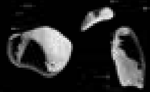


In-Space Manufacturing (ISM): Make it, Don’t Take It!!

Technical Collaboration Center (TCC)
Advanced Manufacturing & Carbon Materials Workshop

August 28, 2018
Hosted by Rice University, Houston

Niki Werkheiser
Manager, NASA In-Space Manufacturing (ISM)
256-544-8406

ISM Project Overview

***ISM Objective:* Develop and enable the technologies and processes required to provide affordable, sustainable on-demand manufacturing, recycling, and repair during Exploration missions.**

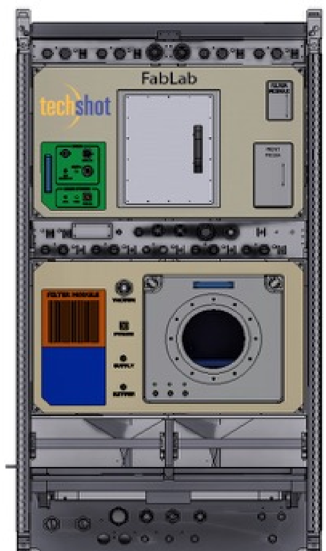
Why is this project important?

- *The operations & logistics approach utilized for ISS is not feasible for long-duration missions.
- ISM provides a “pioneering” approach which will help to enable sustainable, affordable Exploration mission operations and logistics.
- ISM is key to addressing significant logistics challenges for long-duration missions by reducing mass, providing flexible risk coverage, and enabling new capabilities that are required for Exploration missions.

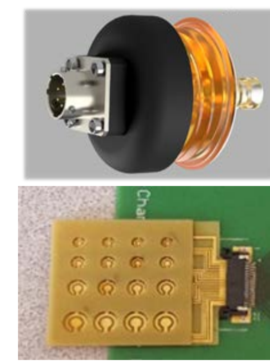
ISS Additive Manufacturing Facility (AMF)

Design Database Development ISM LSS Retaining Plate (Left); LR Urine Funnels (Right)

ISS Refabricator Demo



NextSTEP Multi-material ‘FabLab’



Printed Electronics: LSS Pressure Switch (Top); UV Radiation Sensor (Bottom)

* *Quantitative Benefit Analysis performed in 2016 for ISM Utilization study. The analysis used data from ISS maintenance and logistics tracking, as well as EMC Deep Space Habitat studies.*

ISM Primary Focus Areas

❖ ***In-Space Manufacturing Technology & Material Development: Work with industry and academia to develop on-demand manufacturing and repair technologies for in-space applications.***

- **Two polymer printers are currently on ISS (3DP Tech Demo & AMF). Supporting STMD TDM Archinaut (Made In Space, Inc.) Tipping Point for External ISM.**
- **NextSTEP BAA for the 1st Generation Multi-Material "FabLab" capable of on-demand manufacturing of metallic & electronic components/parts during missions.**

Multi-Material FabLab BAA will result in 1st Generation Exploration System

ISS Refabricator developed via SBIRs with Tethers Unlimited, Inc.

❖ ***In-Space Recycling & Reuse Technology & Material Development: Work with Industry and academia to develop recycling & reuse capabilities to increase mission sustainability.***

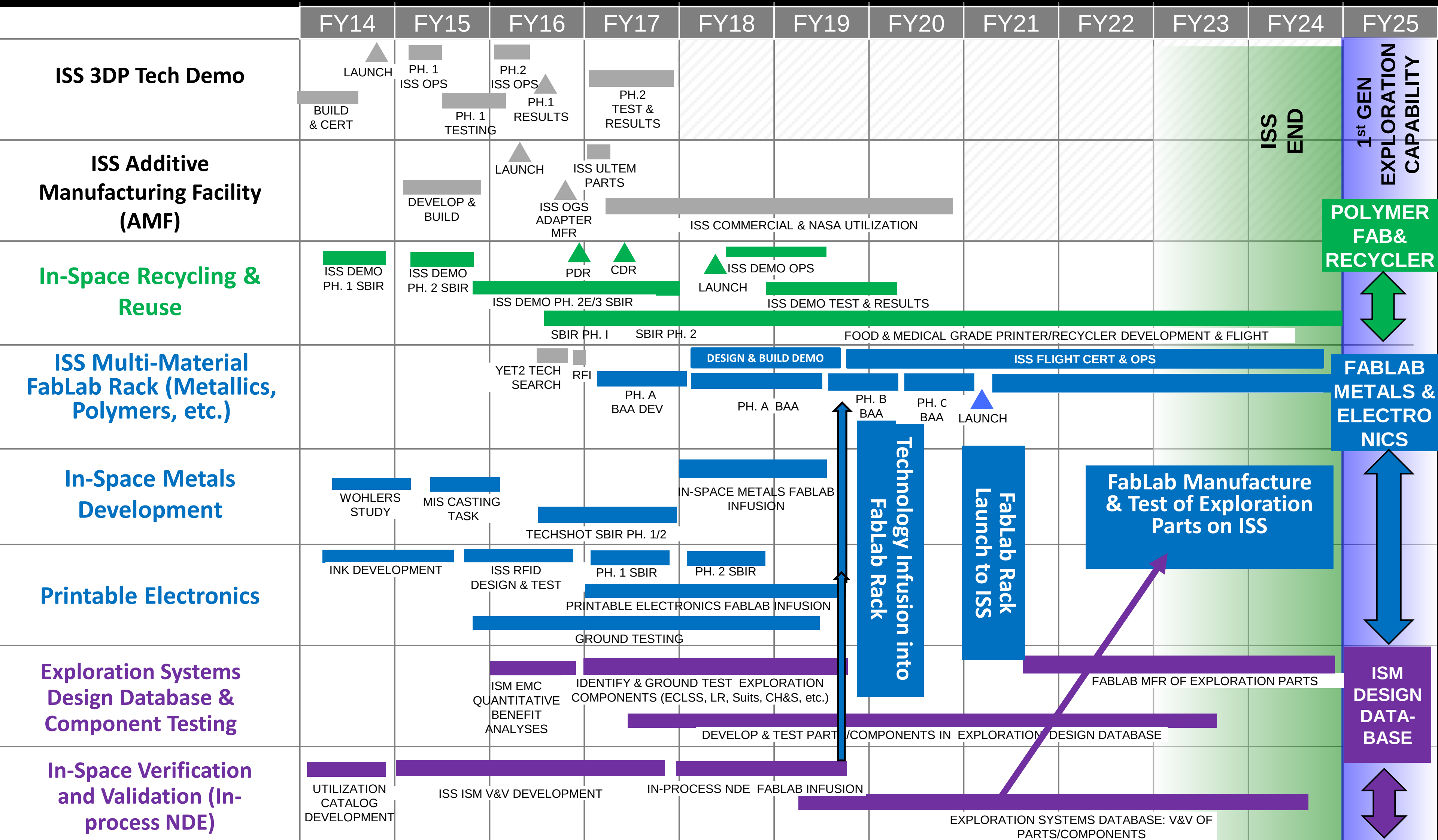
- **Refabricator (Integrated 3D Printer/Recycler) Tech Demo launching to ISS in early 2018.**
- **ERASMUS Phase II SBIR with Tethers Unlimited, Inc. (TUI) developing Food & Medical Grade Recycling Capability.**
- **Common Use Materials Phase II SBIRs (TUI & Cornerstone Research Group, Inc. (CRG))**

❖ ***In-Space Manufacturing Digital Design & Verification Database (i.e. WHAT we need to make): ISM is working with Exploration System Designers to develop the ISM database of parts/systems to be manufactured on spaceflight missions.***

- **Includes material, verification, and design data.**
- **Ultimately, this will result in an ISM Utilization Catalog of approved parts for on-orbit use.**

ISM works with Exploration designers to optimize parts/systems for on-orbit

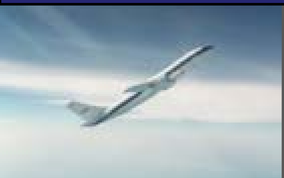
ISS ISM Capability Development Timeline



The ISS serves as a Key Exploration Test-bed for the Required ISM Technology Development and Capability Maturation. The Technology Demonstrations tested on the ISS will culminate in the 1st Generation Exploration ISM Systems.

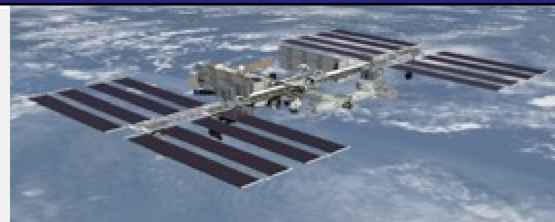
ISM Exploration Capability Roadmap

Ground & ISS Development & Demonstration




3D Print
Plastic Printing Demo

Material Characterization



Mat. Char. & Dev.

Polymer Mfg.

Additive Construction

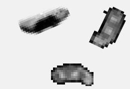
FabLab (Metals, Electronics)

Polymer Mfg. & Recycling

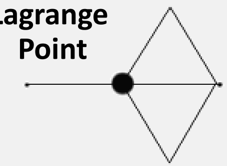
External Mfg.

Exploration Implementation

Asteroids



Lagrange Point



Cislunar

Mars

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

2014

- 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

2015-2017

- ***3DP Tech Demo***
- ***Add. Mfg. Facility (AMF)***
- ***ISM Certification Process Part Catalog***
- ***ISS & Exploration Material & Design Database***
- ***External Manufacturing***
- ***Autonomous Processes***
- ***STEM (Future Engineers)***
- ***Additive Construction***

2018 - 2024

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**

2025 - 2035+

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

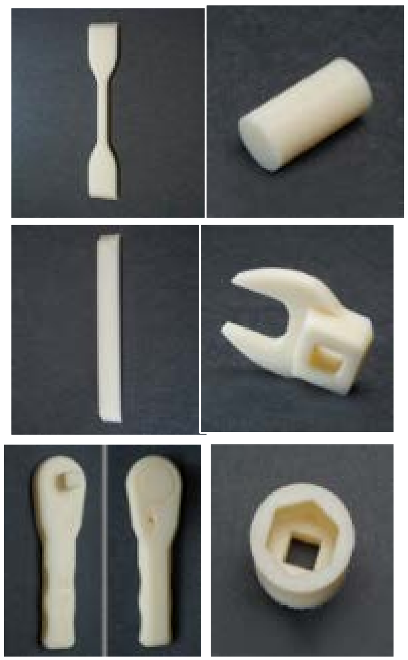
Planetary Surfaces Points FabLab
- Transport vehicle and sites require FabLab capability (adapt for in-situ resource utilization)
- ***Additive Construction & Repair of large structures***

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.

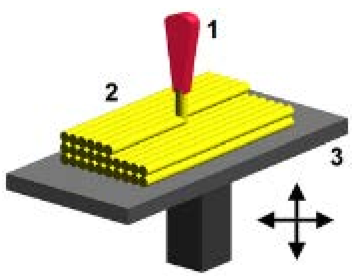
ISM provides a "Design for Maintainability & Repair" approach for Sustainable Exploration missions.

The First Step: 3D Printing in Zero G Technology Demonstration Ph. III SBIR with Made in Space, Inc.

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair



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

ISS 3D Print Tech Demo 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**

And then…Additive Manufacturing Facility (AMF)
Ph. I, II, II-E SBIRs, NASA IDIQ with Made in Space, Inc.

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

- The second 3D Printer, the Additive Manufacturing Facility (AMF), is now operating on ISS.
- This printer is owned and operated by Made in Space, Inc. thru agreement with the ISS National Lab and Center for Advancement of Science in Space (CASIS).
- NASA is one of the customers, as well as other government agencies, industry, and academia.
- AMF can print with ABS, Ultem and High-density Polyethylene.

MADE IN SPACE
madeinspace.us

ISS
U.S. NATIONAL LABORATORY
NASA CASIS
POWERED THROUGH PARTNERSHIP

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

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

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

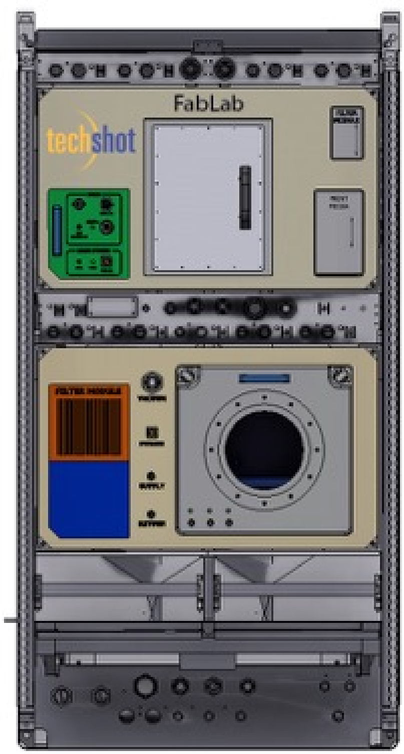
Phase C (18 months)
Goal: Demonstrate the capability of a Phase B ISM FabLab System on the ISS and evaluate risk. Phase C criteria are informed by Phase B results and will be released as a follow-on BAA or other acquisition vehicle.

- NASA solicited proposals for the development of a multi-material fabrication laboratory (FabLab) capable of end-to-end manufacturing during space missions.
- This is the first step toward a fully-integrated, on-demand manufacturing capability that is able to produce finished, ready-to-use metallic and/or electronic products during Exploration missions.
- NASA's strategy is to implement a phased approach of incrementally-increasing capabilities toward enabling Exploration of cislunar space and beyond.
- The Phase B solicitation will be openly competed and is anticipated to be released late in CY 2019.

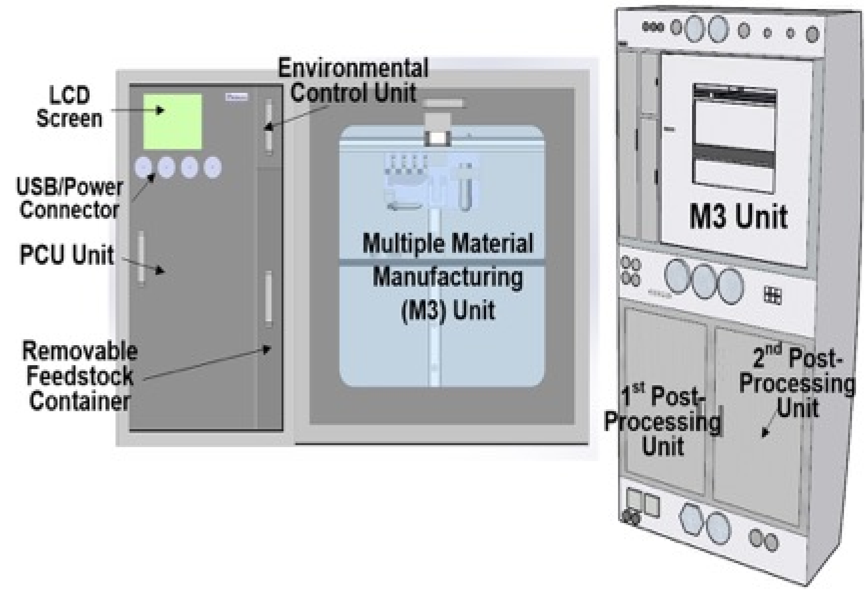
NextSTEP FabLab: Phase A Selectees

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

"The Techshot FabLab" - Techshot, Inc. (Greenville, IN)
Partners: Sciperio, GE Global Systems, University of Louisville, Walter Reed Army Medical Center, Uniformed Services University



"Microgravity Multiple Materials Additive Manufacturing (M3AM) Technology" - Interlog (Anaheim, CA)
Partners: Argonne National Labs, Micro Aerospace Solutions



"Empyrean- Sustainable, In-Space Fabrication Laboratory for Multiple Material Manufacturing, Handling, and Verification/Validation" - Tethers Unlimited, Inc. (Bothell, WA)
Partners: Stratasys, University of Texas El Paso (UTEP), BluHaptics, Vader Systems, IERUS.

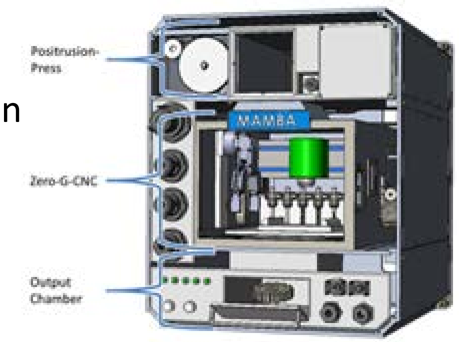
- **Combined funding for the Phase A Awards is approximately $10.2 million**
- **These companies will have 18 months to deliver the prototype, after which NASA will select partners to further mature the technologies for an ISS demonstration and 1st generation Exploration system. .**

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

In-Space Metal Manufacturing Capability SBIR Activities

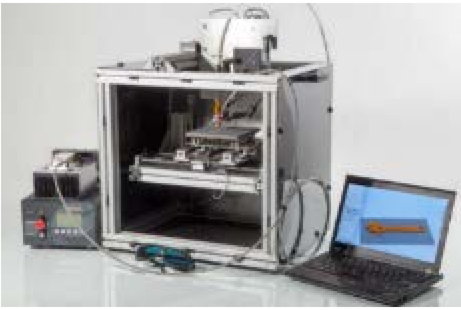
ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

- **Made in Space Vulcan unit (Phase II 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
- **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



Tethers Unlimited MAMBA

- **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



Techshot's SIMPLE, a small metal printer developed under a Phase II SBIR.

- **Ultra Tech Ultrasonic Additive Manufacturing (UAM) system (Phase II 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

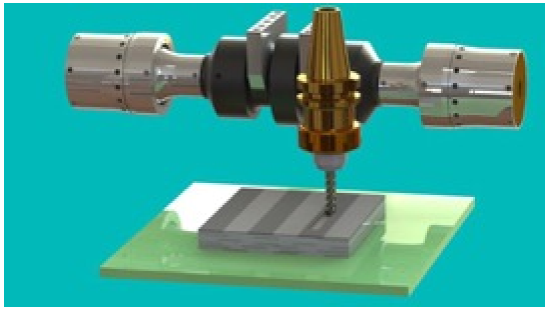
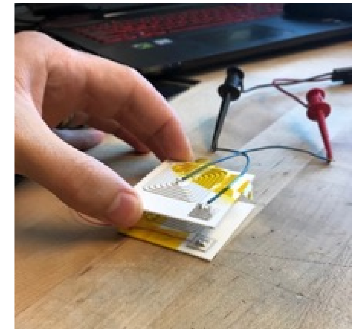


Illustration of UAM process under a Ph. I SBIR

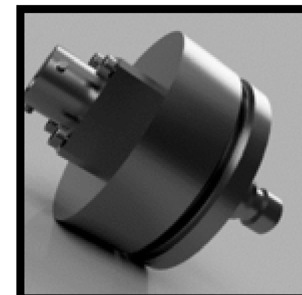
ISM Printable Electronics Development ARC/MSFC Collaboration

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

- Evaluating technologies to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions.
  - 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
  - 2018 SBIR Call for Plasma Jet Printing for In-Space Manufacturing subtopic
- In-house work:
  - Testing and characterization of nScrypt multi-material printer to inform design database and FabLab activities. 4 heads for dispensation of inks and FDM of polymers; also has pick and place capability.
  - ECLSS and ISM collaboration:
    - Design, build and test of printable sensors to detect humidity, CO, CH4, and H2
    - Design, build, and test of printable ECLSS pressure switch
  - Triboelectric Nanogenerator (TENG) for Power Generation: The ARC team designed and tested power generators for small scale power generation. The team also built a small Mars analogue weather chamber for demonstrating that Martian ambient is favorable for this approach.



Printed Wireless Humidity Sensor



Printable ECLSS Pressure switch

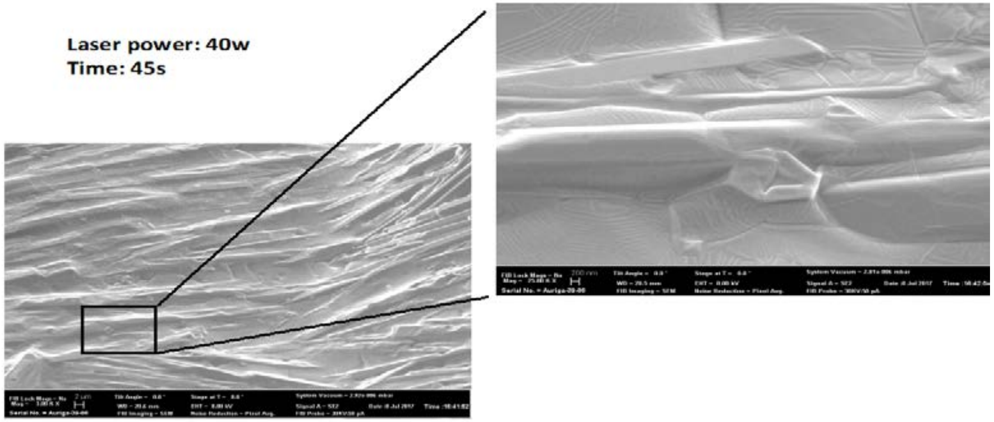
Martian Analogue Weather Chamber (top) with LED's directly powered by TENG (bottom) in the chamber

ISM Printable Electronics: Digital Ink/Materials Development

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

- **Electronic Ink/Materials Development and Testing:**

- **Completed the development of a new Inconel 718 ink and successfully printed on the MSFC nScrypt machine.**
  - Inconel 718 ink samples were provided to Oak Ridge National Laboratories (ORNL) and the University of TN for laser sintering development.
  - The samples had excellent sintering results using a low power 40W laser.



Sintering of Inconel 718 Ink Samples at Oak Ridge National Laboratories

- **Patent and Technology Transfer Underway:**
  - **Ultracapacitor Dielectric Ink: Presented at the TechConnect World Innovation Conference held on 5/15 – 17/17 in Washington, DC.; A U.S. Patent was granted on 8/29/17 and an international patent is currently being applied for.**
  - **Conductor ink**
  - **3D-printed carbon nanotube composite pressure sensor**
  - **Spark Plasma Sintered Supercapacitor for use in electronic applications**

In-Space Recycling & Reuse: ISS Refabricator
SBIR I, II, II-E, III with Tethers Unlimited, Inc.

ISM Focal Area: In-Space Recycling and Reuse

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 payload 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.**
- **Hardware turnover for launch on ISS in Summer 2018.**

In-Space Recycling & Reuse: Food & Medical Grade Refabricator & Sterilizer (Ph. I, II SBIR with TUI)

ISM Focal Area: In-Space Recycling and Reuse

The 1st Generation Exploration Recycler will include a 3D Printer, Recycler, and dry-heat sterilizer in order to fabricate and recycle polymer parts, including food and medical-grade items which make up a high percentage of trashed materials on ISS. This effort is underway through a Phase II SBIR entitled 'Erasmus' with TUI. The Refabricator design and testing is informing the Erasmus activity.

- **ISM is working with the AES Logistics Reduction team at JSC for application cases. TUI digitally reconstructed the NASA-provided urine funnel drawing and made adaptations in order to better support its manufacturability.**
- **TUI provided three types of Urine Funnel specimens out of Foodsafe PLA (0.02mm, 0.05mm, and 0.25mm layer height) and one prototype out of Taulman 680 Nylon (0.20mm layer height).**
- **In addition to the Urine Funnel, the ERASMUS Phase II SBIR activity addresses food (i.e. spoon) and medical grade (i.e. otoscope specula) and specimen production as well.**
- **The prototypes are provided to the JSC Logistics Reduction team for further testing and analyses.**

Printed, Recycled, Sanitized Urine Funnels

Printed, Recycled, Sanitized Spoons

In-Space Recycling & Reuse: Common Use Materials Multiple Ph. I, II , II-E SBIRs

ISM Focal Area: In-Space Recycling and Reuse

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 such as LDPE, HDPE, PET, Nylon, and PVC. ISM is collaborating with ISS packaging and Logistics Reductions teams to identify materials and processes that will provide common use materials that can initially be used for packaging and can also be recycled into useable feedstock for fabrication of parts during the mission.

Two Ph. II-E SBIRs are currently underway with each of the companies including the other as partners on their relative contracts. The result is additional value and efficiency for NASA.

- **Tethers CRISSP (Customizable Recyclable ISS Packaging): 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) focusing 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)

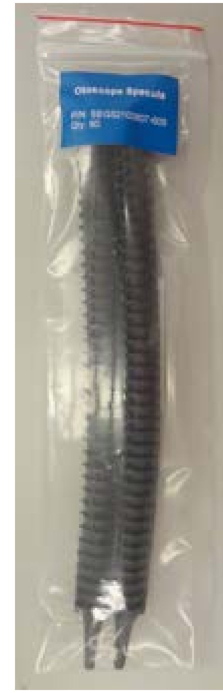
CRG FDM prints using reclaimed anti-static bagging film with reversible cross-linking additive

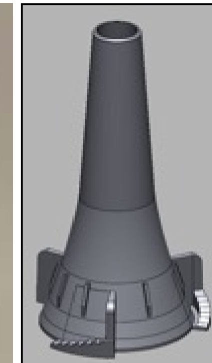
ISM Design Database:
Crew Health and Safety Applications

ISM Focal Area: In-Space Manufacturing Design Database (i.e. WHAT we make)

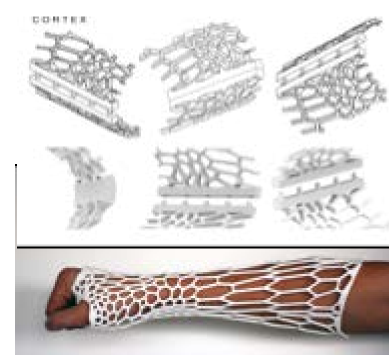
Crews will face unique healthcare challenges during long duration spaceflight missions. ISM is investigating the ways that on-demand manufacturing can assist with nominal medical needs, as well as emergency scenarios.

Areas of Interest	Examples
Medical Tools	Forceps, syringes, clamps, calipers, integrated wound care
Sterile Mfctr. & Recycle	TUI ERASMUS Phase II SBIR
Surgical Aids	Customized training aids, jigs/guides to aid in surgery, 3D models
Dental	Crowns, abutments, bridges, drill guides, aligners, bite guards, custom scans; Terrestrial dental industry early adopters of these technologies and processes.
Orthotics	Customized flexible splints, braces, casts, foot inserts
Auditory Implements	Customized otoscope specula, ear protection, hearing devices, acoustic monitor components
Vision Implements	Customized contact lenses, glasses (lenses and frames), diagnostics
Crew Personal	Urine Funnels (FY17); customized exercise accessories, grooming tools, foot care, etc.
Custom Pharmaceuticals	Customized antibiotics, vitamins and supplements, etc.
Bioprinting	Meat Products, Skin-grafts for Burn Care
Diagnostic Tools	Structured Light Scanners for comparative parametric data throughout mission





Otoscope Specula 'Reverse Engineered' for Crew Medical Office (JSC)



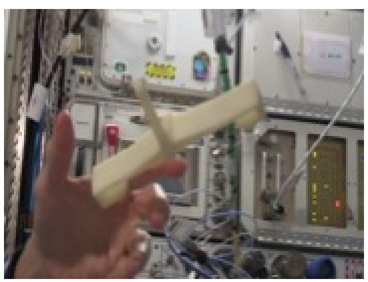
ISM Vanderbilt Senior Design Project

AMF Functional Parts made on ISS (NASA IDIQ with Made in Space, Inc.)

ISM Focal Area: In-Space Manufacturing Design Database (i.e. WHAT we make)

The Made in Space Additive Manufacturing Facility (AMF)

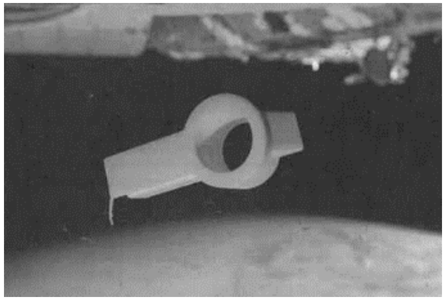
- **Additive Manufacturing Facility (AMF) is the follow-on printer developed by Made in Space, Inc.**
- **AMF is a commercial, multi-user facility capable of printing ABS, ULTEM, and HDPE.**
- **To date, NASA has printed several functional parts for ISS using AMF**



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). Others printed 5-30 and 6-16. All are now installed on BEAM.

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.

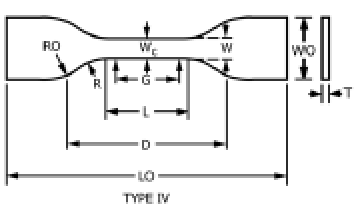


OGS Adapter: adapter attaches over the OGS air outlet and fixtures the velocicalc probe in the optimal location to obtain a consistent and accurate reading of airflow through the port. 7/19/2016.

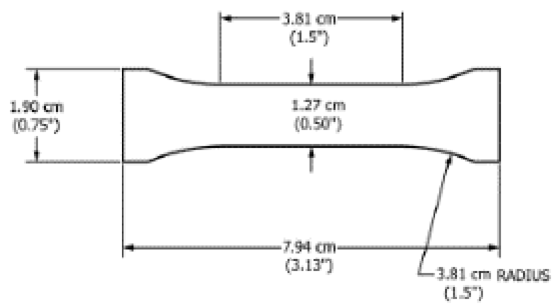
Additive Manufacturing Facility (AMF) with Made in Space, Inc.: Material Characterization

ISM Focal Area: In-Space Manufacturing Design Database (i.e. WHAT we make)

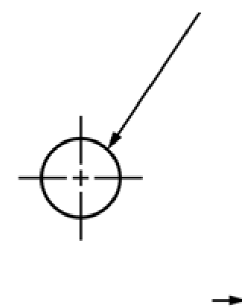
- **To further inform NASA-designed parts to be manufactured on AMF, a materials characterization plan was developed and is now on contract with Made in Space**
- **Initial plan is to develop characteristic properties for ABS produced by AMF, but plan is extensible to other materials**
- **Testing methodology similar to composites. Test coupons are machined from printed panels (*4 mm thickness*).**
- **Panels printed at 0 (for tension and compression), 90, and +/-45 layup patterns.**
    - **Ground panels have been delivered (made with a ground AMF unit equivalent to the flight unit) and are undergoing testing. Flight panels expected in Summer 2018.**



Type IV tensile specimen from ASTM D638



Thin-type compression specimen from ASTM D695. Requires support jig.



Flatwise tension from ASTM C297. Used to measure tensile strength in the through thickness of the specimen.

ISM Design Database
Consumable Sustainability

ISM Focal Area: In-Space Manufacturing Design Database (i.e. WHAT we make)

The nScrypt multi-material printer is being utilized to design and test multi-material parts and components, such as those for Printable Electronics, ECLSS, Logistics Reduction, etc. This effort also better informs the FabLab development. The nScrypt Capability Development Plan was developed and has resulted in completed print parameter optimization for ULTEM, as well as tensile results which are comparable to properties for ULTEM reported on the Stratasys printer specification sheet.

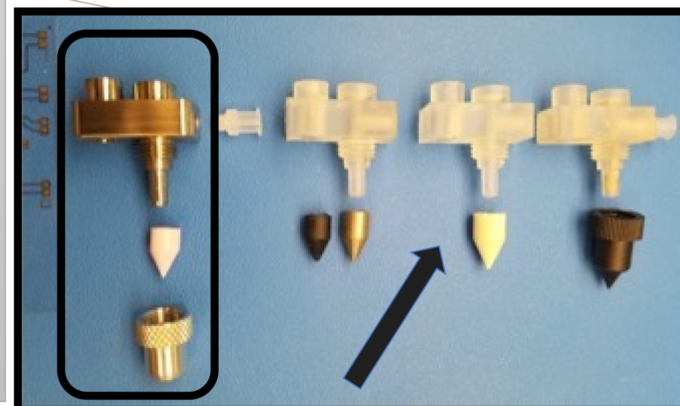
Demonstrated in-house capability to replicate spares and consumables for the nScrypt printer:

- nScrypt Ceramic Tip:
  - COTS: $260/each
  - In-house (MSFC): ~$0.25/each
- nScrypt Smart Pump valve body:
  - COTS: $2500
  - In-house (MSFC): ~$4.00 (for plastic resin for a consumable version of the Smart Pump valve body)

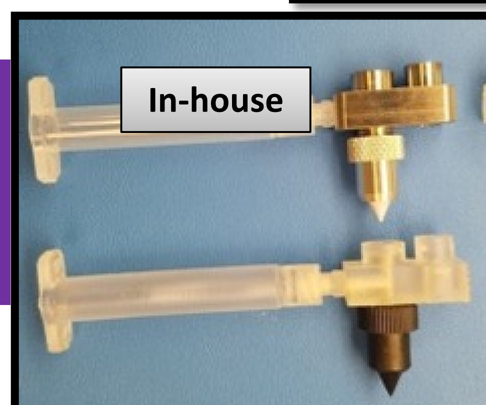
COTS Assembly

- Machined valve body, alumina tip, and tip holder
- ***Expensive and time consuming to clean***
- Inhibits fast multi-material processe

COTS



Comparison of COTS Assembly to In-house Assembly



In-House Printed Consumables and Spare parts

- Printed Valve Body, individual tips and integrated holder, and syringe
- ***Saves thousands of dollars***
- Enables efficient multi-material printing

Initial ISM/ LSS 'Design for Maintainability' Assessment Overview

ISM Focal Area: In-Space Manufacturing Design Database (i.e. WHAT we make)

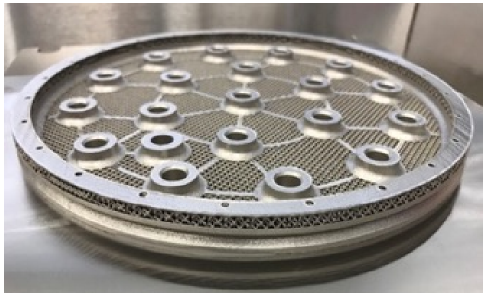
- **ISM and Advanced Life Support Systems (LSS) Projects performed an initial assessment of selected LSS subsystems and components for how to optimize on-demand, in-space manufacturing capabilities.**
- **This assessment was a first step toward an evolution to a 'design for maintainability' approach for long-duration missions rather than the current Orbital Replacement Unit (ORU) approach implemented for ISS hardware.**
- **For this initial assessment, two subsystems were considered:**
    - **The Four Bed Molecular Sieve (4BMS-X), which removes excess carbon dioxide (CO_2) from the International Space Station (ISS) atmosphere**
    - **The Urine Processing Assembly (UPA), which recycles human-generated urine to produce water for consumption and other uses.**
- **This assessment focused on components that have experienced repeated failures and/or those which require high maintenance and multiple consumables.**
- **Forward work includes LSS providing ISM a comprehensive list of items that are plausible consumables, maintenance items, or failure items during missions.**
- **ISM will incorporate the results of this effort into the FabLab development process where applicable.**

Initial ISM/ LSS 'Design for Maintainability' Assessment
Initial 4BMS-X and UPA Candidates Identified

ISM Focal Area: In-Space Manufacturing Design Database (i.e. WHAT we make)

Four Bed Molecular Sieve (4BMS-X) Candidates :

- Zeolite Bed Retaining Plate (pictured)
- Zeolite (desiccant) Bed –Binder Jet System process has potential to be used with a silicate or phenolic binder and the zeolite beads instead of the traditional feedstocks, resulting in printed zeolite structures that would be more resilient to vibration and less likely to cause dusting.
- 4BMS-X Housings
- Air Selector Valves and Potentially Seals
- Blower



"Printed' Modified Dodecahedral Mesh Design for improved flow & strength with decreased mass and production time.

Urine Processor Assembly (UPA) Candidates:

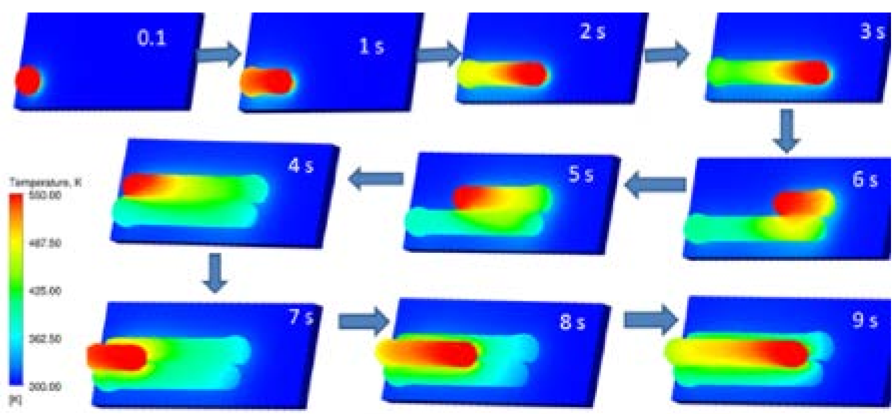
- Structural and Flow Components: Purge Pump Manifold (pictured) and Purge Pump Bracket can be highly optimized for significant mass and lead time reduction.
- Printable Electronics:
  - o Sensors: Wireless Humidity Sensor, temperature, strain gage, etc.
  - o UPA Pressure Switch
  - o Circuit Boards: Deemed Feasible - Work underway
- Filters and Tubing

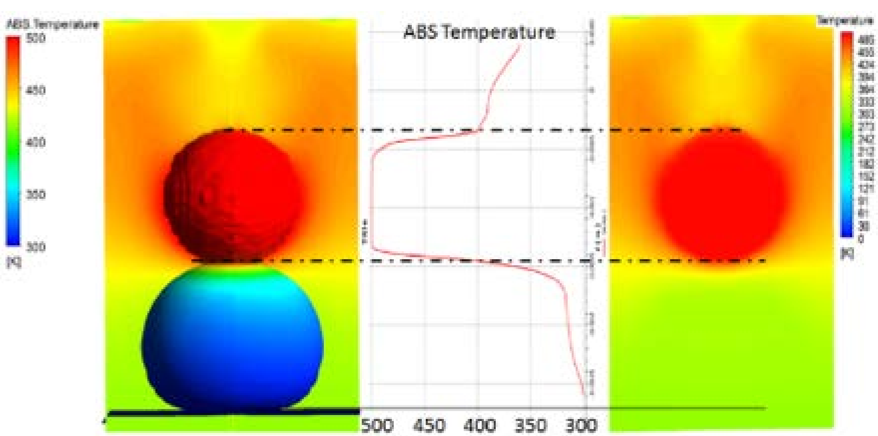
Potential to unify UPA parts, thereby reducing welds and saving material.

"Printable" Pressure Switch

ISM FDM Physics-based Modeling (Ames Research Center)

ISM Focal Area: In-Space Manufacturing Design Database (i.e. WHAT we make)





- Objective is to model FDM process in space (initially for ABS) and predict structural properties of the manufactured parts
- Use physics based analysis of FDM to determine what physics phenomena may be distinct in space-based manufacturing
- Developed FE model in ANSYS CFX for coupled fluid flow and heat conduction problem associated with filament extrusion and deposition
- Performed qualitative analysis of inter-diffusion between two molten roads based on polymer reputation theory for long-chain molecules
- Concluded that the reputation time is much smaller than the time to cool down to glass transition temperature
- ***No significant changes in road shape, filament temperature distribution, die swell, or evolution of temperature profile noted in modeling and simulation due to variation in gravity parameter***

Slide credit: Dr. Dogan Timucin, Ames Research Center

ISM Partnerships: Collaborative Mechanisms

Novel, agile mechanisms for collaboration with external stakeholders across industry, academia and OGA's are the cornerstone of ISM's capability development roadmap.

Collaborative Mechanisms

- SBIRs (27 since 2013 with 3 ISS Demonstrations)
- Future Engineers SAA with ASME (6 national STEM Challenges since 2014)
- National Space Grant Foundation (5 X-Hab Challenges since 2014)
- NASA Tournament Labs (GrabCAD, Yet2, Freelancer Crowdsourcing)
- NextSTEP BAA (FabLab & Hab UTAS Collaboration)
- IDIQ (MIS ISS AMF Operations)
- STMD Tipping Point (MIS Archinaut)
- Multiple Cooperative Agreement Notices (CANs)
- Student Internships, Tech Fellows, and Visiting Professors
- NASA @ Work Challenges
- MSFC TIP/CIF Investments

ISM Partnerships: SBIR Infusion

- **Between 2013-18, ISM has created a new ISM SBIR Topic and multiple subtopics and awarded a total of 38 SBIRs with *three of these resulting in ISS Technology Demonstrations (see backup slide for additional details).***
  - 22 Ph. I
  - 8 Ph. II
  - 5 Ph. II E/X (one additional anticipated in FY18)
  - 2 Ph. III SBIRs
  - 1 IDIQ

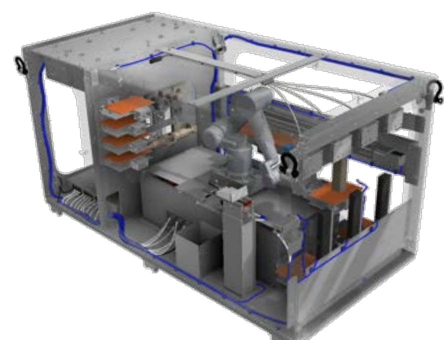
- **20 Current ISM SBIRs and one IDIQ Underway:**
  - 9 Ph. I SBIRS (2018)
  - 6 Phase II SBIRs (2015 - 17) including
  - 2 Phase II-Extended with one additional anticipated in FY18
  - 2 Phase III SBIRs (2013, 2015)

- **Three 2018 ISM SBIR subtopics with 26 Ph. I proposals submitted and 10 proposals recommended for award:**
  - Development of Higher Strength Feedstocks for In-Space Manufacturing (MSFC/9 Proposals)
  - In-situ Monitoring and Development of In-process Quality Control for In-Space Manufacturing Applications (MSFC/11 proposals)
  - Plasma Jet Printing Technology for Printable Electronics in Space (ARC/6 proposals)

ISM Partnerships: HEOMD & STMD

- For several years, HEOMD AES and STMD GCD have provided cost-sharing for ISM with AES providing procurement and GCD providing FTE.
- ISM provided SME's for the 3D Printed Habitat Challenge for formulation, review, and judging. Currently, ISM is working with Branch and Techmer Technologies (winners of the NASA 3D Printed Habitat Centennial Challenge) and Made in Space, Inc. on a proposal to use the Techmer regolith/polymer blend feedstock to fabricate the first regolith-based specimens on ISS using existing 3DP Tech Demo on-orbit.
- ISM provides the Project Lead/Contracting Representative (CoR), as well as technical Subject-Matter Experts (SMEs), for the STMD TDM In-Space Robotic Manufacturing and Assembly (IRMA) MIS Archinaut Technology Development Project (ATDP).

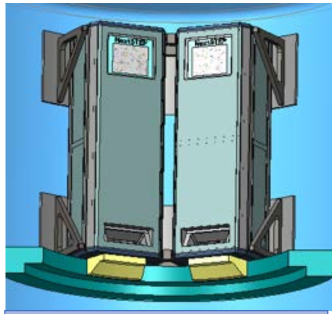
3D Printed Habitat Centennial Challenge Winners: Branch Technology



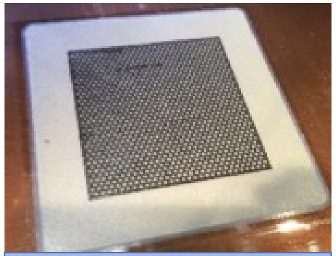
STMD TDM IRMA: MIS Archinaut

ISM Partnerships: AES Projects

- **LSS and NextSTEP UTAS Deep Space Hab Collaboration: Systematically review the design of deep space ECLSS systems and rack layouts for maintainability and build a catalog of parts consistent with micro/low gravity fabrication or repair. Hab Systems/ISM Collaboration: Developing lunar orbital platform for FabLab.**
  - Identified ISM Functional parts for test and analyses and defined technical plans and schedules. Design, test, and analyses efforts will continue to progress through FY18 and FY19.
- **AES Logistics Reduction Team Collaborations:**
  - Collaboration on Common-use Materials Development for Fabrication and Recycling, Food and Medical Grade Polymer Sterilization, Recycling, and Fabrication, and Procter & Gamble Collaboration: Materials R&D.
  - AES LR/ISM REALM Printed RFID Collaboration: Printed RFID antenna using ULTEM & PPSF (high temp, high strength & chemically resistant polymer) for testing at JSC.
- **SynBio Collaboration: ISM has worked with the ARC SynBio for several years with tasks focused on development of biologically-derived feedstocks.**



UTAS Racks



Gridded RFID Antenna printed with MSFC-developed Silver Ink

In Situ Biological Manufacturing

ISM Partnerships: *Other Government Agencies*

ISM is collaborating with cross-cutting DoD sectors to initiate a virtual collaboration platform for government, industry, and academic stakeholders relative to technology development, digital design databases, materials, verification processes, etc. ISM members are active in/with:

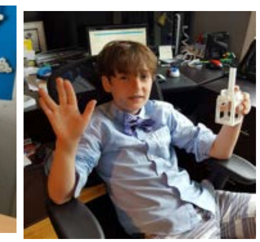
- Team Redstone AM Integrated Product Team (AMRDEC, SMDC, NASA):
- DARPA: Technology Development
- Oak Ridge National Labs: Collaboration with technology, process, and skill development.
- Picatinny Arsenal: Printable Electronics, Materials, and Processes
- AMRDEC with the objective of sharing capability and interests in advanced materials manufacturing**.**
- NextFlex, a Printable Electronics Consortium funded by the Office for the Secretary of Defense.
- America Makes: ISM team member is on the Board with regular involvement in relative activities.

Future Engineers
HEOMD SAA with ASME

Future Engineers is a national platform established in 2014 via a SAA between HEOMD and ASME which focuses on challenging K-12 students to use their imaginations and 3D modeling software to design items related to future space exploration missions.

- **Since 2014, six challenges have been successfully executed, engaging over 2,000 students from 42 states:**
  1. Space Tools Challenge:
  2. Space Container Challenge
  3. Star Trek Replicator Challenge
  4. Think Out of the Box Challenge
  5. Mars Medical Challenge
  6. Two for the Crew Challenge

- **NASA won the Best Student Challenge Award from the U.S. General Services Administration (GSA) as a part of their Five Years of Excellence in Federal Challenge & Prize Competitions.**
- **The Future Engineers Director has Ph. I and II SBIRs from the Department of Education to develop a multi-discipline platform for Future Engineers STEM Challenges.**



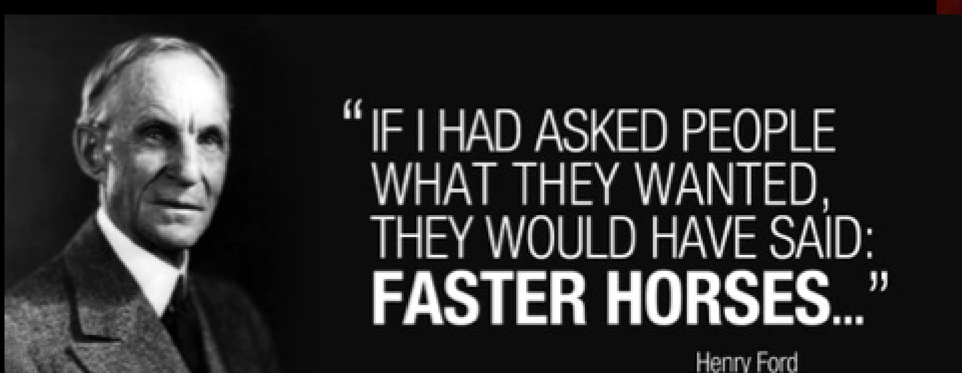
- **Future Engineers Program won the American Society of Association Executives (ASAE) highest honor, the Summit Award in 2015.**
- **The Multi-purpose Maintenance Tool (MPMT), which was the winning Teen part from the first Future Engineers Challenge, was 3D printed on the ISS AMF on 6/10/16. The student winner conducted a live interview with the ISS crew members from the MSFC Payload Ops & Integration Center.**

In-Space Manufacturing Summary

NASA's In-Space Manufacturing (ISM) Objective: Develop and test on-demand, manufacturing capabilities for fabrication, repair, and recycling during Exploration missions.

- **In-space Manufacturing offers:**
  - Dramatic paradigm shift enabling more earth-independent missions
  - 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 heavily leverages the significant and rapidly-evolving terrestrial technologies for on-demand manufacturing .**
  - Requires innovative, agile collaboration with industry and academia.
  - Focuses NASA-unique Investments primarily on developing the skillsets and processes required and adapting the technologies to the microgravity environment & operations.
- **ISM core development areas focus on three key capabilities for 1st Generation Exploration Systems:**
  - ISM FabLab Facility with the capability to manufacture multi-material components, including metals and electronics
  - Polymer Facility capable of fabrication, recycling, and sterilization of plastic materials, including food and medical-grade parts.
  - ISM Design Database & Utilization Catalogue (i.e. WHAT we make)

Questions & Discussion



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

BACKUP

In-Space Manufacturing: Overview and Roadmaps

ISM Capabilities Portfolio

IN-SPACE POLYMERS

- ISS On-demand Mfg. w/polymers
- 3DP Tech Demo
- Additive Manufacturing Facility with Made in Space, Inc. (MIS)
- Material Characterization & Testing

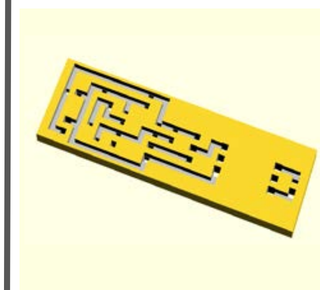
IN-SPACE RECYCLING

- Refabricator ISS Tech Demo with Tethers Unlimited, Inc. (TUI) for on-orbit 3D Printing & Recycling
- Multiple SBIRs underway on common-use materials & medical/food grade recycler

MULTI-MATERIAL FABLAB RACK

- Develop Multi-Material Fabrication Laboratory Rack as 'springboard' for Exploration missions
- In-Space Metals ISS Tech Demo
- nScrypt Multi-Material machine at MSFC for R&D

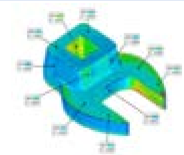
PRINTED ELECTRONICS

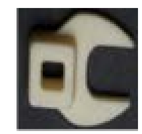


MSFC Conductive & Dielectric Inks patented

- Designed & Tested RFID Antenna, Tags and Ultra-capacitors
- 2017 ISM SBIR subtopic
- Collaboration w/ARC on plasma jet technology

IN-SPACE V&V PROCESS





- Develop & Baseline on-orbit, in-process certification process based upon the DRAFT Engineering and Quality Standards for Additively Manufactured Space Flight Hardware

EXPLORATION DESIGN DATABASE & TESTING

- Develop design-level database for micro-g applications
- Includes materials characterization database in MAPTIS
- Design & test high-value components for ISS & Exploration (ground & ISS)

In-Space Manufacturing Objective

The AES In-space Manufacturing (ISM) project serves as Agency resource for identifying, designing, & implementing on-demand, sustainable manufacturing solutions for fabrication, maintenance, & repair during Exploration missions.

ISM EXPLORATION APPLICATIONS

Unique Agency Expertise & Leveraging of Industry

ISM TECHNOLOGY DEVELOPMENT

ISM Parts/Systems Design Database & Test Articles

Answers WHAT we need to make

- Top-down, quantitative analyses of ISM benefits to crew time, cost, mass, & reliability (w/EMC).
- Provide expertise to NASA User community on AM design optimization & materials.
- Test high-impact parts/systems to inform Exploration technology requirements (bottoms-up).
- Develop In-space Parts Design Database, processes, & materials.

Part/System Requirements, Design, Materials & Processes

ISM

'One-stop shop' for AM design, materials, & technology expertise for NASA User Community.

AM EXPERTS

MATERIAL EXPERTS

DESIGNERS

Leverage industry to meet NASA needs (i.e. Agency knowledge-base for terrestrial technology).

In-space Manufacturing provides Exploration mission benefits to cost, mass, crew time & reliability

Proactive influence during Exploration design phase required for meaningful implementation

ISM Technology Development & Testing

Answers HOW we will make it

- Define NASA requirements for ISM Technologies based on ISS & EMC Applications identified (micro-g effects, performance, & operations)
- Collaborate and establish mechanisms to leverage industry to develop the technologies needed for NASA missions.
- Utilize ISS as test-bed for developing 'FabLab' to serve as springboard for cis-lunar 'proving ground' missions.

Multi-material 'FabLab' Test-bed

3DP Demo

AMF

Recycler

ISM Team

ISM Project Office (MSFC/ST23)
PM: Niki Werkheiser

- Frank Ledbetter (Sr. Advisor)
- Dana Solomon (Resources)
- Leigh Elrod & Libby Creel (Proj. Support)
- Diane Risdon & Jennifer Edmunson (Project Integration Engineers)
- Bob Gower (Schedule)

CSO (QD)
Terry Jones

CE (EE)
Tim Owen

HOW WE MAKE IT ?

ISM Technology Development
Kristin Morgan, Manager

- Fabrication Technology Development & Demonstrations (3D Print Demo, AMF, FabLab)
- Recycling & Reuse Development & Demonstrations (Refabricator, Erasmus)
- Printable Electronics (MSFC ES43/F. Thompson, ARC T/M. Meyyappan)
- External ISM (TDM Archinaut, ST23/L. Huebner)
- Remote & Autonomous Systems Dev
- Ground Testing
- Industry Capability Monitoring
- Relative SBIR Management

Develop & Demonstrate Technology

INTEGRATION

ISM Technical Integration
Tracie Prater, Manager

- ISM Materials & Feedstock Development - Single Use Polymer, Common Use Materials, Metallics, Reinforced, ISRU w(J. Edmunson),
- Process Integration: In-space Single Use Polymer Process (3D Print, AMF); In-space Recycling/Reclaim (Refabricator, Erasmus), Multi-Material Fabrication (Fab Lab metalics w/embedded electronics); ISM/ISRU Collaboration w/ J. Edmunson
- Exploration Capability Team Integration
- Physics-based modeling (w/ARC)
- External Collaboration/Outreach
- Relative SBIR Management

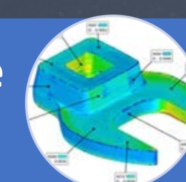
ISM Systems & Foundational Integration

WHAT WE MAKE ?

ISM Design Database
Mike Fiske, Manager

- ISM Utilization Catalogue Development
- Design & certification processes
- Inspection Processes
- "Fab Lab" Use Requirements & Part Development
- ISM Exploration Systems Capabilities Team Utilization Interface
- Part/System Definition for Analogous Missions
- Part/System Design Database External collaboration (Challenges, Crowdsourcing, etc.)

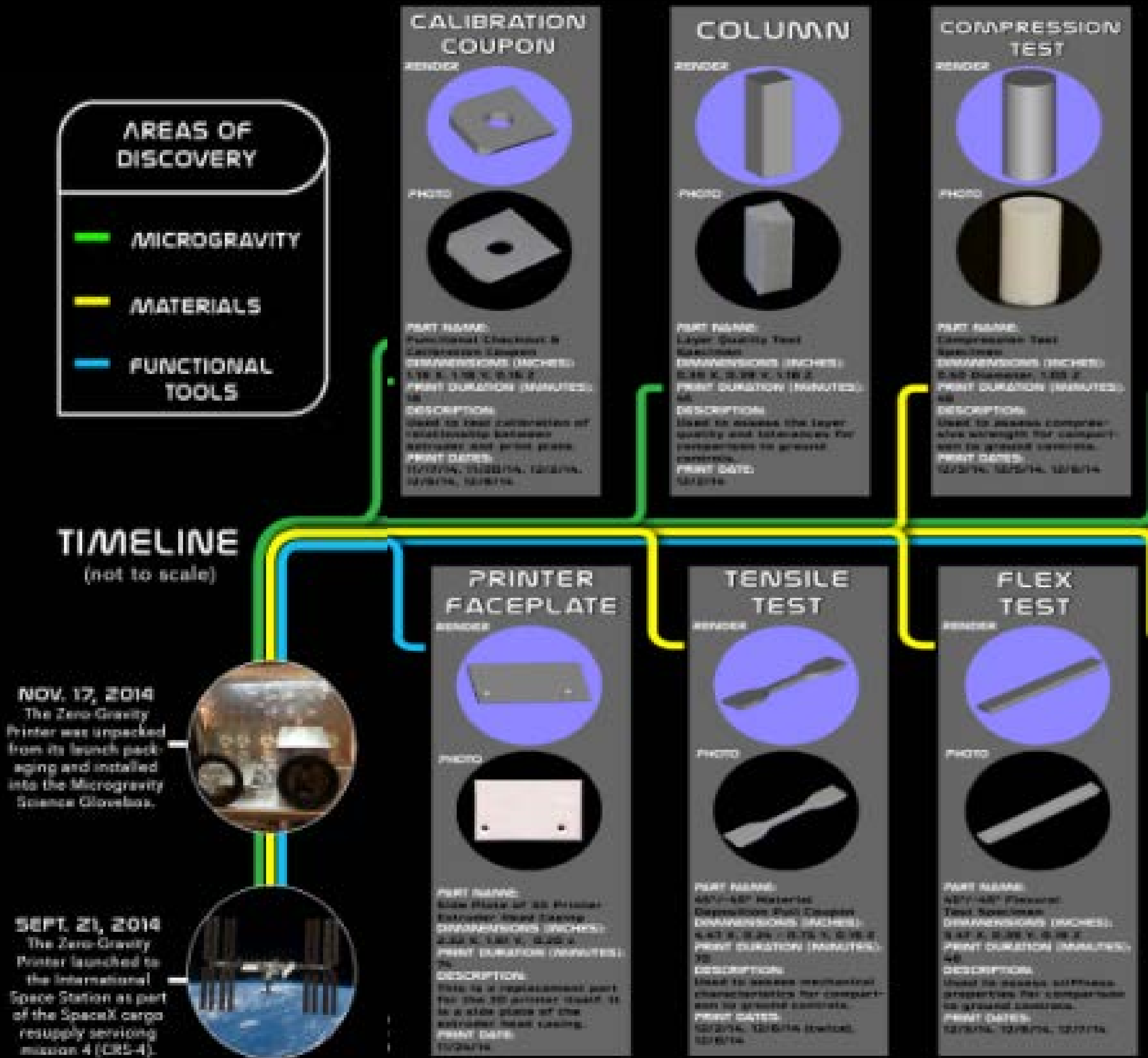
Design & Utilize Parts/Systems



The ISM project serves as an Agency resource for identifying, designing , and implementing on-demand, sustainable manufacturing solutions for fabrication, maintenance, and repair during Exploration missions.

In-Space Manufacturing:
Polymer Fabrication Technology Development

3D Printing in Zero-G Tech Demo Objectives



- The objective of the first phase of the technology demonstration is to confirm that ***Printer and Processes work in microgravity*** via printing of Test Articles & post-flight analyses.
- The objective of the second phase is to ***Demonstrate functionality of utilization parts*** such as crew tools and ancillary hardware.
- First parts printed returned on SPX-5 and will be sent to MSFC for detailed analyses and testing. All results will be published.

Image courtesy of MIS

3D Printing in Zero-g Tech Demo Prints

- Engineering Test Coupons:
  - Column: layer quality & tolerance
  - Tensile: mechanical characteristics
  - Compression: compressive strength
  - Flex: stiffness properties
  - Hole & Feature Resolution: geometric accuracy & tolerances for positive & negative range
  - Torque: torque strength
- Overhang Structure: would be difficult, if not impossible, to print in gravity w/out supports
- Utilization Examples:
  - Crowfoot Tool
  - Sample Container
  - Cubesat Clip
  - Ratchet (test of on-demand capability)

3D Print Tech Demo Specimen Testing
Phase I and II Prints

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

Photographic and Visual Inspection

Inspect samples for evidence of:
- Delamination between layers
- Curling or deformation of samples
- Surface voids or pores
- Damge from specimen removal

Mass Measurement

Measure mass of samples:
- Laboratory scale accurate to 0.01 mg
- Mass measurement used in gravimetric density calculation (volume derived from structured light scanning)

Structured Light Scanning

Scan external geometry of samples:
- Accurate to ± 12.7 µm
- Compare scan data CAD model to original CAD model and other specimens of the same geometry
- Measure volume from scan data
- Measure feature dimensions

Data Obtained

- Thorough documentation of sample in as-built condition

Average Sample Mass

- Geometric Accuracy
- Average Sample Volume

Average Sample Density

- Internal structure and porosity
- Densification
- Evidence of printing errors

- Mechanical Properties: UTS, E, % elongation, UCS, G

- Microstructure data
- Layer adhesion quality
- Microgravity effects on deposition

CT Scanning / X-Ray

Inspect internal tomography of samples:
- Internal voids or pores
- Measure layer thickness / bead width
- Density measurement (mean CT)
- Note any misruns or evidence of printing errors

Mechanical (Destructive) Testing

Mechanical specimens only:
- ASTM D638: Tensile Test
- ASTM D790: Flexural Test*
- ASTM D695: Compression Test

Optical / SEM Microscopy
- External features (warping, voids, protrusions, deformations)
- Internal structure
  - Filament layup
  - Voids
  - Fracture surfaces
  - Delamination

*flexure specimens not part of phase II

3D Printing in Zero G Technology Demonstration Phase I Key Results

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

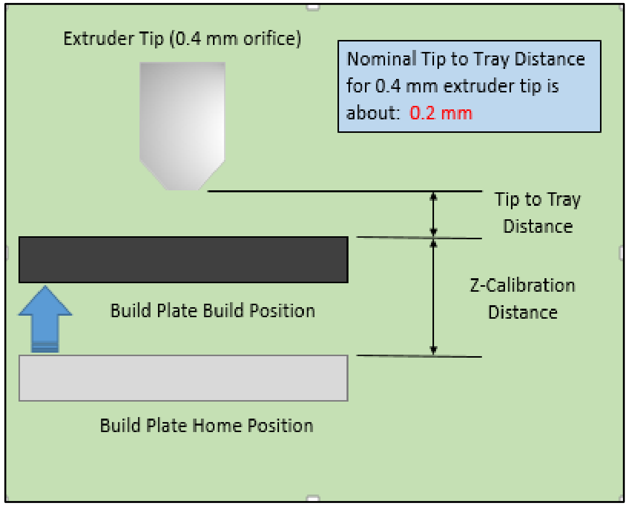
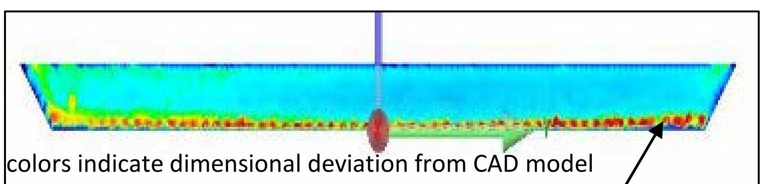


Illustration of z-calibration and tip to tray distances

Structured light scan of flight flexure specimen



Red indicates slight protrusions of material

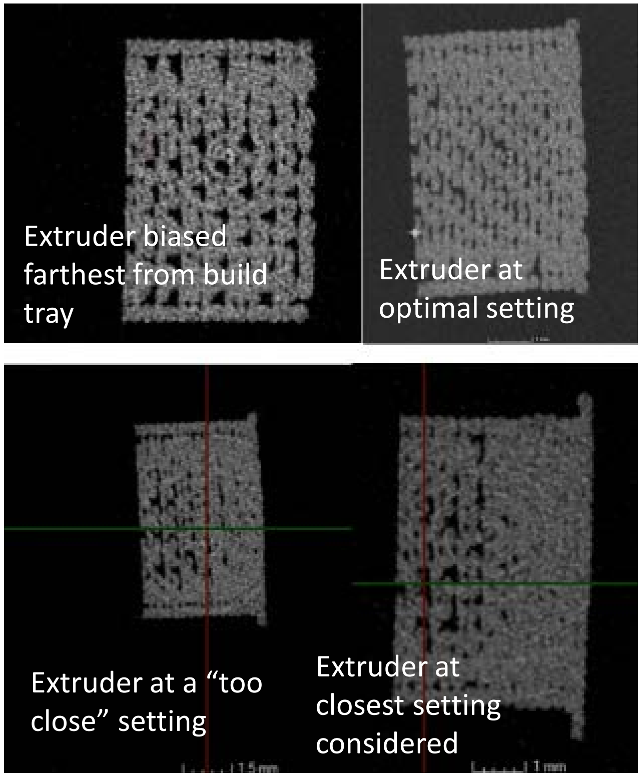
- **Phase I flight and ground prints (ground prints were manufactured on the 3DP unit prior to its launch to ISS) showed some differences in densification, material properties and internal structure**

- **Differences were determined, through SEM analysis, chemical analysis of the specimens, and a subsequent ground-based study using the identical flight back-up unit to be largely an artifact of differences in manufacturing process settings between ground and flight and also attributable to build to build variability.** ***No engineering significant microgravity effect on the FDM process has been noted.***

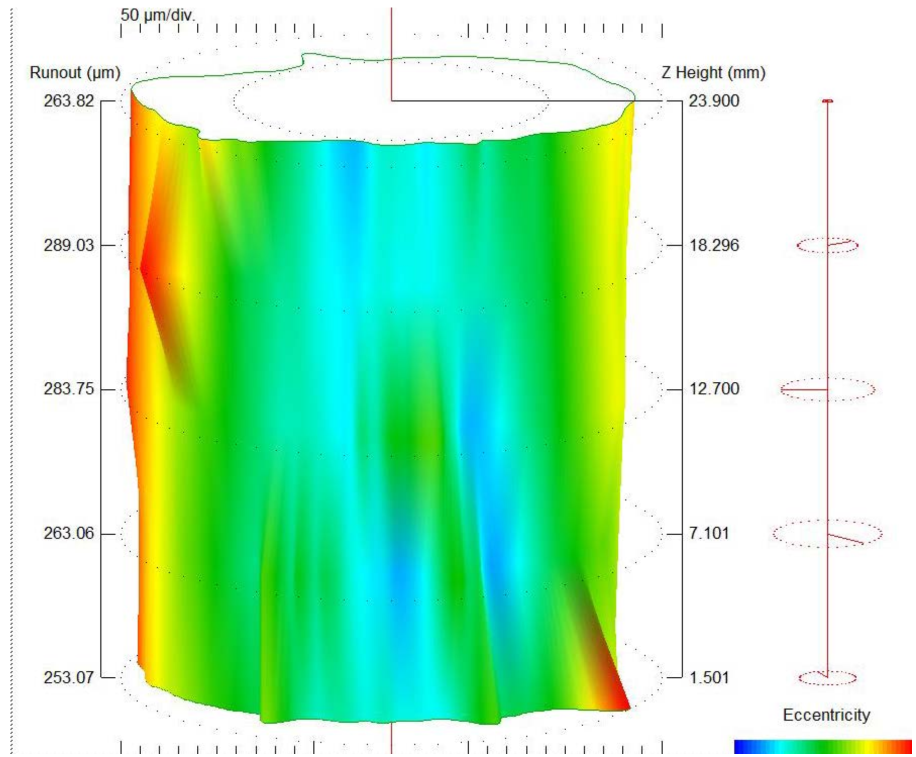
- **Complete results published as NASA Technical Report (July 2016) and published in *Rapid Prototyping Journal***

3D Printing in Zero G Technology Demonstration
Tip-to-Tray Ground-based Study Results

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair



CT cross-section images show evolution of tensile specimen structure with decreasing extruder standoff distance (images from reference , a ground-based study using the flight-back up unit). Bottom half of the specimen becomes denser and protrusions form at base of specimen as extruder standoff distance is decreased.

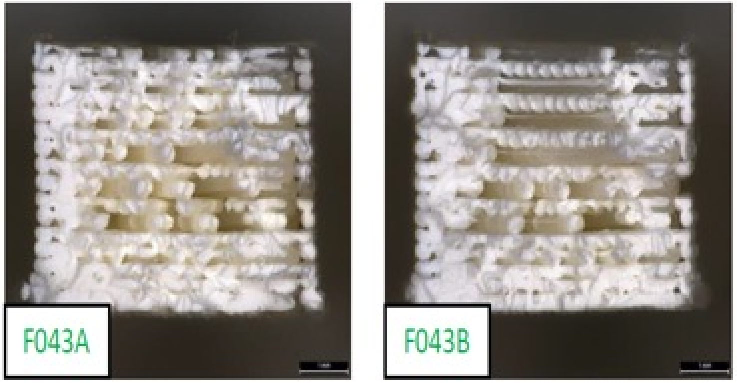


Results of cylinder mapping of compression cylinder from ground based study of extruder standoff distance using the flight backup unit. Off-nominal conditions for the extruder tip biased in either direction result in an increase in cylindricity. The greatest radial separation is observed for the closest extruder setting.

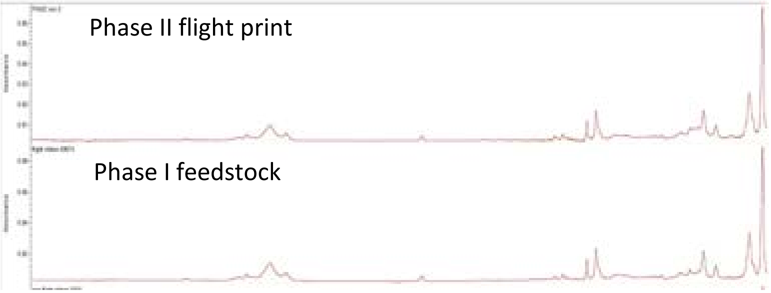
3D Printing in Zero G Technology Demonstration Phase II Key Results

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

- **For phase II operations, 25 specimens were built at an optimal extruder standoff distance.**
- **For the last 9 prints in the 34 specimen print matrix, extruder standoff distance was decreased intentionally to broadly mimic the manufacturing process conditions for the phase I flight prints.**
- **Complete phase II data published on the NASA Technical Reports Server**
- **Key findings:**
  - **All prints to date with 3DP appear to be part of the same family of data (result becomes apparent with greater statistical sampling made possible with phase II operations)**
  - **No substantial chemical changes in feedstock noted through FTIR analysis**
  - **No evidence of microgravity effects noted in SEM analysis, although there is some variation in internal material structure between builds and with changes in process settings**



Densification of first layers observed at slightly closer extruder distance; also noted in phase I.



FTIR comparison of flight phase II print with feedstock from phase I

In-Space Manufacturing:
Metal Manufacturing Technology Development

NextSTEP ISM FabLab: Target Capabilities

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

FabLab capabilities have been divided into minimum and objective capabilities. Phase A proposals must clearly address how minimum capabilities will be met.

Minimum Target Capabilities for a Ground Based Demonstration Prototype at End of Phase A	Objective Target Capabilities Flight Demonstration on the ISS Express Rack for Phase C
I. The system should have the ability for on-demand manufacturing of metallic components, designed to work in the micro gravity environment.	I. On-demand manufacturing of multiple materials in micro gravity, including various aerospace-grade metallics, polymers, composites and conductive (i.e. 'digital') inks are highly desired.
II. ISM FabLab Design must meet ISS Express Rack operational constraints (i.e. volume, power, etc.) as defined in Attachment 1 and maintain a minimum build envelope of 6"x6"x6".	II. ISM FabLab Design must meet ISS Express Rack operational constraints (i.e. volume, power, etc.) as defined in Attachment 1 and provide as large of a build volume as possible.
III. The system should limit required astronaut operations by optimizing Earth-based remote commanding capability for all nominal tasks, including part removal and handling. No nominal task should require more than 15 minutes of astronaut tended time.	III. In addition to the minimum objective, the system will incorporate earth-based remote commanding and/or autonomous capability for all nominal, maintenance, off-nominal[†] tasks, including part removal and handling.
IV. The system should incorporate remote and/or autonomous validation & verification capabilities to assure quality control (tolerances, voids, etc.) of parts produced.	IV. The system should incorporate remediation capability for defects identified during the in-line validation and verification (quality control) process.

NextSTEP ISM FabLab: Deliverables

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

Phase A	Phase B	Phase C
Performance Period: 18 months with a continuation review at 12 months. **Minimum Deliverables:** • Operational Bench-top/Lab-level Prototype Demonstration Report (with priced option for NASA on-site testing) • Preliminary Design Review (PDR) package including a Concept of Operations, Characterization and Test Articles • Technology Readiness Level (TRL) Assessments of capabilities and integrated system with defined maturation paths • Full report of development and test data. ***Note: NASA may elect to extend one or more awardees for additional period of performance in Phase A Technology development if it is deemed in the best interest of the Government.***	**Performance Period:** 12 - 18 months. **Minimum Deliverables:** • Engineering Test Unit (ETU) • Characterization and Test articles • Critical Design Review (CDR) Package for Integrated FabLab Design • Minimum of TRL 4-5 for the integrated system	**Performance Period:** 18 months. **Minimum Deliverables:** • Flight certified ISM FabLab Technology Demonstration System to fly on board the ISS • Operations support • Minimum of TRL 6-7

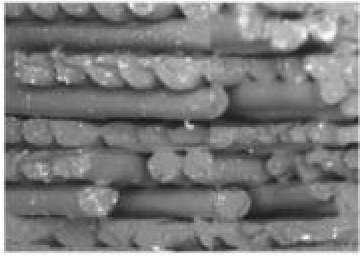
In-Space Manufacturing:
Design Database Development (i.e. WHAT we make)

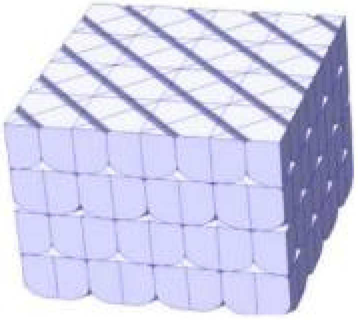
ISM FDM Physics—based Modeling (NASA Ames Research Center)

ISM Focal Area: In-Space Manufacturing Design Database (i.e. WHAT we make)

Structural Modeling of Macroscopic FDM parts

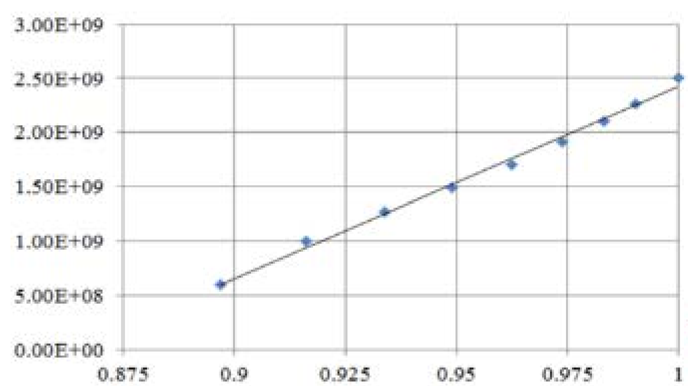
- **Modeled FDM parts as a composite cellular structure with known microstructure (as determined from the deposition process model)**
- **Effective structural parameters of the part were studied analytically based on classical homogenization and laminate theories**
- **Developed a finite-element model in ABAQUS to estimate the elastic moduli of representative volume elements or unit cells in order to verify analytical models**
- **Moduli were simulated for different layups, raster orientations, air gap distribution as a function of volume void fraction**
- **The part strength was estimated using the Tsai-Wu failure criterion**

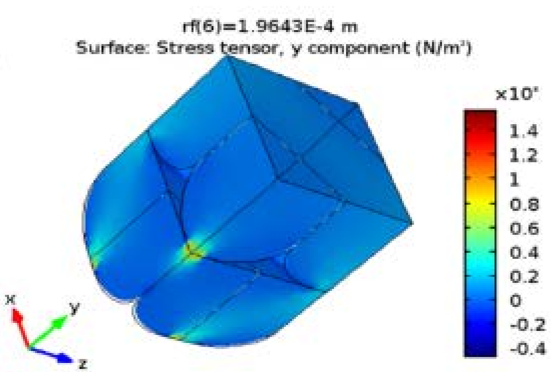




representative volume element

elastic modulus as a function of void fraction





unit cell FE simulation

Slide credit: Dr. Dogan Timucin, Ames Research Center

In-Space Manufacturing:
Heavily leveraging Collaborative Efforts

In-Space Manufacturing (ISM) Flight Projects SBIR Leveraging

ISS 3D Print Technology Demonstration (FY13-15): $4.7M

- ***NASA: $2.7M ($1.2M GCD FTE, Procurement; $1.5M AES FTE, Procurement)***
- ***Ph. III SBIR (MIS): $2.0M* (HEOMD ISS)**
- Resource Breakdown:
  - HEOMD AES: $1.5M
  - 8.9 FTE ($1.1M), $439K (procurement & travel)
  - STMD GCD: $1.2M
  - 6.3 FTE ($775K), $432K procurement

ISS Additive Manufacturing Facility (AMF) (FY12-18): $1.7M

- ***NASA: $400K (AES Procurement)***
- ***SBIR Program: $1.3M SBIR***
- Resource Breakdown:
  - 2012 Ph. I SBIR (MIS): $125K (SBIR funds)
  - 2013-14 Ph. II SBIR (MIS): $700K (SBIR Funds)
  - 2015 Ph. II-E SBIR (MIS): $750K ($500K SBIR Program, $250K ISS)
  - AMF IDIQ Contract for ISS 3D Printing Services (MIS): ~$150K (AES)

ISS Refabricator Technology Demonstration (FY14-18): $5.7M

- ***NASA: $4.2M ($3.0M AES Procurement, $1.2M GCD FTE)***
- ***SBIR Program: $1.5M***
- Resource Breakdown:
  - 2014 Ph. I SBIR (TUI, MIS): $250K (SBIR Program)
  - 2015/16 Ph. II SBIR (TUI): $750K (SBIR Program)
  - 2016/17 Ph. IIE SBIR (TUI): $750K ($500K SBIR Program, $250K AES)
  - Ph. III SBIR (TUI): $2.5M (AES)
  - Internal NASA Resources (FY15-18): 9.5 FTE ($1.2M GCD, $250K (AES)

ISM Leveraging Industry via Novel Contracting

ISM MFCTR & REPAIR

ISM RECYCLE & REUSE

ISM TECHNOLOGY DEVELOPMENT MULTI-MODEL CONTRACT IMPLEMENTATION

2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024

AMF PH. I (2012) & PH. 2 (2013-14) SBIRS

3D PRINT DEMO PH. III SBIR

ISS RECYCLING DEMO PH. I SBIRS

ISS REFABRICATOR DEMO PH. II (2015-16), PH. 2E (2017), & PH. III SBIRS (2017-18) SBIRS

FUTURE ENGINEERS 3D PRINTED DESIGN CHALLENGES SAA
NO FUNDS EXCHANGED

COMMON USE MATERIALS PH. I (2015) & PH. II (2016-17) SBIRS

ERASMUS PH. I (2016) & Ph. II (2017-18) SBIRS

ISM METAL PH. I (2016) & Ph. II (2017-18) SBIRS

PRINTABLE ELECTRONICS PH. I SBIRS (2017)

PRECISION PARTS PH. I SBIRS (2017)

SBIR PH. I (2018) & PH. II SBIRS (2019-20)

50% corporate contribution

FABLAB NextSTEP PH. A BAA (2018-19), PH. B (2019-20), PH. C (2020-24)

ISS ISM TECH DEMOS

3D PRINTER TECHNOLOGY DEMONSTRATION ON ISS (SBIR PH. III)

COMMERCIAL AMF ON ISS (IDIQ CONTRACT ESTABLISHED 2016)

REBABRICATOR TECHNOLOGY DEMONSTRATION ON ISS (SBIRS)

MULTI-MATERIAL FABRICATION LABORATORY ('FABLAB') ON ISS (NextSTEP BAA)

1st Gen. ISM Exploration Systems Deployment

The ISM Project utilizes multiple contracting mechanisms (i.e. SBIRs, BAAs, IDIQs, etc.) in order to leverage rapidly evolving commercial development which results in meaningful cost and schedule benefits to the Agency.

ISM SBIR’s

Company	2018: Development of Higher Strength Feedstocks for ISM	Status
Actuated Medical	AM of PEEK and Fiber-Reinforced PEEK for NASA Applications and Custom Medical Devices	Selected
Intelligent Optical	Thermoplastic Feedstock for 3D Printed Parts with Metal-like Strength	Selected
Geo Composites	Development of Fiber Reinforced Composite Feedstock for ISM of High Strength Parts	Selected
3F, LLC	High-Performance Feeder Filaments for 3D Printing	Selected

Company	2018: In-situ Monitoring & Development of In-process Quality Control for ISM Applications	Status
MIS	In-Situ Monitoring and Process Control (AMARU)	Selected
CRG	Automated In-Process Quality Control of Recycled Filament Production and FDM Printers	Selected
Ler Tech.	In-Situ Monitoring of ISM by Multi-Parameter Imaging	Selected
MetroLaser	Acoustical Signature Analysis for In-situ Monitoring and Quality Control	Selected
Cybernet	Feedback Sensors for Closed Loop Additive ISM	Selected

Company	2018: Plasma Jet Printing Technology for ISM	Status
Space Foundry	Plasma Jet Printing for ISM & ISRU	Selected

Company	2017: In-Space Manufacturing of Precision Parts	Status
UltraTech	ISS Multi-Material Fabrication Laboratory using Ultrasonic Additive Manufacturing (UAM) Technology	Ph. I complete, Ph. II selected
MIS	Vulcan Advanced Hybrid Manufacturing System	Ph. I complete, Ph. II selected
TUI	Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA)	Ph. I complete, Ph. II TBC

Company	2017: In-Space Manufacturing of Electronics	Status
Optomec	Adaptive Laser Sintering System for In-Space Printed Electronics	Ph. I complete
Techshot	Software and Tools for Electronics Printing in Space (STEPS)	Ph. I complete, Ph. II TBC

ISM SBIR's (cont.)

Company	2016: ISS Utilization Open Call	Status
Techshot	Sintered Inductive Metal Printer with Laser Exposure (SIMPLE)	Completed Phase I; Currently Phase II
TUI	ERASMUS Food Contact Safe Plastics Recycler and 3D Printer	Completed Phase I; Currently Phase II

Company	2015: Recycling/Reclamation of 3D Printer Plastic Including Transformations of Launch Package Solutions into 3D Printed Parts	Status
TUI	Customizable, Recyclable ISS Packaging (CRISSP)	Completed Ph. I, II; Phase II-E Awarded
Cornerstone	Reversible Copolymer Materials for FDM 3D Printing of Non-Standard Plastics	Completed Ph. I, II; Phase II-E Awarded
Techshot	Space Plastic Recycling System	Completed Phase I

Company	2014: Recycling/Reclamation of 3D Printer Plastic for Reuse ISS	Status
TUI	ISS Refabricator Technology Demonstration	Completed Phase I, II, II-X; Currently Phase III
MIS	R3DO: A Plastic Recycling System for Creating 3D Printer Feedstock On-Orbit	Completed Phase I

Company	2013: ISS Utilization Open Call	Status
MIS	Additive Manufacturing Facility (AMF)	Completed Phase I, II, II-E, Current IDIQ
MIS	Additive Manufacturing Technology Demonstration (i.e. 3D Printing in Zero-G)	Phase III SBIR Open

In-Space Manufacturing (ISM) SBIR Topic Description

- ***NASA's In-space Manufacturing (ISM) initiative is developing the on-demand manufacturing capabilities required for sustainable, long-duration space missions to destinations such as Mars.*** The ability to manufacture parts in space rather than launch them from earth represents a fundamental paradigm shift in the orbital supply chain model for human spaceflight. In-space manufacturing capabilities will decrease overall launch mass, while increasing crew safety and mission success by providing on-demand manufacturing capability to address known and unknown operational scenarios.

- ***The ISM roadmap includes a broad range of capabilities to address applications for manufacturing of various system parts/components, electronics, bio-printing, and external structures, as well as recycling/reclamation of parts and consumables for reuse.*** The scope of this work includes development and testing of the technologies, as well as developing the techniques and materials that will enable the technologies to become an institutionalized capability during space missions.

- ***This work is achieved thru ground-based development, testing and characterization, as well as utilizing the International Space Station (ISS)*** as a key microgravity test-bed for technology demonstrations in order to fully realize the goal of evolving from earth-reliant to earth-independent.

- NASA is investing in technologies and techniques geared toward advancing the state-of-the-art for in-space fabrication, repair and recycling technologies, as well as material characterization and testing. For technologies that could benefit from demonstration on the ISS, proposals should be written to indicate the intent to utilize the ISS. ***Research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit for NASA testing at the completion of the Phase II that could be turned into a proof-of-concept system for flight demonstration.***

In-Space Manufacturing (ISM) 2018 Subtopics

- ***High-strength Polymer Feedstocks for In-Space Manufacturing (Subtopic Manager: Tracie Prater/MSFC)**:*
  - This subtopic will develop the novel capability for on-demand manufacturing of high-strength polymers in microgravity via innovative techniques, materials, and/or technologies. An on-demand manufacturing capability to fabricate high-strength polymer parts in the microgravity environment is essential to expanding the use of in-space manufacturing beyond low criticality parts, thus providing a much broader range of utilization capability. There is a wealth of material and technology development in industry today in this arena that this subtopic can heavily leverage.

- ***In-situ Monitoring and Development of In-process Quality Control for In-Space Manufacturing (Subtopic Manager: Tracie Prater/MSFC)**:*
  - For in-space manufacturing capabilities to move past being a novel concept to an institutionalized process, a process for inline inspection and verification is required. On-orbit operations and constraints will never allow for the facilities and unique skill-sets that traditional, ground-based off-line quality control (nondestructive testing), including traditional finished part inspection and verification, requires. Thus, developing an in-line approach that is remote/autonomous and requires minimal power and volume is the most viable approach to on-orbit verification and validation of parts built in the space environment. Additionally, once created, this capability will have excellent terrestrial infusion potential, particularly for any remote, on-demand manufacturing and repair user.

In-Space Manufacturing (ISM) 2018 Subtopics (cont.)

- ***Plasma Jet Printing for In-Space Manufacturing of Printable Electronics (Subtopic Manager: Jessica Koehne/ARC):***

  - The ability to print various electronics components in space, on demand eliminates the need for supplying them from earth. Terrestrially, printable electronics is a rapidly growing field that can produce thin film transistors, memory devices, antennas, chem, bio and radiation sensors, energy storage devices such as batteries and supercapacitors, energy harvesting devices and many others on flexible substrates. The most common terrestrial approach to deposit the needed materials on substrates is inkjet printing. This, and other techniques in use now, require post-printing thermal treatment to get consolidated thin films with desirable morphology. Plasma jet printing has recently emerged as an alternative that eliminates this thermal annealing step, providing the desired thin film in one deposition step. Additionally, atmospheric pressure operation eliminates the need for expensive and heavy vacuum pumps, unsuitable for space mission logistics. However, this emerging alternative needs further maturation before it can be used in space missions. Key development areas include adapting common inks and dispersions used in inkjet printing and aerosol systems to plasma jet printers with proper nebulizers for extended deposition times. Additionally, throughput vs. plasma cylinder/nozzle diameter needs to be optimized with possibility of multiple nozzles that can be arranged in a showerhead configuration either to increase throughput or mix various types of feedstock for alloy-type materials. This subtopic seeks to address these core development areas resulting in a plasma jet capability for microgravity applications.