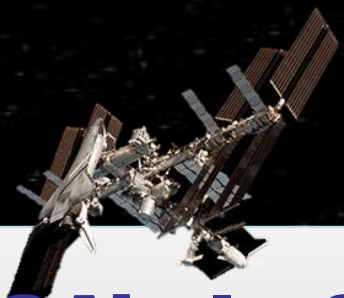

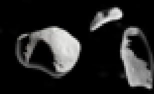


NASA's In-Space Manufacturing Initiative: Initial Results from International Space Station Technology Demonstration and Future Plans

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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

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 EXPLORATION APPLICATIONS

Unique Agency Expertise & Leveraging of Industry

ISM TECHNOLOGY DEVELOPMENT

ISM Parts/Systems Design Database & Test Articles

Answers WHAT we need to make

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

Part/System Requirements, Design, Materials & Processes

ISM

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

MATERIAL EXPERTS / AM EXPERTS / DESIGNERS

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

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

Proactive influence during Exploration design phase required for meaningful implementation

ISM Technology Development & Testing

Answers HOW we will make it

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

Multi-material 'FabLab' Test-bed

In-Space Manufacturing (ISM) Path to Exploration

EARTH RELIANT | **PROVING GROUND** | **EARTH INDEPENDENT**

ISS Platform
- In-space Manufacturing Rack Demonstrating:
  - 3D Print Tech Demo (plastic)
  - Additive Manufacturing Facility
  - Recycling
  - On-demand Utilization Catalogue
  - Printable Electronics
  - In-space Metals
  - *Syn Bio & ISRU*
- External In-space Mfctr. & Repair Demo

ISS

Commercial Cargo and Crew

Space Launch System

Planetary Surfaces Platform
- *Additive Construction, Repair & Recycle/Reclamation Technologies (both In-situ and Ex-situ)*
- *Provisioning of Regolith Simulant Materials for Feedstock Utilization*
- *Execution and Handling of Materials for Fabrication and/or Repair Purposes*
- *Synthetic Biology Collaboration*

Asteroids

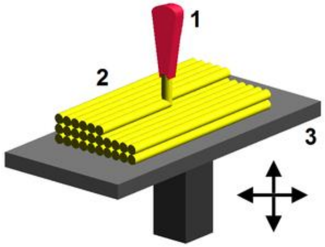
Earth-Based Platform
- Define Capacity and Capability Requirements (work with EMC Systems on ECLSS, Structures, Logistics & Maintenance, etc.)
- Certification & Inspection Process
- Material Characterization Database (in-situ & ex-situ)
- Additive Manufacturing Systems Automation Development
- Ground-based Technology Maturation & Demonstrations *(i.e. ACME Project)*
- *Develop, Test, and Utilize Simulants & Binders for use as AM Feedstock*

** Green text indicates ISM/ISRU collaboration*

3D Printing in Zero G Technology Demonstration Mission

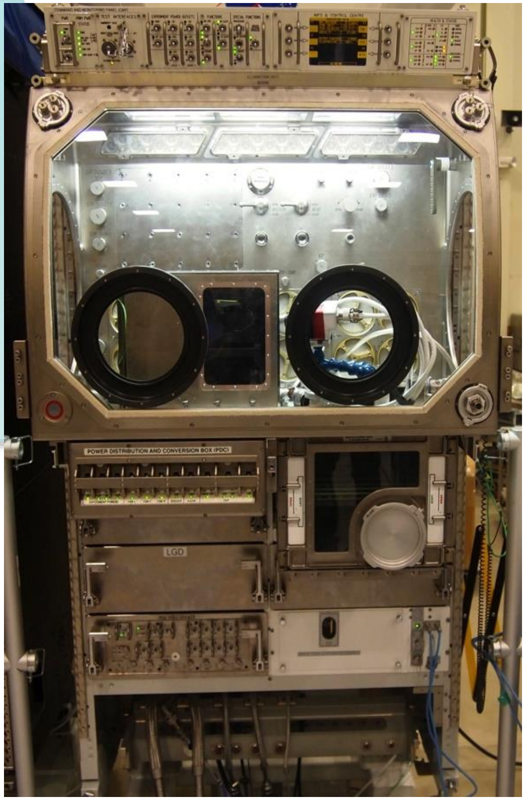
The 3D Print project delivered the first 3D printer on the ISS and investigated the effects of consistent microgravity on melt deposition additive manufacturing by printing parts in space.

Potential Mission Accessories

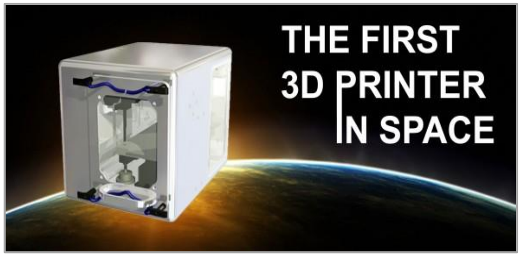


Fused deposition modeling:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table

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)
Est. Accuracy	95 %
Resolution	.35 mm
Maximum Power	176W (draw from MSG)
Software	MIS SliceR
Traverse	Linear Guide Rail
Feedstock	ABS Plastic



Microgravity Science Glovebox (MSG)



Phase I Operations Timeline

- Technology Demonstration Mission via a Small Business Innovation Research contract with Made in Space, Inc.
- Ground Control Samples were made in May 2014 on the flight unit in the MSG mock-up facility at MSFC
- The 3D Print Tech Demo launched to ISS on SpaceX-4 (September 2014)
- Installed in the Microgravity Science Glovebox on ISS in November 2014
- Flight Samples were made in November – December 2014
- Specimens underwent testing from May-September 2015
  - Small sample sizes make comparison between ground and flight specimens difficult
- Data from 3DP phase I out-briefed at a technical interchange meeting at NASA MSFC on Dec. 2-3, 2015
- Results will be published as a NASA technical publication in summer 2016

Phase I Prints

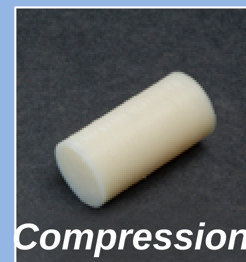
Completed Phase 1 Technology Demonstration Goals

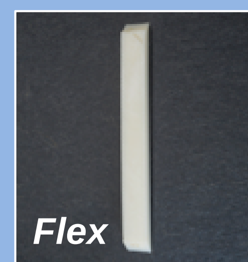
- ➢ Demonstrated critical operational function of the printer
- ➢ Completed test plan for 42 ground control and flight specimens
- ➢ Identified influence factors that may explain differences between data sets

Phase II - TBD

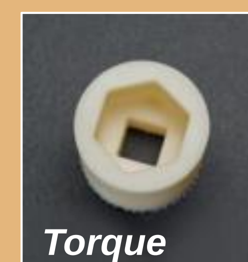
- Better statistical sampling
- Demonstrate critical maintenance functions of printer

Mechanical Property Test Articles



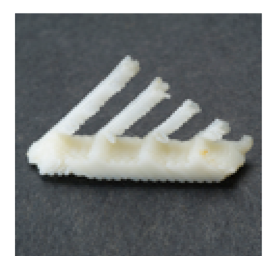


Functional Tools



Printer Performance Capability

AE



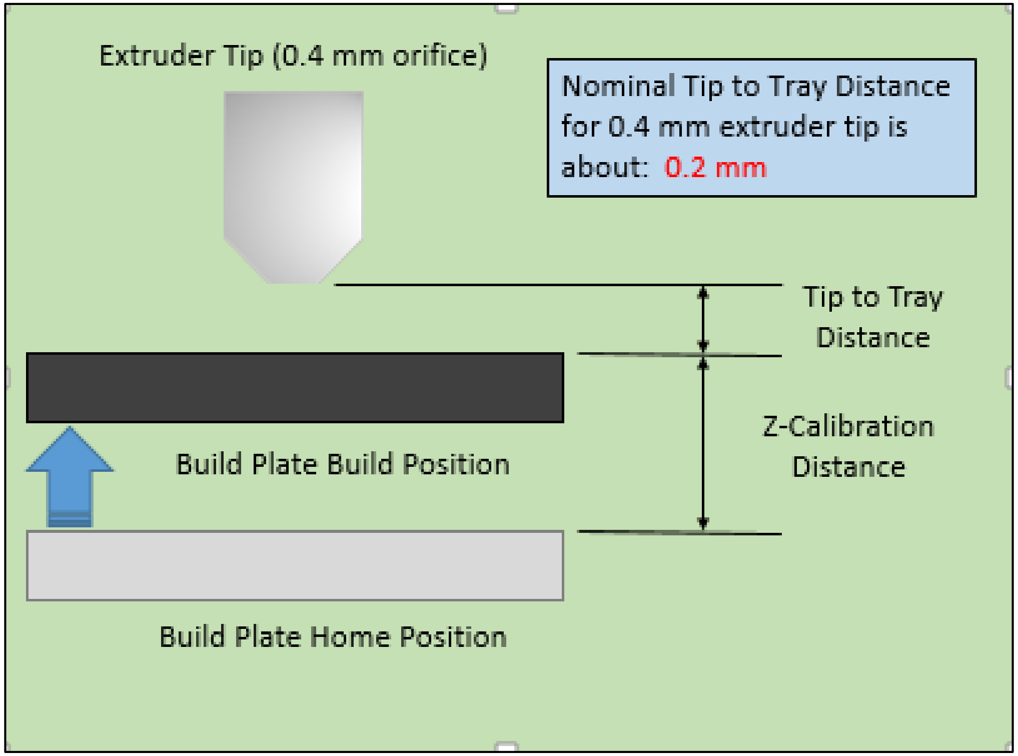
Notes on Printer Operations

- Feedstock for ground and flight are the same material and originate from the same manufacturing lot, but are from different canisters

- Flight feedstock 5-6 months older than ground feedstock at time of printing

- Changes in build tray over course of prints
  - Four separate build trays used for flight prints

- Z-calibration distance (and tip to tray distance, which is determined by the z-calibration setting) was changed slightly during the course of flight prints based on visual feedback
  - Z-Calibration was held constant for ground prints
  - Tip to tray distance is not a directly measurable metric since 3DP unit does not have closed loop positional feedback



Testing of Phase I Prints

Photographic and Visual Inspection

Inspect samples for evidence of:
- Delamination between layers
- Curling or deformation of samples
- Voids or pores
- Sample removal damage

Mass Measurement

Measure mass of samples:
- Laboratory scale accurate to 0.01 mg
- Note any discrepancy between flight and ground samples

Structured Light Scanning

Scan external geometry of samples:
- Accurate to ± 12.7 µm
- Compare scan data CAD model to original CAD model
- Measure volume from scan data
- Measure feature dimensions: length, width, height, diameter, etc.

Data Obtained

- Thorough documentation of sample quality
- Archival Photographs

Average Sample Mass

- Geometric Accuracy
- Average Sample Volume

Average Sample Density

- Internal structure
- Densification

- Mechanical Properties
- Comparison to ABS characterization data

- 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
- Note any discrepancy in spacing between filament lines

Mechanical (Destructive) Testing

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

Optical / SEM Microscopy

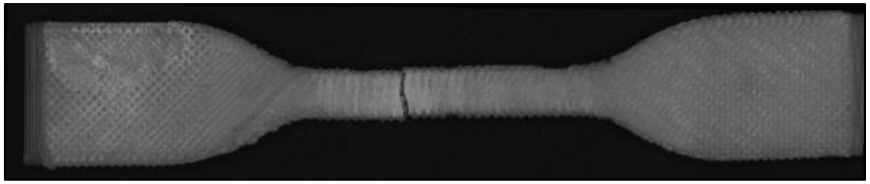
Inspect for discrepancies between flight and ground samples:
- External anomalies noted in previous tests
- microstructure
- Areas of delamination
- Fracture surface of tensile samples

3DP Phase I Key Observations: Material Properties

- **Density**
  - Flight specimens slightly more dense than ground specimens
  - Compression specimens show opposite trend
  - Gravimetric density strongly correlated with other mechanical properties

- **Tensile and Flexure**
  - Flight specimens stronger and stiffer than ground counterparts

- **Compression**
  - Flight specimens are weaker than ground specimens



Optical microscope image of tensile specimen

Mechanical Properties

Material Property	Percent Difference (WRT Ground)	Coefficient of Variation (Flight)	Coefficient of Variation (Ground)
Ultimate tensile strength (KSI)	17.1%	6.0%	1.7%
Modulus of Elasticity (MSI)	15.4%	6.1%	2.7%
Fracture Elongation (%)	-30.4%	26.3%	9.9%
Compressive Strength (KSI)	-25.1%	3.1	5.0
Compressive Modulus (MSI)	-33.3%	9.4%	4.2%
Flexural Strength (PSI)	25.6%	9.3%	6.0%
Flexural Modulus (KSI)	22.0%	9.6%	3.9%

Density

Specimen Type	Percent Difference (WRT Ground)
Tensile	3.4%
Compression	-2.6%
Flexure	5.6%

3DP Phase I Key Observations: XRay and CT

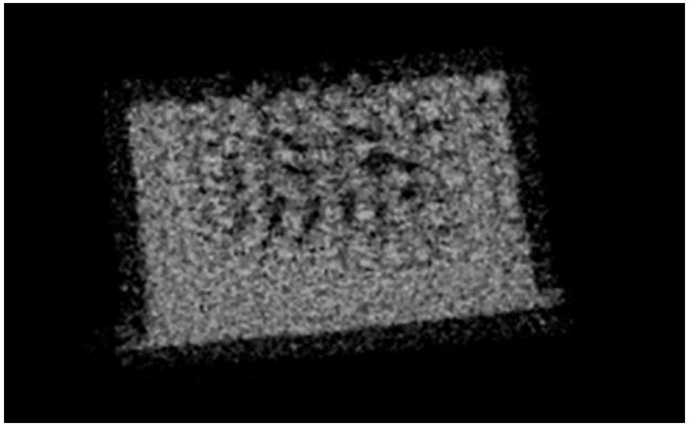
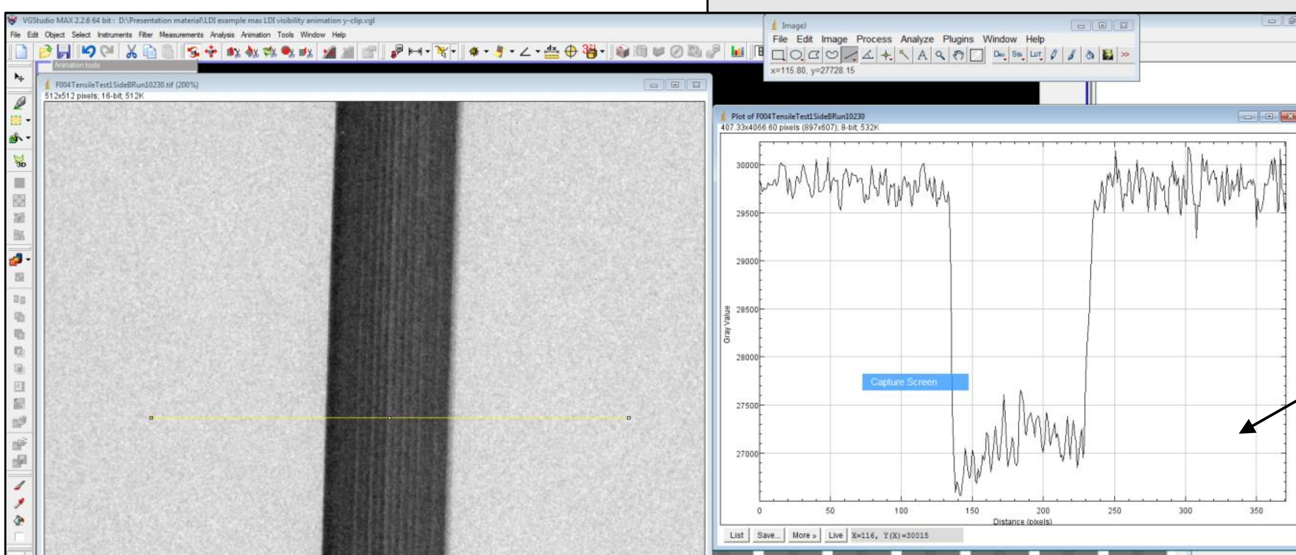


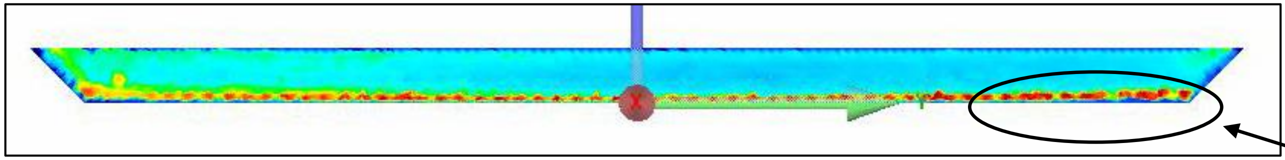
Image from CT scan of flight tensile specimen

- **CT scans show an abrupt step change in density about halfway through the thickness of many specimens**
  - More pronounced densification in lower half of flight specimens
  - Differences in densities (measured as mean CT) between upper and lower half of specimens is not statistically significant
- **Probable voids detected throughout flight and ground articles; no significant difference in number or size of voids between the flight and ground sets**



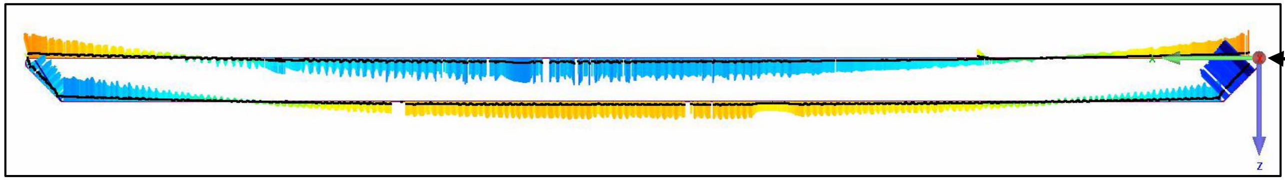
Lower density in upper section of part

3DP Phase I Key Observations: Structured Light Scanning



Flight Flexural Specimen

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



Ground Tensile Specimen

Warping of Samples

- may indicate inconsistent cooling of the specimen leading to internal stress build-up
- Damage sustained during specimen removal process

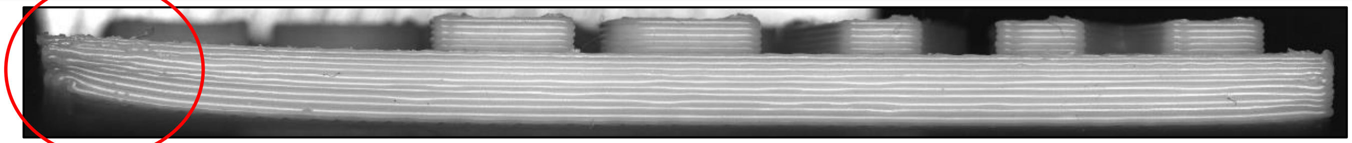
Sidewall surface of compression specimen

Roundness of Circular Samples

- Flight specimens *slightly* more out of round based on structured light scanning results

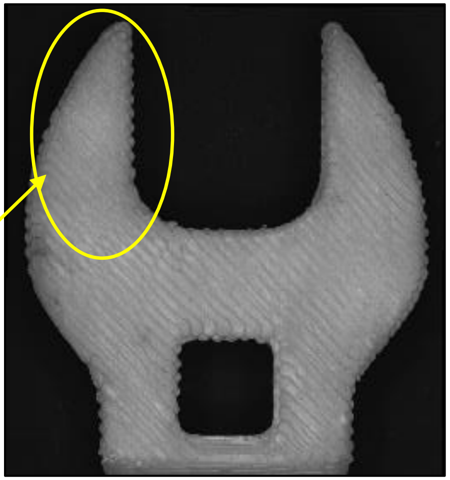
	Eccentricity	Elliptical Cross-Sectional Area (mm^2)	Percent Error of Cross-Section WRT CAD
Flight	0.14	121.7	4.11 %
Ground	0.12	123.0	2.96 %

3DP Phase I Key Observations: Optical Microscopy



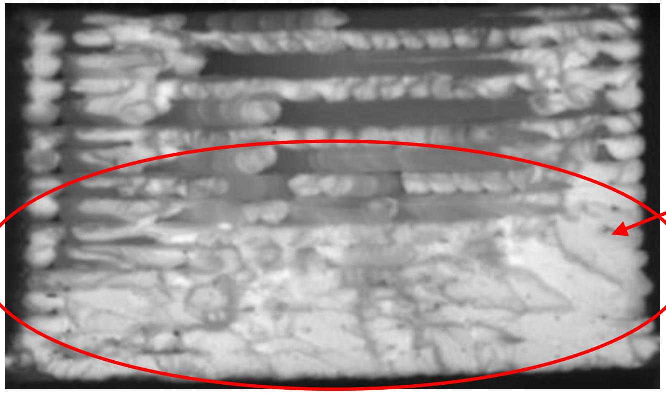
Warping

Side Image Extruder Plate (Ground Specimen)

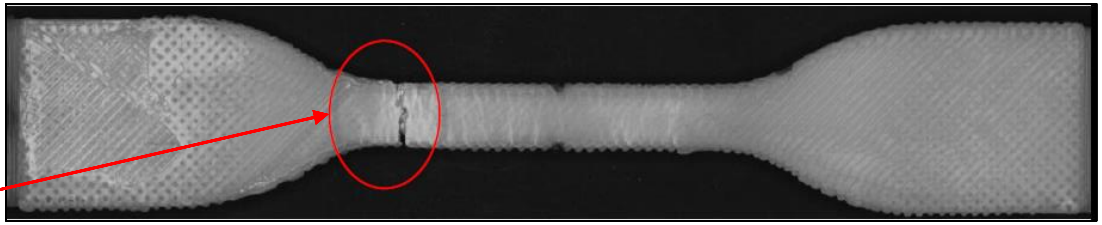


Protrusions

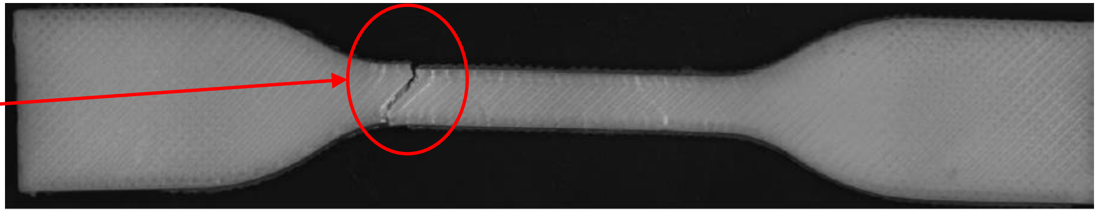
Bottom Surface Crowfoot (Flight Specimen)



Greater Densification of Bottom Layers (Flight tensile)



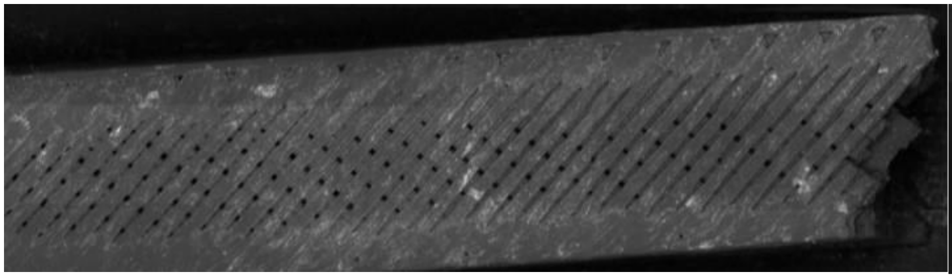
Break in tensile specimen (straight across)



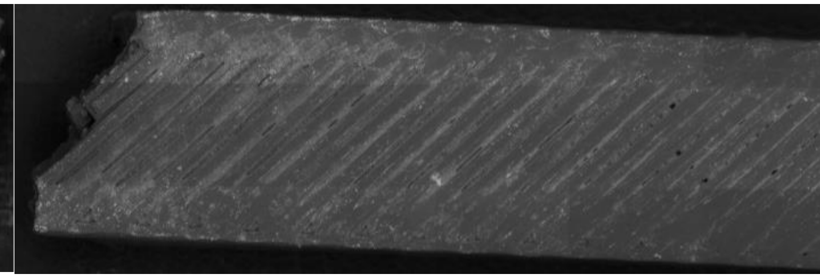
Break in tensile specimen aligned with filament (45°)

3DP Phase I Key Observations: Scanning Electron Microscopy (SEM)

- Structural differences are seen within both ground and flight specimen groups
- Ground sample surfaces are generally more “open” than flight specimens



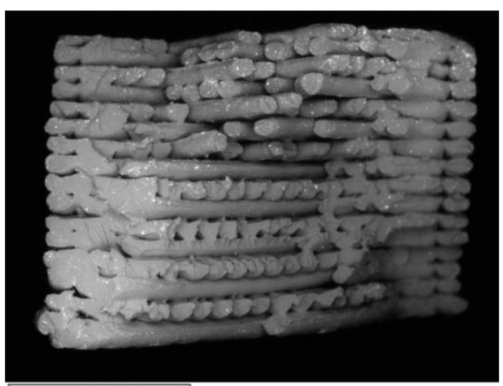
Ground tensile specimen surface

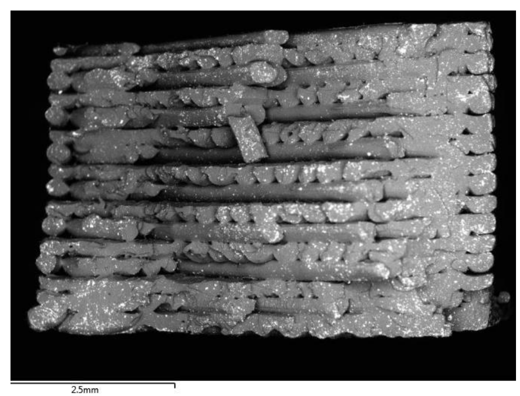


Flight tensile specimen surface

- Fracture surfaces for ground specimens have **open central fibers** and dense fiber agglomeration on sides
- Fracture surfaces for flight specimens have dense **fiber agglomeration on sides and bottom**

Ground tensile fracture surface

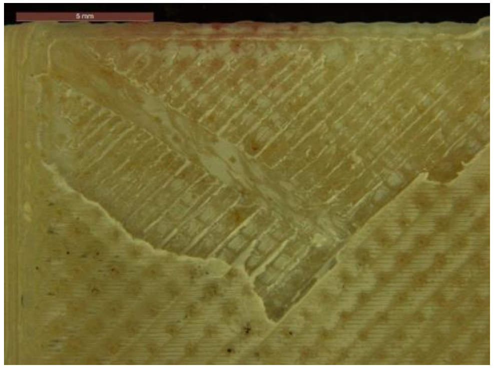




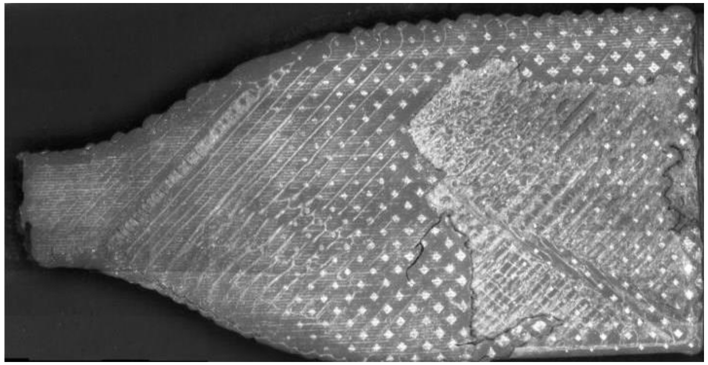
Flight tensile fracture surface

3DP Phase I Key Observations: Scanning Electron Microscopy (SEM)

- “Stuck parts” due to over-adhesion to build tray result in layer delamination upon removal



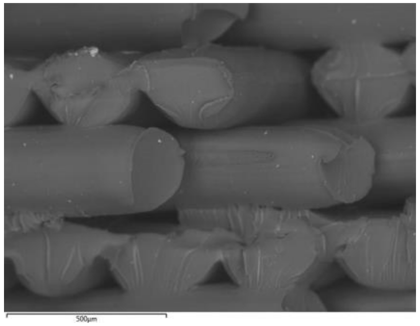
Flight tensile specimen F004

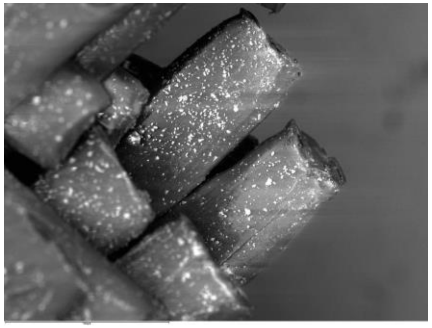


Flight tensile specimen F018

- Fracture surfaces exhibit typical glassy brittle fracture
- Fiber necking more prevalent in ground samples

Ground tensile G015

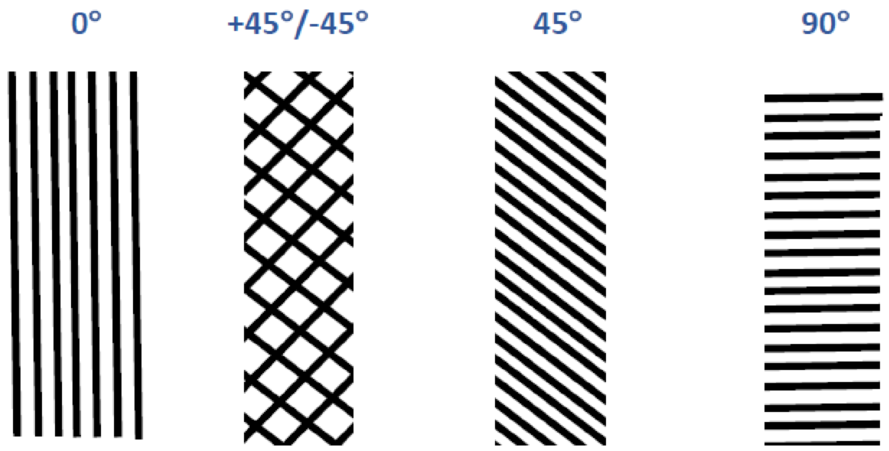


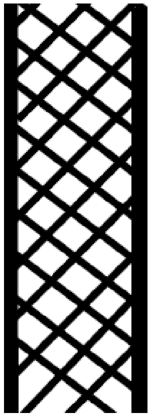


Ground tensile G004

3DP Phase I Key Observations: Scanning Electron Microscopy (SEM)

Raster orientation	Mean yield strength (PSI)
Longitudinal (0)	3700
Diagonal (45)	2274
Transverse (90)	2081
Default (+/- 45)	2741





Characteristic appearance of flight specimens

- Ground and flight specimens built with +/-45 orientation
- More fiber bonding on bottom of flight specimens
- Potentially explains increased strength of flight specimens and reduced elongation

3DP Phase I Follow-On Work

Ground Based Investigations

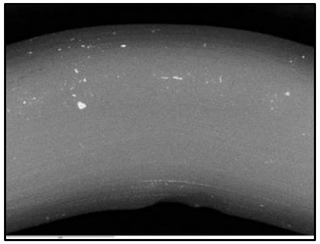
- Study of effect of tip-to-tray distance on part quality and performance
    - Systematic variation of this distance using 3DP backup flight unit
    - Study envelopes commanded values for ground and flight prints
    - Test regime includes surface metrology, mass measurement, structured light scanning, XRay/CT, ,mechanical testing and SEM
    - Complete by October 2016
- Printing with older feedstock
    - Assess hypothesis that flight feedstock being older at time of printing was a contributing variable to observed differences in mechanical properties
    - Study also uses 3DP flight backup unit

Further Analysis of Phase I Specimens

- Chemical composition analysis using Fourier Transform Infrared Spectroscopy
    - Demonstrated **no significant chemical differences between ground and flight prints** in terms of functional groups present and relative concentrations
- Scanning electron microscopy (SEM) of calibration coupons specimens (sparser fill) to better assess microgravity effects
- SEM of layer quality (square column) specimens

On-Orbit Investigations

- Better statistical sampling with specimens from Phase II operations
- Locked manufacturing process to enable assessment of microgravity effects on FDM process



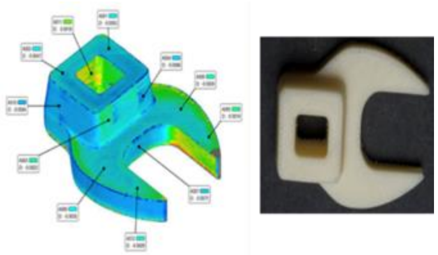
SEM Image
- Deformed ABS Filament with microcracks

3DP Phase I Lessons Learned

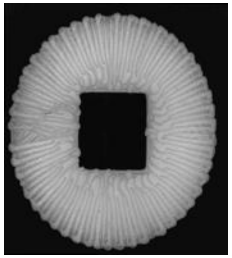
- Need to understand cooling rate and strength relationships
- Adhere to established manufacturing protocols
  - Develop a locked and qualified manufacturing process that will enable true comparison of ground and flight prints for phase II operations
  - Fabricate samples with the same processing parameters
- Fully characterize the samples prior to mechanical testing
- Utilize raw data from mechanical testing
- Video record sample during mechanical testing
- Consider use of noncontact measurement techniques (digital image correlation) to understand elongation behavior
  - Mechanical/elastic in nature

3DP Phase I Executive Summary

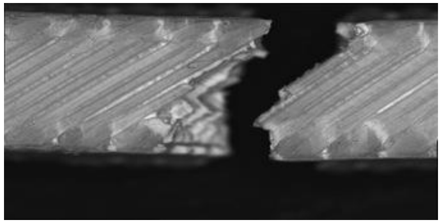
- The Phase I parts (first 21 parts printed) underwent testing and evaluation at the Materials and Processes Laboratory at NASA Marshall Space Flight Center and were compared with “ground truth” samples printed prior to printer’s launch to ISS.
  - Phase I report will be published as NASA technical publication in summer 2016.
- Considerable structural variance within and between ground and flight specimens precludes ascertaining any obvious microgravity influence on FDM process
- Differences noted in testing between the ground and flight specimens could not be linked to microgravity as a processing variable
  - More definitive assessment will be made with SEM analysis of sparser fill calibration specimens
  - “Build” structural variance accounts for difference in measured tensile properties
- Based on the Phase I results, the ISM team developed a go forward plan which includes: (1) Clear objectives defined for Phase II on-orbit prints and (2) Additional ground-based characterization work in order to address variables related to the 3DP data set.
- Complementary microstructural and macrostructural modeling work of FDM at Ames Research Center underway
  - ISM team providing data for model validation



Structured Light Scan Data of Crowfoot Tool 3D Printed on ISS



Optical Microscopy of Ground Control Ratchet Tool Head



Optical Microscopy of Break in Tensile Test Flight Specimen

In-Space Manufacturing (ISM)
Phased Technology Development Roadmap

Earth-based

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

Demos: Ground & ISS

Plastic Printing Demo

Mat. Char.

3D Print Tech Demo

2014

- In-space:3D Print: First Plastic Printer on ISS Tech Demo
- 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

Recycler

Utilization Testing

AMF

2015 - 2017

- ***3D Print Demo***
- ***Add. Mfctr. Facility (AMF)***
- ***In-space Recycler ISS Demo***
- ***ISM Cert Process Part Catalogue***
- ***ISS & Exploration Material & Design Database***
- ***External In-space Mfctr. (w/DARPA & STMD)***
- ***Autonomous Processes***
- ***Future Engineer STEM Challenge***
- ***ACME***

Metal Printing

Fab Lab

Self-repair/ replicate

Digital Mfctr.

External In-space Mfctr

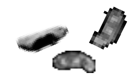
2018 - 2024

ISS: Multi-material "Fab Lab" 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 Demo**
- ***ACME Ground Demos***

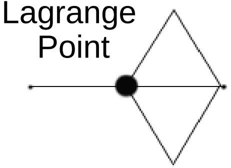
Exploration (Proving Ground to Earth Independent)

Asteroids



Lunar

Lagrange Point



2025-35

Lunar, 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 to specification

Planetary Surfaces Points Fab

- Transport vehicle and sites would need Fab capability
- ***Additive Construction & Repair of large structures***

2035+

Mars Multi-Material Fab Lab

- ***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 Key Exploration Test-bed for the Required Technology Maturation & Demonstrations

** Green text indicates ISM/ISRU collaboratio*

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- Niki Werkheiser, In-Space Manufacturing Project Manager
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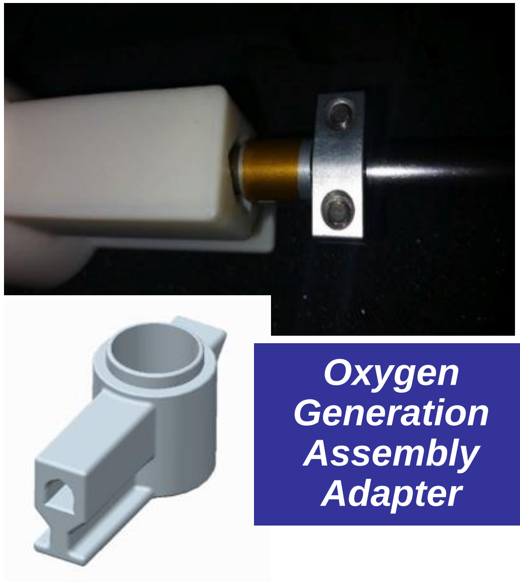
- Steve Newton, In-Space Manufacturing Deputy Project Manager
- Dr. Frank Ledbetter, Senior Technical Advisor for In-Space Manufacturing
- Personnel who worked on testing of phase I prints:
  - Dr. Terry Rolin
  - Dr. Ron Beshears
  - Steven Phillips
  - Catherine Bell
  - Dr. Richard Grugel
  - Erick Ordonez
  - Lewis “Chip” Moore

Questions

Backup Slides

Additional ISM Activities

- Interface with and design of components for ISS stakeholders
  - Oxygen Generation Assembly Adapter allows ISS crew to obtain consistent and accurate airflow velocity measurements for Environmental Control and Life Support Systems (ECLSS) hardware
  - Air Nozzle Adapter (will be used to inflate refillable stowage bags for ISS demo test) for use on ISS
  - Robonaut camera calibration mount (senior design project with Vanderbilt University)
  - OGA and air nozzle will be printed with Additive Manufacturing Facility (AMF)
- Defined phase II prints based on phase I results
  - Streamlined process for operations to conserve crew time
  - TBD as to when phase II prints will occur
- Made in Space Additive Manufacturing Facility (AMF) commercial printer is now on ISS
  - Multi-user facility
  - NASA prints will take place this summer



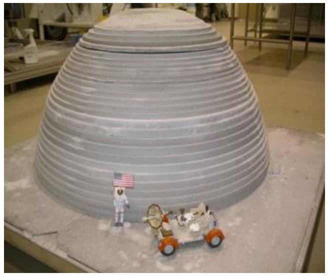
Oxygen Generation Assembly Adapter

ISS Air Nozzle Adapter

Additional ISM Activities

- Tethers Unlimited (TUI) developing an in-space recycler and printer for recycling of printed parts into feedstock
- NASA Science Technology Mission Directorate (STMD) External In-space Manufacturing Tipping Point Project with Made in Space, Inc. entitled “Versatile In-Space Robotic Precision Manufacturing and Assembly System”
- Additive Construction by Mobile Emplacement (ACME)
  - project is in conjunction with the Army Corps of Engineers and is co-led by MSFC and KSC
  - Development of additive construction technologies for use with in-situ resources
- Procurement of Nscrypt machine
  - Multimaterial 3D printer
  - printable electronics capability
- Ongoing development work toward ISS “FabLab”
  - Trade studies of manufacturing processes for in-space applications
  - Logistics analyses
  - Material characterization activities to understand machine and material capabilities and inform requirements development

Feedstock recycler from TUI

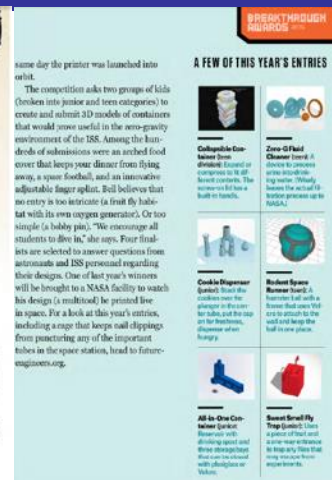


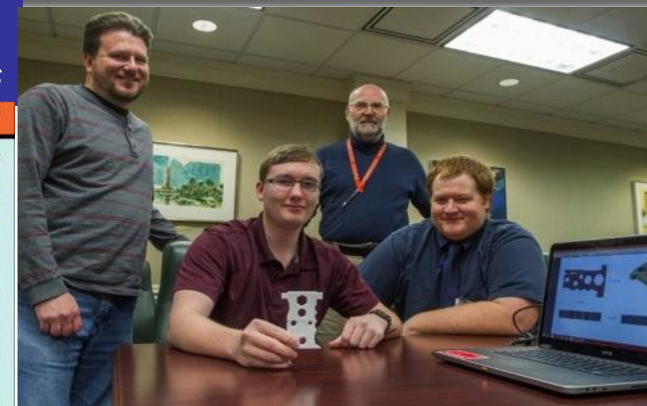
ACME “B-Hut”

ISM Education & Public Outreach ‘Scrapbook’ (Oct, 2015 – April, 2016)

3D Print included as Top 15 ISS events for the ISS 15th Anniversary Infographic Released 11/2/15

Future Engineers listed as ‘Breakthrough Award’ in Nov. Issue of Popular Mechanics





“Design Consultation” with FE Winner, R.J. Hillan, NASA ISM team members, and MIS Design Lead, Mike Snyder 12/4/15

Media Event with ISM and Former ISS Commander Butch Wilmore 11/16/15

National FE Challenge Teen Winner, Ryan B., at California Science Center with Astronaut Leland Melvin 10/27/15

FE Junior Division Winner, Emily T., with her winning design, the Flower Tea Cage

NASA Systems Eng. Excellence Award for 3D Print Demo