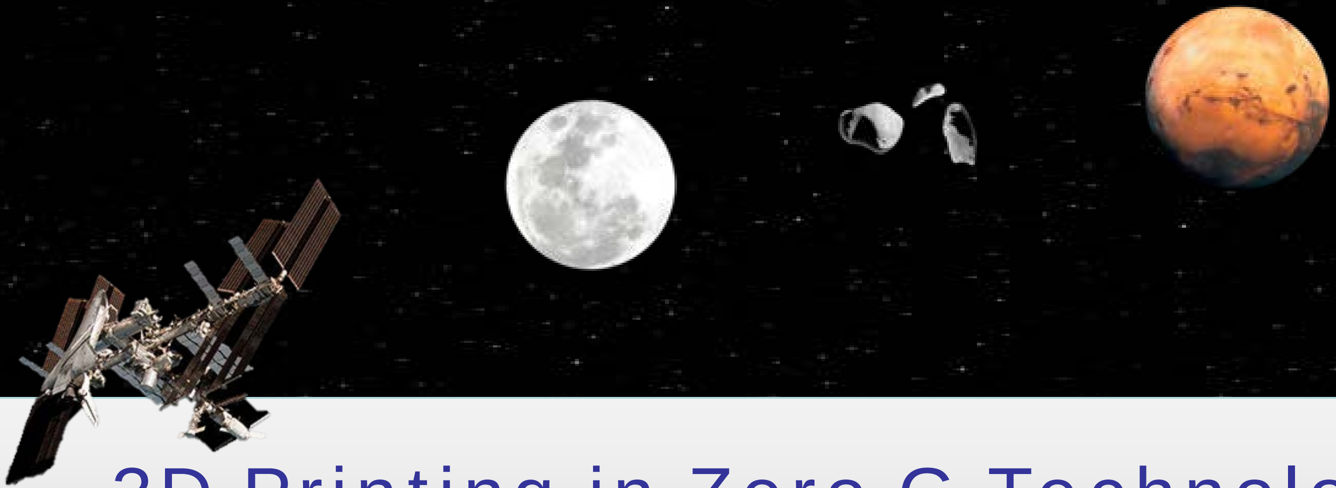

3D Printing in Zero G Technology Demonstration Mission: Summary of On-Orbit Operations, Material Testing and Future Work

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Dr. Frank Ledbetter

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In-Space Manufacturing Project

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In-Space Manufacturing (ISM)

IN SPACE MANUFACTURING

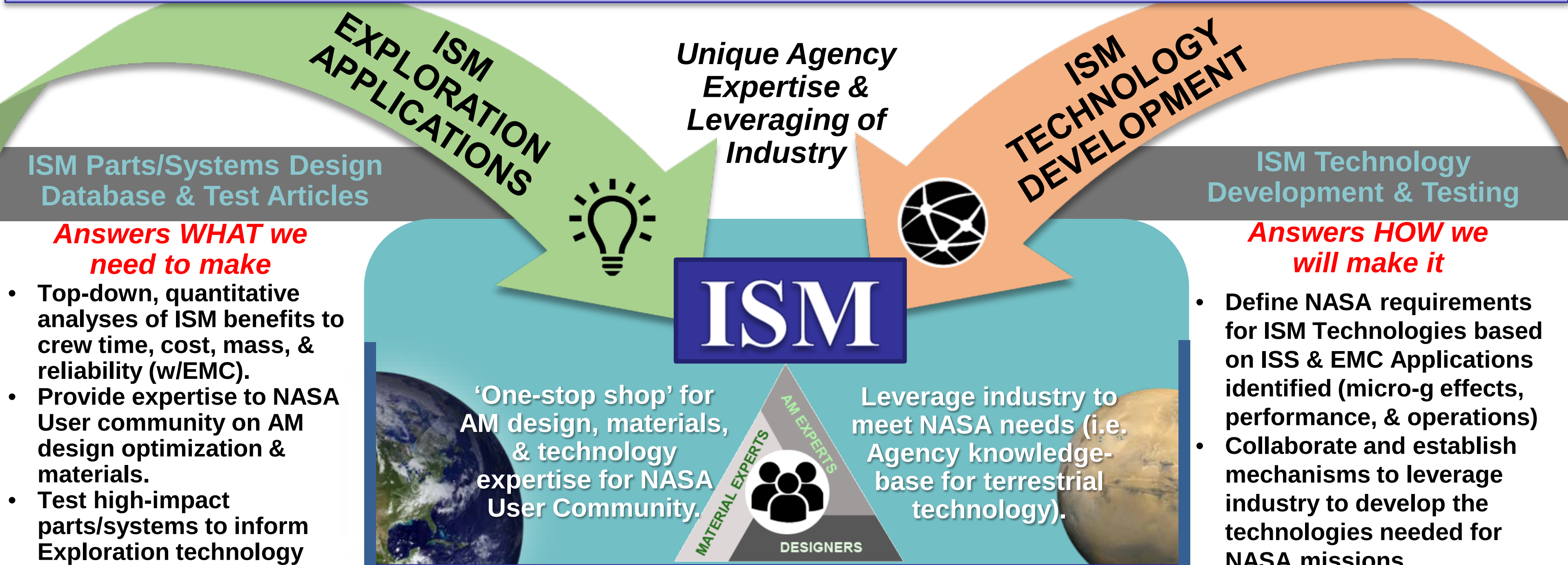
ISM

MAKE IT-DON'T TAKE IT

> ***"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 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.

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

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

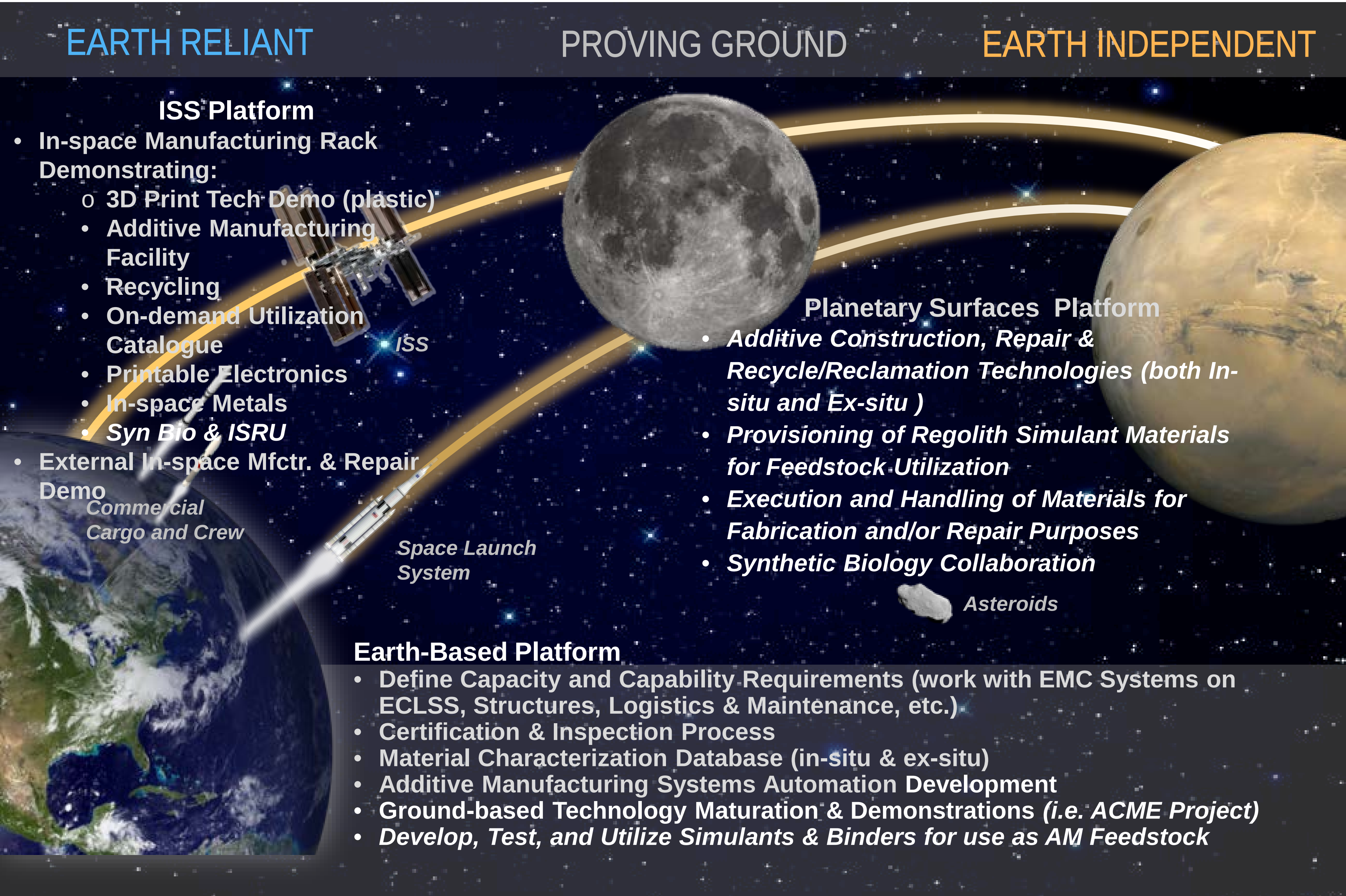
Answers HOW we will make it

- 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.

Part/System Requirements, Design, Materials & Processes

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

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*

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*

3D Printing in Zero G Technology Demonstration Mission

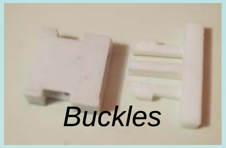
The 3D Print project delivered the first 3D printer on the ISS and investigated the effects of consistent microgravity on melt deposition additive manufacturing by printing parts in space.

Potential Mission Accessories


Threads

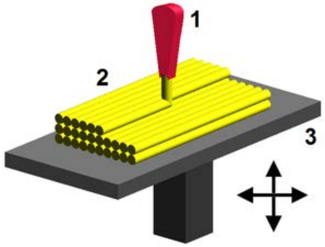

Springs


Containers


Buckles


Caps

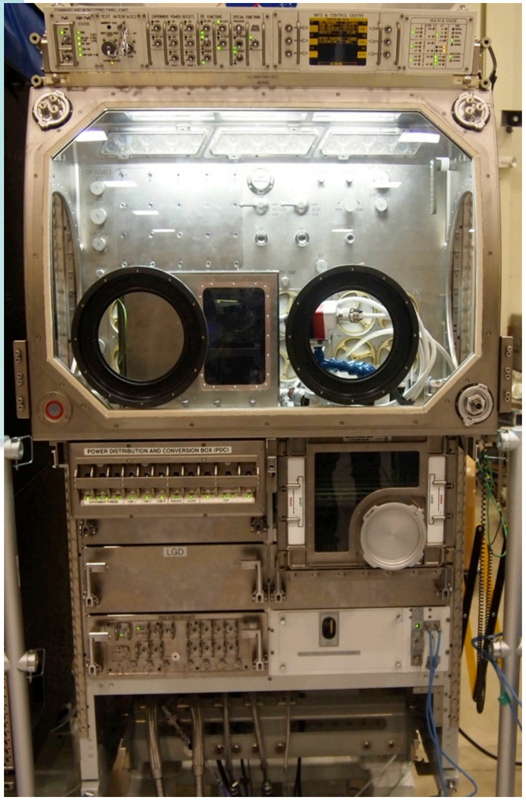

Clamps



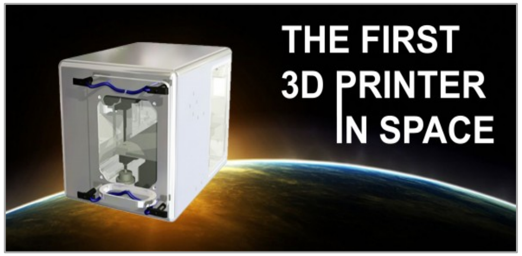
Fused deposition modeling:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table

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 number of specimens 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 – June/July 2016

- Better statistical sampling

Mechanical Property Test Articles


Tensile


Compression


Flex

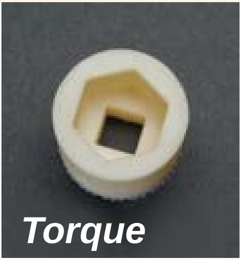
Functional Tools


Crowfoot

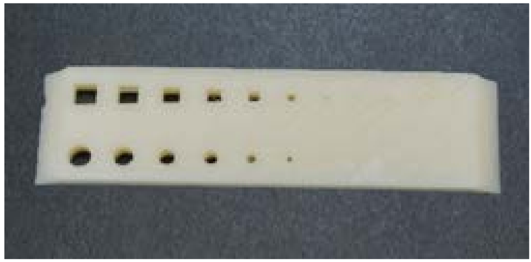

Ratchet


Cubesat Clip


Container


Torque

Printer Performance Capability



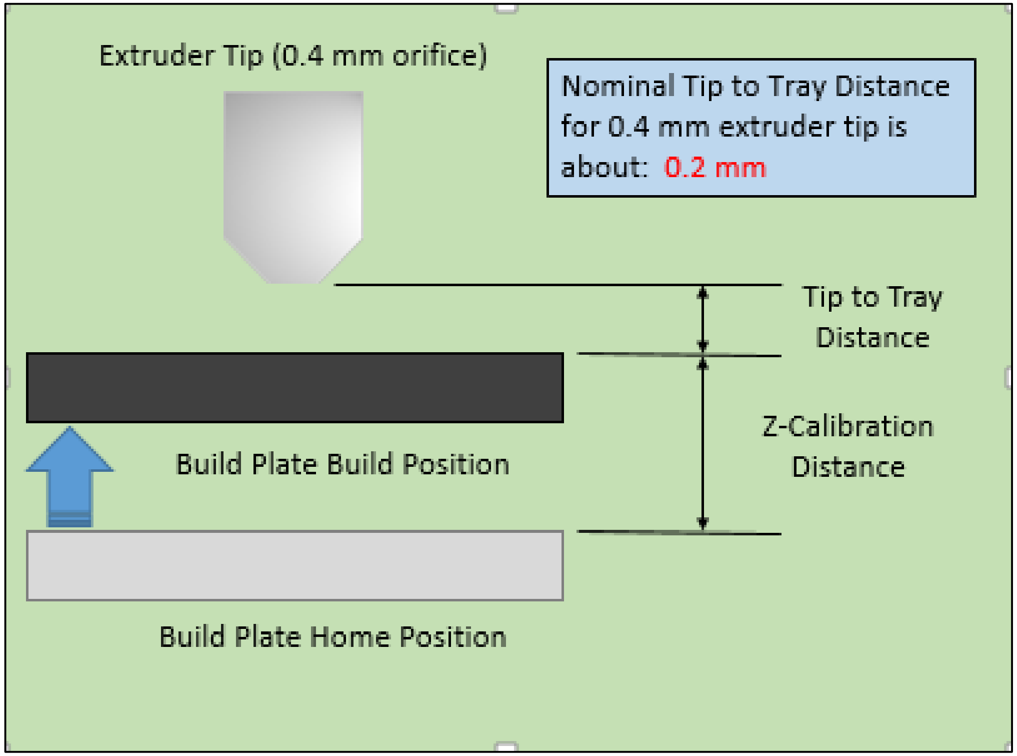
Notes on Printer Operations

- 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

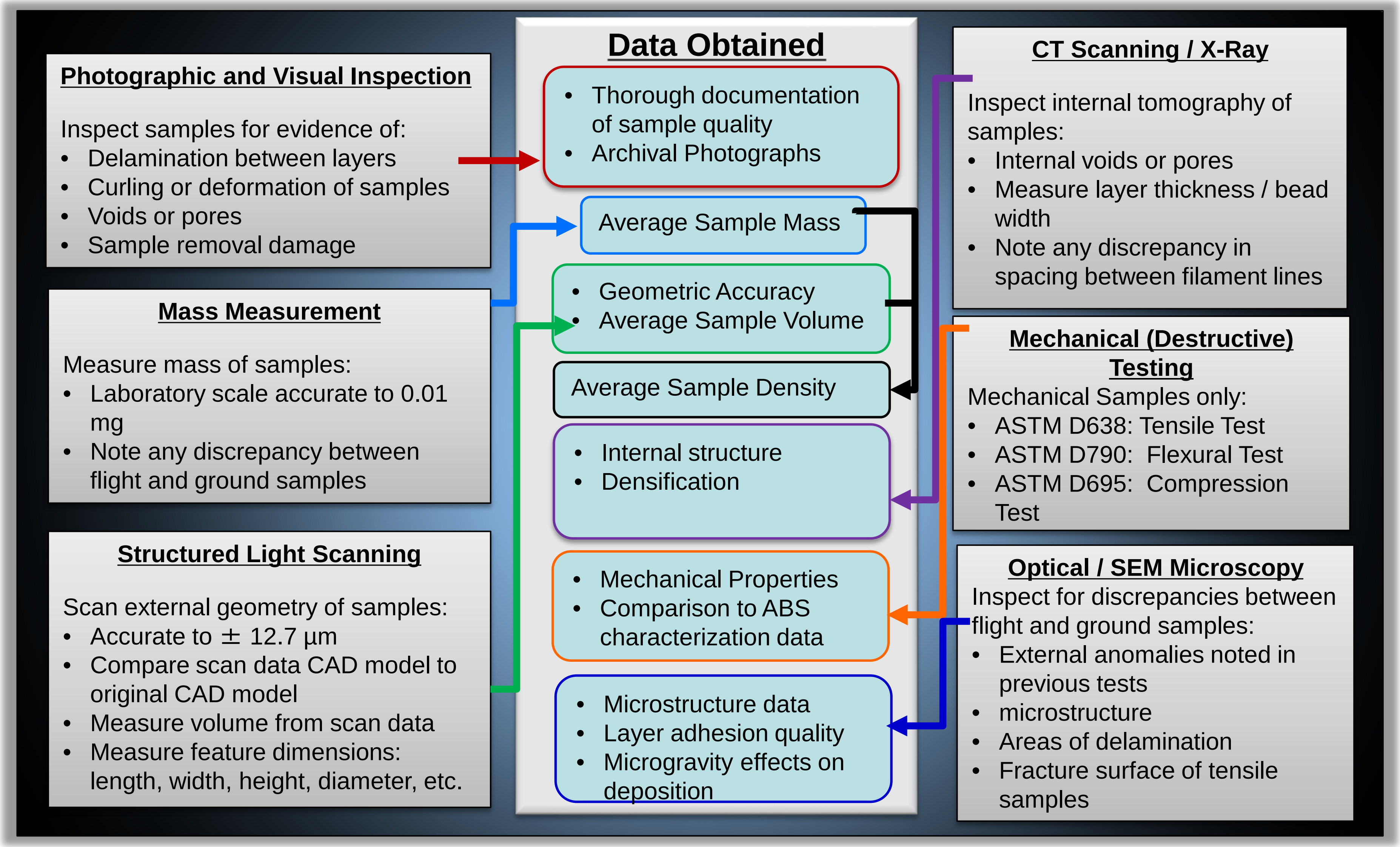
- Changes in build tray over course of prints
  - Four separate build trays used for flight prints

- 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



Nominal Tip to Tray Distance for 0.4 mm extruder tip is about: 0.2 mm

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

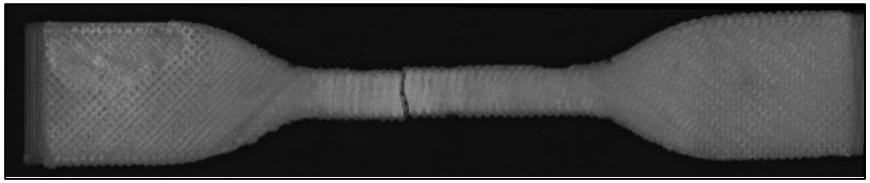
Mechanical (Destructive) Testing

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

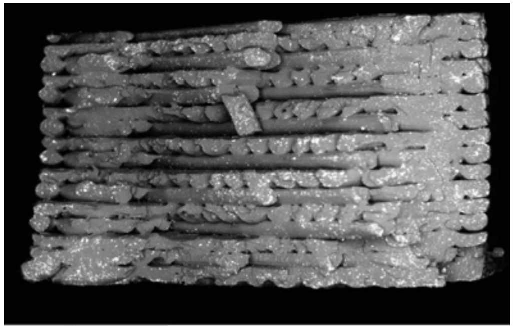
Optical / SEM Microscopy

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

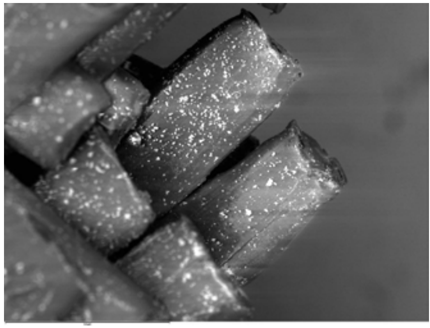
Testing of Phase I Prints



Optical microscope image of tensile specimen post-mechanical testing



Flight tensile fracture surface



Closeup of ground tensile fracture surface

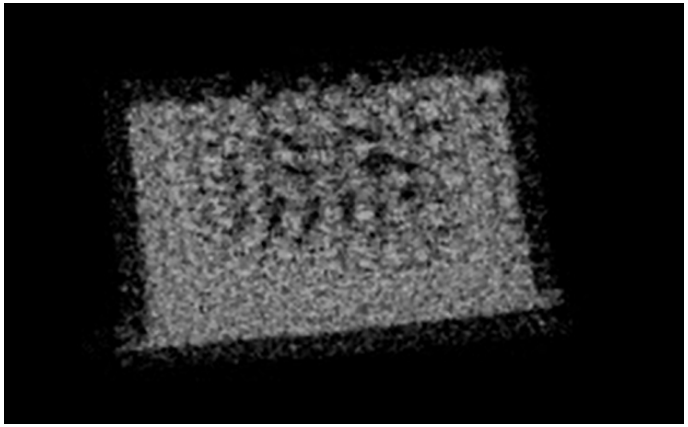
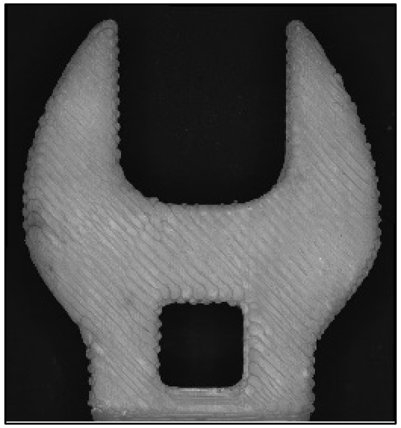
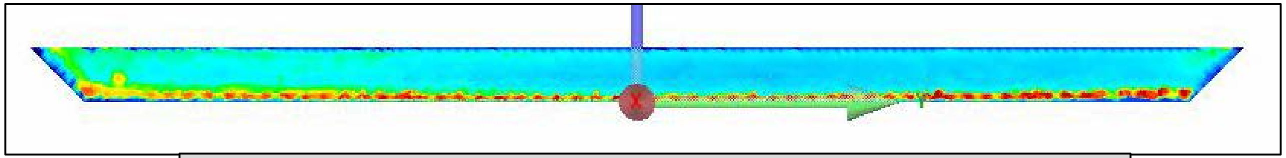


Image from CT scan of flight tensile specimen

Compression specimen



Bottom Surface Crowfoot (Flight Specimen)



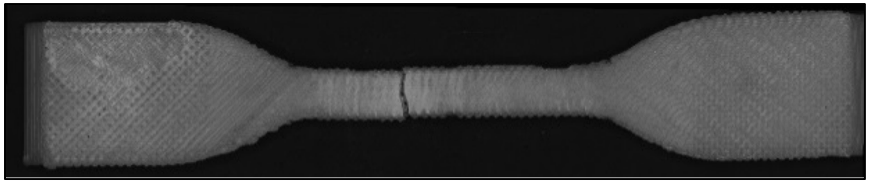
Structured Light Scan of Flight Flexural Specimen

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

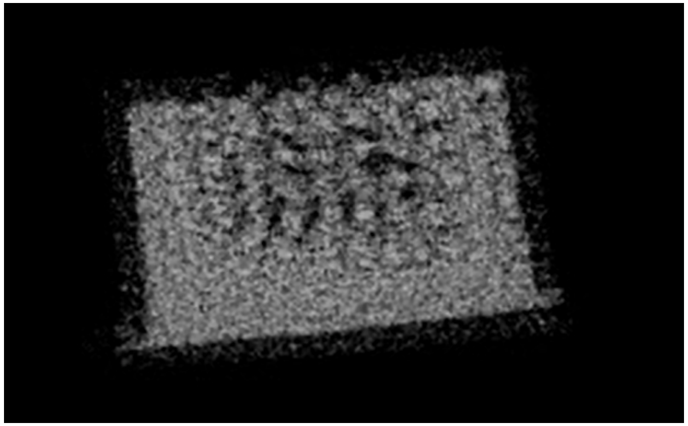
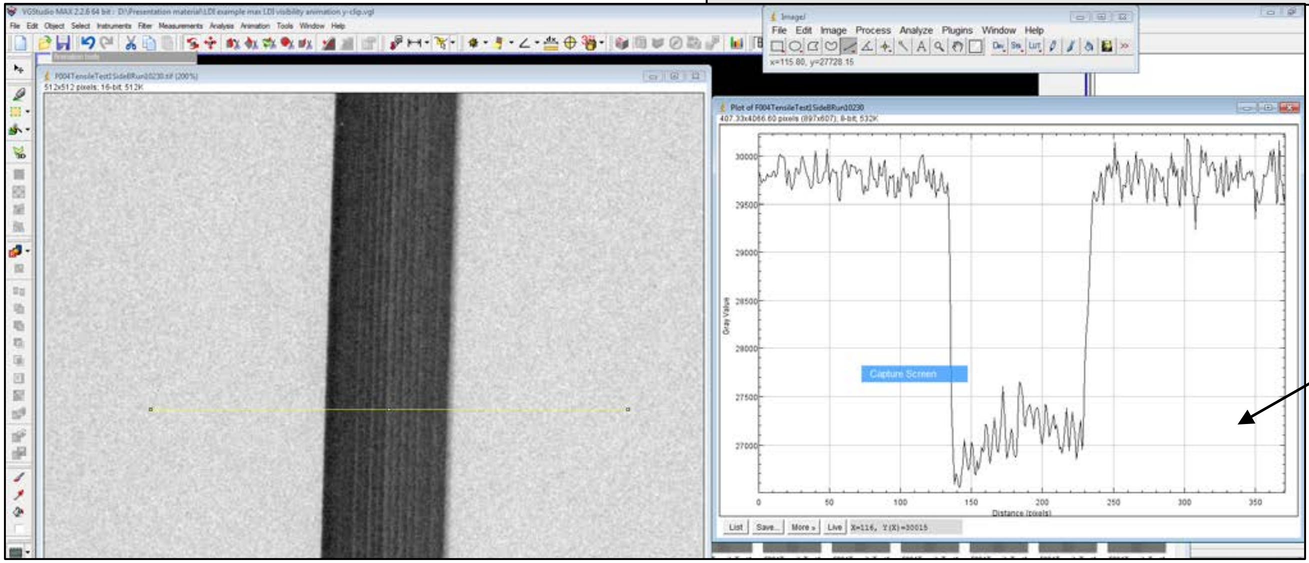


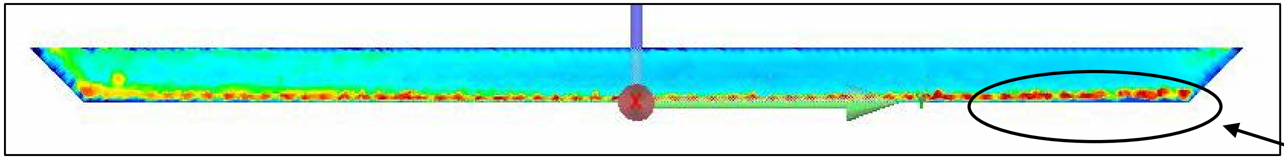
Image from CT scan of flight tensile specimen

- **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**



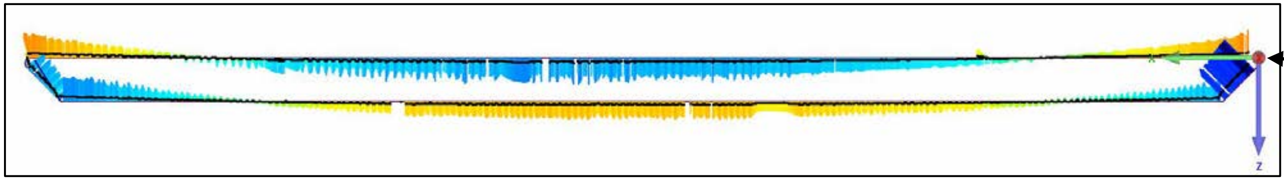
Lower density in upper section of part

3DP Phase I Key Observations: Structured Light Scanning



Flight Flexural Specimen

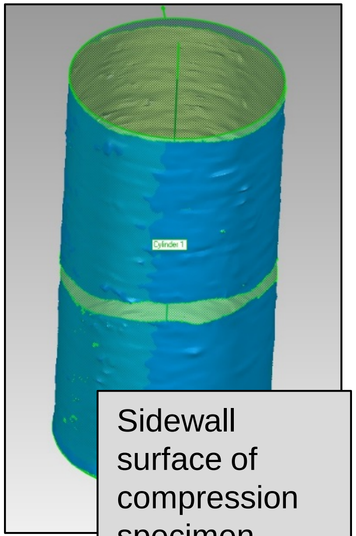
Protrusions along bottom edges indicate that extruder tip may have been too close to the print tray (more pronounced for flight prints)



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

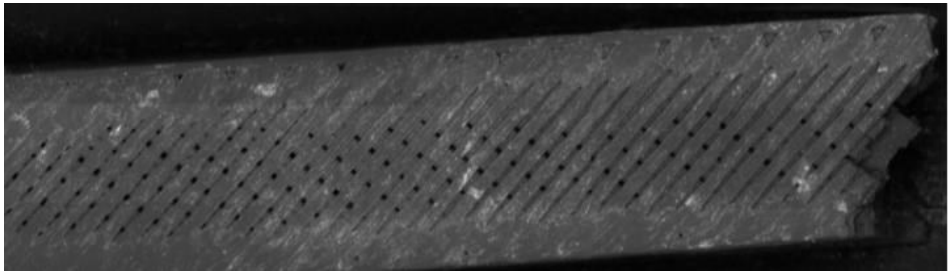
Roundness of Circular Samples

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

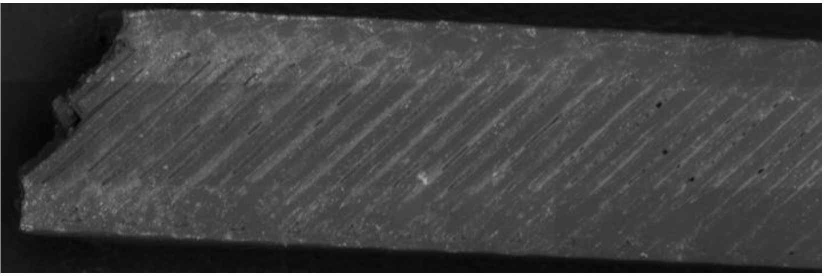
	Eccentricity	Elliptical Cross-Sectional Area (mm^2)	Percent Error of Cross-Section WRT CAD
Flight	**0.14**	**121.7**	**4.11 %**
Ground	**0.12**	**123.0**	**2.96 %**

3DP Phase I Key Observations: 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



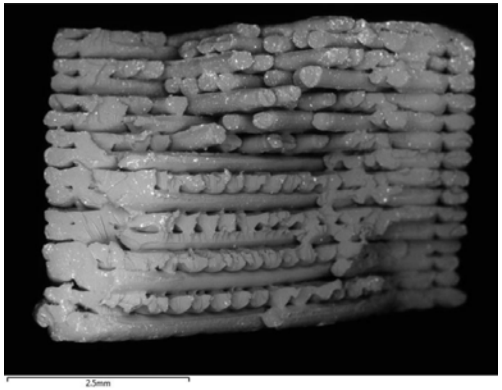
Ground tensile specimen surface

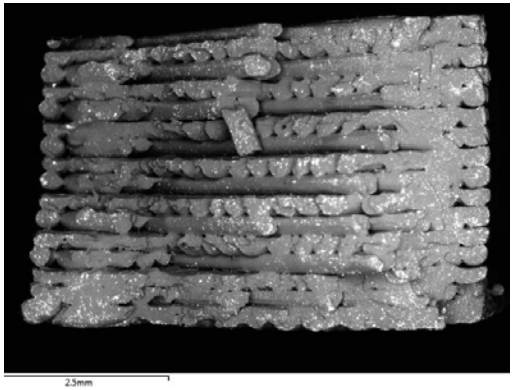


Flight tensile specimen surface

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

Ground tensile fracture surface



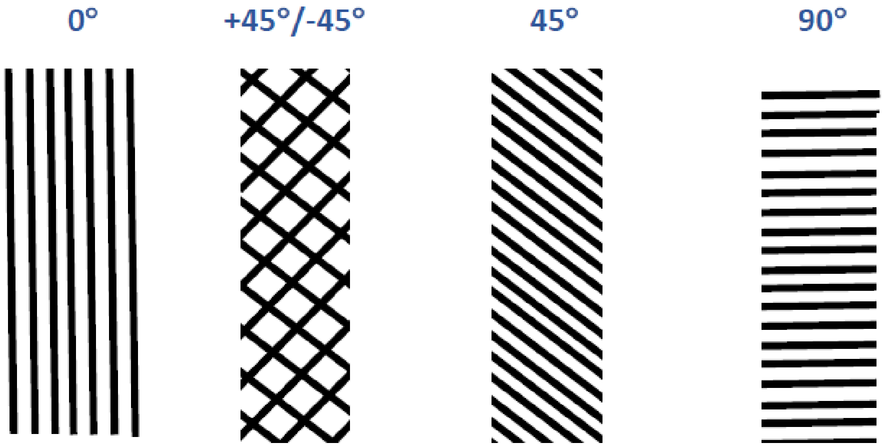


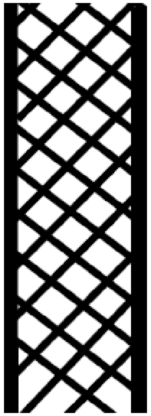
Flight tensile fracture surface

Image credit: Dr. Richard Grugel, NASA MSFC

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



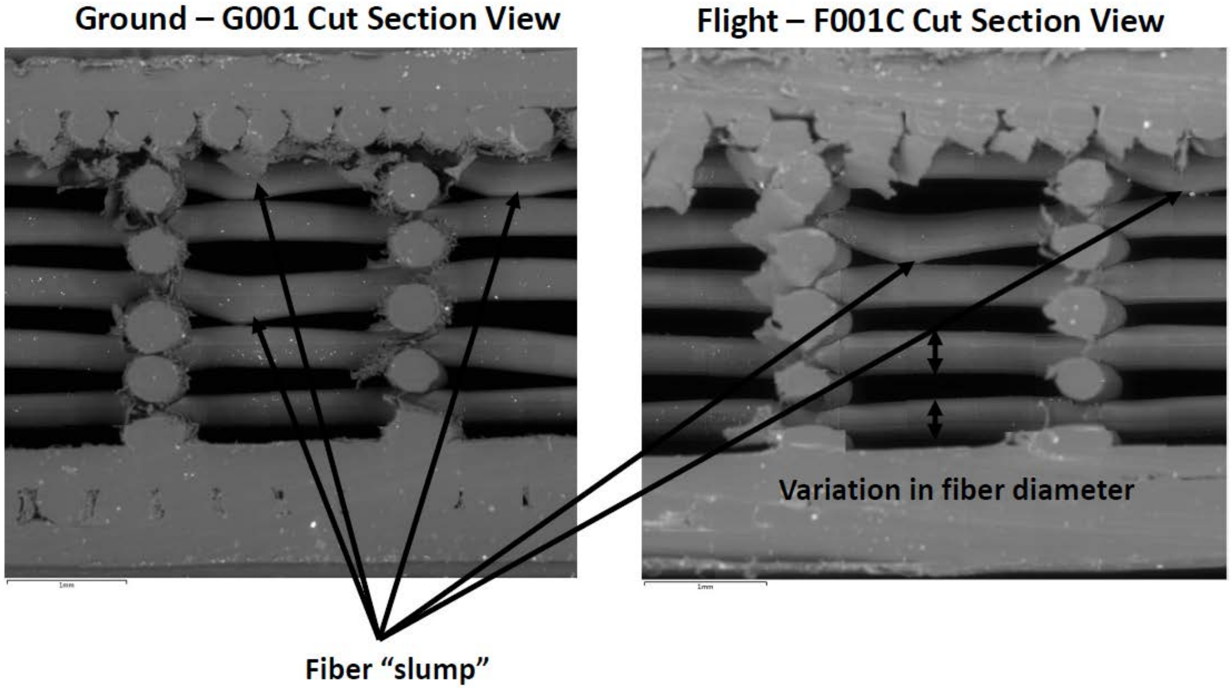


Characteristic appearance of flight specimens

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

Reference: C. Ziemian, M. Sharma, Sophia Ziemian. *IntechScience, Technology and Medicine.* Open access publisher.

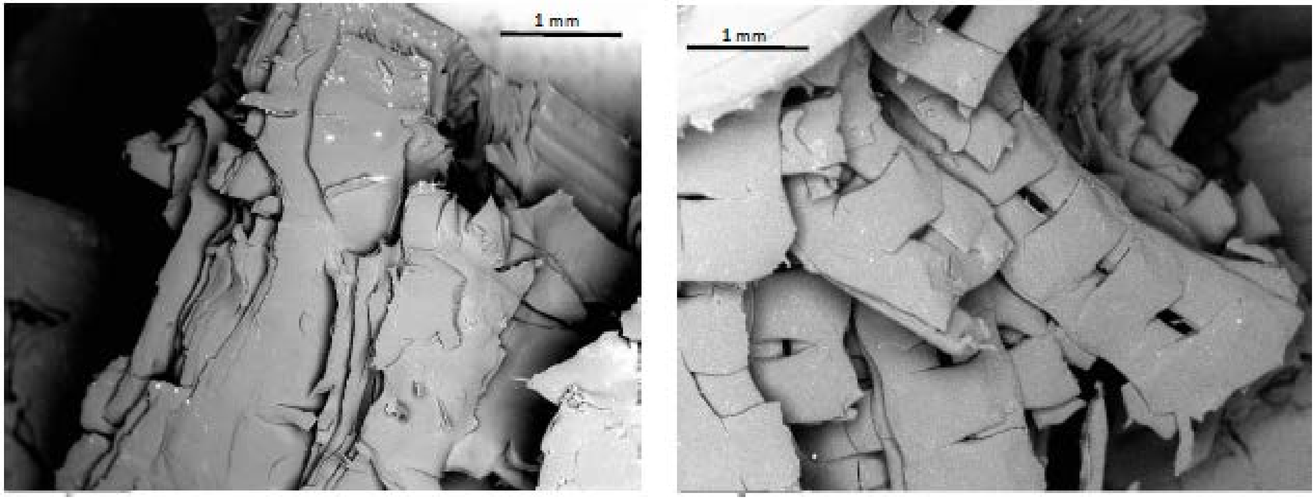
3DP Phase I Key Observations: Scanning Electron Microscopy (SEM)



- Both calibration coupons (ground and flight) show evidence of filament slump.
- Results not suggestive of microgravity effect on materials processing, although differences in manufacturing processing conditions between flight and ground specimens preclude a definitive assessment.
- Phase II prints (completed July 16) will provide additional data.

Image credit: Dr. Richard Grugel, NASA MSFC

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

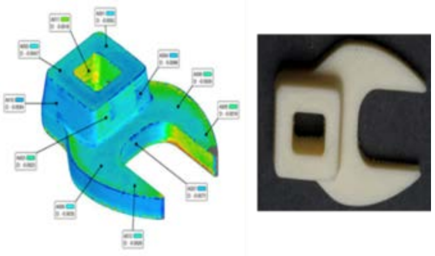


- Comparison of internal structure for ground compression specimen G013 (left) and flight compression specimen F016 (right) post-destructive testing.
- Ground compression specimens exhibit better fiber bonding.
- Likely explains difference comparative weakness of flight specimens.
- Source of structural variations may be changes in tip to tray distance for flight prints (follow-on ground based study and phase II prints will provide additional data)

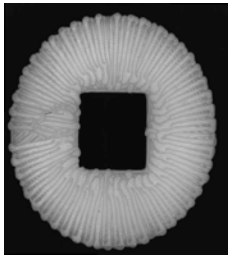
Image credit: Dr. Richard Grugel, NASA MSFC

3DP Phase I Executive Summary

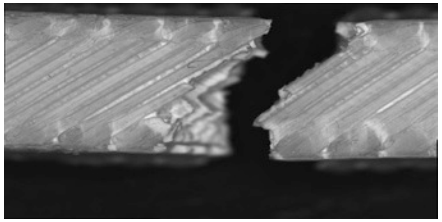
- The Phase I parts (first 21 parts printed) underwent testing and evaluation at the Materials and Processes Laboratory at NASA Marshall Space Flight Center and were compared with “ground truth” samples printed prior to printer’s launch to ISS.
  - Phase I report published as NASA technical publication in summer 2016
- **Differences noted in testing between the ground and flight specimens could not be definitively linked to microgravity as a processing variable**
- 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

3DP Phase I Follow-On Work

Ground Based Investigations

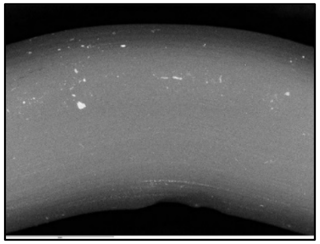
- Study of effect of tip-to-tray distance on part quality and performance
  - Systematic variation of this distance using 3DP backup flight unit
  - Study envelopes commanded values for ground and flight prints
  - Test regime includes surface metrology, mass measurement, structured light scanning, XRay/CT, ,mechanical testing and SEM
  - Complete by October 2016

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) and SEM of layer quality (square column) specimens
  - No microgravity effects observed to date with SEM

On-Orbit Investigations

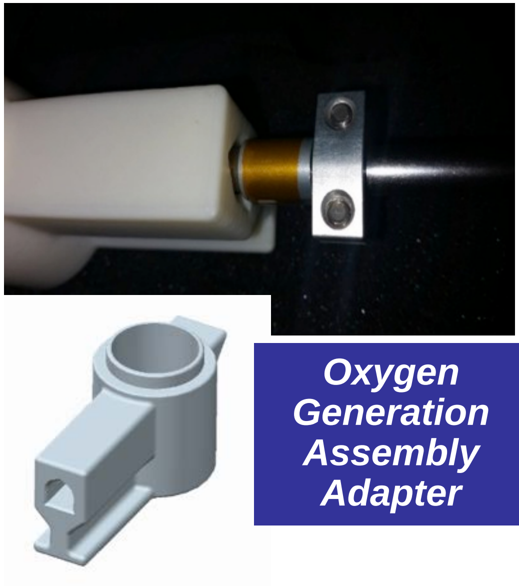
- Better statistical sampling with specimens from Phase II operations
- Phase II prints (34 additional specimens) completed in June and July 2016



SEM Image
- Deformed ABS Filament with microcracks

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)
  - 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
  - Phase II prints took place in June/July 2016
- Made in Space Additive Manufacturing Facility (AMF) commercial printer is now on ISS
  - Multi-user facility



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 Technology 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

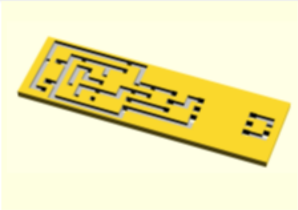
IN-SPACE RECYCLING

- 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

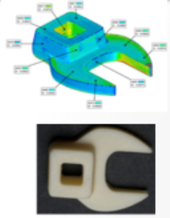
- Develop Multi-material Fabrication Laboratory Rack as 'springboard' for Exploration missions
- In-space Metals ISS Demo
- nScrypt Multi-material machine at MSFC

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

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

- 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

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

Acknowledgements

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- Steve Newton, In-Space Manufacturing Deputy Project Manager
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- Personnel who worked on testing and analysis 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

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

National Aeronautics and Space Administration

INTERNATIONAL SPACE STATION

15th ANNIVERSARY

Human Habitation

45 Crewed Expeditions...so far

November 2, 2000
Expedition 1:
William Shepherd
Sergei Krikalev
Yuri Gidzenko
First Crew Docking

Space Station educational activities on orbit have reached more than **42 million students** across the globe.

32,333 cubic feet of volume

The **International Space Station** weighs **930,000 pounds** and has the same pressurized volume as a **Boeing 747**, providing more livable room than a conventional **six bedroom house**.

More than **1,200 scientific results publications** have been produced.

There have been more than **180 U.S. and Russian spacewalks.**

The Space Station is an international endeavor of global collaboration, with more than **220 people from 17 countries** visiting the ISS since 2000.

Crews have eaten more than **26,500 meals** since Expedition 1. Approximately **7 tons of supplies** are required to support a crew of three for about **6 months**. Some crew favorites include shrimp cocktail, tortillas, and macaroni and cheese.

22 scientific investigations were conducted during Expedition 1. **191 investigations** will be conducted during Expeditions 45 and 46.

29 research racks, about the size of a refrigerator, enable important research aboard the Space Station. This includes 15 attached external payloads.

More than **1,760 research investigations** from researchers in more than **83 countries** and areas have been conducted to date on the orbiting laboratory.

The Water Recovery
reduces crew depen
on cargo resupply of
65% - **from about 1 g**
day to .34 gallon. Th
one of many ways th
International Space S
as a stepping-
space explor

20 objects with 13 different designs, including a ratchet wrench, have been printed by a **3-D printer** aboard the Space Station.

The first research study was **protein crystal growth**, happening before humans lived there. The study of protein crystals in space is **helping treat diseases and disorders on Earth**, such as Duchenne Muscular Dystrophy.

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

POPULAR MECHANICS

EXCLUSIVE: Inside the KOCH BROTHERS' Industrial Empire What do they actually do?

HOW YOUR WORLD WORKS

Indestructible Drones

The Underdog Space Rocket

Superfast 3D Printing

Precision Cancer Treatment

Pluto!

AND 24 MORE BREAKTHROUGHS THAT WILL BLOW YOUR MIND

THE NEW ROBOTIC HAND That isn't a hand at all.

BREAKTHROUGH AWARDS

same day the printer was launched into orbit.

The competition asks two groups of kids (broken into junior and teen categories) to create and submit 3D models of containers that would prove useful in the zero-gravity environment of the ISS. Among the hundreds of submissions were an arched food cover that keeps your dinner from flying away, a space football, and an innovative adjustable finger splint. Bell believes that no entry is too intricate (a fruit fly habitat with its own oxygen generator). Or too simple (a bobby pin). "We encourage all students to dive in," she says. Four finalists are selected to answer questions from astronauts and ISS personnel regarding their designs. One of last year's winners will be brought to a NASA facility to watch his design (a multitool) be printed live in space. For a look at this year's entries, including a cage that keeps nail clippings from puncturing any of the important tubes in the space station, head to future-engineers.org.

A FEW OF THIS YEAR'S ENTRIES

Collapsible Container (teen division): Expand or compress to fit different contents. The screw-on lid has a built-in handle.

Zero-G Fluid Cleaner (teen): A device to process urine into drinking water. (Wisely leaves the actual filtration process up to NASA.)

Cookie Dispenser (junior): Stack the cookies over the plunger in the center tube, put the cap on for freshness, dispense when hungry.

Rodent Space Runner (teen): A hamster ball with a frame that uses Velcro to attach to the wall and keep the ball in one place.

All-in-One Container (junior): Reservoir with drinking spout and three storage bays that can be closed with plexiglass or Velcro.

Sweet Smell Fly Trap (junior): Uses a piece of fruit and a one-way entrance to trap any flies that may escape from experiments.

"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