Carnegie Mellon University

Build Space. In Space. An In-Situ Approach

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IN SITU
Latin: "in position" or "on site“

In-Situ Resource Utilization | ISRU

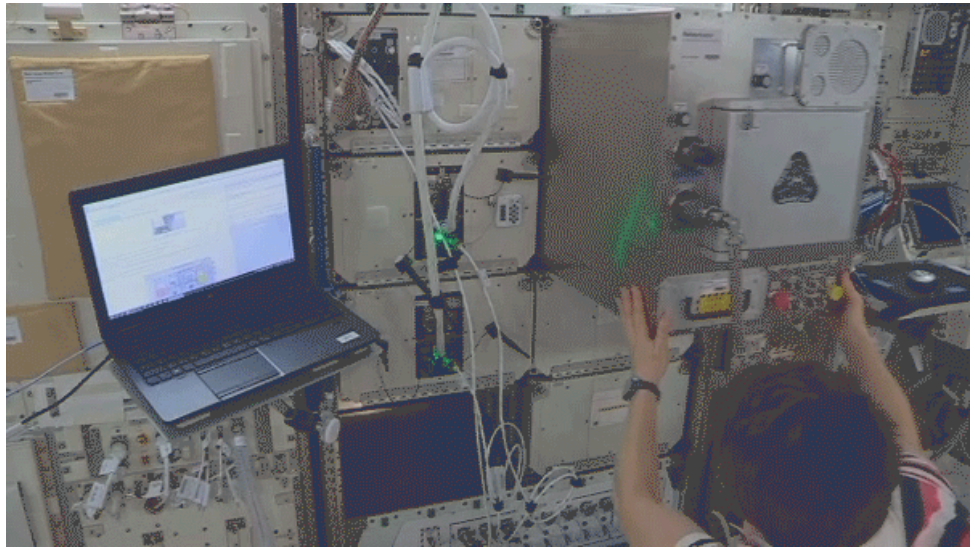
"Harnessing of local natural resources at mission destinations, instead of taking all needed supplies from Earth, to enhance the capabilities of human exploration"~ NASA

In situ supply of life-supporting matters, including water, oxygen, food, solar/electric energy, etc.

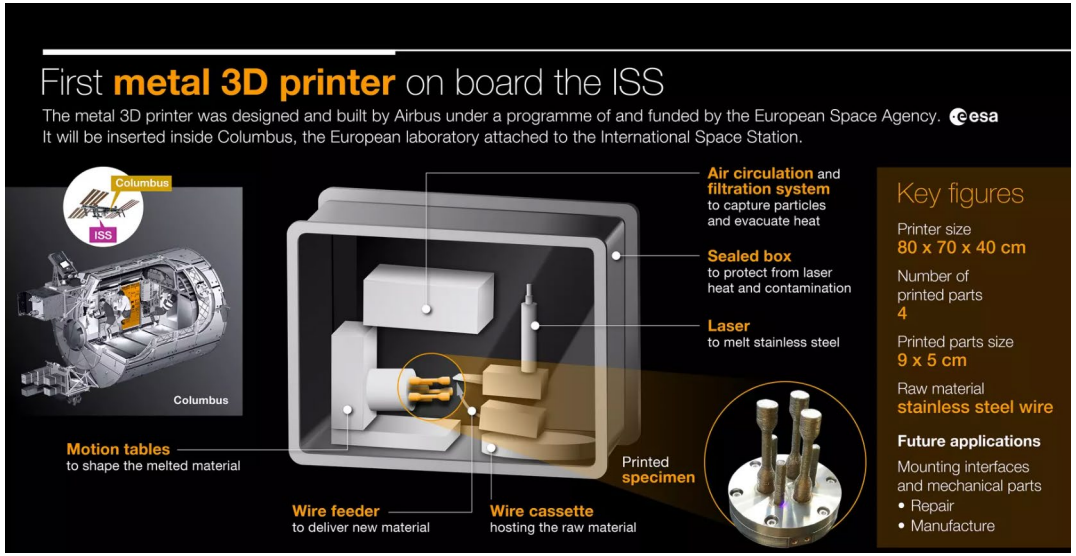
In situ supply of lunar-based rocket propellant, including hydrogen, oxygen, methane (CH_4), etc.

Construction and manufacturing of key facilities, including manned habitat, landing pads, scientific facilities, transport equipment, and maintenance tools.

Recent exponential growth globally in public & private space missions in Additive Mfg and Space Resource Utilization



NASA astronaut Anne McClain installs the Refabricator in Feb. 2019.
Source: NASA



The world's first metal 3D printer for space is on its way to the ISS
Source: Airbus

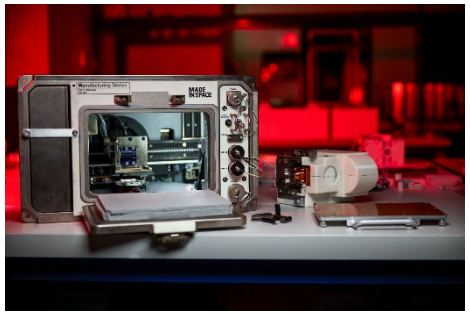
3D printing shakes up the space industry

Several companies have tapped into the domestic space industry with an additive manufacturing process to save money and time.

May 6, 2025

The Washington Post

1st experimental samples of stainless steel from Metal 3D Printer

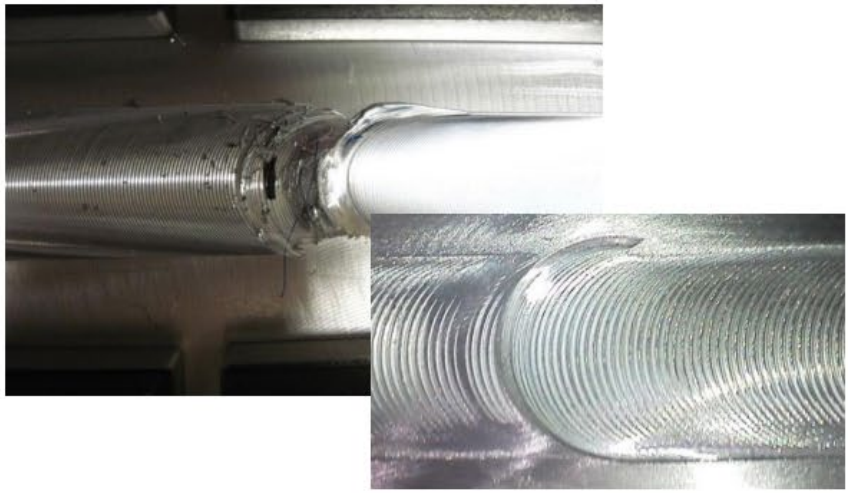


The Redwire Regolith Print Module;
Source: Redwire Space

Why In Situ?

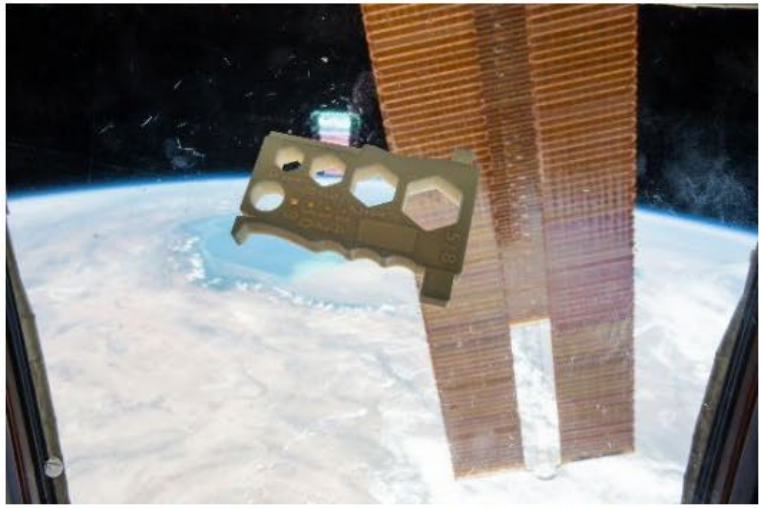
Reduce Launch Burden Related to Cargo Delivery to Space (image credit NASA)

Reduce launch mass through in-situ resource use (image credit ICON) Moon to Mars Objectives

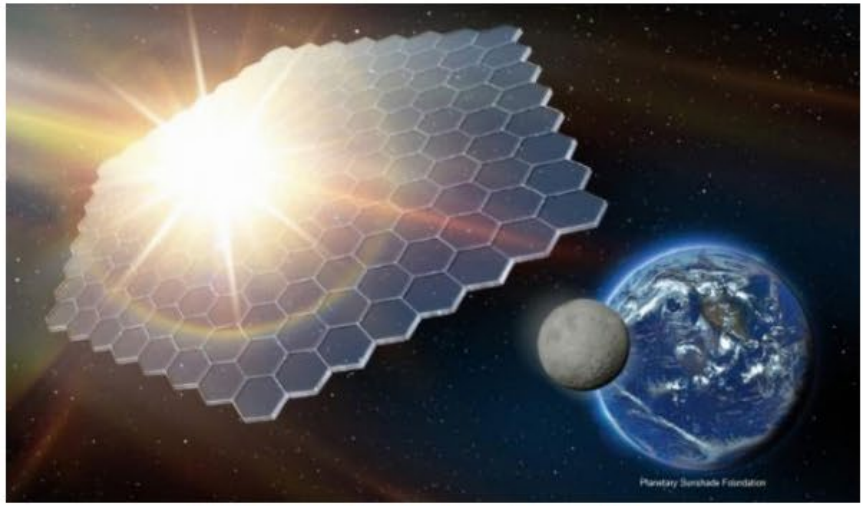


Weld Repair (structural damage, defective weld, damaged weld, etc;)

Recycling and Trash Management (image credit NASA)



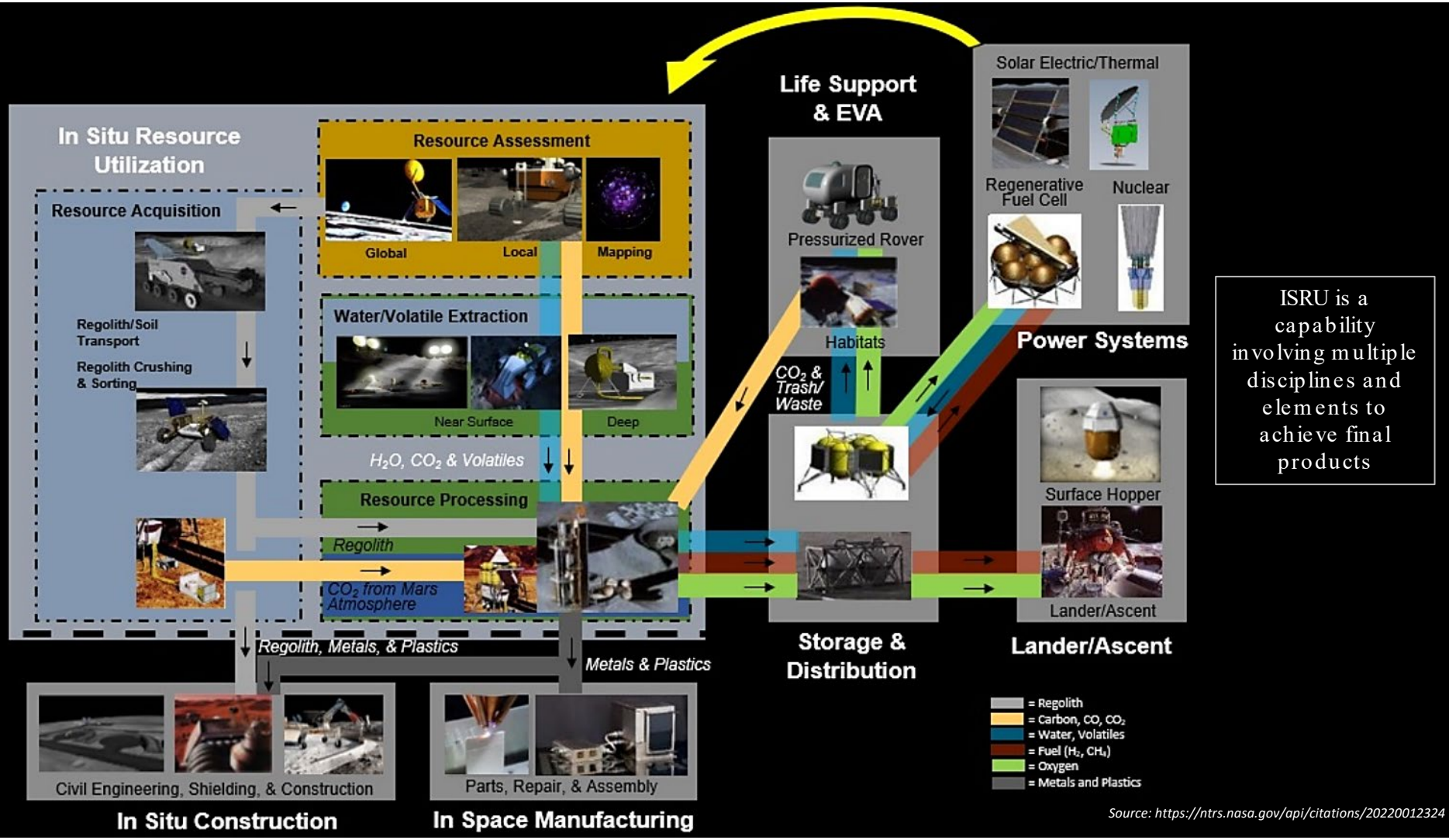
On-demand manufacturing of critical parts and tools (image credit NASA)



Build objects too big or fragile to launch

The ISRU Landscape

Regolith-based Materials and Processes:
- Cementitious
- Geopolymers
- Thermosetting materials, including melting
- Laser sintered
- Microwave sintered



Source: https://ntrs.nasa.gov/api/citations/20220012324

ISRU is a capability involving multiple disciplines and elements to achieve final products

In-Space Manufacturing Challenges

	Free Space	Lunar Surface	Martian Surface
Gravity	0	1/6 Earth's gravity	1/3 Earth's gravity
Atmosphere	$<1x10^{-12}$ torr vacuum	$2x10^{-12}$ torr vacuum	4 torr (95% CO_2; traces of Ar, Ne, O_2, CO)
Temperature	Shade: -200°F Sun: +200°F	Shade: -250°F Sun: +250°F	Shade: -125°F Sun: -25°F
Raw Materials	spent satellites, space debris	regolith (SiO_2 with traces of Al, Fe oxides)	SiO_2, Fe_2O_3, Al_2O_3

- Extremes in the space environment must be considered for in-space manufacturing processes
- Difficult to test for space environmental effects on additive manufacturing processes; Can be simulated by a Physics informed Predictive Digital Twin?

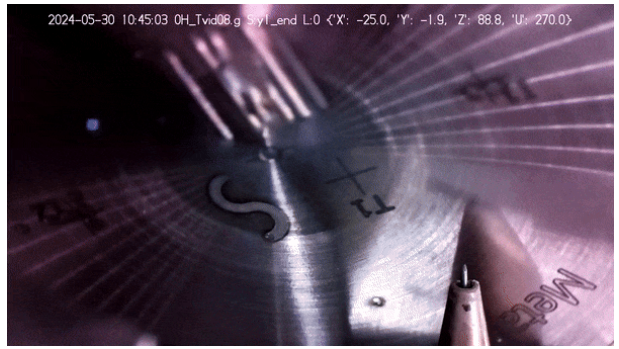
Comparison of Metal AM Processes for In-Space Applications

Metal Fabrication Process	Power Efficiency	Size Adaptability	Consumables	Resolution	Suitability in 0-g
EBF³: Electron beam/wire (Electron Beam Freeform Fabrication)	+	+	+	– wire diameter	+ +
EBM: E-beam/powder bed (Electron Beam Melting)	+	– powder bed size	o powder	+	– – powder handling
DMD/SLM: Laser/powder bed (Direct Metal Deposition/Selective Laser Melting)	–	– powder bed size	– powder, gas	+	– – powder handling
LENS: Laser/powder feed (Laser Engineered Net Shaping)	–	o deposition rate	– powder, gas	+	– – powder handling
SMD: Arc or plasma/wire (Shaped Metal Deposition)	o	+	o gas	– wire diameter	o gas
Subtractive machining	o	o	o chips	+ +	– chip handling

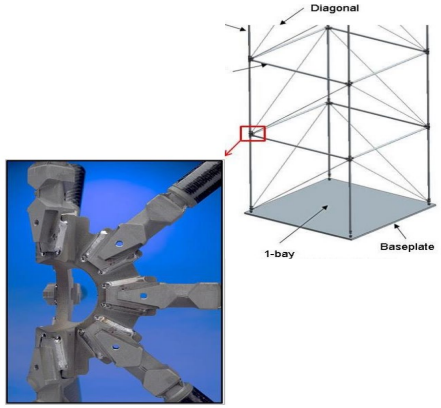
Legend: + + = best, + = above average, o = average, – = below average, – – = worst in class

Electron beam deposition using wire feedstock offers high energy and feedstock efficiency and compatibility with the space environment.

Source: https://ntrs.nasa.gov/api/citations/20160006912

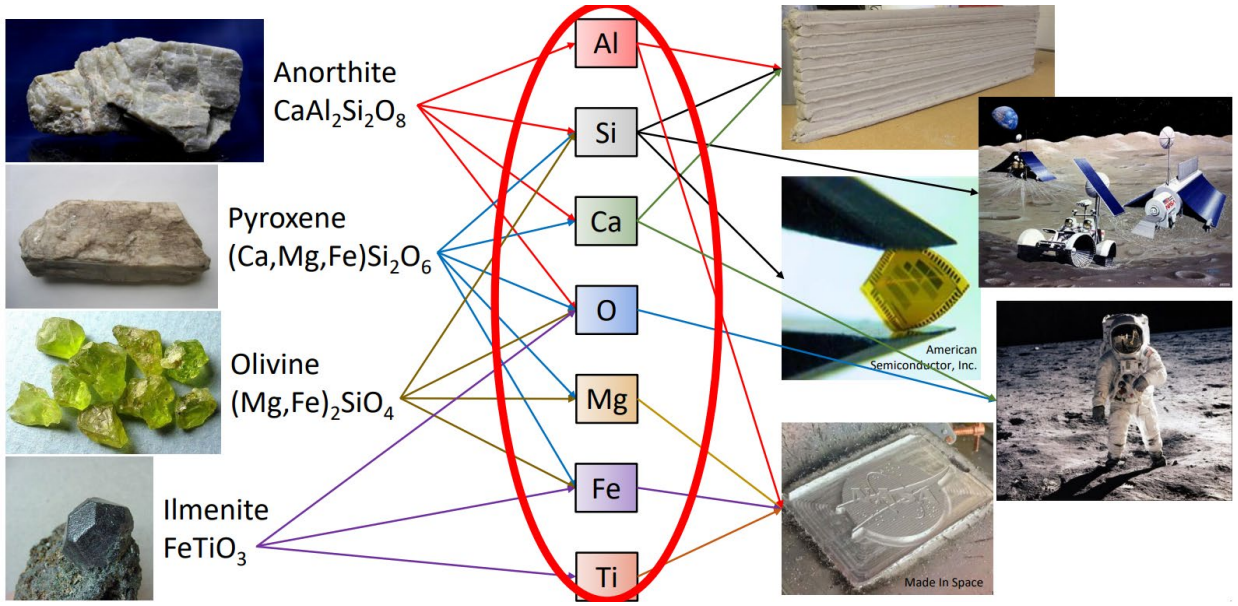


The first metal Additive Manufacturing on the International Space Station has taken place (Source: ESA/Airbus)



EBF³ system used as an electron beam welder

Lunar Regolith Constituents and Extraction



Source: https://ntrs.nasa.gov/api/citations/20220012324

Lunar ilmenite ($FeTiO_3$) possesses potential to extract both oxygen and water when combined with hydrogen, while also providing titanium for components - making it one of the most valuable minerals for sustained lunar operations.

- **Extraction**
- Bucket-Wheel / RASSOR
- Auger Drilling
- Gas Jet Extraction
- Electrostatic levitation
- **Processing**
- Crushing & Sieving
- Magnetic/Electrostatic Separation
- Thermal Sintering
- Chemical Reduction for Metal Recovery

 Source: NASA

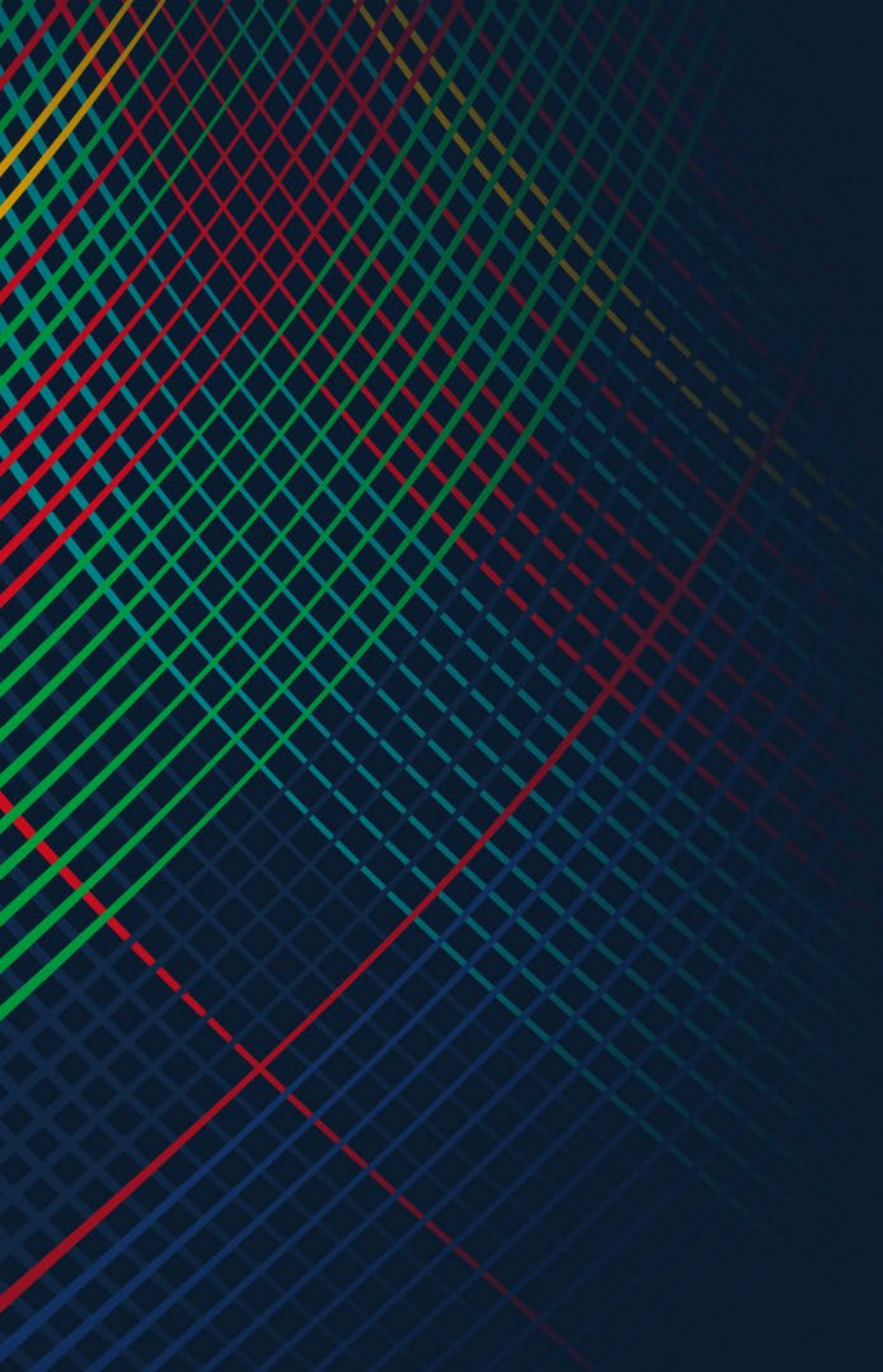
The Enablers

Manufacturing in space is mission-critical beyond low Earth orbit, where resupply is limited. These technologies are key enablers for sustainable space exploration.

Additive Manufacturing (AM)	In-Situ Resource Extraction	Autonomous Robotics and Predictive Models	Robust AI enabled Digital Twin Models	Energy Generation and Storage Systems
Electron Beam and Wire DED have shown positive results for future adaptation	Molten Regolith Electrolysis, Carbothermal Reduction	Autonomous robotic swarms to Mine-Process-Fabricate (offworld)	Physics Informed Digital Twins	NASA Nuclear Kilopower Reactor.
AI (CNN) enabled Real time Process mapping and melt pool Control	Honeybee Robotics Pneumatic Mining Breakthrough	DL/ML based Mineral prospectivity mapping (MPM)	Models trained on Generative Synthetic Data	Can AM Mfg Modules be self reliant; Solar Printing?

To Conclude,

- Multiple Areas of ISRU are under concurrent development phases
- ISRU is a multidisciplinary capability that integrates various elements to produce final outputs.
- Long duration space missions will be challenged by mass and volume constraints for spare parts
- Electron beam / wire deposition offers high energy and feedstock efficiency and compatibility with the space environment



Thank You!

Questions..