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MATERIALS AND STRUCTURES SYMPOSIUM (C2) Advancements in Materials Applications and Rapid Prototyping (9)

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NASA Additive Manufacturing Initiatives for Deep Space Human Exploration

Abstract

Additive Manufacturing (AM) is being infused into aerospace industries at an accelerated pace. Reasons for this rapid adoption include: (1) Innovation Capability e.g. design features such as topology optimization, integrated fluid passages, and mesh structures; (2) Rapid Development and Optimization - ability to quickly iterate the design, development, and test cycle; (3) Affordability – reductions in part counts, cost, and schedule. NASA's Marshall Space Flight Center (MSFC) has taken a leadership role in application of AM technologies for deep space human exploration, leading the Agency's In Space Manufacturing (ISM) initiative and the application of AM for a broad variety of space propulsion systems.

MSFC has championed the development of ISM capabilities since our first reduced-gravity aircraft experiment flew in 1999. Partnering with Made In Space, MSFC placed the first 3D Printer on ISS in 2014 and the second generation printer, the Additive Manufacturing Facility, in 2016. The next ISS technology demonstration will be the Refabricator, a recycler/basic printer scheduled to launch in late Fall 2018. Ground-based development is progressing in common use materials, metals 3D printing, printed electronics, and the new cornerstone of ISM, the FabLab. The latest developments in each area will be described. An overview of NASA's In Space Robotic Manufacturing and Assembly (IRMA) ground-based risk reduction projects will also be presented.

MSFC has aggressively incorporated AM capabilities for design and development of space propulsion components. The capabilities have been rapidly matured and extensively exercised to produce and hot-fire test the Additive Manufacturing Demonstrator Engine, an in-space class prototype engine. This experience base has been extended to support Aerojet Rocketdyne in the application of AM to the RS-25, the Space Launch System Core Stage engine, and to small propulsion systems and thrusters for small satellites and cubesats. The latest developments will be described.

In responding to a request from NASA's Commercial Crew Program for a consistent methodology for evaluation of AM processes and parts, MSFC began development of a draft standard for AM space flight hardware in late 2014. The draft was broadly disseminated for comments in mid-2015, and subsequently revised into two documents, a standard and a specification for AM space flight hardware, which were formally released by MSFC in October 2017. An overview of the key elements of these documents will be presented.

1. Background

NASA's Marshall Space Flight Center (MSFC) has been a leader in the area of additive manufacturing beginning with the arrival of the Fused Deposition Modeler (FDM) in the early nineties. Since that time, MSFC has continued to lead in the development of additive manufacturing (AM) for both "for space" and "in space" applications. The "for space" designation refers to components that are produced on the ground for space flight applications and the "in space" designation refers to those that are produced off planet. To date, this includes test articles and functional parts printed on the International Space Station, but in the future, applications supporting deep space exploration missions are envisioned. A more detailed overview of the development of AM at MSFC for space flight hardware applications is provided in reference 1, including the first reduced gravity aircraft flight experiments and resulting FDM test articles produced by Cooper [2] and the focused development and application of AM for rocket engines, beginning in 2011 [3]. After Cooper's successful demonstration of printing plastics in short microgravity periods on NASA's reduced gravity aircraft, specifically starting in 2004, the Exploration Science and Technology Division at MSFC formulated and implemented the In Situ Fabrication and Repair (ISFR) Program Element for NASA's Human Systems Research and Technology Office [4]. The key elements of ISFR included Fabrication, multi-material, feedstock flexibility, in situ resource utilization; Repair; Habitat Structures emphasizing radiation shielding and automated construction utilizing lunar in situ resources: Nondestructive Evaluation including integrated closedloop control of the process; and Recycling emphasizing reuse of failed parts and conversion of waste products into feedstock. Although the effort was terminated due to a change in Agency priorities, the vision and technology development framework created in 2004 were foundational, forming the basis of NASA's In Space Manufacturing initiative today. [1]

2. In Space Manufacturing

The focal topics of the In Space Manufacturing (ISM) discussion will be the following:

- Results from the initial 3D Printing in Zero-G ISS Technology Demonstration
- Development and characterization of the second generation printer, Additive Manufacturing Facility (AMF)
- Refabricator recycler and printer technology demonstration on ISS

• Fabrication Laboratory (FabLab) development. A summary of the ISM primary focus areas is provided in Figure 1. Other elements of the ISM portfolio and their status will be described briefly.



Figure 1. NASA's In Space Manufacturing Primary Focus Areas

2.1 The First Step: 3D Printing in Zero-G ISS Technology Demonstration

The current In Space Manufacturing initiative began through a Small Business Innovative Research (SBIR) project competitively awarded to Made In Space (MIS) in 2012. MSFC partnered with MIS in the design, development, and testing of the printer, which became the 3D Printing in Zero-G ISS Technology Demonstration, or 3DP. In September 2014, NASA launched the MIS-designed 3DP to ISS. The 3DP printer was operated inside the Microgravity Science Glovebox (MSG) and successfully produced 21 total specimens. These test articles were returned from ISS to MSFC for thorough characterization, along with the ground-based test articles that had been produced prior to the 3DP launch. The material characterization included photographic/visual inspection, x-ray and Computed Tomography (CT), structured light scanning, density, mechanical testing, optical and scanning electron microscopy, and Fourier Transform Infrared Spectroscopy. Detailed description of the results can be found in the reference by Prater et al. [5]. Key observations are summarized in Figure 2.





A ground-based study was conducted to more closely examine the effects of the extruder standoff distance (Z-cal distance) on the printed materials characteristics. A summary of the results from this study indicates that "discrepancies in tensile performance between flight and ground prints can likely be explained by differences in manufacturing process settings, specifically the reduced extruder standoff distance for the flight prints, which resulted in protrusions at the base of the specimen that contribute to enhanced mechanical strength. An explanation for differences in compression specimen structure and performance for 3DP Phase I ground and flight groups cannot be readily extrapolated from this study, but key findings from CT, structured light scanning, and surface metrology suggest that decreasing extruder standoff distance results in specimens with increased dimensional variation (cylindricity), shrinkage, and air gaps in the through-thickness" [6]. No analyses point to operation of the FDM process in microgravity as a substantive, engineering significant, contributing factor to material differences [6].

In addition, a second set of 3DP samples (3DP Phase II) was printed on ISS from June to July 2016 that had specific controlled experiments focusing on the Z-cal distance to lend additional clarity to causes of variability in the Phase I data. A total of 34 test articles were printed. Twenty-five (25) specimens were built using an optimal Z-cal distance. The remaining specimens were printed at a suboptimal Z-cal distance to purposefully attempt to replicate the printing conditions for Phase 1. Detailed description of the results can be found in the reference by Prater et al. [7]. Key observations are summarized in Figure 3. "Phase II data strongly indicated that differences between Phase I ground and flight specimens were attributable to build to build variability and changes in manufacturing

process settings on-orbit rather than operation of the FFF process and/or the technology demonstration hardware in a microgravity environment. The lack of an engineering significant effect of microgravity on material outcomes suggests that specimens produced with a ground-equivalent printer should be representative of material produced on-orbit." [8]





2.2 Second Generation 3D Printer on ISS: Additive Manufacturing facility (AMF)

Made In Space incorporated lessons learned from the initial 3DP to create the second generation 3D printer, which was launched to ISS on April 8, 2016, the Additive Manufacturing facility (AMF), a commercial printer owned by MIS. Upgrades included [9]:

- Capability to print with multiple material feedstocks (three thermoplastics -- ABS, Ultem 9085, and HDPE)
- integral cameras and sensors for automated monitoring
- maintenance procedures/capability modified to reduce crew time
- leveling and calibration done with on-board systems
- build surface modified for appropriate balance between print adherence and ease of removal

MSFC has worked with MIS to have multiple functional parts and demonstration articles printed on ISS as described in reference 1. The AMF mounted in an EXPRESS Rack on the International Space Station is shown in the photograph in Figure 5 with the Multipurpose Precision Maintenance Tool, winning design in the Future Engineers Space Tool Challenge, floating in front.



Figure 4. Photo of AMF on ISS with printed multipurpose tool floating in front (photo courtesy of MIS)

MSFC has also initiated materials а characterization task with MIS to develop baseline design mechanical properties (design values) on the ABS material used in the Additive Manufacturing Facility. ABS has been selected initially to provide comparison with the results from the ISS 3DP printer flight experiment described above. Comparative analysis of ground and flight prints include: photographic/visual inspection, mass measurement, structured light scanning, optical microscopy, mechanical testing, and Fourier Transform Infrared Spectroscopy (FTIR). The mechanical property test matrix is shown in Table 1 [10].

AMF Mechanical	Property Te	st Matrix	ASTM #	Properties
Type, Orientation	Qty (ground)	Quantity (flight)		
Tension, 0	10	10	D638	Modulus, strength, strain, Poisson's
Tension, 90	10	10	D638	Modulus, strength, strain
Compression, 0	10	10	D695	Modulus, "strength," strain
Compression, 90	10	10	D695	Modulus, "strength," strain
Tension, +/-45 (shear)	10	10	D3518	Modulus, strength, strain, Poisson's
Flatwise tension	10	10	C297	z-direction (through- thickness) tensile strength
Range coupon	2	2	n/a	n/a
EMU fan cap	1	1	n/a	n/a
Total	63	63		

Table 1. AMF Test Matrix*

Tethers United, Inc. (TUI). The system has completed environmental testing at MSFC and is scheduled to launch to ISS in November 2018. This technology is the first meaningful step toward a closed-loop manufacturing system, enabling use of polymers which would otherwise represent nuisance/trash materials on a space mission to minimize the use of external resources. This ISS Technology Demonstration will demonstrate the process of fabricating parts using Ultem 9085, recycling them back into useable filament, and printing new parts from the recycled feedstock. [11]. "Refabricator will complete seven printing/recycling cycles. Each printing cycle will produce tensile specimens (for downmass) and a block to serve as the input material for the recycler. Each recycling cycle will produce filament for further printing; some filament from each cycle will remain on the spool for further analysis. Following Phase I payload operations, material specimens will be returned to Earth for testing and evaluation, including mechanical testing and chemical analysis" [10] to assesss the effects of microgravity on the recycling process and the consistency of materials produced over multiple cycles on-orbit. The flight unit is shown in Figure 5.



Figure 5. Refabricator flight unit in preparation for environmental testing at MSFC 2.3.1 Second Generation Recycler: Erasmus

*All tests are at room temperature.

Initial nondestructive characterization has begun at MSFC and complete results are planned to be reported at the 70^{th} IAC.

2.3 Recycling Plastic Materials: Refabricator

The Refabricator is the first repeatable process integrating printing and recycling of plastics for the microgravity environment. It was developed through a Small Business Innovative Research (SBIR) award to Erasmus, also an SBIR award to TUI, will be the next generation for closed-loop recycling during space missions and may result in the first-generation Exploration recycling system. Erasmus builds on lessons-learned from the Refabricator, while also incorporating the additional capability of sterilization. Erasmus integrates a plastics recycler, dry heat sterilizer, UV sanitization routine, and 3D printer to create a system that will enable use of recycled materials for medical-grade and food-safe applications on ISS [12]. Erasmus accepts previously-used plastic waste and parts, sterilizes these used materials, recycles them into food-safe and medical-grade 3D printer filament, and 3D prints new plastic implements. The ability to sterilize plastic materials will enable the re-use of plastic materials that are typically trashed after a single use, without worry of bacterial or viral contamination. The ability to recycle/re-use food containers and implements, as well as medical implements, will significantly decrease the amount of trash produced, while greatly increasing useable feedstock for manufacturing new and/or different items [10]. An ISS technology demonstration of Erasmus is targeted in the 2020 – 2021 timeframe.

2.4 The Next Step: Fabrication Laboratory (FabLab)

In 2017, the In Space Manufacturing project issued a Broad Area Announcement (BAA) for a multimaterial, multi-process fabrication laboratory for ISS [13]. The minimum capabilities for the FabLab, as set forth in the broad agency announcement are outlined below:

- On-demand manufacturing of metallics and other materials in the microgravity environment
 - Includes safety, waste management, and containment of debris
 - Ability to process a range of metals for in-space applications
 - Ability to operate in a reduced gravity environment
- Minimum build envelope of 6"x6"x6"
 - Internal or external build envelope that is as large as possible
 - High geometric part complexity and accuracy
 - Ability to fit within EXPRESS rack constraints (ex. power, mass, volume)
- Earth-based remote commanding
 - Remote commanding for all nominal tasks, including part removal and handling
 - Post-processing requirement on crew for part readiness should be minimized
- In-line remote/autonomous inspection and quality control
 - Incorporate inspection/verification capabilities to ensure quality control (assess tolerances, voids, etc.)
 - Metallurgical quality of finished part

As is clear from the requirements, the key features of the FabLab are (1) ability to print with multiple materials, specifically including metals; (2) remote commanding from Earth, specifically to encompass finished part removal and handling; and (3) take

advantage of the terrestrial developments in the area of in-line inspection to provide part quality control. A phased development is planned, during which FabLab will mature into a flight demonstration onboard the International Space Station. The objective of the first phase (Phase A), is to demonstrate a scalable groundbased prototype of a Fab Lab system in order for NASA to better assess and facilitate development of the technologies to a flight opportunity. The period of performance for Phase A is 18 months from authorization to proceed. The objective of Phase B is to further mature the highest potential technologies developed in Phase A to a pre-flight deliverable. Phase C will be a flight demonstration on ISS to demonstrate the feasibility of this ISM system, to fully the categorize the risk to crew, and to develop, refine and create standards for the manufacturing processes and properties of materials produced in a controlled microgravity environment. [14].

Three companies were competitively selected for Phase A awards: Interlog Corporation of Anaheim, California; Techshot, Inc. of Greeneville, Indiana; and Tethers Unlimited, Inc. of Bothell, Washington [15]. Companies who did not participate in Phase A are eligible to participate in subsequent phases of the Fabrication Laboratory development. Concepts for each of these teams are shown in Figure 6.



Figure 6. Phase A Selectees' Concepts for FabLab

2.5 Additional In Space Manufacturing Portfolio Elements

2.5.1 Metals Printing and Hybrid Manufacturing

2.5.1.1 Vulcan Advanced Hybrid Manufacturing System from Made in Space

MIS completed the Phase I SBIR in December 2017. The system includes fused filament fabrication (FFF), a weld-based additive manufacturing process for metal fabrication, a CNC mill for processing, and an

automated capability for movement of the part between subsystems [16]. Phase I consisted of extensive trade studies for the system and its manufacturing processes/materials, initial material evaluations, and demonstrations of constituent subsystems, including a chip capture system for debris generated during the manufacturing process. Phase II work includes design, construction, and testing of an integrated, prototype unit to perform hybrid manufacturing functions.

2.5.1.2 ISS Fabrication Laboratory using Ultrasonic Additive Manufacturing Technology from Ultra Tech Machinery

Ultra Tech Machinery completed the Phase I SBIR in December 2017. In the Phase I effort, Ultra Tech and subcontractor Fabrisonic, Inc. designed and tested a sonotrode which reduced process forces to enable design of a system compatible with ISS requirements. Phase I also included design of a motion system for the integrated development unit (which includes a CNC), FEA analysis to size components for the eventual system, and a study of the characteristic size of chip debris. Early tests of the prototype system demonstrated quality welds in 6016 T6 and 7075 T6 and enabled material production at significantly lower power and forces. Development of the Phase II system, currently underway, includes the addition of a CNC mill head to enable finishing of parts [8].

2.5.1.3 Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA) Process from Tethers Unlimited

Tethers Unlimited concluded Phase I SBIR in December 2017. MAMBA combines three technologies to provide a precision metallics manufacturing capability for ISS: a press that processes virgin or scrap material into a metal ingot, a CNC mill designed to operate in microgravity, and a robotic assistant to facilitate automated processing of material/parts through the subsystems [17]. MAMBA applies the same Positrusion process used to recycle plastics in the Refabricator to aerospace grade metals. Phase II work will focus on development of the integrated prototype system.

2.5.1.4 Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) from Techshot

Techshot is developing a 3D metal printer under a Phase II SBIR in which a ferromagnetic wire metal filament is heated to its Curie temperature through induction and deposited on a build platform where a low power laser completes the melt [18].

2.5.2 Common Use Materials

The ISM initiative is also supporting SBIR projects to develop "common use" materials for launch packaging. The objective of the research efforts is to design materials for packaging that are intended to be recycled and reused, thereby transforming unused or waste materials, which would otherwise be trash, into an in situ resource to support on-orbit fabrication. There are two SBIR's that are currently in Phase II extensions. 2.5.2.1 Customizable Recyclable International Space Station Packaging (CRISSP) from Tethers Unlimited

The CRISSP Phase II effort matured recyclable launch packaging materials to enable sustainable manufacturing and reuse of otherwise nuisance materials on deep space missions [19]. Tethers developed a customizable material that can provide tailorable vibration protection against launch loads and which is constructed from recyclable materials. The CRISSP Phase II-X effort focuses on redesign and upgrade of TUI's Refabricator system for multi-material capabilities. This effort will increase the number of materials that can be recycled into feedstock filament and re-printed with the system [8].

2.5.2.2 Reversible Copolymer Materials for FDM 3-D Printing of Non-Standard Plastics from Cornerstone Research Group (CRG)

The CRG Phase II developed thermally-reversible polymer materials compatible with fused filament fabrication (FFF) 3D-printing systems [20]. These materials are designed to be recycled, blended, and extruded. Additives can also be combined with existing waste packaging, enabling reclamation of filament for additive manufacturing from packaging materials. In the Phase II-X effort, CRG will conduct further characterization of their thermally reversible material and scale the associated polymer resin production and packaging production processes [8].

2.5.3 Printed Electronics

Historically, many ISS system failures are electronic in nature and the ability to repair or fabricate electronics would be a highly desirable capability for a crewed space missions [21]. Marshall Space Flight Center is utilizing an nScrypt printer to explore the potential of additive electronics for future space mission applications. One of the most novel uses of the nScrypt unit to date is in additive production of a wireless sensor archetype. Wireless sensing networks represent an important focus area for space technology development, as these sensors are key to reducing mass associated with wiring, connectors, brackets and other mechanical parts.

Additional work toward development of an additive electronics capability for ISS is being conducted by Techshot, Inc. and Optomec. Techshot, Inc., in collaboration with nScrypt, is developing the Software and Tools for Electronics Printing in Space (STEPS) as part of a Phase I SBIR. STEPS is a direct write and avionics printing capability for circuits, antennas, and circuit layouts. In another funded Phase I SBIR, Optomec is adapting its patented Aerosol Jet technology for Additive Manufacturing of electronics through the addition of an Adaptive Laser Sintering System (ALSS) module. ALSS can significantly reduce thermal damage to low Tg polymer substrates (such as acrylic, PET, etc.) during sintering of the metal inks, which is a current issue in additive electronics manufacturing. [1,8, 16].

2.5.4 In-situ Quality Control

In-situ monitoring, real time feedback controls, and on-line quality control technologies are needed for both terrestrial-based and in space-based AM to help ensure repeatability in the manufacturing process and the resulting parts. The traditional post-process inspection, qualification and certification processes may be difficult for ISM due to constraints on crew time and equipment limitations. Online quality control (i.e. process monitoring, where in situ monitoring of process signals provides information about the quality of a part produced by a manufacturing process) is of significant benefit in the absence of the capabilities to complete the traditional processes. Qualification and certification processes for ISM will require better machine and feedback control than is currently available with off the shelf printers. While traditional approaches to qualification and certification are also being pursued, a more immediate solution is online/off-line quality control techniques that are uniquely adaptable to ISM. ISM is supporting three projects on real-time, in situ quality assurance of AM parts manufactured in the space environment that were selected under an SBIR Phase I project call in 2018 [8].

3. In Space Robotic Manufacturing and Assembly: A Technology Demonstration Mission

Space NASA's Technology Mission Directorate (STMD) is responsible for developing the crosscutting new technologies and capabilities needed by the agency to achieve its current and future missions. The Technology Demonstration Mission (TDM) program is an element of STMD that is managed by NASA's Marshall Space Flight Center. The TDM projects are helping bridge the gap between scientific and engineering challenges and the technological innovations needed to overcome them. In October 2016. STMD awarded three Broad Area Announcement proposals called "tipping point" projects. A "tipping point" project is defined by STMD as the point at which an investment in a ground development/demonstration or a flight demonstration of a space technology will result in a significant advancement of the technology's maturation, a high likelihood for utilization in a commercial space application, and a significant improvement in the offerors' ability to successfully bring the space technology to market. The selected projects focused on the technologies needed to assemble and manufacture complex systems in space without astronaut extra-vehicular activity, such as large structure assembly, satellite servicing, and even repurposing of satellites [1, 22]. The three projects have

completed their two-year ground based risk reduction efforts. The visions for these three concepts, team membership, and objective summaries follow.

Archinaut: A Versatile In-Space Precision Manufacturing and Assembly System. Made In Space is Project Lead with team members Northrop Grumman Corp., Oceaneering Space Systems, and Ames Research Center. The vision for Archinaut was to develop a system that robotically creates spacecraft and extremely large structures in space which reduces spacecraft cost, reduces limitations rocket launch places on spacecraft design (launch loads and volumes), and removes astronauts from harm's way. The objectives were the following:

- Demonstrate extended structure additive manufacturing of structures in a relevant environment using Extended Structure Additive Manufacturing Machine (ESAMM).
- Demonstrate additive manufacturing and robotic assembly of structures in a relevant environment using Ground-Based Manufacturing and Assembly System Hardware (GBMASH).
- Evaluate part quality through mechanical and structural testing.

MIS completed their ground-based risk reduction objectives in late summer 2018, including printing of the "world's longest printed non-assembled piece" of 37.7 meters. [1, 22]. The concept In Figure 7 depicts Archinaut manufacturing a large antenna structure.



Figure 7. Archinaut Concept by Made In Space

CIRAS: A Commercial Infrastructure for Robotic Assembly and Services.

Northrop Grumman Innovation Systems (NGIS), formerly Orbital ATK, is the Project Lead with team members Glenn Research Center, Langley Research Center, and the Naval Research Laboratory. The vision for CIRAS was to develop a robotic assembly, repair, maintenance and refurbishment capability to enable satellite servicing and large space structure assembly. The objectives were the following:

- Demonstrate long reach and near-field robotic assembly of structures
- Demonstrate methods for reversible mechanical and electrical connection between modules.
- Develop a feasible concept to measure accuracy of assembled structures (i.e. metrology)
- Demonstrate low mass, rigid, reversible structural joining methods (i.e Electron Beam Welding)

NGIS completed their ground-based risk reduction activities in late summer 2018, including maturing fourteen technology elements of CIRAS to TRL 4 or 5. [1, 22]. The CIRAS concept grappling a large satellite for servicing is shown in Figure 8.



Figure 8. CIRAS Concept by Northrop Grumman Innovation Systems.

Dragonfly: In Space Robotic Manufacturing, Assembly, and Reconfiguration of Large Solid Radio Frequency (RF) Reflectors.

Space Systems/Loral is Project Lead with team members Langley Research Center, Ames Research Center, Tethers Unlimited, MDA US & Brampton. The Dragonfly program objective was to demonstrate the following:

- Effective stowage techniques for large solid reflectors
- Assembly interfaces originally designed for EVA operations can be modified for use robotically
- Antenna support structures meet extremely high performance requirements
- Feasible Con Ops for augmenting an existing Geostationary Earth Orbit (GEO) Commercial Satellite

The Dragonfly risk mitigation efforts, also completed in

summer 2018, were to enable the development and demonstration of a robust in-space assembly operating concept using existing robotic and assembly interface technologies in a high fidelity ground testbed [1, 22]. For the Dragonfly concept shown in Figure 9, an ultralightweight robot assembles a large reflector on a communications satellite in GEO.



Figure 9. Dragonfly Concept by Space Systems/Loral

4.0 Additive Construction

MSFC began development of additive construction technologies in 2004. A Lunar Concrete Crafting (LCC) Technology Roadmap was formulated for the In Situ Fabrication and Repair Program Element for NASA's Human Systems Research and Technology Office. As noted previously, the Agency priorities changed in 2005 and the LCC technology development was subsequently terminated, but not before MSFC gained valuable experience in "printing" with lunar regolith simulant-based concrete [1, 23].

A second opportunity to develop additive construction technology for extraterrestrial surfaces occurred in 2014. Professor Behrokh Khoshnevis at the University of Southern California, who developed the contour crafting nozzle for the LCC, contacted MSFC about the possibility of working with the U.S. Army Corps of Engineers on additive construction technology development. Discussions with representatives of the Corps of Engineers Construction Engineering Research Laboratory - Engineer Research and Development Center (CERL-ERDC), Dr. Khoshnevis, subject matter experts in regolith excavation and transport at Kennedy Space Center resulted in an additive construction proposal that was jointly supported by NASA's STMD (Additive Construction with Mobile Emplacement (ACME)) and CERL-ERDC (Automated Construction of Expeditionary Structures (ACES)). Development work began in 2015 and early project development activities are described in references 24 and 25. Series

of basic materials work were conducted for terrestrial materials at CERL-ERDC, and Martian soil simulantbased materials at MSFC. Excavation, transport and delivery of dry goods materials capabilities and hardware were developed at KSC. Hardware development for both ACME and ACES proceeded in phases. Initial work at MSFC focused on refurbishment and reactivation of the small gantry system originally developed under the initiative. Following the initial proof of concept prints, the delivery system was scaled up to a robot arm system. At the time, a trade study was ongoing to assess whether to proceed with scale-up of a gantry system or robot arm delivery system for the third and final phase of development. The decision was made, driven primarily by the CERL-ERDC requirements, to scale up to a gantry mobility system. The resulting gantry system, constructed to meet the CERL-ERDC requirements for construction of a B-hut (16' X 32'), is shown in Figure 10. As shown, the hardware components are at CERL-ERDC in preparation for demonstration prints planned to occur in the fall of 2018.



Figure 10. Additive Construction Technology Development for Planetary and Terrestrial Applications Joint Project Between NASA and U. S. Army Corps of Engineers Construction Engineering Research Laboratory – Engineer Research and Development Center (CERL-ERDC)

5.0 Additive Manufacturing for Rocket Propulsion Systems

Although Marshall Space Flight Center performed various metallic Additive Manufacturing development activities throughout the late 1990s and early 2000s, including work with Laser Engineered Net Shaping, Ultrasonic Object Consolidation, and Electron Beam Manufacturing, development efforts focused on additive manufacturing for liquid rocket propulsion systems did not begin until 2011. However, the intensity of these efforts ramped up quickly. By late 2012, trade studies had been performed to select the concept for the design, development, test, and evaluation of a prototype in-space class additively manufactured demonstrator engine (AMDE). The project officially began in October 2013 [26]. MSFC had also begun to work closely with the RS-25 engine contractor to explore the potential application of additive manufacturing capabilities to support the affordability strategy. The status of those efforts are summarized in the following sub-section. In addition, the lessons learned and experience gained through the development of MADE have been applied to propulsion systems for small spacecraft, as will be summarized later in this section. *5.1 Space Launch System (SLS) Core Stage Engine: RS25*

Concurrent work is under way on developing a new more affordable, expendable variant of the RS-25, the core stage engine for the Space Launch System, which would cost at least 30 percent less and can operate at thrust levels slightly higher than the Space Shuttle Main Engine (SSME). The RS-25 incorporates new materials and new manufacturing processes, as well as new technology like additive manufacturing (AM). The initial applications for AM are typically static, non moving parts, but they demand the same pedigree as the more complex parts as they are still operating in one of the most extreme environments in the world and in a human-rated engine. The goal is to develop additive manufacturing technologies (specifically Powder Bed Fusion and larger scale additive manufacturing technologies) as reliable and routine alternatives to traditional manufacturing methods for hardware in human-rated space propulsion systems. MSFC is actively building hardware in-house, procuring parts from independent vendors, and conducting performance testing. The first test of an AM component, a 3D printed pogo accumulator which eliminated 122 welds, was hot fired on a ground test engine in early 2018. The MSFC Liquid Engine Office (LEO) is helping support MSFC AM work.[27]

5.1.1 Foundational Work

MSFC has invested in 5 powder bed SLM machines with the primary focus of certifying nickel based alloys for flight and developing new alloys, such as Hanes alloys and tungsten. Specific areas of emphasis include: (1) material properties development; (2) nondestructive inspection capabilities; (3) new material development such as copper-alloys and refractory metals. In order to accomplish these developments, MSFC has created a database for extensive tracking of powder, machine, and process parameters to aid in analysis and performed DOE's to determine sensitivities of machine parameters on material properties. Round-robin comparisons were also performed with various vendors to benchmark the MSFC results [27].

5.1.2 Advancing Technology Readiness

NASA MSFC is leading additive manufacturing applications for rocket propulsion systems and development of flight certification standard and specification, as described in a later section. Much of the in-house experience has come from the development and testing of the Additive Manufacturing Demonstrator Engine described in the following section. Throughout this design, development, test, and evaluation (DDT&E) process, MSFC continues to develop and apply unique additive manufacturing techniques including laser-wire additive for use on rocket components such as nozzles; bimetallic additive manufacturing to optimize material properties where needed such as combustion chambers and spark ignition systems; and investigating hybrid additive and subtractive manufacturing solutions to offer interim machining in a single setup. In addition to the design and manufacturing of the components, MSFC has accumulated well over 15,000 seconds of hot-fire time on various additive components including injectors, nozzles, augmented spark ignition systems, and more than 15 combustion chambers. The experience and expertise gained through this DDT&E process is serving as a valuable resource to industry and our RS25 contractor [27].

5.1.3 Advancing Scale

Scale of additive manufacturing is a current focus area, The RS-25 is a large engine with many components well beyond the build volume of current state-of-the-art selective laser melt (SLM) machines. NASA has researched a variety of large scale techniques for liquid rocket nozzles and other applications. Techniques include: blown powder deposition (LENS, LFMT, DED); wire-based freeform deposition (LMD, LDT); arc-based wire deposition (MDDM, Arc-DED); electron beam freeform deposition (EBF^3); and laser hot-wire and hybrid technologies [28,29,30]. See examples in Figure 11. Depositing large scale parts in nickel based superalloys in days allows for potential replacement of forgings or castings with a significant reduction in schedule. The MSFC LEO is working with NASA's Space Technology Mission Directorate to further develop large scale additive manufacturing capabilities as applied to rocket engines [27].

Flexibility inherent in the AM technologies increases design freedom and enables complex geometries. Designers can explore lightweight structures; integrate functionality; customize parts to specific applications and environments. Additive manufacturing for RS-25 is a game changing capability for cost/schedule reduction [27].





Figure 11. Examples of large scale additive deposition technologies evaluated for nozzle applications.

5.2 In Space Class Prototype Engine Development: Additive Manufacturing Demonstrator Engine (AMDE)

MSFC began performing trade studies in late 2012 to select the engine concept for the Additively Manufactured Demonstrator Engine (AMDE), a cost effective prototype engine whose basic design could be used as the first development unit for an upper stage or in-space-propulsion class engine. The project officially began in October 2013. The overarching purpose of the project was to exercise a new Design, Development, Test, and Evaluation (DDT&E) philosophy, a concurrent development model, to get hardware into test early and enabling multiple "analyze-manufacture-test" cycles using additive manufacturing to reduce part costs, fabrication times, and overall part counts. Within one year, each of the major components had completed a Preliminary Design Review (PDR); a subscale injector was successfully hot fired; a preliminary engine layout was established: and the engine PDR had been conducted. Development continued over the following three years, with more than 150 rocket engine parts designed and additively manufactured, encompassing every major component and assembly of the engine. The final component of the engine, the liquid oxygen turbopump arrived earlier in 2018 and is currently being tested in the MSFC test area (See Figure 12). A more detailed summary of the AMDE DDT&E efforts can be found in reference 26.



Figure 12. AMDE Oxygen Turbopump in preparation for test.

NASA and MSFC also invested in development of the capability to use copper as a feedstock for Additive Manufacturing of Main Combustion Chambers (MCC). The Low Cost Upper Stage-Class Propulsion Element (LCUSP) was a 4-year project element under the Advanced Manufacturing Technology (AMT) project within the Game Changing Development Program Office of the NASA Space Technology Mission Directorate. LCUSP developed a copper alloy additive manufacturing process and a bimetallic process to bond a Nickel alloy to the copper alloy. This included process development using Selective Laser Melting (SLM) of GRCop-84, a Glenn Research Center (GRC) developed copper alloy; and Electron Beam Freeform Fabrication (EBF³) of the Inconel 625. The combination of the two materials and processes were demonstrated by successful hot-fire tests. Additionally, materials properties characterization was completed to allow designers to utilize these new materials. LCUSP also fabricated a methane-cooled SLM GRCop-84 thrust chamber and performed a hotfire test with the chamber. This was the first regeneratively-cooled methane coolant SLM copper alloy thrust chamber to be successfully tested. LCUSP has transferred the additive manufacturing process using GRCop-84 developed at MSFC and the materials property data collected by GRC to industry where NASA can now procure a SLM GRCop-84 chamber commercially [31].

The AMDE team achieved dramatic reductions of the Design, Development, Test and Evaluation cycle. The concurrent development model enabled engineers to get their components into testing early in the design cycle enabling rapid iterations to incorporate design improvements. At present, the components of MADE are being prepared for engine assembly operations preceding complete engine test series. A mock-up of the assembly is shown in Figure 13. Future applications of this philosophy are expected to include methane propulsion systems for landers and in space propulsion systems, nuclear thermal propulsion systems, upper stage engines, and the next generation of human-rated space flight engines, as described previously.



Figure 13. Assembled Mock-up of AMDE in the MSFC Engine Lab.

5.3 Small Sat Propulsion Components Development

Lessons learned from the development of the AMDE were applied to the development of propulsion components for small spacecraft. Design of components for CubeSats began in late 2015, with the initial component being a conformal propellant tank. Following the successful fabrication and proof test of the propellant tank, efforts began to design and print small thruster pathfinder parts for proof of concept. These AM pathfinders and component-level tests proved successful and designs then focused on flightlike thruster elements, injectors, reactors, thermal standoffs, and propulsion modules. Design for additive manufacturing techniques were employed to (1) create integral flow passages; (2) utilize mesh structures; (3) topology optimization for light weight and conformal structures; and (4) minimize support materials. The resulting components and assembled thruster in the test rig are shown in Figure 14 [32, 33]. The purposes of this initiative were to 1) adopt and innovate with AM technology for in-space propulsion system; aligning those efforts with NASA's technology roadmaps, 2) develop and test an in-house flight-like proof-ofconcept CubeSat propulsion module with a green propellant for the purposes of manufacturing process definition and TRL maturation, and 3) facilitate knowledge growth and exchange through hands-on task, publication, and partnership.



Figure 14. Small Spacecraft Propulsion Additively Manufactured Test Hardware.

6. NASA's Plans for Development of Standards for Additive Manufactured Components

Certification of additively manufactured components is the subject of discussion in most, if not all, Additive Manufacturing conferences and symposia. Certification is an industry-wide, AM community-wide challenge. Standards development organizations have been working to formulate such standards, with ASTM Committee F42 on Additive Manufacturing taking early leadership. Additional standards organizations that are also working on AM Standards include SAE, AMS, AWS, MMPDS and others. Recently, America Makes and the American National Standards Institute (ANS have released their Standardization Roadmap for Additive Manufacturing (Version 2.0) that was produced by America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC). AMSC is a group of over 300 individuals from more than 170 public and private organizations working to coordinate and accelerate industry-wide additive manufacturing standards and specifications [34].

NASA partners in human-rated space flight programs, Commercial Crew, Space Launch System, and Orion, are actively developing AM components with flight possibly as early as 2018 [1, 35]. For reasons of the clear and immediate need to provide standardization for consistent evaluation of AM processes and components in critical applications, NASA has not been able to wait on America Makes or other national standards organizations to develop AM standards. To bridge this gap, AM subject matter experts at MSFC, in discussions with counterparts in industry and partner organizations, created a draft certification framework entitled "Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware" in late 2014 [1, 36]. The draft was widely circulated for peer review to other NASA Centers; NASA Engineering and Safety Center; industry partners such as Aerojet Rocketdyne, SpaceX,

Boeing, Lockheed Martin; GE, Honeywell, Aerospace Corporation; and certifying Agencies such as the Federal Aviation Administration, United Stated Air Force, and Office of Naval Research. More than 1000 comments were received. Most importantly, the draft also served to shape the approach to additive parts for current human-rated space flight programs, the Commercial Crew Program and the Space Launch System [1, 37].

The original draft standard document was revised and separated into two documents: "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals," [38] and "Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes," [39], which were formally released by MSFC in October 2017.

The purpose of the technical standard (MSFC-STD-3716) is twofold: first, to provide a defined system of foundational and part production controls to manage the risk associated with the current state of L-PFB technology, and second, to provide a consistent set of products the cognizant engineering organization and the Agency can use to gauge the risk and adequacy of controls in place for each L-PFB part [38]. MSFC-STD-3716 lists 65 unique Additive Manufacturing Requirements (AMRs) covering:

- Foundational controls
- Material property requirements
- Design and assessment
- Fundamentals of part production controls
- Post-build operations
- Part inspection and acceptance

Materials properties – Design values Material properties are tracked continuously and used to set witness test acceptance criteria. A Qualified Metallurgical Process is utilized to develop a Process Control Reference Distribution (PCRD) of material properties that reflects not the design values, but the actual mean and variability associated with the controlled AM process. Parts are accepted based on comparison to PCRD, not design values. The approach allows for adoption of new processes without invalidating large allowables investments [37]. All AM parts are assigned a classification. "Part classification is required to enable a consistent evaluation of part risk through defined metrics for consequence of failure, structural demand, and L-PBF associated risks. Without carefully defined part classes, the ability to efficiently and accurately gauge the risk associated with L-PBF parts within and across programs, projects, and suppliers is lost, resulting in risk mitigations that are either not commensurate or not consistent" [38].

The MSFC-STD-3716 delivers:

Certified/Qualified materials

- o Statistical basis
- Certified/Qualified process
 - Process control
 - Material property evaluation
 - Womb to tomb
 - o Statistically substantiated
- Certified/Qualified NDE
 - Statistical basis
 - \circ Tied to Fracture Criticality
- Certified/Qualified design
 - Supported by part classification [40]

The technical specification MSFC-SPEC-3717 is an applicable document to MSFC-STD-3716. MSFC-SPEC-3717 lists 45 unique Process Control and Qualification Requirements (PCQRs) covering:

- Metallurgical process definition
- Qualification of metallurgical processes
- Equipment and facility process control

This specification defines procedural requirements for foundational aspects of process control in L-PBF: definition and qualification of the L-PBF metallurgical process; maintenance, calibration, and qualification of L-PBF equipment and facilities; and training of personnel for L-PBF operations [39]. Laser Powder Bed Fusion Metallurgical Process Qualification definition includes powder feedstock specification, fusion controls (L-PBF machine parameters and operating conditions), and thermal processes [37, 39]. Qualification of the metallurgical process includes requirements for microstructural quality, tolerance to process variations, surface texture, and mechanical properties [37, 39].

Although the MSFC standard was written specifically for the Laser Powder Bed Fusion process it's principles can be applied to any AM process for the purpose of certification [40]. The Materials Technical Fellow of the NASA Engineering and Safety Center (NESC) has formed a team to explore the creation of Agency Standards and Specifications for Additive Manufactured (AM) components. This team includes representatives from nine NASA centers along with representatives from the FAA, Air Force, Navy and Army. The intent is that these documents will be Agency policy for AM. The standards will create requirements with tailoring guidance that can be used to develop process specifications and manufacturing plans for both general and specific applications. The team decided that three separate standards should be created: (1) Manned Space Flight; (2) Non-Manned Space Flight; and (3) Aeronautics. The team has developed a schedule calling for several iterations of the standards with Agency-wide review starting in late 2020 [40].

7. Summary

The Marshall Space Flight Center has been working to develop In Space Manufacturing capabilities since the first reduced gravity flight experiments in 1999. The rationale for this capability was recognized prior to that time and was the genesis of the flight experiment. It is only within the past 5 years that this initiative has begun to gain traction and resource support. However, the NASA Space Technology Mission Directorate has recently identified In Space Manufacturing and On-Orbit Assembly as one of its eight Key Technology Focus Areas. Although the rationale for the benefits of in space manufacturing for deep space human exploration missions has not been described within this paper, the interested reader is directed to the outstanding systems analysis by Owens and deWeck [41], which provides an excellent assessment and detailed explanation of the benefits of ISM for deep space human exploration. They conclude that "ISM has the potential to significantly reduce maintenance logistics mass requirements by enabling commonality of material, as well as opening the possibility of material recycling and ISRU for spares" [41]. Their results "indicate that if a manufacturing capability can be developed to enable on-demand, adaptable production it could have significant implications on risk and logistics for future exploration missions" [41]. "However, failure to incorporate design for maintainability in the initial design process will significantly impact the capability to achieve the logistics mass reduction and commensurate reduction in risk that ISM can enable. This disruptive change will require a major paradigm shift to current design practices" [1].

NASA is actively working with industry partners to develop ISM capabilities in three primary areas: (1) Within the Pressurized Volume: Reduce the logistics challenges and keep astronauts safe and healthy in transit and on extraterrestrial surfaces (tools; spares; food-safe and medical-grade applications); (2) In Space Robotic Manufacturing and Assembly (IRMA): Add new commercial capabilities in spacecraft construction, assembly, and repair in LEO; and (3) Additive Construction: Enable infrastructure (landing pads, berms, roads, habitats, etc.) to be robotically constructed prior to the arrival of astronauts on the extraterrestrial surface, whether that be the Moon or Mars.

MSFC has made a major thrust and is leading development and application of additive manufacturing for rocket propulsion systems. The Space Launch System Liquid Engine Office recognized that the flexibility inherent in the AM technologies increases design freedom and enables complex geometries, allowing designers to explore lightweight structures; integrate functionality; and customize parts to specific

applications and environments. This flexibility can result in reduced part counts, reduced welds, and fewer machining operations, all of which can save cost and schedule. To this end, MSFC has and continues to provide the foundational basics for rocket propulsion applications including materials properties databases, inspection capabilities and new materials development, such as copper alloys. These efforts are advancing the technology readiness levels by taking multiple components through the complete design cycle including hot fire testing, The current focus is on large scale AM technologies for those components that are larger than current build volumes. Concurrent with RS-25 support activities, MSFC engineers successfully exercised a new DDT&E philosophy, a concurrent development model, to build and test AMDE, a prototype in-space class engine which demonstrated significantly reduced costs, schedule and parts counts. Data, experience, and the testbed have been shared with industry for current and future developments. Capabilities developed through AMDE experience have been extended to small satellite propulsion systems components. By embracing design for additive manufacturing techniques, novel designs are being created. These developments are paving the way for incorporation AM and the DDT&E philosophy for future space propulsion systems.

NASA MSFC released MSFC-STD-3716 "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals," and MSFC-SPEC-3717, "Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes," in October 2017. These documents provide a standardized methodology for consistent evaluation of AM processes and components, which are being developed for SLS and Commercial Crew Programs and are being used on commercial launch systems. Although the MSFC standard was written specifically for the Laser Powder Bed Fusion process it's principles can be applied to any AM process for the purpose of certification [40]. The NASA Engineering and Safety Center (NESC) has formed a team, including representatives from nine NASA centers, the FAA, Air Force, Navy and Army, to explore the creation of Agency Standards and Specifications for Additive Manufactured (AM) components. The team is working towards the creation of three separate standards: (1) Manned Space Flight; (2) Non-Manned Space Flight; and (3) Aeronautics with a schedule indicating Agencywide review starting in late 2020 [40].

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