

NASA's In Space Manufacturing Initiatives: Conquering the Challenges of In-Space Manufacturing



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Contributors

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- Mike Snyder: Made In Space, Chief Designer
- Dr. Doug Wells: MSFC Lead, Additively Manufactured Spaceflight Hardware Standard and Specification

Agenda

NASA's In Space Manufacturing Initiative (ISM)

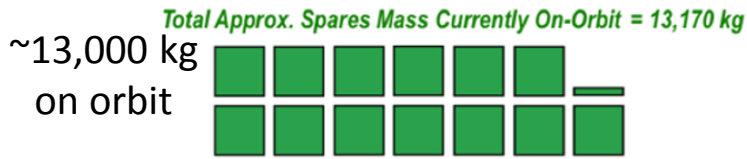
- A. The Case for ISM: WHY
- B. ISM Path to Exploration
- C. In Space Robotic Manufacturing and Assembly (IRMA)
- D. Additive Construction

Challenges to ISM

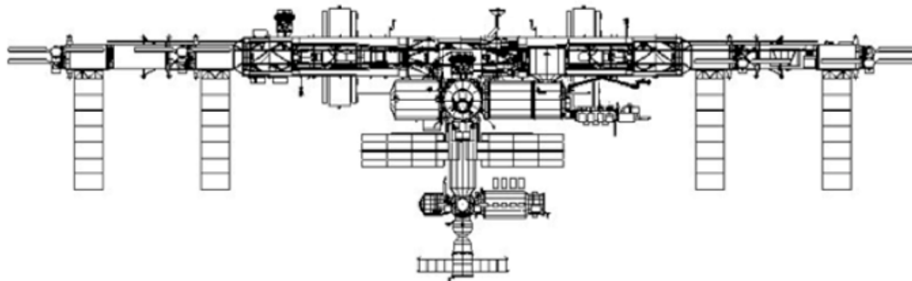
MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware

Summary

Each square represents 1000 kg



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



~3,000 kg Upmass per year

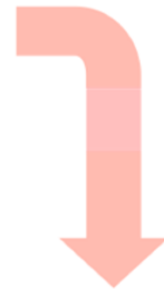
Predicted Annual Average Upmass 2012-2020



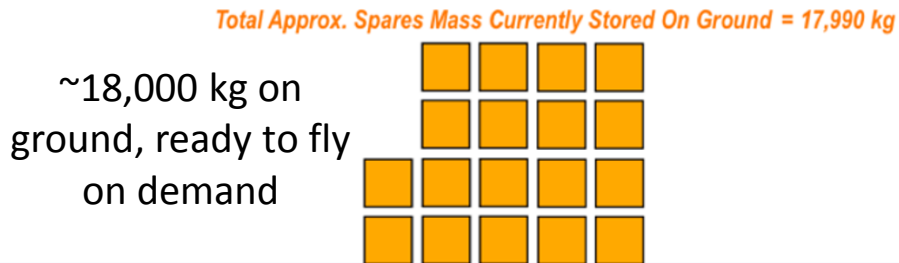
Corrective Maintenance = 1,260 kg

Preventive Maint. / Consumables = 1,930 kg

Total = 3,190 kg



Expected Average Annual Failures = 450 kg*



This is for a system with:

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

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

* - Based on predicted MTBFs

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

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

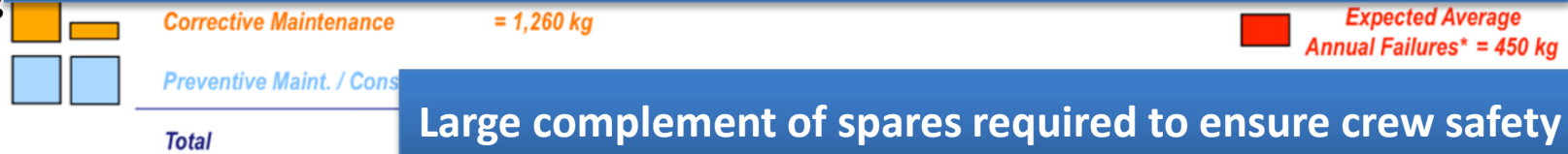
Mass estimates are for mass of spare item only
- do not including any packaging or carrier mass

~95% of all corrective spares will never be used

Impossible to know which spares will be needed

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

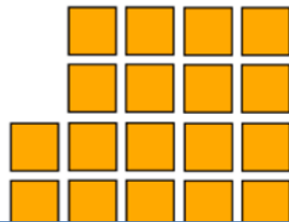
~3,000 kg Upmass per year



Large complement of spares required to ensure crew safety

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

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



This is for a system with:

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

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

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

ISM is a promising technological solution to address these issues.

- ISM offers the potential to:
 - Significantly reduce maintenance logistics mass requirements
 - Maintenance logistics mass is directly linked to the Probability of Loss of Crew (P(LoC))*
 - The cost of driving down risk is an exponential increase in mass requirements.*
- Mitigate risks that are not covered by current approaches to maintainability.*
- Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements*
- Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances*
- ISS is a critical testbed for demonstrating ISM technologies, proving out these capabilities, and performing operational validation of deep space ISM applications.

ISM is a necessary paradigm shift in space operations, not a 'bonus'

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



In-Space Manufacturing (ISM) Path to Exploration

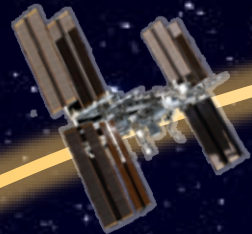


GROUND-BASED

Earth-Based Platform

- Certification & Inspection Process
- Design Properties Database
- Additive Manufacturing Automation
- Ground-based Technology Maturation & Demonstration
- **AM for Exploration Support Systems (e.g. ECLSS) Design, Development & Test**
- **Additive Construction**
- **Regolith (Feedstock)**

EARTH RELIANT ISS



ISS Test-bed – Transition to Deep Space Gateway

- 3D Print Demo
- Additive Manufacturing Facility
- In-space Recycling
- In-space Metals
- Printable Electronics
- Multi-material Fab Lab
- In-line NDE
- **External Manufacturing (IRMA)**
- **On-demand Parts Catalogue**
- **Exploration Systems Demonstration and Operational Validation**

CIS-LUNAR



EARTH INDEPENDENT Mars



Planetary Surfaces Platform

- **Multi-materials Fab Lab (metals, polymers, automation, printable electronics)**
- **Food/Medical Grade Polymer Printing & Recycling**
- **Additive Construction Technologies**
- **Regolith Materials – Feedstock**

Space Launch System

Text Color Legend

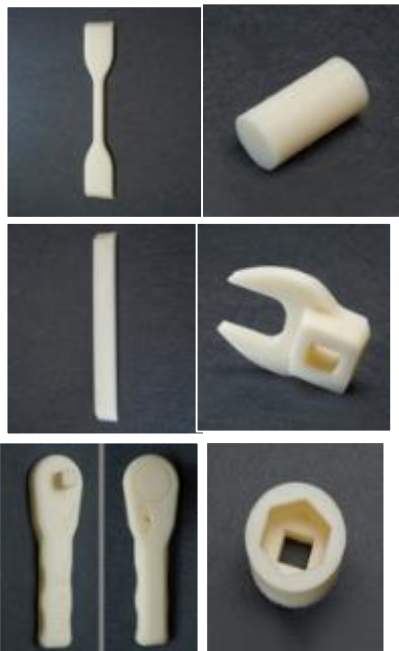
Foundational AM Technologies

AM Capabilities for Exploration Systems

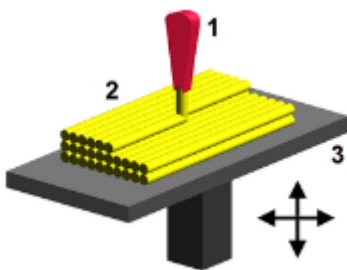
Surface / ISRU Systems



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



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



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



Printer inside Microgravity Science Glovebox (MSG)



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

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

Material Properties

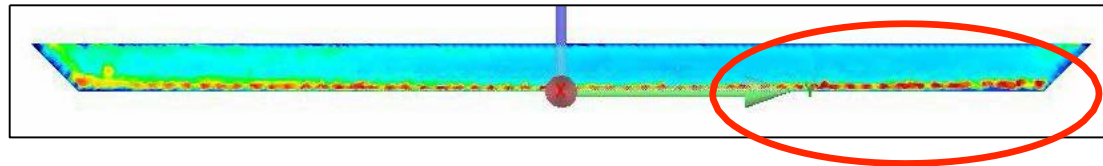
- Tensile and Flexure: Flight specimens stronger and stiffer than ground counterparts
- Compression: Flight specimens are weaker than ground specimens
- Density: Flight specimens slightly more dense than ground specimens; compression specimens show opposite trend

X-ray and CT Scans

- CT scans show more pronounced densification in lower half of flight specimens. [Not statistically significant]
- No significant difference in number or size of voids between the flight and ground sets

Structured Light Scanning

- Protrusions along bottom edges indicate that extruder tip may have been too close to the print tray (more pronounced for flight prints)

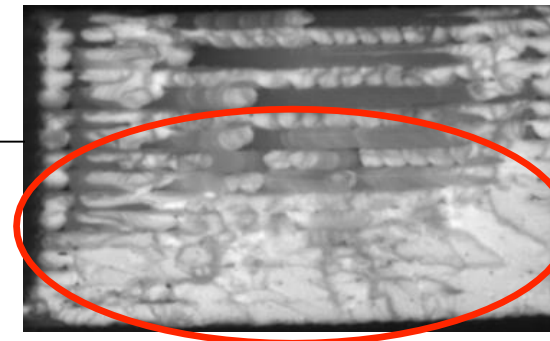


Microscopy

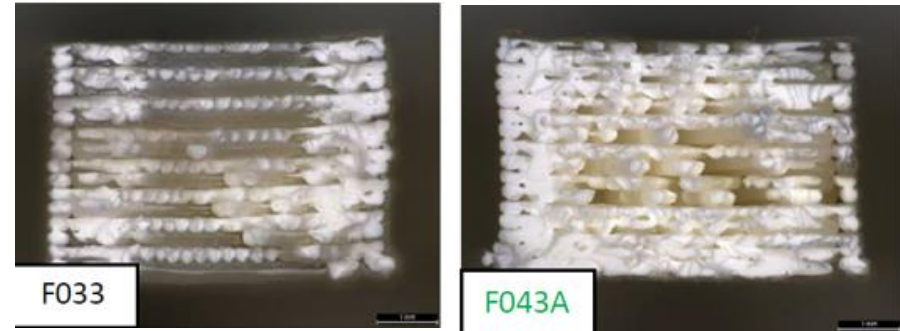
- Greater Densification of Bottom Layers (Flight tensile)

Process

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



- For Phase II operations, 25 specimens (tensile and compression) 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 mimic the manufacturing process conditions for the Phase I flight prints (termed “suboptimal”).
- Complete Phase II data will be published on the NASA Technical Reports Server in December 2017.
- Key findings:
 - All prints to date with 3DP appear to be broadly part of the same family of data
 - No substantive chemical changes in feedstock noted through FTIR analysis
 - No evidence of microgravity effects noted in SEM analysis. Some variation in internal material structure between builds and with changes in process settings



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

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

- **Mass and density data for Phase I and Phase II (all subsets of data) appear to be part of the same data family**
- **Mechanical Properties**
 - Tensile data and comparison with previous results suggest all data collected to date is part of a single large, albeit variable, data set.
 - Ground compression specimen performance is still somewhat distinct (higher) than other specimen sets. Specimens were manufactured at the farthest extruder distance.
- **Structured light scanning**
 - Phase II flight specimens manufactured at the optimal extruder distance exhibit good agreement with the CAD model,
 - Some slight build to build variability in geometry.
 - Suboptimal compression specimens show fiber distortion and distortion in the center of the specimen.
 - Warp and protrusions observed for Phase I tensile specimens are not present in Phase II flight tensile prints.
- **Microscopy**
 - Suboptimal compression specimens:
 - Contain surface defects along the sides that appear to be printing defects where the fiber is distorted.
 - Cross-section showed voids in the center of the sample
 - Mechanically weaker than specimens manufactured at greater standoff distances.
 - Suboptimal tensile specimens show characteristic densification of first layers noted in Phase I flight specimens and subsequent ground-based study.
- **FTIR**
 - Some small chemical changes between Phase I and Phase II flight feedstock (Phase II feedstock 2 years older).
 - Spectra still show a very high degree of similarity and are considered in family with one another.
- **X-ray/CT analysis results still pending**
- **Variations in Phase I data appear to be traceable to:**
 - Printer variability
 - Differences in manufacturing process settings (extruder standoff distance)
 - Data scatter characteristic of many additively manufactured materials and processes.

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



The Made in Space Additive Manufacturing Facility (AMF)

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



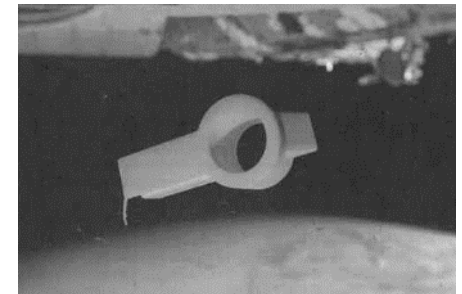
SPHERES Tow Hitch: SPHERES consists of 3 free-flying satellites on-board ISS. Tow hitch joins two of the SPHERES satellites together during flight. Printed 2/21/17.



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



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



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

Prater, Tracie, et al. "NASA's In-space Manufacturing Project: Materials and Manufacturing Process Development Update." Proceedings of the National Space and Missile Materials Symposium. June 2017.

- Technology Demonstration Mission payload conducted under a Phase III SBIR with Tethers Unlimited, Inc.
- Refabricator demonstrates feasibility of plastic recycling in a microgravity environment for long duration missions
 - Closure of the manufacturing loop for FDM has implications for reclamation of waste material into useful feedstock both in-space and on-earth
- Refabricator is an integrated 3D printer (FDM) and recycler
 - Recycles 3D printed plastic (ULTEM 9085) into filament feedstock through the Positrusion process
- Environmental testing of engineering test unit completed at MSFC in April
 - Payload CDR completed in mid-June
 - Operational on ISS in 2018



Refabricator ETU



Prater, Tracie, et al. "NASA's In-space Manufacturing Project: Materials and Manufacturing Process Development Update." Proceedings of the National Space and Missile Materials Symposium. June 2017.

- 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
 - 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)

- Made in Space Vulcan unit (Phase I SBIR)
 - Integrates FDM head derived from 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)
 - Prints parts using sound waves to consolidate layers of metal from foil feedstock
- Tethers Unlimited MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly) (Phase I SBIR)
 - Builds on ReFabricator recycling process
 - Bulk feedstock is CNC-milled
- 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



Illustration of Vulcan Exterior Unit (image courtesy of Made in Space)

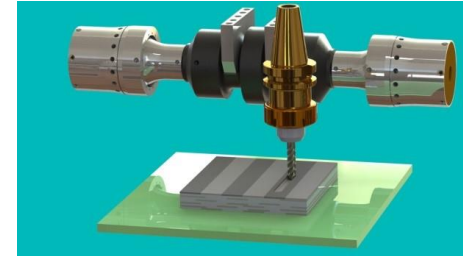
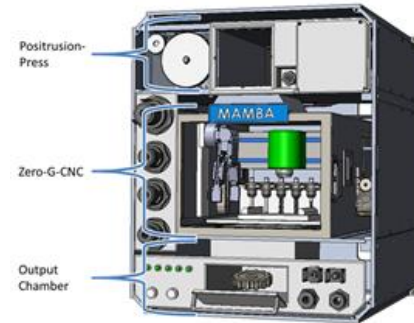
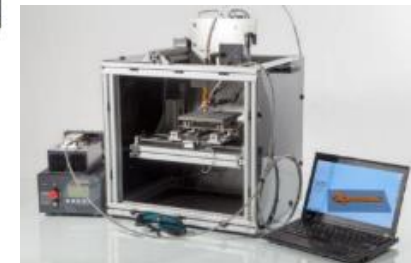


Illustration of UAM process (image courtesy of Ultra Tech)



Tethers Unlimited MAMBA concept. Image courtesy of Tethers Unlimited.

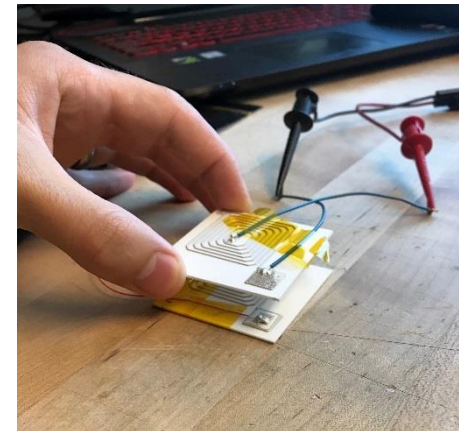


Techshot's SIMPLE, a small metal printer developed under a Phase I SBIR. Image courtesy of Techshot.

- Evaluating technologies to enable multi-material, digital manufacturing of components
- Development of additively manufactured wireless sensor archetype (MSFC)
 - Printed RLC circuit with coupled antenna
 - Capacitive sensing element is pressure, temperature, or otherwise environmentally sensitive material developed at MSFC
 - Sensing material also developed in-house at MSFC
- Design of pressure switch for urine processor assembly (UPA)
 - Existing pressure switch has had several failures due to manufacturing flaw in metal diaphragm
 - In additive design, switching is accomplished via a pressure sensitive material
- Miniaturization and adaptation of printable electronics for microgravity environment will continue through two Phase 1 contracts awarded under SBIR subtopic In-Space Manufacturing of Electronics and Avionics
 - Techshot, Inc. (STEPS – Software and Tools for Electronics Printing in Space)
 - Optomec working on miniaturization of patented Aerosol Jet technology



MSFC nScript multimaterial printer (4 heads and pick and place capability)

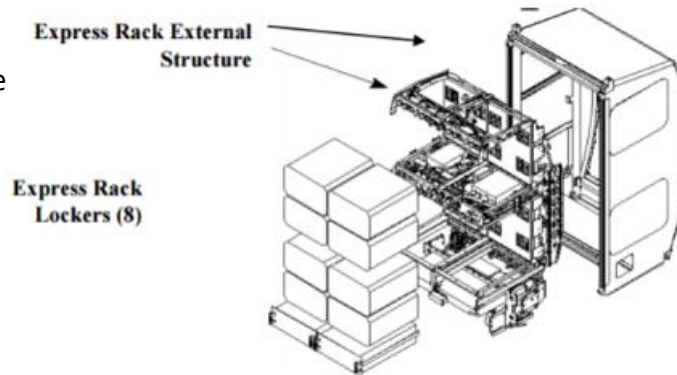


Printed wireless humidity sensor (wires attached for characterization purposes)

Typical EXPRESS Rack structure

Power consumption for entire rack is limited to 2000 W

Payload mass limit for rack is less than 576 lbm



Threshold
The system should have the ability for on-demand manufacturing of multi-material components including metallics and polymers as a minimum.
The minimum build envelope shall be 6" x 6" x 6".
The system should include the capability for earth-based remote commanding for all nominal tasks.
The system should incorporate remote, ground-based commanding for part handling and removal in order to greatly reduce dependence on astronaut time.*
The system should incorporate in-line monitoring of quality control and post-build dimensional verification.

- NASA is evaluating proposals to provide a feasible design and demonstration of a first-generation multimaterial, multiprocess In-space Manufacturing Fabrication Laboratory for demonstration on the ISS
- Minimum target capabilities include:
 - Manufacturing of metallic components
 - Meet ISS EXPRESS Rack constraints for power and volume
 - Limit crew time
 - Incorporate remote and autonomous verification and validation of parts
- Phased approach
 - Phase A – scaleable ground-based prototype
 - Phase B – mature technologies to pre-flight deliverable
 - Phase C – flight demonstration to ISS



In-space Robotic Manufacturing and Assembly (IRMA) Overview



Concept by Made In Space



Concept by Space Systems/Loral



Concept by Orbital ATK

Archinaut

A Versatile In-Space Precision Manufacturing and Assembly System

Dragonfly

On-Orbit Robotic Installation and Reconfiguration of Large Solid Radio Frequency (RF) Reflectors

CIRAS

A Commercial Infrastructure for Robotic Assembly and Services

Tipping Point Objective

A ground demonstration of additive manufacturing of extended structures and assembly of those structures in a relevant space environment.

A ground demonstration of robotic assembly interfaces and additive manufacture of antenna support structures meeting EHF performance requirements.

A ground demonstration of reversible and repeatable robotic joining methods for mechanical and electrical connections feasible for multiple space assembly geometries.

Team

Made In Space, Northrop Grumman Corp., Oceaneering Space Systems, Ames Research Center

Space Systems/Loral, Langley Research Center, Ames Research Center, Tethers Unlimited, MDA US & Brampton

Orbital ATK, Glenn Research Center, Langley Research Center, Naval Research Laboratory



Additive Construction Dual Use Technology Projects For Planetary and Terrestrial Applications



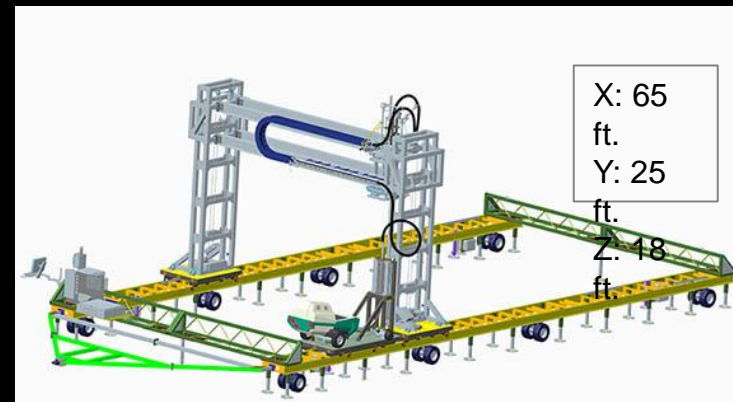
US Army Corps of Engineers.
Engineer Research and Development Center

Additive Construction with Mobile Emplacement (ACME) NASA



Shared Vision: Capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials.

**Automated Construction of Expeditionary Structures (ACES)
Construction Engineering Research Laboratory - Engineer Research and Development Center (CERL – ERDC)**



**B-hut (guard shack)
16' x 32' x 10'**



Model of ACES-3 Gantry System



ACES-3 System in Champaign, IL

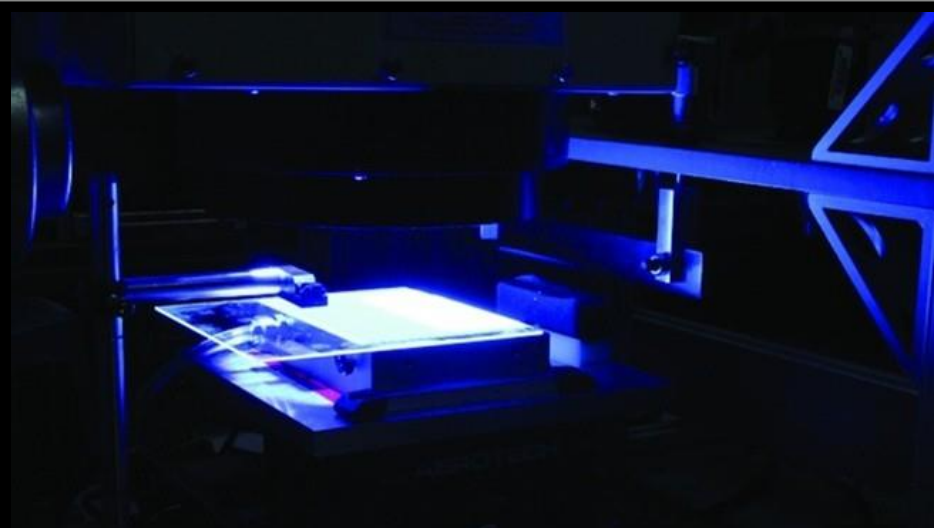


ACES-3 in Champaign, IL, aerial view



KSC Material Delivery System

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



Additive Manufacturing

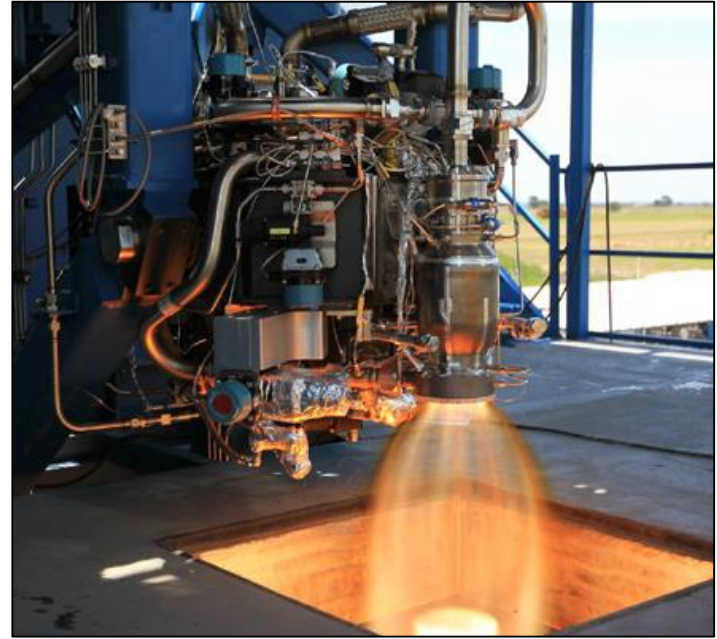
at Marshall Space Flight Center

MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware

Exploration Systems Development ORION and SLS



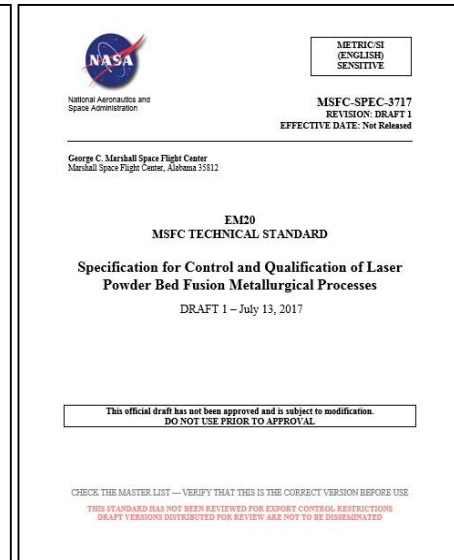
Commercial Crew Program (CCP) DRAGON V2



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

NASA cannot wait for national Standard Development Organizations to issue AM standards.

- Partners in crewed spaceflight programs (Commercial Crew, SLS and Orion) are actively developing AM parts
- In response to request by Commercial Crew Program (CCP), MSFC AM Standard drafted in summer 2015.
- Draft standard completed extensive peer review in Jan 2016.
- **Standard methodology adopted by CCP, SLS, and Orion.**
- Continuing to watch progress of standards organizations and other certifying Agencies.
- Goal is to incorporate AM requirements at an appropriate level in Agency standards and/or specifications.

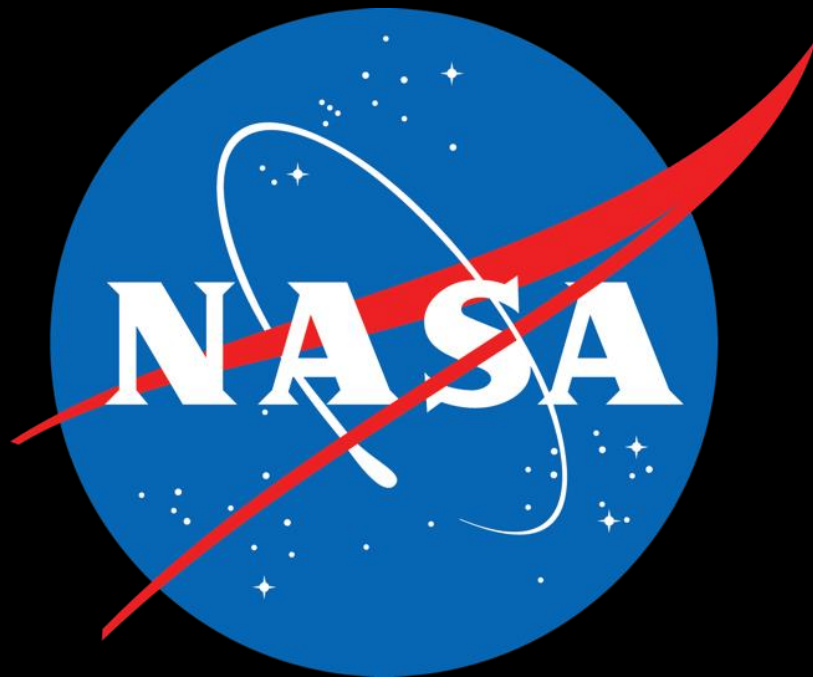


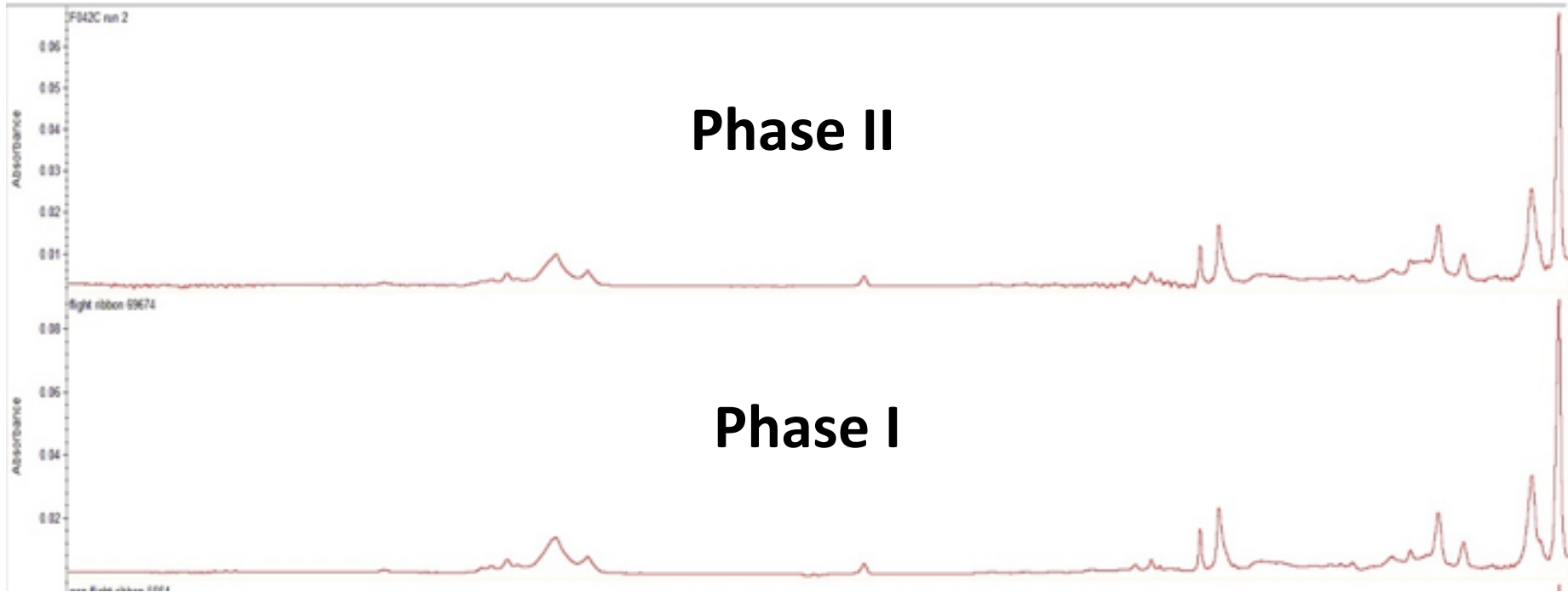
MSFC Standard and Specification
Release Date: October 18, 2018

Standardization is needed for consistent evaluation of AM processes and parts in critical applications.

- Current maintenance logistics strategy **will not be effective** for deep space exploration missions
- ISM offers the potential to:
 - Significantly reduce maintenance logistics mass requirements
 - Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements
 - Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances
 - Mitigate risks that are not covered by current approaches to maintainability
- Multiple projects are underway currently to develop and validate these capabilities for infusion into ISM exploration systems
- ISS is a critical testbed for demonstrating ISM technologies, proving out these capabilities, and performing operational validation of deep space ISM applications.
- Developing and testing FabLab is a major milestone for springboard to DSG/Cis-lunar Space applications
- ISM is a necessary paradigm shift in space operations – design for repair culture must be embraced
- ISM team needs to be working with exploration system designers now to identify high-value application areas and influence design

1. Cirillo, W., Aaseng, G., Goodli_, K., Stromgren, C., and Maxwell, A., "Supportability for Beyond Low Earth Orbit Missions," AIAA SPACE 2011 Conference & Exposition, No. AIAA-2011-7231, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sep 2011, pp. 1-12.
2. Owens, A. C., and O.L. de Weck. "Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign." *AIAA SPACE 2016 Conference & Exposition*. Long Beach, CA. 2016. (submitted for publication)
3. Owens, A. C., In-Space Manufacturing Utilization Study Final Report, September 2016.
4. Prater, Tracie, et al. "NASA's In-space Manufacturing Project: Materials and Manufacturing Process Development Update." *Proceedings of the National Space and Missile Materials Symposium*. June 2017.
5. Prater, T., N. Werkheiser, F. Ledbetter, and A. Jehle. "NASA's In-Space Manufacturing Project: Toward a Multimaterial Fabrication Laboratory for the International Space Station." *Proceedings of the AIAA SPACE Conference*. September 2017.





FTIR comparison of flight Phase II print with Phase I feedstock