National Aeronautics and Space Administration

The Proving Ground: Using Low Earth Orbit as a Test Bed for Manufacturing Technology Development

1st International Conference on 3D Printing and Transportation

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Tracie Prater, Ph.D.
NASA Marshall Space Flight Center
Materials and Processes Laboratory
Huntsville, AL
tracie.j.prater@nasa.gov

MARSHALL
SPACE FLIGHT CENTER

Outline

I. Background: Advanced Manufacturing Technology Development at NASA Marshall Space Flight Center

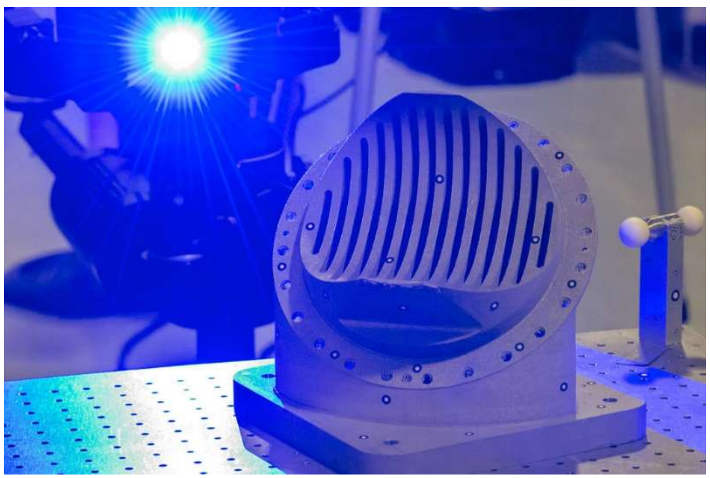
II. Adapting Advanced Manufacturing to the High Frontier: In-Space Manufacturing Technology Development as a Building Block for Future Space Infrastructure

III. Extensibility of in-space manufacturing to on-orbit servicing, assembly, and repair (OSAM)

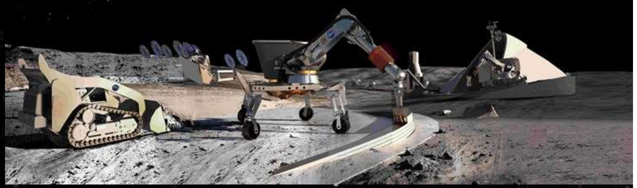
IV. Extensibility of in-space manufacturing to in situ resource utilization (ISRU) technology development

V. Challenges and recommendations

I. Background: Advanced Manufacturing Technology Development at NASA Marshall Space Flight Center



The Spectrum of Advanced Manufacturing at NASA



Planetary Construction

Image from Contour Crafting

On-orbit servicing, assembly, and manufacturing (OSAM)

Image from Made in Space

In Space

For Space

25+Years of Experience

AM for aerospace*

Advantages:

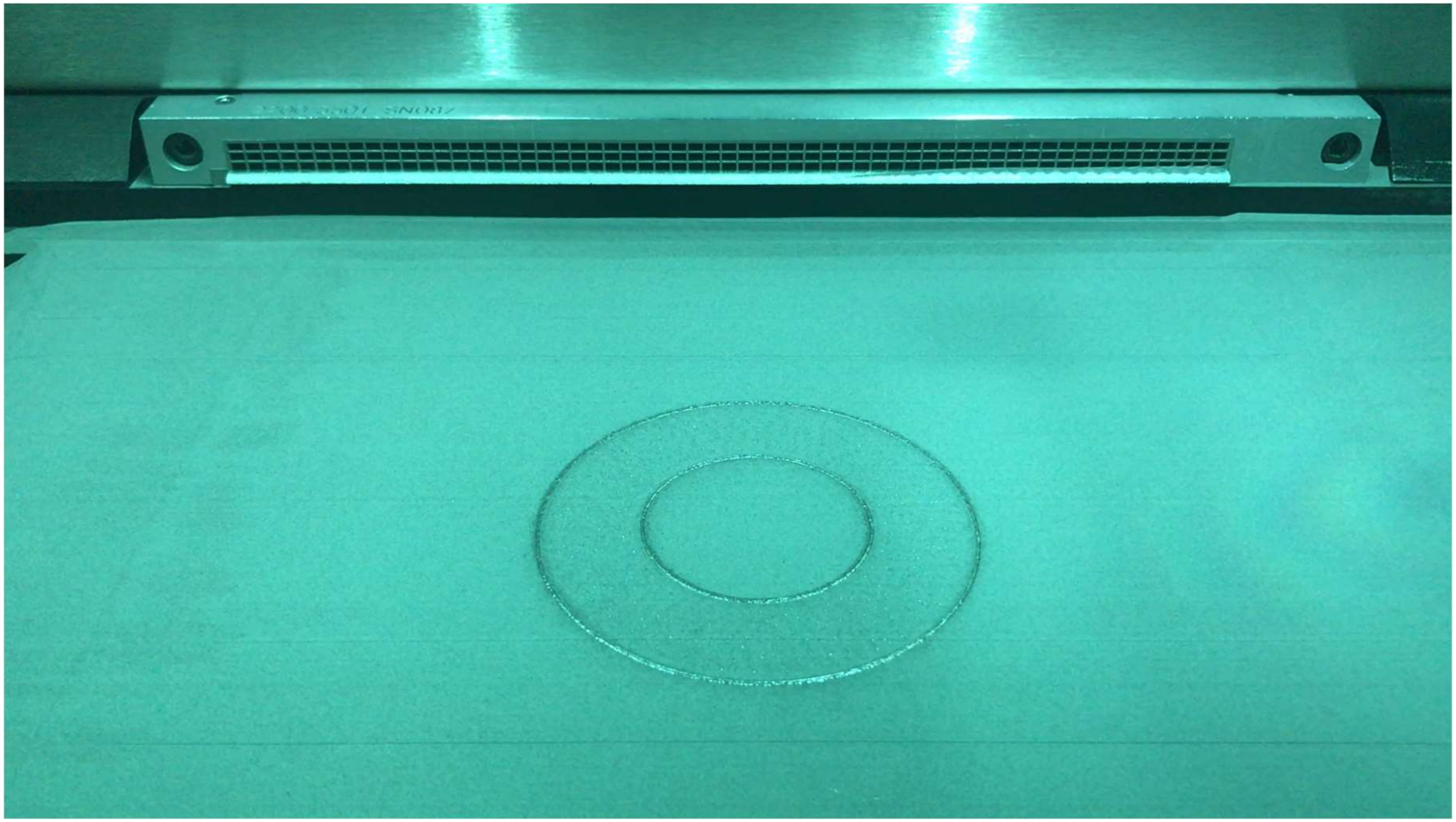
- Ability to fabricate highly complex components; some features may not be fabricated by other methods
- Well suited for custom, low rate production scenarios
- Increased design freedom and customization
- High feature resolution
- Near net-shape complex geometry
- Part count reduction
- Performance improvement (i.e. weight reduction)
- One-off and discontinued parts
- Shorter lead times
- Properties better than cast, but not quite as good as wrought for powder bed fusion techniques

Disadvantages:

- Materials may be limited, depending on process; material feedstocks may not be analogous to “conventional” materials
- Build envelope size limits
- Design constraints: overhang surfaces, minimum hole size
- Surface roughness
- As-built microstructure may require post processing
- Substantial touch labor
- Waste generation
- *Can be* more expensive than traditional manufacturing (high hourly rates offset by reducing labor costs)

*slide adapted from Paul Gradl and Omar Mireles, NASA Marshall Space Flight Center

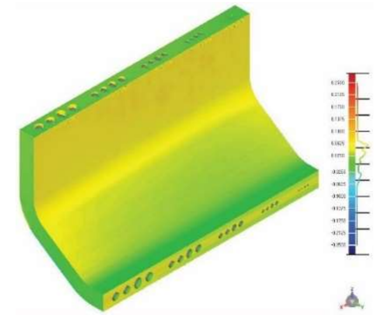
Powder bed fusion processes



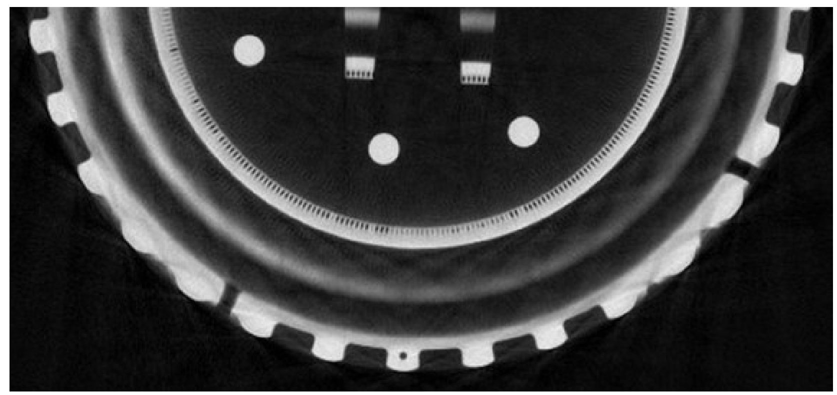
Nondestructive Evaluation for AM

- Structured Light Scanning
  - Surface mapping
  - Geometric distortion/deviation
  - Limited spatial resolution
  - Equipment expensive but operation relatively inexpensive
- X-ray radiography & Computed Tomography (CT)
  - Detect trapped powder
  - Detect Large flaws
  - Limited spatial resolution (excludes micro-focus CT)
  - Material determines scan time/resolution
  - Expensive & time consuming
- Other
  - Visual / Borescope
  - In-situ
  - Ultrasonic
  - Penetrant
  - Infrared

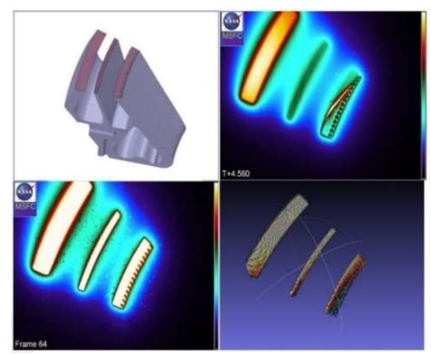
Structured Light Scanning



CAD-scan data comparison



Radiograph showing powder filled channels



In-situ Inspections

*slide adapted from Paul Gradl and Omar Mireles, NASA Marshall Space Flight Center

Part Certification for AM*

NOT MEASUREMENT SENSITIVE

National Aeronautics and Space Administration

MSFC-STD-3716
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20
MSFC TECHNICAL STANDARD

Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals

DRAFT 1 – April 10, 2017

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

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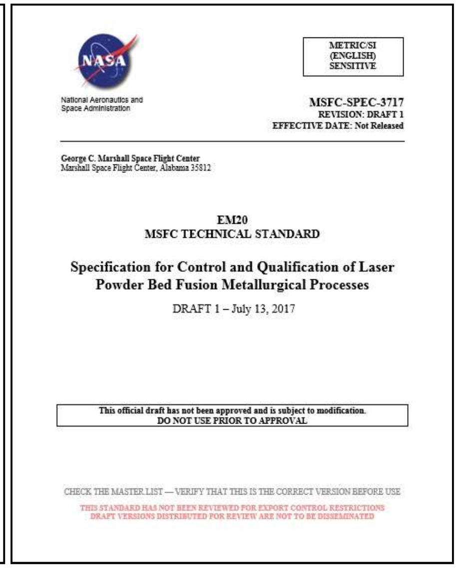

METRIC/SI (ENGLISH) SENSITIVE

National Aeronautics and Space Administration

MSFC-SPEC-3717
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20
MSFC TECHNICAL STANDARD

Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

DRAFT 1 – July 13, 2017

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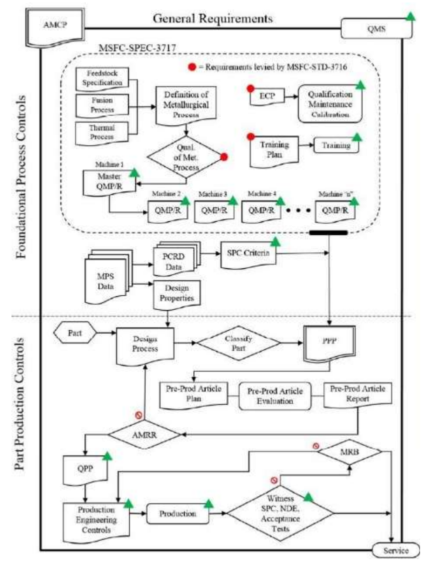


MSFC-STD-3716 & -3717: From powder to acceptance

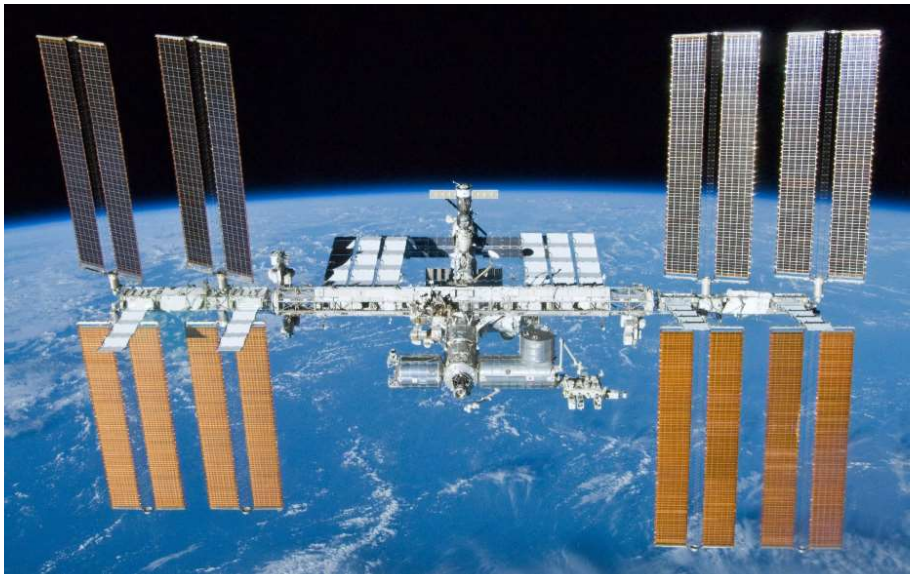
Standardization is needed to establish process controls and ensure reliable production of flight-critical AM components

NASA developed MSFCS-STD-3716 (Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals) and MSFC-STD-3717 (Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Process) in response to programs using AM in human spaceflight applications: Commercial Crew, Space Launch System, and Orion

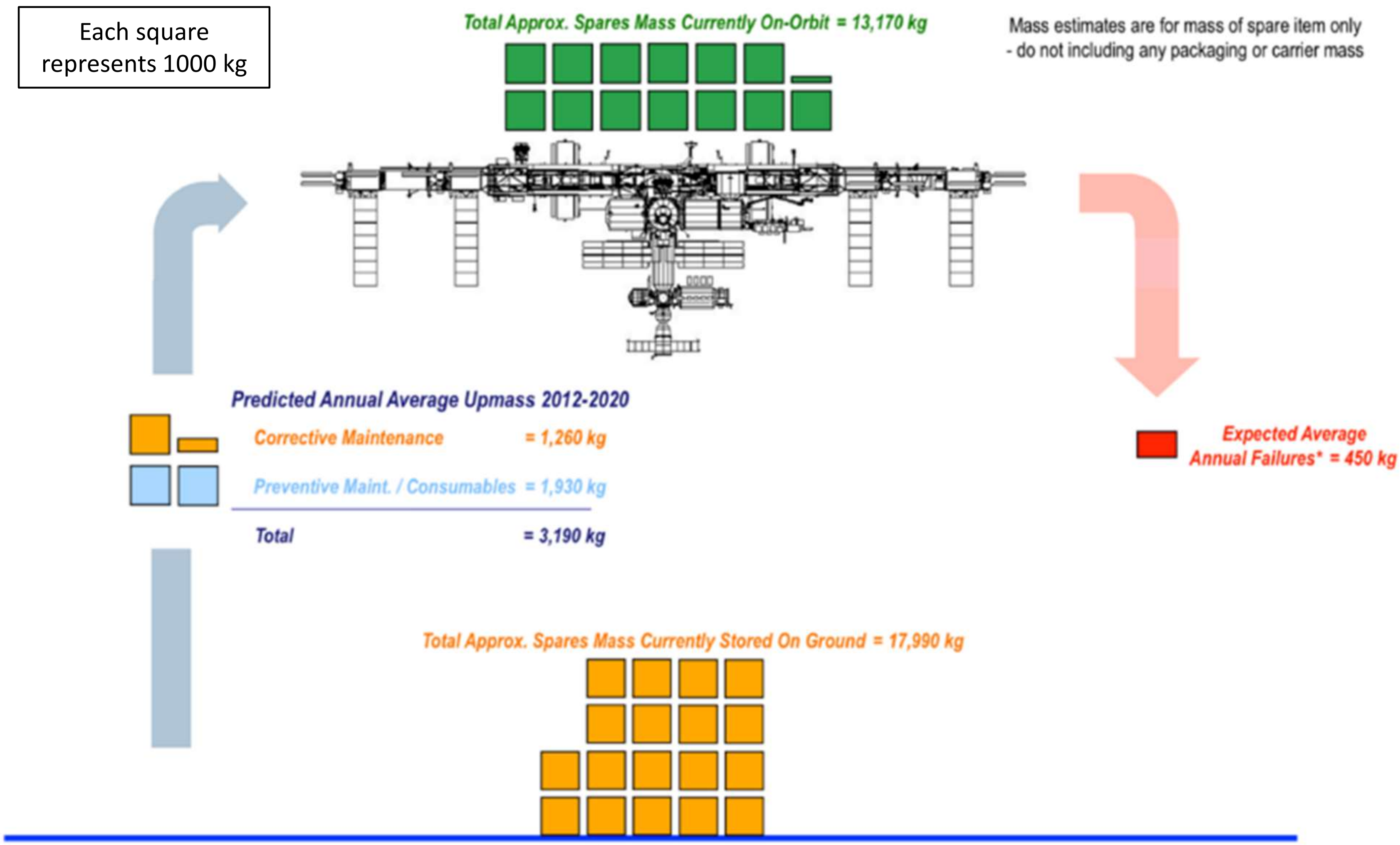
Part certification methodology is driven by criticality of part

*slide adapted from Paul Gradl and Omar Mireles, NASA Marshall Space Flight Center

II. Adapting Advanced Manufacturing to the High Frontier: In-Space Manufacturing Technology Development as a Building Block for Future Space Infrastructure



Why manufacture in space: The logistics quandary of long endurance spaceflight



- Based on historical data, 95% of spares will never be used
- Impossible to know which spares will be needed
- Unanticipated system issues always appear, even after years of testing and operations

* - Based on predicted MTBFs

Image credit: Bill Cirillo (LaRC) and Andrew Owens (MIT)

In-space manufacturing as an approach to sparing

A number of possible solutions exist for logistics on long duration missions:

A. Simplification of system design (which in-space manufacturing can enable)
B. Sparing flexibility & robustness through in-space manufacturing
C. Increased system reliability
D. All of the above will be required for sustainable missions

Advanced manufacturing and additive manufacturing represent highly disruptive and rapidly changing technology areas.

In-space manufacturing takes a "spin-in" approach to technology development, where promising processes for on-demand manufacturing in space can be adapted for testing and evaluation in the sustained microgravity environment of the International Space Station.

Challenges in adapting manufacturing processes for operation in an intravehicular (IVA) environment include:

-safety, including management of particulate
-limits on power, volume, mass
-microgravity effects on the manufacturing process and material outcomes
-verification of parts manufactured on-orbit

Adapting manufacturing processes for ISM

- **Fused Filament Fabrication (FFF)**
  - **3D Printing in Zero G Technology Demonstration Mission**
    - Small Business Innovative Research (SBIR) contract with Made in Space, Inc.
    - Printed 55 parts of Acryonitrile Butadiene Styrene (ABS) from 2014-2016
    - Printer operates in Microgravity Science Glovebox (MSG)
  - **Additive Manufacturing Facility (AMF)**
    - Multi-material commercial facility for polymer printing from Made in Space, Inc.
    - AMF has multiple customers beyond NASA
    - NASA characterization of mechHLD(19test specimens and functional parts printed with AMF is ongoing
  - **ReFabricator payload from Tethers Unlimited, Inc. (TUI)** installed on International Space Station in early 2019
    - capability to recycle printed polymer parts into filament feedstock for further manufacturing with FFF

3D Printing in Zero G Technology Demonstration mission printer in Microgravity Science Glovebox

Additive Manufacturing Facility

ReFabricator (image from TUI)

Adapting manufacturing processes for ISM

- **Fused Filament Fabrication (FFF) with higher strength feedstocks**
  - Addresses gap between the properties of materials typically used with the FFF process and metals
  - ISM seeks development of higher strength feedstocks compatible with the FFF process that would uniquely enable NASA applications, facilitating sparing and/or palliative repair scenarios
  - Actuated Medical, Inc., through a phase II small business innovative research (SBIR) effort, is developing Carbon fiber reinforced PEEK (poly ether ether ketone) feedstock for 3D printing of medical devices
    - Laser-assisted heating following layer deposition significantly reduces anisotropy in the printed part
  - Geocomposites, Inc., in a phase II SBIR, is developing a dual nozzle fused filament fabrication technique and combinations of novel feedstock materials to enable printing of a matrix with continuous fiber reinforcement
    - Material strengths for some configurations are greater than 200 MPa in tension

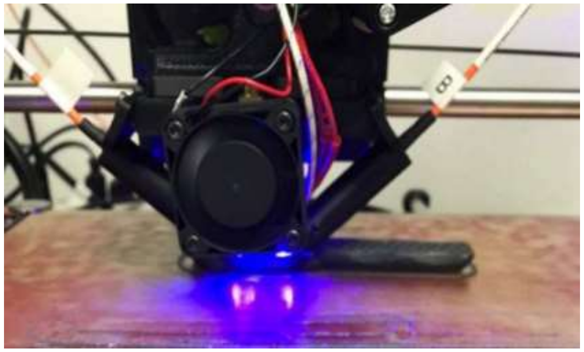


Image from Actuated Medical, Inc.

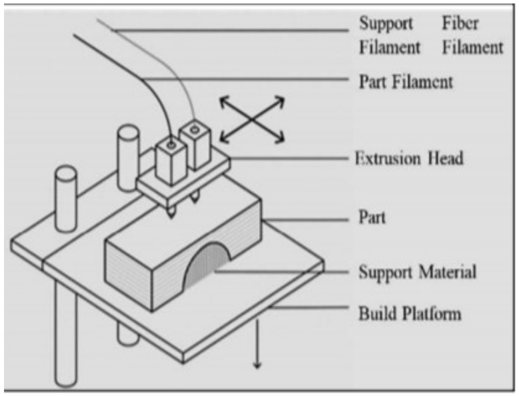
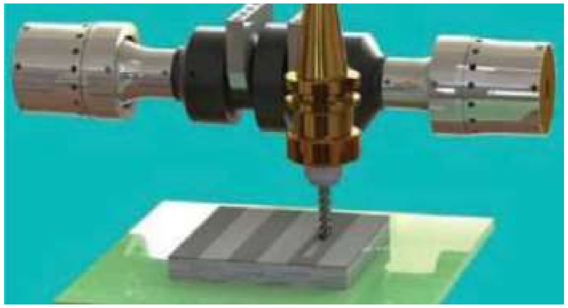


Image from Geocomposites

Adapting manufacturing processes for ISM



Images from Fabrisonic

- **Ultra Tech Machinery and Fabrisonic are developing the ultrasonic additive manufacturing (UAM) process for use on ISS through a phase II SBIR**
  - Manufacturing process is solid state and takes place in ambient air at room temperature.
  - A sonotrode imparts acoustic energy to adjacent layers of metal foil, dispersing the oxide layer and creating a metallurgical bond.
  - UAM is a hybrid process (includes post-process machining in the same unit).

Adapting manufacturing processes for ISM

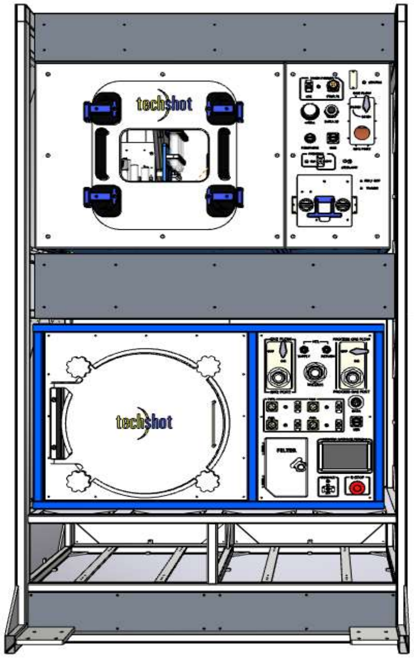
Images from Made in Space, Inc.

- **Vulcan unit from Made in Space (phase II SBIR)**
  - Derived from wire-fed welding process (directed energy deposition)
  - Vulcan unit has multiple subsystems:
    - Additive manufacturing unit (polymers and metals)
    - Mill for finish machining
    - Environmental control unit for debris capture (tested on parabolic flight)
    - Robotic capability for part manipulation (flips additively manufactured part for machining)

Adapting manufacturing processes for ISM

- **Multi-Material Fabrication Laboratory (FabLab)**
  - Parallel efforts under a Broad Agency Announcement (BAA) to develop larger scale facilities for multi-material manufacturing (focus on aerospace metals) and inspection
  - Systems must fit into an EXPRESS rack and are limited to peak power consumption of 2000 Watts, a weight of 576 lbm, and a volume of 16 cubic feet
  - Multimaterial Fabrication Laboratory system being developed by Techshot includes subsystems for printing of metals using a bound-metal deposition type process, postprocessing of material, and in-process monitoring
  - Under a separate effort, TUI is developing a robotic arm for movement of parts between Fabrication Laboratory subystems and a structured light scanning system for part inspection (dimensional verification only)

Image of EXPRESS rack.
Image from NASA.



FabLab Concept
Image from Techshot.

ISS Microgravity Materials Science Research

ISM can leverage the work of microgravity materials science investigations on ISS to better understand materials, manufacturing processes, and postprocessing in the microgravity environment.

Materials Science Research on ISS under ***SLSPRA (Space Life and Physical Sciences Research and Applications)*** continues to provide insight into dynamics that may significantly affect viability and performance characteristics of additive manufacturing processes in either microgravity or reduced gravity environments.

- Pore Formation and Mobility Investigation (PFMI)
  - Dynamics of mushy zone porosity in a thermal gradient
  - Marangoni convection in the region of pores
- Gravitational Effects on Distortion in Sintering (GEDS)
  - Liquid phase sintering, start of ISS operations 11/5/19
- Coarsening in Solid-Liquid Mixtures (CSLM) - isothermal
- *Dendrite Fragmentation and Morphology during Melting and Solidification (currently in development)*

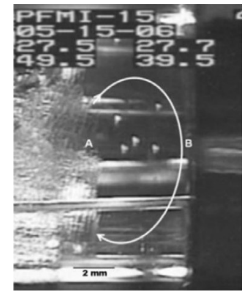
Multiple ISS-based benchmark solidification experiments are being used to anchor multi-scale models of microstructure evolution (e.g. phase field, cellular automata-finite element, dendritic-needle-network) relevant to additive manufacturing process-structure-property-performance (PSPP) linkages at the microscale and above.

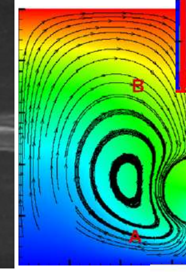
ISS-based thermophysical properties measurements (e.g. density, specific heat, surface tension and viscosity) of metals, semiconductors, oxides and glasses are also providing key inputs to multiscale modeling of additive manufacturing processes.

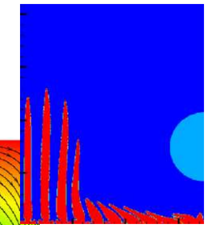
The ISS can also be used as a platform to conduct targeted experiments to better understand the observed or predicted effects of microgravity or reduced gravity on materials production and repair processes needed to sustain extended duration Gateway or lunar surface operations.

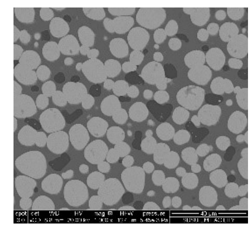
Slide credit: Dr. Louise Strutzenberg, NASA MSFC

Effect of Bubble-Induced Convection on Solidification
Nabavizadeh, Eshraghi, Felicelli, Tewari & Grugel, Int. J. Multiphase Flow 116 (2019) 137

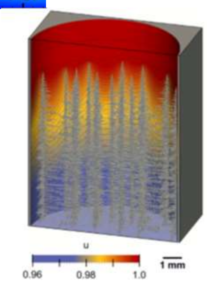




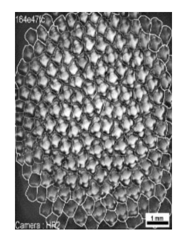


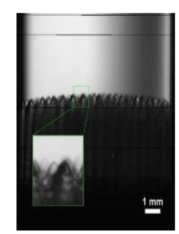


GEDS W-heavy alloy, Earth sintered
www.nasa.gov: ISS mission pages GEDS)



3D dendritic needle network model
D. Tourret & A. Karma, Acta Mater. 120 (2016) 240





Axial and transverse views of dendritic interface in DECLIC-DSIR (2018)
IAC-19-A2.6.2 Mota, Ji, Lyons, Strutzenberg, Trivedi, Karma & Bergeon (October 2019)

III. Extensibility of in-space manufacturing to on-orbit servicing, assembly, and manufacturing (OSAM)

Image from Made in Space

- Some technologies demonstrated in an IVA environment can be deployed in the external environment and scaled up for OSAM applications

Archinaut

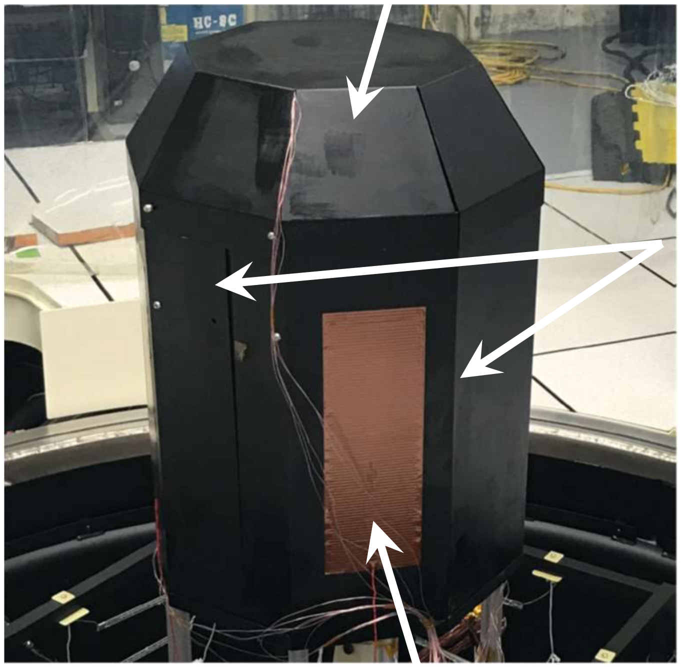
Made In Space, Inc., (MIS) is developing Archinaut, an in-space robotic precision manufacturing and assembly system, for larger-than-deployable structures

- Extruder that successfully operates in space-like environment
- Traversing system for out-of-volume printed part manipulation
- Robotic assembly for printed and pre-fabricated spacecraft parts
- In-Situ Inspection and Validation of printed parts

- Polyetherimide-polycarbonate (PEI/PC) selected as primary print material
- Demonstrate extended structure additive manufacturing of structures in a space-like environment using Extended Structure Additive Manufacturing Machine (**ESAMM**)
- Demonstrate additive manufacturing and assembly of structures in a space-like environment using Ground-Based Manufacturing and Assembly System Hardware (**GBMASH**)
- Leverages/builds on experience with FFF in the microgravity environment from the 3D Printing in Zero G Technology Demonstration Mission and Additive Manufacturing Facility

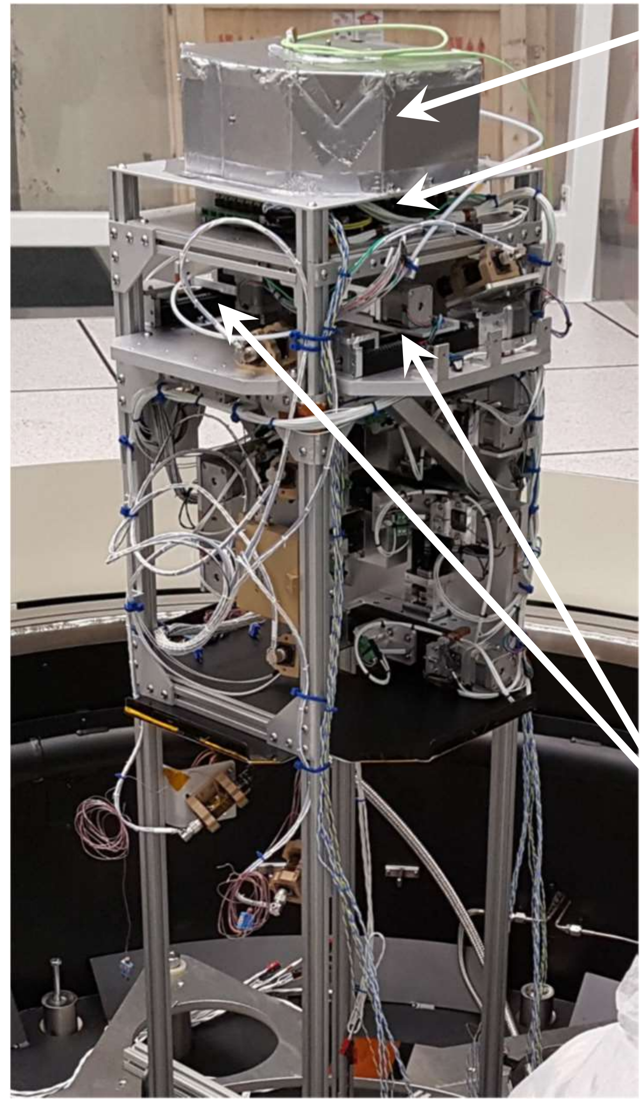
Archinaut: ESAMM

Shroud



Radiator
Areas

Heater



Feedstock

Electronics

X-Y Extruder
Gantry

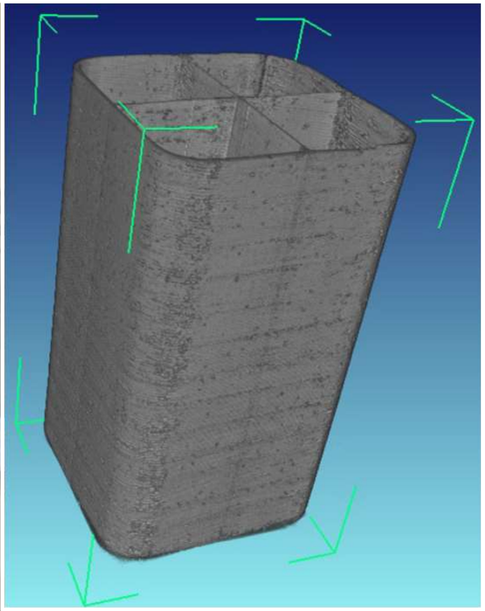
Slide credit: Lawrence Huebner, NASA LaRC

Archinaut: GBMASH

Slide credit: Lawrence Huebner, NASA LaRC

Archinaut phase I outcomes

- First known 3D print demonstration in a simulated external space environment
  - Vacuum/cyclic temperature (0-40°C)
- Post-print inspection, material characterization, and structural/mechanical properties performed on printed parts
- Traversing system for out-of-volume printed part manipulation
- Robotic assembly for printed and pre-fabricated simulated spacecraft parts
- In-situ inspection and validation of printed parts
  - Shape-from-shading technique in which V&V cameras use photometric stereo to create normal maps of printed surfaces on each pixel in the image (compared with known reference)
- Used ESAMM to produce the world's longest 3D-printed structure (37.7 m long)
- Archinaut One continues through a phase II effort and will be flight demonstration



CT scan of vacuum sample produced by ESAMM

Slide adapted from Lawrence Huebner, NASA LaRC

Welding in Space

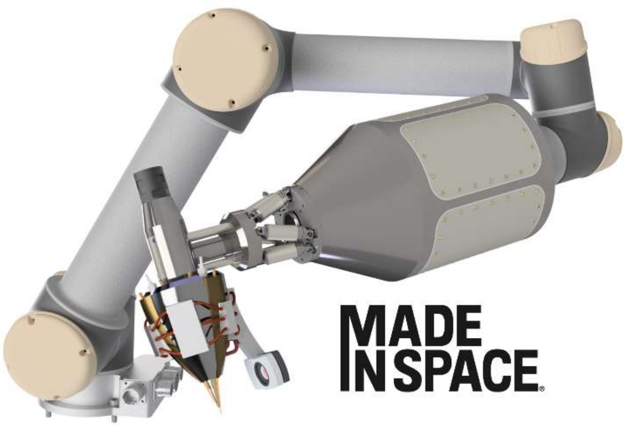
2019 SBIR subtopic on in-space welding focused on adaptation of welding technologies for joining of structures in the space environment and repair

Under a phase I SBIR, Made in Space is developing MELD for autonomous or teleoperated in space repair, fabrication, and additive manufacturing

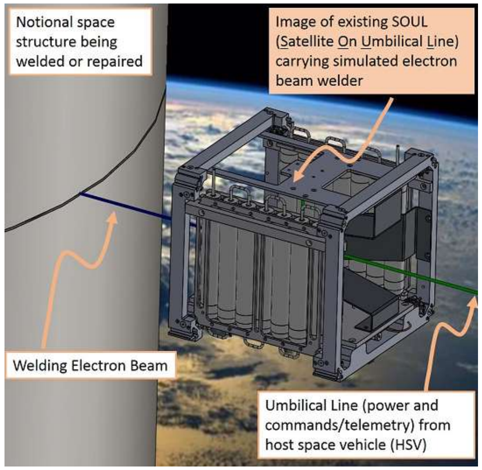
- Operable with or without attachment to the robotic arm
- 1 handed manual operations of the end-effector are possible
- Performs welding in a variety of conditions
- Orbital, Lunar, and Martian environments.
- Capable of fusing
  - Metals: Aluminum, Stainless Alloys, Titanium
  - Non-metals: Ceramics, Regolith
- In-situ analysis of weld integrity and quality

Also under a phase I SBIR, Busek, Inc. is developing a semi-autonomous, teleoperated welding robot for joining of metals in space

- welding robot will be an adaptation of a Busek developed system called SOUL (Satellite On Umbilical Line) with a suitable weld head attached to it



MELD. Image from Made in Space. Used with permission.



Conceptual representation of a SOUL welder repairing a curved space structure. Image from Busek, Inc. Used with permission.

Metal recycling technologies

- **Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA), a ground based prototype system in development from TUI,** can process virgin or metal scrap material into ingots
  - MAMBA is a metal press and milling system to create precision parts
  - Debris from machining of metal to fabricate a net-shape part is collected and can be used for further ingot manufacturing
  - Phase II effort is building a prototype integrated system including the ingot press, CNC mill, and mechanism to move parts between subsystems

- While ISM is focused on recycling of metal parts in a crewed environment, metal recycling technology development also has alignment with on-orbit servicing, assembly, and manufacturing (OSAM)
  - Recycling may be a way to satisfy end of mission protocols and repurpose what would otherwise be "space junk"
  - ISM can potentially be used to demonstrate potential processes which can be scaled up for these applications

Testing of AM materials in the space environment

- Materials International Space Station Experiment (MISSE) provides a platform for evaluating long term material performance in the space environment (vacuum, atomic oxygen, ultraviolet radiation)
- MISSE-9 evaluated additively manufactured materials in the space environment, including polyetherimide (Ultem 1010 and 9085), electrostatic-dissipative polyetherketoneketone (ESD-PEKK), polyphenylsulfone (PPSF), Inconel 718, and Glenn Research Copper 84 alloy (GRCop-84)
- Samples were manufactured at Marshall Space Flight Center (MSFC), Stratasys (original equipment manufacturer for fused filament fabrication systems), and Made in Space
- Results of ground-based simulations of space environmental effects (AO and UV) published in NASA Technical Publication: “Space Environmental Effects on Additively Manufactured Materials”: https://ntrs.nasa.gov/search.jsp?R=20180006417
- Flight data from MISSE-9 will inform materials selection for both ISM (for parts produced in a crewed environment which have external use scenarios) and OSAM. An additional experiment on additively manufactured materials is being flown on MISSE-10.

MISSE-9 flight specimens. Image from NASA and Alpha Space.

IV. Extensibility of in-space manufacturing to in situ resource utilization (ISRU) technology development

Cargo bags filled with trash on ISS for downmass in Cygnus cargo capsule. Image from NASA.

“Common use” materials

- Within ISM, common use materials refer to materials which are intended to be recycled on space missions. These materials, which would otherwise be nuisance packaging, can be repurposed as in situ feedstocks for manufacturing.

- Cornerstone Research Group (CRG) developed a novel material to enable reprocessing of space mission waste packaging plastics.
  - The application of CRG's thermally reversible (RVT) polymers combined with a plastic recycling, blending, and extrusion process will allow packaging materials to be processed into a copolymer blend filament suited to an FFF 3-D printing system
  - This approach offers two implementation routes including: (1) an RVT additive that can be combined with existing waste packaging during a reclamation process to produce 3-D printer filament and (2) RVT based replacement packaging material that can be directly reclaimed into 3-D printer filament
  - Under a separate SBIR activity, CRG is also developing a capability for in-process monitoring of filament production

- In the CRISSP (Custom, Recyclable ISS Packaging) project, TUI developed a process for 3D printing customized foams with specific vibration damping characteristics.
  - TUI matured and optimized infill generation software to enable design of foams optimized for a given payload's vibration sensitivities
  - Key outcomes of the Phase II effort were development of a process for packaging supplies and components for launch with materials that are readily recyclable and can be used for further processing on-orbit

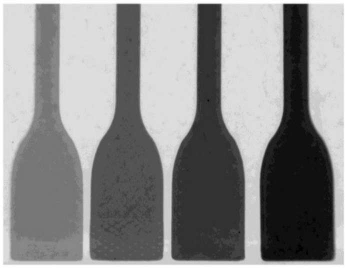
CRISSP. Image from TUI.

Development of regolith/polymer feedstock blends

- Under a NASA XHab project, South Dakota State University students developed and evaluated several basalt loaded filaments for use in fused filament fabrication systems.
  - Basalt is a rock material indigenous to many planetary surfaces. Basalt fiber can be included in traditional polymer (plastic) materials used for 3D printing to enhance their strength, impact resistance, and radiation resistance.
  - Promising filaments were mechanically tested as well as exposed to X-Ray radiation to give a qualitative indication of shielding performance. The team used simulations to predict the filament's estimated interaction with gamma rays.

- Also under an XHab project, University of Connecticut students investigated Ultem polymers blended with regolith simulant materials to create filaments with specific electrical properties.

- Other polymer blends with basalt fiber reinforcement with potential applicability for ISM were developed through NASA's Centennial Challenges program 3D Printed Habitat Competition:
  - PETG with basalt fiber reinforcement (Branch Technology, Foster + Partners in phase II; material developed by Techmer, Inc.)
  - PLA with basalt fiber reinforcement (AI Space Factory in phase III; material developed by Techmer, Inc.)



XRay image of tensile specimens with various levels of basalt fiber reinforcement. From left to right: 0%, 10%, 25%, and 40%. Image from South Dakota State University.

PLA/basalt fiber reinforced material in the phase III 3D Printed Habitat Challenge (a NASA Centennial Challenge). Image from NASA and AI Space Factory.

V. Summary, Recommendations, and Challenges

"Every revolutionary idea seems to evoke three stages of reaction:

1. *It's completely impossible.*
2. *It's possible, but it's not worth doing.*
3. *I said it was a good idea all along."*

-Arthur C. Clarke

Manufacturing in space removes constraints

Constraint[1]	Constraint removed by ISM?
Structures must be designed for launch loads.	ISM enables structures which are optimized for operation in space, not for launch loads.
Structures must fit within launch vehicle payload fairings.	ISM enables structures whose size is limited only by the fabrication volume of the ISM capability.
Materials must be disposed of at the end of their lifecycle.	Materials can be recycled and used for further manufacturing.
All the spare parts and equipment needed for on-orbit servicing or repair and replacement activities must be prepositioned.	Spare parts can be made on-demand. ISM capabilities can enable on-orbit servicing and repair of equipment.
Component reliability and redundancy (R&R) largely driven by mission life/duration.	Redundancy is augmented by ISM capability to make components on demand. R&R requirements may be reduced in some instances when an ISM capability is present.

Paradigm shift

1. Table adapted from Moraguez, Matthew. "Technology Development Targets for In-Space Manufacturing." Master's thesis. MIT, 2018

Recommendations and Challenges

- ISM can "stand in the gap" by offering near-term platforms for technology demonstration for processes and materials which are extensible to OSAM and planetary construction
- To take advantage of ISM, systems must be designed to leverage ISM capabilities. ISM has been interfacing with designers and using ISS databases to define a part catalog. This "what we make" of ISM informs capability requirements for future platforms (build rate, reliability, tolerances, material properties)
  - Systems on future exploration missions must be designed for accessibility and maintainability.
- While initially intended to be demonstrated in a crewed environment with overall system constraints driven by implementation of platforms on ISS, many processes and systems in the technology development pipeline for ISM are scaleable and adaptable to other manufacturing scenarios in the space environment (ex. manufacturing outside a crewed habitat, on a planetary surface).
- In many cases, there is not yet sufficient knowledge about the processes or materials to develop standards. For systems that will deployed on exploration missions beyond ISS, we must have performed sufficient characterization to establish baseline design values. This characterization is essential for establishing standards and guidelines for design using ISM systems.
- No single process represents a panacea for the challenges in logistics faced by long duration, long endurance missions. ISM would include a suite of technologies for manufacturing and recycling.

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