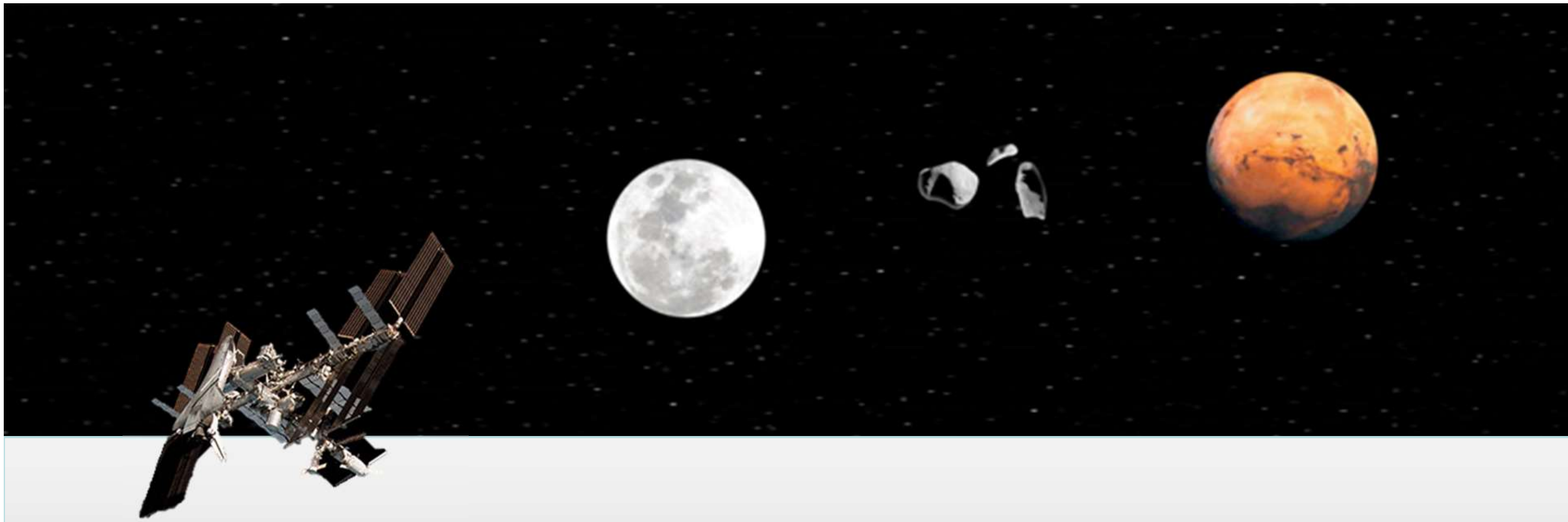

An Overview of NASA's In-Space Manufacturing Project

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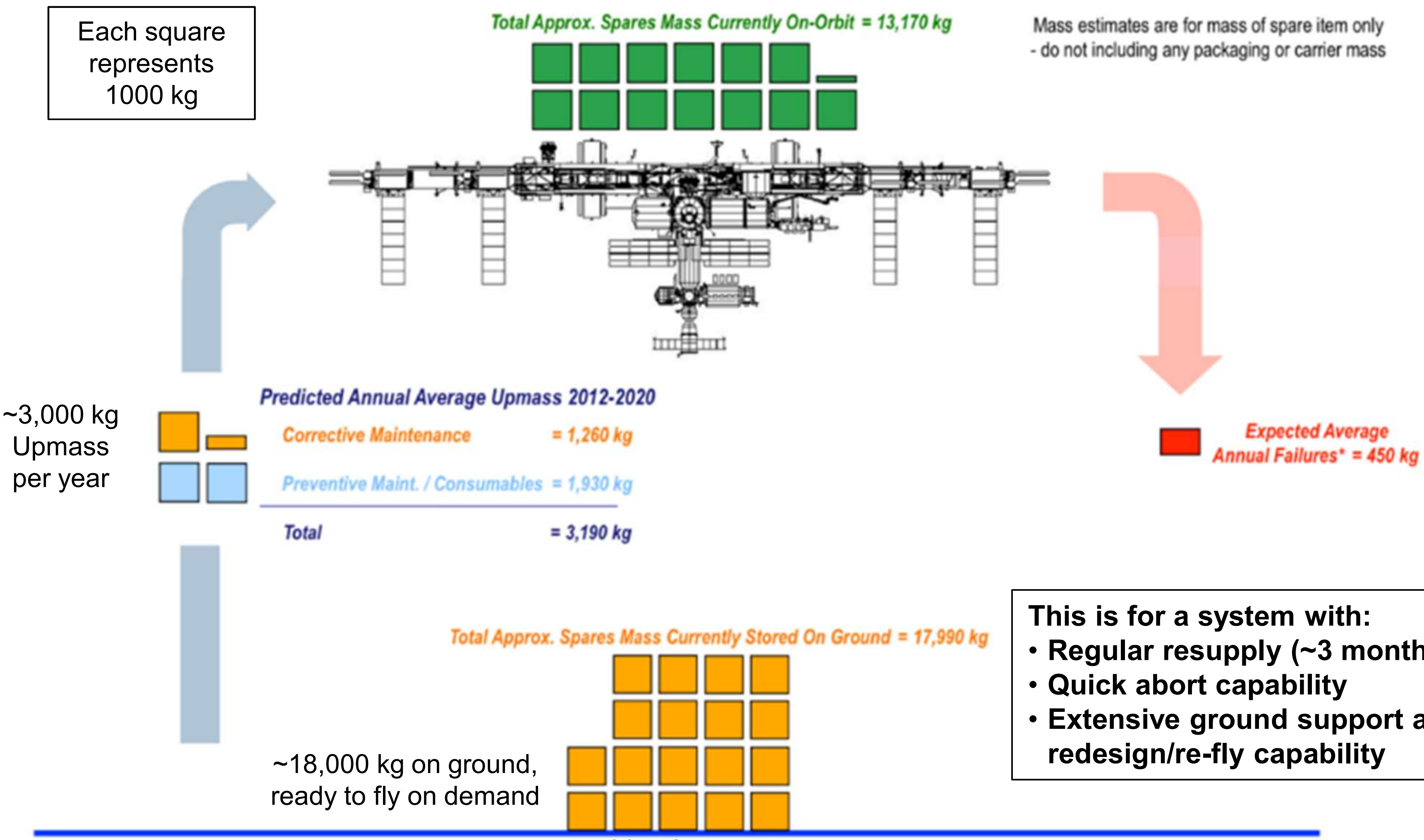
In-Space Manufacturing (ISM)

"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: ISS Logistics Model



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

* - Based on predicted MTBFs

Image credit: Bill Cirillo (LaRC) and Andrew Owens (MIT)

ISM 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 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 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.

Core ISM Focus Areas

- **In-Space Manufacturing & Repair: Work with industry and academia to develop on-demand manufacturing and repair technologies for in-space applications.**
  - Two polymer printers currently on ISS (3D Print Tech Demo & AMF). Supporting STMD TDM Archinaut (MIS) Tipping Point for External ISM.
  - NextSTEP Phase A Broad Agency Announcement (BAA) for the 1st Generation Multi-Material "FabLab" Demonstration capable of metallic manufacturing in-space.

Commercial MIS Additive Manufacturing Facility (AMF) on ISS developed via SBIRs

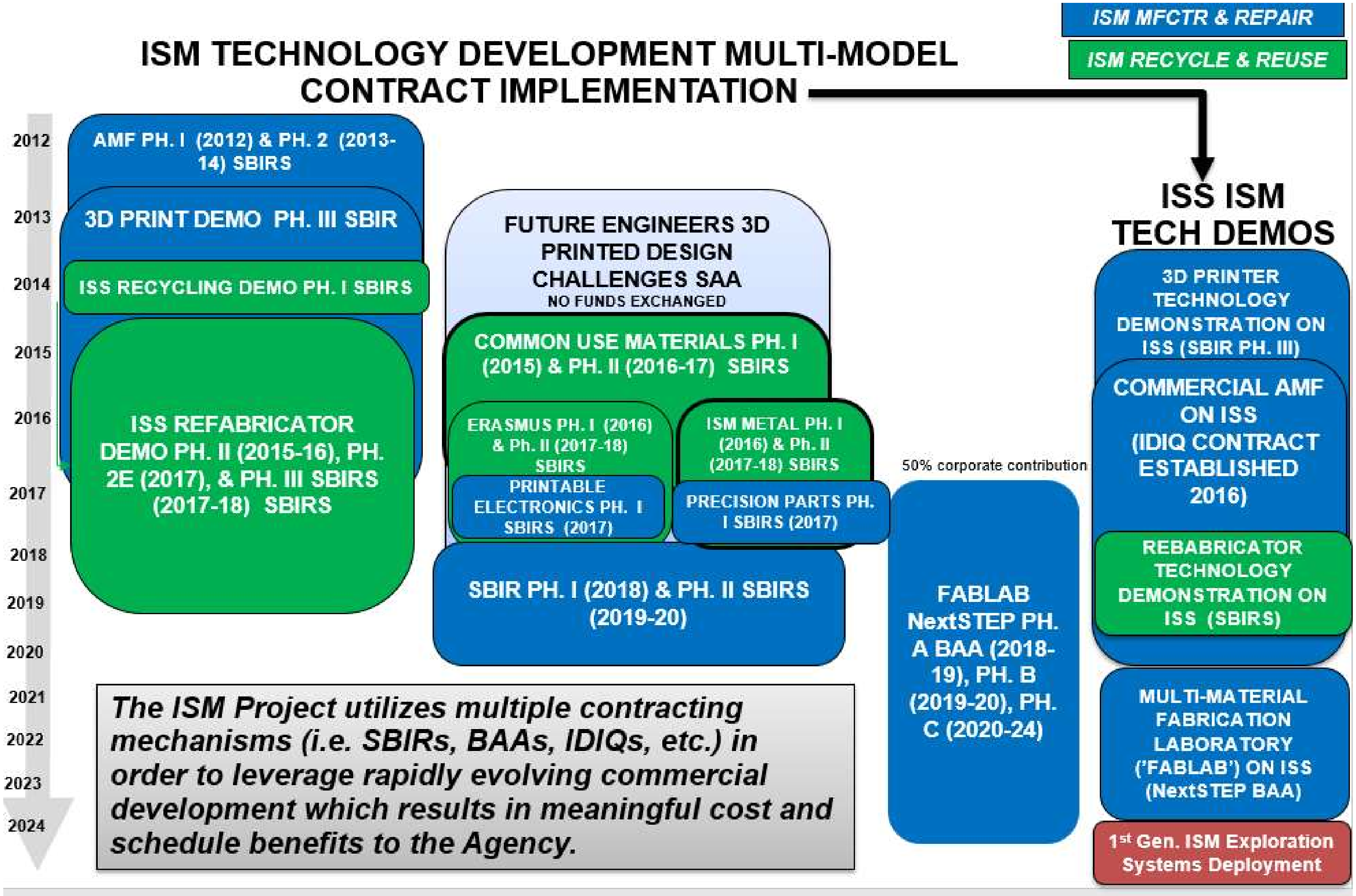
- **In-Space Recycling & Reuse: Develop recycling & reuse capabilities to increase mission sustainability.**
  - The Refabricator (integrated 3D Printer/Recycler) Tech Demo launching to ISS in early 2018.
  - ERASMUS Phase II SBIR with TUI developing Food & Medical Grade Recycling Capability.
  - Common Use Materials Phase II SBIRs (TUI & CRG).

ISS Refabricator developed via SBIRs with Tethers Unlimited, Inc.

- **In-Space Manufacturing Design 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 maintainability & repair

ISM Technology Development Road Map



In-Space Manufacturing (ISM) Phased Technology Development Roadmap

Earth-based	Demos: Ground & ISS			Exploration Missions		

3D Print
Plastic Printing Demo

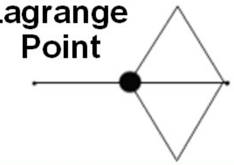
Material Characterization

Recycler
Mat. Char.
Utilization Testing
AMF

Metal Printing
FabLab
External Mfg.
Self-Repair/ Replicate

Asteroids

Lagrange Point



Cis lunar

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. Mfctr. Facility (AMF)***
- ***ISM Certification Process Part Catalog***
- ***ISS & Exploration Material & Design Database***
- ***External Manufacturing***
- ***Autonomous Processes***
- ***Future Engineers***
- ***Additive Construction***

2018 - 2024

ISS: Multi-Material FabLab EXPRESS 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+

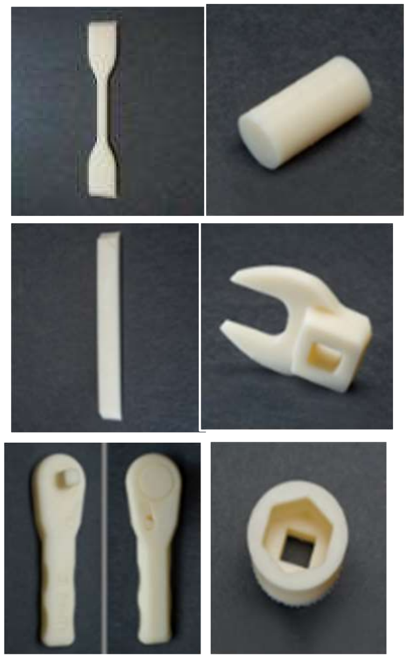
Cislunar, Lagrange FabLabs
- Initial Robotic/Remote Missions
- ***Provision feedstock***
- ***Evolve to utilizing in-situ materials (natural resources, synthetic biology)***
- ***Product: Ability to produce, repair, and recycle parts & structures on demand; i.e.. "living off the land"***
- Autonomous final milling

Planetary Surfaces Points FabLab
- Transport vehicle and sites would need FabLab capability
- ***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.

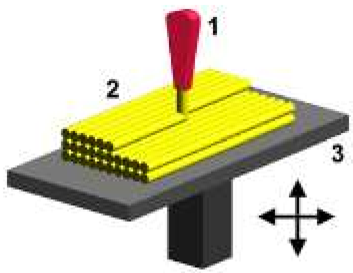
ISS Serves as a Critical Exploration Test-bed for the Required Technology Maturation & Demonstrations

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.

- **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



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

3D Print Specifications	
Dimensions	33 cm x 30 cm x 36 cm
Print Volume	6 cm x 12 cm x 6 cm
Mass	20 kg (w/out packing material or spares)
Power	176 W
Feedstock	ABS Plastic

Printer inside Microgravity Science Glovebox (MSG)

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

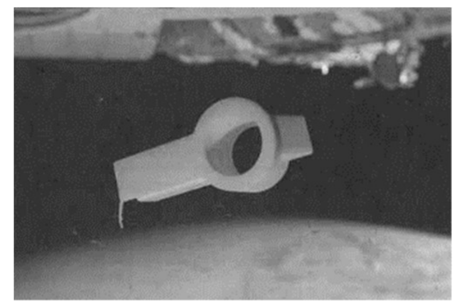
The Made in Space Additive Manufacturing Facility (AMF)

- 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). 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.

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
- Refabricator is an integrated 3D printer (FDM) and recycler
  - Recycles 3D printed plastic into filament feedstock through the Positrusion process
- Environmental testing of engineering test unit and integration testing completed at MSFC in April
  - Payload CDR completed in mid-June 2017
  - Operational on ISS in 2018

CoECI Freelancer Winning Patch Design for Refabricator

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

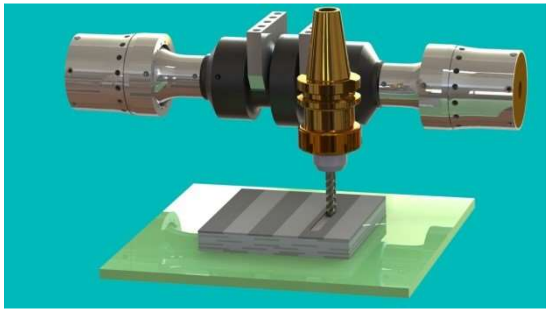
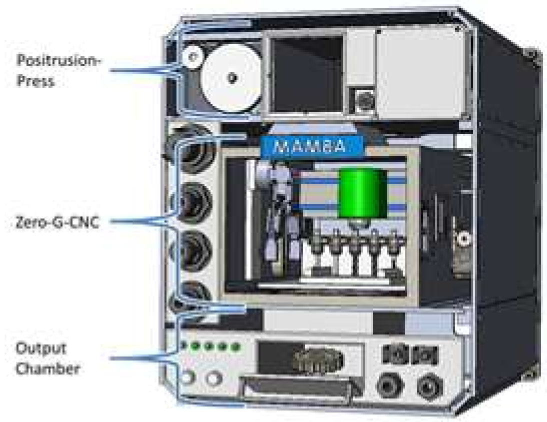


Illustration of UAM process
(image courtesy of Ultra Tech)

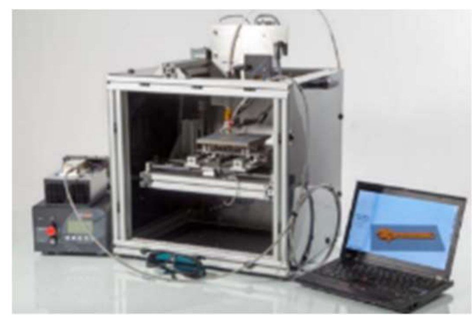
Toward a In-Space Metal Manufacturing Capability

- 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.

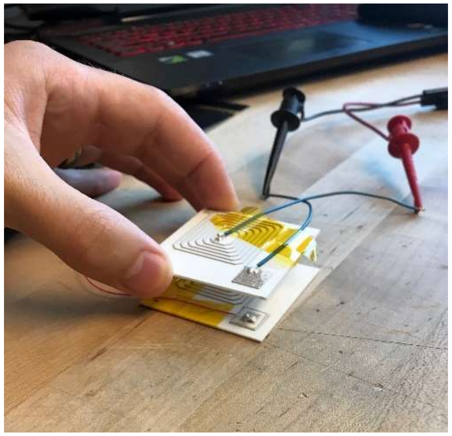
Ground-based work on additive electronics

- 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

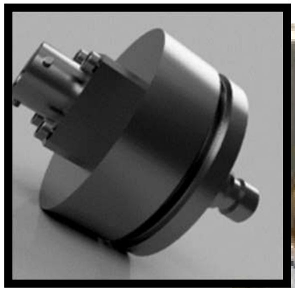
- Developed and demonstrated the functionality of a passive wireless humidity sensor intended for the in-line monitoring of systems.
  - Sensing material also developed in-house at MSFC
  - ECLSS and ISM are planning to perform ground development testing of sensors in the ECLSS environment which introduce the presence of CO, CH4, and H2

- Completed initial design concept of the first printable ECLSS pressure switch.
  - 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)



Printable ECLSS pressure switch

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

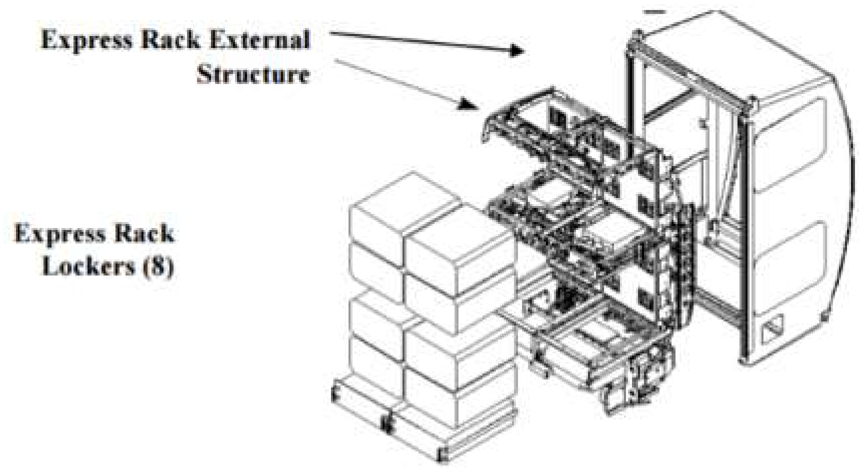
CRISSP (image from Tethers Unlimited)

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

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:**
  - Efficiency gain and risk reduction for deep space exploration
  - “Pioneering” approach to maintenance, repair, and logistics will lead to sustainable, affordable supply chain model

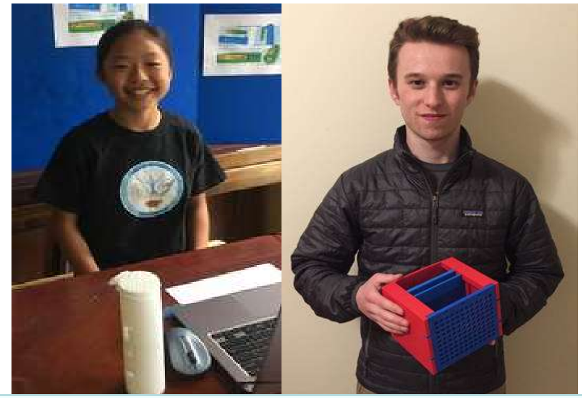
- **In order to develop application-based capabilities for Exploration, ISM must leverag the significant and rapidly-evolving terrestria technologies for on-demand manufacturing**
  - Requires innovative, agile collaboration with industry and academia
  - NASA-unique Investments to focus primarily on 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

Future Engineers

- 5th Future Engineers Challenge: Mars Medical
  - The Teen and Junior Division winners of the Future Engineers Mars Medical Challenge were announced on 3/28/17. The winners were selected from a total of 745 entries submitted from 34 states. The winning design for the Teen Division is the Duel IV/Syringe Pump, and the winning design for the Junior Division is the Drug Delivery Device.



Mars Medical Challenge Junior (Left) and Teen (Right) Winners

- 6th Future Engineers Challenge: Two for the Crew
  - The "Two for the Crew" Challenge to design a 3D print that combines the functions of two pieces of ISS equipment into one kicked off on 9/21/17 at the National Air and Space Museum. The winning part will be manufactured on the ISS AMF.

"Two for the Crew" Challenge Kickoff at the Udvar-Hazy Center of the National Air & Space Museum on 9/21/17

- **Future Engineers awarded a Phase II SBIR with the Department of Education with the objective to broaden the Future Engineers Platform across disciplines, Agencies, industry, and academia.**

www.futureengineers.org

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2. Prater, T.J., Bean, Q.A., Werkheiser, N., et al. "Summary Report on Results of the 3D Printing in Zero G Technology Demonstration Mission, Volume 1." NASA/TP-2016-219101 NASA Technical Reports Server. http://ntrs.nasa.gov/search.jsp?R=20160008972
3. Prater, T.J., Bean, Q.A., Werkheiser, N., et al. "Analysis of specimens from phase I of the 3D Printing in Zero G Technology demonstration mission." *Rapid Prototyping Journal* (in queue for publication)
4. Prater, T.J., Bean, Q.A., Werkheiser, N., et al. "A Ground Based Study on Extruder Standoff Distance for the 3D Printing in Zero G Technology Demonstration Mission." (in queue for publication on NASA Technical Reports Server in June 2017)
5. Prater, T.J., Bean, Q.A., Werkheiser, N., et al. "NASA's In-Space Manufacturing Initiative: Initial Results from the International Space Station Technology Demonstration Mission and Future Plans." *Proceedings of the 2016 National Space and Missile and Materials Symposium.*
6. In-Space Manufacturing (ISM) Multi-Material Fabrication Laboratory (FabLab). Solicitation Number: NNHZCQ001K-ISM-FabLab. https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=8a6ebb526d8bf8fb9c6361cb8b50c1f8

Extra slides: Centennial Challenge on 3D Printing of Habitats, 3DP

Potential of 3D Printing Technologies for Space and Earth

- **Autonomous systems can fabricate infrastructure (potentially from indigenous materials) on precursor missions**
  - Can serve as a key enabling technology for exploration by reducing logistics (i.e. launch mass) and eliminating the need for crew tending of manufacturing systems
- **Also has potential to address housing needs in light of unprecedented population growth**
  - Disaster response
  - Military field operations

Artist's rendering of manufacturing operations on a planetary surface

Centennial Challenge: 3D Printed Habitat

Objective: Advance additive construction technology needed to create sustainable housing solutions for Earth and beyond

Autonomous, Sustainable Additive Manufacturing of Habitats		
Phase 1	**Phase 2**	**Phase 3**
Design: Develop state-of-the-art architectural concepts that take advantage of the unique capabilities offered by 3D printing. **Prize Purse Awarded:** $0.04M	**Structural Member:** Demonstrate an additive manufacturing **material** system to create structural components using terrestrial/space based materials and recyclables. **Prize Purse:** $1.1M	**On-Site Habitat:** Building on material technology progress from Phase 2, demonstrate an automated 3D Print System to **build a full-scale habitat**.

Mars Ice House, winner of the Phase I competition from Space Exploration Architecture and Clouds AO

Phase II Competition: Level 3 Results

1st place, $250,000: Branch Technology and Foster + Partners

2nd place, $150,000: Penn State University

Testing of Phase I and Phase II Prints

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

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

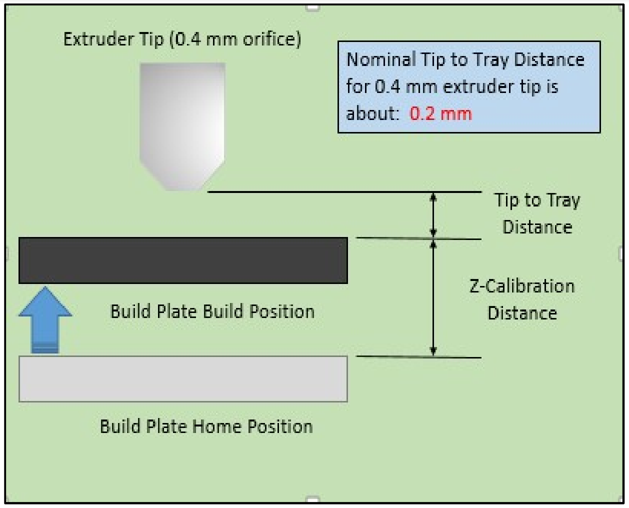
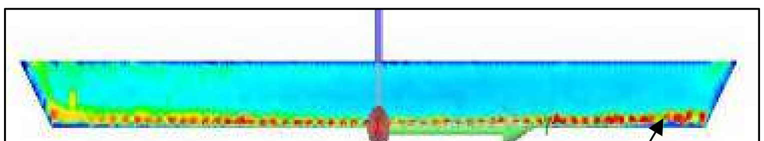


Illustration of z-calibration and tip to tray distances

Structured light scan of flight flexure specimen

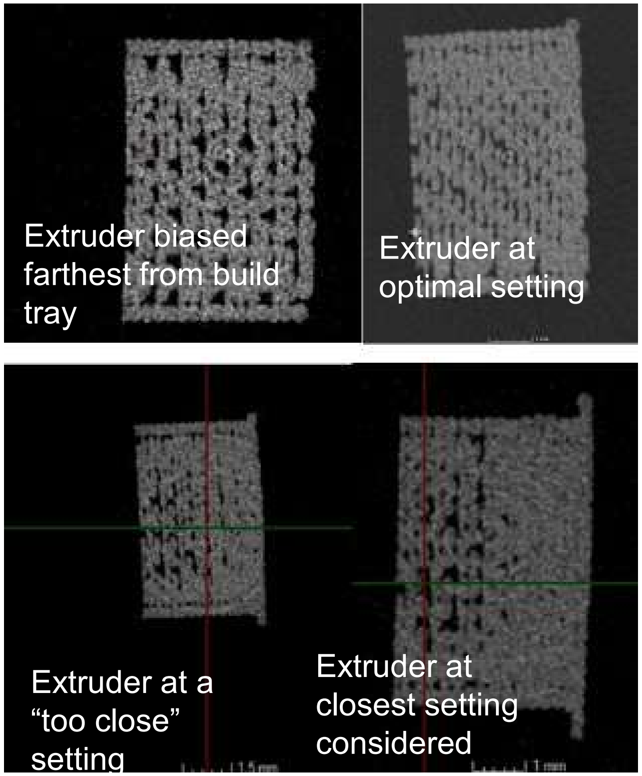


colors indicate dimensional deviation from CAD model

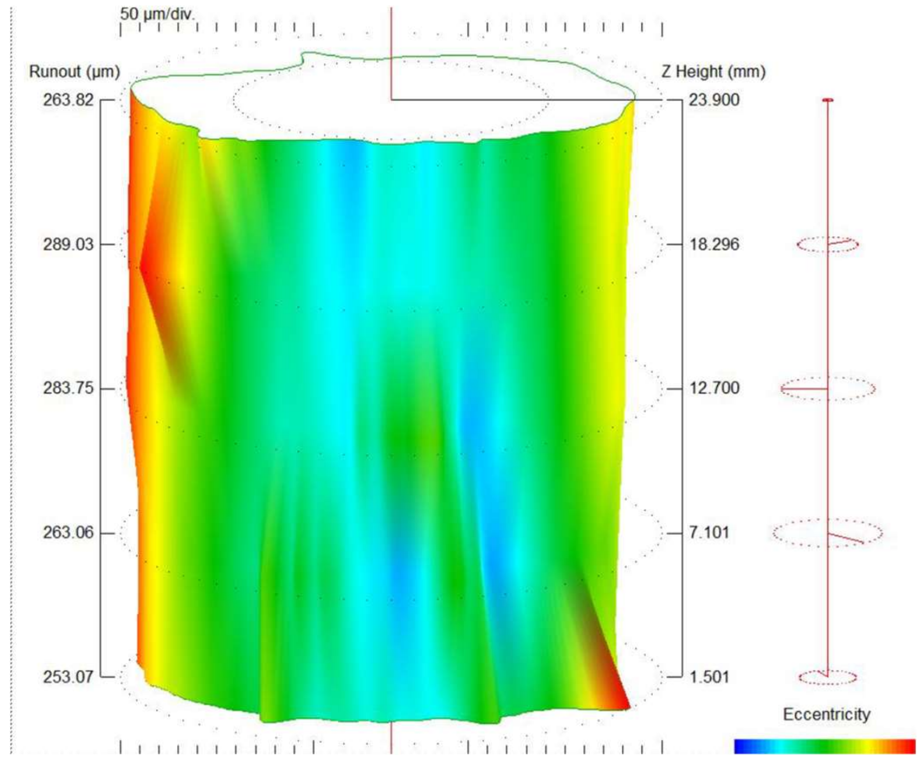
Red indicates slight protrusions of material

- 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 in queue for publication in *Rapid Prototyping Journal (*late 2017*)*

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (ground-based study)



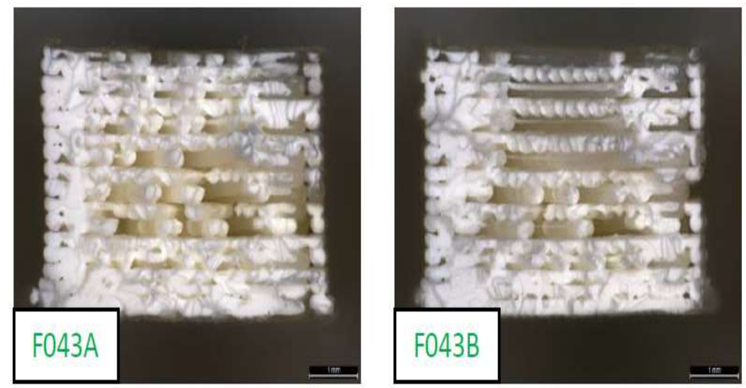
CT cross-section images show evolution of tensile specimen structure with decreasing extruder standoff distance (images from reference , a ground-based study using the flight-back up unit). Bottom half of the specimen becomes denser and protrusions form at base of specimen as extruder standoff distance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



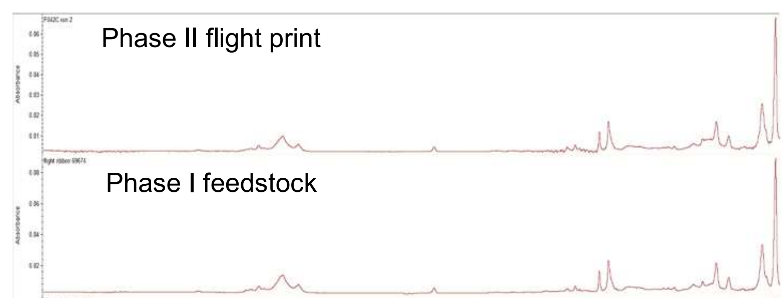
Results of cylinder mapping of compression cylinder from ground based study of extruder standoff distance using the flight backup unit. Off-nominal conditions for the extruder tip biased in either direction result in an increase in cylindricity. The greatest radial separation is observed for the closest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

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

- 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 will be published on the NASA Technical Reports Server in late November 2017
- 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

Use Scenarios for ISS Fabrication Capabilities: Biomedical applications

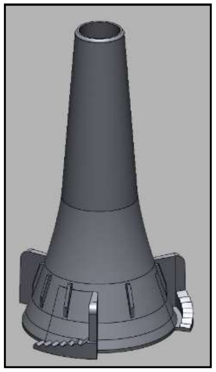
- ERASMUS form Tethers Unlimited
  - Manufacturing modulus for production of medical grade plastics, along with the accompanying sterilization procedures required for subsequent use of these materials
  - Bacteria and viruses can become more virulent in the space environment and crew's immune systems 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)



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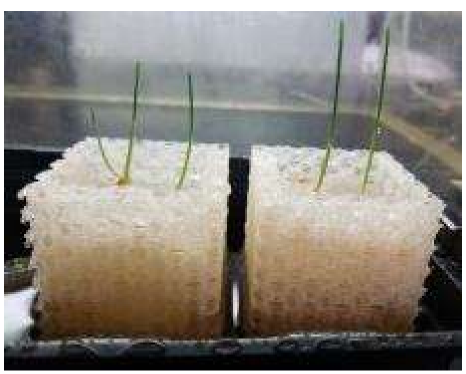
3D Printing with Biologically Derived Materials

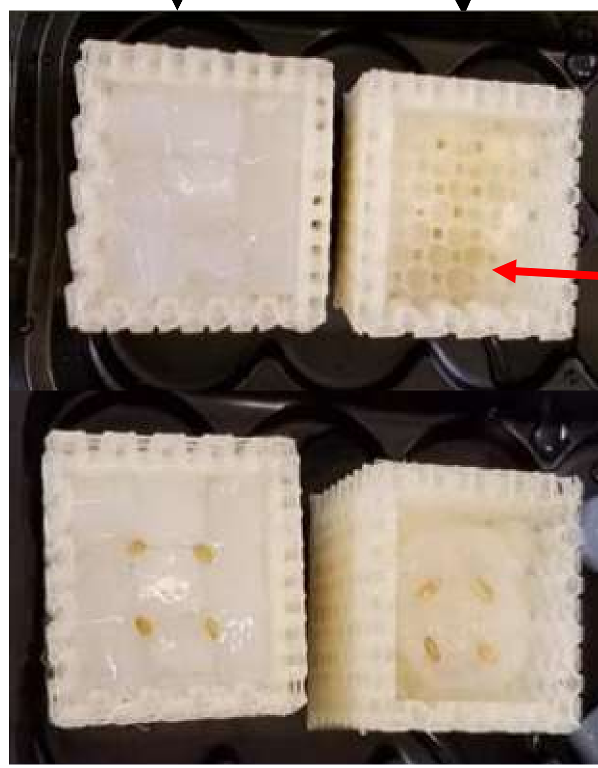
- Use biologically derived filament materials and/or materials from inedible plant mass to create 3D printed substrate blocks for plant growth
- Collaborative activity between VEGGIE project/payload at Kennedy Space Center, Synthetic Biology team at Ames Research Center, and In-space Manufacturing team at NASA Marshall



COTS microbial cellulose

ARC microbial cellulose

Microbial cellulose used as seed germinating platform



Moisture Retainer
-Starch polymer

3D Printed plant growth blocks from MSFC (PLA/PHA)

Seeds allowed to germinate for 3 days