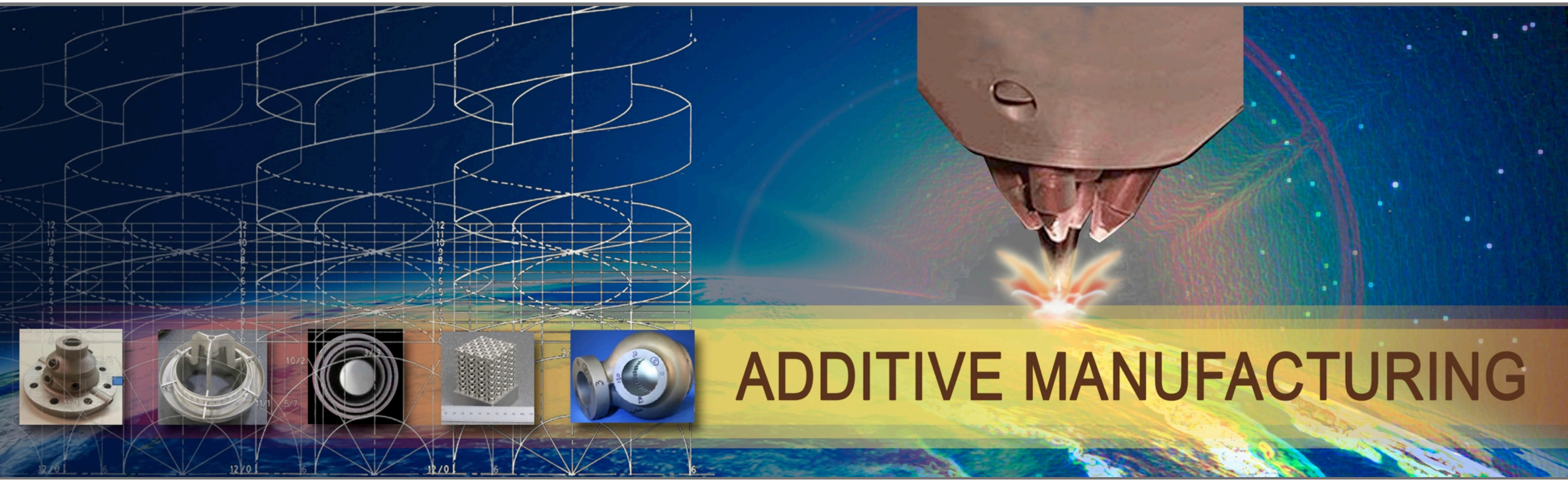


9th AIRTEC 2014 International Congress
Frankfurt/Main, Germany • October 28-30, 2014

Overview of NASA Initiatives in 3D Printing and Additive Manufacturing

R. G. Clinton, Jr.
Deputy Manager, Science & Technology Office
Marshall Space Flight Center

Agenda

- NASA Headquarters Structure and Sponsorship
- Aeronautics Applications
- "FOR Space" Additive Manufacturing
- "IN Space" Additive Manufacturing
  - National Research Council Committee on Space-Based Additive Manufacturing (COSBAM) Report Synopsis
  - Initiatives
- Cross-Cutting Activities
- Summary

Acknowledgements

Ames Research Center – Jessica Koehne

Glenn Research Center – Michael Meyer, Bob Carter

Goddard Space Flight Center – Peter Hughes, Aprille Ericsson

Jet Propulsion Laboratory – Kendra Short

Johnson Space Center – Michael Waid

Kennedy Space Center – Jack Fox

Langley Research Center – Karen Taminger

Marshall Space Flight Center – Frank Ledbetter, Kristin Morgan, Niki Werkheiser, Janet Salverson

National Research Council COSBAM – Dwayne Day, Betsy Cantwell

University of Southern California – Berok Khoshnevis

NASA Structure Related to Additive Manufacturing

- **Administrator**
- **Deputy Administrator**
- **Associate Administrator**
  - Chief of Staff
  - Associate Deputy Administrator
  - Associate Deputy Administrator for Strategy and Policy
  - Assistant Associate Administrator

- Office of Safety and Mission Assurance (OSMA)
- Aeronautics Research Mission Directorate
- Science Mission Directorate
- Human Exploration and Operations Mission Directorate
  - Exploration Systems Development Division
  - International Space Station Division
  - Advanced Exploration Systems Division
- Space Technology Mission Directorate
  - Game Changing Development
  - Flight Opportunities
  - SBIR/STTR
  - Space Technology Research Grants (STRG)
  - NIAC/CIF

Centers

- Ames Research Center
- Armstrong Flight Research Center
- Glenn Research Center
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Johnson Space Center
- Kennedy Space Center
- Langley Research Center
- Marshall Space Flight Center
- Stennis Space Center

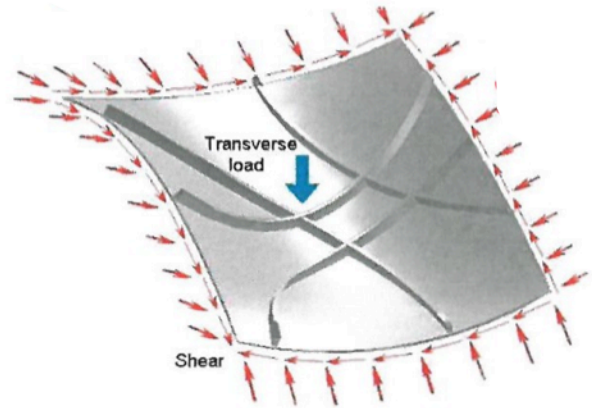
Legend

- Multiple R&D Activities (green): Glenn Research Center, Goddard Space Flight Center, Johnson Space Center, Kennedy Space Center, Langley Research Center, Marshall Space Flight Center
- Printed Electronics Primary Focus (blue): Ames Research Center, Jet Propulsion Laboratory
- Limited Activities (white): Armstrong Flight Research Center, Stennis Space Center

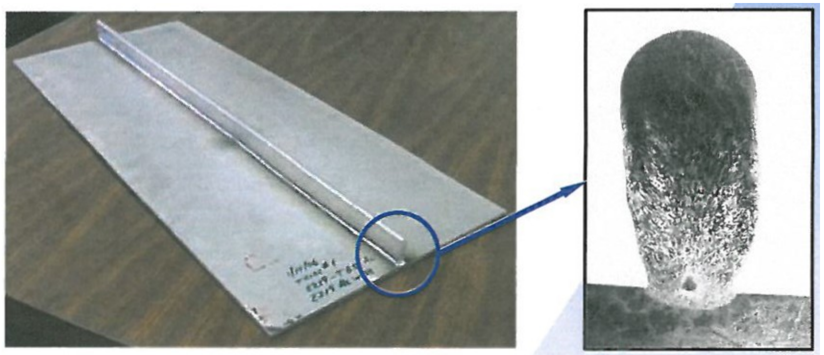
Aeronautics Applications

AM for Aeronautics at Langley Research Center: Structures

- Engineered materials coupled with tailored structural design enable reduced weight and improved performance for future aircraft fuselage and wing structures
- Multi-objective optimization:
  - Structural load path
  - Acoustic transmission
  - Durability and damage tolerance
  - Minimum weight
  - Materials functionally graded to satisfy local design constraints
- Additive manufacturing using new alloys enables unitized structure with functionally graded, curved stiffeners
- Weight reduction by combined tailoring structural design and designer materials



Design optimization tools integrate curvilinear stiffener and functionally graded elements into structural design



High toughness alloy at stiffener base for damage tolerance, transitioning to metal matrix composite for increased stiffness and acoustic damping

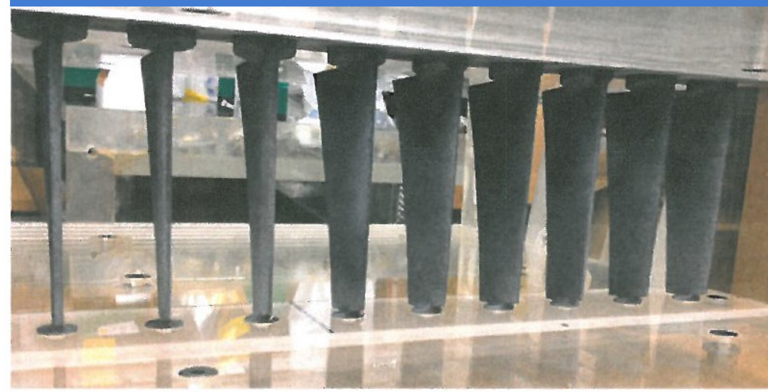
POC: *Karen.M.Taminger@nasa.gov*

AM for Aeronautics at Glenn Research Center: Propulsion

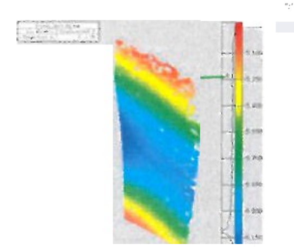
- Objective: Conduct the first comprehensive evaluation of emerging materials and manufacturing technologies that will enable fully non-metallic gas turbine engines.
- Assess the feasibility of using additive manufacturing technologies to fabricate gas turbine engine components from polymer and Ceramic matrix composites.
  - Fabricate prototype components and test 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
- Focusing on high temperature and fiber reinforced polymer composites fabricated using FDM, and fundamental development of high temperature ceramics / CMC's using binder jet process

NASA GRC POC: Joseph Grady

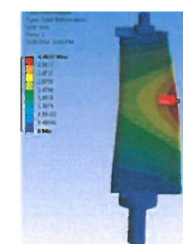
A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing



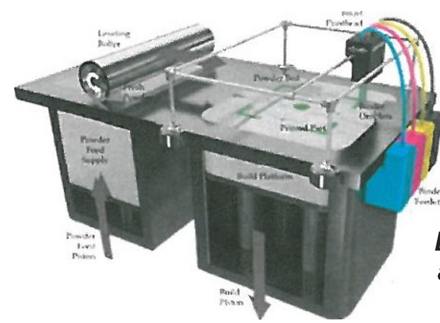
Polymer Vane Configuration in Cascade wind tunnel Rig



Digital Image CorrelationMeasurements



Finite Element Analysis

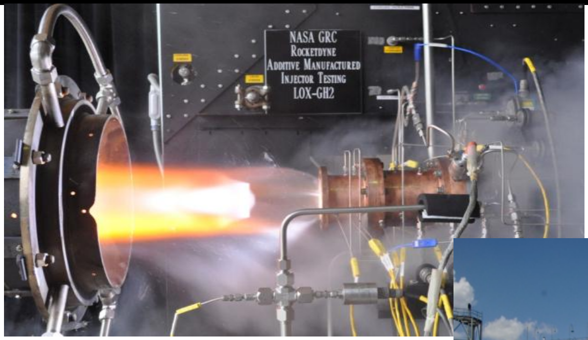


Binder jet process was adapted for SiC fabrication

“FOR Space” Additive Manufacturing

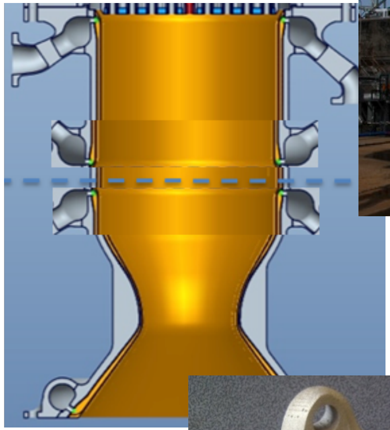
FOR Space Applications: Rocket Propulsion

- GRC and Aerojet Rocketdyne tested an additively manufactured injector in 2013 under the Manufacturing Innovation Project (MIP) and Advanced Manufacturing Technologies (AMT) Project.
- MSFC successfully tested two complex injectors printed with additive manufacturing August 2014
- GRC, LaRC, and MSFC Team building on success of MIP and AMT projects to develop and hot fire test additively manufactured thrust chamber assembly
  - Copper combustion chamber and nozzle produced via Selective Laser Melting (SLM)
  - Grade from copper to nickel for structural jacket and manifolds via EBF^3
- RL10 Additive Manufacturing Study (RAMS) task order between GRC and Aerojet-Rocketdyne sponsored by USAF.
  - Related activity - Generate materials characterization database on additively manufactured (AM) Ti-6Al-4V to facilitate the design and implementation of an AM gimbal cone for the RL10 rocket engine.
- GRC, AFRL, MSFC Additive Manufacturing of Hybrid Turbomachinery Disk:



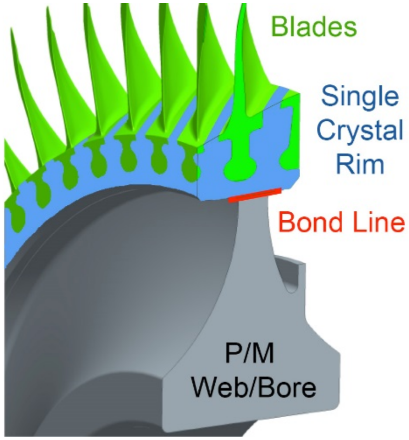
GRC and Aerojet Rocketdyne test

MSFC AM engine test



CAD sketch of rocket nozzle

Full Scale from ORNL



Hybrid Disk Concept

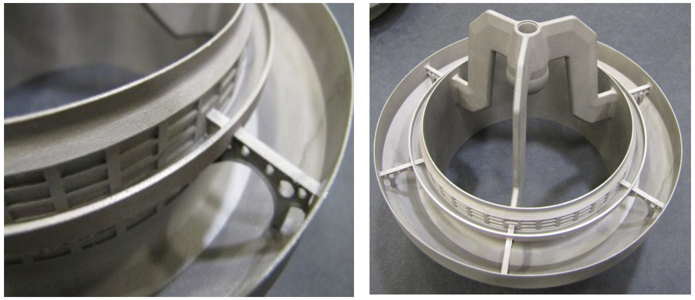
FOR Space Applications: Rocket Propulsion (concluded)

- Powder Bed Fusion (PBF) technologies enable rapid manufacturing of complex, high-value propulsion components.
- Flexibility inherent in the AM technologies increases design freedom; enables complex geometries. Designers can explore lightweight structures; integrate functionality; customize parts to specific applications and environments.
- Goal: reduce part count, welds, machining operations → reduce $ and time

J-2X Gas Generator Duct

Pogo Z-Baffle

Turbopump Inducer



RS-25 Flex Joint

Part	Cost Savings	Time Savings
J-2X Gas Generator Duct	70%	50%
Pogo Z-Baffle	64%	75%
Turbopump Inducer	50%	80%

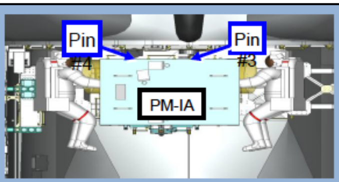
RS-25 Flex Joint	Heritage Design	SLM Design
Part Count	45	17
# Welds	70+	26
Machining Operations	~147	~57

FOR Space Applications: Environmental Control and Life Support Systems and ISS Tools

- AM techniques can create extremely fine internal geometries that are difficult to achieve with subtractive manufacturing methods.

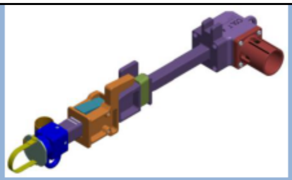
ISS Urine Processor Assembly

Air Filter/ Scrubbers

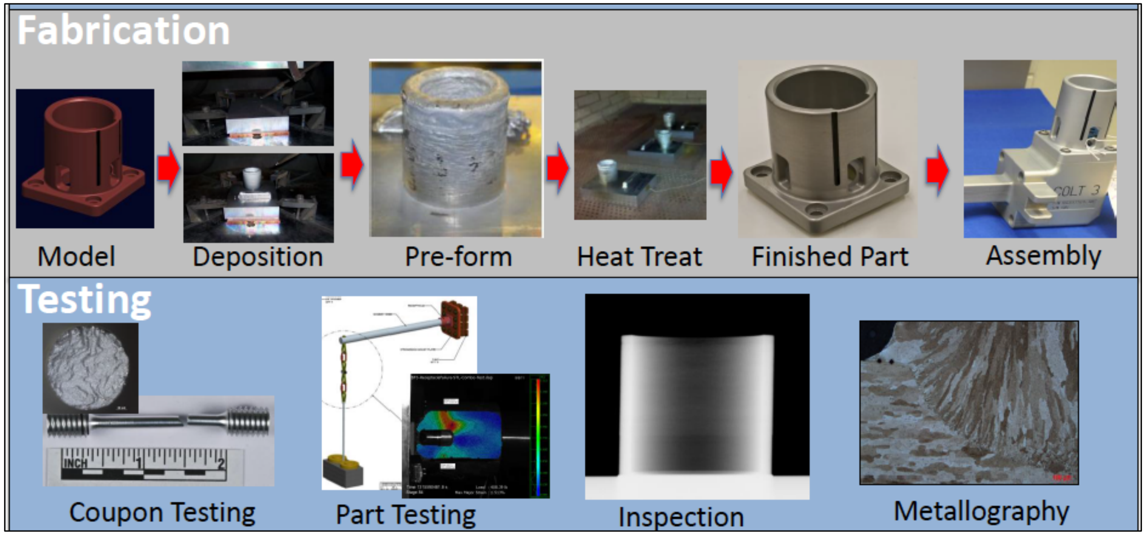


STS-135 Pump Module Return

ISS EVA Tool Fabrication & Certification Demo



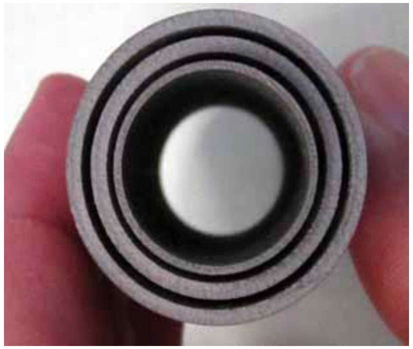
COLT EVA Contingency Tool



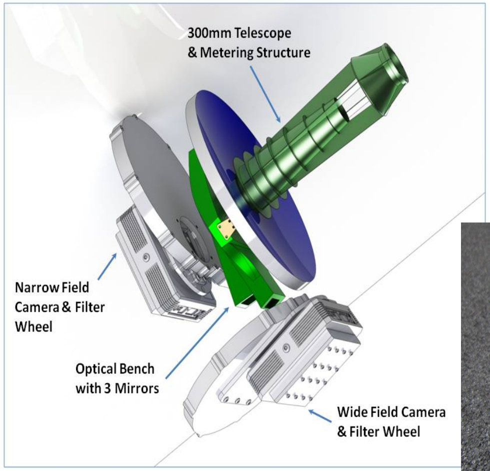
- ISS Tool Design for Manufacturability and Processing
- Structural Integrity Verification
  - Material Properties
  - Non-destructive Evaluation
  - Structural Analysis and Testing

FOR Space: Spacecraft Instruments and Components – Goddard Space Flight Center

- GSFC's first Additive Manufacturing (AM) part for instrument prototype/possible flight use (FY12) - Titanium tube - in a tube – in a tube for cryo thermal switch for ASTRO-H
- First to fly AM component in space (FY13) – battery case on suborbital sounding rocket mission
- Miniaturizing telescopes: Utilize new Direct Metal Laser Sintering (DMLS) to produce dimensionally stable integrated instrument structures at lower cost
- Unitary core-and-face-sheet optical bench material
  - Features tailored alloy composition to achieve desired coefficient of thermal expansion
- Efficient radiation shielding through Direct Metal Laser Sintering:
  - 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 shielding

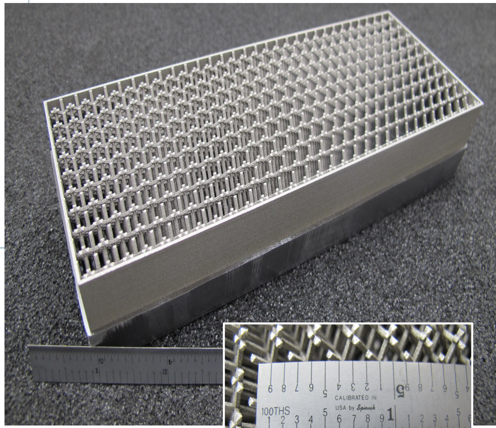


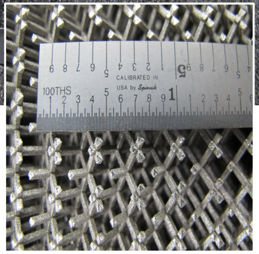
Battery Case

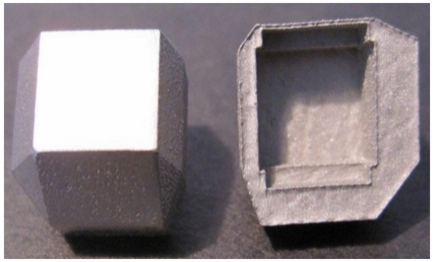


0.3m Telescope via DMLS

Optical bench core material sample



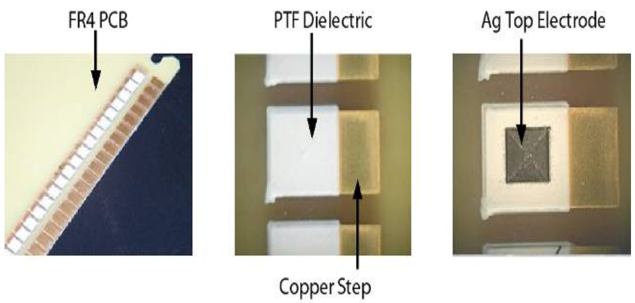


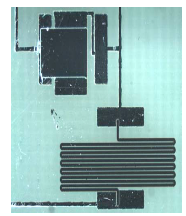


DMLS printed shield

FOR Space: Spacecraft Electronics, Sensors and Coatings – Goddard Space Flight Center

- Aerosol jet printing of various circuit building blocks: crossovers, resistors, capacitors, chip attachments, EMI shielding.





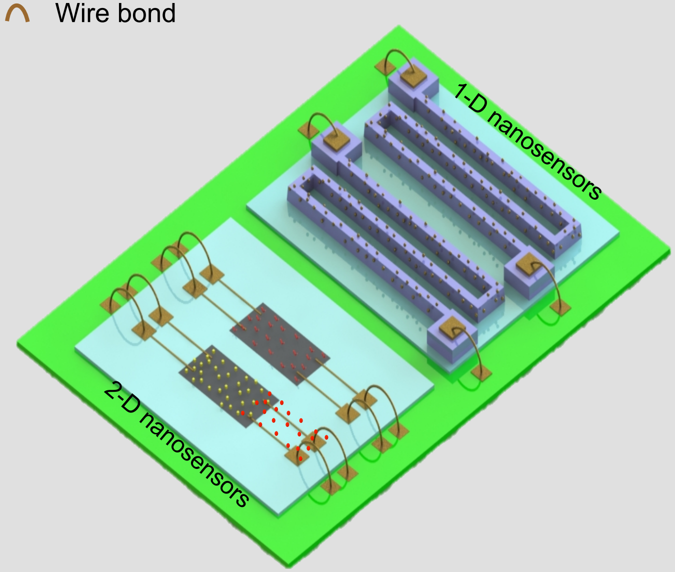
Printed RC filter

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

- Nanosensors printed directly on a daughter board for chemical detection
- Super-black nanotechnology coating: Enable Spacecraft instruments to be more sensitive without enlarging their size. Demonstrated growth of a uniform layer of carbon nanotubes through the use of Atomic Layer Deposition.

Printed Nanosensor

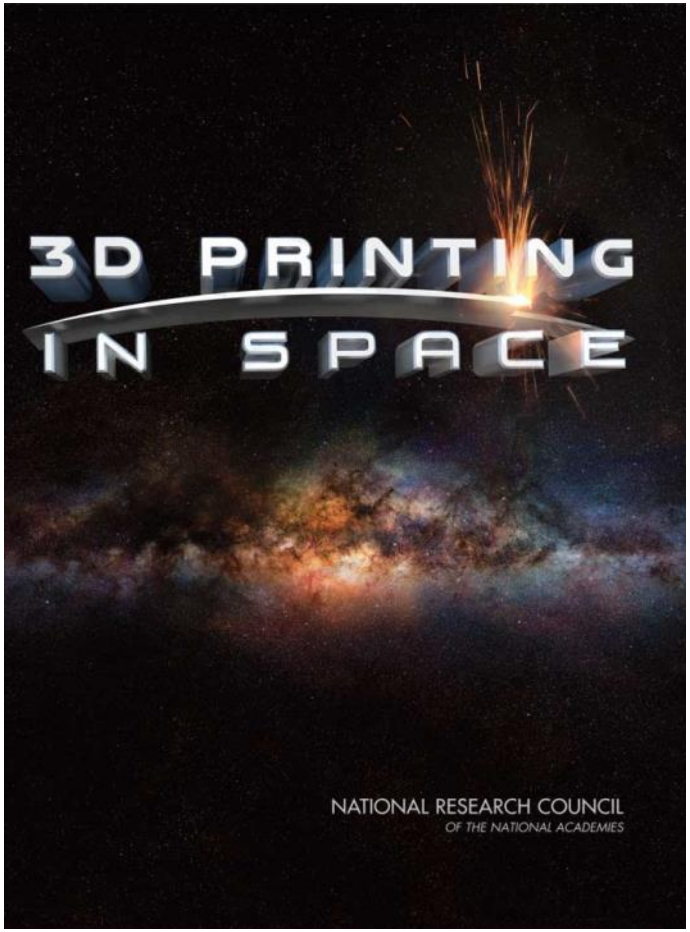
- Graphene
- Functional groups for selectivity
- Printed Circuit Board
- Contact pad
- Metal lead
- Wire bond
- Nanowires
- Metal cluster for selectivity



“IN Space” Additive Manufacturing

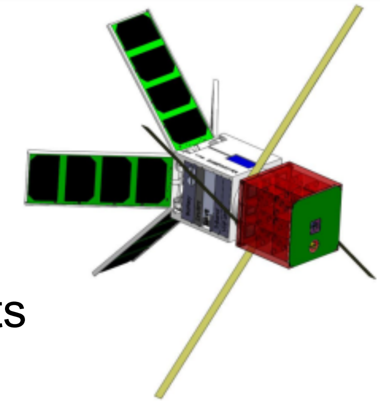
National Research Council Committee on Space-Based Additive Manufacturing of Space Hardware – Task Summary

- The Air Force Space Command, the Air Force Research Laboratory Space Vehicles Directorate, the NASA Office of the Chief Technologist and the Space Technology Mission Directorate requested the US National Research Council (NRC) to
  - Evaluate the feasibility of the concept of space-based additive manufacturing of space hardware
  - Identify the science and technology gaps
  - Assess the implications of a space-based additive manufacturing capability
  - Report delivered in July
  - Printed in September

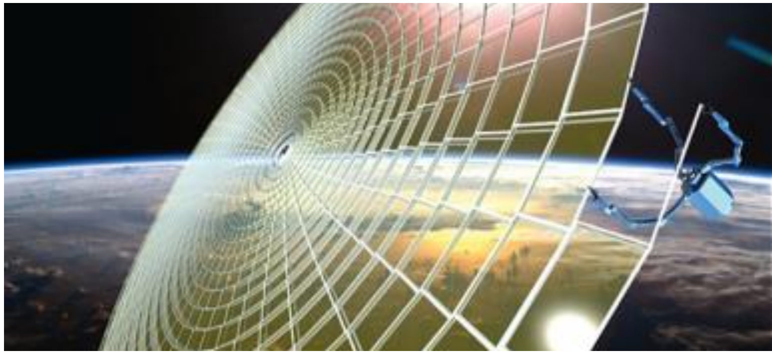


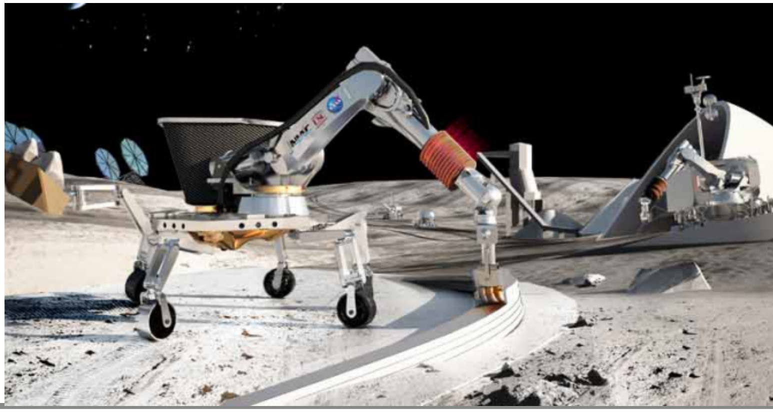
NRC Report: http://www.nap.edu/download.php?record_id=18871

NRC Report: The Promise (of In Space Manufacturing)



- Manufacturing components
- Recycling
- Creating sensors or entire satellites
- Creating Structures Difficult To Manufacture On Earth Or Launch
- Using resources on off-Earth surfaces





NRC Report: Summary Findings (10 Findings in 5 Categories)

- **Additive manufacturing in space has great potential.** Space system configurations that are currently dominated by requirements to survive ground manufacturing, assembly, test, transport, and launch could be reexamined as AM capability becomes available, and *additive manufacturing might provide the means to transform space architectures*.

However, there are many technological and regulatory hurdles before such a vision could be achieved.

- **Terrestrial challenges remain unresolved.** Before moving additive manufacturing technology to the space environment, further development in several fundamental areas needs to be complete and well understood. These areas represent barriers to a wider use, even in a ground-based environment, and *preclude additive manufacturing techniques moving immediately to a space-based environment*.
- **Space related challenges magnify terrestrial ones.** The space environment (zero gravity, vacuum) poses additional constraints, and additive manufacturing is even more of a systems engineering and industrial logistics problem compared to additive manufacturing on the ground.
- **Technology not implementable without supporting infrastructure.** Supporting infrastructure and environment which are relatively straightforward and easy considerations on the ground (i.e. rent factory space, connect to the local power grid) are not simple for space - issues such as supply chain logistics, integrated processes, minimal human interaction, and quality control are more pronounced.

NRC Report: Summary Recommendations for Air Force and NASA

- **Analysis**. Agencies need to do systems *and* cost benefit analyses (CBA) related to the value of AM in space. The analyses should not focus just on how AM could replace traditional manufacturing but how it can enable entirely new structures and functionalities that were not possible before. A specific area where a CBA would be helpful is in the manufacture of smaller satellites on the ISS.
- **Investment**. Targeted investment is needed in areas such as standardization and certification, and infrastructure. The investment should be strategic, and use workshops and other information-sharing forums to develop roadmaps with short and long-term targets.
- **Platforms**. Given the short life of the ISS, agencies should leverage it to the extent feasible to test AM and AM parts.
- **Cooperation, coordination and collaboration**. Instead of stove-piped parallel development in multiple institutional settings, it is critical that there be cooperation, coordination and collaboration within and across agencies, sectors, and nations. It would be useful to develop working groups, conferences and leverage existing efforts such as the *America Makes*.
- **Education and training**. Agencies need to develop capabilities related to relevant fields such as material science and others that would be important for the development of the field of AM.

NASA IN Space Manufacturing Technology Development Vision

Science & Technology Office

Earth-based

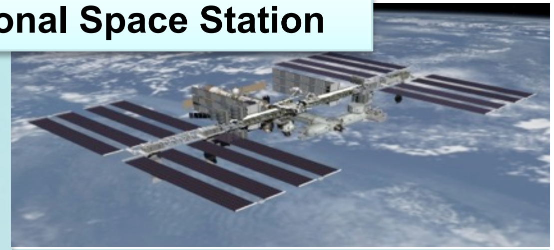
Pre-2012

Ground & Parabolic centric:

- Multiple FDM Zero-G parabolic flights
- Trade/System Studies for Metals
- Ground-based Printable Electronics/Spacecraft
- Verification & Certification Processes under development
- Materials Database
- Cubesat Design & Development

International Space Station

3D Print Tech Demo



Metal Printing

Optical Scanner

Printable Electronics

SmallSats

Recycler

Add Mfg. Ctr. Facility

Self-repair/ replicate

2014

- **POC 3D Print: First Plastic Printer on ISS Tech Demo**
- **NIAC Contour Crafting**
- **NIAC Printable Spacecraft**
- **Small Sat in a Day**
- **NRC Study**
- **Center In-house work in additive, SynBio, ISRU, robotics**

2015

- Next Generation 3DPrint
- Print-a-Sat: First cubesat printed in space
- Recycler Demo: recycle printed plastic part back into feedstock
- Metal Demo
- ISS Printed Part Utilization Catalogue

2016 2017 2018

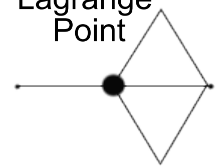
ISS: *Utilization/ Facility Focus*

- Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
- Printable Electronics Tech Demo
- Synthetic Bio Demo
- SmallSat Build & Deploy

Exploration

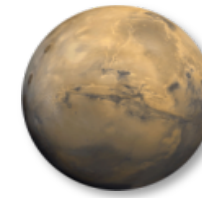
Asteroids

Lagrange Point



Lunar

Mars



2020-25

Lunar, Lagrange FabLabs

- Initial Robotic/ Remote Missions
- Provision some feedstock
- Evolve to utilizing in situ materials (natural resources, synthetic biology)
- Product: Ability to produce multiple spares, parts, tools, etc. “living off the land”
- Autonomous final milling to specification

2025

Planetary Surfaces Points Fab

- Transport vehicle and sites would need Fab capability
- Additive Construction

2030 - 40

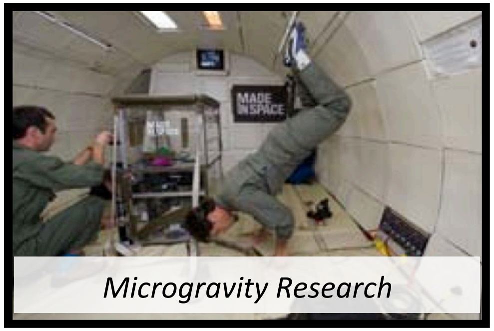
Mars Multi-Material Fab Lab

- Utilize in situ resources for feedstock
- Build various items from multiple types of materials (metal, plastic, composite, ceramic, etc.)
- Product: Fab Lab providing self-sustainment at remote destination

Meets objectives of Agency Decadal Survey AP10 and STMD Technology Areas 7 and 12

ISS Technology Demonstrations are Key in ‘Bridging’ Technology Development to Full Implementation of this Critical Exploration Technology.

IN Space Manufacturing: ISS Tech Demo – 3D Print

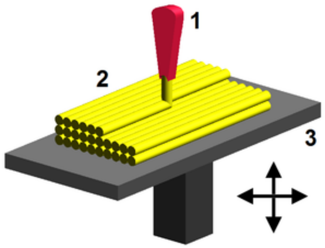


Microgravity Research

3D Print Ground Testing

Potential Mission Accessories

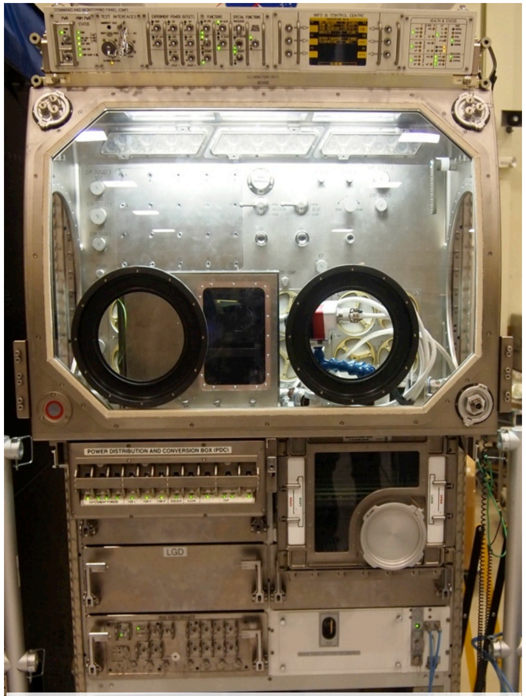
The first 3D Printer in space was delivered to the ISS on SpaceX-4 and will investigate the effects of consistent microgravity on melt deposition additive manufacturing by printing parts in space.



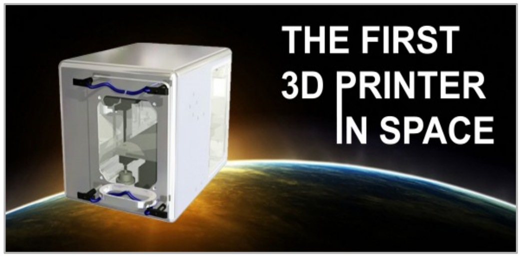
Melt deposition modeling:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table

3D Print Specifications

Dimensions	33 cm x 30 cm x 36 cm
Print Volume	6 cm x 12 cm x 6 cm
Mass	20 kg (w/out packing material or spares)
Est. Accuracy	95 %
Resolution	.35 mm
Maximum Power	176W (draw from MSG)
Software	MIS SliceR
Traverse	Linear Guide Rail
Feedstock	ABS Plastic

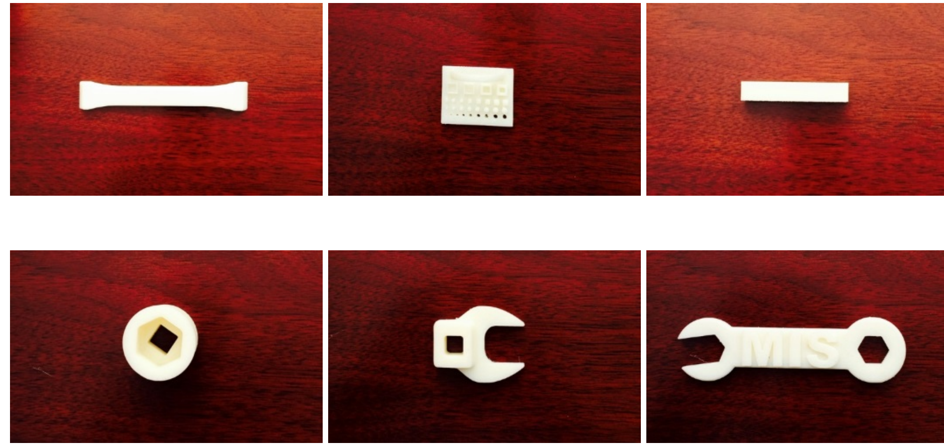


3D Print in Micro-G Science Glovebox (MSG)

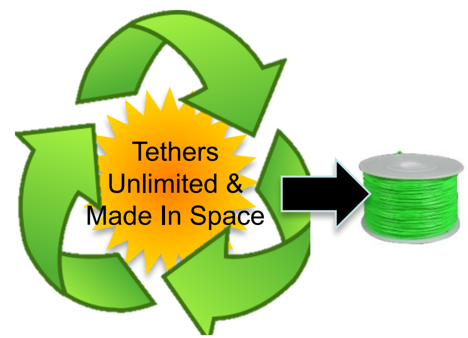


IN Space Manufacturing (ISM) Activities

- **3D Printing in Zero-G Continuation:**
  - MSFC analyses of Flight Parts compared to ground samples, publish results
- **Utilization Catalogue Development**
  - MSFC/JSC working with ISS IVA Tools and Operations Support Offices to define, first AM Parts for In-space Utilization
- **ISS Scanner/In-space Verification & Validation**
  - Made in Space, Inc.: provides CoTS Scanner for ISS Flight
- **In-space Materials Characterization Database**
  - MSFC Foundation for In-space utilization, analyses, testing, & verification
- **Recycler Tech Demo**
  - Two Phase I SBIRs awarded which will be completed early FY15.



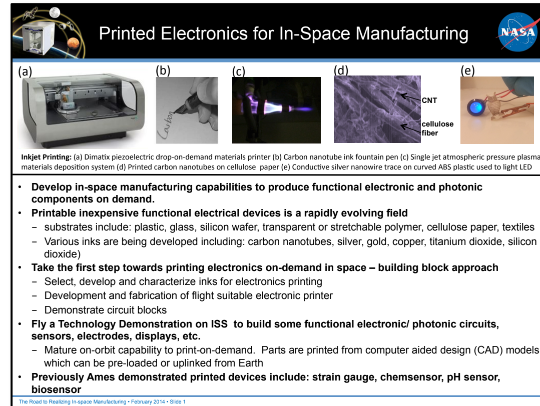
Original Part Printed

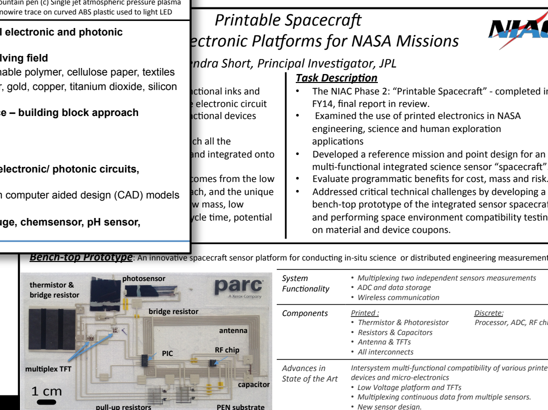


Recycle printed part back into Feedstock Filament

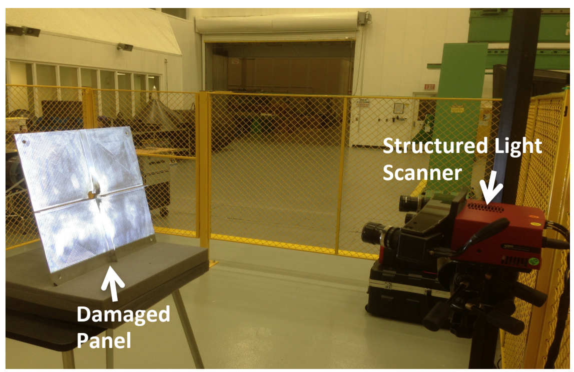
IN Space Manufacturing (ISM) Activities

- **Printable Electronics**
  - ARC/MSFC/JPL: Develop in-space manufacturing capabilities to produce functional electronic and photonic component on demand.
- **In-space Additive Repair**
  - JSC/MSFC: working with JSC and MMOD Office to develop and test process for ground-based repair of MMOD simulated damaged panels for future in-space capability.

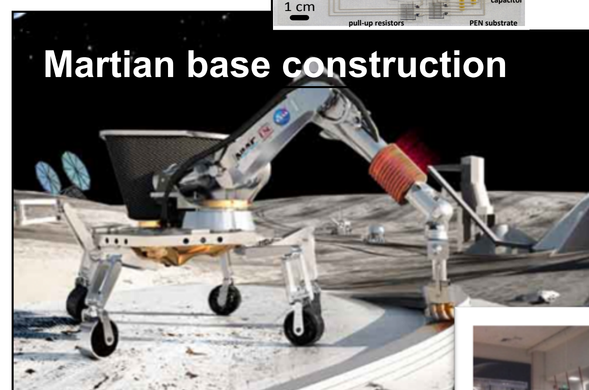


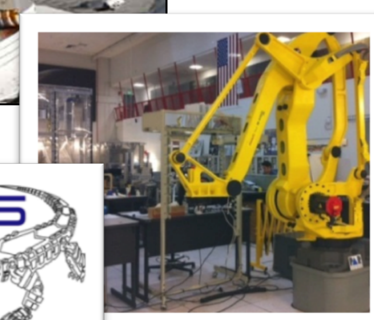


Close-up of simulated MMOD Damage to External ISS Panel



Scanning the Damaged Panel





SWAMP WORKS
NASA KENNEDY SPACE CENTER

- **Additive Construction**
  - Co-led by KSC & MSFC: Joint project with Engineer Research and Development Center – Construction Engineering Research Laboratory, U. S. Army Corp of Engineers.

Cross-Cutting

Cross-Cutting: Additive Manufacturing Development Processing-Structure-Property Relationships

Technical Objectives

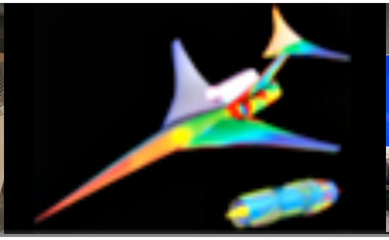
Build the standard level of information on AM powder bed fusion processes that is required for qualification of any new critical process used for aerospace applications

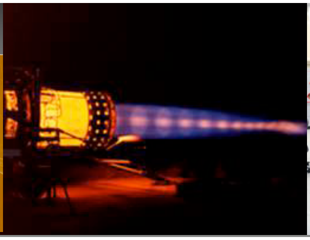
Expand and extend the manufacturing base for aerospace hardware through standardization and qualification of critical AM processes. Better understanding of controlling process parameters and process failure modes will be achieved through completion of this study. Opportunities for industry participation are available in each of the tasks below.

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.*

Related Task: Process Modeling – GRC,MSFC *Objective: Use precipitation modeling to predict location specific microstructure in as-fabricated and post-processed 718, which has been fabricated with selective laser sintering*






Cross-Cutting: Certification – NDE

Foundational NDE Methodology for Certification of Additive Manufacturing (AM) Parts and Materials

- **Purpose:** Develop certification methodologies designed to ensure the production of safe and reliable AM parts for spaceflight applications. Emphasis will be placed on metals and AM processes used in fabrication of propulsion system components.
- **Justification:** AM is a rapidly emerging technology and there is a recognized lag in AM process and part validation and certification methodologies. NDE has been identified as one key technology to close this gap.
- **Summary:** The OSMA state of the art AM report will be used to define highest priority needs/gaps for NDE of AM parts. Resources will be used to down select and optimize NDE techniques that will then be combined with NDE modeling for a cost-effective methodology for verifying part quality. A workshop will be held mid year to assess progress and further define needs.

Summary

- NASA, including each Mission Directorate, is investing in, experimenting with, and/or utilizing AM across a broad spectrum of applications and projects.
- Centers have created and are continuing to create partnerships with industry, other Government Agencies, other Centers, and Universities.
- In-house additive manufacturing capability enables rapid iteration of the entire design, development and testing process, increasing innovation and reducing risk and cost to projects.
- For deep space exploration, AM offers significant reduction to logistics costs and risk by providing ability to create on demand.
- There are challenges: Overwhelming message from recent JANNAF AM for Propulsion Applications TIM was “certification.”
- NASA will continue to work with our partners to address this and other challenges to advance the state of the art in AM and incorporate these capabilities into an array of applications from aerospace to science missions to deep space exploration.