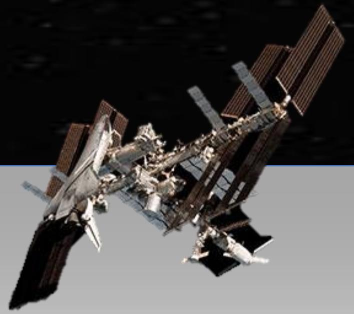

In-Space Manufacturing (ISM): Make it, Don't Take It!!

Passive Wireless Sensor Technology (PWST) Workshop
Session 7: Additive Manufacturing Technology Vision

December 13, 2018

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ISM Project Objectives

<u>ISM Objective:</u> Develop and enable the technologies, materials, and processes required to provide sustainable on-demand manufacturing, recycling, and repair during Exploration missions.

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

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

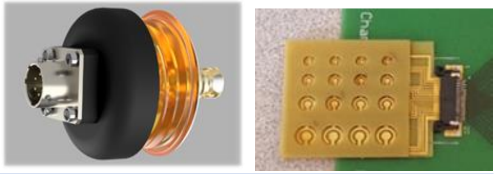
- ***In-Space Manufacturing Digital Design & Verification Database (i.e. WHAT we need to make): ISM is working with Exploration System Designers to develop the ISM database of parts/systems to be manufactured on spaceflight missions.***

Made in Space, Inc. ISS Additive Manufacturing Facility (AMF)

ISS Refabricator Demo with Tethers Unlimited, Inc.

NextSTEP Multi-material 'FabLab' Private Public Partnership

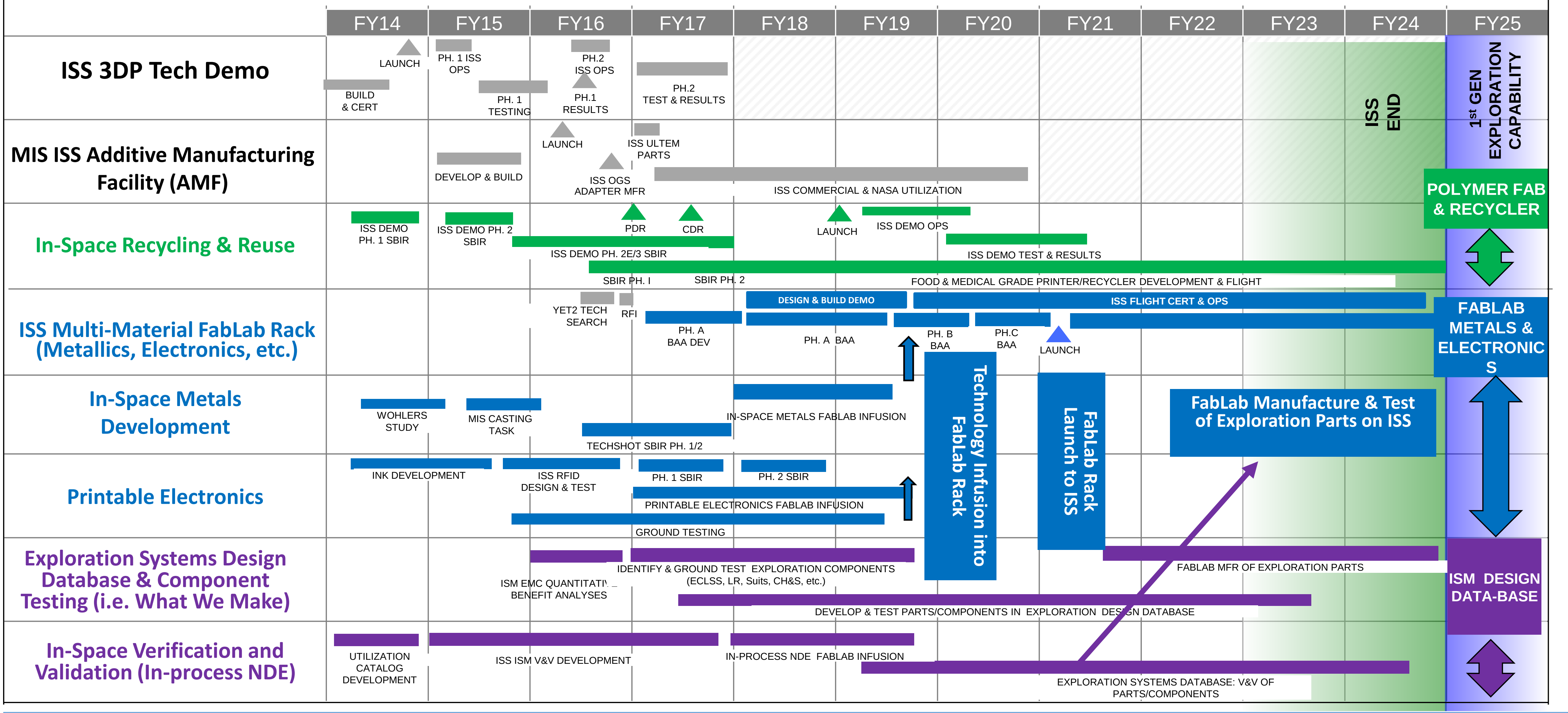
Design Database Development Printed Life Support System (LSS) Retaining Plate (Left); Urine Funnels (Right)



Printed Electronics: LSS Pressure Switch (Left); UV Radiation Sensor (Right)

Collaborative Leveraging with Industry and Academia

ISS ISM Capability Development Timeline

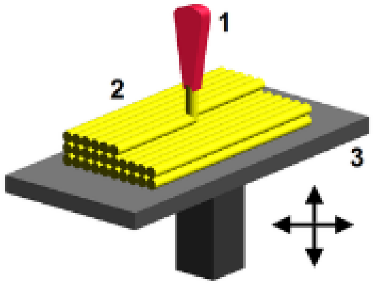


The ISS serves as a Key Exploration Test-bed for the Required ISM Technology Development and Capability Maturation. The Technology Demonstrations tested on the ISS will culminate in the 1st Generation Exploration ISM Systems.

The First Step: 3D Printing in Zero G (3DP) 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 (FDM) by printing 55 specimens to date in space. Made in Space, Inc. (MIS) developed the flight hardware under a Phase III SBIR.



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

ISS 3DP Demo 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

Commander 'Butch' Wilmore holding container printed on 3DP

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 & Repair

- The second 3D Printer, the Additive Manufacturing Facility (AMF), is now operating on the ISS.
- This printer is owned and operated by Made in Space, Inc. through 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.

Examples of NASA parts fabricated on the MIS AMF

MADE IN SPACE
madeinspace.us

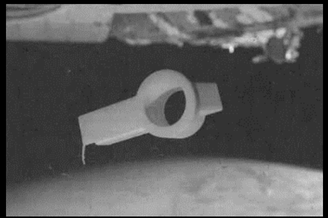
ISS
U.S. NATIONAL LABORATORY

NASA CASIS
POWERED THROUGH PARTNERSHIP

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

REM Shield Enclosure: Enclosure for radiation monitors inside Bigelow Expandable Activity Module (BEAM). Printed 3/20/17, 5/30/17, and 6/16/17.

Antenna Feed Horn: Collaboration between NASA Chief Scientist & Chief Technologist for Space Comm and Nav, 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.

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

WE ARE HERE!

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

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 openly competed 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.

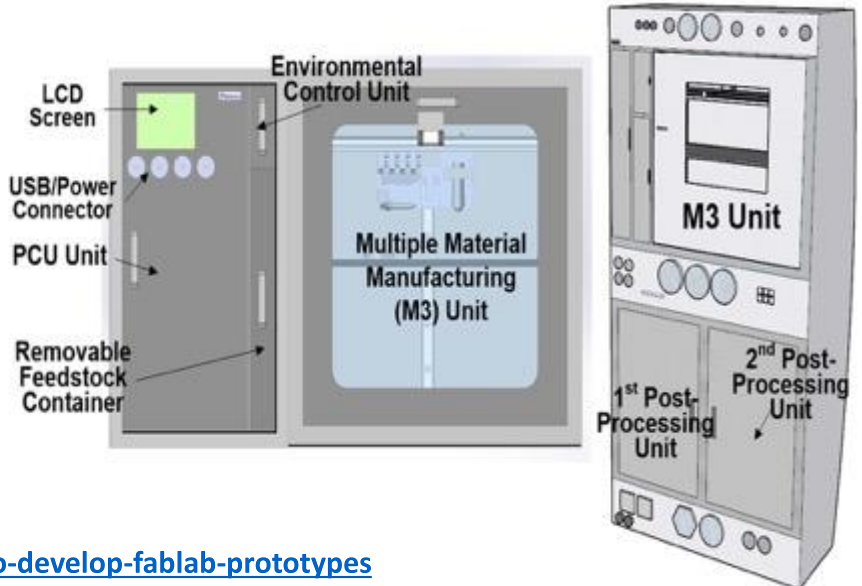
NextSTEP FabLab: Phase A Selectees

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

- **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.**

“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.

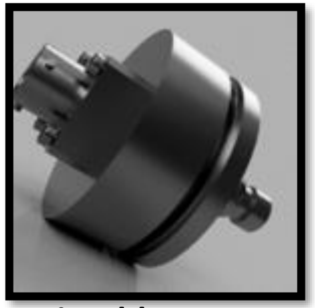
NASA 12/7/17 Selection Announcement: https://www.nasa.gov/press-release/nasa-selects-three-companies-to-develop-fablab-prototypes

ISM Printable Electronics Development
MSFC/ARC/GRC Collaboration

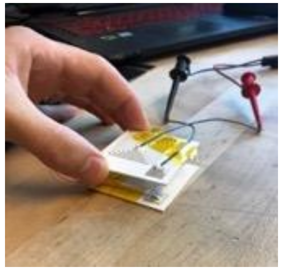
ISM Focal Area: In-Space Manufacturing & Repair

Developing technologies, materials and processes to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions.

- Working with multiple NASA centers, industry (including small businesses), academia, and Other Government Agencies (OGAs).
- Focal Activities
  - Testing and characterization of various processes in order to inform technology design and requirements.
  - Testing and developing electronic inks
  - Working with system users, such as ECLSS, Logistics Reduction Team, Habitats, Structures, etc. to identify candidates for on-demand manufacturing of electronics and building and testing pathfinder parts.
  - Triboelectric Nanogenerator (TENG) for Power Generation: The Ames 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.



Printable ECLSS Pressure switch Concept



Printed Wireless Humidity Sensor

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

In-Space Recycling & Reuse: ISS Refabricator
Phase I, II, II-E, III SBIR 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.**
- **The Refabricator was launched to ISS on the Cygnus rocket in November 2018.**

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

ISM Focal Area: In-Space Recycling and Reuse

- **Next Generation Recycler: The Refabricator data is being used to inform the design of the 1st Generation Exploration Recycler, which will incorporate a dry-heat sterilizer and UV light into the existing 3D Printer and Recycler unit. This will substantially increase mission sustainability as it will enable the additional capability of fabricating and recycling food and medical-grade items which currently make up a high percentage of trashed materials on the ISS.**
  - This effort is underway through a Phase II SBIR entitled "ERASMUS" with TUI.
  - Under this SBIR, ISM and TUI digitally reconstructed, fabricated and recycled the traditionally manufactured urine funnel design for the JSC AES Logistics Reduction team.
  - 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.


Refabricated Urine Funnels (Left; Refabricated Spoons (Right)

- **Common Use Materials Development: 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. ISM is collaborating with JSC ISS packaging and Logistics Reductions teams to identify materials and processes that will provide common use materials which can initially be used for packaging and then be recycled into feedstock during the mission.**
  - Two Phase II-E SBIRs are currently underway with TUI focusing on recyclable foam packaging made from thermoplastic materials using FDM and with
  - Cornerstone Research Group (CRG) focusing on development of reversible copolymer materials.

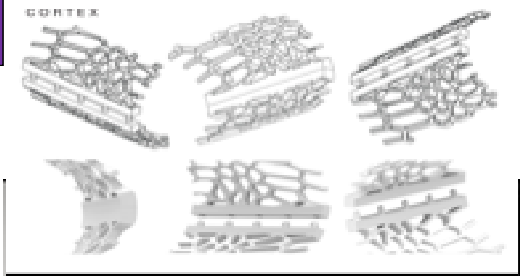

TU Recyclable Launch Container (Left); CRG Printed Part from Recycled Baggie (Right)

ISM Design Database: Crew Health and Safety Applications

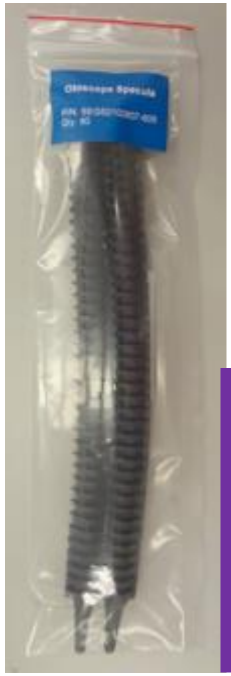
ISM Focal Area: In-Space Manufacturing Design Database (i.e. WHAT we make)

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	Next Generation Refabricator with integrated dry-heat sterilizer and UV light to enable food and medical grade polymer refabrication
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; 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



ISM Vanderbilt Senior Design Project



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

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 (38 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: Meaningful SBIR Infusion & Collaborations with Other Government Agencies (OGAs)

- **Between 2013-18, ISM has created a new ISM SBIR Topic and multiple subtopics and awarded a total of 38 SBIRs and one IDIQ contract. T*hree of the subtopics have already resulted in ISS Technology Demonstrations.***
  - 22 Phase I SBIRs
  - 8 Phase II SBIRs
  - 5 Phase II E/X SBIRs
  - 2 Phase III SBIRs
  - 1 IDIQ

- **ISM is collaborating with cross-cutting DoD sectors relative to technology development, digital design databases, materials, verification processes**
  - Team Redstone (AMRDEC, SMDC, NASA)
  - Navy (NavSea, NavAir)
  - Air Force (AFRL)
  - DARPA
  - Oak Ridge National Labs (ORNL)
  - Picatinny Arsenal
  - America Makes
  - NextFlex

Future Engineers 3D Print Design in Space Challenges

Future Engineers is a national platform established in 2014 via a Space Act Agreement between NASA and the American Society of Mechanical Engineers (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.

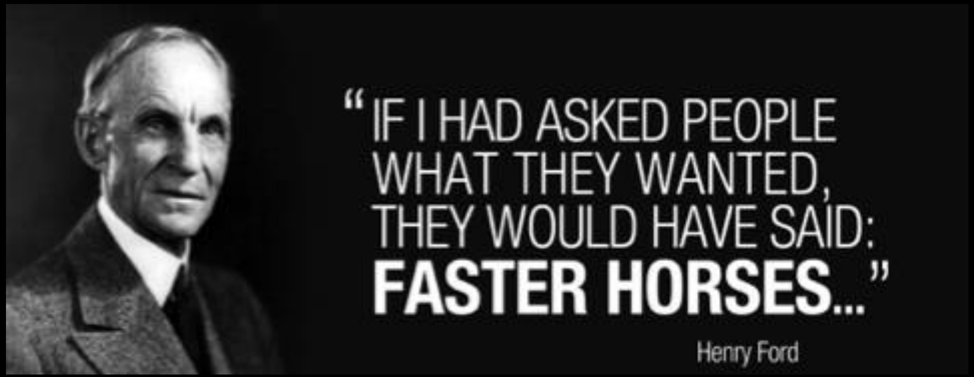
- **Since 2014, six challenges have been successfully executed via the FE virtual 'one-stop-shop' virtual platform (www.futureengineers.org), engaging over 2,000 students from 42 states.**
- **For the first and sixth challenges, prizes included the student-designed parts being 3D Printed on the ISS and the student designers conducting live interviews with ISS astronauts to discuss the benefits of the the parts they designed.**
- **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.**

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

Acronym List

- 3DP: 3D Printing in Zero-G
- 4BMS-X: Four Bed Molecular Sieve
- ABS: Acrylonitrile Butadiene Styrene (thermoplastic)
- ACME: Additive Construction with Mobile Emplacement
- AES: Advanced Exploration Systems
- AF: U.S. Air Force
- AM: Additive Manufacturing
- AMF: Additive Manufacturing Facility
- AMRDEC: Aviation and Missile Research, Development and Engineering Center
- ARC: Ames Research Center
- ASAE: American Society of Association Executives
- ASME: American Society of Mechanical Engineers
- ATDP: Archinaut Technology Development Project
- BAA: Broad Agency Announcement
- BEAM: Bigelow Expandable Activity Module
- CAD: Computer Aided Design
- CAN: Cooperative Agreement Notice
- CASIS: Center for the Advancement of Science in Space
- CDR: Critical Design Review
- CH_4: Methane
- CH&S: Crew Health and Safety
- CIF: Center Innovation Fund
- cm: centimeter
- CNC: Computer Numerical Control
- CO: Carbon Monoxide
- CO_2: Carbon Dioxide
- COR: Contracting Officer Representative
- COTS: Commercial Off-the-Shelf
- CRG: Cornerstone Research Group, Inc.
- CSO: Chief Safety Officer
- CT: Computerized Tomography
- DARPA: Defense Advanced Research Projects Agency
- DoD: Department of Defense
- E: Elastic (Young’s) Modulus
- ECLSS: Environmental Control and Life Support System
- EMC: Evolvable Mars Campaign
- ETU: Engineering Test Unit
- EXPRESS: Expedite the Processing of Experiments to Space Station

Acronym List (cont.)

- FabLab: Fabrication Laboratory
- FDM: Fused Deposition Modeling
- FE: Finite Element
- FTE: Full Time Equivalent (Civil Servant)
- FTIR: Fourier-Transform Infrared Spectroscopy
- FY: Fiscal Year
- G: Shear Modulus
- GCD: Game Changing Division
- GFE: Government Furnished Equipment
- GRC: Glenn Research Center
- GSA: General Services Administration
- H2: Hydrogen Gas
- HDPE: High-Density Polyethylene (thermoplastic)
- HEOMD: Human Exploration and Operations Mission Directorate
- IDIQ: Indefinite Delivery Indefinite Quantity
- IRMA: In-Space Robotic Manufacturing and Assembly
- ISM: In-Space Manufacturing
- ISRU: In-Situ Resource Utilization
- ISS: International Space Station
- JSC: Johnson Space Center
- kg: kilogram
- LCD: Liquid Crystal Display
- LDPE: Low-Density Polyethylene
- LR: Logistics Reduction
- LSS: Life Support Systems
- µm: micrometer
- M3: Multiple Material Manufacturing
- M3AM: Microgravity Multiple Materials Additive Manufacturing
- MAMBA: Metal Advanced Manufacturing Bot-Assisted Assembly
- MAPTIS: Materials and Processes Technical Information System
- mg: milligram
- MIS: Made In Space, Inc.
- mm: millimeter
- MSFC: Marshall Space Flight Center
- MSG: Microgravity Science Glovebox
- NDE: Non-Destructive Evaluation
- NextSTEP: Next Space Technologies for Exploration Partnerships
- NIAC: NASA Institute for Advanced Concepts
- NRC: National Research Council
- OGA: Other Government Agency
- OGS: Oxygen Generation System

Acronym List (cont.)

- ORU: Orbital Replacement Unit
- PCU: Power Control Unit
- PDR: Preliminary Design Review
- PEEK: Polyether Ether Ketone
- PET: Polyethylene Terephthalate
- PLA: Polylactic Acid / Polylactide (bioplastic)
- PVC: Polyvinyl Chloride
- R&D: Research and Development
- REM: Radiation Environment Monitor
- RFID: Radio Frequency Identification
- SAA: Space Act Agreement
- SBIR: Small Business Innovative Research
- SEM: Scanning Electron Microscopy
- SIMPLE: Sintered Inductive Metal Printer with Laser Exposure
- SMDC: Space and Missile Defense Command
- SME: Subject-Matter Expert
- SPHERES: Synchronized Position Hold, Engage,
- Reorient, Experimental Satellites
- STEM: Science, Technology, Engineering and Mathematics
- STMD: Space Technology Mission Directorate
- TDM: Technology Demonstration Missions
- TENG: Triboelectric Nanogenerator
- TIP: Technology Investment Program
- TRL: Technology Readiness Level
- TUI: Tethers Unlimited, Inc.
- UAM: Ultrasonic Additive Manufacturing
- UCS: Unconfined Compressive Strength
- UPA: Urine Processor Assembly
- USB: Universal Serial Bus
- UTAS: United Technologies Corporation Aerospace Systems
- UTEP: University of Texas El Paso
- UTS: Ultimate Tensile Strength
- UV: Ultraviolet
- V&V: Verification and Validation
- W: Watt
- X-Hab: Exploration Habitat