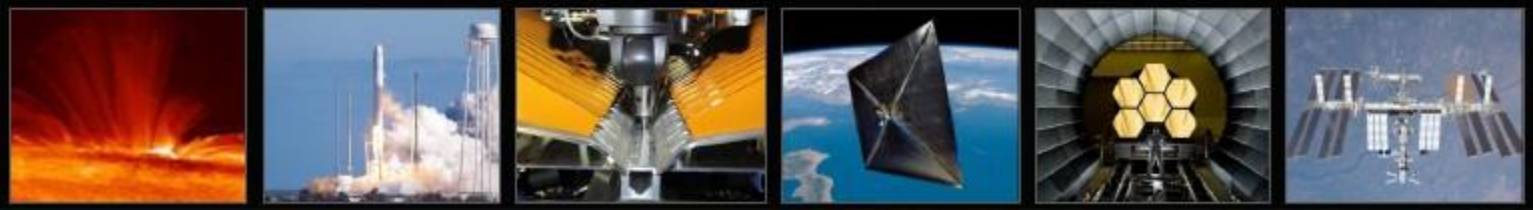
NASA's In Space Manufacturing Initiative For Exploration – Why, How, What!

Manufacturing Problem Prevention Program

November 1, 2016

Aerospace Corporation



R.G. Clinton, Jr.

Acting Manager, Science and Technology Office

NASA, Marshall Space Flight Center

Contributors

- Niki Werkheiser: NASA MSFC In Space Manufacturing Program Manager
- Andrew Owens: MIT PhD Candidate, Evolvable Mars Campaign
- Dr. Tracie Prater: NASA MSFC In Space Manufacturing Materials Characterization
- Mike Snyder: Made In Space Chief Designer

Agenda

- **NASA's In Space Manufacturing Initiative (ISM) For Exploration**
  - In Space Manufacturing Path to Exploration
  - Evolvable Mars Campaign (EMC) Quantitative Benefits Assessment
  - ISM Portfolio
  - ISM Program Timeline
- **Summary**

In-space Manufacturing 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 Platform

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

Space Launch System

PROVING GROUND Cis-lunar

Asteroids

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
- AM Exploration Systems

Text Color Legend

Foundational AM Technologies

AM for Exploration Systems

Surface / ISRU Systems

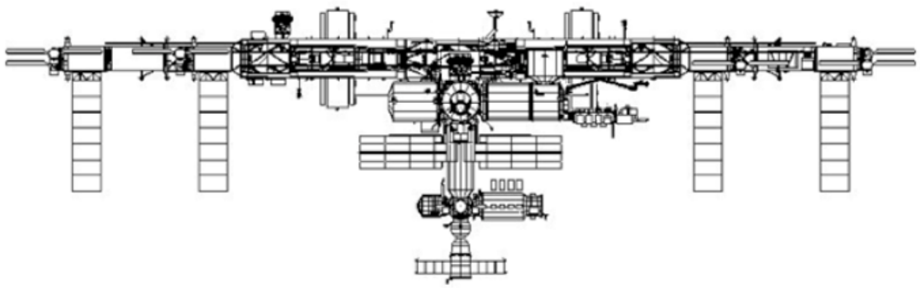
EMC: Maintenance Logistics Models

Each square represents 1000 kg

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

~13,000 kg on orbit

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

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

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

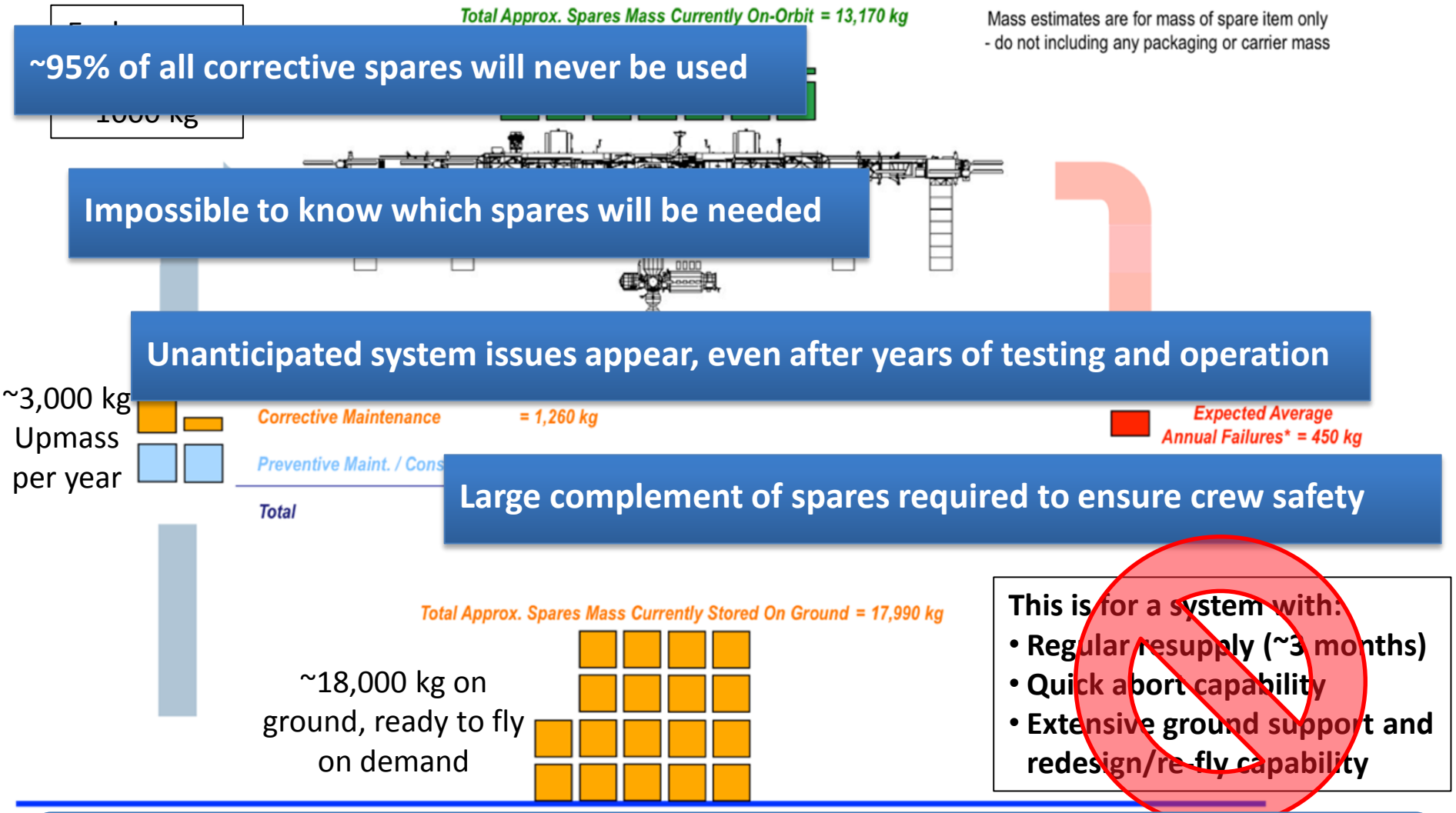
This is for a system with:

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

* - Based on predicted MTBFs

Cirillo et al. 2011

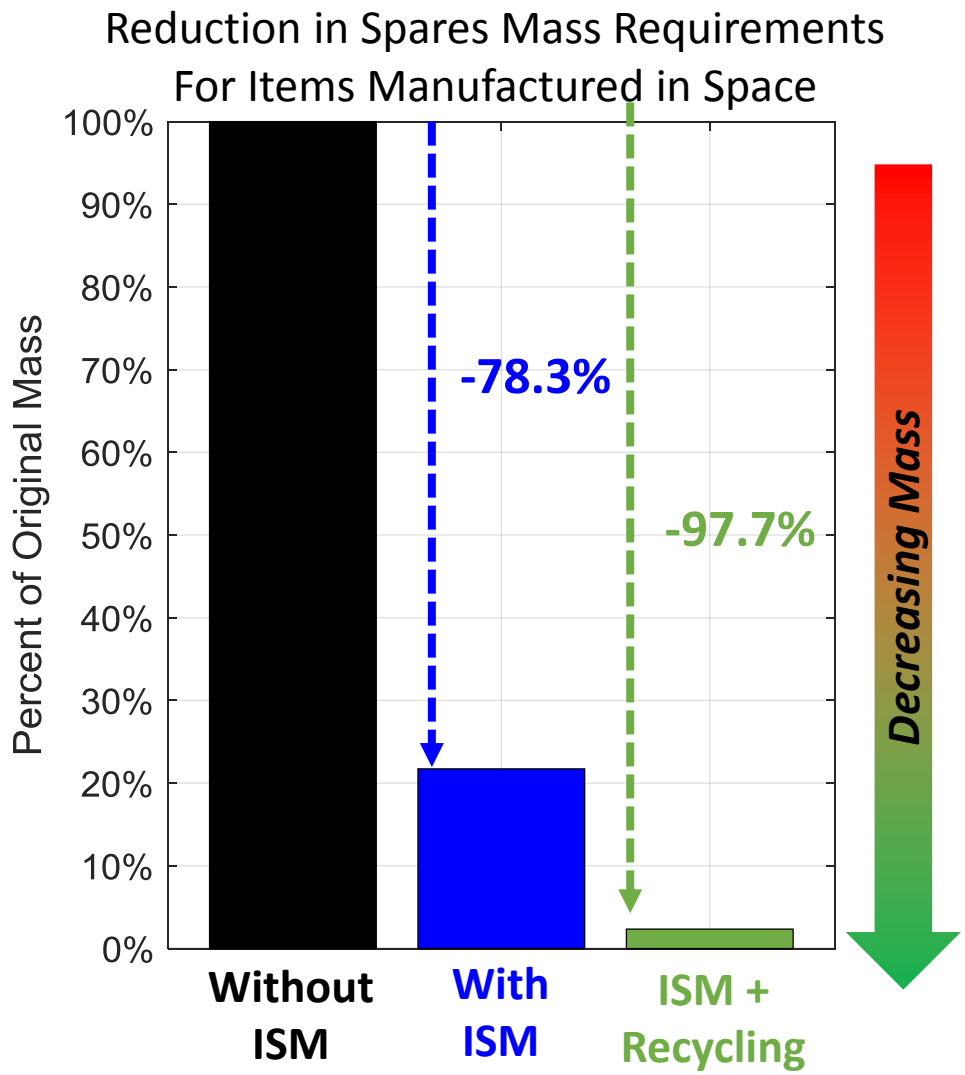
EMC: Maintenance Logistics Models



Current maintenance logistics strategy
will not be effective for long-duration missions beyond LEO

Cirillo et al. 2011

EMC: ISM Provides Solutions



This case examined parts associated with fluid flow (i.e. fans, valves, ducts, piping, etc.). Approx. 1/3 of total components were assumed to be manufactured in-space.

ISM significantly reduces the mass that needs to be carried to cover maintenance demands by enabling on-demand manufacturing from common raw materials

ISM enables the use of recycled materials and in-situ resources, allowing even more dramatic reductions in mass requirements

ISM enables flexibility, giving systems a broad capability to adapt to unanticipated circumstances. This mitigates risks that are not covered by current approaches to maintainability.

In-Space Manufacturing is a strong solution to maintenance logistics challenges that can

- **Reduce mass**
- **Mitigate risk**
- **Enable adaptable systems**

Owens and de Weck 2016

EMC Conclusions and Recommendations

EMC Conclusions

- **ISM is a necessary paradigm shift in space operations, not a 'bonus'**
- **Applications should look at recreating *function*, not form**
- **ISM is a capability, not a subsystem, and has broad applications**

EMC Key Recommendations

- **ISM team needs to be working with exploration system designers now to identify high-value application areas and influence design**
  - Define driving functional and interface requirements
  - Provide expertise to designers to translate traditional design to ISM design
  - Perform testing and demonstration
- **Monitor and leverage rapidly advancing commercial advanced manufacturing technologies**
  - Adapt commercial technology for spaceflight applications to take advantage of cost/schedule savings
  - Collaborate with industry, academia, other government
- **ISS is a critical testbed for driving out these capabilities**
  - Develop technology and process experience via on-orbit testing
  - Identify demo/test opportunities for existing ISM infrastructure (3DP, AMF)
  - Develop and test FabLab in preparation for springboard to Cis-lunar 'Proving Ground'

In-space Manufacturing Portfolio

IN-SPACE POLYMERS

- ISS On-demand Mfctr. w/polymers.
- 3D Print Tech Demo
- Additive Manufacturing Facility with Made in Space, Inc.
- Material Characterization & Testing

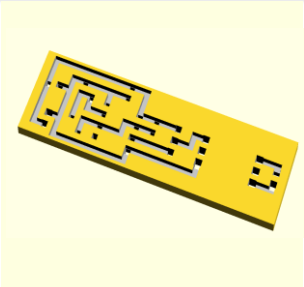
IN-SPACE RECYCLING

- Refabricator ISS 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 'FAB LAB' RACK

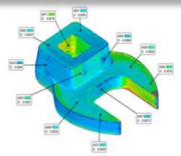
- Develop Multi-material Fabrication Laboratory Rack as 'springboard' for Exploration missions
- In-space Metals ISS Demo
- nScrypt Multi-material machine at MSFC for R&D

PRINTED ELECTRONICS



- MSFC Conductive & Dielectric Inks patented
- Designed & Tested RFID Antenna, Tags and ultra-capacitors
- 2017 ISM SBIR subtopic
- Collaboration w/Ames 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 (In-transit & Surface Systems

- Develop design-level database for applications
- Materials dev. & characterize for feedstocks (in-transit & surface) in MAPTIS DB.
- Design & test high-value components for ISS & Exploration (ground & ISS)

3D Printer International Space Station (ISS) Technology Demonstration - Results

- Ground Control specimens were printed in May 2014 on the flight unit in the Microgravity Science Glovebox (MSG) mock-up facility at MSFC
- The 3D Print Tech Demo launched to ISS on SpaceX-4 in September 2014
- Installed in the Microgravity Science Glovebox on ISS in November 2014
- A total of 21 specimens were printed on ISS in the MSG in November-December 2014, including the uplinked ratchet handle.
- Specimens underwent inspection and testing at MSFC from May to September 2015:
  - Structured light scanning
  - X-ray and CT scan
  - Microscopy
  - Density
  - Mechanical testing
- Small population sizes make comparisons between ground and flight specimens non-definitive

Results were published as a NASA technical publication in June 2016

Phase I Prints

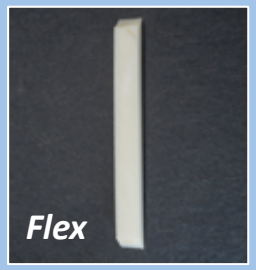
Completed Phase 1 Technology Demonstration Goals

- Demonstrated critical operational function of the printer
- Completed test plan for 42 ground control and flight specimens
- Identified influence factors that may explain differences between data sets

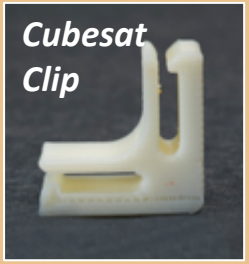
Phase II – Objectives

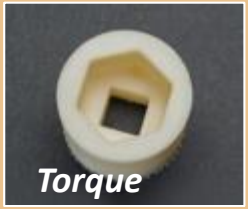
- Statistical sampling
- Demonstrate critical maintenance functions of printer
- Definitive determination of potential microgravity influences on properties and parts

Mechanical Property Test Articles

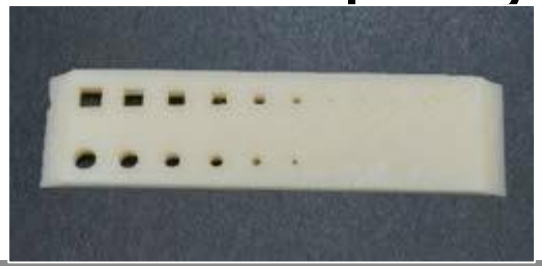


Functional Tools





Printer Performance Capability



3DP Phase 1 Key Observations

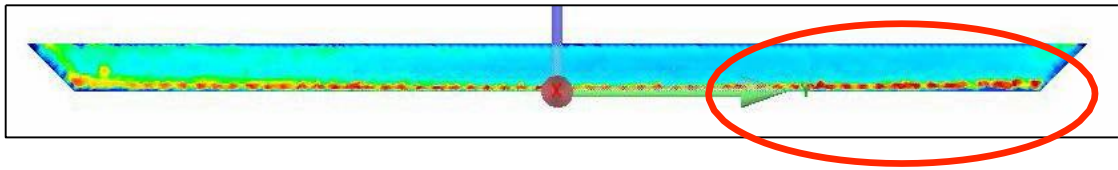
Material Properties

- 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

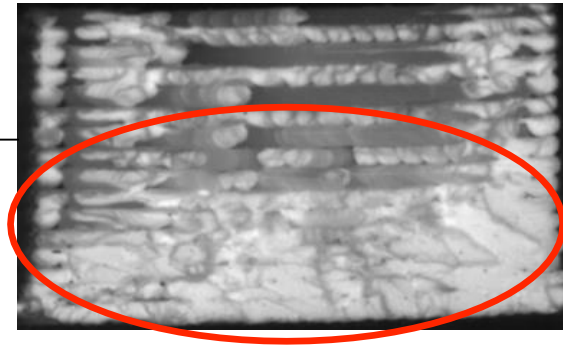
Structured Light Scanning



- 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

In-Space Manufacturing Elements

AMF - Additive Manufacturing Facility (SBIR Phase II-Enhancement) with Made In Space (MIS)

- First commercial in-space manufacturing platform
- Incorporates lessons learned from 3D Printer ISS Tech Demo
  - Maintenance procedures/capability modified to reduce crew time
  - Leveling and calibration done with on-board systems
  - Build surface modified for appropriate balance between print adherence and ease of removal
  - Integral cameras and sensors for automated monitoring
- Expanded materials capabilities:
  - ABS
  - HDPE
  - PEI/PC
- AMF launched on March 22, 2016. Printing on ISS initiated in June 2016.

Additive Manufacturing Facility

Material Characterization Database Development

- Objectives:
  - Characterize and document any microgravity effects on printed parts and resulting mechanical properties
  - Develop design-level database for microgravity applications
- Additional on-orbit prints of engineering test articles:
  - 3D Printer – Complete
  - AMF – In the Works

AMF Mechanical Property Test Matrix

Type, Orientation	Qty (ground)	Quantity (flight)	ASTM #
Tension, 0	10	10	D638
Tension, 90	10	10	D638
Compression, 0	10	10	D695
Compression, 90	10	10	D695
Tension, +/-45 (shear)	10	10	D3518
Flatwise tension	10	10	C297
Range coupon	2	2	n/a
EMU fan cap	1	1	n/a
Total	63	63	

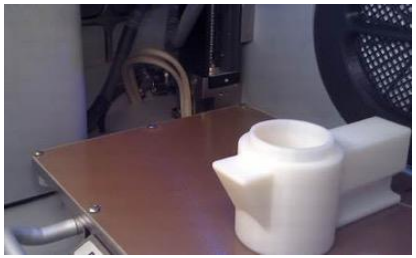
In-Space Manufacturing Elements

On-demand ISM Utilization Catalogue Development

- Objective:
  - Develop a catalogue of approved parts for in-space manufacturing and utilization
- Joint effort between MSFC AM M&P experts, space system designers, and JSC ISS Crew Tools Office and Vehicle Systems Office
- Documenting on-orbit printing process with users and ISS Program (safety, human factors, etc.)
- Developing V&V/Quality Control/Certification process for Candidate Part inclusion in catalogue based upon the DRAFT Engineering and Quality Standards for Additively Manufactured Space Flight Hardware

In-space Recycler ISS Tech Demonstration Development (SBIR 2014)

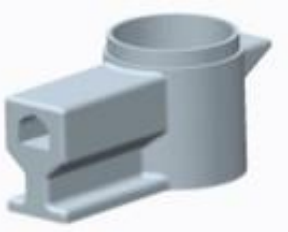
- Objective: Recycle 3D printed parts into feedstock to help close logistics loop
- Phase 1 recycler developments completed by Made In Space and Tethers Unlimited
- Phase II SBIR awarded to Tethers Unlimited for the In-Space Recycler
- Combined SRR/PRR held at MSFC on 10/18-10/19/2016 for ISS Refabricator (Integrated Printer/Recycler)
- ISS Technology Demonstration planned in FY 2018



OGA Adapter on ISS AMF Print Tray

Manual Inlet Test on ISS

ISM OGS AAA Inlet Adaptor Design



Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo

In-Space Manufacturing Elements

Multi-Material Fabrication Laboratory (FabLab) Development

- ISM is developing integrated, Multi-material FabLab Rack to serve as a 'springboard' from ISS to Exploration missions.
- FabLab will be competed via a NextStep2 BAA.
- FabLab Phase A BAA will heavily leverage industry in developing an integrated system that meets NASA's performance, operational and safety requirements within the form, fit and function of an ISS rack.
  - ISM worked with Yet2, Inc. to perform a technology search that identified more than 80 technologies with 43 sources from academia, government, industry, and international sources.
  - FabLab RFI was released on 9/8/16 with industry submitted on 10/14/16.
  - Industry responses received will be used to edit requirements for FabLab Phase A BAA.
  - FabLab will use a Phased Development Approach
    - Phase A: Operational Proof of Concept
      - Multi-material on-demand manufacturing capability including metallic (primary) and polymers
      - Earth=based remote commanding for printing, part handling, and removal
      - In-process monitoring
    - Phase B: Ground Demonstration Article
    - Phase C: Flight Demonstration System for ISS
- Phase A will be released in early 2017.

Multi-Material FabLab BAA

In-Space Manufacturing Elements

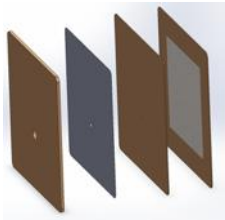
Launch Packaging Recycling (Common Use Materials) SBIR 2015

- Objective: Develop common use ISS packaging material(s) that can be recycled to product Feedstock for Future Fabrication needs
- Two Phase II SBIRS award in Spring 2016
  - Cornerstone, Inc.
  - Tethers Unlimited
- Collaboration with AES Logistics Reduction and Repurposing

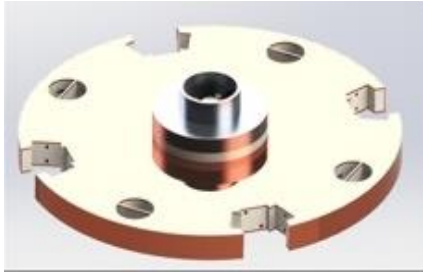
Common Use Materials for Recycling/Reclaiming for 3D Printing

In-space Printable Electronics Technology Development

- Objective: Develop capability to print electronics in microgravity environment for space exploration applications.
- Collaborating with Xerox Palo Alto Research Center (PARC), NASA Ames Research Center, and AMRDEC
- Roadmap targeting ISS technology demonstration
- Printed a Radio Frequency Identification (RFID) antenna as part of the RFID Enabled Autonomous Logistics Management Tech Demo for ground feasibility testing as JSC
- Additive ultracapacitors have been developed, tested, & patented for use on Pulsed Plasma Thruster for Cubesats



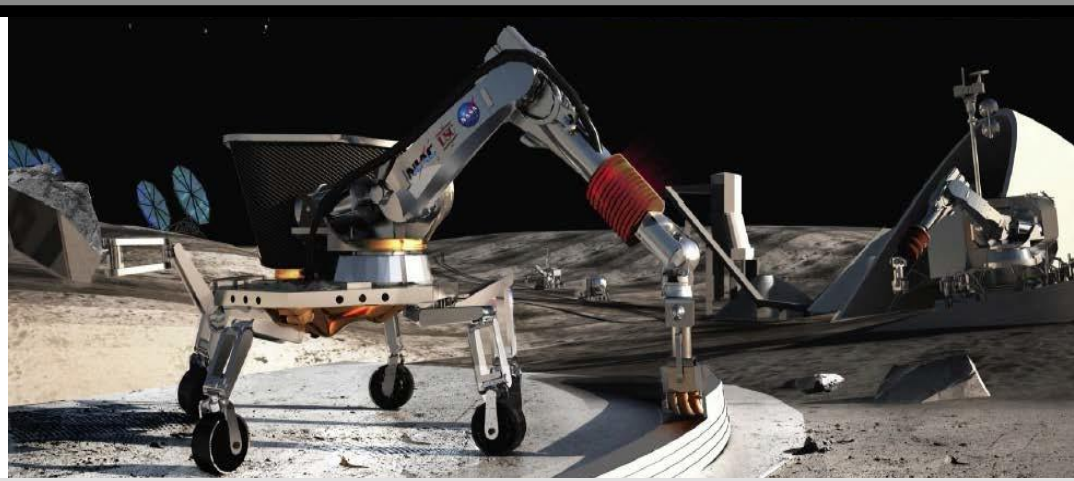
3D Printed RFID Antenna, layers



Cubesat Pulsed Thruster ultracapacitor structure (top view – ultracap is white material)

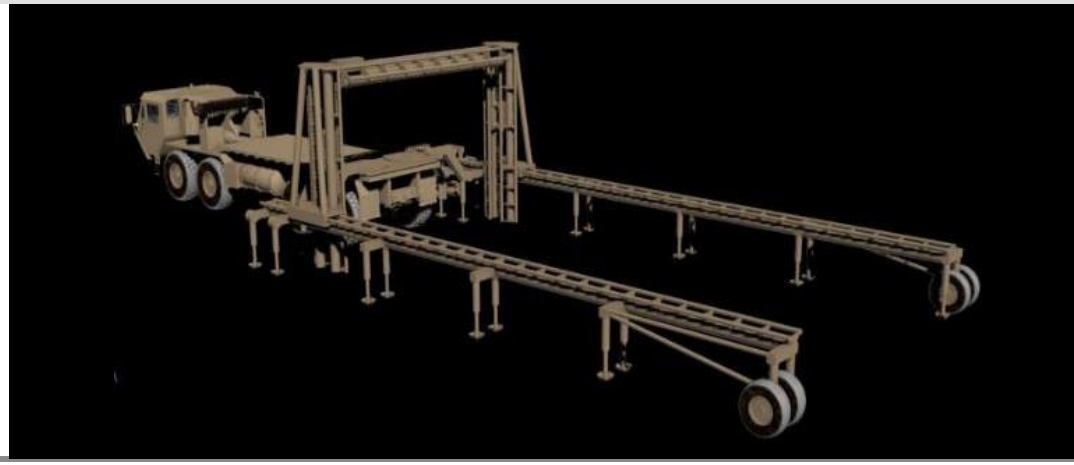
Collaborative Additive Construction Projects

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)



Collaborative Additive Construction Projects

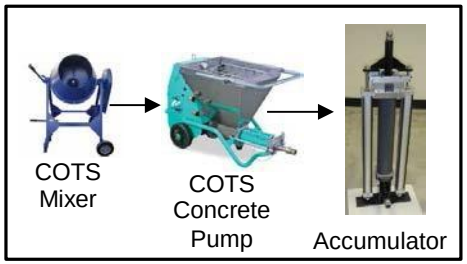
Additive Construction with Mobile Emplacement (ACME)

Planetary Regolith-based Concrete

Candidate Binder Materials

- Sorel-type cement (Mg0-based)
- Sulfur cement
- Polymers / trash
- Portland cement

Manual feed



ACME 2 Nozzles

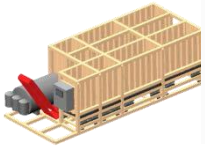
Subscale Optimized Planetary Structure

Gantry → ***Materials*** → ***Dry Good Feed*** / ***Liquid Storage*** → ***Continuous Delivery and Mixing System*** → ***Nozzle*** → ***Print Trials***

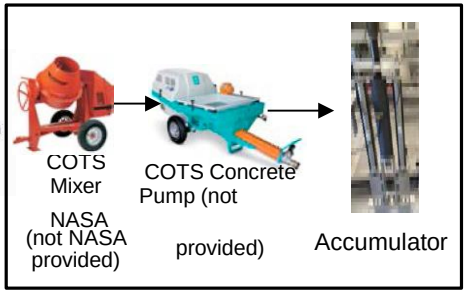
ACME 3

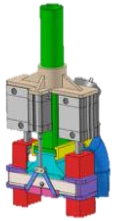
S.B. ACES 3

Portland Cement



Storage Subsystems





ACES 2 Nozzle

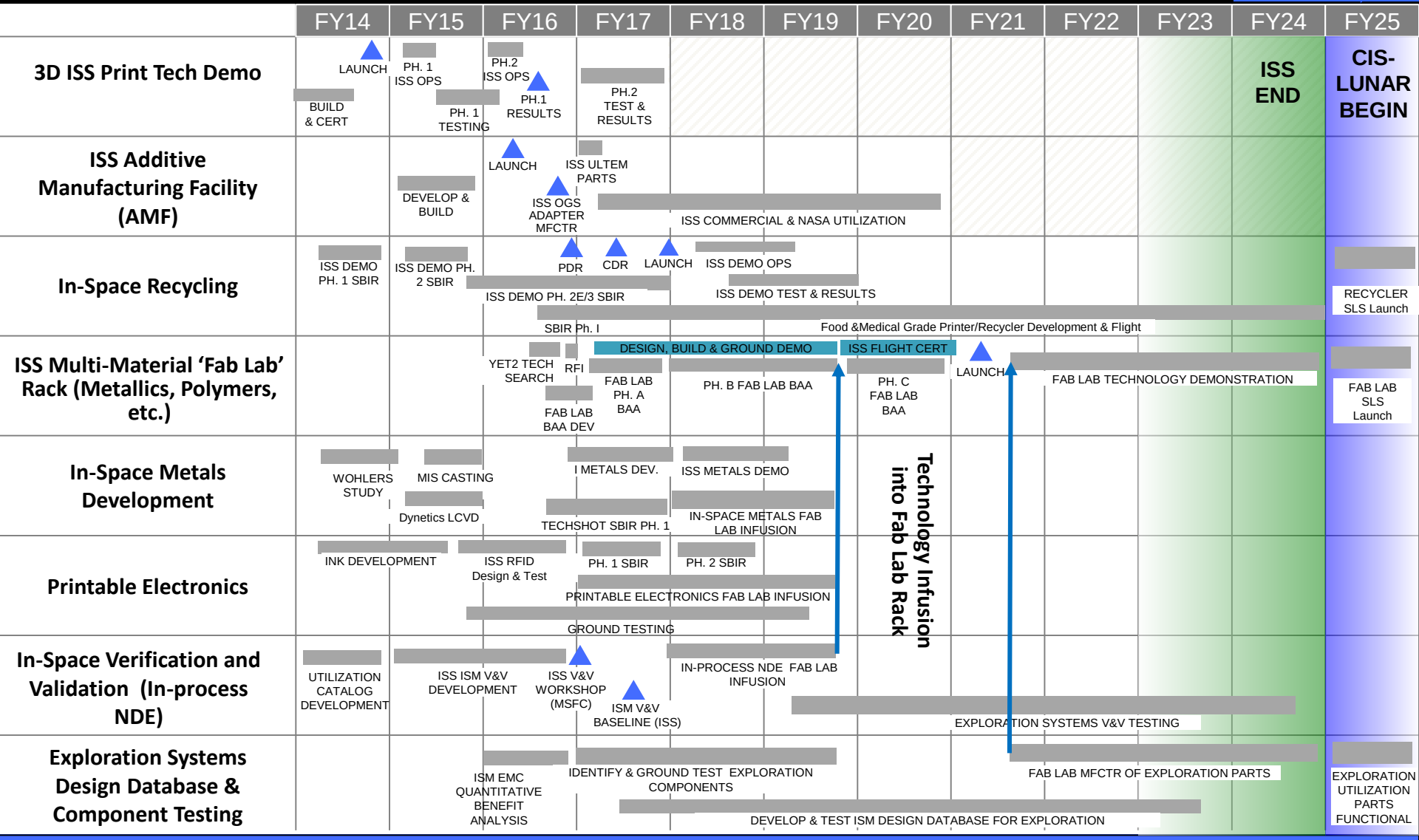
Guard Shack
(6' x 6' x 8')

Automated Construction of Expeditionary Structures (ACES)

Synergistic technologies for planetary and terrestrial use

In-space Manufacturing Program Timeline

Transition to 'Proving Ground'



ISM must influence Exploration design now & develop the corresponding technologies. At the current resource levels, ISM will not achieve needed capability within the required mission timeframe.

Summary: In-Space Manufacturing

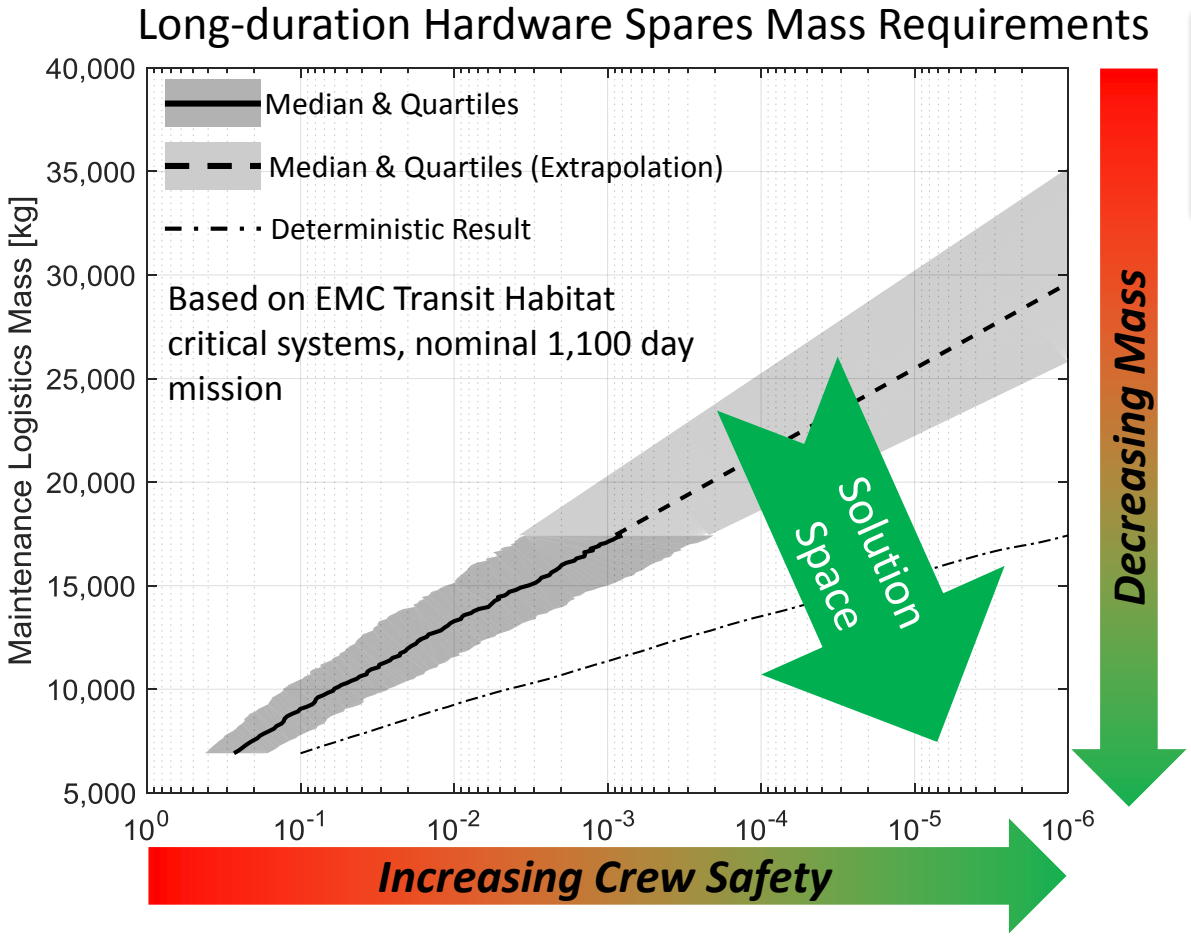
- **In-space manufacturing is a critical capability needed to support NASA's deep space exploration missions**
  - Increase in reliability
  - Reduction in logistics burden (make it or take it)
  - Recycling capabilities
  - Flexibility in design
- **NASA has taken the first step towards in-space manufacturing capability by successfully demonstrating 3D print technology on ISS**
- **The journey through development and proving ground trials is a long one**
  - Foundational technologies are yet to be demonstrated
  - Design for repair culture needs to be embraced
  - Applications need to be validated in operational environment
  - ISS is a critical testbed

In order to have functional capability that supports the Exploration timeline, ISM must work with Exploration systems designers now to identify high-value application areas and influence design process.

The Future Is Closer Than You Think

BACKUP CHARTS

EMC: Maintenance Logistics Challenges



Crew safety will always be a primary NASA concern. Mass & risk are interdependent.

Insufficient ISS statistical data complicates a true understanding of hardware/operations needs.

This only takes into account maintenance logistics for transit habitat and not transit utilization logistics or any surface operations or maintenance. Estimates will increase as this data is incorporated.

A limited number of possible solutions exist:

A. **Simplification of system design (which ISM can help to enable)**
B. **Sparing flexibility & robustness through In Space Manufacturing**
C. **Increased transportation system capability**
D. **Increased system reliability**
E. **All of the above will be required for sustainable missions**

Simon et al. 2015; Owens and de Weck 2016; Stromgren et al. 2016

Technology Development for External In Space Manufacturing and Assembly

Space Technology Mission Directorate's Tipping Point Projects – Robotic In-Space Manufacturing and Assembly of Spacecraft and Space Structures

- **Dragonfly: On-Orbit Robotic Installation and Reconfiguration of Large Solid RF Reflectors**
  Space Systems Loral of Palo Alto, California
  - Project provides the next generation of performance advancements in GEO ComSats: more apertures for greater geographic coverage variation, reconfigurable apertures for mission/fleet versatility, larger apertures for greater throughput, and mission enabling unique optics.
- **Public-Private Partnership for Robotic In-Space Manufacturing and Assembly of Spacecraft and Space Structures**
  Orbital ATK of Dulles, Virginia
  - Project will perform an integrated ground demonstration including robotically deployed rigid backbone and welding using precision alignment.
- **Versatile In-Space Robotic Precision Manufacturing and Assembly System - *Made in Space, Inc. of Moffett Field, California***