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N A S A In-Space Manufacturing Project: Update on Manufacturing Technologies and Materials to Enable More Sustainable and Safer Exploration

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Abstract:

N A S A In-Space Manufacturing (ISM) project seeks to develop the materials, processes, and manufacturing technologies needed to provide an on-demand manufacturing capability for deep space exploration missions. The ability to manufacture and recycle some parts on demand rather than launch them from earth has the potential to reduce logistics requirements on long duration missions and enhance crew safety. With the launch of the first 3D printer (built and operated by Made in Space through a Small Business Innovative Research (SBIR -- contract) to the International Space Station (ISS) in 2014, the ISM project demonstrated the feasibility of operating an on-demand manufacturing system in a microgravity environment. This paper will provide an update on recent advancements in ISM under three key technology areas: manufacturing, recycling, and development of a design database.

ISM continues to pursue development of manufacturing technologies for space applications and use the ISS as a critical test bed to prove out these technologies before deploying them on next generation exploration systems. Activities under this focus area include: characterization of materials manufactured using the Additive Manufacturing Facility (AMF), the second generation commercial 3D-printer on ISS, also owned and operated by Made in Space; development of prototype payloads for metal manufacturing through phase II SBIR contracts with Tethers Unlimited, Made in Space, and Ultra Tech Machinery; development of a multi-material fabrication laboratory capable of processing metals and providing inspection of manufactured parts through a Broad Agency Announcement (Techshot, Interlog, and Tethers Unlimited); an in-line sensing system for ISM platforms; and development of higher strength feedstocks for 3D polymer printers.

In the area of recycling, the Tethers Unlimited Refabricator payload (an integrated 3D printer and recycler for ULTEM 9085) launched to ISS in November 2018 and began operating in early 2019. This payload represents the first demonstration of on-orbit recycling; downmassed specimens will assess material degradation in the polymer over multiple recycling cycles to define limits on material re-use. Other work in the recycling area includes development of common use materials intended to be reused and recycled on space missions (Tethers Unlimited and Cornerstone Research Group) and a sterilization capability for multiple-use materials (ERASMUS from Tethers Unlimited). Concurrent with manufacturing technology and materials development work is creation of a design database, a curated list of parts that can be manufactured using the suite of In-Space Manufacturing capabilities.

Acronyms

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
AMF	Additive Manufacturing Facility
AMI	Actuated Medical, Inc.
ARC	Ames Research Center
BFF	BioFabrication Facility
CNC	Computer Numerical Control
CT	Computed Tomography
CRG	Cornerstone Research Group
CRISSP	Customizable Recyclable International Space Station Packaging
EXPRESS	Expedite the Processing of Experiments for Space Station
FCE	Flight Crew Equipment
FFF	Fused Filament Fabrication
GFE	Government Furnished Equipment
HDPE	High Density Polyethylene
ISM	In-Space Manufacturing
ISS	International Space Station
IVA	Intra-Vehicular Activity
LEO	Low-earth Orbit
MAMBA	Metal Advanced Manufacturing Bot-Assisted Assembly
MIS	Made in Space
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PC	Polycarbonate
PEEK	Polyether ether ketone
PLA	Polylactic acid
SBIR	Small Business Innovative Research
SIMPLE	Sintered Inductive Printer with Laser Exposure
TUI	Tethers Unlimited
UAM	Ultrasonic Additive Manufacturing

1. Project Purpose and Overview

NASA's In-Space Manufacturing (ISM) project is managed at the Marshall Space Flight Center in Huntsville, Alabama. The primary focus of ISM is to facilitate use of the International Space Station (ISS) as a testbed to mature the manufacturing technologies needed to support sparing, repair, and recycling within the crewed environment on long duration, long endurance missions. Long duration missions correspond to the typical time a crew member spends on ISS (6 months to 1 year). Long endurance refers to mission

scenarios where cargo resupply is limited. While ISS is long duration, it is not long endurance since it can be readily accessed by multiple launch vehicles and the time from launch to docking is relatively short compared to non-low earth orbit (LEO) missions. For the class of missions which can be characterized as long duration and long endurance, In-Space Manufacturing shows immense potential to achieve gains in logistics reduction by a) reducing the number of spare parts and orbital replacement units which much be upmassed and b) enabling recycling of materials which would otherwise be nuisance materials (scrap/trash) or consumables [1, 2]. This fundamental paradigm shift from traditional logistics models, which rely on changeout of orbital replacement units (stowed on the ISS) rather than repair of a unit at the component level. The implementation of ISM on future space mission thus depends on design of exploration systems which are accessible and intended to be repaired rather than simply changed out with an identical full-scale unit stored on-orbit.

Testing of manufacturing technologies on ISS as payloads allows NASA to evaluate the potential of various processes to meet on-demand manufacturing needs on missions beyond (LEO). ISS is a unique environment for manufacturing which presents numerous challenges. Manufacturing hardware for operation in an IVA environment must satisfy all safety considerations and demonstrate sufficient mitigation of all standard and unique hazards. Any debris generated during the manufacturing process must be completely removed from the system prior to opening for part removal. Materials must satisfy ISS requirements for flammability and toxicity. Payload accommodations for ISS constrain the manufacturing processes which can be adapted for testing (Figure 1). In an ISS EXPRESS rack configuration, systems must consume no more than a maximum of 2000 W of power (this is for a system occupying a full rack, smaller payload accommodations may have an upper limit that is proportionally less than this value), weigh less than 576 pounds (assumed weight is for a full rack, subsize accommodations will be scaled from this value), and occupy less than 16 cubic feet. The 16 cubic feet in volume is for a full rack consisting of 8 lockers; this proportionally scales to 4 cubic feet for a double locker configuration and 2 cubic feet for an individual locker. Additionally, it is anticipated that many manufacturing processes will be impacted in

some way by operation in the absence of gravity (for example, a process where the feedstock is melted and resolidifies may result in parts with a greater porosity than those produced terrestrially due to the dominance of surface tension effects in 0g). The ISS environment uniquely enables comparison of specimens manufactured in space with those made on the ground. Characterizing the impact of microgravity on material outcomes enables design for manufacturing using a particular process in microgravity. Once manufacturing processes and systems have been proven on ISS, they can be considered for use in exploration class systems on the long duration, long endurance missions envisioned for the future. This paper considers the portfolio of technologies currently being developed under the In-Space Manufacturing project, with a particular emphasis on how these processes serve to advance the state of the art for future human spaceflight.

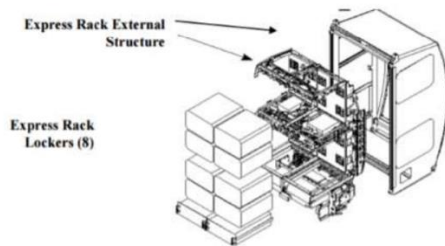


Fig. 1. Diagram of EXPRESS Rack. Each rack is divided into 8 lockers.

2. Polymer manufacturing

The In-Space Manufacturing project began in 2014 with the launch of the 3D Printing in Zero G technology demonstration mission, developed under a small business innovative research (SBIR) contract with Made in Space (MIS), Inc. This hardware printed 55 parts of acrylonitrile butadiene styrene (ABS) plastic on ISS, which were subsequently downmassed to earth for testing and analysis [3]. In 2016, the project began using the Additive Manufacturing Facility (AMF), a second generation printer also developed by Made in Space, to conduct additional materials characterization studies using the flight printer and a ground-based equivalent unit. The AMF studies derive their testing methodology from composites in that mechanical test specimens are machined from printed panels rather than printed directly [4]. The layup pattern of the panels was varied to consider the directional dependence of properties and the degree of anisotropy. To date, over 100 mechanical test coupons have been

evaluated as part of this effort. Typical materials test regimes include density measurements, nondestructive evaluation (structured light scanning to compare dimensions of the printed part with the CAD geometry; sometimes CT scans are also performed), mechanical testing, and fracture analysis using scanning electron microscopy (SEM). While testing for 3DP and AMF have both revealed differences in microgravity and ground-produced specimens of identical geometries, these discrepancies are hypothesized to be the result of variations in manufacturing process parameters and settings rather than a significant microgravity influence. As a forced extrusion process with a wire plastic feedstock, fused filament fabrication can operate independently of the gravity vector. Additionally, computational models of the FFF process in 1g and 0g have not predicted significant impacts on the underlying physics of the manufacturing technique [3].



Fig. 2. 3D Printing in Zero G technology demonstration mission.

Since 2015, the ISM project has supported work on materials recycling and reuse strategies. Foams and films ensure hardware for ISS survives launch loads without incurring damage. Currently a variety of polymer materials are used for launch packaging and the cumulative mass of these materials can be substantial. However, none of these materials are reused or reprocessed on ISS. Instead, packaging materials are organized into small parcels of trash (referred to as), which are then loaded into the Cygnus capsule, and consumed during re-entry. The work under the recycling/reuse component of the In-Space Manufacturing portfolio focuses on reuse of plastics and packaging materials through a) manufacturing technology development for i) recycling and ii) printing with recycled materials and b) development of materials which are intended to be reused and recycled. Under the customizable, reusable ISS Packaging effort (now in a phase II-X SBIR contract), Tethers Unlimited (TUI), Inc.

developed a custom slicing engine to enable 3D printing of custom infill structures of off-the-shelf polymer feedstocks (ULTEM 9085, ABS, HDPE, PLA, and PC). 3D printed foams with various infill patterns were vibration tested to establish a correlation between the structure of the material and the resulting vibration properties (attenuation of acoustic energy). The CRISSP slicer and infill generation software allows a user to print exactly the foam structure needed to protect a component or piece of hardware from specific vibration levels [5]. The CRISSP effort also included degradation studies in polymer materials over multiple recycling cycles to determine which materials are best suited for a space mission recycling ecosystem.



Fig. 3. CRISSP foams from Tethers Unlimited. Image from TUI.

A complementary approach to development of common use materials for ISS packaging is being performed by Cornerstone Research Group, who under multiple phases of SBIR funding have developed a Polyethylene-based thermally reversible material which can be processed into films and foams and recycled into filament for 3D printing [6]. This material shows negligible degradation in mechanical properties over multiple recycling/printing cycles. The material also passed toxicity testing at White Sands Test Facility. Foam samples which underwent vibration testing also performed strongly relative to foams currently used in ISS applications.

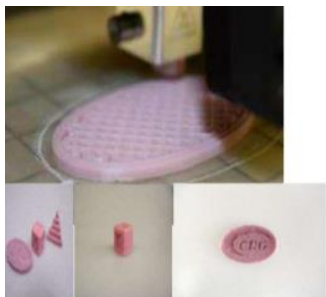


Fig. 4. Example of thermally reversible materials developed by Cornerstone Research Group (CRG) for 3D printing and recycling. Image from CRG.

In early 2019, Tethers Unlimited and NASA's In-Space Manufacturing project installed the Refabricator payload on ISS. The Refabricator has the capability to reprocess a printed block of ULTEM 9085 into filament feedstock (without grinding or pelletizing) via a process known as Positrusion [7]. The extruded filament is fed into a print head to 3D print parts or input blocks that can be used to create additional filament. Specimens produced with the Refabricator system are expected to arrive at MSFC for testing in early 2020. The specimen set will include tensile specimens for mechanical testing and segments of filament for chemical analysis. TUI is working under parallel SBIR efforts to redesign the Refabricator to support recycling of multiple materials.

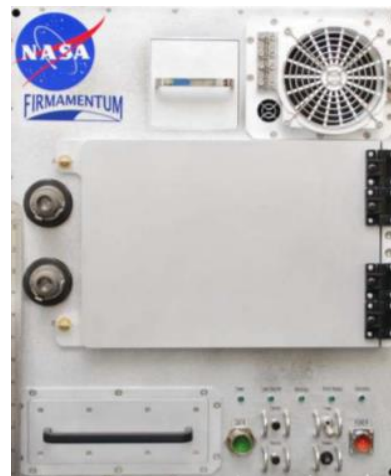


Fig. 5. Refabricator unit.

Manufacture of food tools and medical devices in an IVA environment is seen as a high potential target application for In-Space Manufacturing. However, the value proposition for making this class of parts on-demand rather than prepositioning them in stowage is lessened without an accompanying sterilization capability. Sterilization is needed to minimize the risk of exposure of crew to harmful bacteria and viruses (some of which may be more virulent in the space environment). Traditionally sterilizers are large systems with a high power draw and may be incompatible with ISS payload accommodations. Many sterilizers also require water for decontamination. Water is limited on ISS and is

Fig. 14. Image of cortisol sensor. Coin is shown for scale.

Gas/vapor sensors and humidity monitoring are needed to continuously monitor the cabin air quality in ISS and future habitats. These small, compact sensors could potentially replace bulky instruments currently used for this purpose. For example, mass spectrometers provide very accurate quantitative information about the constituents of the ambient, but they are heavy, have a large power draw, and cannot characterize variations in elemental concentrations across the cabin environment. In contrast, postage stamp-sized chip-based sensors are small, have very low power requirements, and, if calibrated properly, will provide reliable measurements of gases and vapors across a volume (it is possible to deploy multiple printed sensors across the cabin in a networked fashion) [18]. NASA has developed printed sensors for monitoring carbon dioxide and ammonia (ammonia has a high level of toxicity and leakage of ammonia in systems which use it for cooling represents a serious safety concern). The NASA research group has used machine learning to convert the measured signal of ammonia $\pm$ which is resistance in this case $\pm$ into analyte concentrations.

Fig. 15. Image of first-generation CO₂ sensor.

Radiation exposure is also serious concern in space missions, particularly for exploration missions beyond low earth orbit where radiation exposure levels increase by orders of magnitude. Radiation exposure poses threats to both crew health (increased risk of cancer) and payload electronics. Radiation sensors capable of fingerprinting various

types of radiation based on their energy levels and intensity are needed. Towards this goal, a printed gamma ray detector was developed [19]. This sensor detects the conductivity change in carbon nanotubes upon exposure to radiation; the magnitude of this conductivity change is indicative of particular radiation levels. It is also able to detect gamma radiation at flux levels.

Additional developments with on-demand printing capabilities include energy storage and power generation. Most modern printed sensors require only milliwatt (mW) levels of power for operation, which can be locally generated from vi EUDWLRQV DQG RWKHU PRYHPHQWV electronics research group has exploited triboelectric power generation mechanisms to print energy scavenging devices which can provide a continuous supply of tens of mW power (this harvested energy is used to run the printed sensors). Supercapacitors are ideal devices for energy storage, as they have charging rates which far exceed conventional batteries. Through optimization of various inks for electrodes and active layers, NASA has printed supercapacitors with a specific capacitance of 150 F/g. These supercapacitors have completed a thousand charge and discharge cycles without any significant degradation in performance. The development of a printed array of mini-antennas to harvest power for electronic applications is a compelling technology also being developed by ISM through a university collaboration 7KL V 3UHFWHQ QD' will harvest watts of electromagnetic radiation energy (Wi-Fi) through printed antennas on flexible substrates and utilize a rectifier circuit for power conversion.

Future development of printed electronics technologies will involve development of multi-material 3D printers to manufacture advanced sensors and devices on-demand as they are needed for ISS, Lunar Gateway, and future habitats on the Moon and Mars. Future phases of the Fabrication Laboratory activity are intended to include development of printed electronics capabilities. Parallel development of advanced functional materials for sensors and devices are also needed to fully realize the WHFKQRORJ\ ¶ V S R W H Q W L O L Q V X S S R spaceflight.

5. In-process sensing

Inspection of parts produced on-orbit and certification of them for use in an application or

be manufactured on long duration space missions (and using requirements for those parts to inform requirements for ISM platform) ongoing design database activity. The ISM project currently has a database of candidate parts for In-Space Manufacturing which originate from the following sources:

- 1) ISS databases cataloging part failures and problem reporting. When considering the information in these databases, ISM focused on identifying components from environmental control and life support systems which require regularly scheduled repair and replacement or have failed on ISS previously.
- 2) The ISS medical toolkit manifest, which catalogs medical items pertinent to emergent and non-emergent on-orbit medical scenarios. Historically the medical community has been an early adopter of additive manufacturing, as the technology provides unique opportunities for patient customization and can reduce logistics/lead times for medical consumables in operationally remote scenarios. The toolkit contains many medical devices of both polymer and metal materials which could in theory be manufactured on a space mission (assuming devices can be manufactured to medical standards and represent FDA-approved items).
- 3) The Intravehicular Activity (IVA) Government Furnished Equipment (GFE) Flight Crew Equipment (FCE) manifest, which catalogs tools, equipment and supplies needed for various ISS on-orbit scenarios. This manifest has yielded many items to date suitable for replacement via additive manufacturing technologies if lost or broken.
- 4) In the next year, the database will also expand to include heritage spacesuit components, with candidate parts identified based on historical documentation of spacesuit designs and continued conversations with the spacesuit design community.

The ISM project also has plans to expand the capability of the database and, in the future, implement a manufacturing execution capability so that a crew member could initiate manufacture of a part on an ISM manufacturing platform directly from the database interface. A related activity under a NASA Space Technology Research Fellowship uses candidate parts identified from ISS part databases to develop a systems modeling framework for assessing the utility of a manufacturing process in various mission scenarios [25]. This activity will also help to define requirements for future ISM manufacturing platforms by providing insight into the materials, build rates, reliability levels, and tolerances needed to realize the potential of a particular manufacturing technology for logistics reduction. The NSTRF and design database activities will provide a critical bridge between the ñ how we make ò aspects of the ISM project.

7. Computational modeling

Computational modeling work at NASA ARC has served as an invaluable complement to work on In-Space Manufacturing process development and testing of manufacturing systems on ISS. The NASA ARC physics-based modeling group has provided analysis and modeling support of In-Space Manufacturing since 2014. The ARC team has significant experience in modeling physics phenomena and materials in microgravity. Work includes:

- Development and validation of models to support understanding of processes in zero-G environments
- Elucidation of material features of materials manufactured in micro-gravity that are distinct from earth-processed specimens
- Enabling physics-based analysis of the ISM payloads before launch
- Clarification of possible gaps in experimental performance.
- The support of verification and validation of parts manufactured in-space

To date, the ARC group has supported the In-Space Manufacturing demonstration of fused filament fabrication (3D Printing in Zero G technology demonstration mission), the in-space polymer recycling demonstration (Refabricator), and in-space metals manufacturing process development (the Multi-material Fabrication Laboratory, or ñ F a b). Computational models of FFF can predict the strength of the manufactured parts based on

