and compression values
- Strength-to-weight ratio
- Stiffness
- Thermal and electrical conductivity (both high and low values may be desired)
- Porosity (to hold a hard vacuum)
- Outgassing (molecular losses to a hard vacuum)
- Coefficient of thermal expansion and impact on dimensional stability
- Fracture toughness
- Thermo-optical properties
- Coating adhesion
- Bondability
- Etc.

# Selected NASA HQ efforts on AM

- Issues with regard to Process Control, Inspection, Properties of Materials, Standards, Qualification & Certification, etc. are well recognized.
  - NASA/TM-2014-0000 (in draft), “Nondestructive Evaluation Of Additive Manufacturing, State-of-the-Discipline Report”
  - Overwhelming message from recent JANNAF AM for Propulsion Applications TIM was “certification.”
- Per a request from NASA and the Air Force, the US National Research Council\* (NRC) conducted a study on 3D Printing In-Space.
  - Evaluate the feasibility, identify the science and technology gaps, and assess implications
  - Report delivered in September, 2014
  - See: [http://www.nap.edu/download.php?record\\_id=18871](http://www.nap.edu/download.php?record_id=18871)

\*NRC is the operating arm of the National Academy of Sciences and the National Academy of Engineering



# Some Key Conclusions of the NRC Study

- AM has significant potential for space efforts:
  - May reduce logistics and in-space storage by offering the potential to manufacture replacement parts and tools in-space.
  - Potentially enable the in-space manufacturing and construction of large structures and facilities.
- Additive manufacturing presents potential opportunities, both as a tool and as a potential paradigm-changing approach to designing hardware for in-space activities.
- The specific benefits and potential scope of additive manufacturing remains undetermined. Significant technology development needs to be done.
- The International Space Station (ISS) provides an excellent opportunity for both civilian and military research on additive manufacturing technology.
- Targeted investment is needed in areas such as standardization, certification, and infrastructure



# Commercial Movement toward Standards

- SAE International:
  - Recognizing that existing standards and specifications developed for additive metallic materials do not appear to address aerospace requirements for statistically substantiated A and B basis design values.
  - Formed “SAE International Additive Manufacturing Task Group” to address standardization approaches for process dependent metallic materials.
- American Society for Testing and Materials International:
  - Developing Additive Manufacturing Technology Standards in four discipline areas, ten standards released so far:
    - **Design:** (1 standard for AM File format)
    - **Materials:** (6 standards concerned with alloy Ti-6Al-4V, Ti-6Al-4V ELI, UNS N07718, UNS N06625 and powder characterization)
    - **Terminology** for AM (1 standard)
    - **Test Methods:** (2 standards for reporting data, AM-Coordinate Systems and Test Methodologies)

# Representative, NASA-funded, Additive Manufacturing Development Processing-Structure-Property Efforts

## Task Objectives

1. Build Interactions / Effects – ARC/LaRC/MSFC **Objective:** *Understand how basic AM build factors influence part properties.*
2. Powder Influence / Effects – GRC **Objective:** *Understand how basic powder feedstock characteristics influence a part's physical, mechanical, and surface properties.*
3. Thermal Processing / Effects – LaRC/MSFC **Objective:** *a) Understand how standard wrought thermal processes influence AM mechanical properties, and b) explore the potential cost and benefit of AM-specific thermal processing.*
4. Surface Improvement / Effects – MSFC **Objective:** *Understand how as-built and improved AM surface texture influence part performance and fatigue life.*
5. Applied Materials Characterization – GRC/LaRC/MSFC **Objective:** *Enable use of AM parts in severe aerospace environments.*
6. Qualification of AM Critical Components – MSFC **Objective:** *Develop an Agency-wide accepted practice for the qualification of AM processes for aerospace hardware.*



# NASA OCT's "Massless" Exploration Vision

- Mason Peck, NASA Chief Technologist, August 2013 Presentation-

Creating a Space Station from an Asteroid



**NASA/OCT; Long-term Vision of Possibilities**



# Representative AM Technologies at NASA Goddard



# Titanium Tube-in a Tube-in a Tube

GSFC PI: D. Robinson/543

## Objective:

**FY12 flight support:** GSFC's first Additive Manufacturing (AM) part for instrument prototype/possible flight use

## Innovation:

Titanium "tube-in a tube-in a tube" for a cryo thermal switch on ASTRO-H



*"Fabricating this part using conventional methods requires making five different-sized tubes and welding them together," he added. "I'd estimate that it would take about three months to receive this part and I'd expect to pay between \$10,000-\$20,000. But with this new 3D-printing process, the part cost only \$1,200 and took two weeks for the finished part to get into my hands," Robinson said.*



# GSFC's first AM Flight Components

GSFC PI: J. Didion/545

## Objective

- First flight bus system demonstration of 3D printed parts. (FY13)
- Sounding rocket experiment with AM components were flown out of WFF.

## Innovation:

Structural parts to hold batteries, made of PEKK, were **donated** by Oxford Performance Materials (OPM)

## Application:

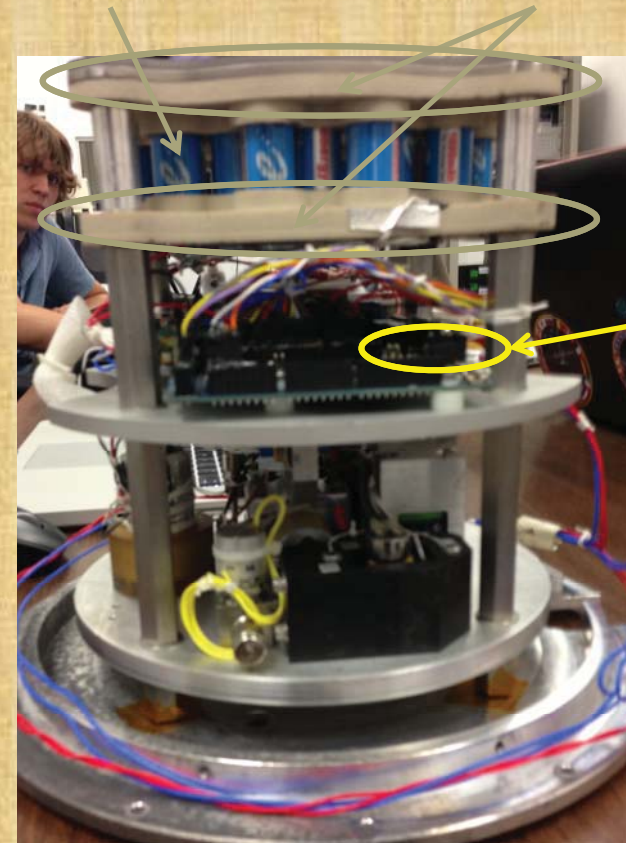
June 2013, in partnership with University of Nebraska **students** who assembled the experiment. GSFC acted as program manager and provided a technology experiment, Jeff Didion's electro-hydrodynamic (EHD) fluid pump for thermal control.



Batteries in blue

Battery case to power EHD thermal control experiment

AM parts in tan color



EHD Experiment



# Miniaturizing Telescopes through 3D Printing

GSFC PI: J. Budinoff/544

## Objectives:

Utilize new Direct Metal Laser Sintering (DMLS) to produce dimensionally stable integrated instrument structures at lower cost

- Demonstration of DMSL fabrication of integrated metallic telescope and optical benches
- Demonstration of hybrid composite/DMLS metallic/glass instrument structures

## Innovation:

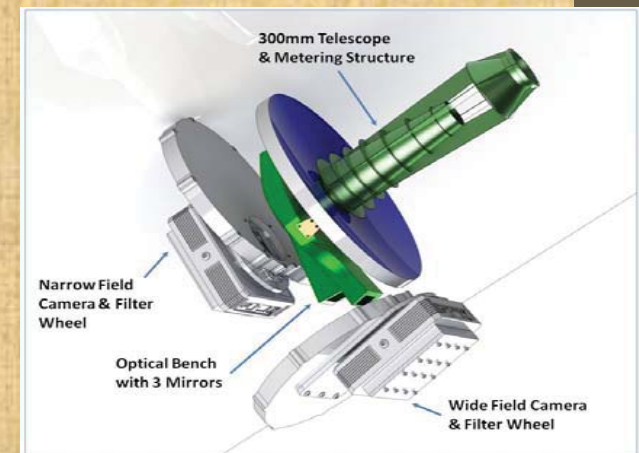
Creating thin-walled structures in flight instruments is a challenge when using this technique. Build direction, post build heat treatments, and machined removal of build support structures are engineering challenges which must be overcome so future flight programs will avoid these costs.

## Applications:

Small Space flight Optics and Telescopes



CubeSat-class 50-mm (2") imaging camera/instrument - mirrors and integrated optical-mechanical structures- manufacturing with 3D-printed parts



0.3m Telescope via DMLS



# Super-black Nanotechnology Coating

GSFC PI: J. Hagopian/551

## Objective:

Desire Spacecraft instruments more sensitive without enlarging their size. Demonstrated growth of a uniform layer of carbon nanotubes through the use of Atomic Layer Deposition.

## Innovation:

Marriage of the two technologies allows NASA to grow nanotubes on 3-D components, such as complex baffles and tubes commonly used in optical instruments

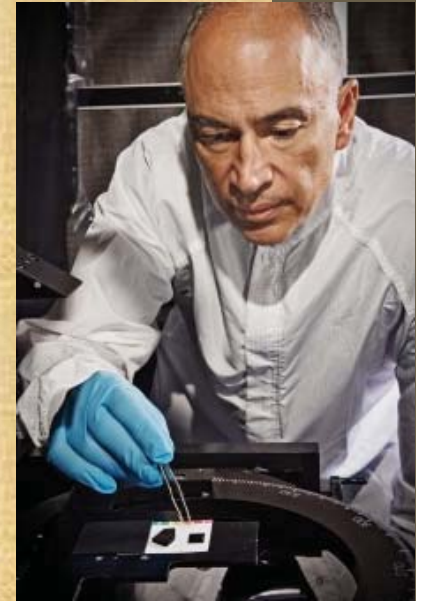
## Applications:

- Cubesats, a class of less-expensive tiny satellites called reduce the cost of space –science- missions.
- Suppression of stray light that can overwhelm faint signals that sensitive detectors are supposed to retrieve

Carbon-nanotube coating is one of the materials to be tested on the International Space Station as part of the Materials Coating Experiment. The super-black material occupies the “D” slot on the sample tray.



Robotic Refueling Mission-Phase 2 task board that will be installed on the orbital outpost's Express Logistics Carrier 4. The Materials Coating Experiment can be seen on the left.



J. Hagopian works with a nanotube material sample





# AM for Stable Light-weight Small Structures

GSFC PI: T. Stephenson/541

## Objectives:

Develop new alloys and apply advanced manufacturing techniques to improve dimensional stability and lower mass. We have four efforts using the Fe-Ni binary system as a model:

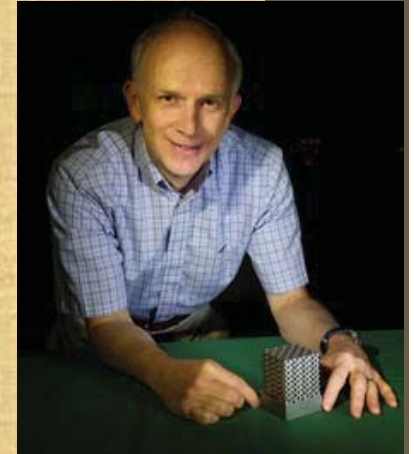
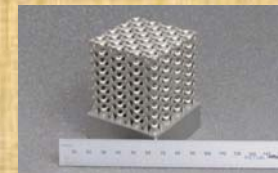
- Invar<sup>®</sup> Metal Matrix Composites
- Engineered structures based on the AM paradigm
- Tailored composition for microstrain (CTE) matching
- Combined approached for hybrid structures

## Innovation:

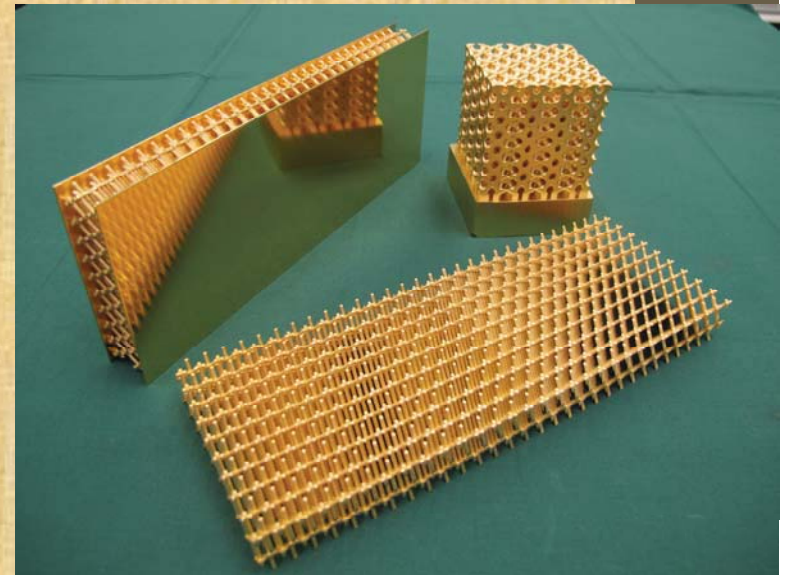
Never-before-attempted manufacturing techniques with new alloy compositions for proof-of-concept novel structures. The innovation resides in coupling these 2 approaches to make hybrid, compositionally graded structures.

## Applications:

Ensures stable, lighter weight structures for optical benches, precision optics and sensors for all future missions



The **first** Invar<sup>®</sup> structure ever produced by DMLS, and the GRID 45 structure had been fabricated from metal . (GSFC FY13 IRAD)





# Australian and GSFC - ALD to the Rescue

GSFC PI: V.Dwivedi/545

## Objective:

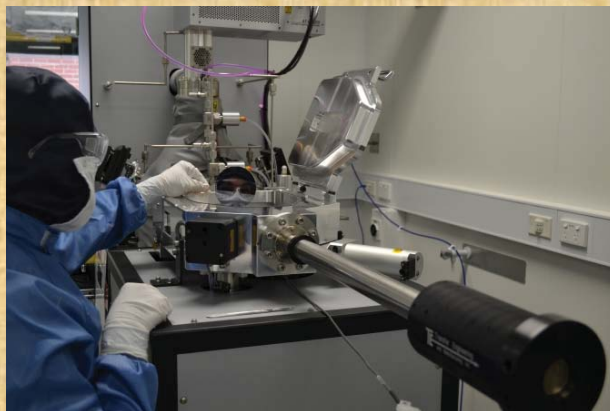
Atomic Layer Deposition (ALD) is one of many techniques for applying thin films. Australia Melbourne Centre for Nanofabrication (MCN) fine-tuned the recipe for laying down the catalyst layer (detailing the precursor gas, the reactor temperature and pressure) needed to deposit a uniform foundation.

## Innovation:

Technicians can accurately control the thickness and composition of the deposited films, even deep inside pores and cavities thus the unique ability to coat in and around 3D objects.

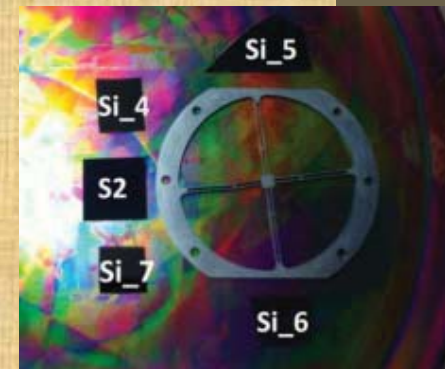
## Application:

GSFC and UMD are now advancing ALD reactor technology customized for spaceflight applications. GSFC has successfully grown carbon nanotubes on the samples provided to MCN. They demonstrate properties very similar to those grown using other techniques. Our ultimate goal of applying a carbon-nanotube coating to complex instrument parts is nearly realized.



Lachlan Hyde, an ALD expert at Australia's MCN, works with one of the organization's two ALD systems (left)

Australia's MCN applied a catalyst layer using atomic layer deposition to this occulter mask. (right)





# Efficient Radiation Shielding Through Direct Metal Laser Sintering

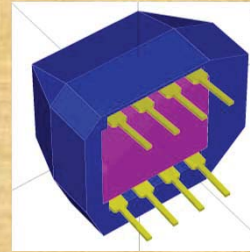
GSFC PI: Lauenstein/561

## Objectives:

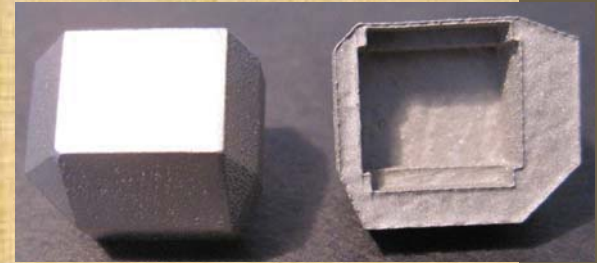
Develop a method for mitigating risk due to total ionizing dose (TID) using direct metal laser sintering (DMLS) and the commercially-available Monte-Carlo particle transport code, NOVICE, to enable otherwise difficult to fabricate, component-level radiation shielding. Reduces infusion risk of new electronics technologies through effective mitigation of TID exposure risks

## Innovation:

This technology provides a mass- and cost-efficient method for mitigating risk due to TID through use of the NOVICE code to optimize shield designs for individual package types. It also creates CAD files directly importable to DMLS 3-D printers. Adhesion methods of the shields are also developed.



Clockwise from above: NOVICE-generated image of Inconel-625 shield on CERDIP 8-lead package; DMLS printed shield; Inconel-625 and CoCr shields covering op-amps mounted on PCB.



## Application / Mission:

- Long-duration missions (e.g. GOES, TDRS programs)
- Harsh radiation environment missions such as the radiation belts of Earth and Jupiter (e.g. Europa Clipper)
- Small-satellite initiatives offering minimal collateral shielding



# Budding Nanodetectors: Partnership with NEU and GSFC

GSFC PI: M. Sultana/553

## Objective:

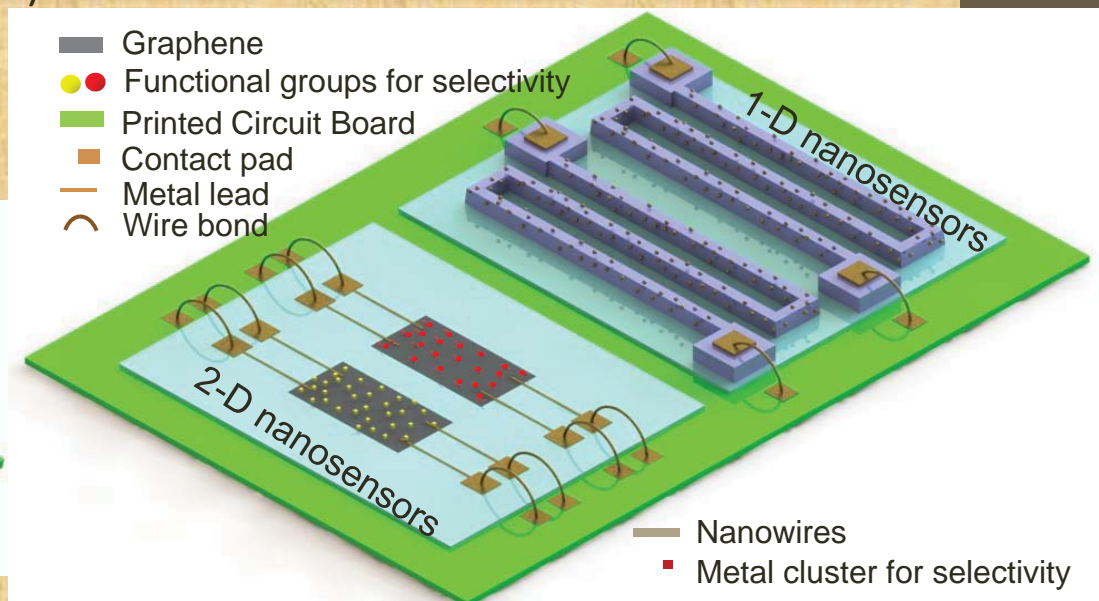
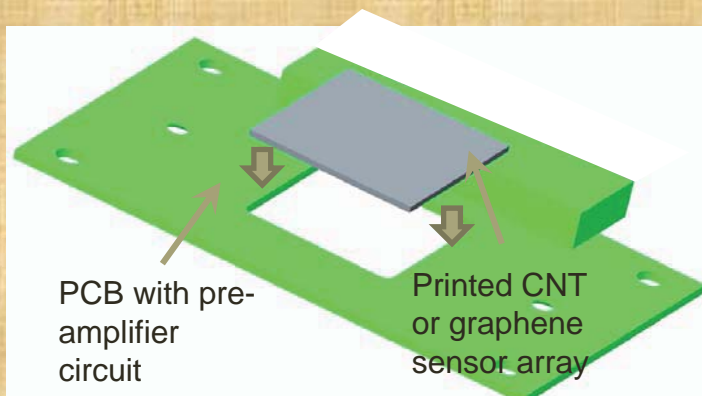
To print out nanosensors and their leads using 3-D printing techniques on a daughter board that can be connected to a self-contained pre-amp PCB.

## Innovation:

Will significantly increase the signal, and thus the sensitivity, and enable the detection of minute concentration of gases (e.g. ppb level or possibly single molecule, which is unprecedented)

## Applications:

Planetary & Earth science, DOE





# Promising 3D Printing Application in Electronics

## Objective:

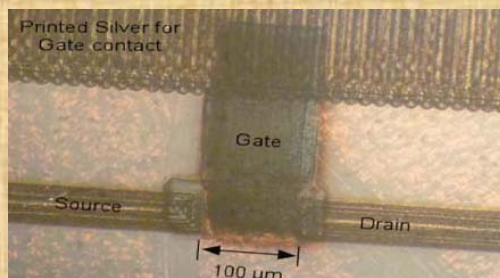
Demonstrate 3D manufacturing of various circuit building blocks, including Crossovers, Resistors, Capacitors, Chip Attachment, Power Sources, and detector strips; and evaluate abilities and limitations of these demonstrations.

## Innovation:

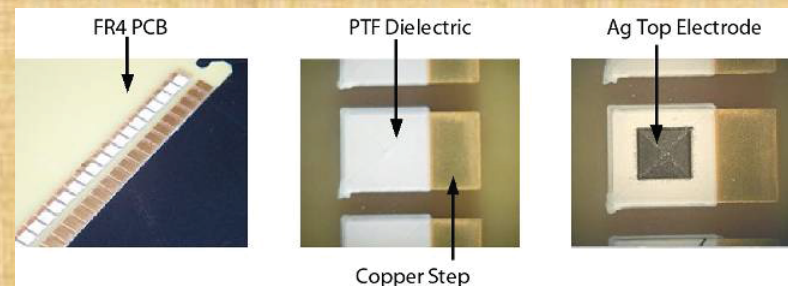
Optomec's aerosol jet thin-film conformal printing process can print a broad spectrum of conformal functional circuitry, including sensors, EMI shielding, antennas, and a variety of active and passive components, and COTS attachment technology.

## Application:

GSFC is evaluating the viability of aerosol jet printing technology for electronics and detector applications. Potential applications include printed wiring board fabrication, chip-on-board attachment, microshutter array assemblies, millimeter wave circuitry, and high-sensitivity detector strips.



Printed CNT thin film transistors (Optomec)



Multi-layer deposition, Polyimide dielectric and Ag deposited onto Cu pads to make a simple capacitor



# Other NASA Centers

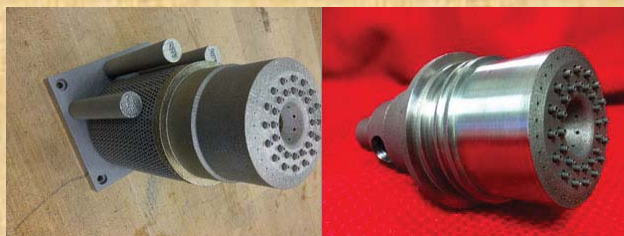
- JSC - 3D printer for ISS application/demonstration. Launch in FY14. FDM machine: deposits plastic via a wire feed through an extruder head. Previously tested during 2011 in microgravity environments on suborbital flights.



- GRC - Titanium DSLM header for rocket engine



- MSFC – injector for rocket engine. Planned for SLS application.



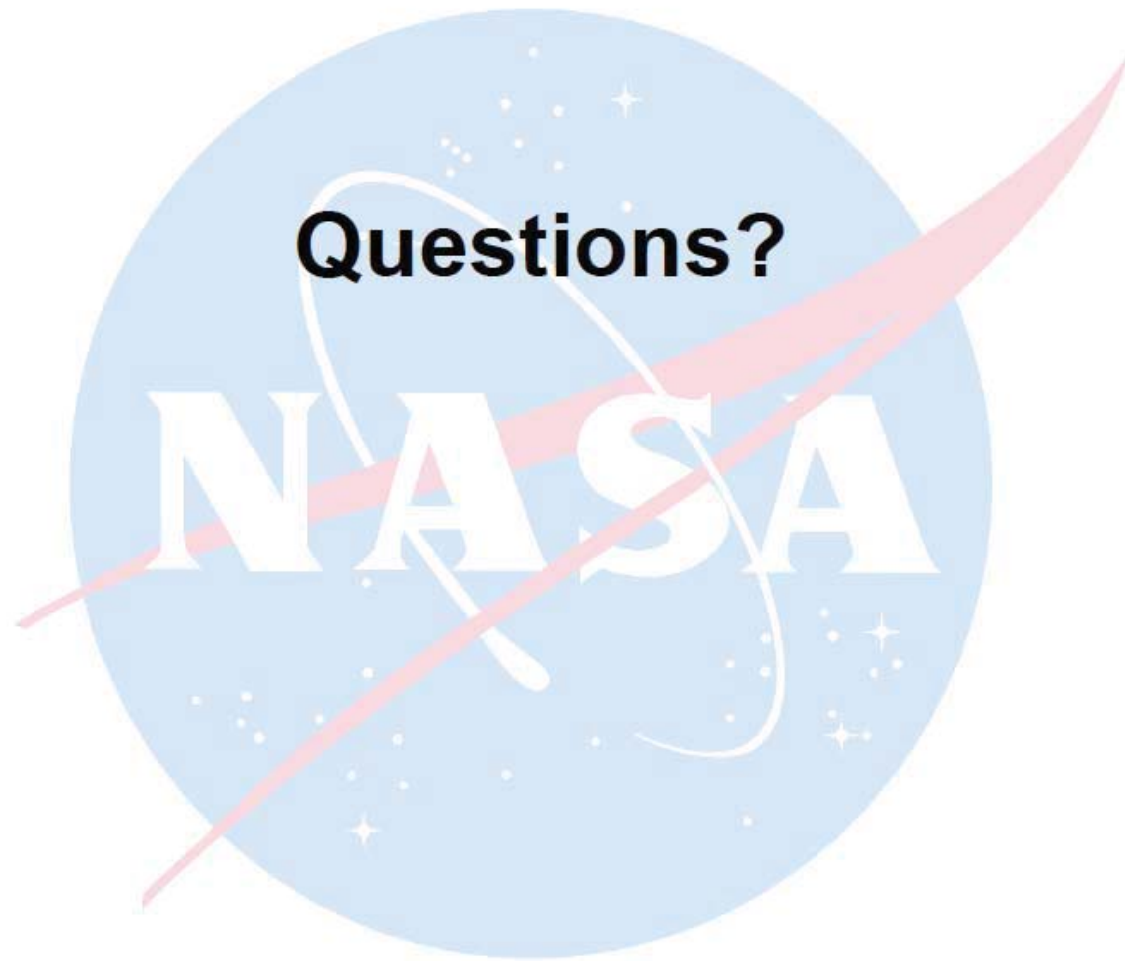
*Left: 3-D printed rocket injector as it looked immediately after it was removed from the selected laser melting printer. Right: Injector after inspection and polishing.*



Injector Testing

# Summary

- Standardization, certification, and infrastructure are widely perceived as key areas needing development.
  - This issue is particularly important for demanding applications such as aerospace.
  - Investments here should be strategic, complement industry lead efforts, and focus on information-sharing.
- Aerospace applications, with its low-volume production, need for custom designs with rapid turn-around, integrated components, and a focus on low mass and high performance, are well suited for AM technology
- Goddard and other NASA Centers are pursuing a wide variety of AM technologies, focusing on both “for space” and “in space” applications



**Questions?**

**NASA**