International Space Station (ISS) 3D Printer Performance and Material Characterization Methodology

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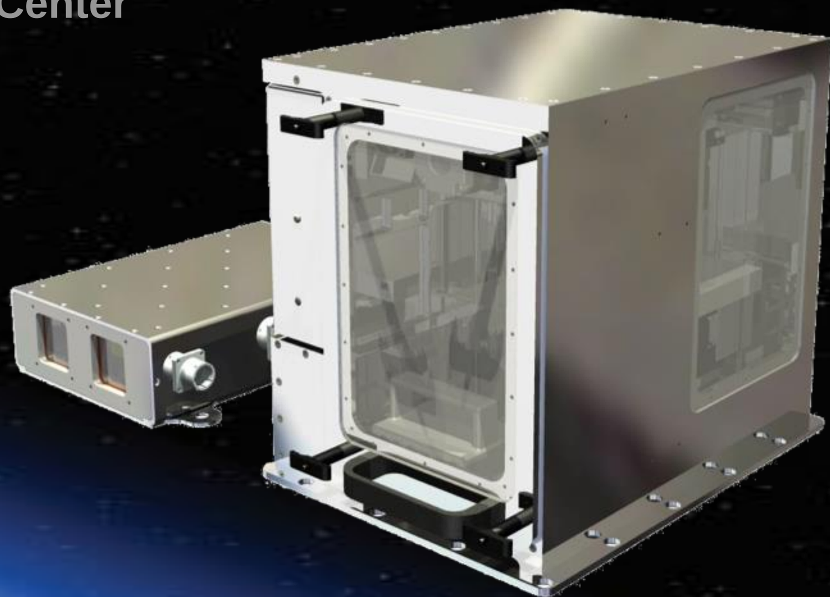
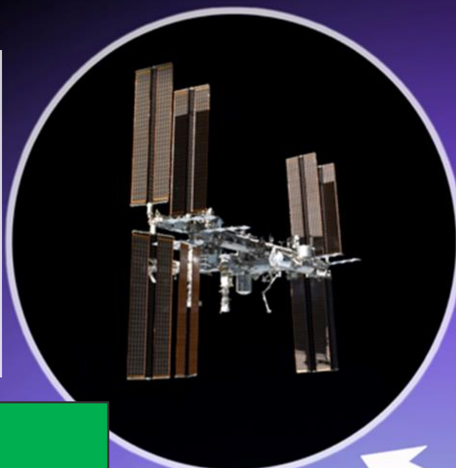


In-Space Manufacturing Overview

International Space Station (ISS) Technology Demonstrations are Key to 'Bridging' necessary Technology Development to Full Implementation of the Required In-space Manufacturing Capabilities **for Exploration Missions.**

ISS Platform
- 3D Print Tech Demo
- Future Engineers Print
- Additive Manufacturing Facility (AMF)
- In-space Plastic Feedstock Recycling
- Utilization Catalogue



Planetary Surfaces Platform

In-situ Feedstock Test Beds and Reduced Gravity Flights Which Directly Support Technology Advancements for Asteroid Manufacturing as well as Future Deep Space Missions.
- Additive Construction
- Regolith Materials Development & Test
- Synthetic Biology: Engineer and Characterize Bio-Feedstock Materials & Processes

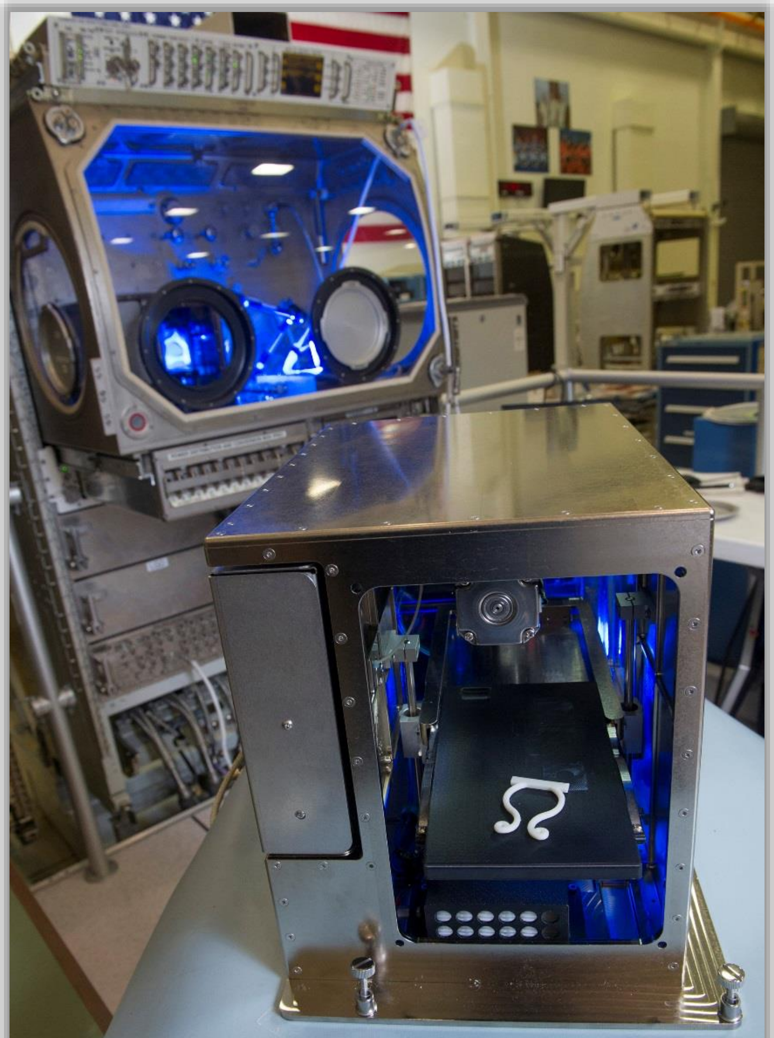
Benefits
- On demand access to replacement parts and tools
- Streamlined orbital supply chain
- Critical technology for exploration missions

Earth-based Platform
- Certification & Verification of Parts Produced In-space
- In-space Characterization Database
- Printable Electronics & Spacecraft
- External In-space Manufacturing (not currently funded)

Earth-based Platform (cont.)
- In-space Metals Manufacturing Process Study (not currently funded)
- Additive Repair Ground Testing
- Self-Replicating/Repairing Machines
- In-situ Feedstock Development & Test: See Asteroid Platform
- Automation and Sensor Development

3D Print Technology Demonstration

- First manufacturing capability on the International Space Station
- Phase 1: Proof of concept experiment
- 21 parts made on the ground with the flight unit and flight feedstock
- Same 21 parts made on orbit
- Comparisons will be made between flight and ground samples
  - Porosity
  - Layer adhesion
  - Mechanical properties
- Phase 2 will incorporate practical application



3D Print Flight Unit with the Microgravity Science Glove Box Engineering Unit in the background

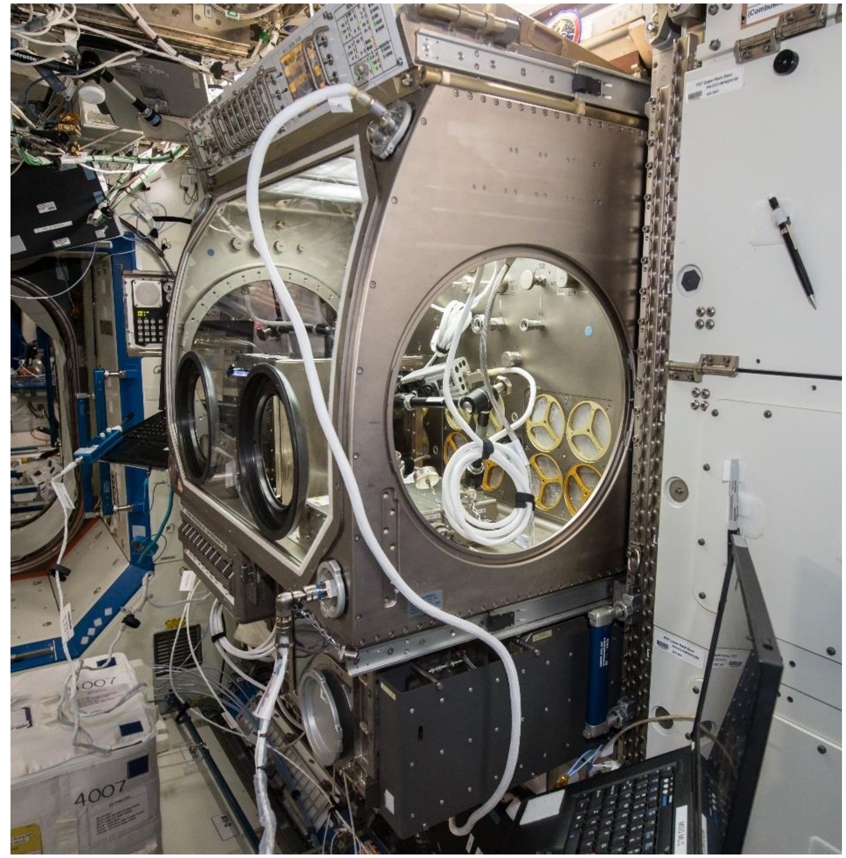
Cube Sat Clip

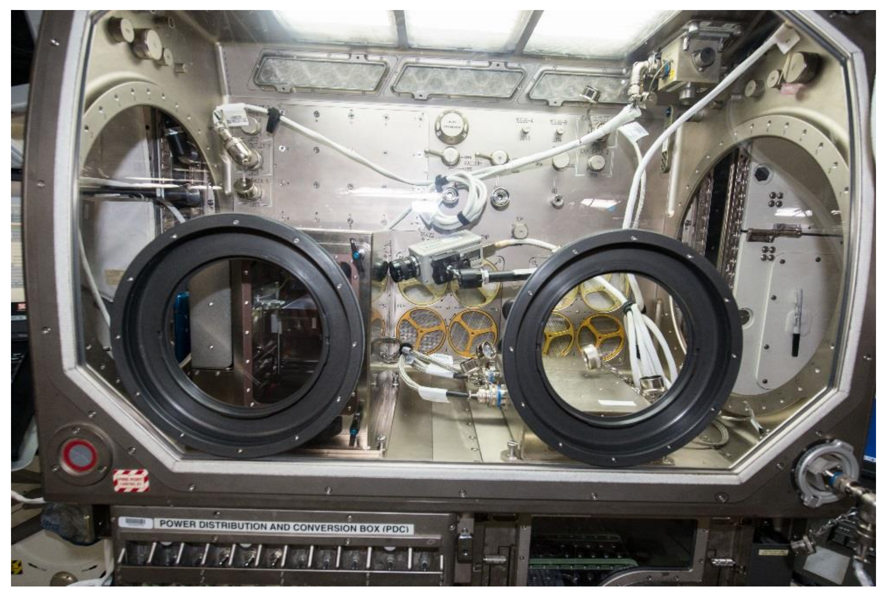
Tensile Coupon

Range Coupon

3D Print Phase I Timeline

- Launch via Falcon 9 rocket (SpaceX-4) 12:52AM Central on 21 Sept 2014
- Docking with ISS 5:52AM Central 23 September 2014
- Installation in MSG on 17 November 2014
- Phase I printing (following calibration) 24 November 2014 to 15 December 2015 (as crew time allowed)
- Removed from MSG on 16 December 2014 and stowed
- Phase I prints returned to Earth (SpaceX-5) 10 February 2015
- Unboxed at MSFC 6 April 2015
- Begin testing 28 April 2015





3D Print Ground and Flight Sample Testing

Non-Destructive Evaluation

- Initial inspection
  - Visual
  - Photographic
- Structured Light Scanning
- Mass/Density
- Computed Tomography
- Optical Microscopy
- Scanning Electron Microscopy

Phase 1 Test Plan

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:
- Will use laboratory scale accurate to 0.1 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

- Computed tomography
- Layer thickness / Bead Width

- Mechanical Properties
- Comparison to ABS characterization data

- Microstructure data
- Layer adhesion quality

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
- Inter-laminar microstructure
- Areas of delamination
- Fracture surface of tensile samples

3D Print Sample Testing Techniques

Visual and photographic Inspection

- Identification and documentation of anomalies, damage (e.g., print tray removal damage)
- Identification and documentation of any visual differences between flight and ground samples (initial identification of microgravity effects)
- Attention will be given to any signs of delamination between layers, curling of the sample, surface quality, damage, voids or pores, and any other visually noticeable defect.

3D Print Sample Testing Techniques

- Structured Light Scanning
  - ATOS Compact Scan Structured Light Scanner
  - Blue light grid projected on the surface
  - Stereo-images captured
  - Image processing provides
    - A CAD model of the printed part
    - A comparison of the printed part and the original CAD file from which the part was printed
    - A statistically valid determination of the volume of the sample

3D Print Sample Testing Techniques

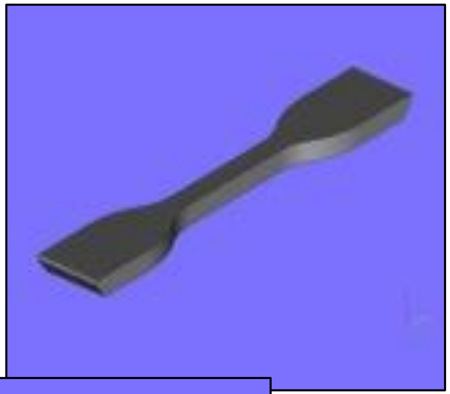
- Mass Measurement / Density Calculation
  - Mass measurement using a calibrated laboratory scale accurate to 0.1mg repeated five times for a mean mass
  - Density calculation requires the volume determined by structured light scanning
    - Provides information on void space or expansion of the material created during the printing process
    - Flight samples will be compared with their respective ground samples to assess any differences

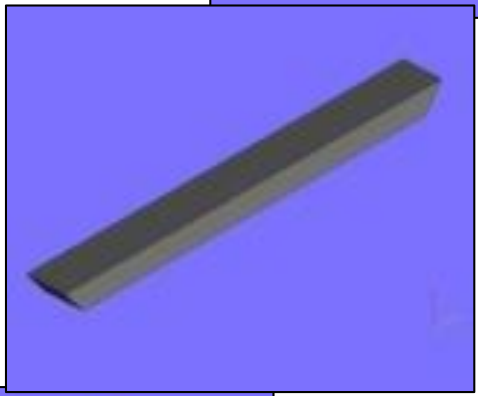
3D Print Sample Testing Techniques

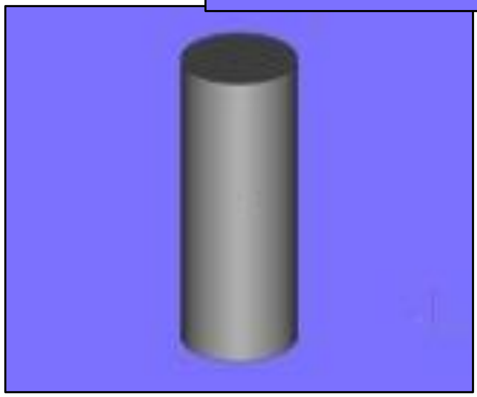
- Computed Tomography
  - Phoenix Nanome|x 160
  - X-ray scans
  - Provides 2D and 3D models of the internal structures that could affect mechanical properties
    - Internal voids
    - De-lamination of the ABS layers
  - Resolution as low as 8-10 microns is possible

3D Print Sample Testing Techniques

- ASTM Standards
  - D638 for tensile testing
    - Tensile strength, tensile modulus, and fracture elongation
  - D790 for flexure testing
    - Flexural stress and flexural modulus
  - D695 for compression testing
    - Compressive stress and compressive modulus







3D Print Sample Testing Techniques

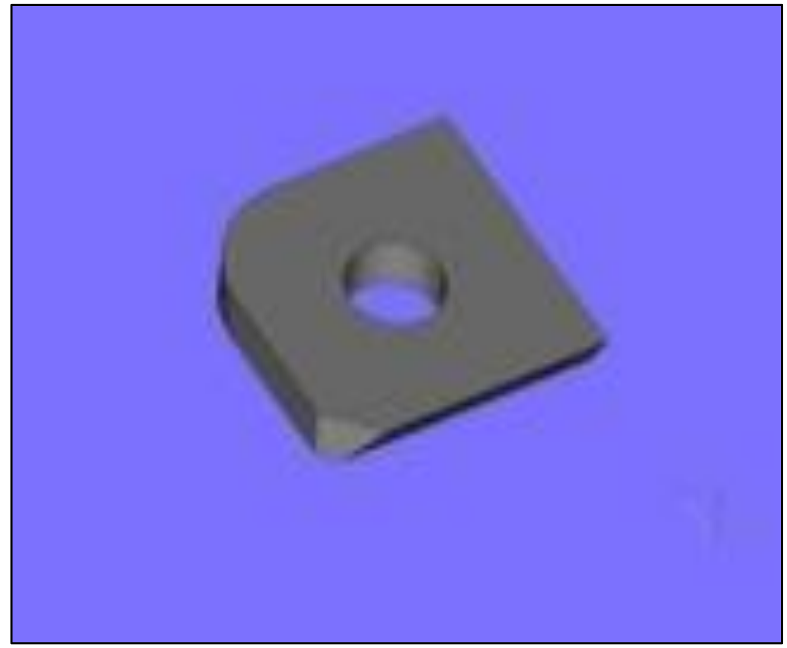
- Optical (Leica M205 A) and Scanning Electron Microscopy (Hitachi S-3700N)
  - Detail the surface microstructures of the layers
  - Detail the surface of the flight prints damaged by over-adhesion to the build tray; it is hoped this will identify the root cause of the over-adhesion
  - Inter-laminar regions will be investigated; flight and ground samples will be compared
  - Defects or anomalies noted by the initial inspection will be examined, as well as the fracture surfaces from the mechanical tests

Storage and Handling of Samples

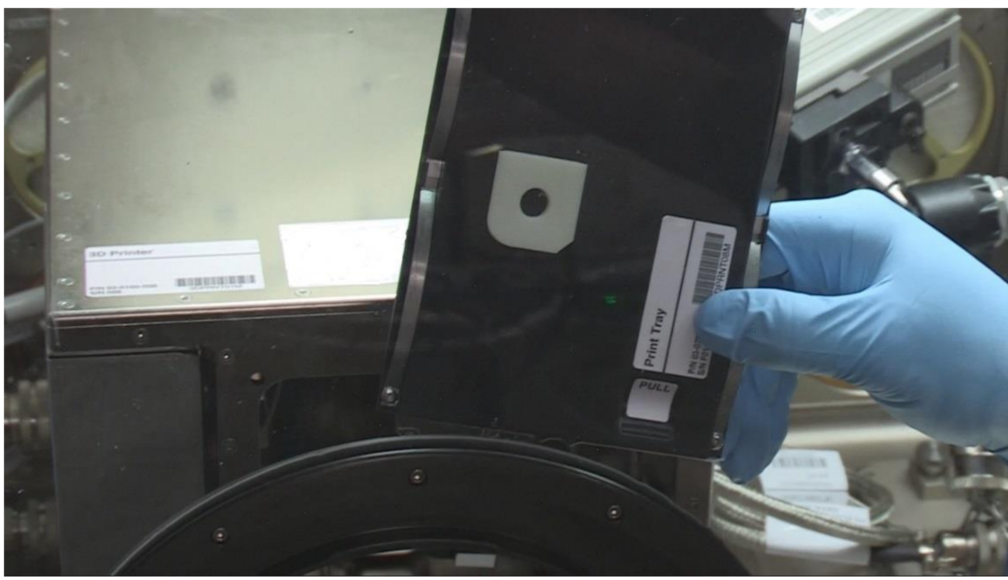
To eliminate any potential differences in flight versus ground results caused by environmental factors, the following storage and handling instructions were followed:

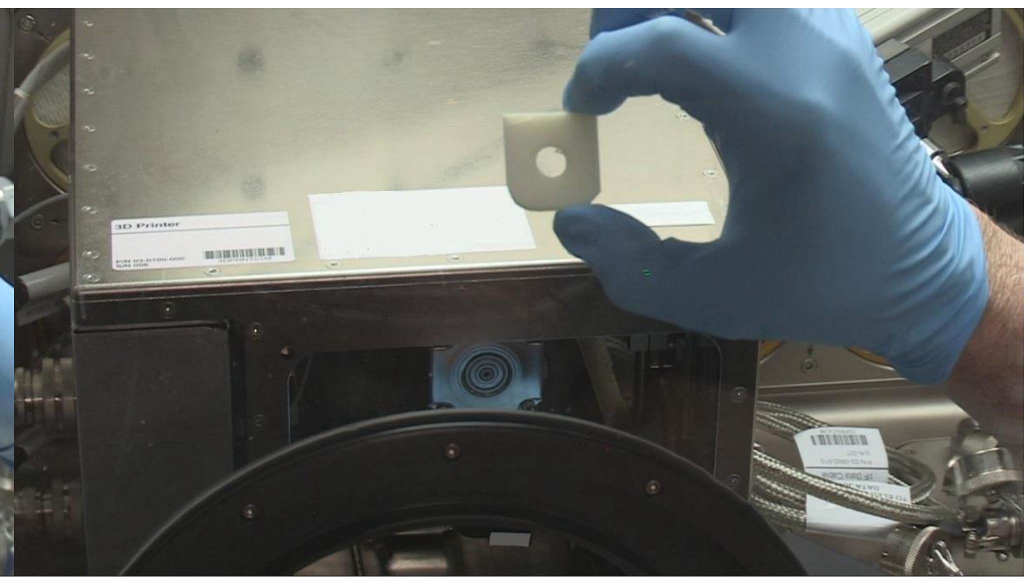
- All samples shall be stored individually in clearly marked and sealed plastic bags.
- Desiccant shall be placed in each bag with the sample.
- When not in use, samples shall be stored in a dry place at room temperature and away from direct sunlight.
- All handlers of the samples shall wear latex or other suitable gloves to avoid direct skin contact.
- The samples are to be kept dry at all times and kept away from any moisture source unless otherwise specified for a specific test.
- The samples themselves will not be labeled, to avoid mixing up the samples only 1 sample will be tested at a time.
- Once testing of a sample is completed, the sample shall be returned to its bag and the next sample may be tested.
- Once the test conductors have completed testing all of the samples, they shall notify and return the samples to the Principal Investigator.

Calibration Coupon

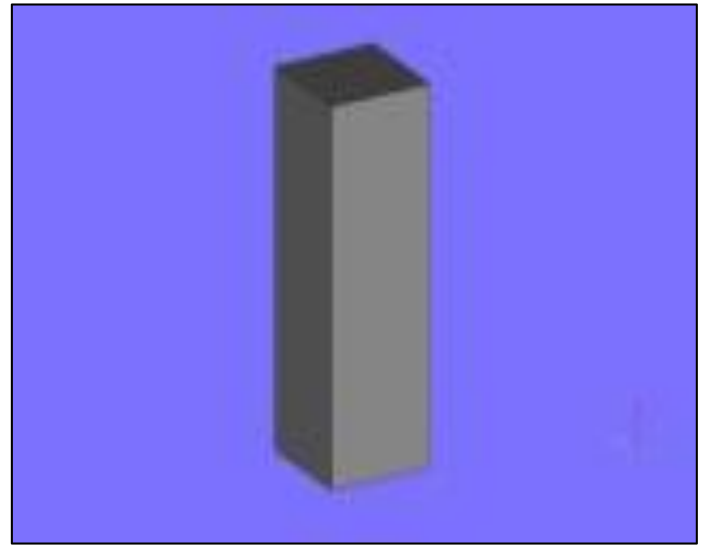


- Sample 001
- 3.00cm x 3.00cm x 0.41cm
- Printed to test calibration of the distance between the extruder and print plate



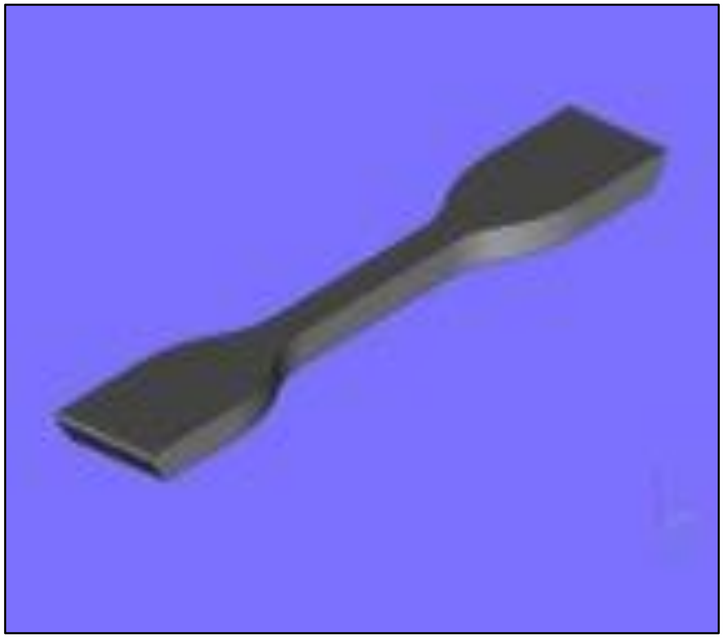


Layer Quality Test Specimen



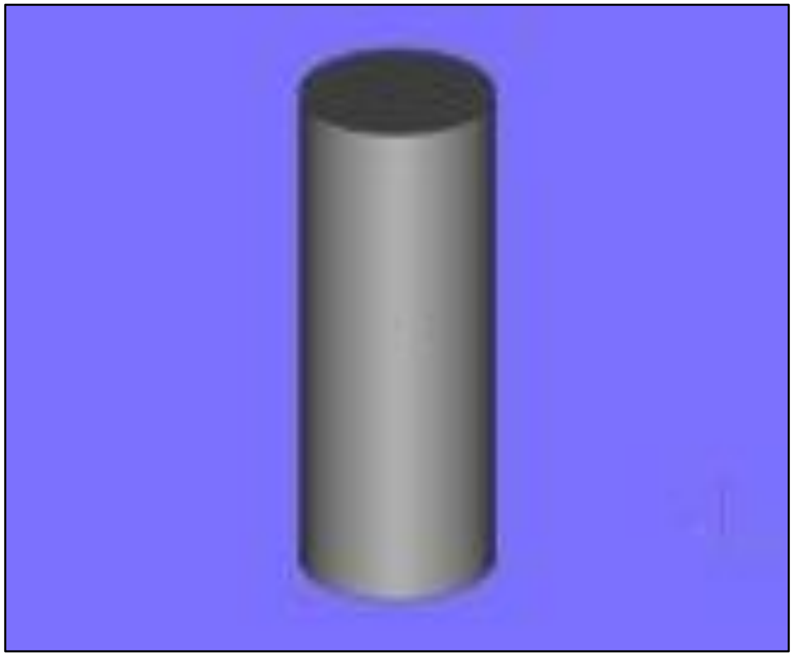
- Sample 003
- 1.00cm x 1.00cm x 3.00cm
- Printed to assess the layer quality and tolerances

Tensile Coupon



- Samples 004, 012, 015, and 018
- 11.35cm x 1.91 cm (neck width 0.61cm) x 0.41cm
- Printed to assess the tensile strength of the printed material at 45°C/-45°C lay-up orientation

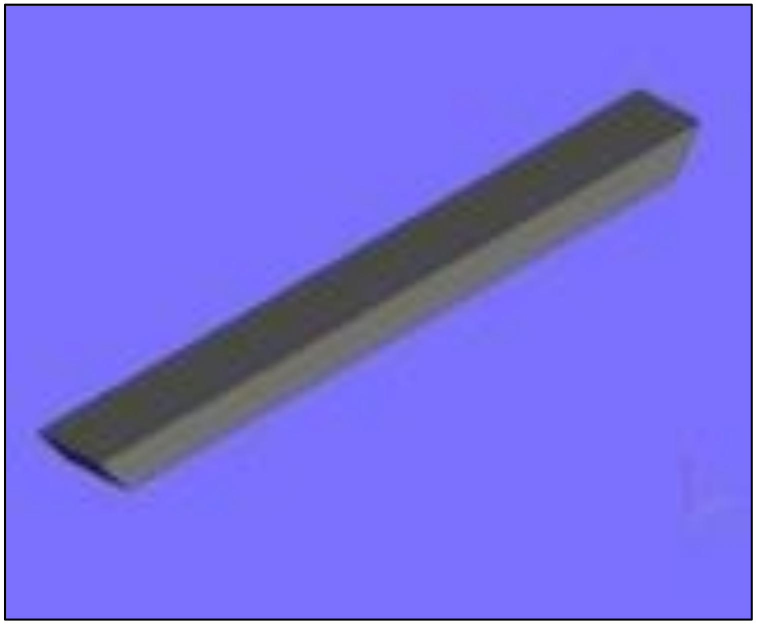
Compression Coupon

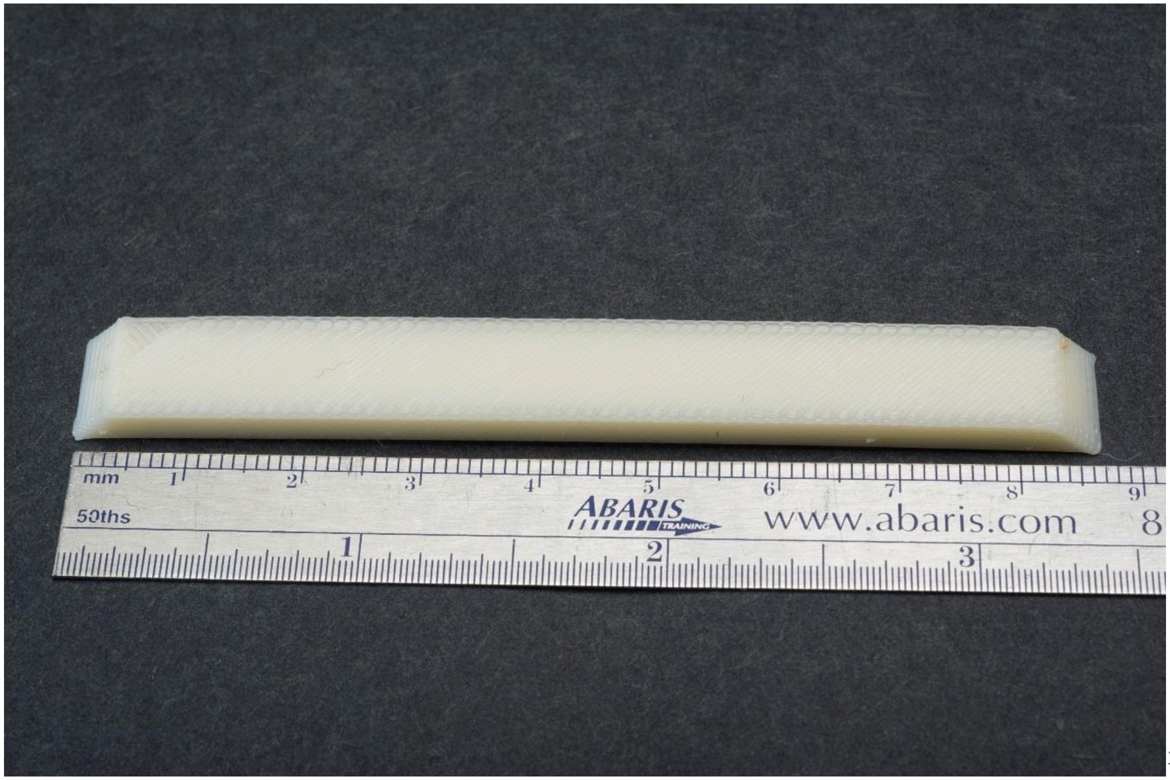


- Samples 005, 013, and 016
- Diameter 1.27cm, height 2.54cm
- Printed to assess the compressive strength of the printed material

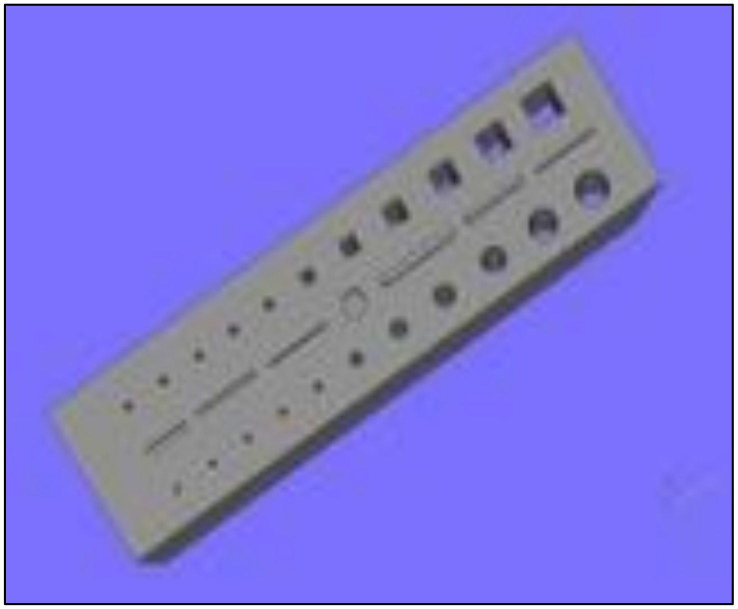
Flexural Coupon

- Samples 006, 014, and 017
- 8.81cm x 0.99cm x 0.41cm
- Printed to assess flexure properties of the printed material at 45°C/-45°C lay-up orientation

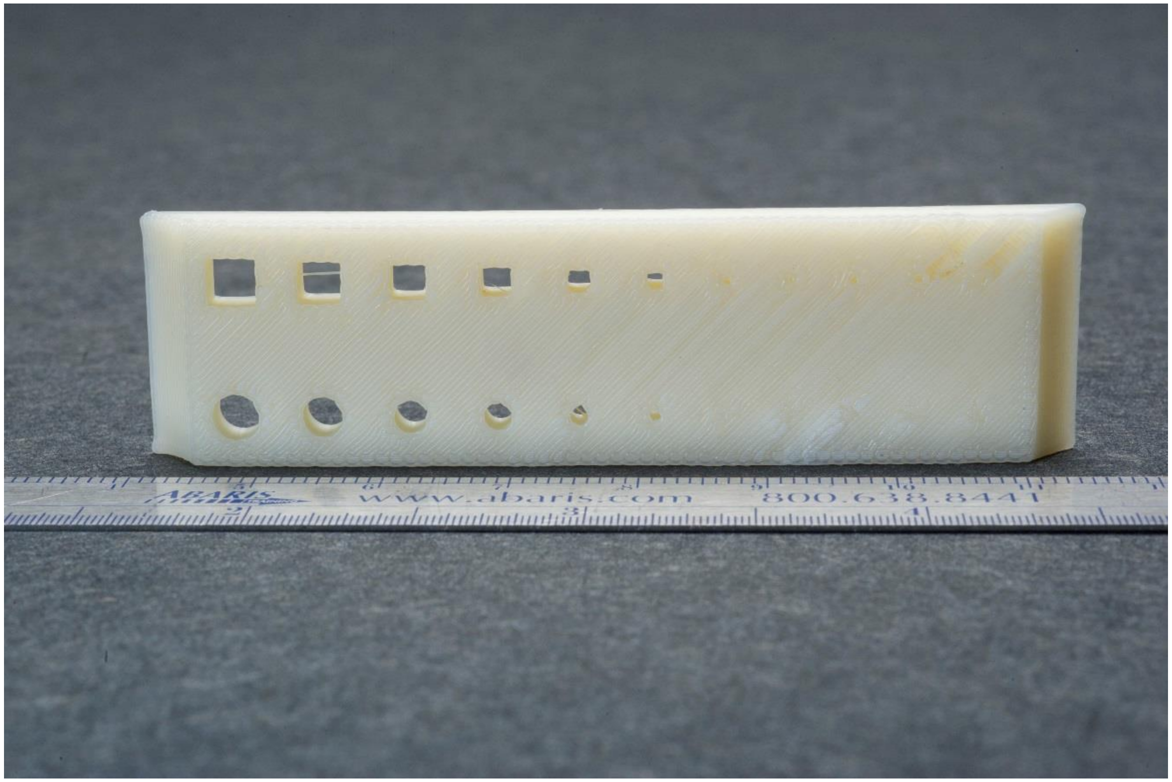




Negative Range Coupon

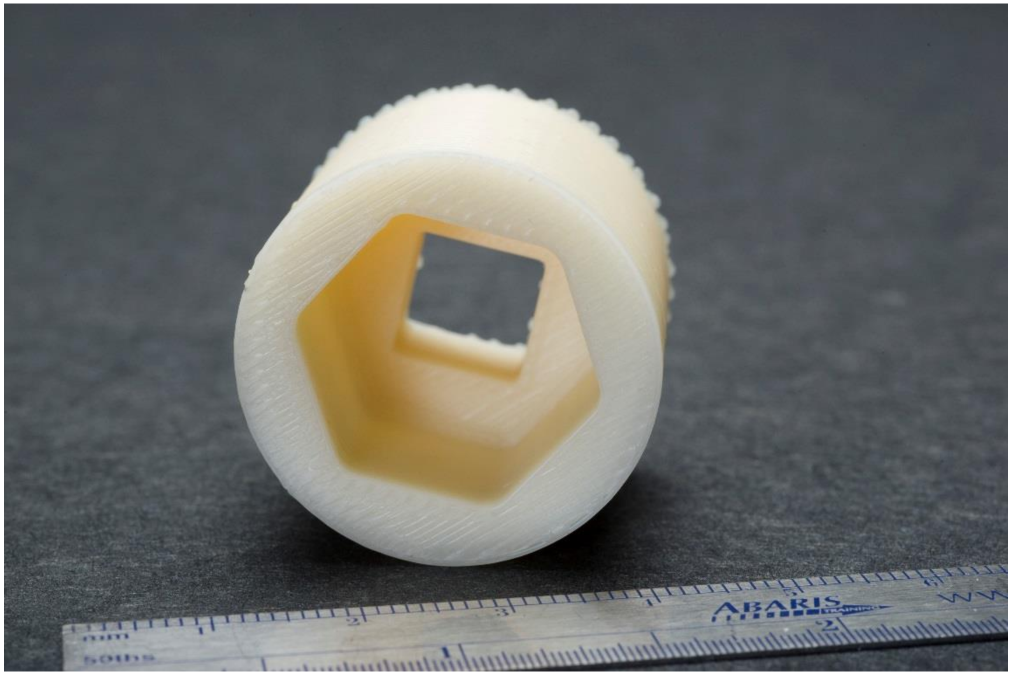


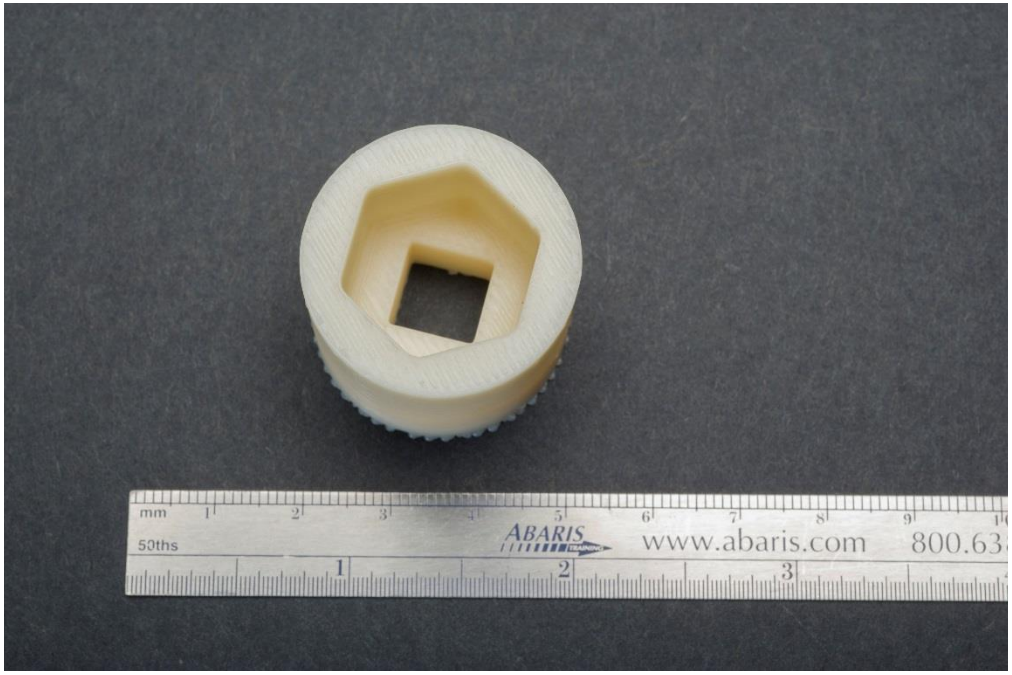
- Sample 007
- 7.49cm x 2.01cm x 0.43cm
- Printed to test performance, geometric accuracy, and tolerances of the 3D Print for voids of specific geometry



Torque Tool Specimen

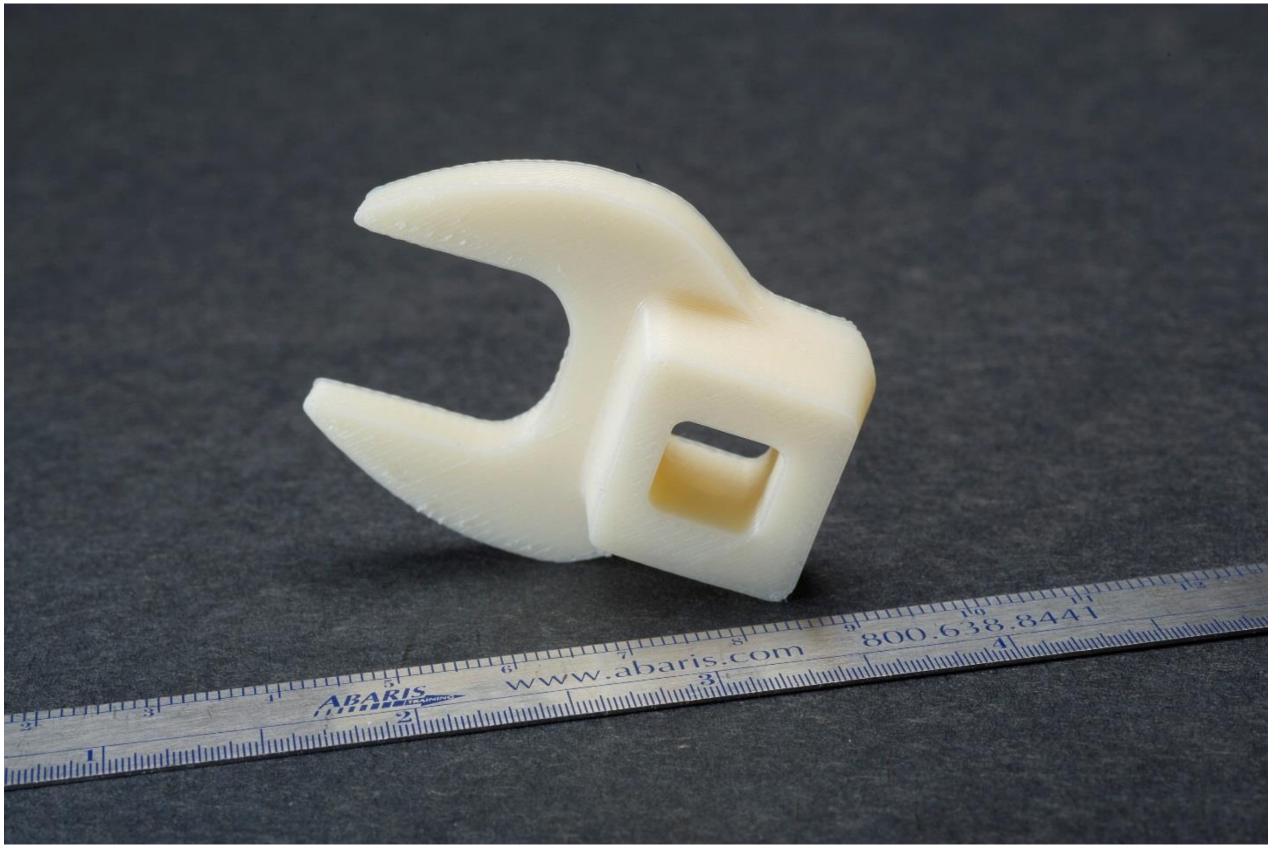
- Sample 008
- Diameter 3.00cm x height 2.50cm
- Printed to demonstrate the ability to fabricate replacement crew tools



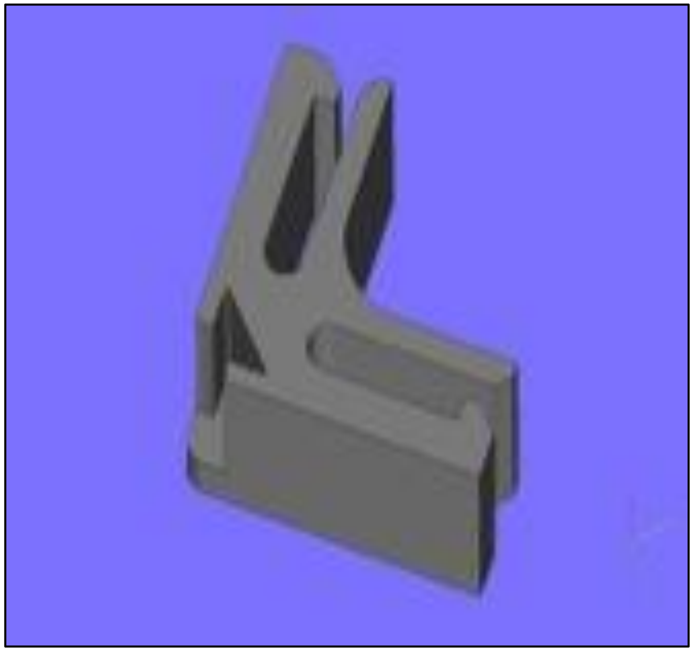


Crowfoot Specimen

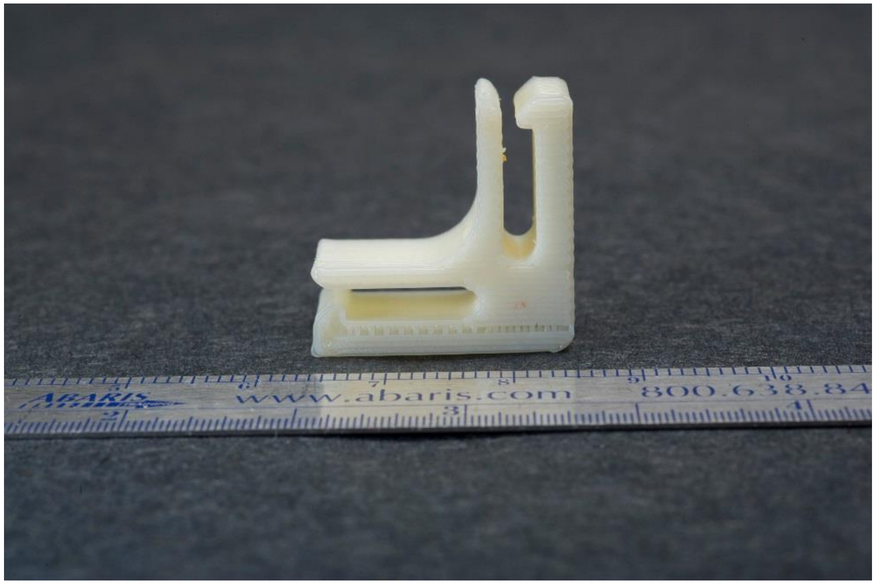
- Sample 009
- 4.70cm x 3.99cm x 1.30cm
- Printed to demonstrate the ability to fabricate replacement crew tools

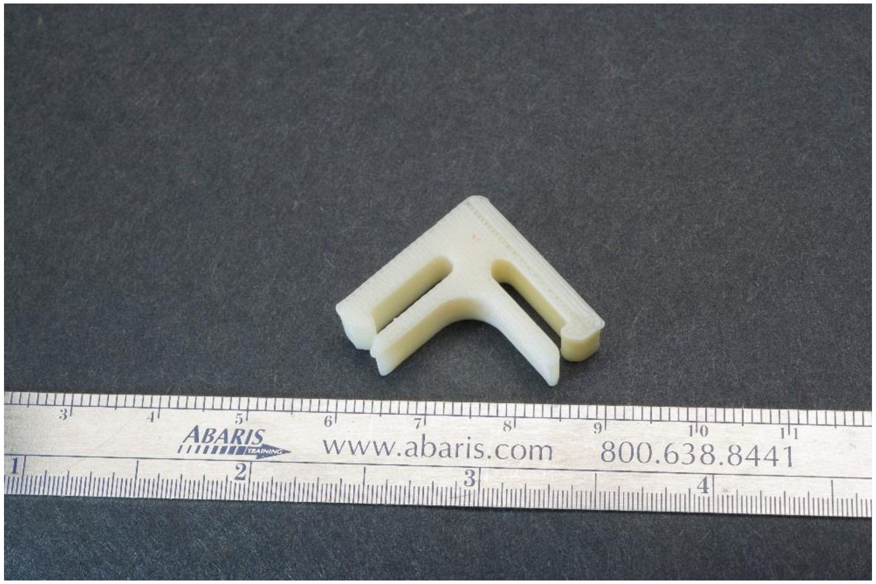


Structural Clip Component

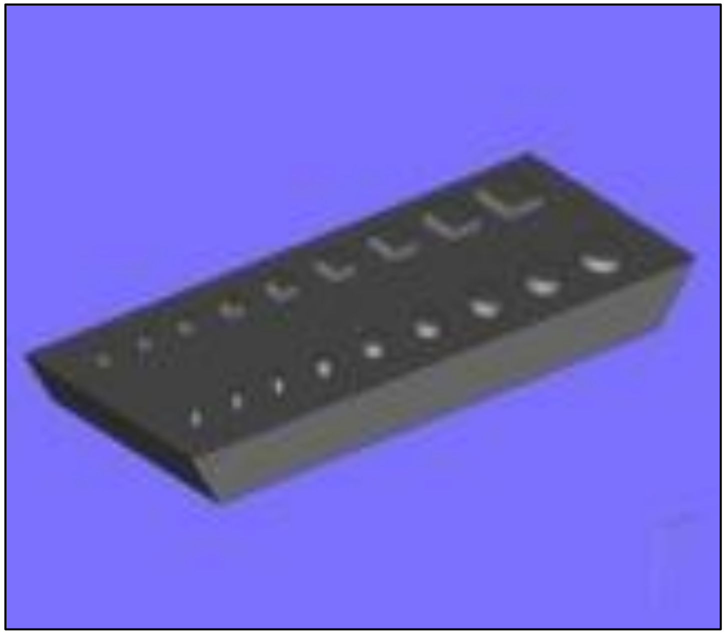


- Sample 010
- 2.69cm x 2.10cm x 0.90cm
- Structural connector / spacer that can be utilized to assemble avionics / electronics cards on-orbit
- Printed to demonstrate the ability to fabricate structural components, potentially eliminating the constraints imposed by launch loads on spaceflight structures



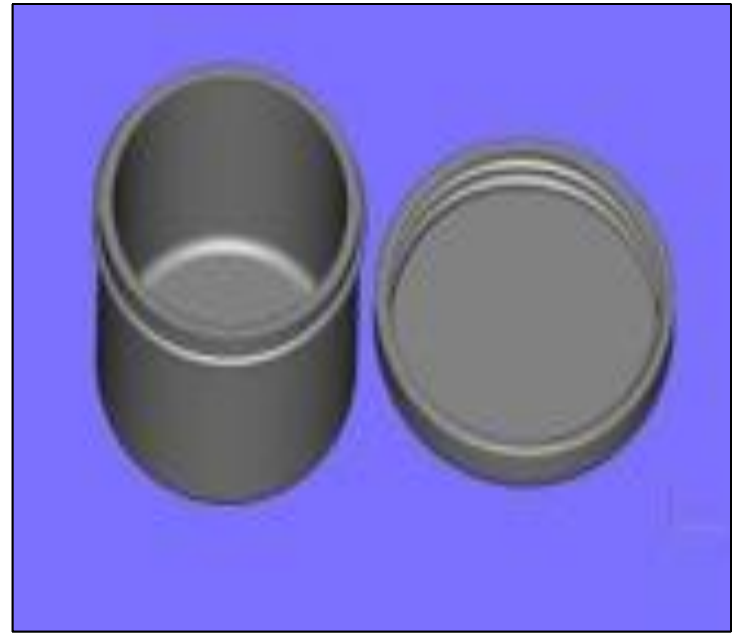


Positive Range Coupon

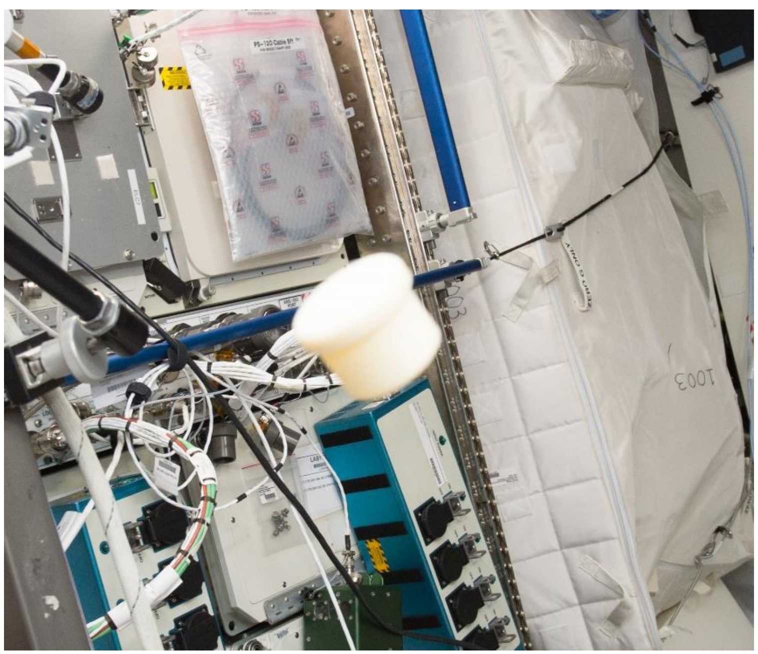


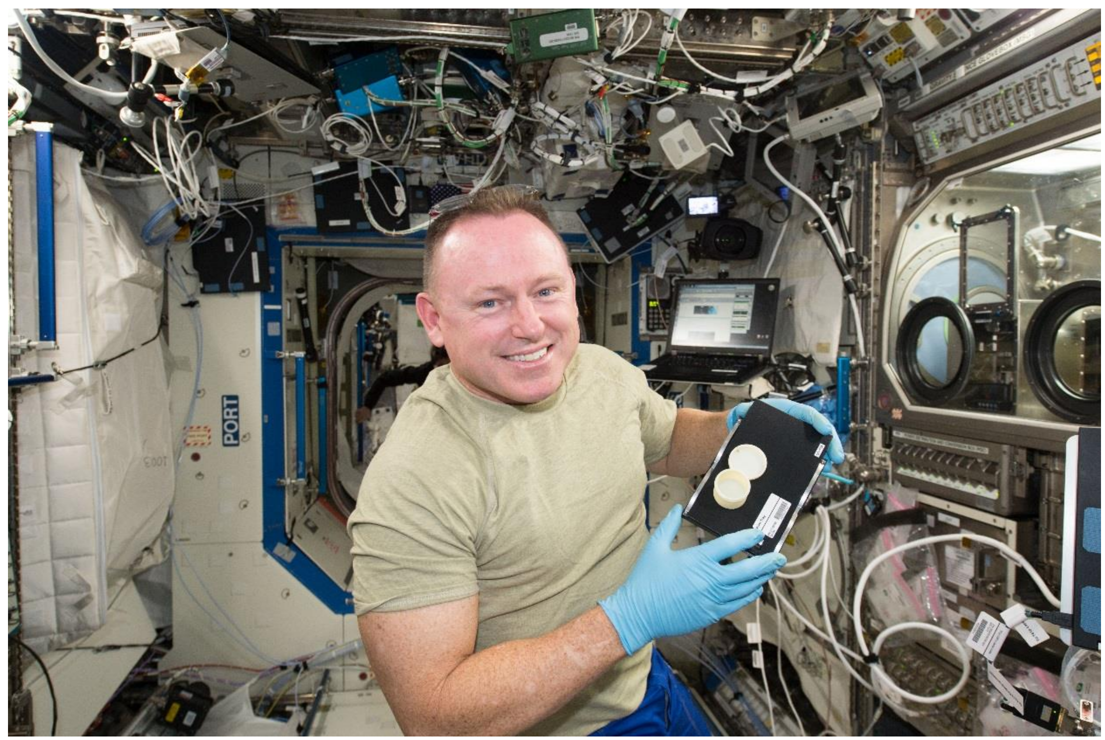
- Sample 011
- 6.12cm x 2.01cm x 0.51cm
- Printed to test performance, geometric accuracy, and tolerances of the 3D Print for positive relief features

Sample Container

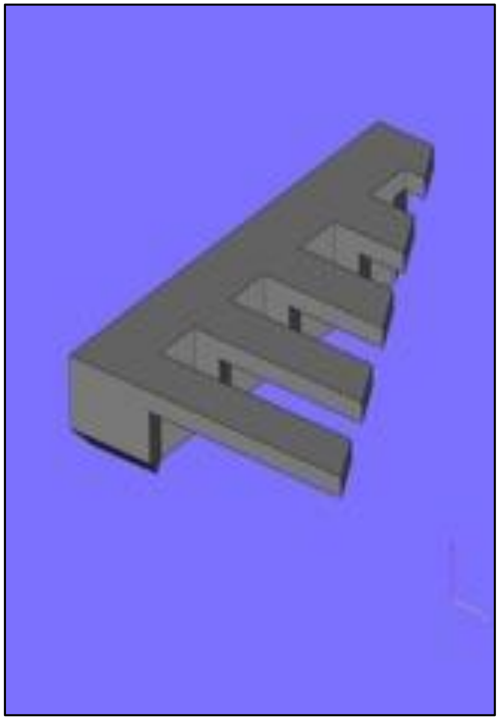


- Sample 019
- Body diameter 4.03cm, body height, 3.28cm
- Top diameter 4.60cm
- Printed to test the printer's capability to produce two items at one time with interlocking-capable threads

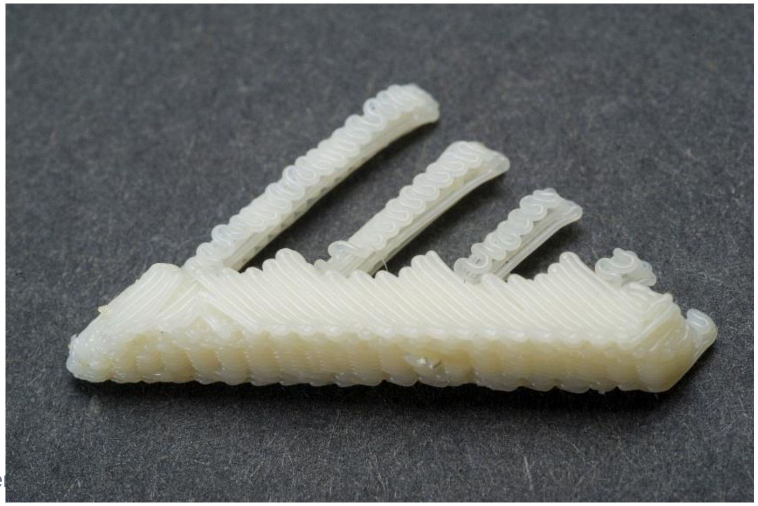


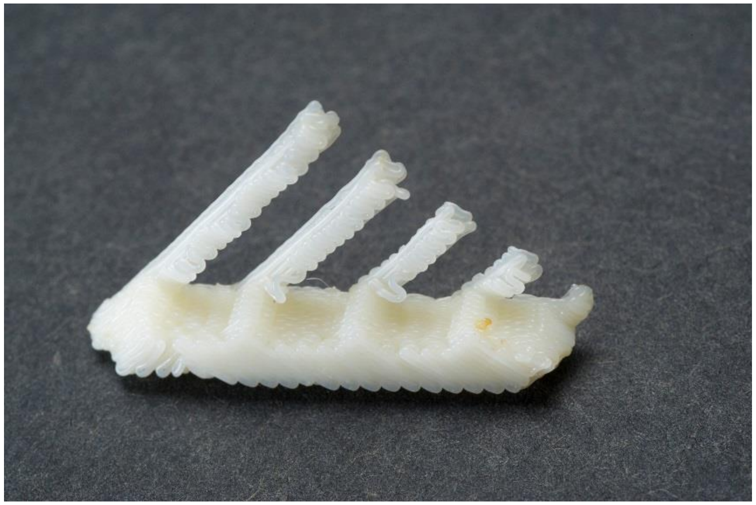


Microgravity Structure Specimen



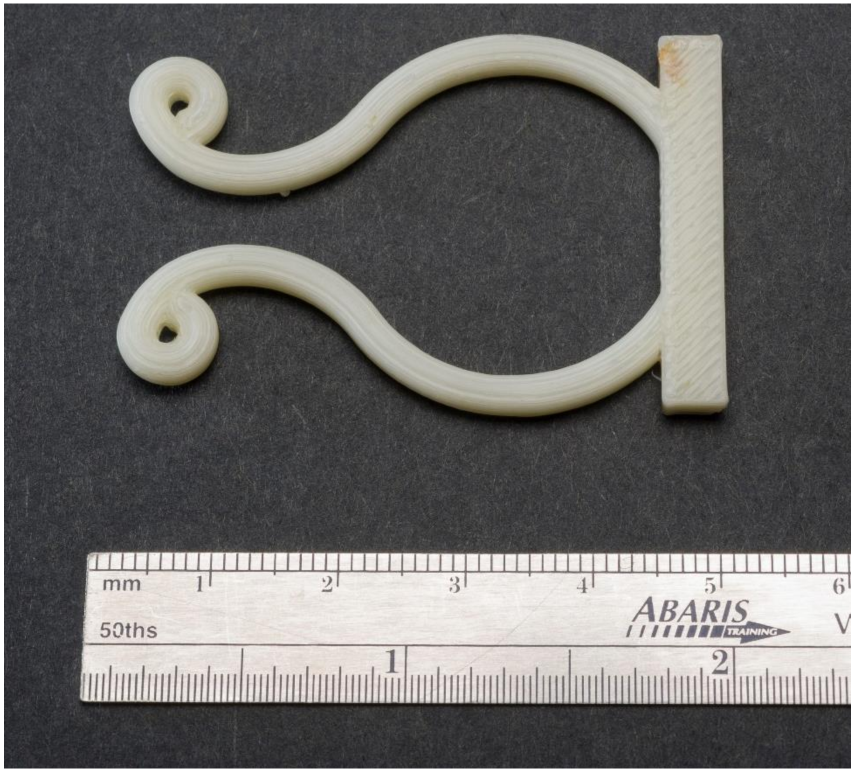
- Sample 020
- 2.46cm x 2.21cm x 0.51cm
- Printed to demonstrate fabrication of a part that would be difficult, if not impossible, to successfully 3D print in the pictured orientation due to gravity (i.e., sag, overhang, etc.)
- Used to determine if benefits exist to printing in microgravity (i.e., the ability to print large overhangs without supports)

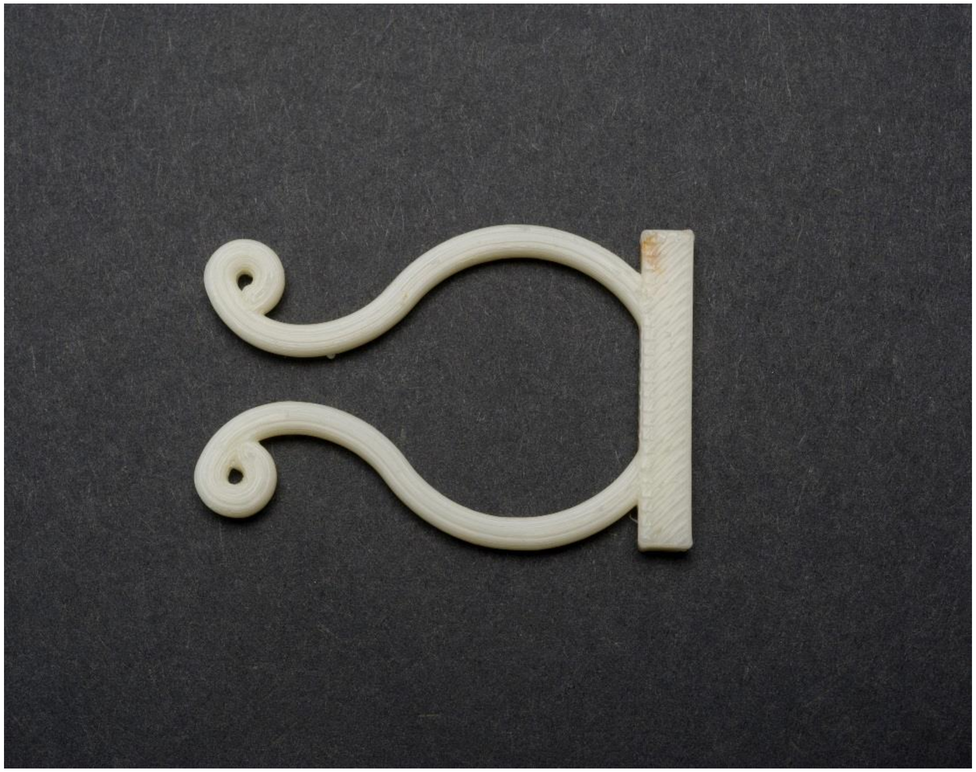




Wire Tie

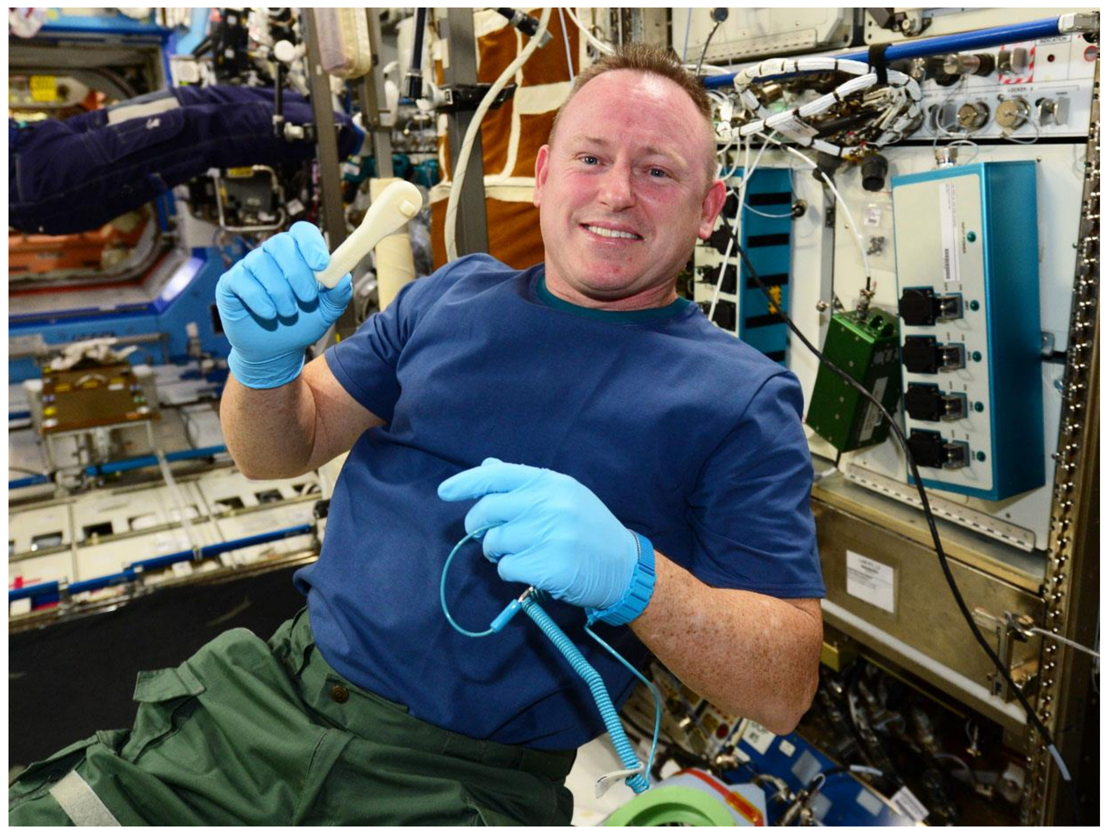
- Sample 021a
- 1.92cm x 1.30cm x 0.12cm
- Printed to demonstrate the flexibility of the material after printing





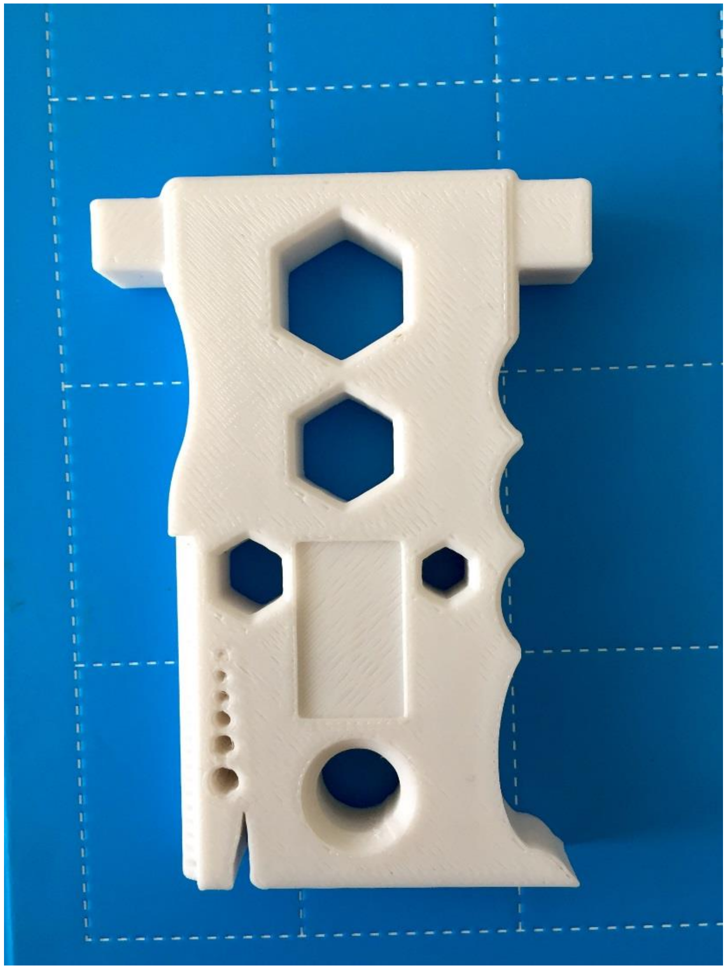
Ratchet

- Sample 021b
- 11.35cm x 3.30cm x 2.59cm
- The software file for this part was uplinked, illustrating how a part can be designed on Earth and manufactured in space, on demand



3D Print Forward Work

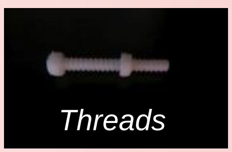
- Finalizing Phase II samples (including Future Engineers STEM print)
- Testing of Phase I samples
- Printing of Phase II samples
- Delivery of Phase II samples to Earth
- Phase III?

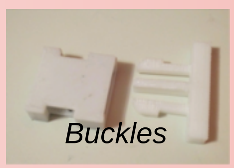


Path Forward: Near Term ISS Technology Demonstrations

Recycler

- Recycling / Reclaiming 3D Printed Parts and / or packing materials into feedstock filament
- Crucial capability to sustainability in-space
- Reduce up-mass of feedstock resupply and down-mass of packaging waste





Additive Manufacturing Facility

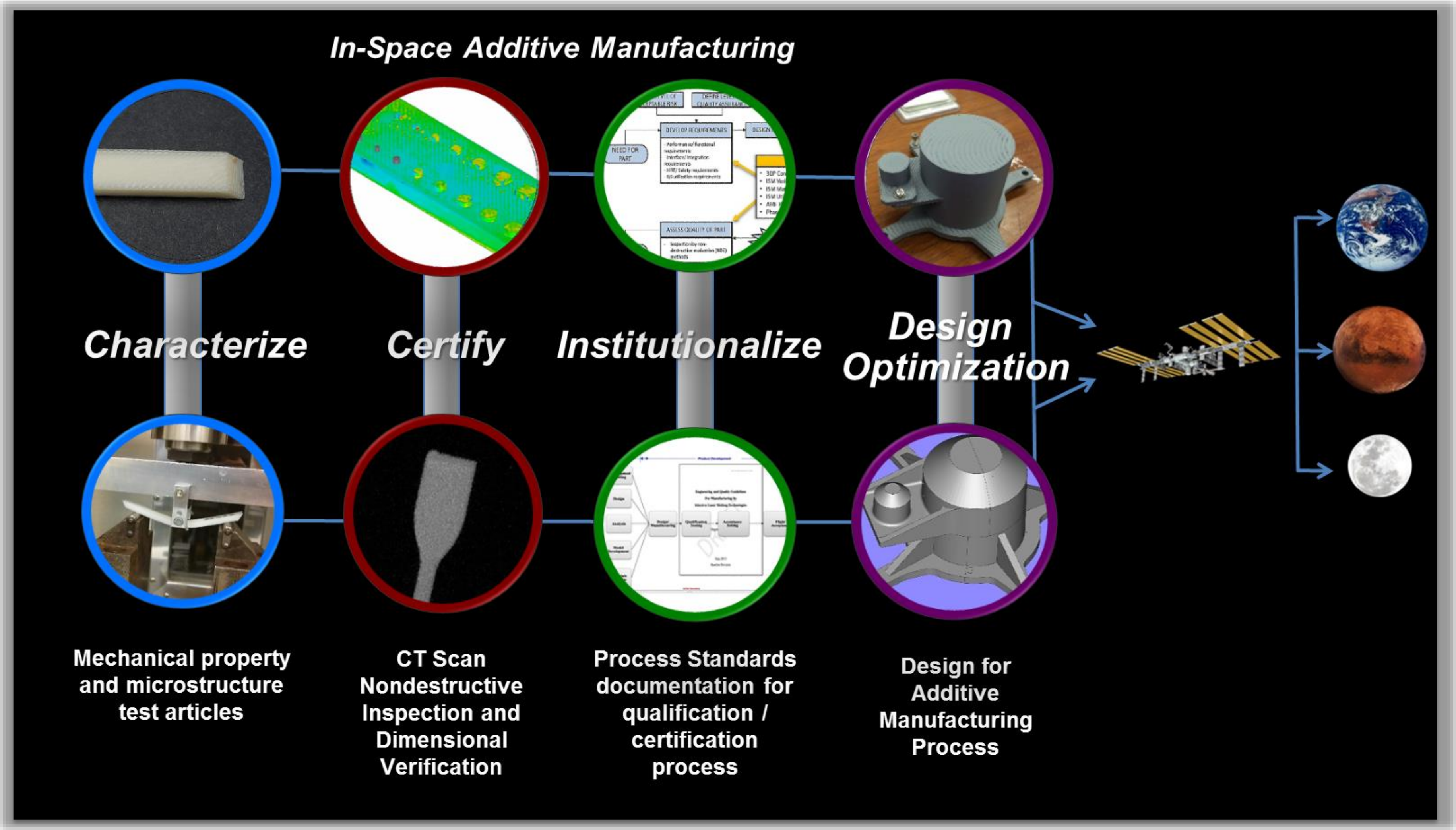
- Next generation 3D Printer developed by Made In Space
- Commercial 3D Printer on ISS for both external and NASA customers
- New material capabilities (for more usable, robust parts)

Image: NASA

External Structures & Repairs

- Perform repairs on tools, components, and structures in space
- Repair with AM technologies such as 3D Print and metallic manufacturing technologies (e.g. E-beam welding, ultrasonic welding, EBF3) to perform the repair.

Utilization Catalogue



- Provides astronauts with a library of pre-approved part files to build as needed
- Begin by re-designing crew tools and non-critical replacement parts
- Influence space station and exploration systems designs to incorporate AM design philosophy
- Ongoing effort will include replacement parts for critical systems

NASA