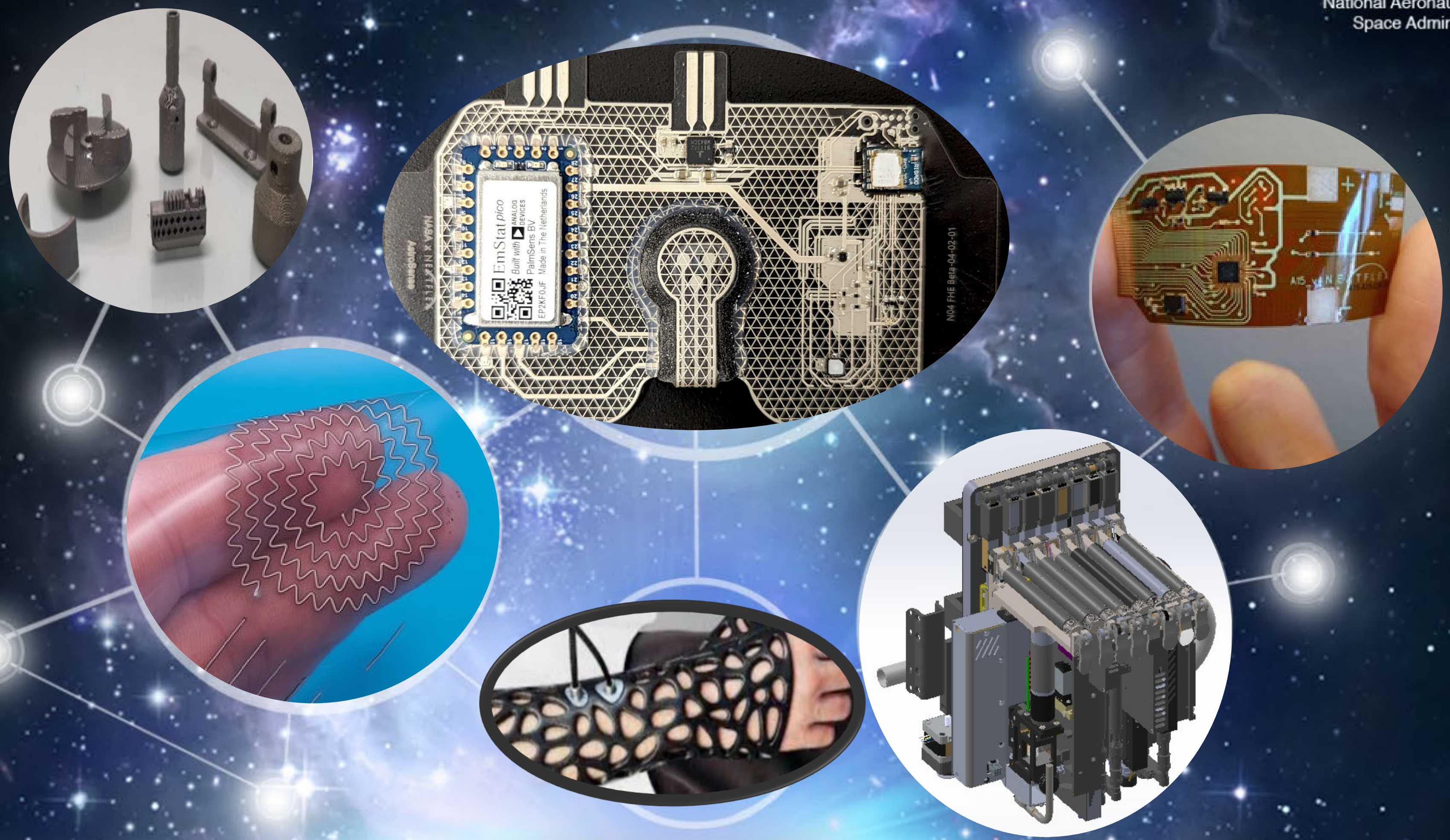


National Aeronautics and Space Administration

In Space Manufacturing
NASA MSFC

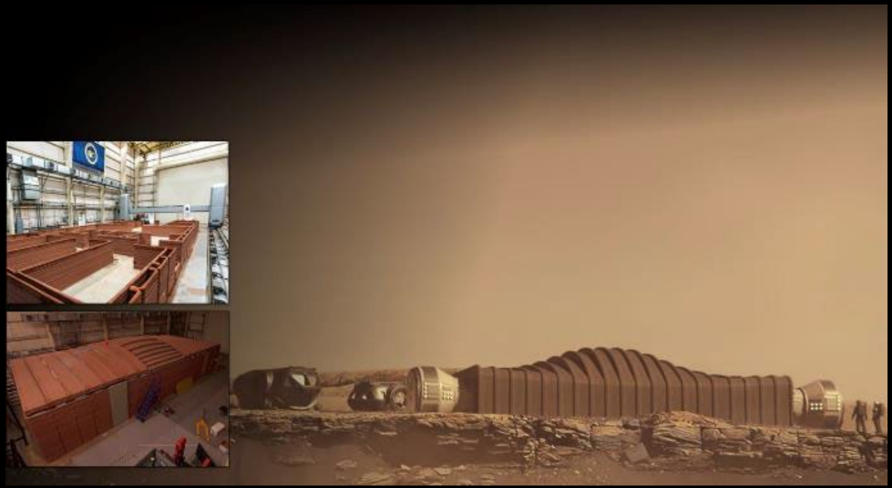
Dr. Jennifer M. Jones | October 17, 2023 | MP3 Workshop

Approved for public release

Why In-Space Manufacturing??

Reduce Launch Burden Related to Cargo Delivery to Space (image credit NASA)

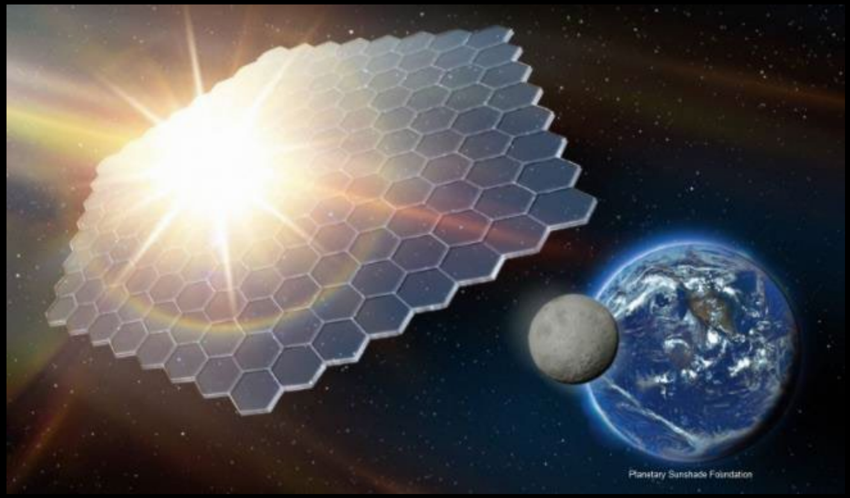
Reduce launch mass through in-situ resource use (image credit ICON)



Moon to Mars Objectives (image credit Redwire)

Recycling and Trash Management (image credit NASA)

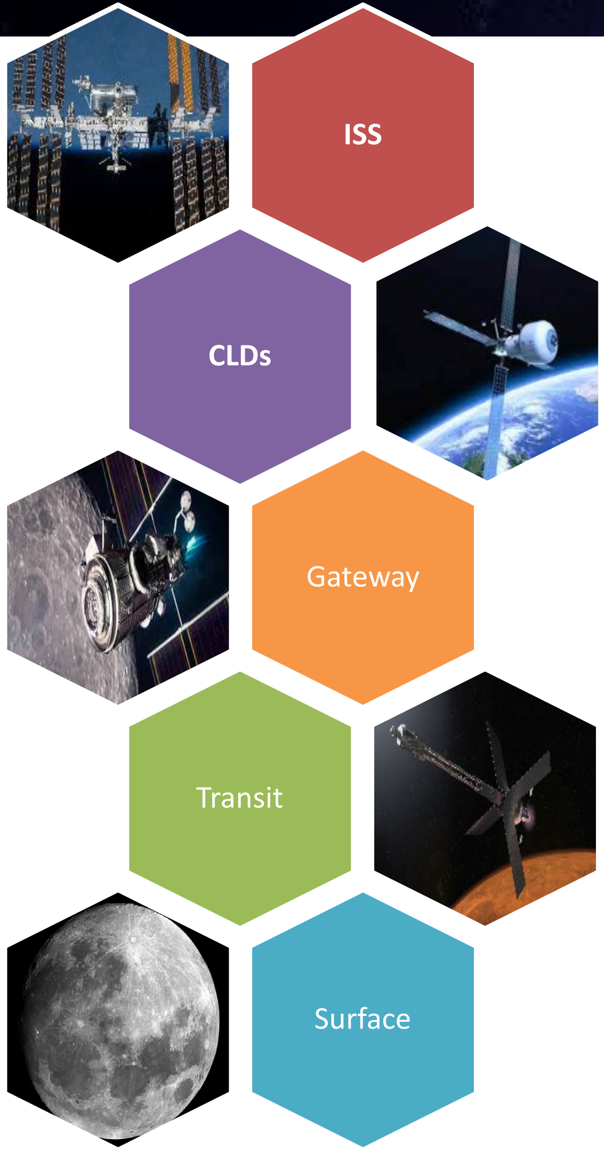
On-demand manufacturing of critical parts and tools



Build objects too big or fragile to launch

Bring → Recycle & Reuse → In-Situ Resource Utilization

In-Space Manufacturing Goals & Objectives



1) Develop a Space Economy

Applications: Manufacture goods for Government and Industry

- Leverage the microgravity environment
- Enable Outfitting of Habitats
- Manufacturing goods in space for Earth

Focus: AM/Welding of Metals, Polymers, Electronics, Logistics Reduction, Biomanufacturing, and Computational Modeling/Digital Twins

2) Enable Sustainable Deep Space Missions

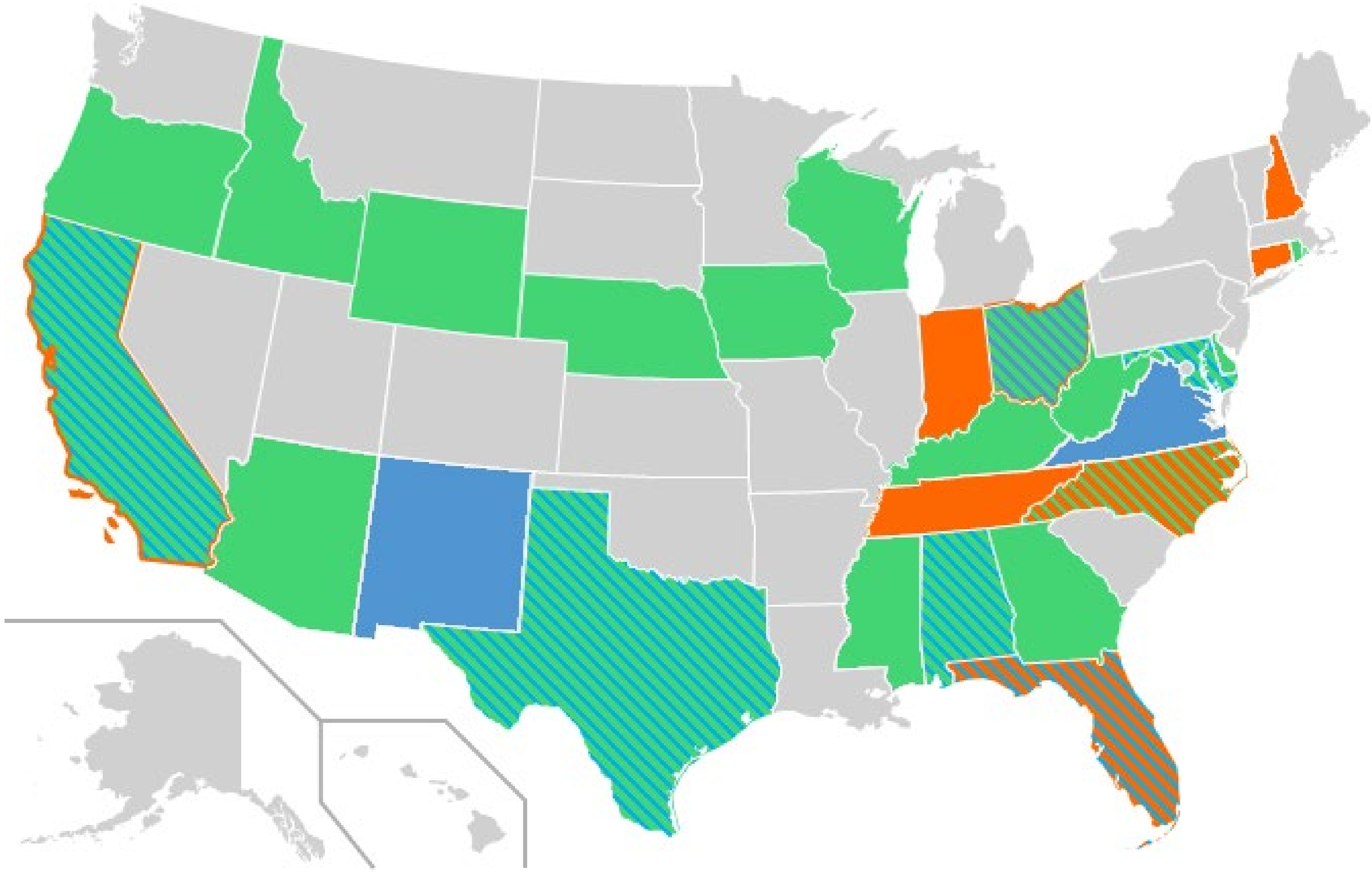
Applications: Living Sustainably on the Lunar and Martian Surfaces

- Medical Devices
- Crew Tools & Engagement
- Habitats Outfitting & Infrastructure
- EVA Aids (ex. modular excursion devices)

Focus: Enabling living and working in space to be sustainable → reducing operations cost.

Takeaway: NASA is investing in the development of enabling agile manufacturing technologies for use in space.

Collaborations & Partnerships

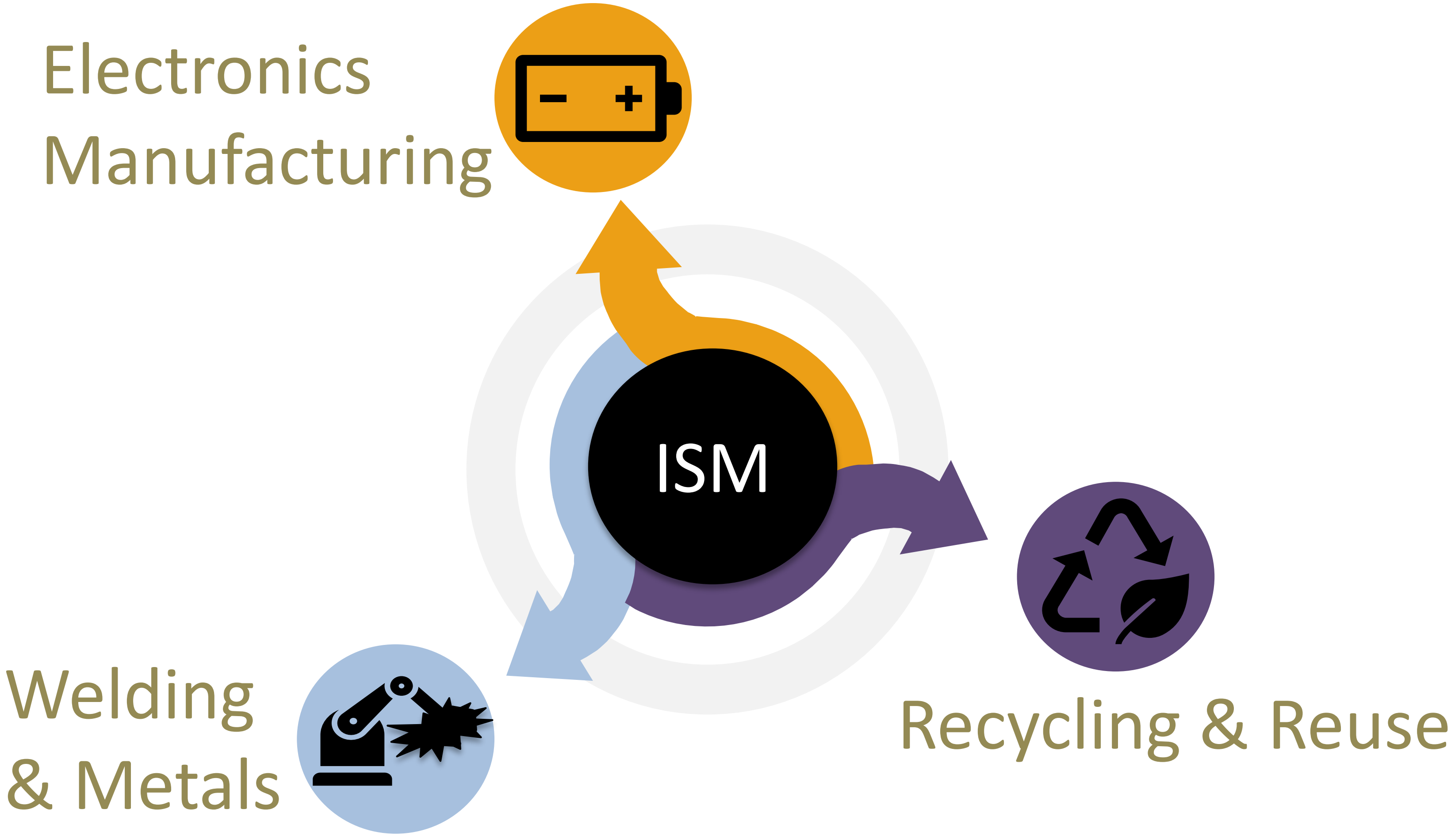


Academic
- University of Louisville
- University of California Berkley
- University of Nebraska
- University of Alabama Huntsville
- Appalachian State
- Auburn University
- Boise State
- Georgia Tech
- California Tech
- Iowa State University
- Florida A&M University
- Oregon State
- West Virginia University
- Youngstown State University
- University of El Paso
- University of Wisconsin
- University of Wyoming
- University of Delaware
- University of Texas El Paso
- Ohio State University
- Mississippi State
- Northern Arizona University
- University of Delaware

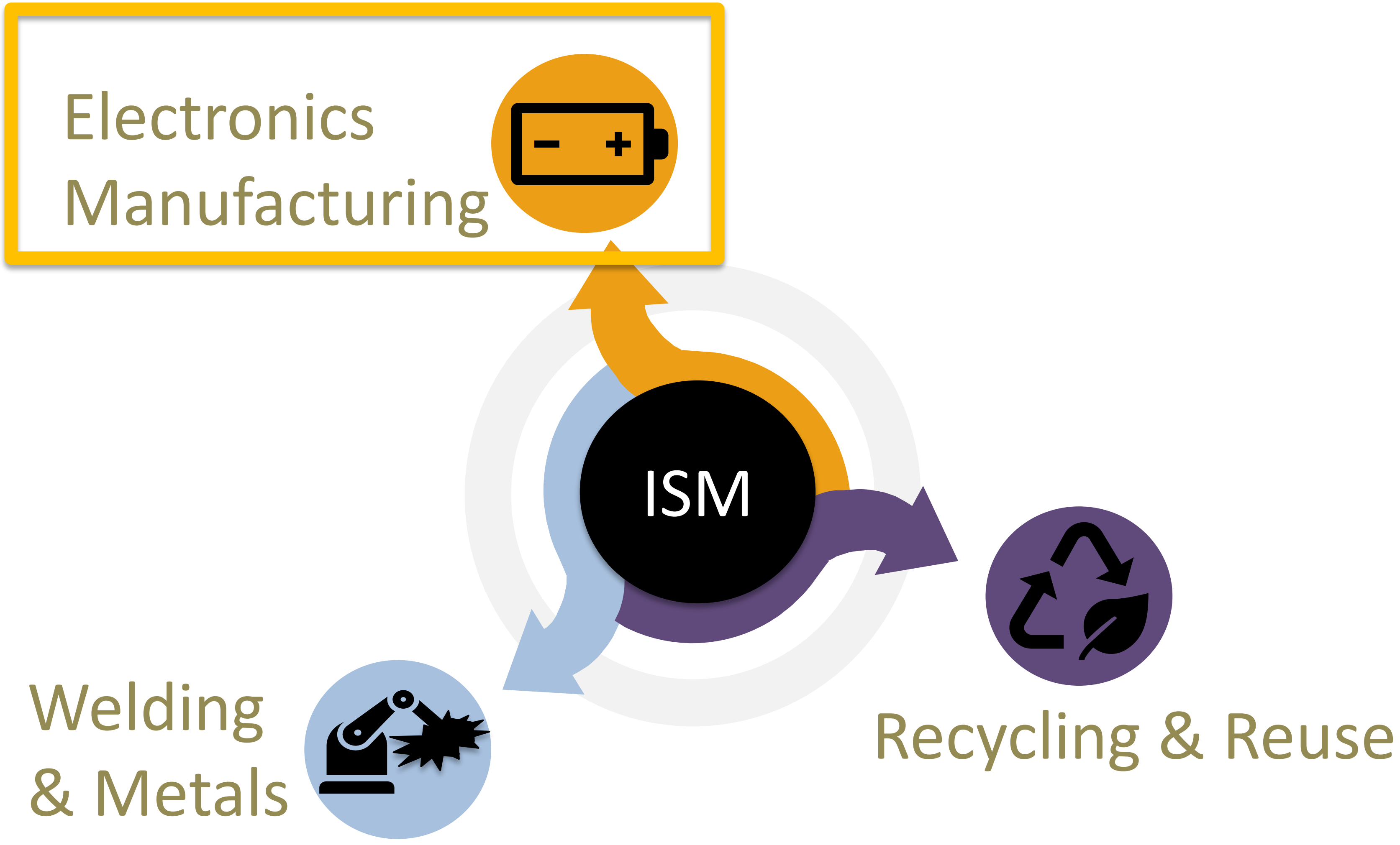
NASA Centers
- Marshall Space Flight Center
- Ames Research Center
- Johnson Space Center
- Kennedy Space Center
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Glenn Research Center
- Langley Research Center
- White Sands Test Facility

Industry
- Techshot
- Redwire Space
- Cornerstone Research Group
- Goeppert
- NextFlex
- nScrypt
- Multi3D
- Branch Technologies
- Intel
- Fujifilm
- Axiom Space
- Faraday Incorporated
- LambdaVision

In Space Manufacturing Focus Areas



In Space Manufacturing Focus Areas



On Demand Manufacturing of Electronics (ODME) Technology Focus Areas

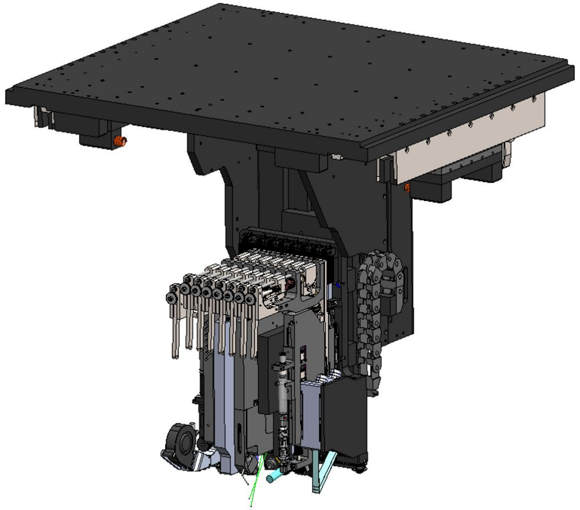
In Space for Space *EXPLORATION*	In Space for Earth *COMMERCIALIZATION*	Ground Development *TECH MATURATION*
Microelectronics	Semiconductor Fabrication	Printed Semiconductors & Components
Sensors	Semiconductor Crystals/ Wafers	Next-Generation Deposition Systems
Power & Energy	Semiconductor 2D Materials	Advanced Toolplate Tools
		Lunar Surface Inkless Deposition Systems

ODME – Advanced Toolplate Development

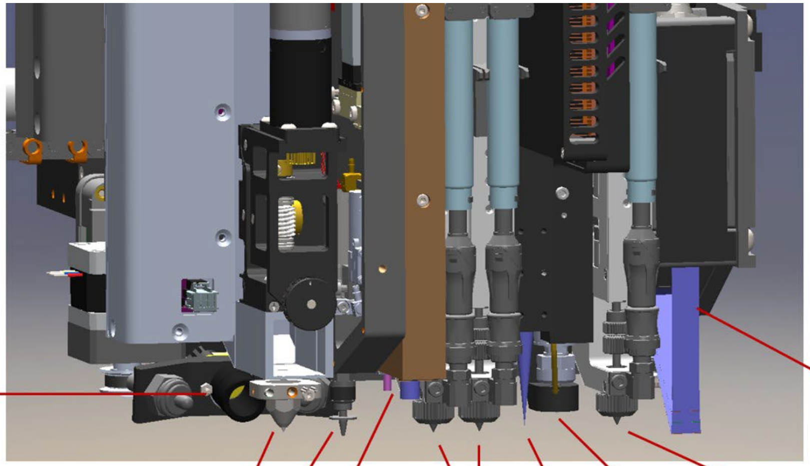
The ODME Advanced Toolplate is a major technology development for Multi-material 3D printing.

- The new Advanced Toolplate is 40% the volume of the previous Toolplate.
- Generation 3 tools are 35% smaller than generation 2, enabling a doubling in the number of tools on the Toolplate from four (4) to eight (8), thus doubling the ODME process capability and minimizing crew time in changeovers.
- New toolheads are also being developed for the Advanced Toolplate, including EHD inkjet (semiconductors) and Faraday electrodeposition (Phase II SBIR).

Target applications for infusion:
- Semiconductors / commercialization
- Microelectronics for future missions
- Sensors – HRP and ECLSS



Motion Gantry and Advanced Toolhead Assembly



Images provided by Sciperio.

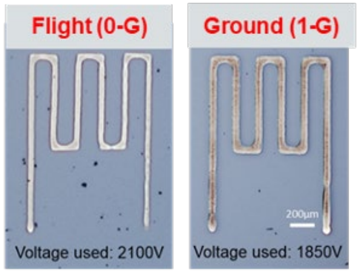
ODME – Electrohydrodynamic Inkjet Development

ODME is working with academic partners to develop a next-generation thin film deposition system for semiconductors and microelectronics.

EHD inkjet uses an electric field rather than piezoelectric force for very precise deposition. This system has the potential to advance thin film deposition SOA into the nanometer range.

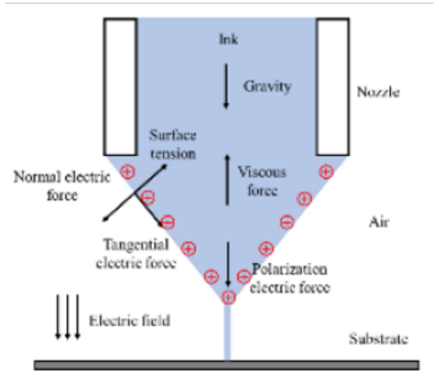
- ODME and Flight Opportunities have already completed two parabolic flight campaigns (120 parabolas) of zero gravity testing of this system prior to FY23. Two additional campaigns are planned for FY24.

- ODME, with the University of Wisconsin and Sciperio, are developing a new EHD inkjet toolhead for the Advanced Toolplate.
- A parabolic flight campaign to test the Advanced Toolplate and new toolheads planned for Spring 2024.



Line width 53 µm

Line width 62 µm



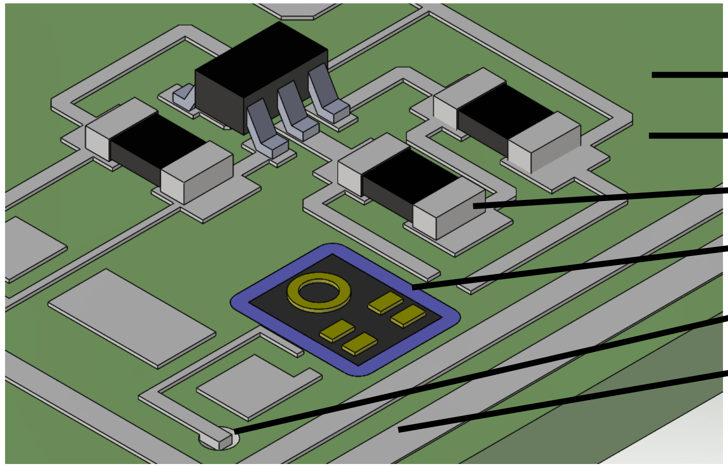
Target applications for infusion:
- Semiconductors / commercialization
- Microelectronics for future missions
- Sensors – HRP and ECLSS

SPEC	DMP-2850 IJ (Industry Std)	EHD Inkjet
Minimum feature size	30 microns	0.5 microns
Ink viscosity	4-8 centipoise	0.1 - 500 centipoise
Ink surface tension	28-32 dynes/cm	1 - 800 dynes/cm
Droplet size	1pL - 10pL	0.1fL - 10pL

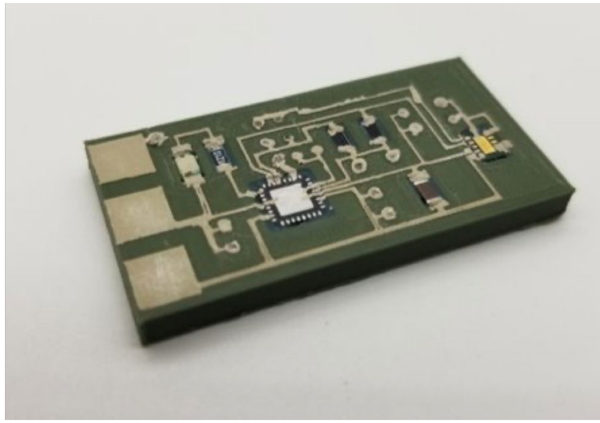
ODME – Multilayer Process Development

ODME is developing the capability to fabricate more complex printed electronics comprising multiple layers on flexible and non-flexible substrates. ODME has a collaborative project with Auburn University on this research. ODME and Auburn have made significant progress in the second year of their research on multilayer processing.

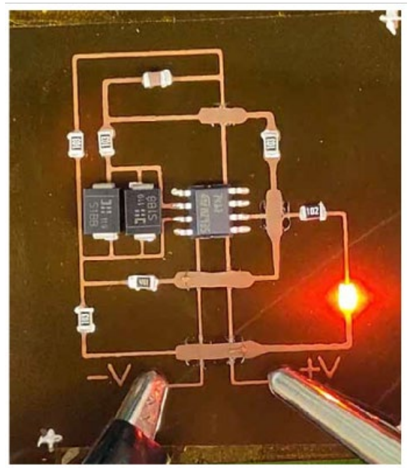
- Development and evaluation of multiple multilayer deposition processes and materials.
- Successful printing of a Multilayer flexible printed circuit board.
- Demonstrated with a functional LED blinking circuit board.
- ODME and Sciperio also developed and fabricated a functional multilayer CO_2 sensor.



Target applications for infusion:
- Microelectronics for future missions
- Sensors – HRP and ECLSS



Multilayer CO_2 sensor



Multilayer functional blinking circuit

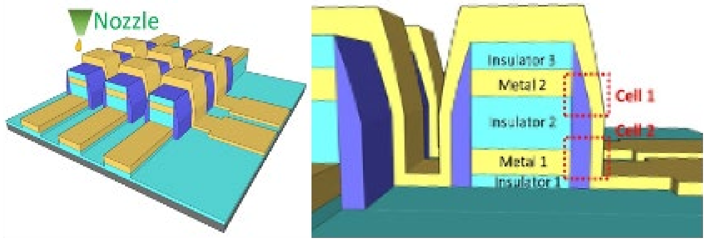
ODME – Printed Semiconductor Development

Tech maturation through ODME development is a critical phase of commercialization of printed semiconductors. ODME is collaborating with Intel, Axiom Space, TEL, Arizona State, and Univ. of Wisconsin to develop printed ReRAM memory chips for microgravity production.

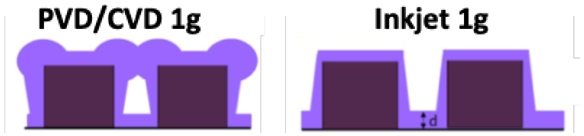
SEADS = Space Enabled Advanced Devices and Semiconductors

- ODME EHD Inkjet process used to print nanocircuits of printed memory chips.
- The EHD process is significantly faster with much higher product yields, and it eliminated a secondary etch process required by current ground-based semiconductor fabrication.
- ODME and the Intel team have successfully demonstrated this technology on the ground in FY23, with a planned demonstration on parabolic flight testing in November.

Target applications for infusion:
- Semiconductors / commercialization

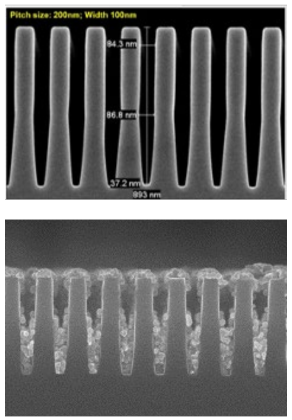


3-dimensional memory planned as demo printed electronic device for parabolic flights



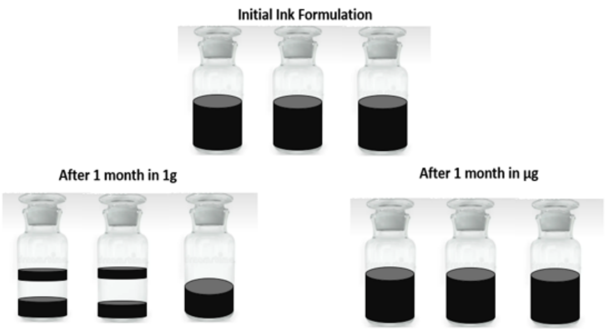
- Combination of inkjet printing and μg offer high step coverage without voiding problem. Beneficial for 3D memory fabrication with high density and high performance

Trench to be filled



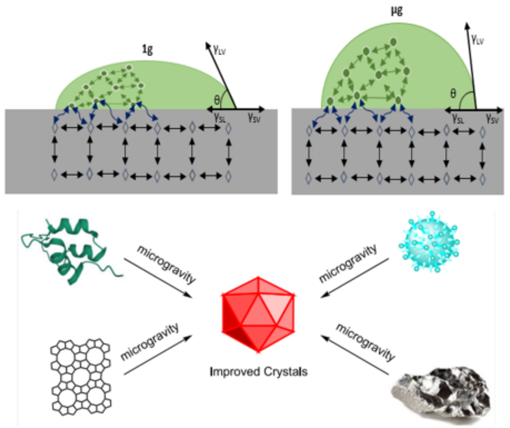
Materials-related mg impacts

Sample preparation stage (before printing)



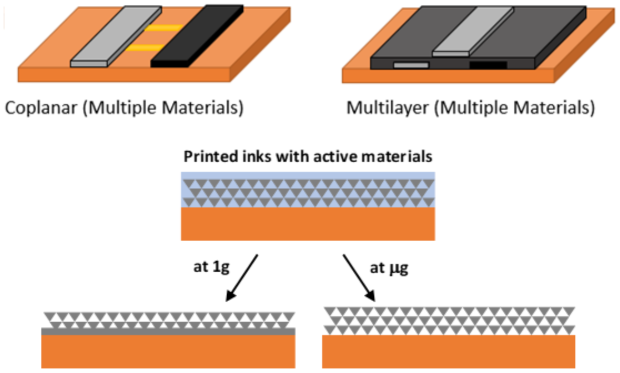
- μg removes convection, sedimentation, and buoyancy that can disrupt physical and chemical processes.
- Less aggregation and sedimentation of colloidal active materials → higher stability and longer ink shelf life
- Higher stability allows more loading of active materials (less additives).

Manufacturing stage (during printing/fab)



- Diffusion and surface tension-dominant processes enables more uniform structures at individual molecule level.
- In printing, μg allows less spread of the printed layers → higher resolution
- In crystal growth, μg allows bigger crystal size and fewer defects → high quality

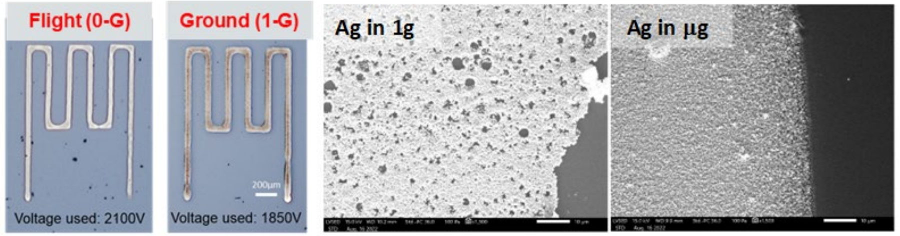
Application stage (after printing)



- In printing, higher concentration of the active material in inks allows superior performance and operation stability.
- In crystal growth, better crystal quality gives superior efficiency and lifetime.
- Multilayer fabrication is enabled to form integrated systems with multiple functional devices. More complex devices.

Demonstration examples of mg impacts

Inkjet and EHD printing in μg



Dec-2021 flight test

ISU-Silver-35s1 (S35s1)	
Silver content (wt.%)	35 ± 2
Average particle size (nm)	150 - 200
Viscosity (cP)	300 - 500
Solvent	DMSO
Surfactant (wt.%)	1%
Aged (months)	Fresh

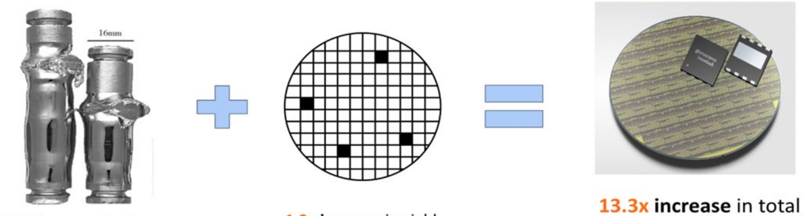
May-2022 flight test

ISU-Silver-35s1 (S35s1)	
Silver content (wt.%)	50 ± 2
Average particle size (nm)	150 - 200
Viscosity (cP)	300 - 500
Solvent	DMSO
Surfactant (wt.%)	0.6-1%
Aged (months)	Fresh

Resistivity (μΩ·cm) Bulk Silver = 1.59 μΩ·cm		
Sintering (30 min)	35% Ink	50% Ink
50 °C	4.27E+8	19795
100 °C	1.06E+7	2213
150 °C	123.3	15.27
200 °C	19.68	2.98

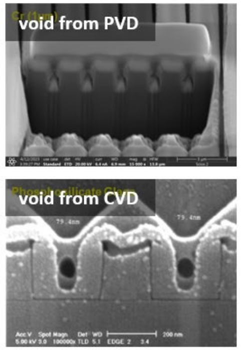
- Micro-structures of printed patterns results in denser structure with less porosity
- Silver loading can be increased from 35% (at 1g) to 50% (at mg) due to less agglomeration → 8.1 times higher conductivity
- Under mg, larger voltage can be used for reducing printed line width (higher resolution) for EHD mechanism.

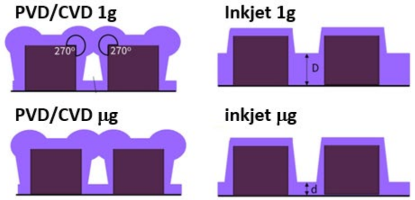
Crystal growth

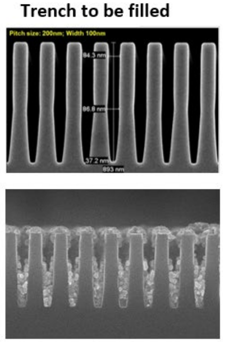


- From the studies of 500 entries in last 50 years, 89% of macromolecules crystals, 79% of inorganic crystals, and 81% of semiconductor crystals reported improved crystal structures in mg.

Trench filling - Fabrication

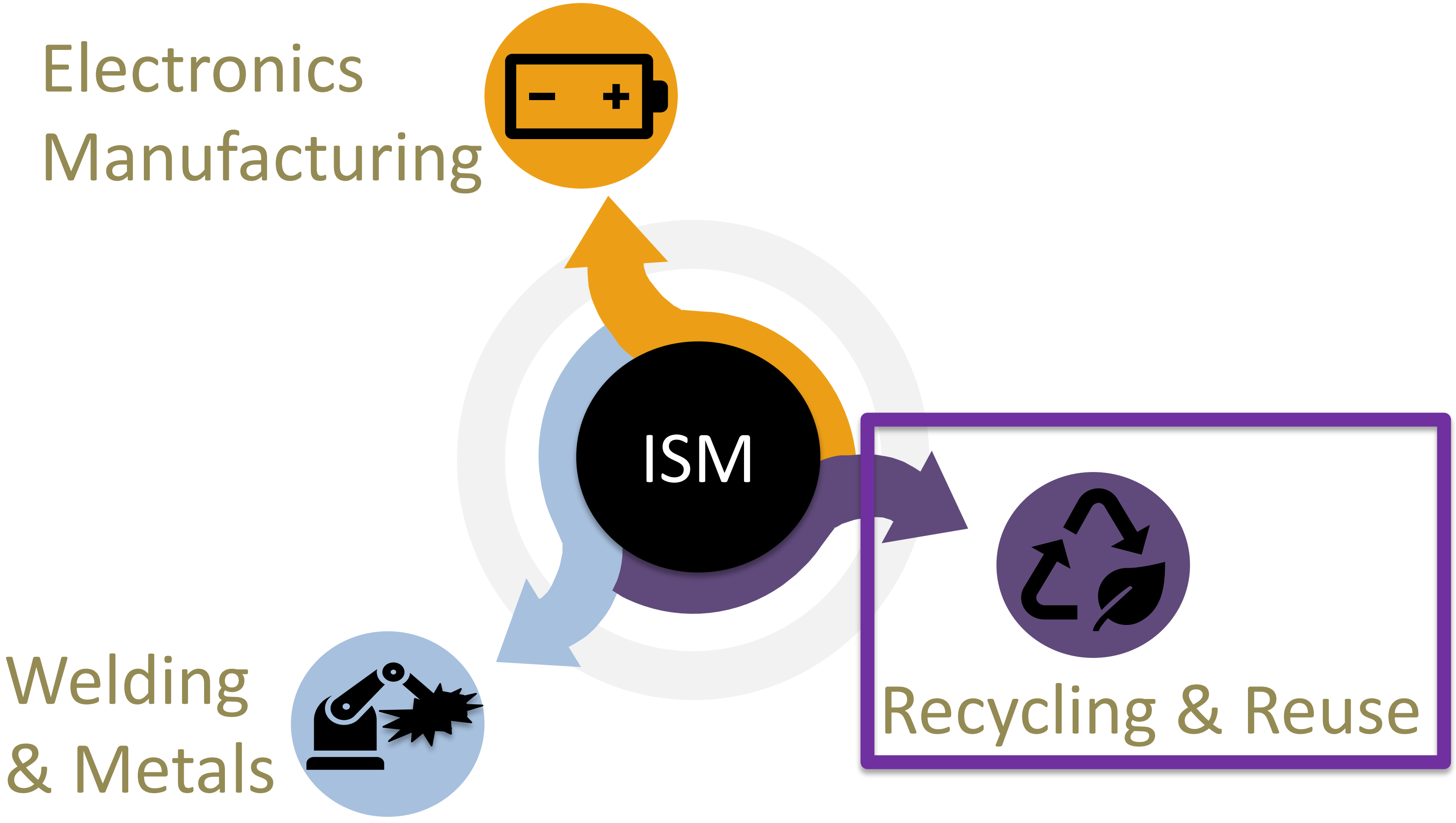






Combination of inkjet printing and mg offer high step coverage without voiding problem. Beneficial for 3D memory fabrication with high density and high performance

In Space Manufacturing Focus Areas



Recycling and Reuse

Waste Materials

A trash container is pictured on a trajectory away from the International Space Station and toward the Earth's atmosphere for a fiery, but safe disposal.

Ongoing Trade Study into source materials

Intentional design with common use materials suitable for R&R and ISM

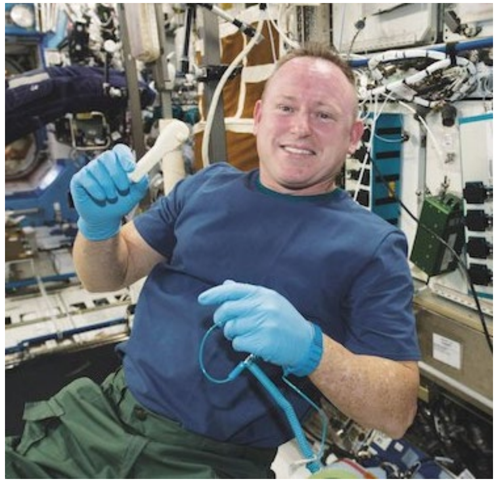
Sorting
Processing
Grinding
Extruding

Recycled feedstock

Polymers and metals

In-Space Manufacturing

Quick, Cheaper, Flexible

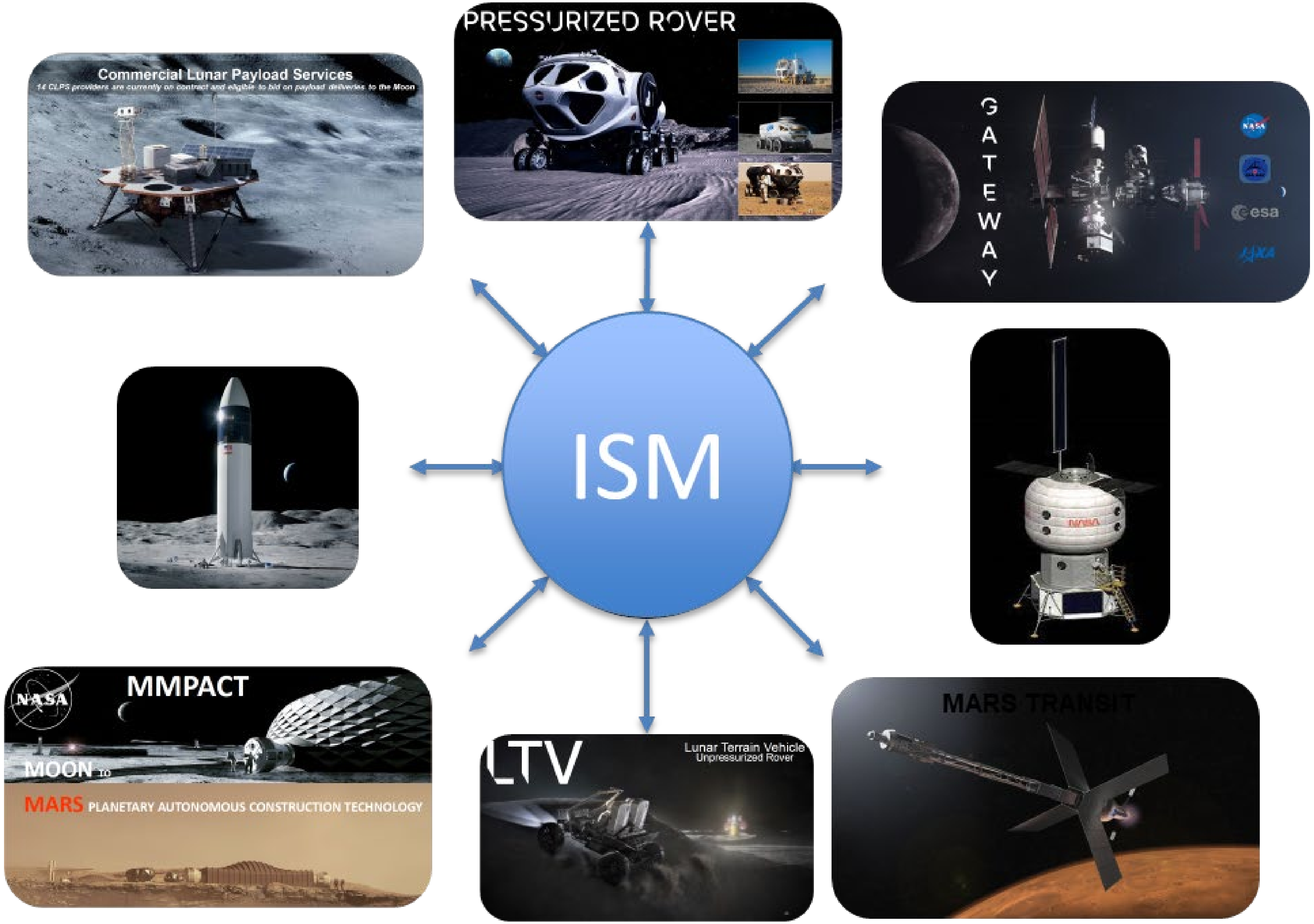


NASA Astronaut Barry (Butch) Wilmore holds a ratchet wrench created in 2014 with the 3D printer aboard the International Space Station using a design file transmitted from the ground

Outfitting

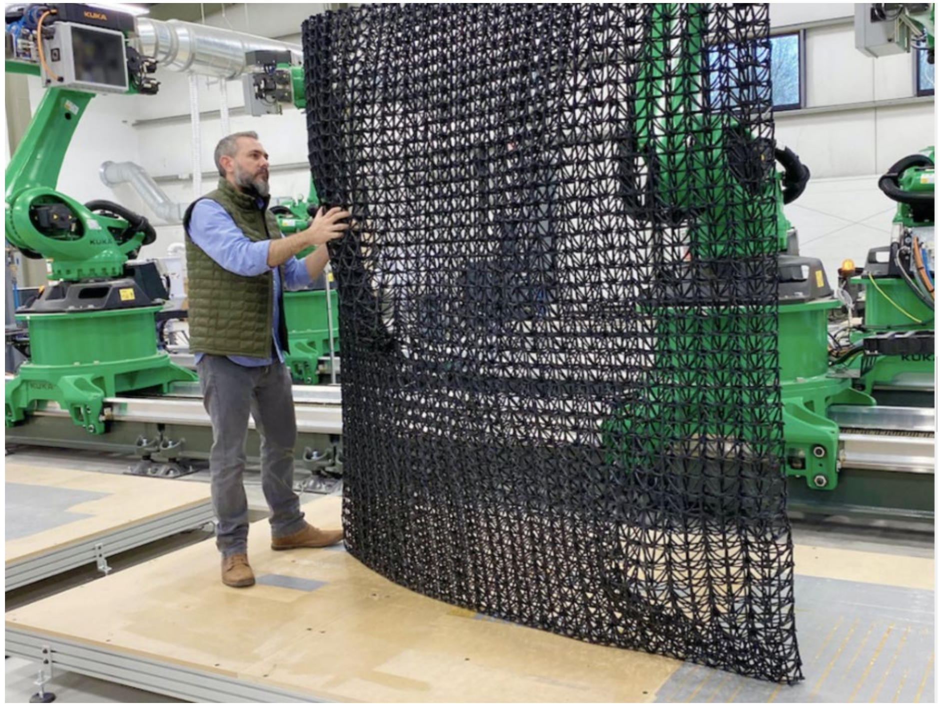
In situ installation of subsystems on location as well as the associated planning and preparation required for this process.

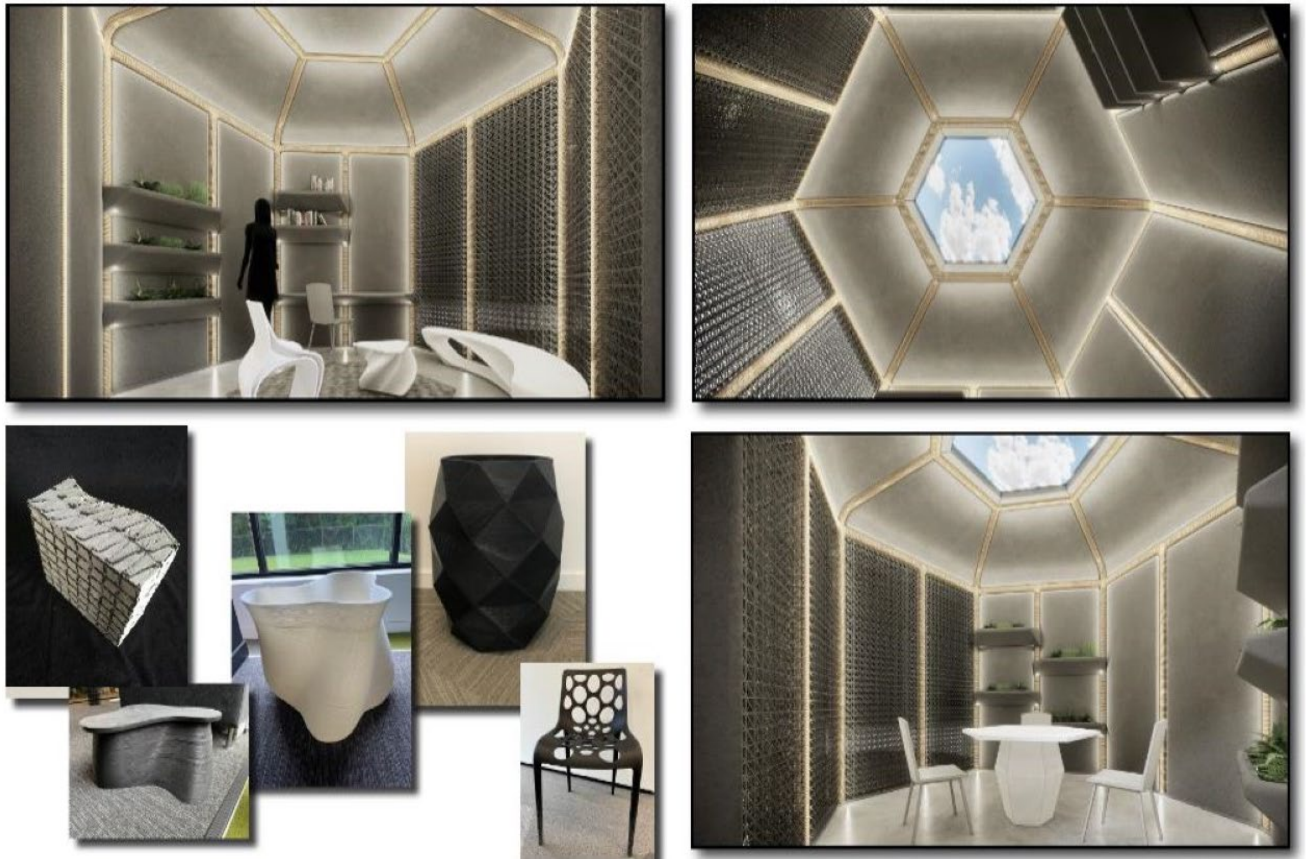
Examples: Utilities, furniture, wall partitions, storage, life support equipment, exercise equipment, hygiene amenities, cleaning and sanitation supplies, wearables, science instrumentation, tools, computers, communication equipment, personal items, etc.



Freeform Manufacturing For Outfitting

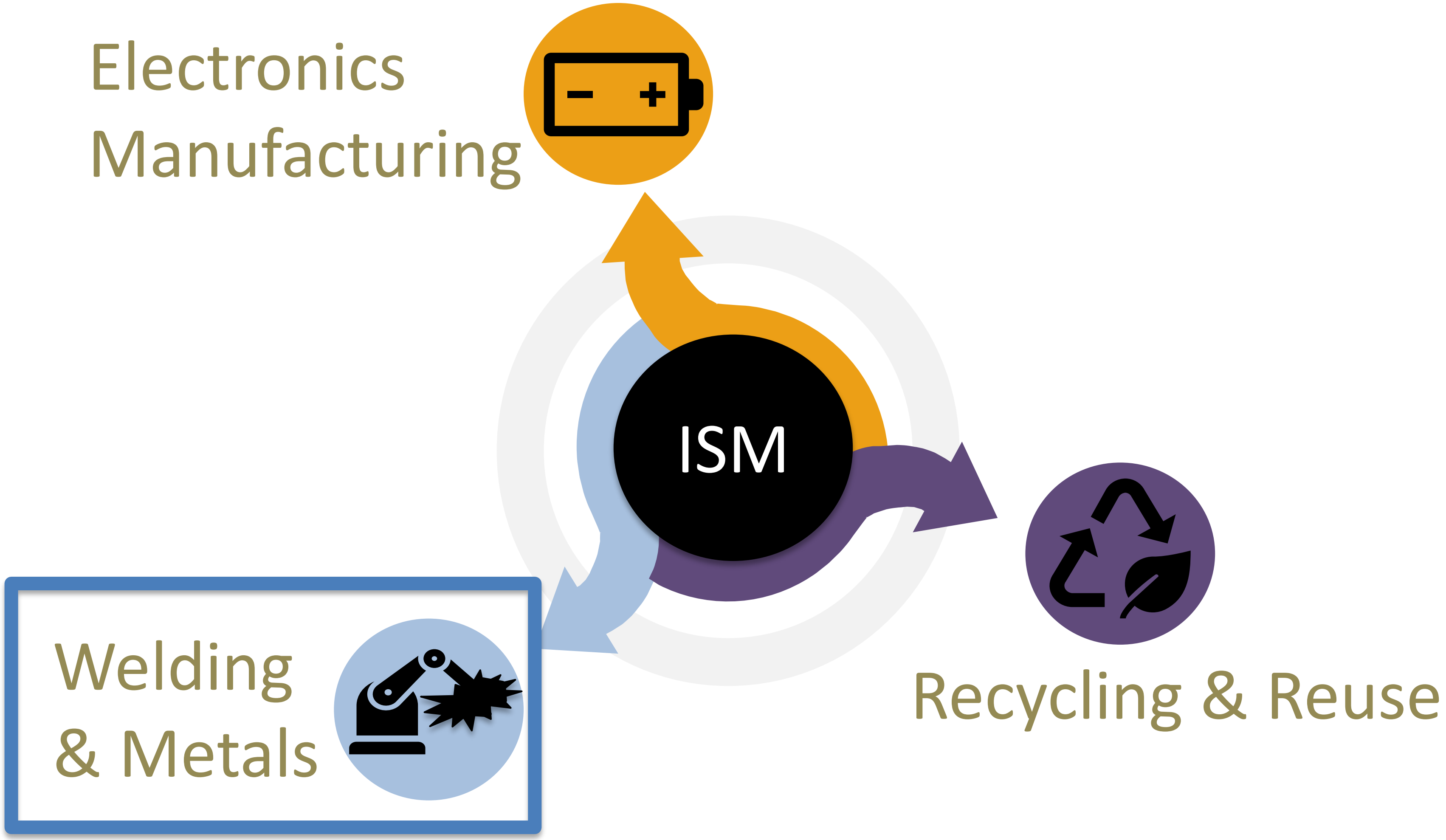
Branch Technology





Images provided by Branch Technology.

In Space Manufacturing Focus Areas



On Demand Multi-materials Manufacturing FabLab

Print Module

- Advanced Toolplate:
    - Printing of Metal and Polymer Parts
    - Finish Milling
- Inspection Subsystem
    - Defect Detection and Remediation
- Environmental Control
    - FOD capture system
- Electronics Manufacturing
    - Smart Pumps, Directed Energy, Pick and Place, etc.
- Avionics and Control

Furnace Module

- Sintering of Metal Parts
- Brazing of Assemblies
- Avionics and Controls
- 2000W Peak Power

Process Gas Drawer

- Provides Argon to Furnace Module

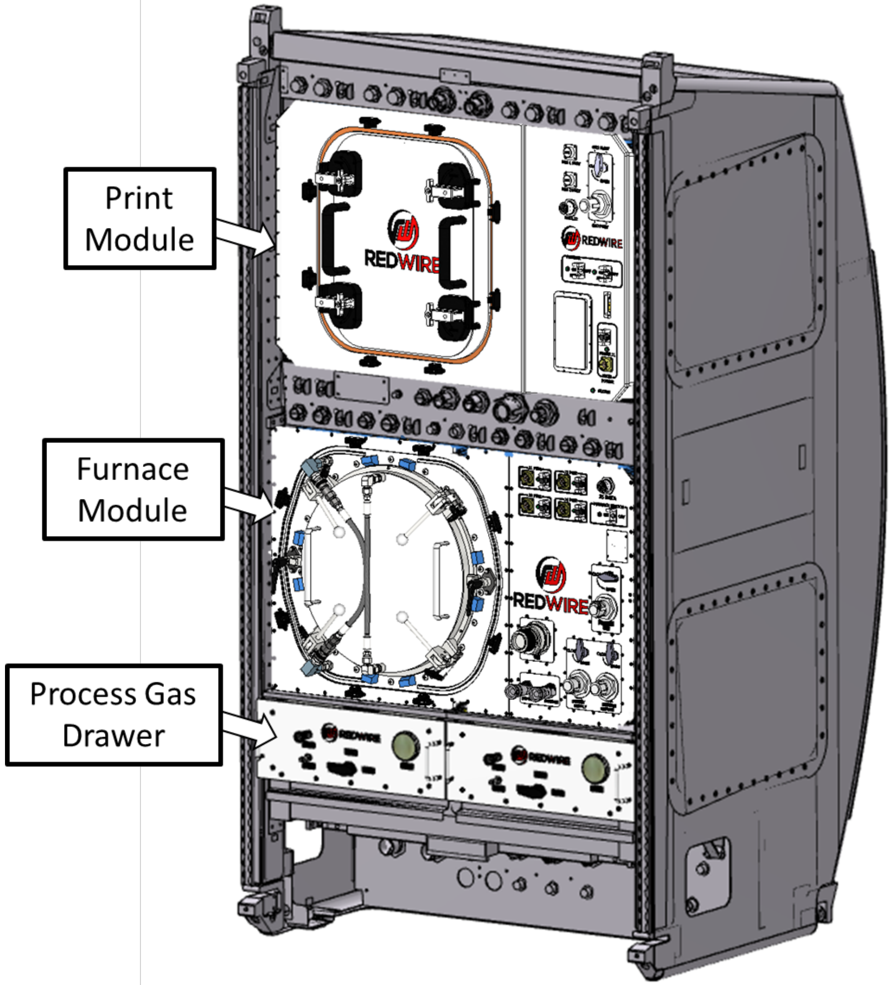


Image provided by Redwire Space Technologies, Inc.

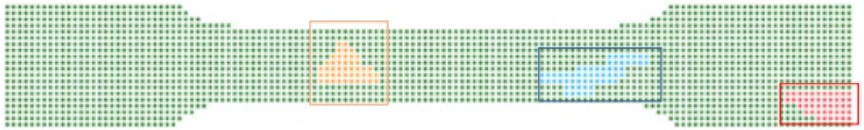
Full Payload

- Glovebag concept for FOD control
- Part Transfer Box for transport between modules
- Remote Commanding for limited crew interaction
- Compatible with science investigations beyond the ISM project

Bound Metal Deposition Printed Parts with FabLab

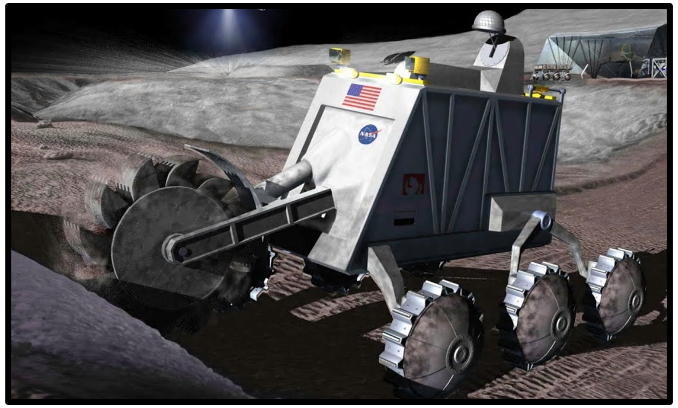
Ideal Point Cloud

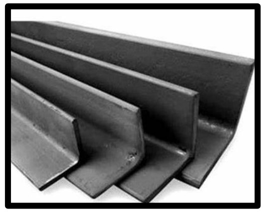
Scanned Point Cloud Data

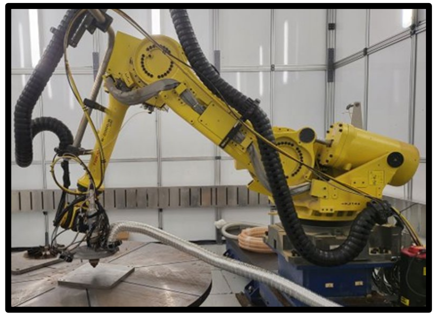


Images provided by Redwire Space Technologies, Inc.

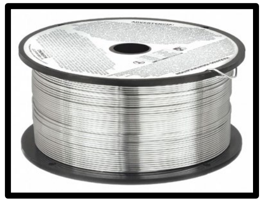
Future: In-situ Resource Utilization and Manufacturing

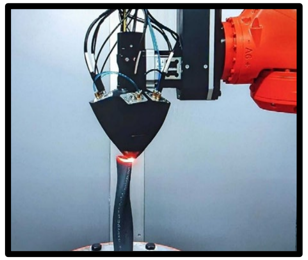


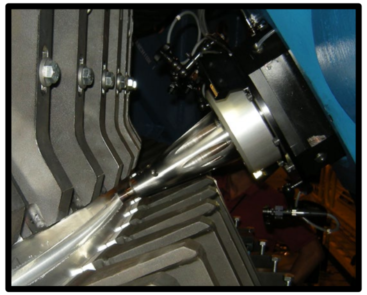


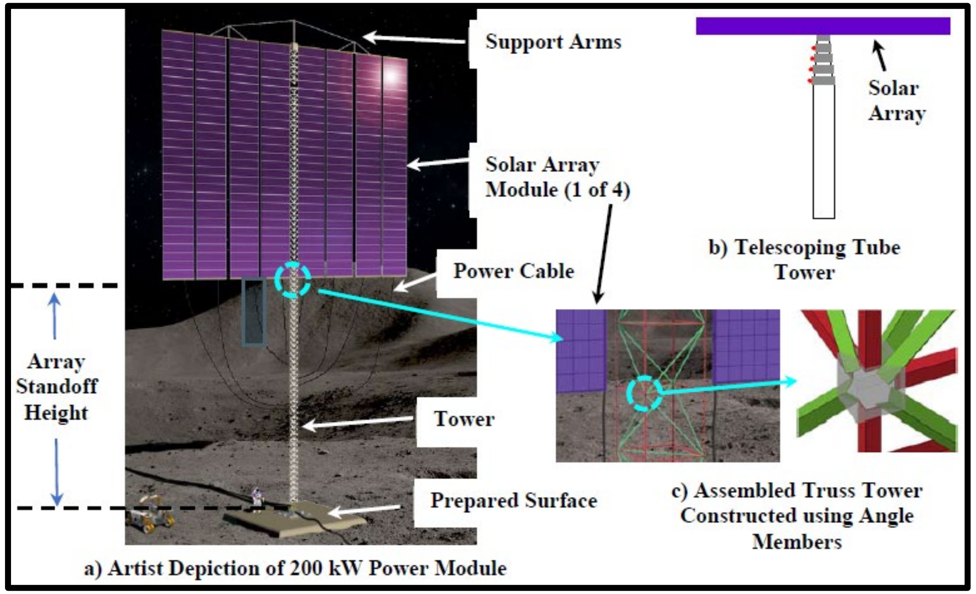


Extract/Recycle Resources → Refine Materials → Integrated Welding/AM → Collaborate to Build Structures (Power/Comm Towers, Habitats, Vehicles, etc;)



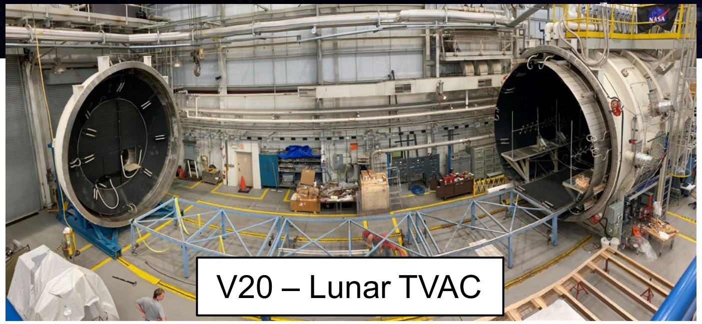






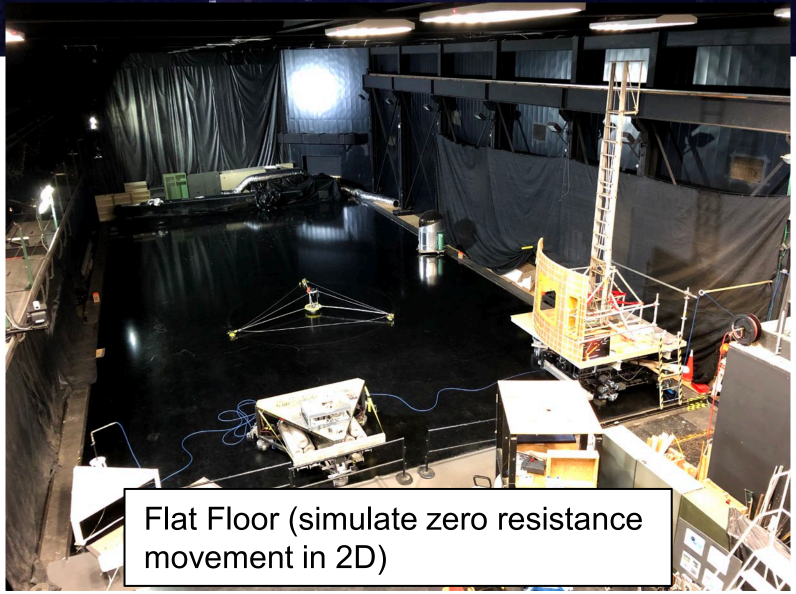
Computational Modeling, AI/ML and Digital Twins Enable All Steps of this Process

MSFC Capabilities



V20 – Lunar TVAC

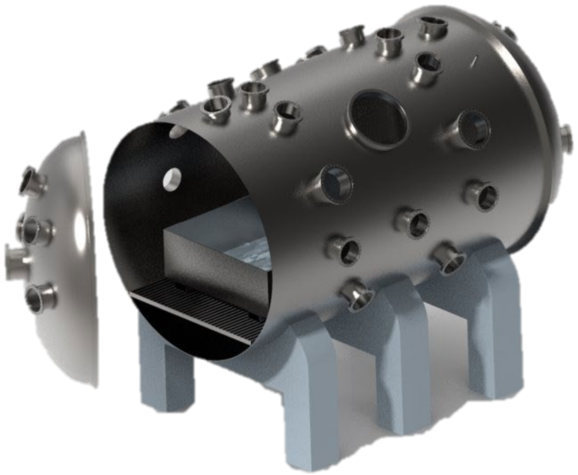
Solar Wind Chamber



Flat Floor (simulate zero resistance movement in 2D)

Weld/AM Development & Manufacturing Facilities

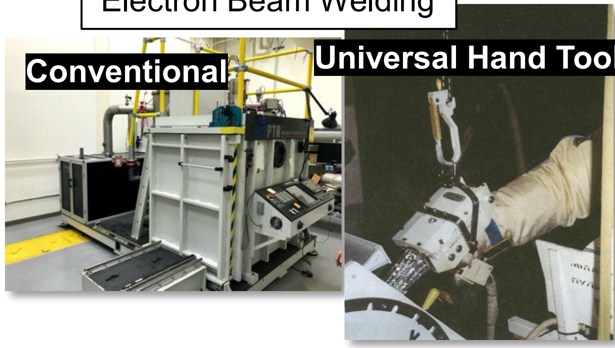
UV Radiation Test Chamber



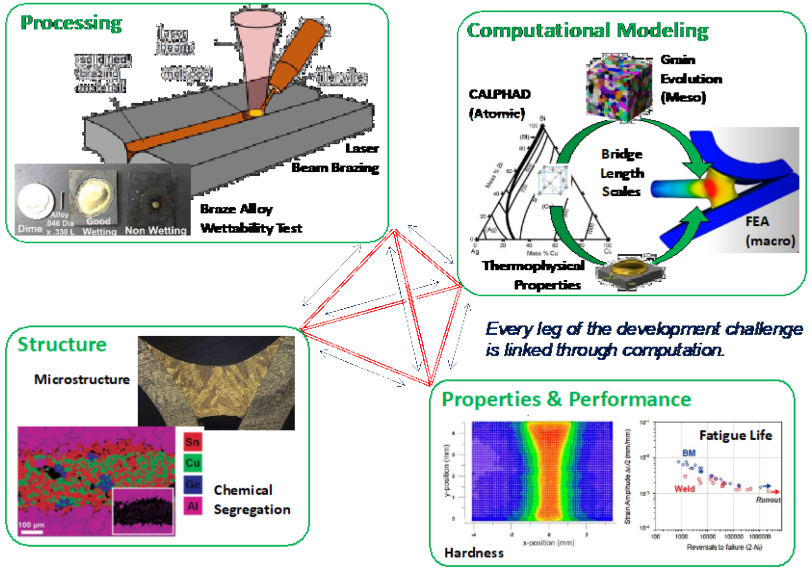
Planet Chamber (combines multiple environments => atmosphere, radiation, temperature, regolith)

Charging from Plasma Environments Chamber

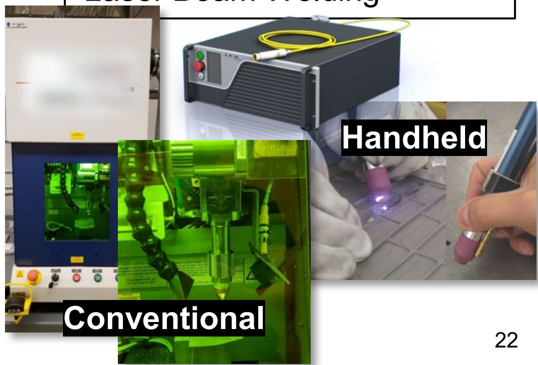
Electron Beam Welding



Computational Materials Modeling



Laser Beam Welding



High Fidelity Experiments Coupled with Computational Modeling, AI/ML, and Digital Twins Enable Sustainable ISM

Questions?:

ISM Leadership Team
Zachary Courtright
Christopher Roberts
Curtis Hill
Brady Kimbrel
Sara Rengifo
Frank Ledbetter
Jennifer M. Jones

NASA Marshall Space Flight Center
Huntsville, AL 35601