INTERNATIONAL SPACE STATION (ISS) 3D PRINTER PERFORMANCE AND MATERIAL CHARACTERIZATION METHODOLOGY

Q.A. Bean and K.G. Cooper
NASA Marshall Space Flight Center/EM42
Huntsville, Alabama

J.E. Edmunson
Jacobs Technology Inc./Engineering and Science Services and Skills Augmentation
NASA Marshall Space Flight Center/ZP30
Huntsville, Alabama

M.M. Johnston and M.J. Werkheiser
NASA Marshall Space Flight Center/ZP30
Huntsville, Alabama

ABSTRACT

In order for human exploration of the Solar System to be sustainable, manufacturing of necessary items on-demand in space or on planetary surfaces will be a requirement. As a first step towards this goal, the 3D Printing In Zero-G (3D Print) technology demonstration made the first items fabricated in space on the International Space Station. From those items, and comparable prints made on the ground, information about the microgravity effects on the printing process can be determined. Lessons learned from this technology demonstration will be applicable to other in-space manufacturing technologies, and may affect the terrestrial manufacturing industry as well.

The flight samples were received at the George C. Marshall Space Flight Center on 6 April 2015. These samples will undergo a series of tests designed to not only thoroughly characterize the samples, but to identify microgravity effects manifested during printing by comparing their results to those of samples printed on the ground. Samples will be visually inspected, photographed, scanned with structured light, and analyzed with scanning electron microscopy. Selected samples will be analyzed with computed tomography; some will be assessed using ASTM standard tests. These tests will provide the information required to determine the effects of microgravity on 3D printing in microgravity.

INTRODUCTION

NASA has long been interested in 3D printing in space. In the late 1990s, NASA's George C. Marshall Space Flight Center (MSFC) teamed up with NASA's Lyndon B. Johnson Space Center to conduct initial ground and zero-gravity (zero-g) flight studies with a Stratasys Fused Deposition Modeler (v1600) 3D printer [1]. Experiments included building parts with the machine turned sideways and upside-down on the ground, and 2 hours of cumulative zero-g drop time on board the KC135 NASA Reduced Gravity aircraft. Printed parts were made with Acrylonitrile Butadiene Styrene (ABS) plastic and included various geometries ranging from simple rectangular bars to free-spanning bridge-and-pier structures. The results of the tests yielded satisfactory data to warrant going forward with further experiments in space.

The 3D Printing In Zero-G (3D Print) technology demonstration is the first payload to perform 3D printing (additive manufacturing, or building parts layer-by-layer) in the consistent microgravity environment of the International Space Station (ISS) [e.g., 2]. This demonstration is the first step towards In-Space Manufacturing, which will provide in-situ fabrication and repair in space and on planetary surfaces. In-Space Manufacturing addresses the fact that long-duration and long-distance planetary missions are extremely difficult to resupply from Earth; this requires a change from the current spares, maintenance, repair, and hardware design model that has been used on the ISS. In-Space Manufacturing is a critical, key part of sustaining a human presence off-Earth; the ability to produce a needed part/tool/object on demand provides risk mitigation for Deep Space Missions.

3D PRINT TECHNOLOGY DEMONSTRATION

The 3D Print payload was designed to operate within the Microgravity Science Glovebox (MSG), which provided containment, circulation to the outside of the printer and electronics box, as well as cooling capabilities to prevent the printer from overheating. The 3D Print used extrusion-based additive manufacturing, which involves building an object out of plastic, in this case ABS, deposited by a wire feed via an extruder head. The 3D Print team chose to use ABS plastic because of its relatively low extrusion temperature, its low toxicity, and its low mass. It is also a fairly strong material commonly used in commercial 3D printers. The 3D Print payload also contains its own experimental Environmental Control Unit, which is designed to regulate cooling and filtration of the air within the printer volume. Parts were printed from data files loaded on the device at launch, as well as an additional file uplinked to the device while on orbit. Additional parts, to be printed at a later time on 3D Print, are currently under discussion and will be uplinked as crew time on the ISS becomes available.

THE 3D PRINT TEAM

The 3D Print technology demonstration was jointly funded by the NASA Human Exploration and Operations Mission Directorate (through the Advanced Exploration Systems and International Space Station Programs) and the Space Technology Mission Directorate (Game Changing Development Program). Design, build, and craftsmanship of the 3D printer was the responsibility of the commercial company Made in Space, Incorporated (MIS); MIS was under contract to provide NASA with the 3D printer through a Small Business Innovative Research Phase III award. The NASA team provided guidance for the design (e.g., which components were already flight qualified, and how to mitigate Electromagnetic Interference), early prototype and flight unit qualification testing, payload integration management through the MSG group, ground operations personnel, the flight to the ISS, as well as crew time for the printer’s operation.

THE 3D PRINT MISSION, PHASE I

The 3D Print payload was launched via a Falcon 9 rocket at 12:52AM Central (United States) on 21 September 2014 on SpaceX-4. The SpaceX-4 capsule docked with the ISS at 5:52AM Central on 23 September 2014; 3D Print was unloaded and remained in stowage until installation in MSG on 17 November 2014. Following installation, the 3D Print payload was calibrated to identify the ideal distance of the print head from the print tray to assure adhesion of the prints to the tray. The Phase I printing, following the calibration of the device, occurred from 24 November 2014 to 15 December 2014 as crew time allowed. 3D Print was removed from the MSG on 16 December 2014 and stowed until crew time becomes available for Phase II prints. The Phase I prints were brought to Earth on SpaceX-5 on 10 February 2015, and unboxed at MSFC on 6 April 2015.

3D PRINT MISSION GOAL, OBJECTIVES, AND REQUIREMENTS

The ISS is currently the only test bed for investigating the effects of consistent microgravity on additive manufacturing. The main goal of 3D Print is to broaden the technical understanding of the physics affecting the material characteristics of 3D printed parts in microgravity. In addition to this primary goal, specific objectives were determined for 3D Print and include:

1. Perform extrusion-based additive manufacturing with ABS filament material on-board the ISS
2. Demonstrate nominal extrusion and traversing activities
3. Perform ‘on-demand’ print capability via computer-aided design (CAD) file uplink for requested parts as defined
4. Mitigate functional risks and design risks for future facilities and technology advancements
5. Test print volume scalability
6. Replace and refill filament material (i.e., feedstock) on demand
7. Perform science, technology, engineering, and mathematics (STEM) outreach activities

The requirements of the mission are:

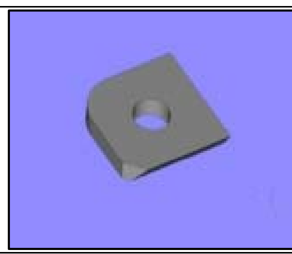
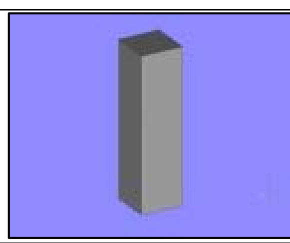
1. Obtain critical design and operational parameters as effected by microgravity
2. Produce 3D objects that generate processing data to understand 3D printing in microgravity
3. Demonstrate critical operations functions (feedstock replacement, part removal)
4. Demonstrate critical maintenance functions (print head replacement, cable switch
5. Produce at least one tool to be evaluated by crew
6. Demonstrate the ability to uplink from ground to ISS and print
7. Print volume > 5cm X 5cm X 5cm
8. Perform STEM activities

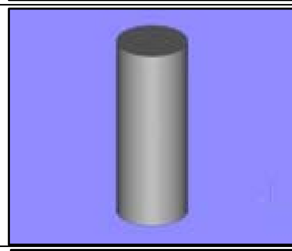
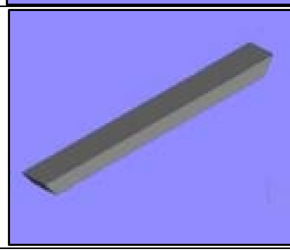
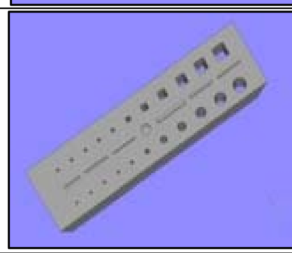
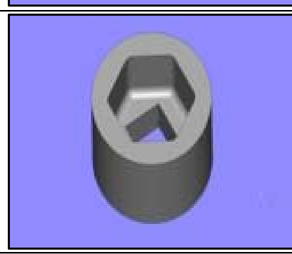
The Phase I portion of the 3D Print mission will satisfy requirements 1, 2, 3, 6, and 7. The Phase II portion will satisfy requirements 4, 5, and 8. The following test methodology, and the results produced, will address the objective of "mitigate functional risks and design risks for future facilities and technology advancements" as well as the requirements of "obtain critical design and operational parameters as effected by microgravity" and "produce 3D objects that generate processing data to understand 3D printing in microgravity".

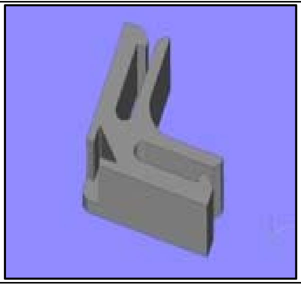
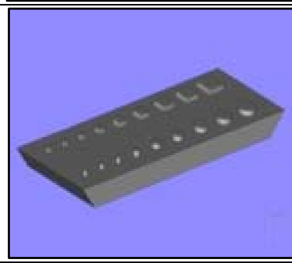
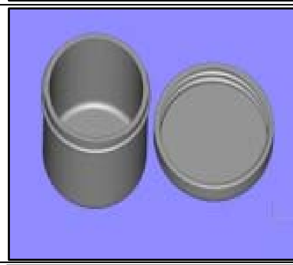
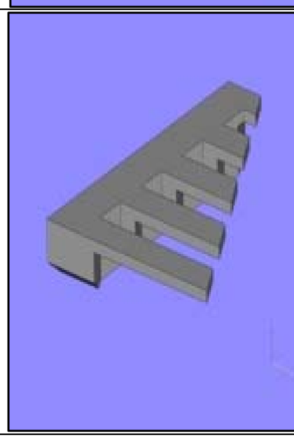
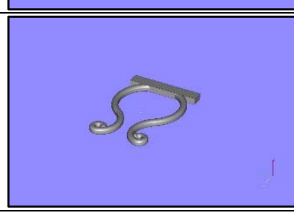
EXPERIMENTAL SETUP AND METHODS

For these experiments, the filament used was undyed ABS plastic at 1.75mm diameter; the filament was heated to a temperature between 230°C and 250°C, at which time it was soft enough to feed through a 0.4mm extruder tip. A set of 20 samples (three mechanical test coupons were printed multiple times during Phase I) was built with the flight unit and flight feedstock prior to launch (the Ground Control Samples). Additional sets were built using the flight backup unit (identical to the flight unit) with flight feedstock on the ground (Comparison Samples). Mechanical test specimens were built with a 45° / -45° lay-up with a solid infill. Certain geometry samples were selected to provide the maximum amount of information about materials properties and microgravity effects on the printing process. These geometries are shown in Table 1.

Table 1: Dimensions of printed items and selection criteria for printing

Sample Number	Sample Name	Image	Specification* (cm)	Selection Criteria
001	Calibration Coupon		Length: 3.00 Width: 3.00 Height: 0.41	This functional checkout and calibration coupon was printed to test calibration of the distance between the extruder and print plate.
002	Extruder Head Casing	Proprietary Image Not Available for Release	Length: 5.89 Width: 4.09 Height: 0.51	This is a replacement part for the 3D printer itself; it is a side plate of the extruder casing.
003	Layer Quality Test Specimen		Length: 1.00 Width: 1.00 Height: 3.00	This layer quality test specimen was printed to assess the layer quality and tolerances.

004, 012, 015, 018	Tensile Coupon		Length: 11.35 Width: 1.91 Neck Width: 0.61 Height: 0.41	The 45°/-45° material deposition pull coupon was printed to assess the tensile strength of the printed material at 45°/-45° lay-up orientation.
005, 013, 016	Compression Coupon		Diameter: 1.27 Height: 2.54	This compression test specimen was printed to assess compressive strength of the printed material.
006, 014, 017	Flexural Coupon		Length: 8.81 Width: 0.99 Height: 0.41	This flexural test specimen was printed to assess flexure properties of the printed material at 45°/-45° lay-up orientation.
007	Negative Range Coupon		Length: 7.49 Width: 2.01 Height: 0.43	This coupon will test the performance, geometric accuracy, and tolerances of the 3D Print for voids of specific geometry.
008	Torque Tool Specimen		Diameter: 3.00 Height: 2.50	This coupon will be used to demonstrate the ability to fabricate replacement crew tools.
009	Crowfoot Specimen		Length: 4.70 Width: 3.99 Height 1.30	This coupon will be used to demonstrate the ability to fabricate replacement crew tools.

010	Structural Clip Component		Length: 2.69 Width: 2.10 Height: 0.90	This is a structural connector / spacer that can be utilized to assemble avionics / electronics cards on-orbit.
011	Positive Range Coupon		Length: 6.12 Width: 2.01 Height: 0.51	This coupon will test the performance, geometric accuracy, and tolerances of the 3D Print for positive relief features.
019	Sample Container		Body Diameter: 4.03 Body Height: 3.28 Top Diameter: 4.60	This set will test the printer’s capability to produce two items at one time with interlocking-capable threads.
020	Microgravity Structure Specimen 1		Length: 2.46 Width: 2.21 Height: 0.51	This is a test 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).
021a	Wire Tie		Length: 1.92 Width: 1.30 Height: 0.12	To demonstrate the flexibility of the material after printing.
021b	Ratchet		Length: 11.35 Width: 3.30 Height: 2.59	This part was uplinked, illustrating how a part can be designed on Earth and manufactured in space, on demand.

Note: part 021a is a ground control sample and 021b is a flight sample. Neither one has the respective flight and ground samples, although data obtained from these parts will still be useful to ascertain the overall functionality of the machine and process.

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:

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

SELECTED TESTS

Tests were identified to provide the maximum amount of data with the minimal amount of destructive techniques. The test sequence will provide the necessary information for failure analysis as well. Storage and handling recommendations will be followed during testing.

Each ground and flight sample and print tray will undergo a thorough visual and photographic inspection. During the inspection, photographs will be taken from different angles and with appropriate scale representation (e.g., a standard ruler) and a digital camera with 8 or greater Megapixel resolution for print-quality images. This inspection will allow notation of any anomaly or damage (e.g., any damage that occurred when the print was removed from the print tray). It will also aid in identification of any visual differences between the flight and ground samples; these differences will be noted. Close attention will be given to any signs of delamination between layers, curling of the sample, surface quality, damage due to removal from the print tray, voids or pores, and any other visually noticeable defect. All of the findings from this inspection shall be given to NASA Marshall Space Flight Center's Failure Analysis Branch, who will conduct the optical and scanning electron microscopy analysis, to direct the concentration of their efforts to these defects.

Structured light scanning will also be completed to give a detailed, statistically valid data set regarding the surface geometric variations between the printed part, CAD model, and part volume of the flight and ground samples. The scanning will take place at NASA Marshall Space Flight Center using the ATOS II, Triple Scan blue LED scanner. The scanner has an accuracy of +/- 12.7 microns at these volumes and the capability to capture stereoscopic images at a resolution of 5 million pixels per scan. The samples will be coated in talcum powder (non-reactive with the ABS plastic) to reduce the reflectivity of the sample surfaces and provide a more accurate scan. The talcum powder grain size is approximately 10 microns in diameter, and will have little effect on the measurements made by the scanner.

The software package that accompanied the ATOS scanner uses the stereoscopic images to capture the fringe pattern sent out from the central LED projector contained in the scanner. The software triangulates all of the surface data (using the grayscale pixels - black and white contrast from the fringe pattern) to determine the shape of the geometry. Through this process the software generates a complete 3 dimensional model of the object being scanned. The software also provides real time feedback to show if it is missing surface data anywhere on the object. The missing data will be captured in subsequent scans to assure all sides of the object are scanned. The software package also has the capability of comparing the model of the object generated from the scans with the original CAD model from which the print was made. This will show any deviations from the original CAD created in the printing process.

Two-dimensional oblique and three-dimensional computed tomography (3D-CT) scans will be completed following structured light scanning on specific samples (Table 2) to image and characterize any internal structures that could affect mechanical properties. The samples will be imaged on a Phoenix Nanome|x 160 using X-rays to determine the existence of any internal voids or evidence of de-lamination of the ABS layers. To conduct 3D-CT, 2D images will be acquired through a 360 degree rotational axis; the successive 2D images will be stitched together to form a 3D image of the sample. Depending on the sample's geometry, resolution as low as 8-10 microns is possible. If 2D measurements are necessary, the computed numerically controlled (CNC) table is calibrated to a measurement accuracy in the z-axis of 5 microns. The system has a detail detectability as low as 0.4 microns in 2D mode.

A measurement of the mass using a calibrated laboratory scale accurate to 0.1 mg will be repeated five times to determine the calculated mean mass of the recorded measurements. A calculation of the density using the volume determined by structured light scanning will follow. The density data will provide information on void space or expansion of the material created during the printing process. Each flight sample will be compared with its respective ground sample to assess any differences; these differences will be noted.

Destructive testing will commence after the non-destructive tests are complete. These tests will use ASTM standards. The tensile test will follow a standard method defined in ASTM D638 [3] and will yield the tensile strength, tensile modulus, and fracture elongation of the printed material. Note, a Type I specimen would generally be chosen for this application, however the Type I was too large for the build volume. A Type IV specimen was chosen to accommodate build volume. The flexural test, ASTM D790 [4], will provide the flexural stress and modulus of the printed samples. The compression test, ASTM D695 [5], will determine the compressive stress and modulus of the prints.

Optical and scanning electron microscopy (SEM) pictures and analysis will detail the surface microstructures of the layers and areas of the flight prints damaged by over-adhesion to the build tray; this will help determine the root cause of the over-adhesion issues observed during operation. Inter-laminar regions will be investigated to ascertain if there is a difference in the layer adherence between flight and ground samples. Defects or anomalies noted by the visual and photographic inspections will be examined, as well as fracture surfaces from the mechanical tests.

Optical analysis on a Leica M205 A Optical Microscope will include photographing and stereo-photographing six orientations of the samples (x, y, and z axes from the top and bottom of each) and macroscopically visible regions of interest or defects at an angle that best highlights the feature along with a visible scale. Images of magnification 10X, 50X, and 100X will be acquired with a visible reference scale bar.

Scanning electron microscopy will be completed using a Hitachi S-3700N. The uncoated samples will be imaged using secondary electrons in a low vacuum mode to investigate morphology and surface topography, particularly in areas of delamination, fracturing from the ASTM testing, and over-adherence to the print tray. The SEM process will include taking standard calibration images at magnifications of 50X and 500X; all images will include a scale bar.

Table 2: Planned testing for each sample type.

Sample Numbers	Sample Name	Photographic / Visual Inspection	Measure Mass, Calculate Density	Structured Light Scanning	CT Scan	Mechanical Testing (ASTM Standard)	Optical, SEM Analysis
001	Calibration Coupon	X	X	X			X
002	Extruder Head Casing	X	X	X			X

003	Layer Quality Test Specimen	X	X	X	X		X
004, 012, 015, 018	Tensile Coupon	X	X	X	X	D638	X
005, 013, 016	Compression Coupon	X	X	X	X	D695	X
006, 014, 017	Flexural Coupon	X	X	X	X	D790	X
007	Negative Range Coupon	X	X	X			X
008	Torque Tool Specimen	X	X	X	X		X
009	Crowfoot Specimen	X	X	X			X
010	Structural Clip Component	X	X	X			X
011	Positive Range Coupon	X	X	X			X
019	Sample Container	X	X	X			X
020	Microgravity Structure Specimen 1	X	X	X			X
021a	Wire Tie	X	X	X			X
021b	Ratchet	X	X	X	X		X

EXPECTATIONS

Due to the anisotropic nature of printed ABS plastic, it is expected the material will behave more like a composite during testing. This behavior, if shown, will be noted in the results. It is expected the tests listed above will address the 3D Print requirements, as noted in Table 3. The requirements satisfied by the tests conducted here are highlighted in Table 3.

Table 3: 3D Print Requirements and Success Criteria. Gray highlights indicate criteria satisfied by the tests outlined in this paper.

	3D Print Requirement	**Data Needed**	**Success Criteria**	**Test Conducted**
1	Obtain critical design and operational parameters as effected by microgravity	1A. Extruder Head Speed compared to ground	1A-1. Layer adhesion	SEM / Visual Analysis
			1A-2. Re-solidification	Mechanical Testing
			1A-3. Dimensions within tolerances	Structured Light Scanning
			1A-4. Surface Finish	
		1B. Feedstock feed rate compared to ground	1B-1. Layer adhesion	SEM / Visual Analysis
			1B-2. Re-solidification	Mechanical Testing
			1B-3. Dimensions within tolerances	Structured Light Scanning
			1B-4. Surface Finish	

		1C. Ideal extruder temperature compared to ground	1C-1. Layer adhesion	SEM / Visual Analysis
			1C-2. Re-solidification	Mechanical Testing
			1C-3. Dimensions within tolerances	Structured Light Scanning
			1C-4. Surface Finish	
2	Produce 3D objects that generate processing data to understand 3D printing in microgravity	2A. Layer adhesion complete	2A-1. Layer adhesion Data	SEM / Visual Analysis
			2A-2. Re-solidification Data	Mechanical Testing
		2B. Corners at 90 degrees	2B-1. Dimensions within tolerances	Structured Light Scanning
		2C. Geometry tolerances of ground vs ISS samples	2C-1. Determine dimensional tolerances	
			2C-2. Surface Finish data obtained	
		2D. Mass / Density of part printed on ground vs ISS.	2D-1. Mass / Density comparison data obtained	Mass / Density Measurement / CT Scan
3	Demonstrate critical operations functions (feedstock replacement, part removal)	3A. Obtain feedstock replacement time.	3A-1. Obtain time to replace feedstock on ISS vs ground. Have successful print after replacement.	Collect time data
		3B. Obtain part removal time	3B-1. Obtain time to remove part on the ISS and on the ground.	
		3C. Obtain pre-print prep time	3C-1. Obtain pre-print prep time on the ISS and on the ground.	
		3D. Extruder nozzle replacement/ or plug removal	Skip if not performed on-orbit	
4	Demonstrate critical maintenance functions (print head replacement, cable switch)	4A. Extruder head replacement	4A-1. Demonstrate successful extruder head replacement	Crew performs replacements
		4B. Electronic cable replacement	4B-1. Demonstrate cable replacement and successful print after replacement	
5	Produce at least one tool to be evaluated by crew	5A. The selection of a reasonable challenging, but useful crew tool.	5A-1. Successfully build a useful crew tool.	Tool built
			5A-2. Crew successfully uses the crew tool in a relevant application once.	Tool used by crew
6	Demonstrate the ability to uplink from ground to ISS and print	6A. Demonstrate uploading a CAD file via existing ISS IT	6A-1. Successful uplink to ISS with CAD file attached.	MIS uploads and prints part

		6B. Demonstrate loading the CAD file to the MSG computer.	6B-1. Successfully uploaded CAD file to the MSG computer on the ISS	
		6C. Print the uploaded part	6C-1 Successful print of the uploaded CAD file.	
7	Print volume > 5cm X 5cm X 5cm	7A. Design printer for bigger volume	7A-1. Verify that build space in 3DP is bigger than required.	Verify build volume meets or exceeds requirements
		7B. Demonstrate that the entire volume is printable.	7B-1. Verify during the flight V&V testing that the actual print volume is bigger than required.	
8	Perform STEM activities	8A. Incorporate STEM into ISS prints	8A-1. Incorporate STEM into the planned ISS prints.	Build STEM / Future Engineers part
		8B. Have STEM participants watch their print, print on the ISS	8B-1: Evidence of STEM participants watching ISS 3DP demo.	

UNEXPECTED

Super-adhesion of the samples to the print tray during on-orbit printing was not observed while printing the ground samples and is suspected to be the effect of microgravity. Analysis of the test results and comparison of the flight and ground prints and print trays using the methods listed above are expected to yield a better understanding of the cause of this unexpected super-adhesion during on-orbit printing (e.g., inefficiency of convection to provide the necessary heat transfer); lessons learned will be applied to the design of the next generation of space-based 3D printers.

SUMMARY AND CONCLUSIONS

The first prints obtained from the 3D Printing In Zero-G technology demonstration will be compared to samples printed on the ground from the identical feedstock on a printer with identical form, fit, and function to determine the effects of microgravity on the 3D printing process. Each print will undergo a visual and photographic inspection, mass measurement, density calculation, structured light scan, as well as optical and scanning electron microscopy. Select samples will be CT scanned to determine the internal geometry of the printed samples. The tensile, compression, and flexure coupons will be tested using ASTM standards to characterize the strength of the flight samples relative to the ground samples. The results of this work will be presented at a later date.

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