Additive Manufacturing for Human Space Exploration

Aerospace Innovative Technology Summit
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Birmingham AL

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Science and Technology Office
NASA Marshall Space Flight Center

Agenda

NASA's In Space Manufacturing Initiative (ISM)

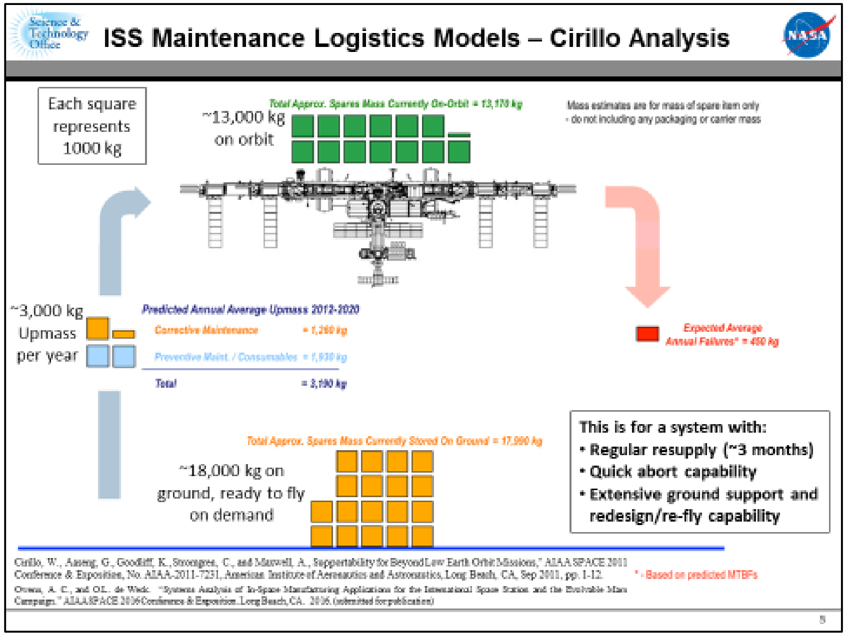
- The Case for ISM: WHY
- ISM Path to Exploration
- In Space Robotic Manufacturing and Assembly (IRMA)

Additive Manufacturing (AM) Development For Liquid Rocket Engine Space Flight Hardware

MSFC Standard and Specification For Additively Manufactured Space Flight Hardware

Summary

The Case for ISM: WHY



ISS Maintenance Logistics Models – Cirillo Analysis

Each square represents 1000 kg

~13,000 kg on orbit

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only
- do not including any packaging or carrier mass

~3,000 kg Upmass per year

Predicted Annual Average Upmass 2012-2020

Corrective Maintenance	= 1,260 kg
Preventive Maint. / Consumables	= 1,930 kg
Total	= 3,190 kg

Expected Average Annual Failures* = 450 kg

Total Approx. Spares Mass Currently Stored On Ground = 17,990 kg

~18,000 kg on ground, ready to fly on demand

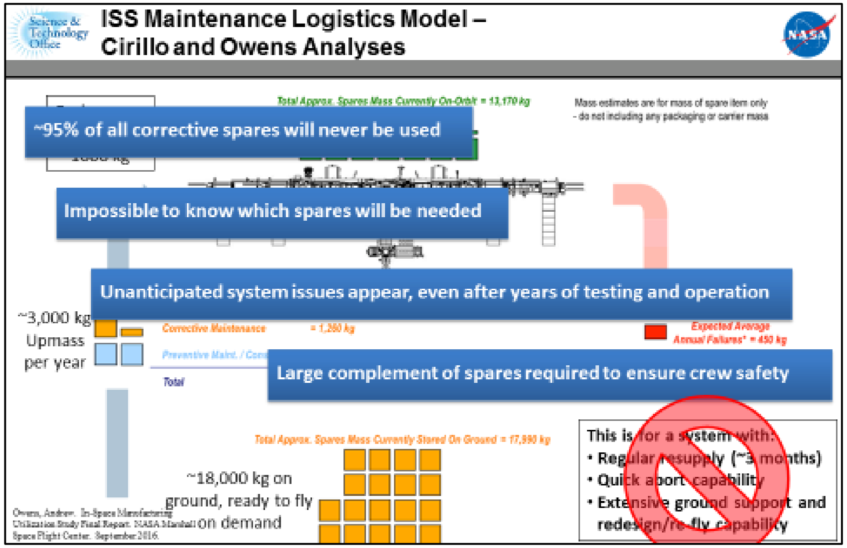
This is for a system with:
- Regular resupply (~3 months)
- Quick abort capability
- Extensive ground support and redesign/re-fly capability

Cirillo, W., Aaseng, G., Goodliff, K., Stromgren, C., and Maxwell, A., "Supportability for Beyond Low Earth Orbit Missions," AIAA SPACE 2011 Conference & Exposition, No. AIAA-2011-7231, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sep 2011, pp. 1-12.

Owens, A. C., and O.L. de Weck. "Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign." AIAA SPACE 2016 Conference & Exposition. Long Beach, CA. 2016. (submitted for publication)

* - Based on predicted MTBFs

5



ISS Maintenance Logistics Model – Cirillo and Owens Analyses

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only
- do not including any packaging or carrier mass

~95% of all corrective spares will never be used

Impossible to know which spares will be needed

Unanticipated system issues appear, even after years of testing and operation

Large complement of spares required to ensure crew safety

~3,000 kg Upmass per year

Corrective Maintenance = 1,260 kg

Preventive Maint. / Cons

Total

Expected Average Annual Failures* = 450 kg

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Owens, Andrew. In-Space Manufacturing Utilization Study Final Report. NASA Marshall Space Flight Center. September 2016.

Current maintenance logistics strategy ***will not be effective*** for deep space exploration missions

Benefits from Incorporation of ISM

ISM offers the potential to:
- Significantly reduce maintenance logistics mass requirements
- Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements
- Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances
- Mitigate risks that are not covered by current approaches to maintainability

Science & Technology Office

ISM Path to Exploration - Key Thrust Areas

FabLab

MSFC

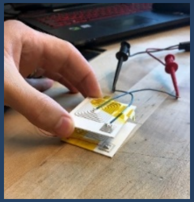
First Plastics Printer

Made In Space

2nd Generation Plastics Printer

Made In Space

Printed Electronics

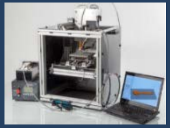


MSFC

Recycler/ Printer

ers

IN SPACE MANUFACTURING
MAKE IT - DON'T TAKE IT



Techshot

Made In Space

UltraTech

Tethers Unlimited

Common Use Recyclable Materials

Cornerstone Research Group

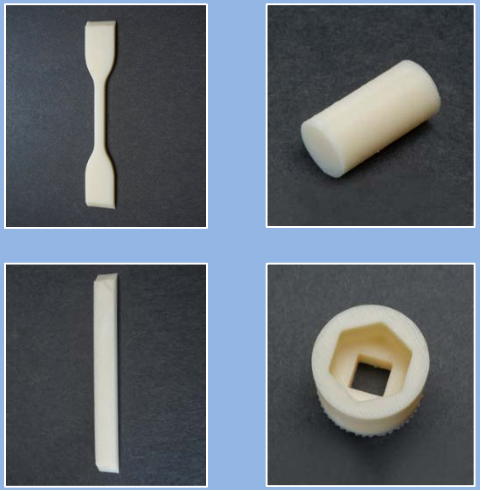
Tethers Unlimited

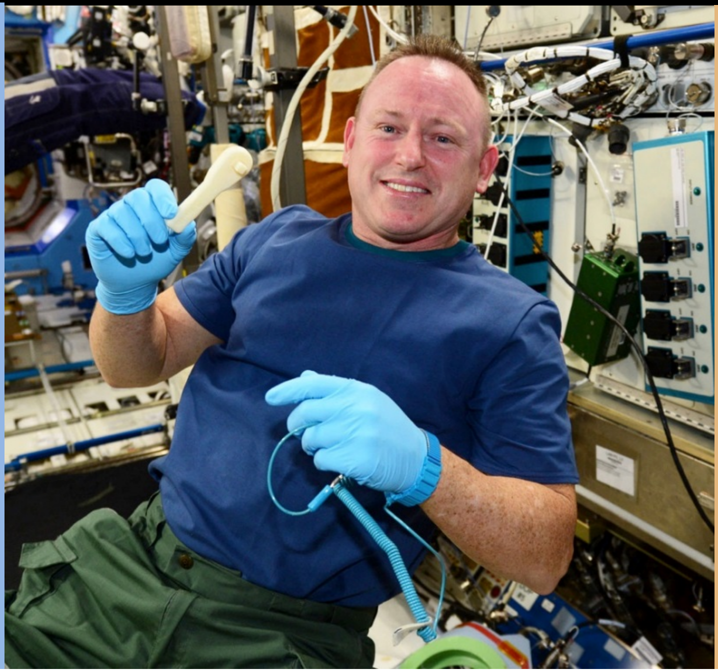
Health & Medical

Tethers Unlimited

The First Step: 3D Printer International Space Station (ISS) Technology Demonstration

Mechanical Property Test Articles

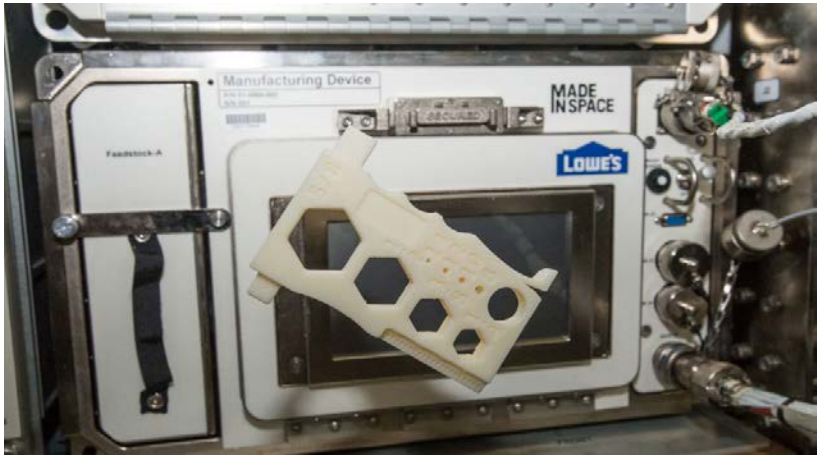




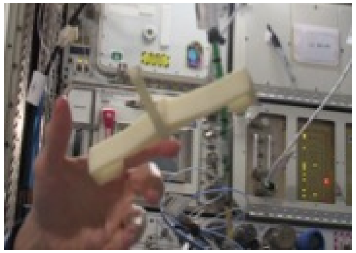
Functional Tools

- A total of 21 parts were printed on ISS, including the uplinked ratchet handle.
- Comprehensive nondestructive inspection and testing performed on all articles
- Mechanical property differences observed between flight and ground samples
- Phase II ISS prints targeted extruder standoff distance as probable cause for differences observed in Phase I data.
- **Overall, we cannot attribute any of the observations to microgravity effects.**
- Lessons Learned were incorporated into the next generation 3D Printer for ISS – Additive Manufacturing Facility (AMF) by Made In Space

ISM Utilization and the Additive Manufacturing Facility (AMF): Material Characterization and Functional Parts



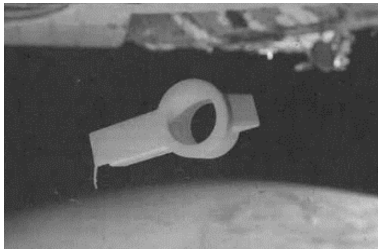
AMF on ISS with printed multi-purpose tool floating in front (photos courtesy of MIS)



SPHERES Tow Hitch

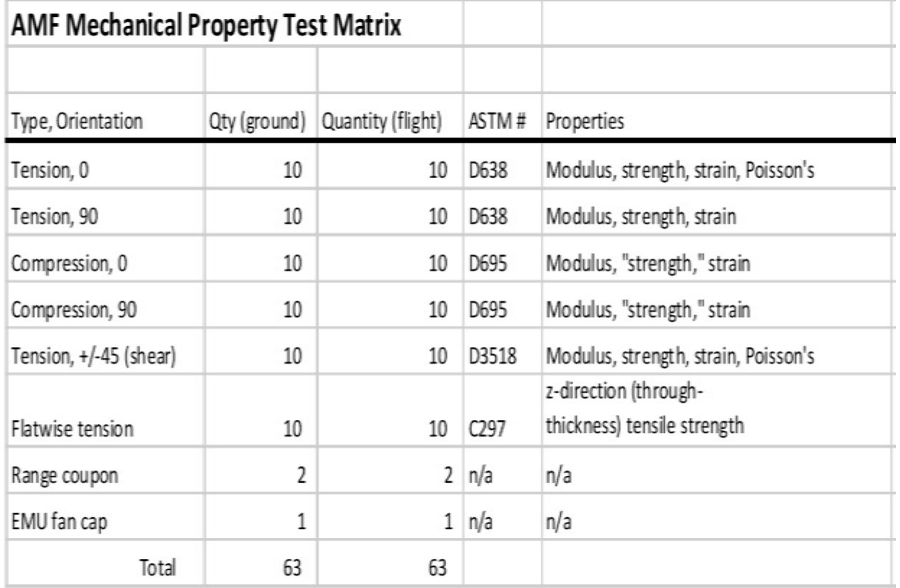
Antenna Feed Horn

REM Shield Enclosure



OGS AAA Adapter

- Additive Manufacturing Facility (AMF), the second generation printer, is a commercial, multi-user facility developed by Made in Space, Inc.
- Upgrades beyond 3DP include:
  - a) Print with multiple material (ABS, ULTEM 9085, and HDPE
  - b) Integral cameras/sensors for automated monitoring
  - c) Maintenance procedures reduce crew time
  - d) Leveling and calibration with on-board systems
- Materials characterization task developing baseline mechanical properties on ABS (test matrix below)



AMF Mechanical Property Test Matrix

Type, Orientation	Qty (ground)	Quantity (flight)	ASTM #	Properties
Tension, 0	10	10	D638	Modulus, strength, strain, Poisson's
Tension, 90	10	10	D638	Modulus, strength, strain
Compression, 0	10	10	D695	Modulus, "strength," strain
Compression, 90	10	10	D695	Modulus, "strength," strain
Tension, +/-45 (shear)	10	10	D3518	Modulus, strength, strain, Poisson's
Flatwise tension	10	10	C297	z-direction (through-thickness) tensile strength
Range coupon	2	2	n/a	n/a
EMU fan cap	1	1	n/a	n/a
Total	63	63		

NextSTEP Multi-Material Fabrication Laboratory (FabLab) Broad Agency Announcement (BAA)

WE ARE HERE!

NextSTEP
Next Space Technologies for Exploration Partnerships

DESIGN

Phase A (18 months)
Goal: Demonstrate a scalable ground-based PROTOTYPE of an ISM FabLab System able to mature into flight demonstrations on the ISS within three years.

BUILD

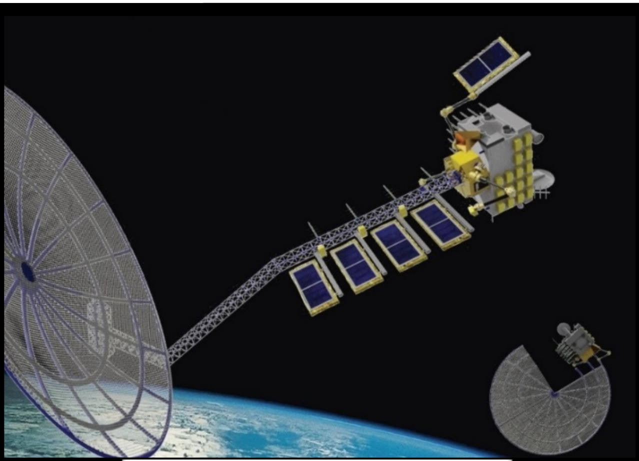
Phase B (12 months)
Goal: Mature the Phase A ISM FabLab System prototype into a flight integration deliverable. Phase B criteria and needed path are informed by Phase A results and will be released under a follow-on BAA.

FLY

Phase C (18 months)
Goal: Demonstrate the capability of a Phase B ISM FabLab System on the ISS and evaluate risk. Phase C criteria are informed by Phase B results and will be released as a follow-on BAA or other acquisition vehicle.

- NASA solicited proposals for the development of a Multi-Material Fabrication Laboratory (FabLab) capable of end-to-end manufacturing of precision parts for sparing, repair, and logistics support. during space missions.
  - ♦ High degree of autonomy
  - ♦ On-demand manufacturing of metallics and other materials in the microgravity environment
  - ♦ Minimum build envelope of 6”x6”x6”
  - ♦ Earth-based remote commanding
  - ♦ In-line remote/autonomous inspection and quality control
- This is the first step toward a fully-integrated, on-demand manufacturing capability that is able to produce finished, ready-to-use metallic, plastic, and/or electronic products during Exploration missions.
- The Phase B solicitation will be openly competed and is anticipated to be released late in CY 2019.

In-space Robotic Manufacturing and Assembly (IRMA): Phase 1 Concepts

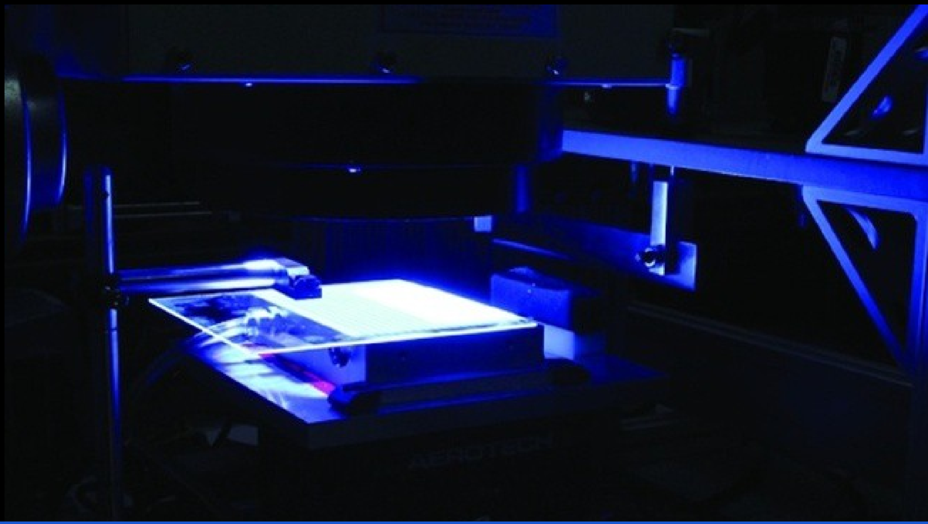

Concept by Made In Space


Concept by Space Systems/Loral


Concept by Orbital ATK

	Archinaut	Dragonfly	CIRAS
	A Versatile In-Space Precision Manufacturing and Assembly System	In-Space Robotic Manufacturing, Assembly and Reconfiguration of Large Solid Radio Frequency (RF) Reflectors	A Commercial Infrastructure for Robotic Assembly and Services
Tipping Point Objective	A ground demonstration of additive manufacturing of extended structures and assembly of those structures in a relevant space environment.	A ground demonstration of robotic assembly interfaces and additive manufacture of antenna support structures meeting EHF performance requirements.	A ground demonstration of reversible and repeatable robotic joining methods for mechanical and electrical connections feasible for multiple space assembly geometries.
Team	Made In Space, Northrop Grumman Corp., Oceaneering Space Systems, Ames Research Center	Space Systems/Loral, Langley Research Center, Ames Research Center, Tethers Unlimited, MDA US & Brampton	Orbital ATK, Glenn Research Center, Langley Research Center, Naval Research Laboratory

Status: 2-year risk reduction developments completed. Phase 2 proposals selected for flight demo



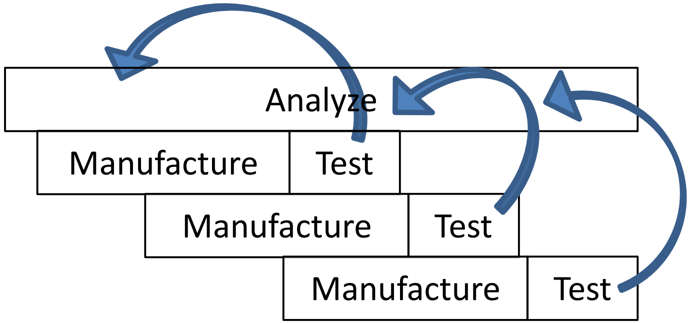
Additive Manufacturing

at Marshall Space Flight Center

Additive Manufacturing Development for Liquid Rocket Engine Space Flight Hardware

Additive Manufacturing Design and Development for Space Propulsion System Applications

Concurrent Development Model



Analyze

Manufacture | Test

Manufacture | Test

Manufacture | Test

Strategic Vision:

- Defining the Development Philosophy of the Future
- Building Foundational Industrial Base
- Building Experience
- Developing “Smart Buyers” to enable Commercial Partners
- Enabling and Developing Revolutionary Technology
- SLM Material Property Data, Technology, and Testbed shared with US Industry

Focus Areas:

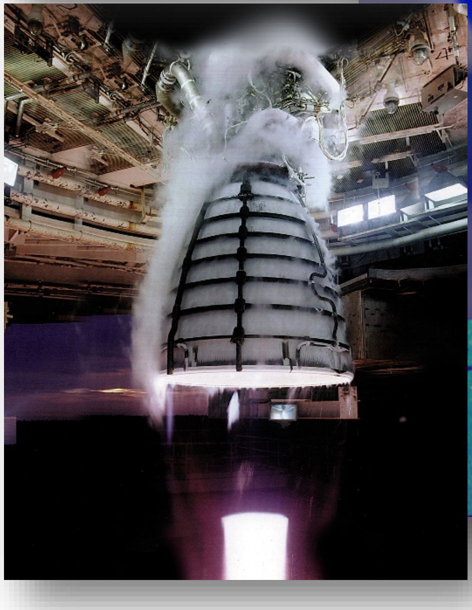
- SLS Core Stage Engine, RS-25
  - Process development and characterization
  - Material property characterization and database development (Inconel 718)
  - Pathfinder component fabrication
- In Space Propulsion Class Additive Manufacturing Demonstrator Engine (AMDE)
  - Chambers
  - Injectors
  - Nozzles
  - Valves
  - Turbomachinery
- Small Satellite Propulsion Components

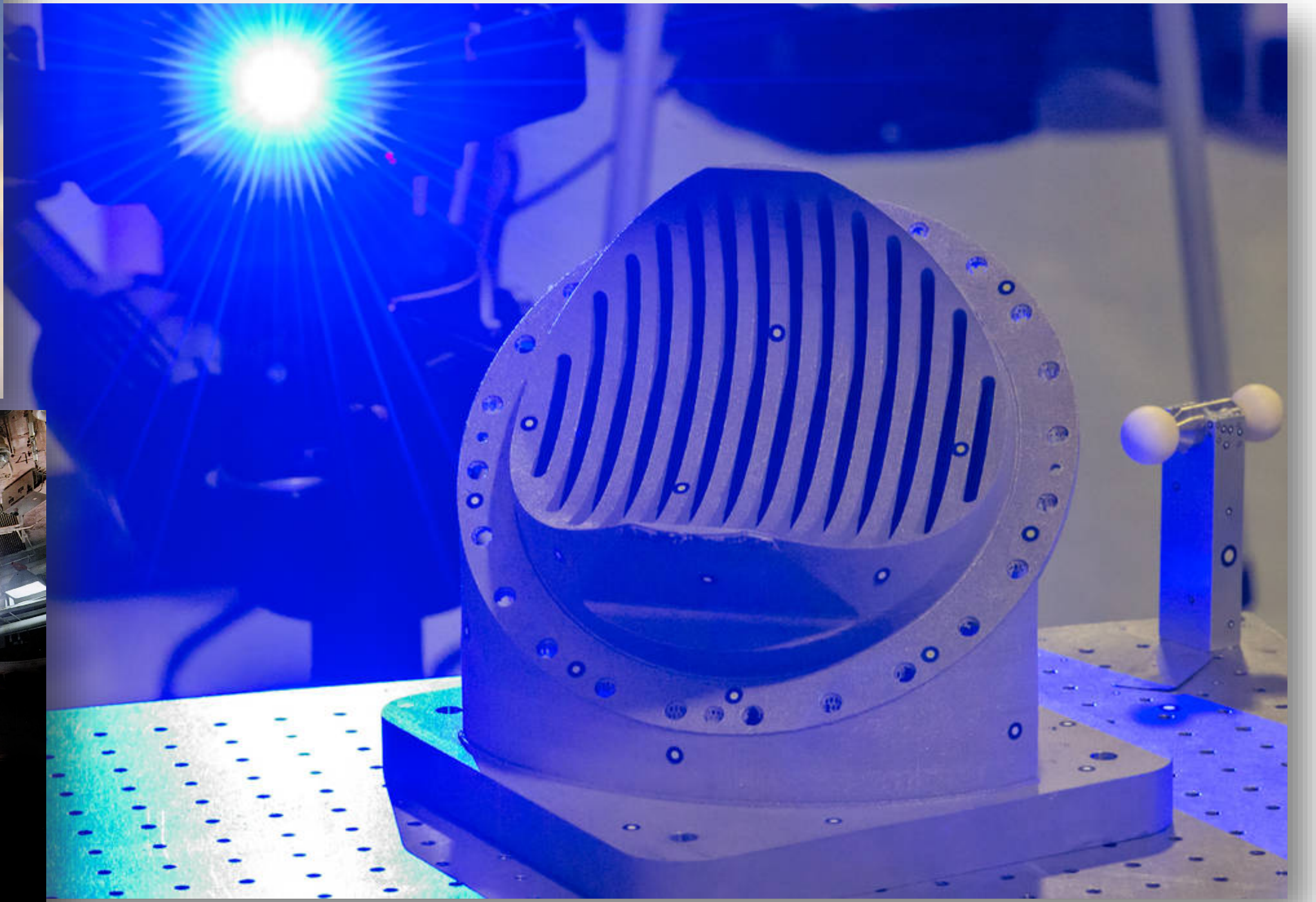
SLS Program / RS-25 Engine Example Pogo Z-Baffle

Inconel 718

Used existing design with additive manufacturing to reduce complexity from 127 welds to 4 welds

- 1 of 35 part opportunities being considered for RS-25 engine





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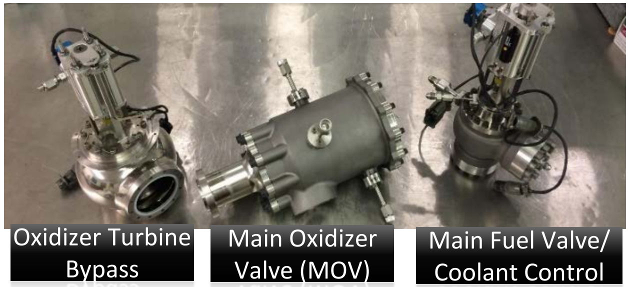
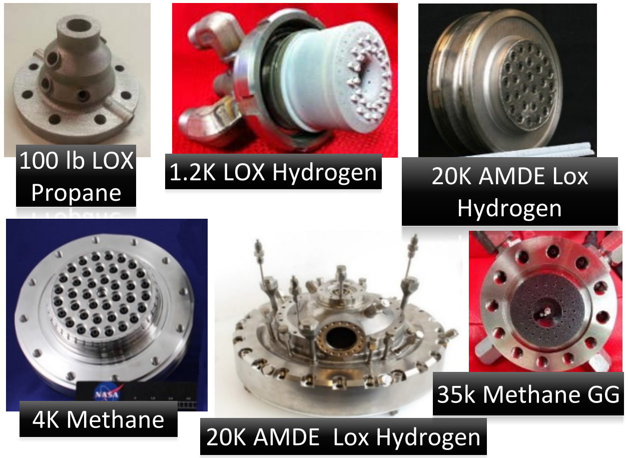
Additive Manufacturing Demonstrator Engine (AMDE) Development


Oxidizer Turbine Bypass

Main Oxidizer Valve (MOV)

Main Fuel Valve/ Coolant Control

Valve Development


100 lb LOX Propane

1.2K LOX Hydrogen

20K AMDE Lox Hydrogen

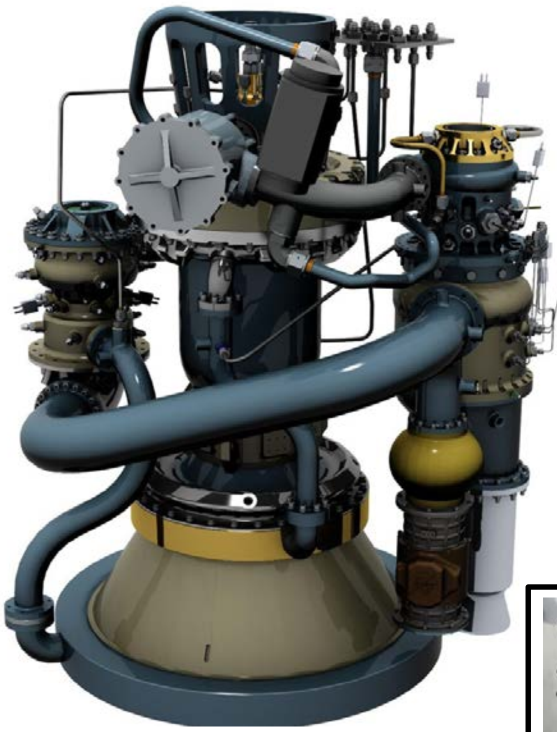
4K Methane

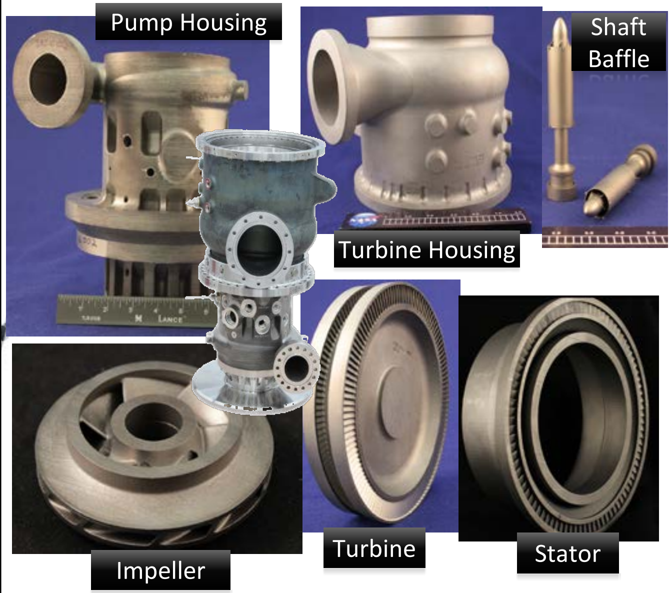
20K AMDE Lox Hydrogen

35k Methane GG

Injector Development

Copper Main Combustion Chamber Development




Pump Housing

Turbine Housing

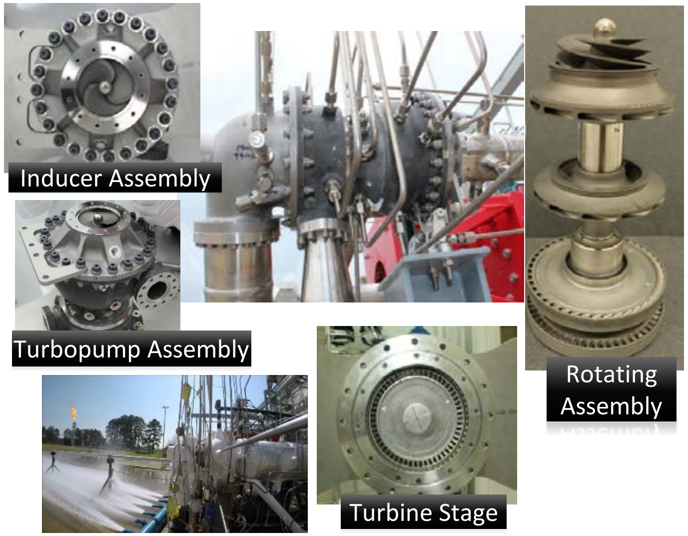
Shaft Baffle

Impeller

Turbine

Stator

Liquid Oxygen Turbopump Development


Inducer Assembly

Turbopump Assembly

Rotating Assembly

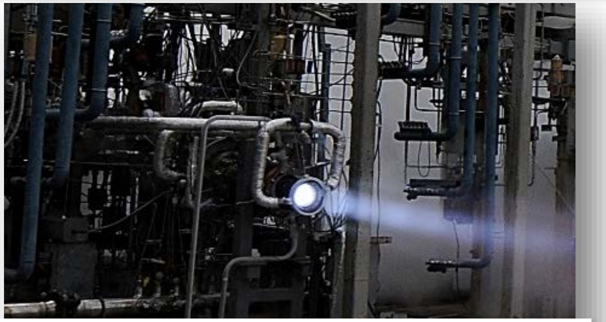
Turbine Stage

Fuel Turbopump Development

Additive Combustion Chambers Assembly and Testing

GRCop-84 3D printing process developed at NASA and infused into industry

GRCop-84 AM Chamber Accumulated **2365 sec** hot-fire time at full power with no issues



LOX/Methane Testing of 3D-Printed Chamber Methane Cooled, tested full power

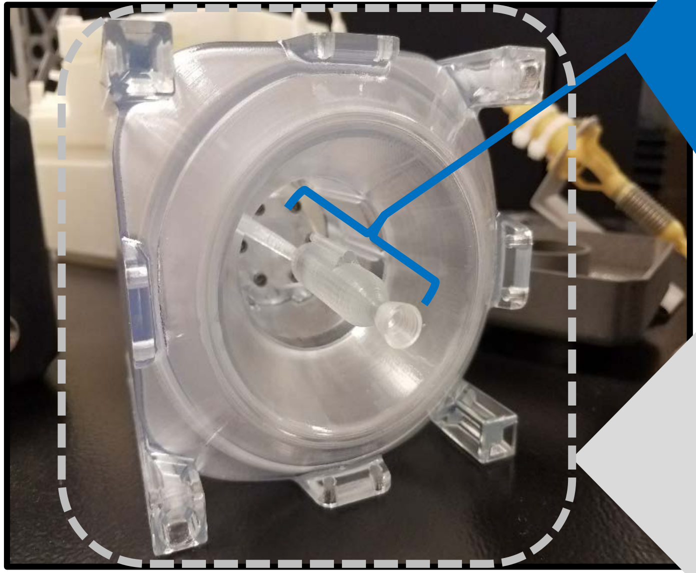
Ox-Rich Staged Combustion Subscale Main Injector Testing of 3D-Printed Faceplate

Morgan, K. L., Gradl, P., "Additive Manufacturing Overview: Recent Propulsion Applications," Additive Manufacturing for Defense and Government Conference, July 2017

Small Satellite Propulsion Components Design and Development

CubeSat cuboidal tank design:

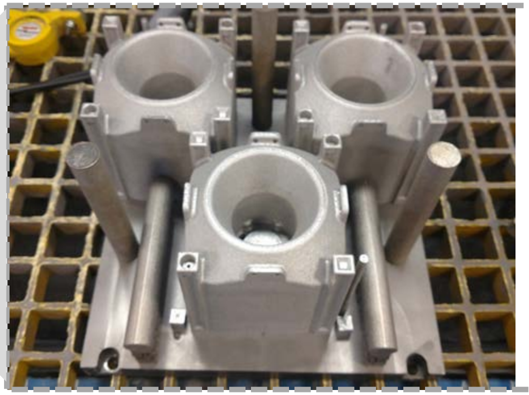
- Topology optimized
- Printed
- Successfully hydrostatic proof tested



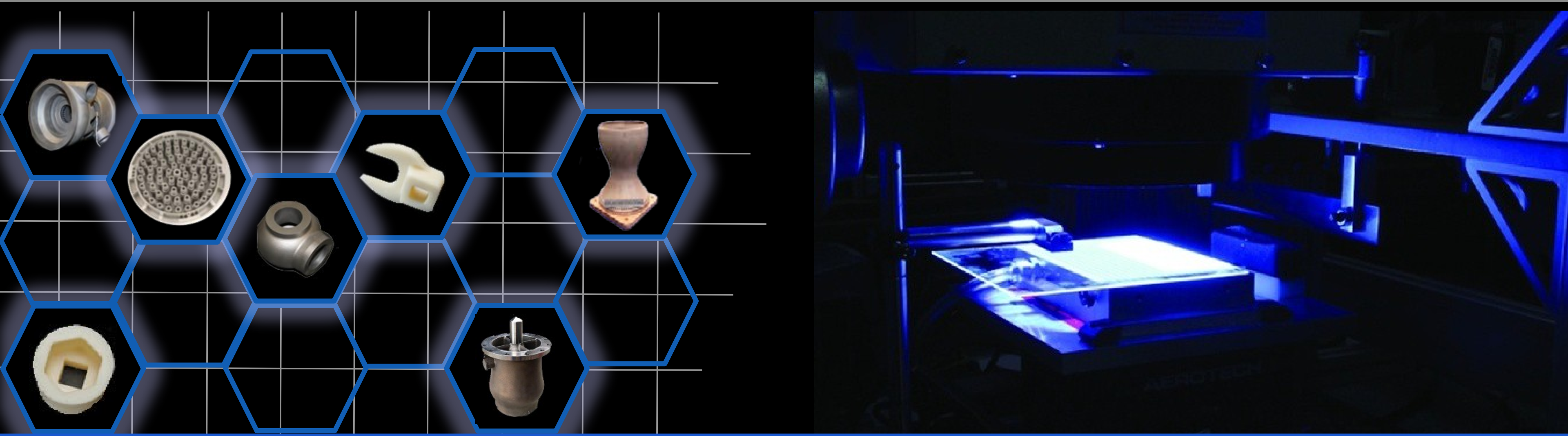
CubeSat propulsion system (1 Newton SLA Model)

AM Thruster Components

- **Monopropellant thruster thermal standoff - topology optimized with integrated flow passages**
- **Injector**
- **Reactor**



Detailed design and fabrication of 3U and 6U CubeSat Propulsion Modules



Additive Manufacturing

at Marshall Space Flight Center

MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware

NASA's Plans for Development of Standards for Additive Manufactured Components

NASA MSFC has developed AM standards in response to near term Programmatic Needs

- Program partners in manned space flight programs (Commercial Crew, SLS, and Orion) are actively developing AM parts
  - AM parts are currently used for commercial space flight
  - MSFC standard is currently being used for certification via tailoring
- MSFC-STD-3716 lists 65 unique Additive Manufacturing Requirements
- MSFC-SPEC-3717 lists 45 unique Process Control and Qualification Requirements
- Although the MSFC standard was written specifically for the Laser Powder Bed Fusion process it's principles can be applied to any AM process for the purpose of certification
- The NESC formed a team to explore creation of Agency Standards and Specifications for Additive Manufactured (AM) components.
  - This team includes representatives from nine NASA centers along with representatives from the FAA, Air Force, Navy and Army.
  - One standard each for Crewed, Non-Crewed, and Aeronautic Projects
- Separate specification to cover Equipment and Facility Process Control
- Standards are planned to be ready for Agency-wide review in late 2020

METRIC/SI (ENGLISH) SENSITIVE

National Aeronautics and Space Administration

MSFC-SPEC-3717
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20
MSFC TECHNICAL STANDARD

Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

DRAFT 1 – July 13, 2017

NOT MEASUREMENT SENSITIVE

National Aeronautics and Space Administration

MSFC-STD-3716
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20
MSFC TECHNICAL STANDARD

Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals

DRAFT 1 – April 10, 2017

Summary: In Space Manufacturing Applications

Conclusions from Systems Analysis of ISM Utilization for the Evolvable Mars Campaign:

Why ISM

- Current maintenance logistics strategy will not be effective for deep space missions
- ISM has the potential to significantly reduce maintenance logistics mass requirements by enabling material commonality and the possibility of material recycling and ISRU for spares
- ISM should be considered and developed in parallel with the systems design

NASA is actively working to develop ISM capabilities:

- **Within Pressurized Volume:** Reduce the logistics challenges and keep astronauts safe and healthy in transit and on extraterrestrial surfaces. ISS is a critical testbed.
- **External/Free Space - IRMA:** Develop new commercial capabilities for robotic spacecraft construction, repair, refurbishment, and repurposing in Earth orbit

To achieve functional capability supporting the Exploration timeline, ISM must work with Exploration systems designers now to promote culture change; identify high-value application areas; and influence the design and maintainability philosophy.

Summary: Space Propulsion System Applications

MSFC has made a major thrust in the application of AM for development of liquid rocket engines ranging from the Space Launch System Core Stage RS-25 engine, to In-Space Class prototype engines, to Cubesat propulsion systems.

- Process development, material property characterization, and component fabrication trials for RS-25 Inconel 718 material applications.
- New design and development philosophy successfully exercised to build AMDE, a prototype in-space class engine incorporating additive manufacturing to reduce costs, schedule and parts counts.
    - Designed and additively manufactured > 150 rocket engine parts in 2.5 years
    - Encompassed every major component and assembly of the engine
    - Developed and demonstrated capability to additively manufacture with copper.
    - Data, expertise, and testbed shared with industry for current/future developments
- Capabilities developed through AMDE experience have been extended to small satellite propulsion systems components design and development

NASA MSFC created a Standard and a Specification for AM Spaceflight Hardware in response to near-term programmatic demand.

- Shaped the approach to additive parts for current human-rated space flight programs through early release of Draft Quality Standard approach.
- Standard and Specification provide a framework for consistent evaluation of AM Laser Powder Bed Fusion processes, properties, and components.


NASA

The First Step: The 3D Printing in Zero G Technology Demonstration Mission

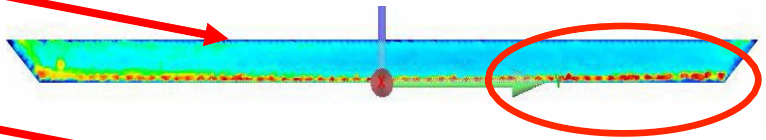
The 3DP in Zero G Tech Demo delivered the first 3D printer to ISS and investigated the effects of consistent microgravity on fused deposition modeling

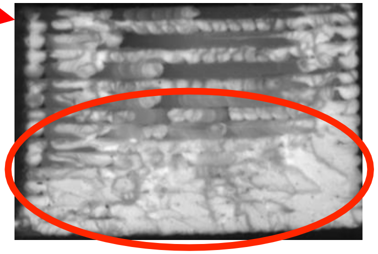
Phase I Prints (Nov-Dec 2014): mechanical property test articles; range coupons; and functional tools

Printer inside Microgravity Science Glovebox (MSG)

<u>Key Observations</u>:

- Tensile and Flexure: Flight specimens stronger and stiffer than ground specimens
- Compression: Flight specimens are weaker than ground specimens
- Density: Flight specimens slightly more dense than ground specimens; compression specimens show opposite trend
- Structured Light Scanning: Protrusions along bottom edges (more pronounced for flight prints)
- Microscopy: Greater Densification of Bottom Layers (flight tensile and flexure)



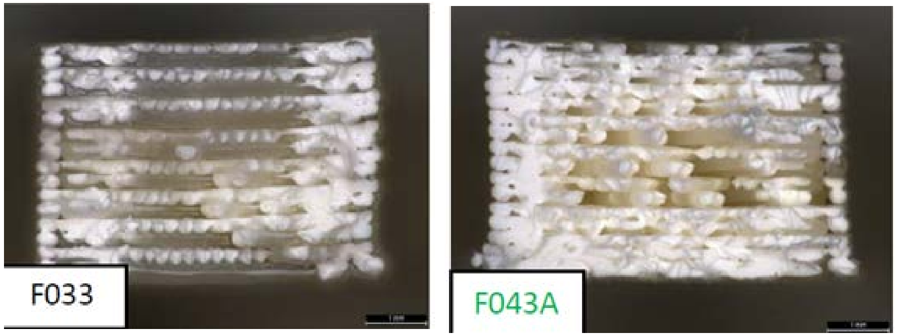


<u>Conclusions</u>

- Z-Calibration distance variation suspected to be primary factor driving differences between flight and ground samples
- Potential influence of feedstock aging are being evaluated further

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase II)

- Phase II Prints:
  - 25 specimens (tensile + compression) built at an optimal extruder standoff distance.
  - 9 specimens printed with intentionally decreased extruder standoff distance to mimic Phase I flight process conditions
- Key findings:
  - No substantive chemical changes in feedstock
  - No evidence of microgravity effects noted in SEM, SLS, CT analysis. Some internal structure variation between builds and with changes in process settings (primarily compression)
  - All prints to date with 3DP appear to be broadly part of the same family of data
  - Phase I data variations appear traceable to:
    - Differences in manufacturing process settings (extruder standoff distance)
    - Data scatter - characteristic of many additively manufactured materials and processes.
    - Printer variability

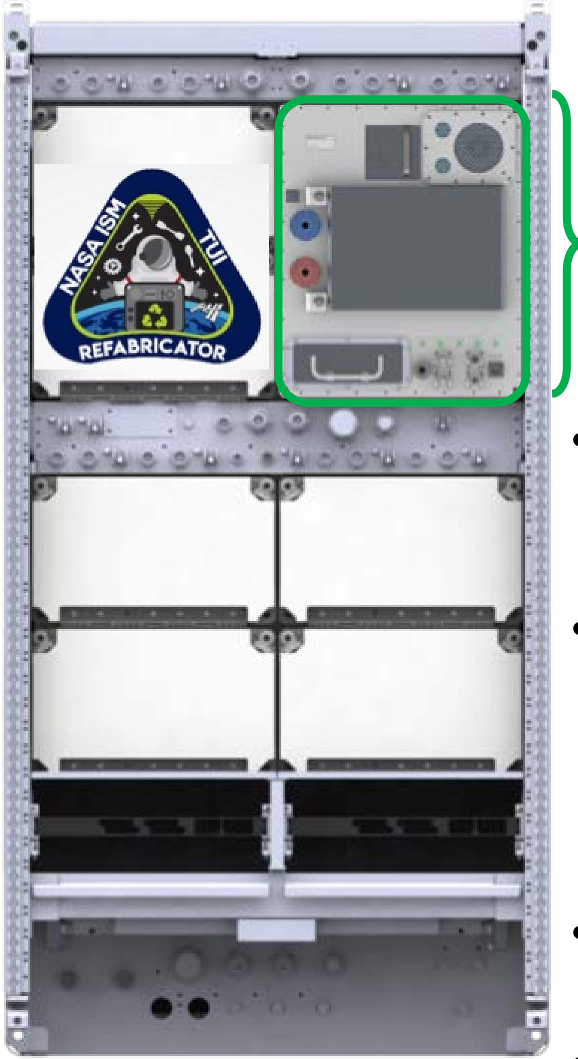


Cross-section of PII tensile specimen manufactured at optimal extruder setting (left) compared with specimen manufactured at a reduced extruder standoff distance (right). Right image has a cross-section characteristic with PI flight prints.

Specimen set	Average ultimate tensile strength (KSI)	Coefficient of variation
Phase II	3.68	6.71
Phase II optimal	3.63	6.61
Phase II off-suboptimal	3.93	0.07
Phase I ground	3.46	1.71
Phase I flight	4.04	5.95

Overall, we cannot attribute any of the observations to microgravity effects.

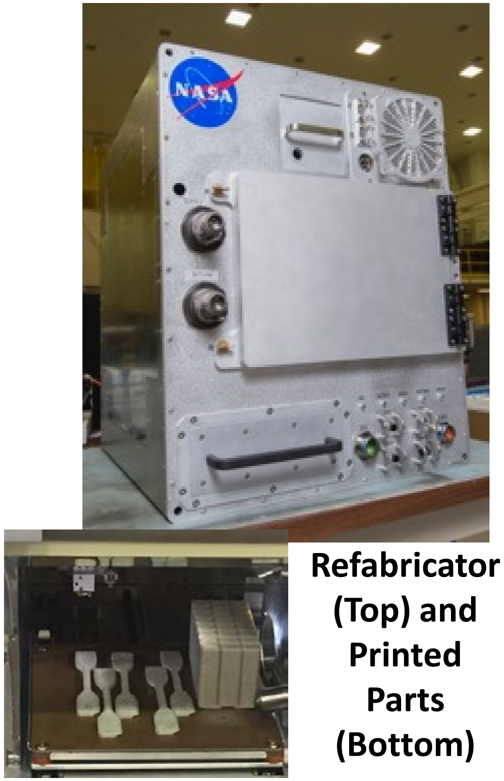
In-Space Recycling & Reuse: ISS Refabricator Closing the Manufacturing Loop



Mission Goal of Refabricator

Demonstrate how the integrated polymer Recycler/3D Printer can increase mission sustainability by providing a repeatable, closed-loop process for recycling plastic materials/parts in the microgravity environment into useable feedstock for fabrication of new and/or different parts.

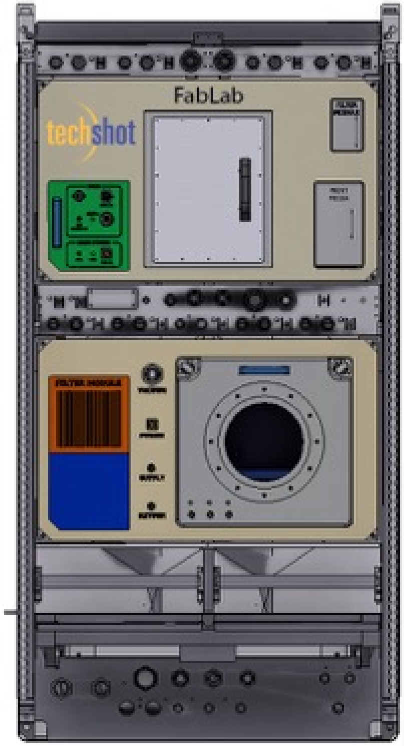
- Technology Demonstration Mission conducted under SBIR contract with Tethers Unlimited, Inc. (TUI)
- Refabricator is an integrated 3D printer (FDM) which recycles ULTEM plastic into filament feedstock through a novel TUI process which requires no grinding.
- Designed to be self-contained and highly automated.
- Installation and activation on the ISS EXPRESS Rack on 2/14/19



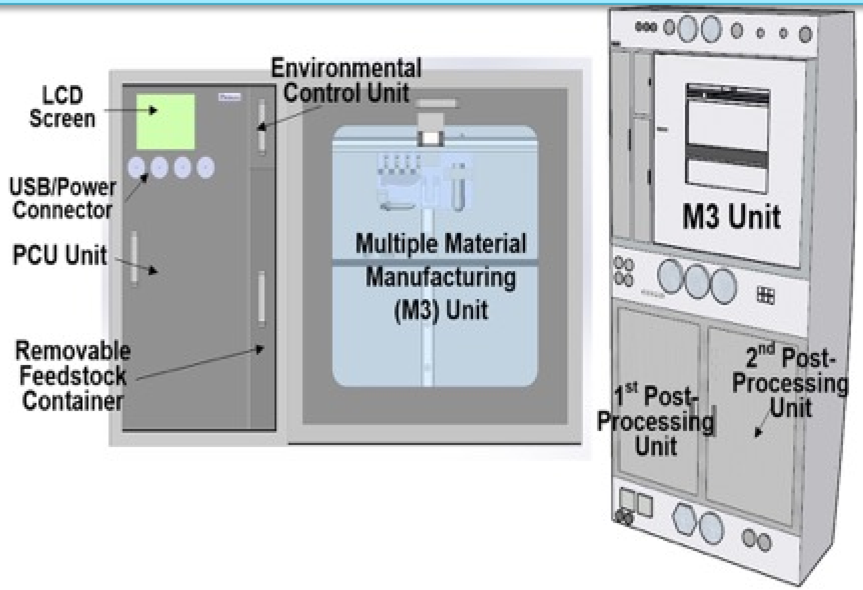
Refabricator (Top) and Printed Parts (Bottom)

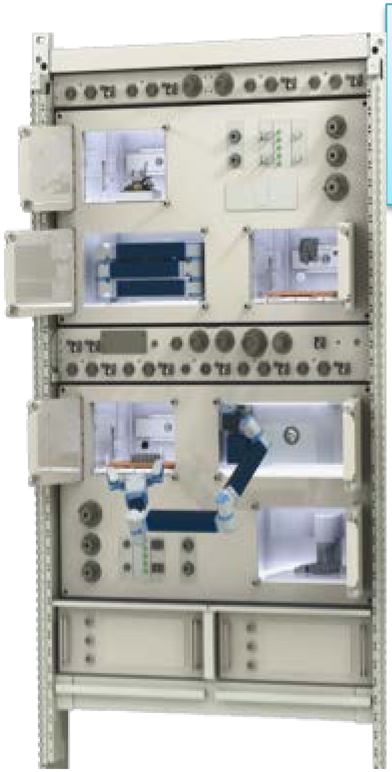
NextSTEP FabLab: Phase A Selectees

”The Techshot FabLab” - Techshot, Inc. (Greenville, IN)
Partners: nScrypt, TM Vacuum Products, University of Louisville, VITO



“Microgravity Multiple Materials Additive Manufacturing (M3AM) Technology” - Interlog (Anaheim, CA)
Partners: Argonne National Labs, Micro Aerospace Solutions, Illinois Institute of Technology





“Empyrean- Sustainable, In-Space Fabrication Laboratory for Multiple Material Manufacturing, Handling, and Verification/Validation” - Tethers Unlimited, Inc. (Bothell, WA)
Partners: IERUS, Olis Robotics

- **These companies will have 18 months to deliver the prototype, after which NASA will select partners to further mature the technologies for an ISS demonstration and 1st generation Exploration system. .**

NASA 12/7/17 Selection Announcement: https://www.nasa.gov/press-release/nasa-selects-three-companies-to-develop-fablab-prototypes

In Space Manufacturing Challenges

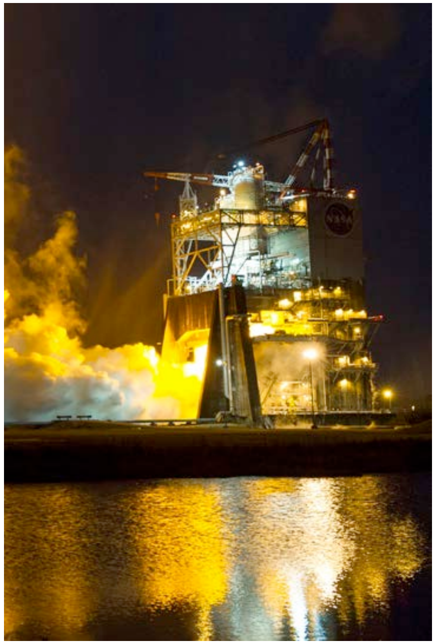
- Lack of demonstrated metallic AM capability in microgravity.
  - MSFC has 4 SBIR projects working on metallic AM systems targeted for use in microgravity
  - MSFC is currently evaluating proposals submitted in response to our FabLab solicitation, which is expected to include a metallic AM printing capability.
- Operating in the space environment.
  - Space operations face constraints that terrestrial operation do not such as power, volume, and environmental limitations
  - Operations of these capabilities and resulting printed parts must be safe for the astronauts.
  - Certification of parts fabricated on orbit or in transit
  - Overall, the technologies developed must be much smaller, safer, and much more autonomous than earth-based counterparts.
- Culture change.
  - Systems that plan to use on-demand manufactured parts must institute a ‘design for maintainability’ approach.
  - ISM team needs to be working with exploration system designers now to identify high-value application areas and influence design
  - ISM is a necessary paradigm shift in space operations, not a ‘bonus’

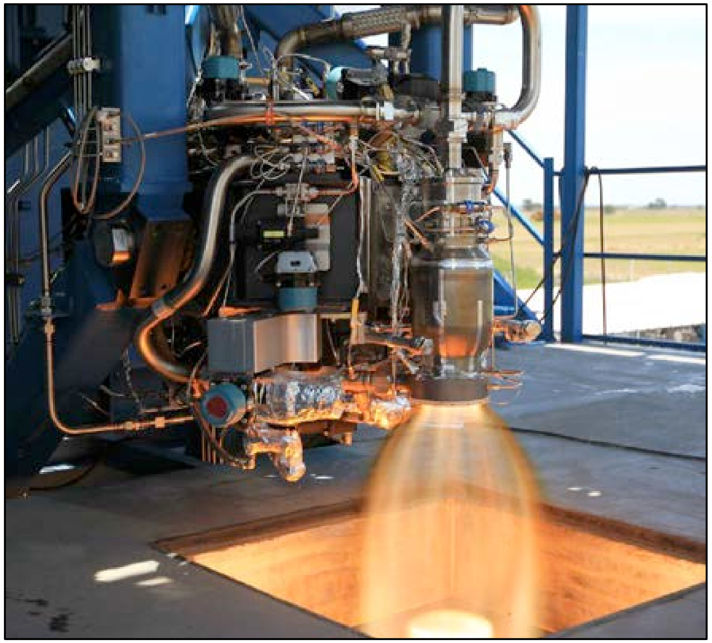
SLM GRCop-84 Chamber Testing

AM in the Human Exploration and Operations Portfolio

Exploration Systems Development
ORION and SLS

Commercial Crew Program (CCP)
DRAGON V2





NASA Exploration Programs and Program Partners have embraced AM for its affordability, shorter manufacturing times, and flexible design solutions.