The Multimaterial Fabrication Laboratory: In-Space Manufacturing as an Enabling Technology for Long Endurance Human Spaceflight

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In-Space Manufacturing (ISM)

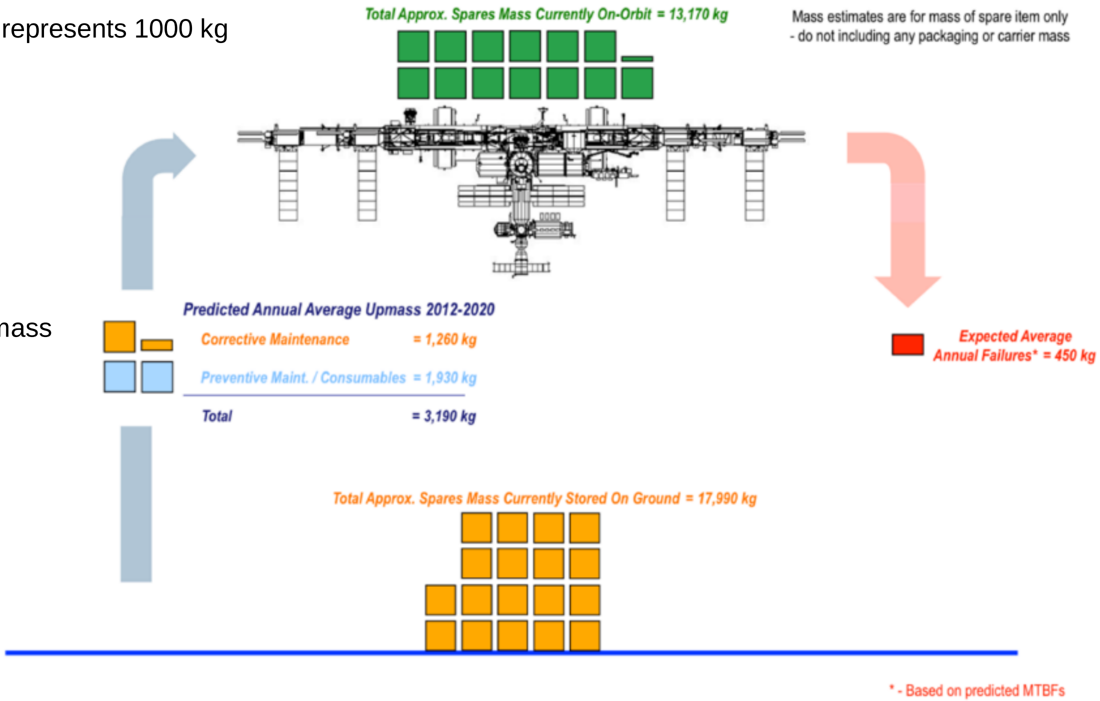
"If what you're doing is not seen by some people as science fiction, it's probably not transformative enough."

-Sergey Brin

The Current Paradigm: The ISS Logistics Model

Each square represents 1000 kg

~3,000 kg of upmass per year

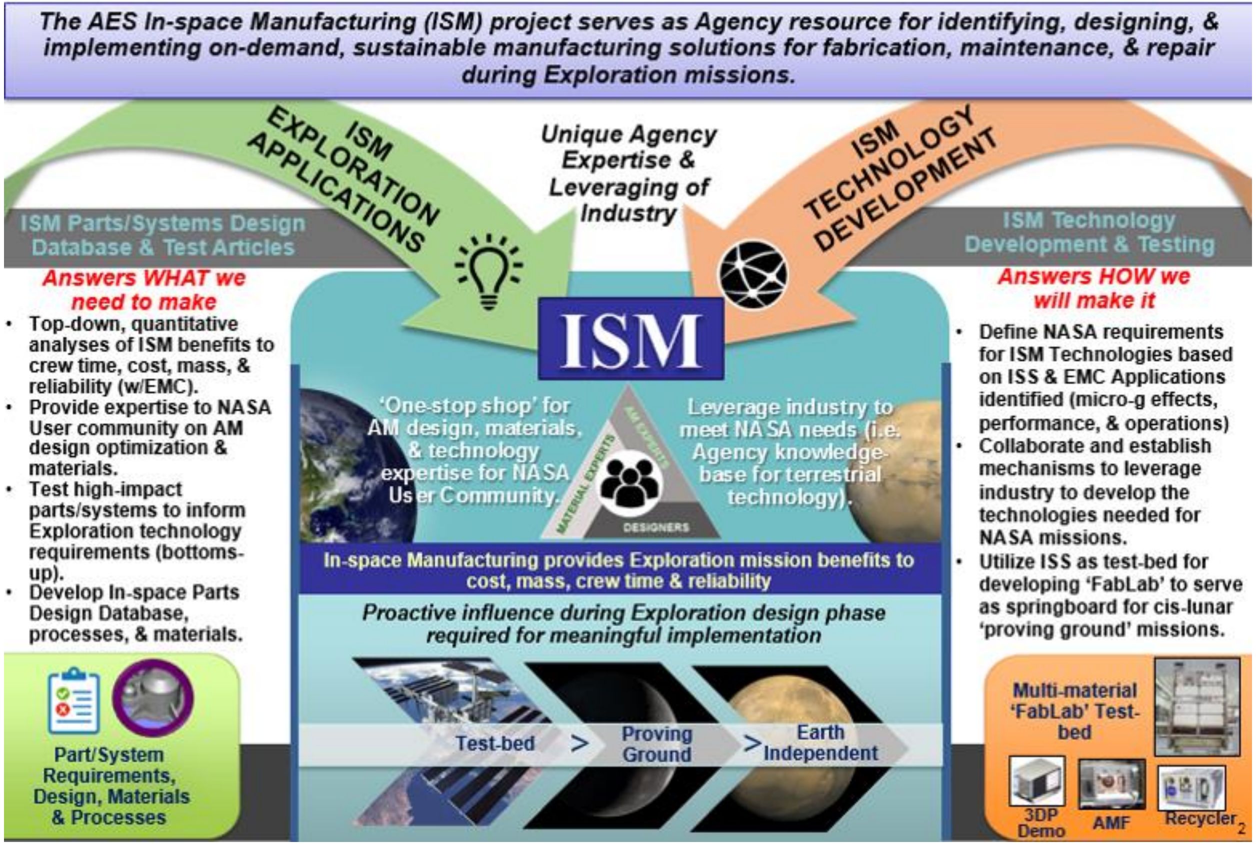


This is for a system with:

- **Regular resupply (~3 months)**
- **Quick abort capability**
- **Extensive ground support and redesign/re-fly capability**

- Based on historical data, 95% of spares will never be used
- Impossible to know which spares will be needed
- Unanticipated system issues always appear, even after years of testing and operations

ISM Core Objectives



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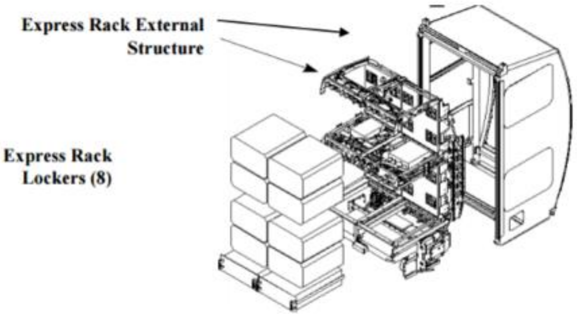
The Multimaterial Fabrication Laboratory for ISS ("FabLab")

- NASA proposal opportunity (closed on 9/15/2017) seeking feasible design and demonstration of a first-generation In-Space Manufacturing Fabrication Laboratory for demonstration on the ISS
- Minimum target capabilities include:
  - Manufacturing of metallic components
  - Meet ISS EXPRESS Rack constraints for power and volume
  - Limit crew time
  - Incorporate remote and autonomous verification and validation of parts
- Federal Business Opportunities link to solicitation: www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=8a6ebb526d8bf8fb9c6361cb8b50c1f8



Power consumption for entire rack is limited to 2000 W

Payload mass limit for rack is less than 576 lbm

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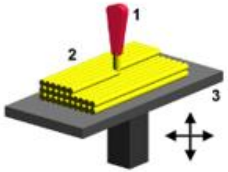
The First Step: The 3D Printing in Zero G Technology Demonstration Mission

The 3DP in Zero G tech demo delivered the first 3D printer on the ISS and investigated the effects of consistent microgravity on fused deposition modeling by printing 55 specimens to date in space.



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

Printer inside Microgravity Science Glovebox (MSG)

- **Phase I prints (Nov-Dec 2014)** consisted of mostly mechanical test coupons as well as some functional tools
- **Phase II specimens (June-July 2016)** provided additional mechanical test coupons to improve statistical sampling

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)
Power	176 W
Feedstock	ABS Plastic

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

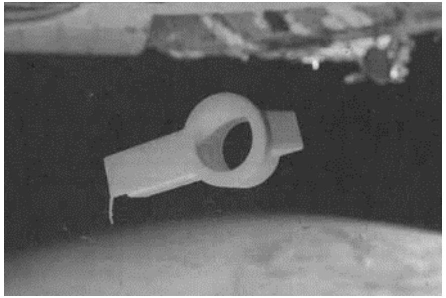
The Made in Space Additive Manufacturing Facility (AMF)

- Additive Manufacturing Facility (AMF) is the follow-on printer developed by Made in Space, Inc.
- AMF is a commercial, multi-user facility capable of printing ABS, ULTEM, and HDPE.
- To date, NASA has printed several functional parts for ISS using AMF

SPHERES Tow Hitch: SPHERES consists of 3 free-flying satellites on-board ISS. Tow hitch joins two of the SPHERES satellites together during flight. Printed 2/21/17.

REM Shield Enclosure: Enclosure for radiation monitors inside Bigelow Expandable Activity Module (BEAM). Printed 3/20/17 (1 of 3).

Antenna Feed Horn: collaboration between NASA Chief Scientist & Chief Technologist for Space Communications and Navigation, ISM & Sciperio, Inc. Printed 3/9/17 and returned on SpaceX-10 3/20/17.



OGS Adapter: adapter attaches over the OGS air outlet and fixtures the velocicalc probe in the optimal location to obtain a consistent and accurate reading of airflow through the port. 7/19/2016.

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ReFabricator from Tethers Unlimited, Inc.: Closing the Manufacturing Loop

- Technology Demonstration Mission payload conducted under a phase III SBIR with Tethers Unlimited, Inc.

- Refabricator demonstrates feasibility of plastic recycling in a microgravity environment for long duration missions
  - Closure of the manufacturing loop for FDM has implications for reclamation of waste material into useful feedstock both in-space an on-earth

- Refabricator is an integrated 3D printer (FDM) and recycler
  - Recycles 3D printed plastic (ULTEM 9085) into filament feedstock through the Positrusion process

- Environmental testing of engineering test unit completed at MSFC in April
  - Payload CDR completed in mid-June
  - Operational on ISS in 2018

ReFabricator Engineering Test Unit (ETU)

Toward an In-Space Metal Manufacturing Capability

- Made in Space Vulcan unit (phase I SBIR)
  - Integrates FDM head derived from the additive manufacturing facility (AMF), wire and arc metal deposition system, and a CNC end-mill for part finishing

- Ultra Tech Ultrasonic Additive Manufacturing (UAM) system (phase I SBIR)
  - UAM prints parts by using sound waves to consolidate layers of metal drawn from foil feedstock (similar to ultrasonic welding)
  - Solid state process that avoids complexities of management of powder feedstock
  - Work is to reduce the UAM process’s footprint by designing and implementing a higher frequency sonotrode
  - Scaling of system also has implications for robotics and freeform fabrication

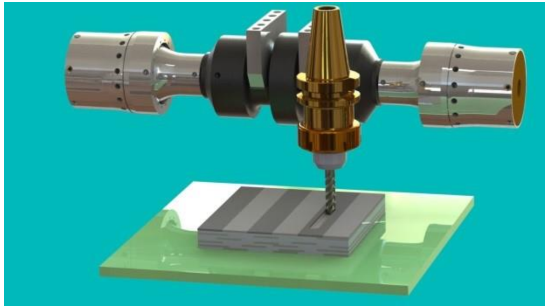
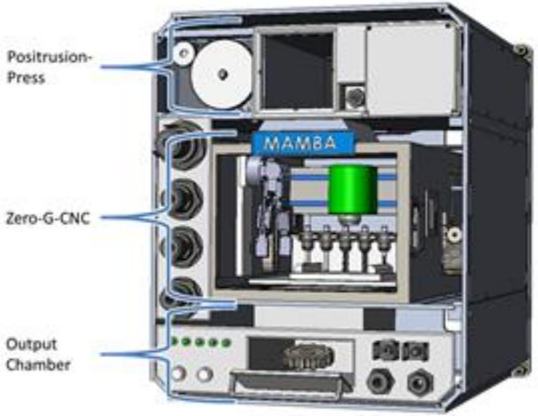


Illustration of UAM process (image courtesy of Ultra Tech)

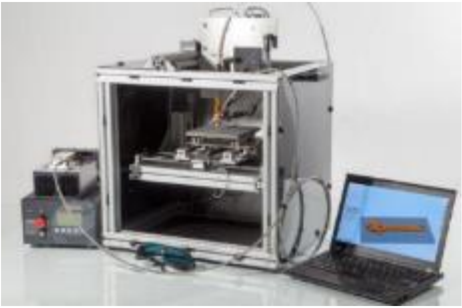
Toward an In-Space Metal Manufacturing Capability

- Tethers Unlimited MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly)
  - Phase I SBIR
  - Ingot-forming method to process virgin or scrap metal
  - Bulk feedstock is CNC-milled
  - Builds on recycling process developed through ReFabricator payload

- Techshot, Inc. SIMPLE (Sintered Inductive Metal Printer with Laser Exposure)
  - Phase II SBIR
  - AM process with metal wire feedstock, inductive heating, and a low-powered laser
  - Compatible with ferromagnetic materials currently
  - Test unit for SIMPLE developed under phase I SBIR; phase II seeks to develop prototype flight unit



Tethers Unlimited MAMBA concept. Image courtesy of Tethers Unlimited.



Techshot's SIMPLE, a small metal printer developed under a Phase I SBIR. Image courtesy of Techshot.

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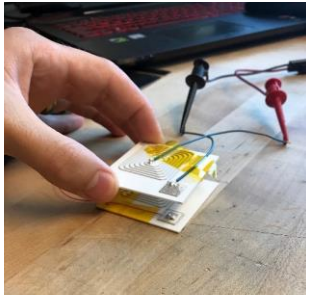
Ground-based work on additive electronics

- evaluating technologies to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions
  - In-house work uses nScrypt printer
    - 4 heads for dispensation of inks and FDM of polymers; also has pick and place capability

- Development of additively manufactured wireless sensor archetype (MSFC)
  - Printed RLC circuit with coupled antenna
  - Capacitive sensing element in circuit is pressure, temperature, or otherwise environmentally sensitive material
  - Sensing material also developed in-house at MSFC

- Design of pressure switch for urine processor assembly (UPA)
  - Existing pressure switch has had several failures due to manufacturing flaw in metal diaphragm
  - In additive design, switching is accomplished via a pressure sensitive material turning a transistor on when the system exceeds a certain pressure

- Work on miniaturization and adaptation of printable electronics for microgravity environment will continue through two contracts (phase I) awarded under SBIR subtopic In-Space Manufacturing of Electronics and Avionics
  - Techshot, Inc. (STEPS – Software and Tools for Electronics Printing in Space)
    - Direct write and avionics printing capability for ISS
  - Optomec working on miniaturization of patented Aerosol Jet technology



Printed wireless humidity sensor (wires attached for characterization purposes)

nScrypt multimaterial printer

Materials Development: Recyclable Materials

- Logistics analyses show the dramatic impact of a recycling capability for reducing initial launch mass requirements for long duration missions
  - Current packaging materials for ISS represent a broad spectrum of polymers: LDPE, HDPE, PET, Nylon, PVC

- Tethers CRISSP (Customizable Recyclable ISS Packaging) seeks to develop common use materials (which are designed to be recycled and repurposed) for launch packaging
  - Work under phase II SBIR
  - Recyclable foam packaging made from thermoplastic materials using FDM
  - Can create custom infill profiles for the foam to yield specific vibration characteristics or mechanical properties

- Cornerstone Research Group (CRG) is working under a phase II SBIR on development of reversible copolymer materials
  - Reversible copolymer acts as a thermally activated viscosity modifier impacting the melt properties of the material
  - Designs have strength and modulus values comparable to or exceeding base thermoplastic materials while maintaining depressed viscosity that makes them compatible with FDM

CRISSP (image from Tethers Unlimited)

FDM prints using reclaimed anti-static bagging film with reversible cross-linking additive (image from Cornerstone Research Group)

Use Scenarios for ISS Fabrication Capabilities: Biomedical Applications

- ERASMUS form Tethers Unlimited
  - Manufacturing modulus for production of medical grade plastics, along with the accompanying sterilization procedures required for subsequent use of these materials
  - Bacteria and viruses can become more virulent in the space environment and crew's immune systems may be compromised
  - Enables reuse of consumables/supplies or consumables manufactured from recycyled material

- Senior design project on medical capabilities and ISM
  - Medical industry has traditionally been an early adopter of AM
  - Lattice casts are custom designed to fit the patient, waterproof, and provide greater comfort and freedom in movement
  - Scan of limb can be imported into CAD software and custom mesh/lattice generated
  - Printed in multiple interlocking segments due to printer volume constraints

- Given logistical constraints of long duration spaceflight on consumables and unanticipated issues which may arrive even with a healthy crew, ISM will continue to explore evolving capabilities to best serve exploration medicine

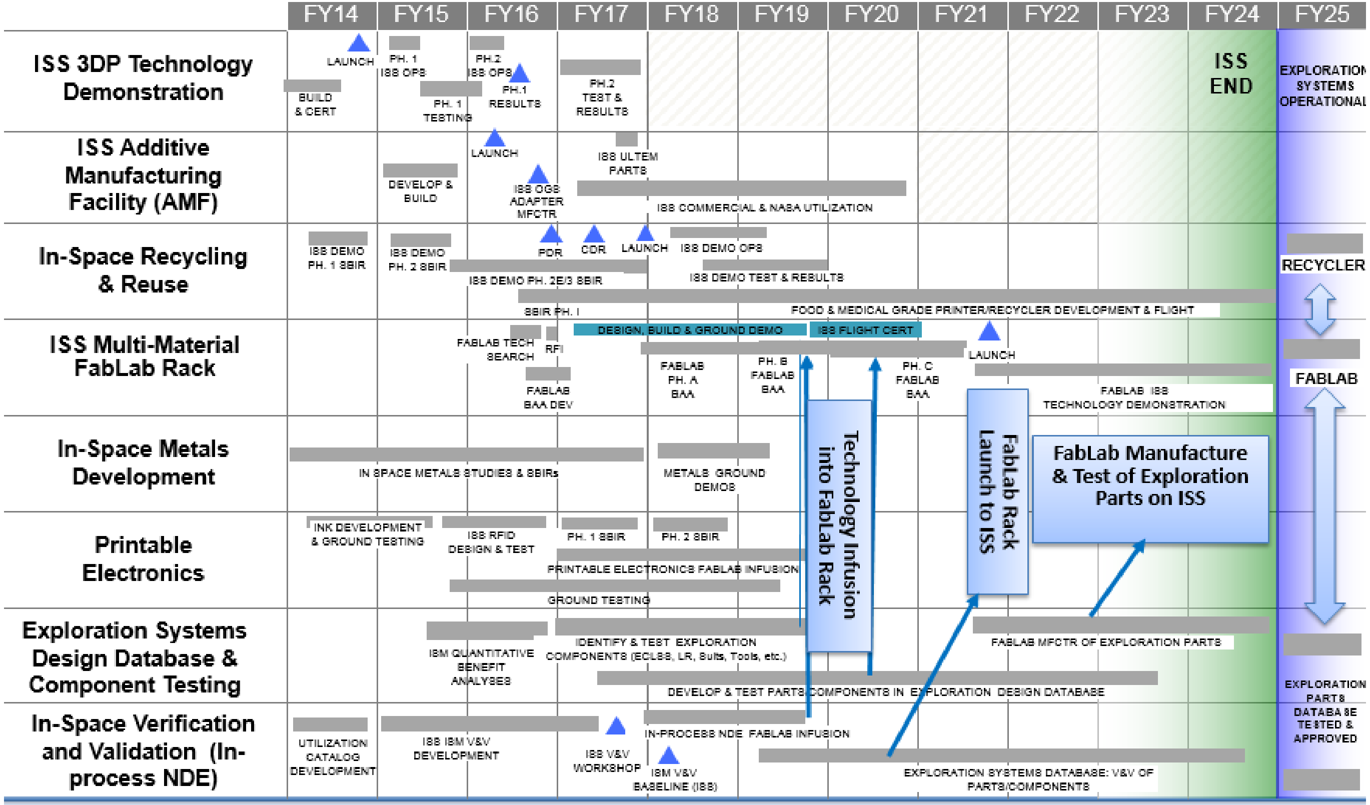
Potential food and medical consumables for manufacture and sterilization using the Tethers Unlimited ERASMUS system

One piece of a two piece lattice cast (senior design project)

Fabrication Laboratory Overview

- **Aligned with vision of in-space manufacturing project to develop and test on-demand, manufacturing capabilities for fabrication, repair and recycling during Exploration missions**
- ISM offers:
    - Dramatic paradigm shift in development and creation of space architectures
    - Efficiency gain and risk reduction for deep space exploration
    - "Pioneering" approach to maintenance, repair, and logistics will lead to sustainable, affordable supply chain model
- In order to develop application-based capabilities for Exploration, ISM must leverage the significant and rapidly-evolving terrestrial technologies for on-demand manufacturing
    - Requires innovative, agile collaboration with industry and academia
    - NASA-unique Investments to focus primarily on developing the skillsets and processes required and adapting the technologies to the microgravity environment and operations
- **Ultimately, an integrated "FabLab" facility with the capability to manufacture multi-material components (including metals and electronics), as well as automation of part inspection and removal will be necessary for sustainable Exploration opportunities**

ISS Technology Development Roadmap for ISM



NASA is working with industry and academia to adapt rapidly evolving terrestrial manufacturing, repair, and recycling technologies for in-space applications.

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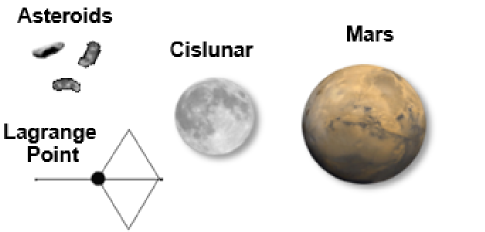
ISM Exploration Technology Development Roadmap

Ground & ISS Development & Demonstration				Exploration Implementation		
	 3D Print *Plastic Printing Demo* *Material Characterization*	 *Mat. Char. & Dev.* *Polymer Mfctr.* *Additive Construction*	*FabLab (Metals, Electronics)* *Polymer Mfctr. & Recycling* *External Mfg.*			
Pre-2012	**2014**	**2015-2017**	**2018 - 2024**	**2025 - 2035+**		
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	• ISS 3DP Tech Demo: First Plastic Printer on ISS • NIAC Contour Crafting • NIAC Printable Spacecraft • Small Sat in a Day • AF/NASA Space-based Additive NRC Study • ISRU Phase II SBIRs • Ionic Liquids • Printable Electronics	• ***3DP Tech Demo*** • ***Add. Mfctr. Facility (AMF)*** • ***ISM Certification Process Part Catalog*** • ***ISS & Exploration Material & Design Database*** • ***External Manufacturing*** • ***Autonomous Processes*** • ***STEM (Future Engs.)*** • ***Additive Construction***	ISS: Multi-Material FabLab Rack Test Bed *(Key springboard for Exploration 'proving ground')* • Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics, embedded electronics, autonomous inspection & part removal, etc. • In-Space Recycler Tech Demo • ACME Ground Demos	*Cislunar, Lagrange FabLabs* • Initial Robotic/Remote Missions • ***Provision feedstock*** • ***Evolve to utilizing in-situ materials (natural resources, synthetic biology)*** • ***Product: Ability to produce, repair, and recycle parts & structures on demand; i.e.. "living off the land"*** • Autonomous final milling	*Planetary Surfaces Points FabLab* • Transport vehicle and sites require FabLab capability (adapt for in-situ resource utilization) • ***Additive Construction & Repair of large structures***	*Mars Multi-Material FabLab* • ***Provision & Utilize in situ resources for feedstock*** • ***FabLab: Provides on-demand manufacturing of structures, electronics & parts utilizing in-situ and ex situ (renewable) resources.*** Includes ability to inspect, recycle/reclaim, and post-process as needed autonomously to ultimately provide self-sustainment at remote destinations.

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ISS serves as a Key Exploration Test-bed for the Required ISM Technology Maturation & Demonstrations

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The Multimaterial Fabrication Laboratory for ISS

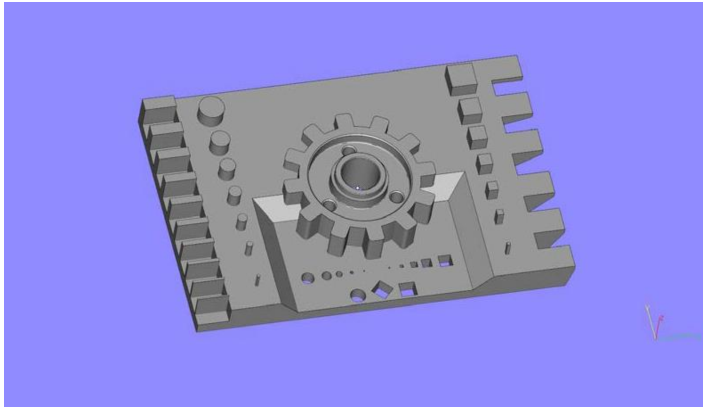
- **Broad Agency Announcement (BAA) for multimaterial, multiprocess fabrication laboratory for the International Space Station**
- Phased approach
  - Phase A – scaleable ground-based prototype
  - Phase B – mature technologies to pre-flight deliverable
  - Phase C – flight demonstration to ISS

Threshold	Objective
The system should have the ability for on-demand manufacturing of multi-material components including metallics and polymers as a minimum.	Multi-material capability including various aerospace-grade metallic, polymer, and/or conductive inks significantly increase the merit of the proposal.
The minimum build envelope shall be 6” x 6” x 6”.	As large of a build-volume and/or assembly capability as possible within the Express Rack volume constraints listed in Section 3.
The system should include the capability for earth-based remote commanding for all nominal tasks.	Remote commanding and/or autonomous capability for all tasks (nominal and off-nominal.
The system should incorporate remote, ground-based commanding for part handling and removal in order to greatly reduce dependence on astronaut time.*	The system should incorporate autonomous part handling and removal in order to greatly reduce dependence on astronaut time.*
The system should incorporate in-line monitoring of quality control and post-build dimensional verification.	The system should incorporate in-situ, real-time monitoring for quality control and defect remediation capability.

***** *Astronaut time is extremely constrained. As a flight demonstration, the ISM FabLab would be remotely commanded and operated from the ground, with the ultimate goal being to introduce as much eventual autonomy as possible. As a minimum, there should be no greater than 15 minutes of astronaut time required for any given nominal activity, with the end-goal being to apply the same rule to maintenance and off-nominal operations as well.*

The Multimaterial Fabrication Laboratory for ISS

- Core of the FabLab solicitation is an expansion of the material envelope for in-space manufacturing capabilities
  - Ability to fabricate quality aerospace grade materials in a controlled and repeatable manner on orbit
- Must provide system for raw feedstock and handling
- Must meet overarching ISS requirements (power, volume, interfaces) and demonstrate manufacturing processes are robot to changes in gravity vector
- Build geometrically complex components
- In-line system for verification and validation (current capabilities on-orbit are limited to visual inspection)



Example of range coupon taken from the BAA

Summary

- Multiple projects underway currently that infuse into ISM exploration systems
  - continued payload operations and materials characterization of specimens manufactured in microgravity
  - development and operation (in the 2018 timeframe) of a recycling payload for ISS by Tethers Unlimited, which represents the first closure of the manufacturing loop for in-space manufacturing
  - development of hybrid manufacturing (additive and subtractive) ground demonstration units with potential extensibility to on-orbit manufacturing
  - materials development work to enable maximum reuse of spaceflight materials (includes fundamental materials work on development of recyclable packaging materials, common use materials, and biologic feedstocks)
  - in-house and SBIR activities related to additive manufacturing of electronics (miniaturization of systems, development of conductive dielectric inks and metal inks, fabrication and testing of additively manufactured antennas, ultra-capacitors, and wireless sensors using the nScrypt)
  - continued exploration of ISM capabilities to support crew health and safety

- AM is a highly disruptive area and ISM seeks to leverage innovations in the broader field
  - To provide a rapid, on-demand suite of manufacturing capabilities to support long endurance exploration missions, ISM seeks to develop a FabLab, targeted for implementation on ISS in the early 2020s
  - ISS is near term test bed for in-space manufacturing systems that will be deployed on exploration missions

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Tennessee Valley Interstellar Workshop

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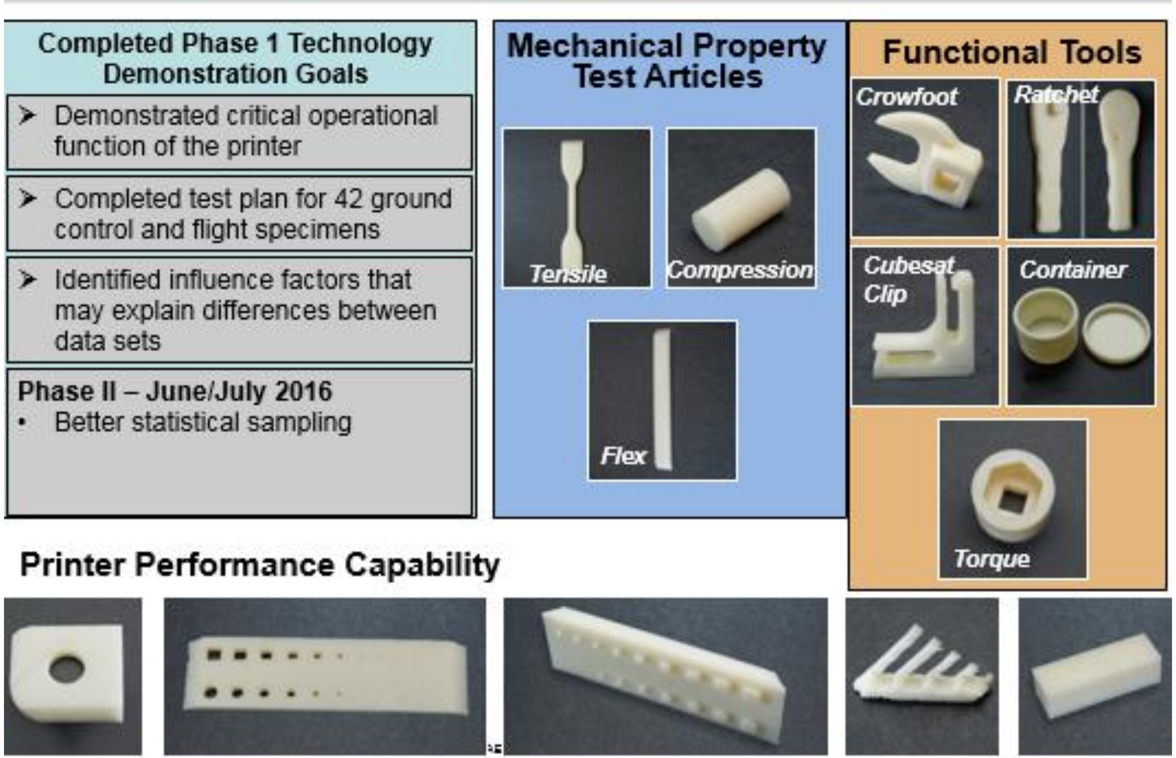
Tau Zero Foundation

3D Printing in Zero G Technology Demonstration Mission



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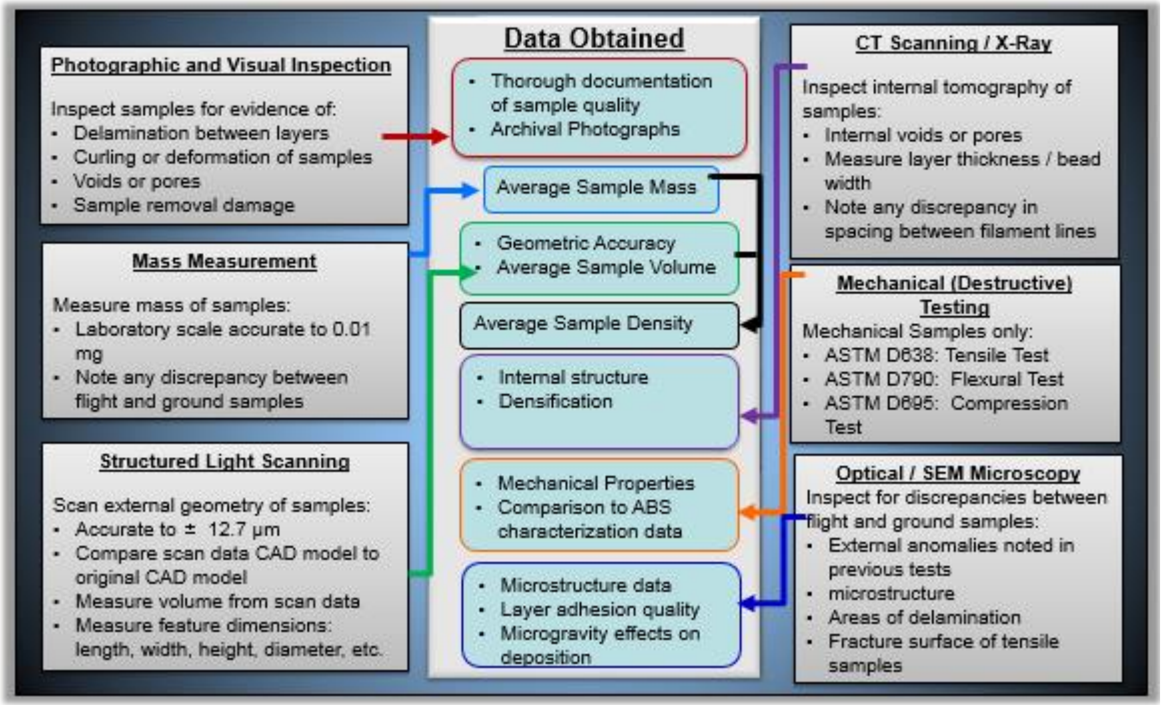
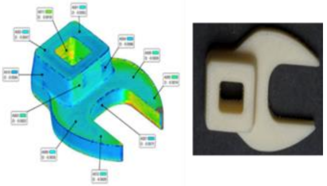
3D Printing in Zero G Tech Demo

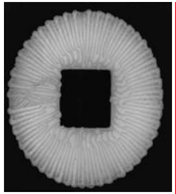


3D Printing in Zero G Technology Demonstration Mission

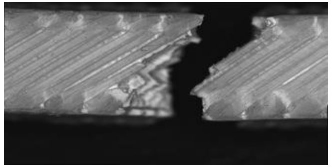
- The Phase I parts (first 21 parts printed) underwent testing and evaluation at the Materials and Processes Laboratory at NASA Marshall Space Flight Center and were compared with “ground truth” samples printed prior to printer’s launch to ISS.
  - Phase I report published as NASA technical publication in summer 2016, Phase II report will be published in Fall 2017
- **Differences noted in testing between the ground and flight specimens could not be definitively linked to microgravity as a processing variable**
- Additional ground-based characterization work in order to address variables related to the 3DP data set has also been subsequently published
- Complementary microstructural and macrostructural modeling work of FDM at Ames Research Center
  - Found no impact of microgravity on FDM process
    - ISM team providing data for model validation



Structured Light Scan Data of Crowfoot Tool 3D Printed on ISS



Optical Microscopy of Ground Control Ratchet Tool Head



Optical Microscopy of Break in Tensile Test Flight Specimen