ISS National Laboratory

CENTER FOR THE ADVANCEMENT OF SCIENCE IN SPACE

2020 International Space Station U.S. National Laboratory Additive Manufacturing in Space Workshop

Virtual Event Discussion Summary

September 10, 2020

The 2020 International Space Station (ISS) U.S. National Laboratory Additive Manufacturing in Space Workshop held on July 28, 2020 was hosted by the Center for the Advancement of Science in Space (CASIS), manager of the ISS National Lab.

Contents

About the Organizer:

In 2005, Congress designated the U.S. orbital segment of the ISS as the nation's newest national laboratory to optimize its use for improving the quality of life on Earth, promoting collaboration among diverse users, and advancing science, technology, engineering, and mathematics (STEM) education. In 2011, the Center for Advancement of Science in Space (CASIS), a nonprofit, nongovernment organization, was selected as manager of the ISS U.S. National Laboratory. This unique orbiting laboratory is available for use by non-NASA U.S. government agencies, academic institutions, and the private sector, providing access to a permanent microgravity research environment, a powerful vantage point in low Earth orbit, and the extreme and varied conditions of space. To learn more about the ISS National Laboratory, visit www.ISSNationalLab.org.

I. EXECUTIVE SUMMARY

The 2020 International Space Station (ISS) U.S. National Laboratory Additive Manufacturing in Space Workshop was a virtual event held on July 28, 2020. Workshop objectives included a discussion of 1) pathways enabling additive manufacturing in microgravity, toward potential production of new materials with enhanced properties, and 2) how ISS-based additive manufacturing can advance terrestrial manufacturing, in-space industrial production, and in-situ resource utilization. Materials research is a national priority, and as a key focus area for the ISS National Lab, CASIS holds materials-related workshops annually as part of the ISS Research and Development Conference (ISSRDC).

For the 2020 virtual workshop, CASIS invited experts in additive manufacturing and microgravity research and development (R&D) from industry, academia, and government, as well as ISS additive manufacturing service providers, to present their views on current trends, research, and challenges in a seminar-style main session. The second part of the workshop consisted of breakout sessions in three topic areas—microgravity-specific materials and processes, in-situ resource utilization, and in-space production—for small-group discussion of the workshop objectives.

Key points from main session presentations are highlighted within the body of this summary document. Below are key discussion points from the breakout sessions:

- Additive manufacturing in microgravity enables new options such as the use of soft materials (e.g., elastomers, foams, and rubbers), low-viscosity inks, and new polymer options (e.g., longer cure-time thermosets, filled polymer systems, continuous fiber reinforcement, and semi-crystalline polymers). ISS studies directed at producing materials with enhanced properties should consider these options.
- Accurate measurement of thermophysical properties and wetting behavior, enabled by microgravity studies, are essential for the modeling of additive manufacturing processes both in space and on Earth and should be a priority focus of research on the ISS.
- Additive manufacturing using a variety of recycled, onboard waste materials would provide useful data for in-situ resource utilization onboard crewed spacecraft. There is a need: 1) for in-space studies on the radiation resistance, solidification, and cooling characteristics of additive manufacturing products from in-situ, lunar regolith-type materials; 2) for processes to convert these in-situ materials into suitable additive manufacturing feedstocks; and 3) to ascertain whether such processes are plausible on the ISS.
- Novel approaches to in-space production are necessary where terrestrial systems do not readily translate to microgravity conditions. For example, metal additive manufacturing in microgravity changes product microstructure and porosity. Thus, studies should consider metal-wire (e.g., for directed energy deposition) or polymer-filament systems, along with "mixed-media" products such as fiber-reinforced plastics or metal-wire-reinforced ceramics.
- Understanding the requirements, material properties, and design options specific to space applications is important for products made and used in space, especially for large, exposed structures. Updated design tools will aid in leveraging the variety of nonuniform shapes and structures possible through space-based additive manufacturing.
- Industry and academia should work with NASA to develop standards and evaluation systems for products additively manufactured in space. R&D on the ISS can accelerate this effort, especially the development of standards and benchmark data (a need noted at several points during the workshop).

II. INTRODUCTION

Materials research on the ISS primarily takes advantage of two conditions: persistent microgravity and the harsh environment of low Earth orbit (LEO). In microgravity, gravity-driven phenomena such as buoyancy-driven fluid flows and sedimentation are nearly negligible. This presents the opportunity to clarify different effects (such as diffusion, interfacial tension, and other atomic-scale phenomena) on the formation processes and properties of materials. Moreover, using external platforms attached to the ISS, material samples can be exposed to the LEO environment to study material degradation mechanisms.

Workshop Objectives and Plan

Additive manufacturing was identified as a key topic for ISS research at the 2019 ISSRDC Materials Science in Space Workshop, which was co-sponsored with NASA. The 2020 workshop focused specifically on the topic of additive manufacturing in hopes of understanding how the ISS can best contribute to advancements in this field.

The workshop objectives were to determine pathways for additive manufacturing in microgravity to potentially produce materials with enhanced properties and to determine how ISS additive manufacturing can advance terrestrial manufacturing, in-space industrial production, and in-situ resource utilization.

CASIS invited additive manufacturing and microgravity research experts from industry, academia, and government to present their views on current trends, research, and challenges. Current operators of additive manufacturing facilities on the ISS also presented, with an emphasis on how to advance and grow space-based, industrial-scale additive manufacturing activity.

Following the presentations, attendees were invited to attend one of three breakout sessions, each focusing on a specific area of additive manufacturing in space:

- **Microgravity-Specific Materials and Processes:** Identify types of current or new additive manufacturing materials and space-based studies that have the potential to advance both space- and ground-based additive manufacturing; explore theories on how to harness the microgravity environment to achieve new materials, microstructures, and material properties.
- **In-Situ Resource Utilization (ISRU):** Identify key challenges and solutions for applying additive manufacturing to ISRU in space and in remote Earth environments.
- **In-Space Production (ISP):** Discuss the scale-up of current additive manufacturing activities on the ISS and identify any limitations and gaps in understanding.

The breakout sessions consisted of discussions in the format of a "fireside chat," with two representatives from the R&D community discussing a series of questions from a guest moderator as well as questions submitted by attendees. All attendees reconvened post-breakout, and the representatives from each breakout session presented key discussion points, which are highlighted in sections V-VII of this summary document.

III. WORKSHOP DETAILS

Agenda

The workshop was a half-day event held July 28, 2020 from 12:00 to 4:30 p.m. EDT.
Recordings of the workshop presentations are available on the 2020 Additive Manufacturing In Space Workshop webpage.

- **Welcome, Objectives & Deliverables, and Agenda**
  Etop Esen, CASIS
- **Presentation: Industry Trends in Additive Manufacturing**
  Michael Petch, 3D Printing Industry
- **Presentation: Opportunities, Innovations, and Challenges in Additive Manufacturing Technology**
  Brandon Ribic, America Makes
- **Presentation: Additive Manufacturing for Space—Large Format Additive Challenges**
  Chris Schuppe and Amber Andreaco, GE Additive
- **Presentation: Wettability and Interfacial Phenomena in Additive Manufacturing Under Microgravity**
  Amy Peterson, University of Massachusetts-Lowell
- **Presentation: Applications of In-Situ Resource Utilization in Additive Manufacturing Off Earth**
  Jennifer Edmunson, Jacobs Space Exploration Group, supporting NASA MSFC
- **Presentation: Additive Manufacturing Materials Now and in the Future**
  Bill Jarosinski, Linde
- **Presentation: The Future of Additive Manufacturing in Space**
  Rob Hoyt, Tethers Unlimited and Justin Kugler, Made In Space
- **Concurrent Breakout Sessions**
  Three discussions led by session-chairs and attended by participants
- **Overview of Key Discussion Points**
  Presented by session moderators to all attendees
- **Wrap Up and Close**
  Etop Esen, CASIS

Breakout Sessions

Microgravity-Specific Materials and Processes
Session Chair: David Johnson, Xerox PARC
Session Chair: Scott Roberts, NASA Jet Propulsion Laboratory
Moderator: Christopher Williams, Virginia Tech

In-Situ Resource Utilization
Session Chair: Jennifer Edmunson, Jacobs Space Exploration Group, supporting NASA MSFC

Session Chair: Bill Jarosinski, Linde
Moderator: Jeffrey Montes, Blue Origin

In-Space Production
Session Chair: Allison Beese, Penn State University
Session Chair: Justin Kugler, Made In Space
Moderator: Jay Sutherland, Corning

CASIS Organizing Committee
Etop Esen *(lead organizer)*
Ryan Reeves
Ken Savin

CASIS Communications Team
Amy Elkavich *(lead and editor)*
Amelia Smith
Emily Tomlin

Speaker Bios
Speaker bios are available on the 2020 Additive Manufacturing in Space Workshop webpage (see speaker bios).

IV. MAIN SESSION PRESENTATIONS

The main session presentations provided participants with an overview of current trends in the additive manufacturing industry and academic research that benefit from space, including technology development for additive manufacturing of materials and hardware, standards development, economics, and investment activity. Many of the presentations served as a technical briefing from industry leaders in additive manufacturing, highlighting challenges within the additive manufacturing industry—especially for space and remote Earth applications. Presenters were chosen to participate in the workshop based on their experience in the field of additive manufacturing, their work on the ISS, or their expertise in a related field.

Key Points Related to ISS Research

- Advancements in additive manufacturing continue globally at a rapid pace, fostered by collaborations between industry, government, and research institutions. In aerospace, trends noted by Michael Petch of 3D Printing Industry include satellite manufacturing, rocket engine components and sensors, and manufacturing of off-Earth landing systems and monitoring instruments. These application areas should be monitored (and occasionally reevaluated) for opportunities to perform targeted additive manufacturing studies on the ISS.

- Feedstock-process-structure-property relationships for a wide variety of 3D printed materials (e.g., metallic alloys, polymers, and composites) have been studied by America Makes. Brandon Ribic noted that these studies included some focus on surface tension effects and on material performance when subjected to ultraviolet degradation and high temperatures—all areas of direct ISS research interest. Analyzing the results of this research may reveal which 3D printing materials may be best suited for use in microgravity to address specific industrial design and use challenges. Additionally, ISS data on 3D printing in microgravity should be included in datasets being used for developing computational models of additive manufacturing.

- GE Additive representatives Chris Schuppe and Amber Andreaco noted that a current challenge encountered with powder bed fusion (PBF) additive manufacturing for “large-format” metal structures, such as rocket nozzles, is a necessity to print in sections and then “stitch,” or join, the printed parts. Research opportunities to explore for the ISS include studying how the joining process affects finished material properties such as fatigue capability in microgravity (to complement ground studies) and performing LEO exposure studies with PBF material samples. PBF at the large industrial scale is progressing but remains a technical challenge due to process complexity, post-print finishing requirements, and safety concerns for human operators. Addressing these issues is critical for the viability of off-Earth PBF.

- When gravity is not dominant, the forces of surface energy, diffusion, and capillarity become significant determinants of layer wettability in additive manufacturing. Amy Peterson, from the University of Massachusetts-Lowell, suggested that for material extrusion (which is currently used on the ISS), smaller thickness layers and tamping/pinning procedures could be implemented to promote wetting and coalescence of material layers. Also, a broader range of viscoelastic or viscoplastic materials than is used on Earth may be considered for microgravity 3D printing, because slumping should be less of a concern in space than it is on Earth. A PBF technique for microgravity reported in literature indicates that PBF on the ISS could be possible from a technical standpoint. However, the safety hazards of working with powder in a closed environment in microgravity, such as on the ISS, are an open area of concern. See Section V for a complementary discussion from the Microgravity-Specific Materials and Processes breakout session.

- In-situ resources encompass minerals and rocks on Earth that are also found on other planetary bodies, materials on the ISS such as waste packaging and used equipment parts, and substances produced by the ISS life support system, such as CO_2. Jennifer Edmunson of the Jacobs Space Exploration Group (supporting NASA Marshall Space Flight Center, MSFC) pointed out that it is still unclear to what extent any of these materials can be economically converted and used as 3D printing feedstocks. Additive manufacturing studies of recycled waste materials onboard the ISS may partly address this question, and exposure to the LEO environment outside the ISS may further test the durability of the resulting 3D printed materials. For ISRU on other planetary bodies using regolith-type materials, material conversion processes used on Earth should be tested to determine whether they are suitable for reduced-gravity operations or whether new technologies and materials are required. See Section VI for a complementary discussion from the ISRU breakout session.

- The evolution of material formulations and processes for the manufacture of heavy metal (e.g., nickel, iron, and cobalt) alloy powders was described by Bill Jarosinski of Linde. These powders were traditionally used as coatings to withstand oxidation, corrosion, and high-temperature impacts on jet engine components. More recently, the technology has been leveraged to make metal alloy powders with tailored material compositions for laser PBF. However, aspects of this technology are gravity dependent, and Jarosinski's presentation underscored challenges associated with trying to adapt known Earth-based processes and readily available materials to off-Earth ISRU. ISS research could contribute to closing these knowledge gaps by testing ISRU materials (i.e., minerals and rocks) as 3D printing feedstocks and by testing raw-material refining processes for operation in microgravity. Accomplishing the latter may require redesigns of conventional conversion equipment and new ISS facilities. See Section VI for a complementary discussion from the ISRU breakout session.

- Tethers Unlimited representative Rob Hoyt and Made In Space representative Justin Kugler discussed several installed or planned ISS facilities for in-space manufacturing. Among these, the Tethers Refabricator is a combined plastics recycler and 3D printer designed to demonstrate a closed-loop manufacturing and plastics recycling process on the ISS. Tethers is also working with NASA to develop a "FabLab," which incorporates a metal 3D printer for in-situ manufacturing of precision parts in space. Made In Space operates its Additive Manufacturing Facility, the first commercial platform for additive manufacturing to be installed on the ISS, and indicated its ongoing work on a combined additive-subtractive demonstration facility with NASA. Made In Space also operates the Plastics Recycler on the ISS. These new and planned additive manufacturing facilities will be critical for performing several of the studies recommended from this workshop.

V. BREAKOUT SESSION: MICROGRAVITY-SPECIFIC MATERIALS AND PROCESSES

Session Chair: *David Johnson, Xerox PARC*
Session Chair: *Scott Roberts, NASA Jet Propulsion Laboratory*
Moderator: *Chris Williams, Virginia Tech*

Key Questions

1. Which materials should be a key focus for additive manufacturing research and production on the ISS? How can we leverage microgravity to provide a step-change in performance of 3D printed materials?
2. What are the gaps in the current technology for additive manufacturing in space?

Key Discussion Points Related to ISS Research

- Accurate measurement of thermophysical properties and wetting behavior, enabled by microgravity studies, is essential for modeling of additive manufacturing processes both in space and on Earth and should be a priority for research focus on the ISS.
- Microgravity additive manufacturing opens new material options such as soft materials (e.g., elastomers, foams, and rubbers), low-viscosity inks, new polymer options (e.g., longer cure time thermosets, filled polymer systems, continuous fiber reinforcement, and semi-crystalline polymers).
- New geometries and architectures are possible by removing constraints around support structures, slumping, and size limitations. Novel processes such as multi-axis printing technologies enable the fabrication of large, sparse structures that are challenging to produce on Earth.
- Microgravity and the closed system of the ISS will limit some processing options including the use of powder feedstocks, sintering processes that involve off-gassing, and the options of some metals such as chromium, magnesium, or nickel. The research community would benefit from clear direction of which materials and processes are not permissible in the closed system of the ISS.

Additional Discussion Themes

Needs:

- **Characterization of thermophysical properties and wetting behavior:** A fundamental understanding of thermophysical properties and wetting behavior, combined with accurate models, are necessary for future in-space additive manufacturing. Thermophysical properties (e.g., surface tension, surface energy, viscosity, and density) as well as undercooling can be accurately measured in microgravity for model development for both Earth-based and in-space manufacturing. Additionally, additive manufacturing processes are highly dependent on wetting behavior, particularly in the absence of gravity, and a better understanding of surface tension and dynamic wetting of droplets on impact is needed.

- **Understand which materials and processes are permissible on the ISS:** Additive manufacturing of "green" components that require sintering involve off-gassing of toxic chemicals. High-temperature melting of metals during additive manufacturing can create hazardous metal fumes. The consideration of crew health and safety in the closed environment of the ISS can constrain materials and processes choices, and there is a need to clearly understand these constraints to know which materials and processes are off limits. Additionally, if there are potential ways to enable the use or study on the ISS of currently disallowed materials that are important engineering materials (such as a molten droplet of stainless steel or Inconel®), it would be extremely useful to the modeling community. Alternatively, it would be helpful to know if there are commercial launch service providers or aerospace companies that have or may be considering the development of platforms on free flyers or on uncrewed space launch vehicles after undocking or unberthing from the ISS that would support future R&D using potentially hazardous materials.

Opportunities:

- **Cooling in the absence of convection:** The lack of convection in microgravity could provide an opportunity to improve directional solidification. Although microstructure is not inherently affected by gravity, the microstructure is highly dependent on the cooling rate and heat transfer orientation, which change in the absence of buoyancy-driven convection.
- **Freedom in the choice of polymer working material:** In microgravity, viscosity is no longer the driving parameter, reducing issues involving sedimentation and improving the shelf life of polymers for ink-based printing. The reduced dependency on viscosity expands the range of polymer working materials for both fused deposition modeling (FDM) and direct write printing and could enable printing with softer materials, materials with longer cure times, colloids, filled polymer systems, systems with continuous fiber reinforcement, etc.
- **Improved semi-crystalline polymers:** Additive manufacturing of semi-crystalline polymers in microgravity could result in improved properties due to the lack of buoyancy-driven convection and reduced dimensional shrinkage. At a minimum, microgravity could be used to study the crystalline formation in semi-crystalline polymers.
- **Improved thermoset materials:** In microgravity, thermoset materials retain their shape longer without slumping, eliminating the need for rapid-cure or quick-cure materials. Slower curation could result in improved materials or open the door to new thermosets not otherwise possible for additive manufacturing.
- **Freedom from support structures:** The reduction of slumping in microgravity provides an opportunity to examine the extended performance of existing processes to reduce or eliminate support structures as well as novel processes that do not involve supports. This could include novel processes such as multi-axis printing technologies that enable the fabrication of large, sparse structures that are challenging to produce on Earth. The ability to eliminate support structures also has important implications for bioprinting.

- **New additive manufacturing materials and morphologies:** In the absence of gravity, it may be possible to print new morphologies using capillary-driven flow to manufacture novel, fragile parts. In addition, microgravity may allow for additive manufacturing of materials not otherwise possible such as soft materials like foams, rubber, and elastomers.
- **Reducing material anisotropy by eliminating layering:** Employing processes such as reverse tomography photopolymerization that enable the production of an entire part at once could provide opportunities for high-speed production and reduced anisotropy through layers. Reverse tomography photopolymerization may also reduce maintenance such as vat recoating.
- **Wire-based processes:** Wire-fed systems that use a laser or electron beam for fusing would be easy to pack and safer than using loose powders on the ISS; however, they would require post processing with subtraction-based techniques to achieve true net shape.
- **Production of large structures:** There may be opportunities to use UV curing polymers to create large structures in space that cannot be launched from the ground. It may be possible to print long structures (such as beams and photovoltaic supports) that cure in sunlight.
- **Electronics fabrication:** The ability to print objects that contain electronics and are already functional would maximize astronaut time; however, the challenges involved in printing electronics on Earth are not solved in space. Although, it may be possible to print conductive tracers on the surface of objects.

Challenges:

- **Powder-based processes:** Powder-based processes have been recently demonstrated in a reduced gravity environment using force air to maintain the powder in the bed. There are also opportunities for powder-based processing using regolith. However, the use of powders in a closed system such as the ISS poses major safety concerns due to powder flammability and explosion risk, health hazards to the crew, and the potential for powders to clog air filters.
- **Off-gassing from sintering:** Exhausting fumes is a limiting factor in the closed environment of the ISS, unlike on Earth. It may be possible to explore whether there are ways to reclaim vapors and recycle them into fuel, reuse as binders, etc.; however, this may be extremely challenging in a crewed vehicle.
- **Cleaning printed components and machinery:** It is challenging to clean residue from machinery and parts in microgravity (it is not possible to tilt or shake objects to remove residue), and crew time for such efforts is limited. Automated systems for cleaning that do not rely on gravity are needed.

VI. BREAKOUT SESSION: IN-SITU RESOURCE UTILIZATION (ISRU)

Session Chair: *Jennifer Edmunson, Jacobs Space Exploration Group, supporting NASA MSFC*
Session Chair: *Bill Jarosinski, Linde*
Moderator: *Jeffrey Montes, Blue Origin*

Key Questions

1. What are the key challenges and solutions for applying additive manufacturing to ISRU in space and in remote Earth environments? Which additive manufacturing techniques are best suited for ISRU?
2. What research on the ISS can uniquely contribute to the development of additive manufacturing technology for ISRU?

Key Discussion Points Related to ISS Research

- ISS research should aim to demonstrate the recycle and re-use of packaging for 3D printing. Expand recycling studies to cover different types of materials (i.e. beyond just packaging) on the ISS, in preparation for recycling on new platforms/planetary surfaces/installations. Establish standards for printed products. This work will be very useful for Gateway.

- Explore creative solutions for use of waste materials, whether for additive manufacturing or for other uses such as a source of carbon. Perform tests with multi-material combinations, for example metallic and polymer feedstocks that can use existing additive manufacturing facilities in orbit.

- Research on the ISS should include radiation resistance studies for 3D printed building materials (i.e., Materials International Space Station Experiment (MISSE) Flight Facility exposure experiments).

- Solidification experiments with lunar-type materials in microgravity on the ISS may help us understand how such processes will work on the Moon for additive manufacturing in lunar gravity (1/6 of Earth gravity) by comparison with previous ISS solidification testing using other materials. Such experiments should build on the extensive ISS solidification research conducted with metals. Materials for thermal barrier coatings (TBC) (i.e., high temp ceramics) were suggested for study if applicable for ISRU and if ISS furnaces can achieve the high temperatures necessary. Additionally, sintering experiments were suggested with lunar or TBC materials, especially where phase transformation is involved, to understand the effects on microstructure and stability.

- Different additive manufacturing feedstock "recipes," formulated based on combinations of the materials found in lunar regolith, may be studied using ISS additive manufacturing facilities. In addition to understanding their suitability for material extrusion or other additive manufacturing processes that may be available on the ISS in the future, other processing characteristics, such as cooling, can also be studied. Cooling rates may be much slower and less predictable in nonconvective, off-Earth, reduced gravity environments subject to radiant heat; this may result in unwanted nucleation and formation of undesirable materials. Glass and glass ceramics produced from lunar regolith were suggested for focused studies in this area.

Additional Discussion Themes

Materials Available for ISRU

- **Materials for additive manufacturing:** Other planetary bodies (such as the Moon, Mars, asteroids, etc.) are comprised of elemental minerals, oxides, ores, and rocks—similar to materials found and processed on Earth—that may be used in additive manufacturing. In many cases, landing locale will determine what in-situ resources are available and therefore what can be built using an additive process.
  - Some materials that could be used, such as oxides or minerals, can be found on the lunar surface, but we only know superficially what is present close to, or on the surface. Below approximately two meters, the material composition is unknown.
  - Challenge: Significant prospecting will be needed to identify locations of reservoirs of material for ISRU.
- **Pseudo-refining:** The constituent elements of ore and rock are typically fully separated and purified in Earth-based extraction through complex, energy-intensive refining processes and then recombined into desired feedstock materials for additive manufacturing. For off-Earth, reduced gravity environments, it should be determined whether such full refining processes are necessary, or if less intensive, partial (or “pseudo”) refining may be sufficient to produce the feedstock materials. Redesigns or adaptations of conventional additive manufacturing processes to suit such pseudo-refined feedstocks would also have to be considered.
  - The research community should assess opportunities to use existing lunar metal oxides and other minerals that do not require an extreme or high level of processing (requiring less energy to process/phase into something that can be used for additive manufacturing).
  - There may be ways to use the reducing environment on other planetary bodies to accomplish reduction of mineral oxides.
  - Earth-based processes, in consideration of gravity, favor lighter materials like titanium. Off-Earth processes in reduced gravity may favor the use of other materials.
  - Researchers will need to assess the required level of purity needed for additive manufacturing feedstock materials in order to reliably print structures with the necessary strength, microstructure, porosity, or other desired properties.
- **Glass and glass ceramics:** The potential for using glass and glass ceramics from lunar regolith and similar materials in additive manufacturing was discussed (follow-up written comments were also provided by Richard Weber, Materials Development, Inc.).
  - Glass processing by 3D printing (fused filament, powder bed sintering, and binder/sintering methods) has been demonstrated terrestrially. However, questions relating to handing, processing, and use of these materials in low-gravity environments need to be addressed.
  - High-silica materials found in regolith are good glass formers, or may already be present in regolith as glasses. Solar energy may be used to melt regolith into glasses. Glasses may be converted to glass ceramics that could be used to improve fracture toughness for structural components. Glasses formed under vacuum may be stronger than those that form in an oxidizing environment.

    - ISS research should provide benchmark data on the properties and performance (in the LEO environment) of glass and glass ceramics from lunar regolith. Such work would highlight the potential for additive manufacturing as a route to extracting value from these resources in situ.

- **Power source challenge:** The power source/energy required to perform some level of processing prior to manufacturing may present manufacturing limitations. Concentrated solar energy may be sufficient to produce minimal changes of certain materials and material phases but may not be a fully viable solution. More research is needed.
    - Further research on various energy options may include the following: wind, microwaves, or nuclear (by seeking thorium and uranium-rich areas on the Moon).
    - Researchers should consider the use of self-propagating, high-temperature synthesis (i.e., the phase reaction can propagate itself, or self-sustain exothermic reactions, once initiated). The terrestrial analog uses materials such as thermite.

Applications for In-Situ Additive Manufacturing

- **Concrete 3D printing:** The use of concrete for 3D printing large structures (such as bridges, shelters, and towers) terrestrially has been demonstrated by several organizations, including the U.S. Marine Corps (USMC), the U.S. Army Corps of Engineers (USACE), ICON, and GE Additive.
    - NASA MSFC has printed subscale structures using 3D printed paste (a concrete with smaller aggregate), including Martian regolith simulant. Contour Crafting and others have also printed with cementitious materials. There is active research on additive manufacturing of concrete for terrestrial uses.
    - Challenge: For space-based ISRU, there is a need to identify which lunar materials (i.e., oxides, elements) would be suitable for the manufacture of cement/concrete-like products in situ.
- **Landing pads:** The first large structures to be printed (if not transported from Earth) will likely be landing pads. The availability of these pads is considered critical to avoid generating dust and dangerous orbital debris. Construction of habitats was additionally regarded as important.
    - Challenge: 3D printing of landing pads or other large structures in space will be difficult due to low pressure, near-vacuum conditions that promote the loss of volatiles and may potentially result in foam formation instead of solid structures.
    - Is there an opportunity for new processes, products, or procedures? Some participants suggested testing cold spray additive manufacturing, currently being used with titanium, copper, steel, and aluminum in terrestrial applications.
- **Standards and test procedures**: A process (or standard testing methods) for evaluating products manufactured in space needs to be developed.
    - Nondestructive evaluation (NDE) techniques need to be developed that are readily adaptable to the ISS and beyond. These techniques will set the limits of acceptability to qualify materials for use.

- Feedstock production methods and technologies need to be tested. For example, atomization may not be a viable option due to the complexity and energy requirements involved.
- Solutions: Researchers need to develop an in-process monitoring technique, and perhaps, return manufactured material to the ISS or other space station for testing.

Additive Manufacturing Technology for ISRU

- **Printing large structures:** Based on the discussion on applications, an extrusion-type additive manufacturing process, where the printing material is a slurry directed in place by various methods (robot, gantry, etc.), appears to be the most widely used process for printing large structures.

VII. BREAKOUT SESSION: IN-SPACE PRODUCTION

Session Chair: *Allison Beese, Penn State University*
Session Chair: *Justin Kugler, Made In Space*
Moderator: *Jay Sutherland, Corning*

Note: *John Vickers, Ph.D., Principal Technologist for Advanced Manufacturing at NASA MSFC, participated substantially in the dialogue.*

Key Questions

1. How can we achieve scale-up of current additive manufacturing activities on the ISS, and what are the current limitations and gaps in understanding?
2. What is the current state of additive manufacturing and production on the ISS, and what does the future of production in space look like?
3. Are there unique materials and products that should be the focus of in-space production using additive manufacturing in microgravity?

Key Discussion Points Related to ISS Research

- New approaches to in-space production will be needed where terrestrial systems are inadequate. As an example, powder metal additive manufacturing systems do not readily translate to microgravity conditions, so metal-wire (e.g., for directed energy deposition) or polymer-filament systems should be considered, along with "mixed-media" products like fiber-reinforced plastics or metal-wire-reinforced ceramics. Metal additive manufacturing in microgravity will result in changes to product microstructure and porosity.
- Understanding the requirements, material properties, and design options specific to space applications is important for products made and used in space, especially for large, exposed structures. For example, certain support structures (e.g., for telescopes and sensors), need to maintain functional surface precision, in some cases on the order of microns, while other support structure (e.g., solar arrays) positions must be maintained to a few centimeters. New design tools are needed to leverage the variety of nonuniform shapes and structures made possible using additive manufacturing.
- Industry and academia should work with NASA to develop standards and evaluation systems for materials made in microgravity (or less than 1g) environments, including additively manufactured products. In-orbit work on the ISS can accelerate this effort.

Additional Discussion Themes

In-Orbit vs. Terrestrial Additive Manufacturing

With respect to differences in microgravity versus terrestrial additive manufacturing, results depend on the type of material and/or feedstock.

- When using polymer feedstocks, in-orbit additive manufacturing does not show substantial differences in the end product versus terrestrial production, based on Made In Space's experience. In some cases, Made In Space observed better layer adhesion and more uniform beads in orbit, but this did not result in any significant difference in the end product. The fact that there is no substantial difference in objects printed in space (using polymer feedstocks) is good for NASA, because ground tests can be trusted to faithfully predict what will be produced in orbit. This allows production of quick and inexpensive demo prints on Earth that NASA can then test in simulated environments to ensure proper function and durability prior to sending the command to the ISS printer. At the same time, the lack of structural differences using polymer feedstocks may also limit the potential for material performance advantages for in-space additive manufacturing.
- However, this is not true for metals—many differences related to microgravity were discussed for in-orbit additive manufacturing using metals, which would result in changes in microstructure and porosity. In microgravity, the lack of convection-driven mixing in the melt pool impacts elemental mixing/homogeneity of composition during deposition, as well as cooling rates. Chemical segregation during solidification, as well as slower cooling rates, will impact the phases formed. The particular phases formed will depend on the local compositions as well as the kinetics of phase transformations, but both elemental segregation and changes in cooling rate could result in different phases being formed in orbit versus on Earth. Additionally, the decreased cooling rate in orbit may result in grain growth during fabrication. However, it was noted that there are also solid-state joining techniques that may lend themselves to production in microgravity, such as ultrasonic additive manufacturing or friction stir welding, in which the metal is not melted upon deposition.

Scaling Up to Larger Objects

Additive manufacturing removes some launch-related restrictions:

- Structures do not have to support their own weight, so one could use small machines to print larger objects, rather than being limited to smaller objects as is traditionally the case.
- In-orbit robotic manufacturing is currently being developed. In-orbit additive manufacturing enables engineers to treat the whole of space as the build volume, allowing them to optimize structural product design for in-orbit operations, unrestricted by considerations of folding and durability for the process of transport from the ground.
- In-orbit fabrication can thus lower production costs by simplifying certain design aspects—and it makes scaling up of size follow a linear cost increase (versus the historical disproportionate jumps in cost for increasingly large objects). Large-scale missions need this affordability and the structural focus on in-orbit performance.

The type of materials needed to support the structural integrity of large objects will not mimic the currently proven approaches with respect to feedstocks. Amongst speakers, there was some convergence on next steps for making larger structures, namely that metal-wire (e.g., for directed energy deposition) or polymer-filament feedstock may be better than powder processing for material delivery, reduction of material waste, and the potential to build structures not confined to the dimensions of the additive manufacturing build chamber.

- Polymer materials on their own do not have high enough thermal stiffness to achieve scale-up that will meet performance requirements.
- Metal-wire-based additive manufacturing scale-up will likely require subtractive machining to meet surface profile requirements at some locations.
- Lessons learned from terrestrial work to scale up product size will need to be applied to in-orbit additive manufacturing. Private-sector efforts on the ground are evaluating the roles for metals, directed energy deposition, and in some cases polymers for fiber reinforcement. Some early findings may be applicable for ultra-large scale (i.e., larger than 30 meters on any axis) efforts in space.
- While additive manufacturing of ceramics presents processing challenges, including powder management and binder supply and removal, some non-oxide ceramics, such as silicon carbide and boron carbide, offer exceptional stiffness-to-weight performance when compared with metals and polymers. This could help justify ceramics for use in large-scale structures. Multi-stage assembly processes (e.g., block or Lego approach) enable modular assembly and help to address issues related to sintering energy requirements by limiting the surface areas of joined interfaces. The requirements for large objects are still unknown.
- For certain support structures (e.g., telescopes and sensors), one needs to maintain functional surface precision—in some cases on the order of microns—to obtain high-quality data from certain instruments. For other support structures (e.g., solar arrays), positions must be maintained to a few centimeters. Understanding thermal effects (depending on position/orientation) and vibration effects is critical to achieving optimal designs that meet application requirements. There is still much work to be done to characterize the requirements and devise design solutions.

Hybrid Solutions

To overcome issues related to scale up and begin to address more complex needs, processing regimes for fabrication need to be established, and there is a likely need for integration of multi-material manufacturing. For example, terrestrial solutions such as steel-reinforced concrete optimize strength performance and cost by joining dissimilar materials.

- Made In Space is seeking to develop a diverse toolbox of capabilities for manufacturing and assembly in orbit, but this work is ongoing and in its infancy. The printing of a CubeSat structure in orbit has been demonstrated by Made In Space, including transportation of the structure to the ground for analysis, the in-orbit addition of other functional components launched to the ISS, and deployment. Made In Space indicated they have not seen a robust demand for end-to-end provision of in-orbit CubeSat printing, assembly (using human or robotic interaction to snap-on components), and deployment services.

- Cross-compatibility in additive manufacturing processing conditions and interfaces is key for multi-material additive manufacturing (e.g., lightweight materials versus strong materials). Different additive manufacturing materials may require vastly different processing temperatures, making them a poor match for processing, even if together they provide other performance advantages. Current efforts show substantial barriers if materials do not adhere or are not compatible with surface materials (and coatings for existing satellites, etc., for servicing). There is a lot of work left to be done in this area.
- From one perspective, there may be opportunities for alloy development and design (either terrestrially or in orbit). However, another perspective may emphasize the value of commercial off-the-shelf (COTS) feedstocks as standard materials that are already well understood and available.

Ensuring Quality

There is a significant knowledge and process gap in how to ensure the quality of materials printed in orbit, particularly as the U.S. advances toward the goals of Artemis and longer-term human spaceflight missions. Development and validation of processes is a critical step.

- Current additive manufacturing products and tools have been deemed safe and effective, from Made In Space's perspective. After hundreds of test prints, trust was built after empirically determining that there were no functional or microstructural differences between the terrestrial and in-space prints.
- For future exploration, part validation will be more real-time, and confidence must be established in a new way. End-to-end quality depends on inspection, process monitoring, feedstock quality, and nondestructive analysis (hyperspectral, etc.) to confirm that an in-space build matches its terrestrial twin.
- Recycling of used items produced using in-orbit additive manufacturing will be important in the future, but challenges exist in adding a subtractive element for flight-critical components—additive manufacturing does not meet all current needs for tolerance and design. Misprints and defects can be shuffled into a recycler, and debris also needs to be auto-captured and recovered for disposal or reuse. Some of this work is in progress, but these procedures and standards are also in their infancy.
- At the same time, potential problems with recycling of powders for feedstock may arise due to morphology shifts.

Development of Standards is not a Trivial Pursuit

- There is a critical need for the development of standards in qualification and testability. In-situ health monitoring, where physical access and inspection is unlikely, is an active area for NASA and other government agencies. A related guidance document is soon to be released: NASA Protocol 6030, which will discuss metals and polymers for human-rated and nonhuman standards. However, this is still a significant technology gap because at all aspects and stages of the product life cycle, modeling and testing capabilities are needed. Some standards are already available for materials, parts, and standardization of process, but more process-oriented standards (with broader applicability) need to be developed.

- Important groundwork is being done to establish the relationship of processing to microstructure and properties in terrestrial additive manufacturing. Monitoring during fabrication is currently being done to try to establish those parameters, followed by destructive testing to gauge performance. Because there are notable changes in microstructure in microgravity, particularly a problematic increase in porosity in the absence of buoyancy forces for bubble removal, we will need to evaluate these rules separately: we must establish how is should be evaluated and how these defects impact performance, as we extend resulting design tools and programs to space. This will require some destructive evaluation to establish in-orbit parameters. Thus, standards and technology for nondestructive evaluation must build on early insight gleaned from terrestrial models, dedicated in-orbit studies and modeling, and destructive evaluation of in-space prints.
- NASA is working closely with the Federal Aviation Administration, the ASTM International Additive Manufacturing Center of Excellence, the Materials Genome Initiative, and parallel efforts out of the Air Force Research Laboratory to investigate computationally driven materials. These methodology approaches need to be extended to space, but this is emerging technology with many unanswered questions.

Rethinking Design

- Justin Kugler of Made In Space suggested that for the future, because in-space additive manufacturing allows some advantages over the traditional approach of terrestrial design and launch, we should think smarter about design improvements in space rather than mimicking historical ground designs, to optimize items for space performance. New design tools are needed to leverage the variety of nonuniform shapes and structures made possible using additive manufacturing.
- Allison Beese of Penn State University commented on the benefits and drawbacks of future on-site design with respect to geometry and materials selection. She acknowledged the likely future need and value as human habitation expands into space but reiterated that cooling rates, microstructure, and defects inherent in in-orbit additive manufacturing are still not well understood even on the ground. We need to understand these details on the ground and in space, and then tools and guidelines need to be developed for in-space activities.

VIII. THE PATH FORWARD

The Future of Additive Manufacturing in Space

This ISS National Lab is positioned to support the next step in answering the fundamental question of how microgravity and the extreme space environment can each intrinsically and uniquely enhance additive manufacturing. Based on the cutting-edge opportunities, developments, and challenges discussed during this workshop, CASIS will convene a follow-up workshop with subject matter experts to discuss the most promising paths forward for future research and commercialization efforts designed to contribute to the advancement of additive manufacturing in orbit. Collaborative and creative approaches between NASA and other government organizations, companies already conducting additive manufacturing or related activities in orbit, and commercial businesses yet to conduct research on station will be essential to the success of LEO economic development in this area and areas enabled by this technology.

For additional information on the 2020 ISS National Lab Additive Manufacturing in Space Workshop and access to related ISS National Lab activities and content, visit the 2020 Additive Manufacturing In Space Workshop webpage.

While this workshop focused on nonbiological materials, materials and applications for 3D bioprinting were covered in a separate 2020 ISS National Lab workshop (previous workshop reports are available online at www.issnationallab.org/workshops/).