In Space Manufacturing and Extraterrestrial Construction

- How Did We Get Here
- Where Are We
- Where Should We Be Going

CHALLENGE: Establish the Foundation for Mission Readiness

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NASA Principal Investigator, MMPACT

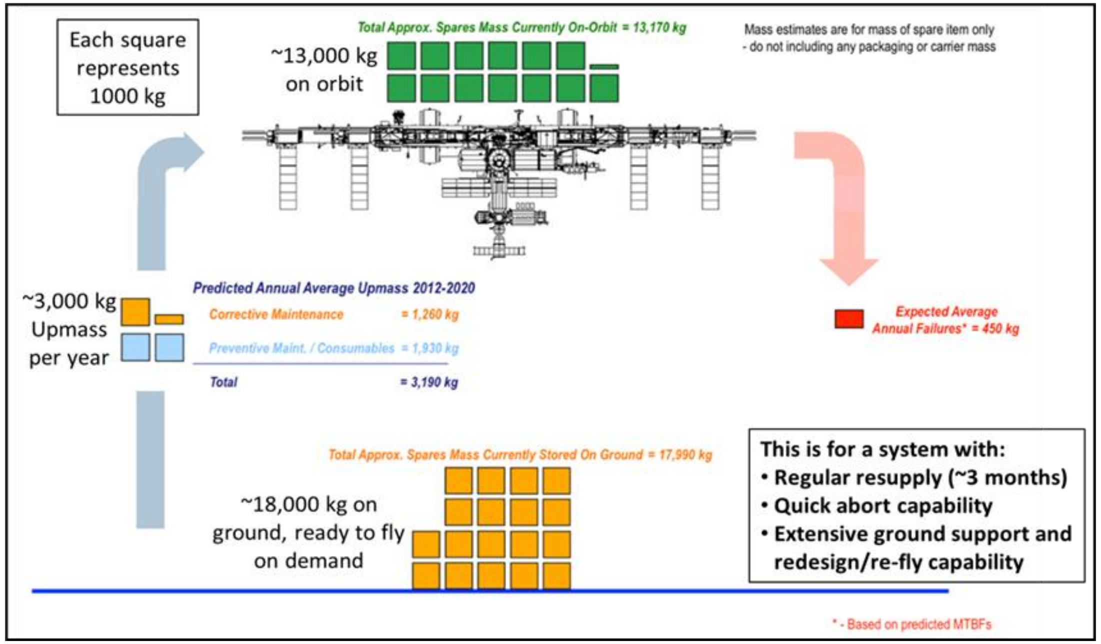
DARPA NOM4D Phase 3 Kickoff Meeting
MSFC
January 29, 2025

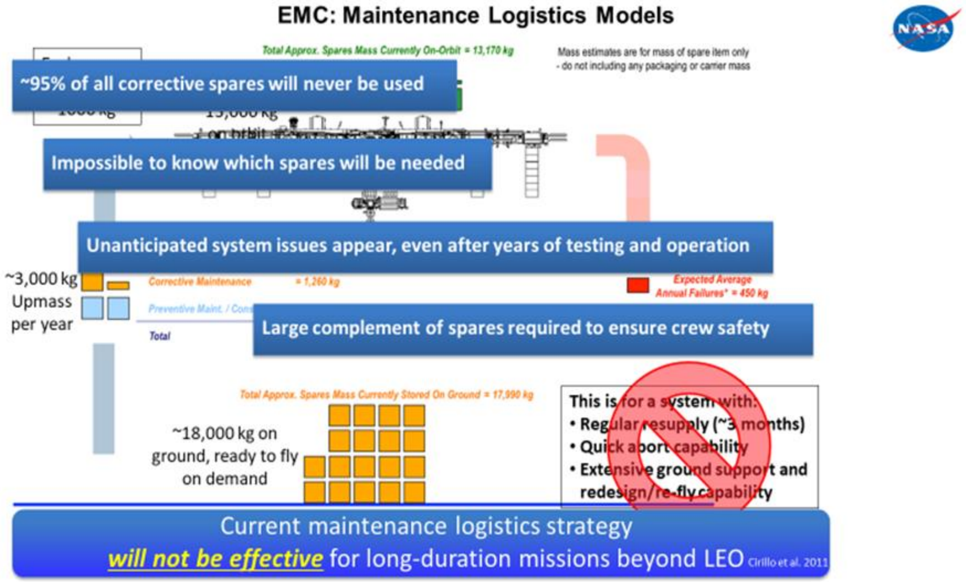
Agenda

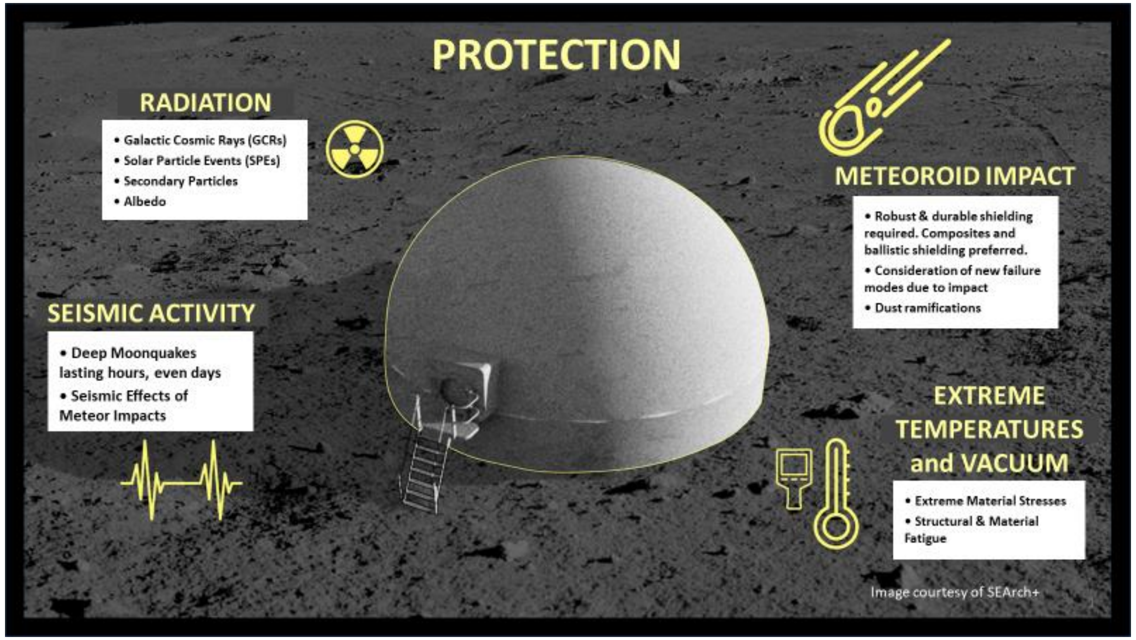
- Why – The Case for In Space Manufacturing and Extraterrestrial Construction
- How Did We Get Here
  - In Space Manufacturing
  - Extraterrestrial Construction
- Where Are We
  - In Space Manufacturing
  - Extraterrestrial Construction
- Where Should We Be Going
- CHALLENGE: Establish the Foundation for Mission Readiness

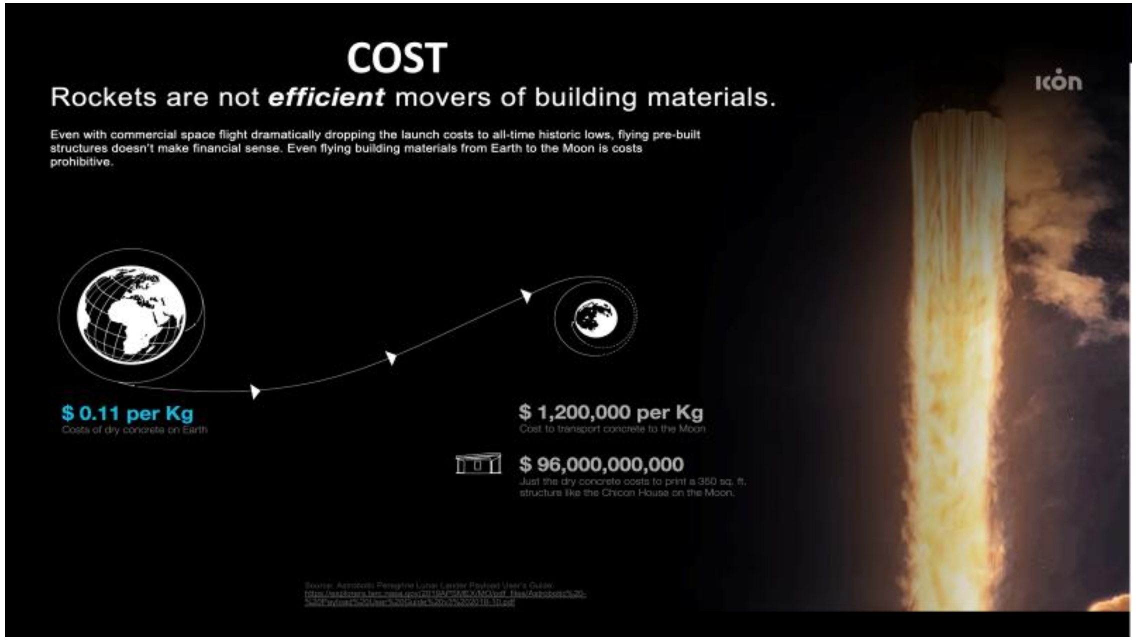
Why: In Space Manufacturing and Extraterrestrial Construction

Evolvable Mars Campaign (EMC): Maintenance Logistics Models – Cirillo Analysis









In Space Manufacturing

How Did We Get Here?

How Did We Get Here: In Space Manufacturing

AM processes tested in μg

Year	Process	Material	Platform
1995	MJT	Silicone oil	Sounding rocket
1999	MEX	ABS	PFC
2002	MJT	Aqueous glycerol	PFC
2006	MJT	Aqueous glycerol	Drop tower
2007	DED	Aluminum 2319	PFC
2011	MEX	ABS	PFC
2013	MEX	ABS	PFC
2014	MEX	ABS	ISS
2016	MEX	PLA	ISS
2016	MEX	PLA	PFC
2016	MEX	PLA	PFC
2016	MEX	ABS	ISS
2016	DED	Aluminum alloy	PFC
2018	VPP	Alumina resin	PFC
2019	MEX	ULTEM 9085	ISS
2019	MEX	Biomaterial	ISS
2019	PBF	316L stainless steel	PFC
2019	PBF	Polystyrene	PFC
2020	PBF	Regolith simulant	Drop Tower
2020	MJT	Polystyrene suspension	Satellite

Note: ABS, acrylonitrile butadiene styrene; PLA, polylactic acid; CFR-PLA, carbon fiber-reinforced PLA.

From Hoffman and Elwany [19]


Principal Investigator Ken Cooper conducting first microgravity Additive Manufacturing pathfinder experiments on NASA's reduced gravity aircraft.

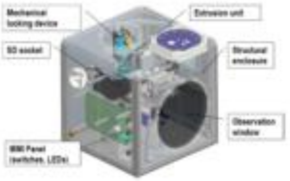
Flight-weight electron beam freeform fabrication (EBF3) system.


Astronaut Butch Wilmore holding ratchet handle. First part uploaded from ground and printed on ISS using the MIS 3DP printer

Additional Made in Space (Redwire) In Space Manufacturing Technology Demonstrations on ISS and Reduced Gravity Aircraft

Refabricator – combined plastic materials recycler and printer – for Technology Demonstration on ISS. Image courtesy of Tethers Unlimited, Inc.


Made in Space (MIS) (Redwire) Additive Manufacturing Facility (AMF) installed in ISS ExPRESS Rack

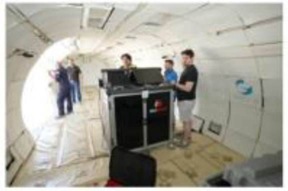


Portable on-Board 3D Printer (P3DP) – overall architecture


Turbine Ceramic Manufacturing Module (TCMM) Launched to ISS in 2020


Redwire Regolith Print (Modified AMF) Launched to ISS in 2021

Redwire Bioprinter EDU successful parabolic flight tests in 2024



2019 | 2020 | 2021 | 2022 | 2023 | 2024

Redwire Recycler Launched to ISS in 2019

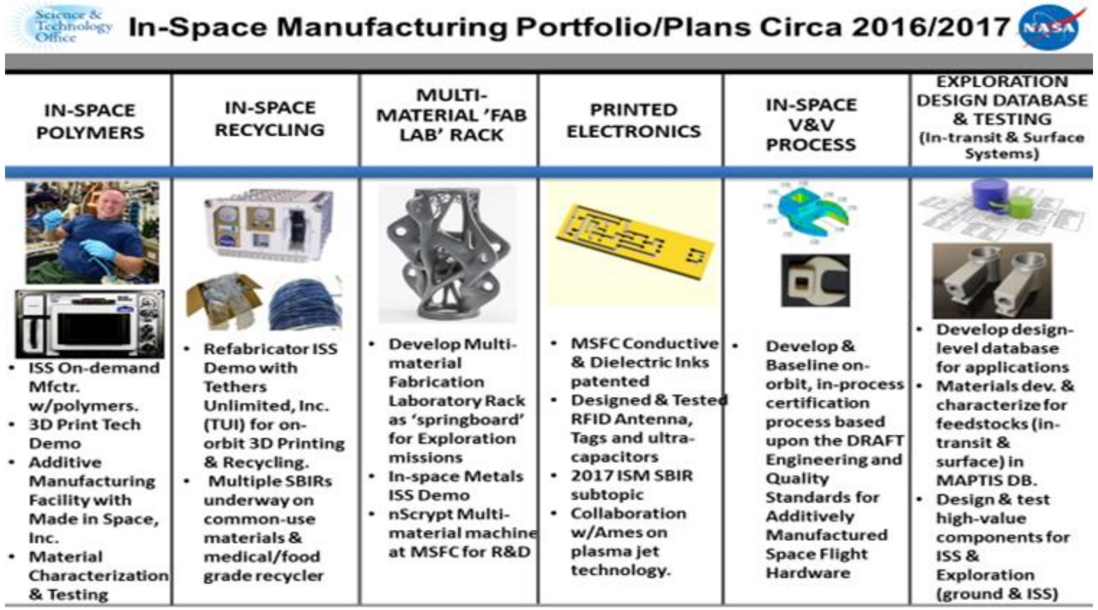

Vulcan Additive/Subtractive Manufacturing of Polymers and Metals Parabolic Flight Test in 2021

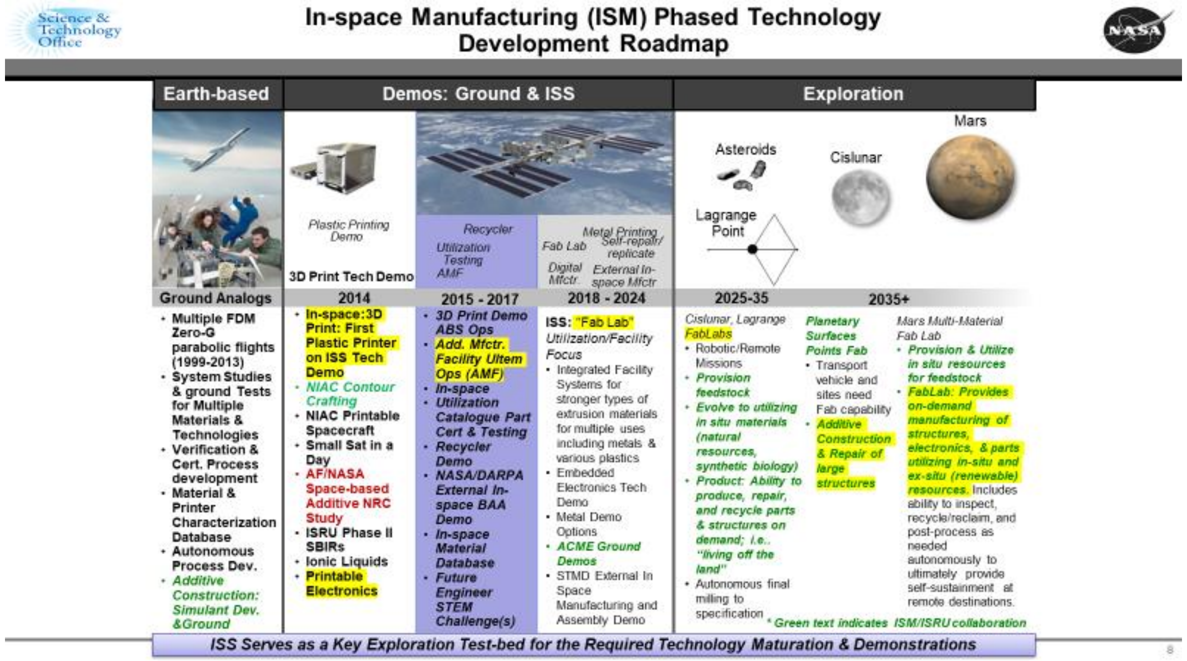
MSTIC Autonomous Semiconductor Manufacturing Platform Launched to ISS in 2024

Early Microgravity Additive Manufacturing Experiments Compiled by Hoffman and Elwany* with Added Photos and Graphics of Key AM Technology Demonstrations

* Hoffman and Elwany, "In-Space Additive Manufacturing: A Review," Journal of Manufacturing Science and Engineering, February 2023, Vol 145

How Did We Get Here: In Space Manufacturing





In-Space Manufacturing Project Portfolio Circa 2022

Objective: provide a solution towards sustainable, flexible missions through development of on-demand fabrication, replacement, and recycling capabilities

On Demand Metals Manufacturing

Provide a capability for on-demand 3D printing of metal parts

Image Courtesy of Made In Space

Recycling and Reuse

Develop materials and recycling technologies to create an on-orbit recycling ecosystem

Image Courtesy of Cornerstone Research Group

On Demand Electronics Manufacturing

Develop printed electronics, sensors, and power devices for testing and demonstration on ISS

Quotes

"What will we build? **We will build EVERYTHING**."
- Dr. Don Pettit, Astronaut

"A manufacturing facility right there with vats of various materials and specs for all of the parts? Yeah! Yeah, absolutely that's the way to go… Yes. **That's the only way to go, honestly**."
- Ivy McLeod, ISS Operations Support Officer

"On a 19th century whaler, they had a carpenter, who was the most important guy on the ship. And the carpenter had basic supplies: wood, rope, and basic tools. And they were expected to fix anything that broke… That model might be useful to us in a Mars trip… **Everybody is very excited about 3D printers, and I think that's a great idea**."
- Dr. Stan Love, Astronaut (Exploration Branch Chief)

"It may not be possible to develop a [Deep Space Habitat] that has a sufficient level of reliability to support human missions to Mars **if NASA continues to use current approaches to maintainability**."
- EMC Systems Analysis Team (Stromgren et al. 2016)

"[ISM] could provide **volume packaging savings**, since raw materials can be stored more densely than final components."
- Molly Anderson, STMD Principal Technologist for Next-Generation Life Support (JSC)

"ISM likely provides a **blanket coverage** against a broad set of uncertainties **that you can't get anywhere else**."
- Bill Cirillo, EMC SAT Lead

"[Additive manufacturing] can provide a full range of possibilities from producing devices, to foods, to medications. It's amazing how a technology that only a few years ago was considered 'way out there' has become ubiquitous. **I have no doubt that this technology has already transformed the way we approach exploration, and it will only continue to benefit us in the future**." *- Dr. John Allen, Crew Health & Safety Program Executive*

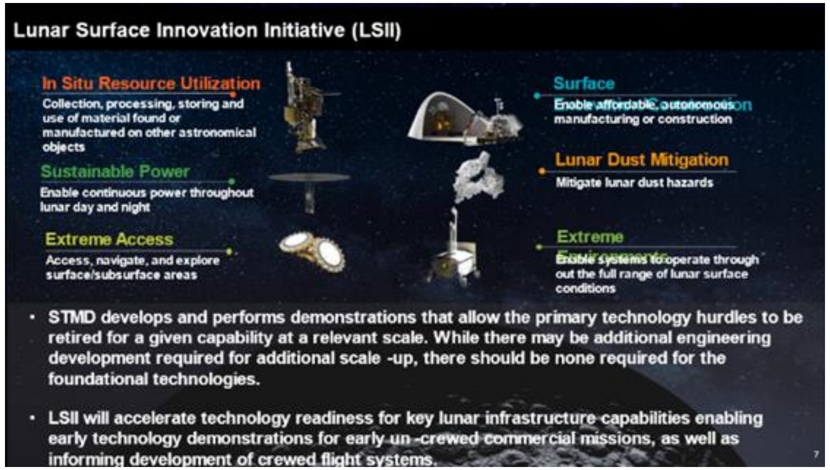
Extraterrestrial Construction

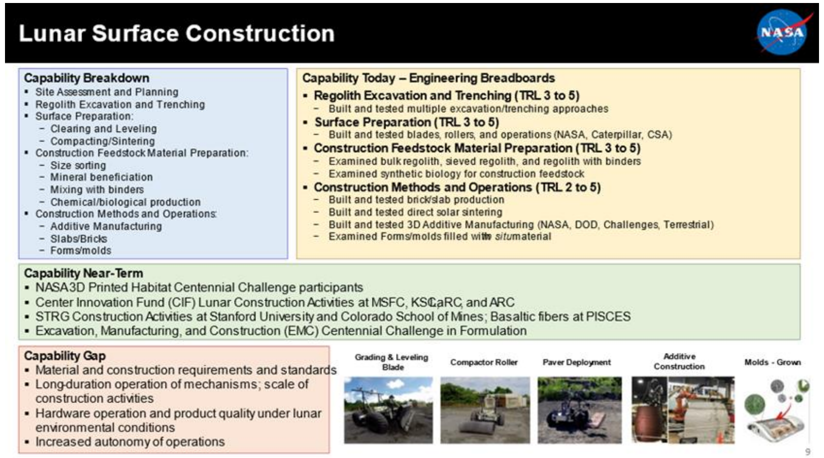
How Did We Get Here?

How Did We Get Here: Extraterrestrial Construction

Administration/Agency Direction Created Cyclical Interest in Extraterrestrial Construction

- A confluence of events was the catalyst for the current global interest in extraterrestrial construction
  - NASA’s announcement of the Centennial Challenge for the design and construction of a 3D Printed Mars Habitat in May 2015.
  - Jan Woerner, ESA Director General (November 2016): “Moon Village is not a single project, nor a fixed plan with a defined time table. It’s a vision for an open architecture and an international community initiative.”*
  - Vice President Pence (October 2017): "We will return American astronauts to the moon, not only to leave behind footprints and flags, but [also] to build the foundation we need to send Americans to Mars and beyond." **
  - Vice President Pence (March 2019): “At the direction of the President of the United States, it is the stated policy of this administration and the United States of America to return American astronauts to the Moon within the next five years.” ***
  - NASA Space Technology Mission Directorate creation of the Lunar Surface Innovation Initiative: “The Lunar Surface Innovation Initiative (LSII) aims to spur the creation of novel technologies needed for lunar surface exploration and accelerate the technology readiness of key systems and components. The LSII activities will be implemented through a combination of unique in-house activities, competitive programs, and public-private partnerships.”





*Jan Woerner, “Moon Village: A Vision for Global Cooperation and Space 4.0” https://blogs.esa.int/janwoerner/2016/11/23/moon-village/

** Wall, M., & Space.COM, “U.S. Will Return to the Moon, Pence Says” Scientific American, October 6, 2017.

***Foust, J., “Pence calls for human return to the moon by 2024” Space News, March 26, 2019.

How Did We Get Here: Extraterrestrial Construction

ESA's Discovery Campaign on Off-Earth Manufacturing and Construction

- Campaign was launched on the Open Space Innovation Platform (OSIP) in October 2019
- Scope: "Innovative ideas on enabling technologies for insitu construction, manufacturing and maintenance of infrastructure and hardware, to support long-term human exploration of a planetary body"*
- The Campaign Comprised Six Themes:
  - Regolith Handling
  - Regolith Processing
  - Resource Management
  - In-Situ Manufacturing/Recycling
  - Habitat Design and Construction
  - Power
- Regolith Processing Projects Included:
  - Microwave Heating
  - Lithographic Ceramic Manufacturing
  - Compaction
  - Fused Layer Deposition
  - Laser Sintering (Mobile Selective Laser Melting)
  - Laser/Focused Light Additive Manufacturing
  - Metal Extraction and Additive manufacturing
- In-situ Manufacturing/Recycling Projects Included:
  - ISRU and Space Debris for Lunar Construction
  - Off-earth Manufacturing Via Self-growing 3D Printer
  - Polymer 3D FFF Printer Using Recycled Filaments
  - Lithography Metal Manufacturing from Recycled Scrap Metals
- Habitat Design and Construction Projects Included:
  - Robot Construction with Found Material
  - Off-earth Additive Manufacturing for Greenhouses
  - Modular Robotic System for In-situ Lunar Construction Tasks
- Workshop on Project Status in Late 2021

* OSIP Off-Earth Manufacturing and Construction Summary of Campaign. https://www.ucl.ac.uk/research/domains/sites/research_domains/files/esa_osip_off-earth_manufacturing_and_construction_summary_esa_labucl_workshop_06-05-2021_v1.pdf

In Space Manufacturing

Where Are We?

Where Are We – In Space Manufacturing

ESA Metal 3D Printer Technology Demonstrator Development Timeline
Image Courtesy of Rob Postema, (‘© ESA/Airbus’)

ESA Metal 3D Printer Technology Demonstrator
Image Courtesy of Rob Postema, (‘© ESA/Airbus’)

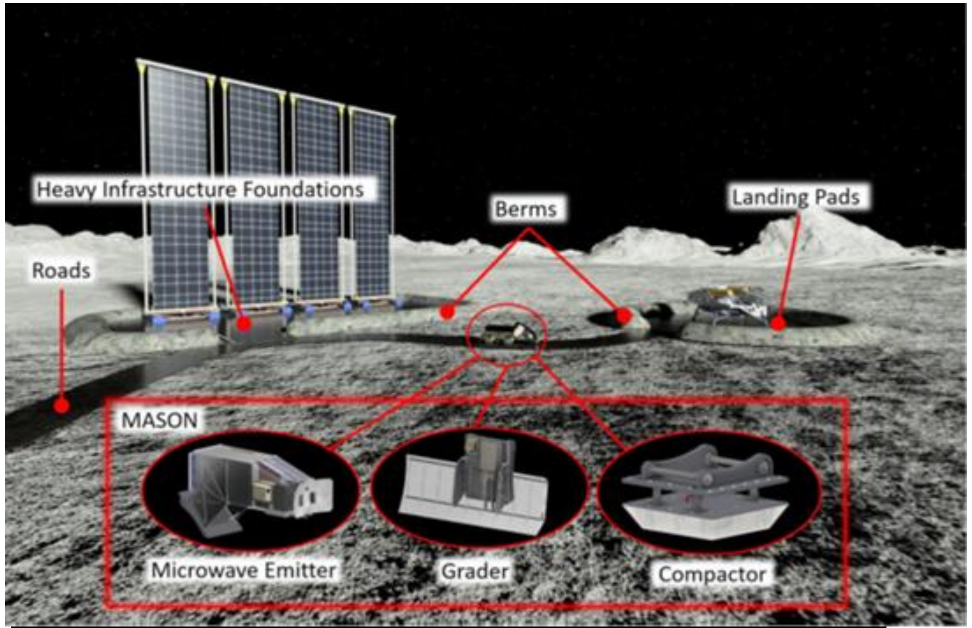
- Metal 3D Printer Technology Demonstrator was developed by the industrial team led by Airbus Defence and Space SAS under a contract with the European Space Agency, co-funded by Airbus Defence and Space SAS, (‘© ESA/Airbus’)
  - The objective of the ESA, Airbus, and Space SAS effort is to develop an AM Machine that will demonstrate the capabilities of this technology to perform metal deposition in 3D under sustained microgravity conditions on ISS and manufacture test specimens also to familiarize with operations (crew vs. ground, level of autonomy). (‘© ESA/Airbus’)
  - The system succeeded in printing the reference line in support of commissioning the Metal 3D printer on ISS in late May 2024 and has completed printing the first test specimen.

First Metal Parts Printed on ISS. Image Courtesy of R. Postema and © ESA/Airbus

Extraterrestrial Construction

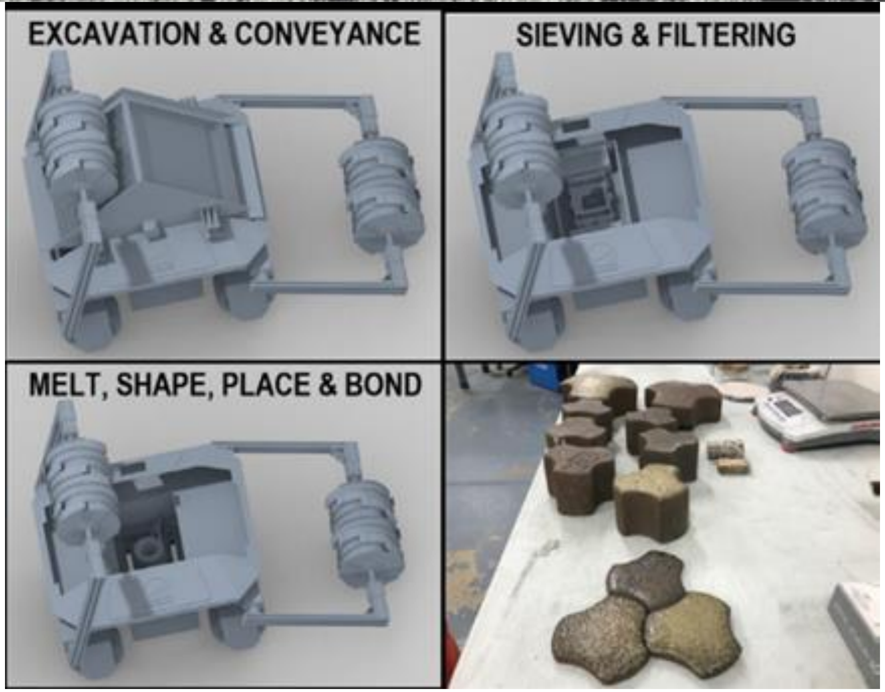
Where Are We?

Where Are We – Extraterrestrial Construction

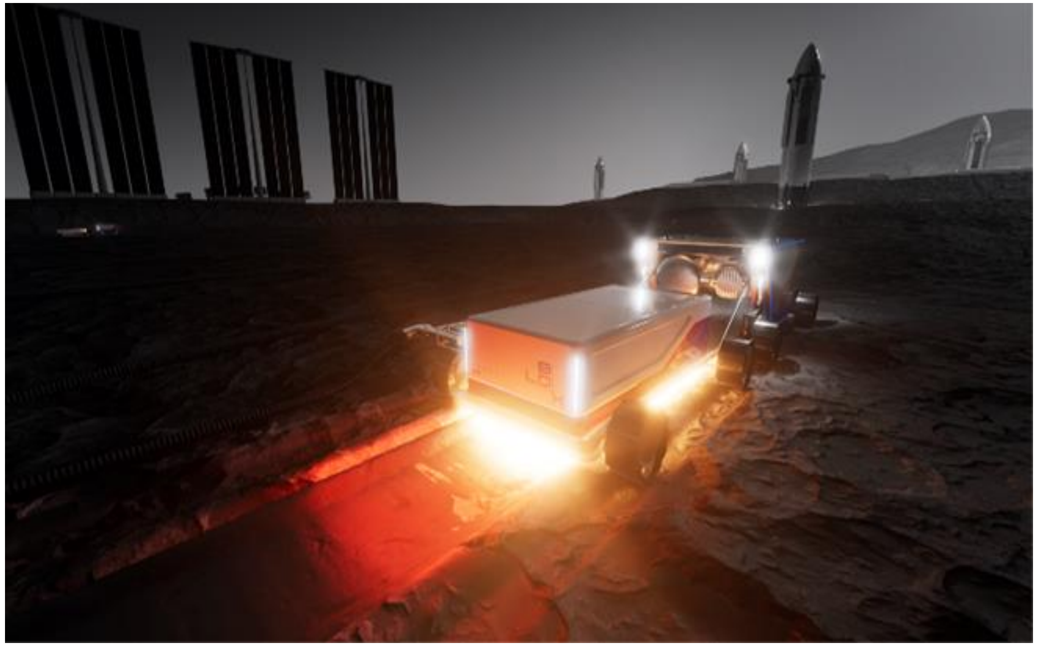


Mason Tool Suite Subsystems and Vision of Future Operations on the Moon. Image Courtesy of Huebner/Redwire

Concept of AI SpaceFactory LINA Shelter Construction Operations on the Lunar Surface. Image from REACT Poster/KSC Gelino

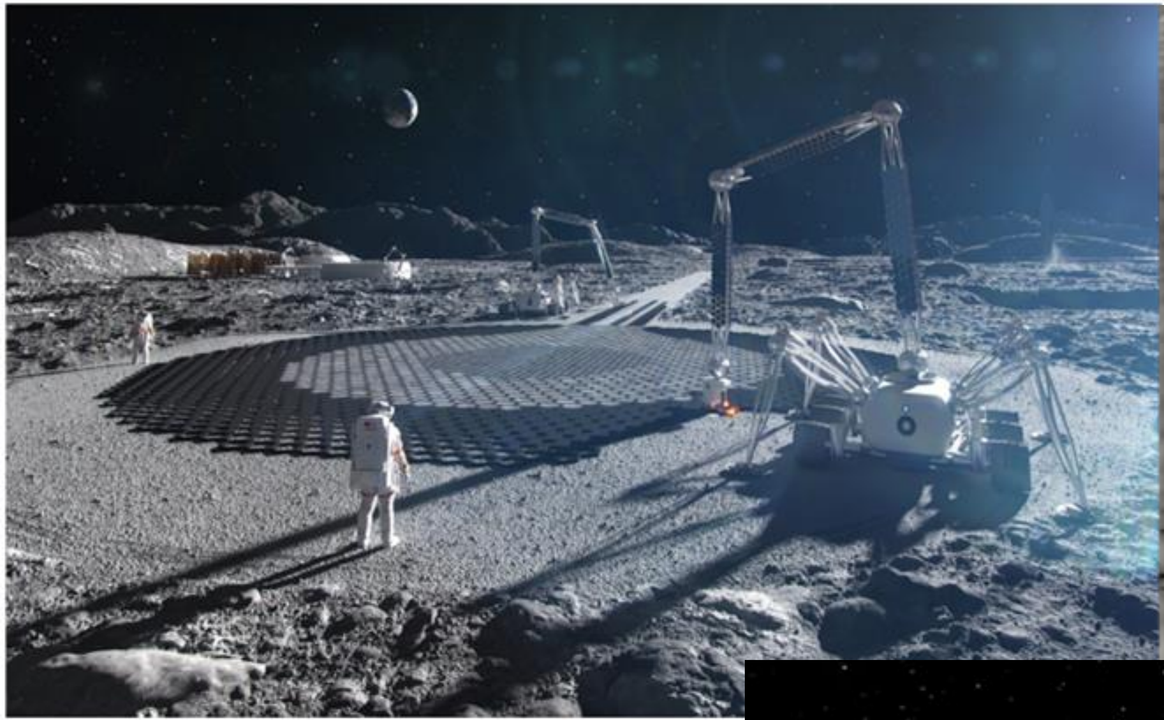


Primary Subsystems of Astroport's Brickbot and Formed Regolith Tiles. Image Courtesy of Sam Ximenes, Astroport

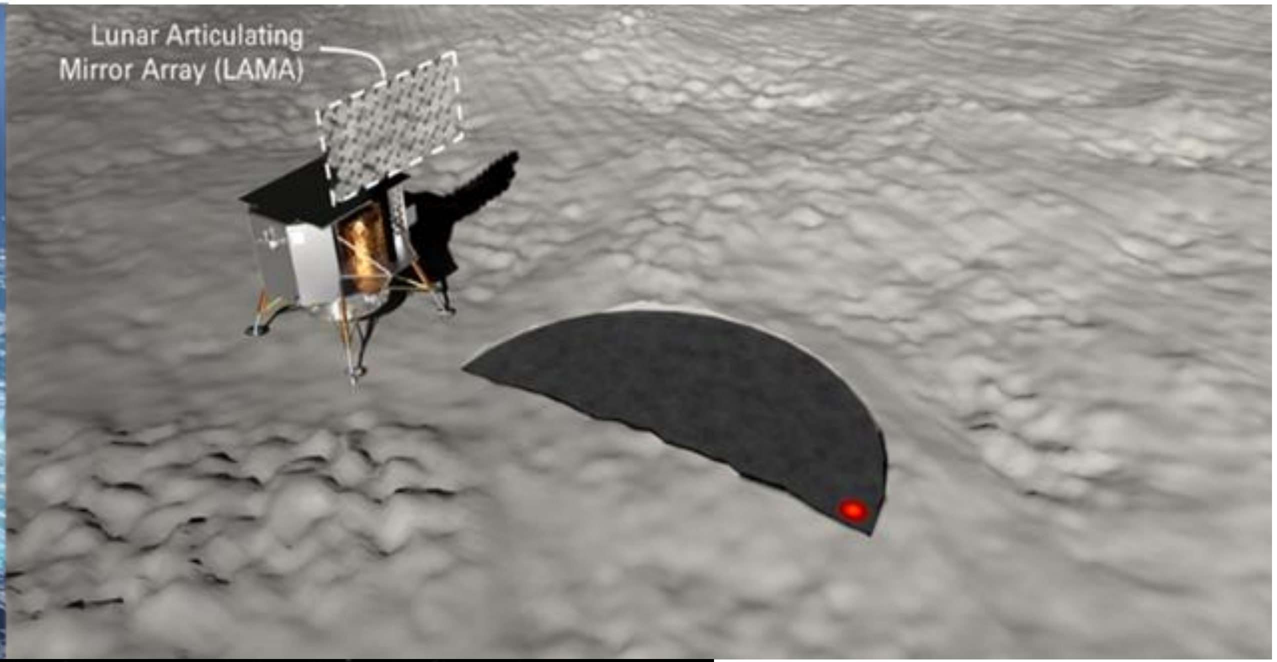


Concept of Ethos System Creating a Landing Pad the Lunar Surface. Image Courtesy of Kevin Cannon. Ethos

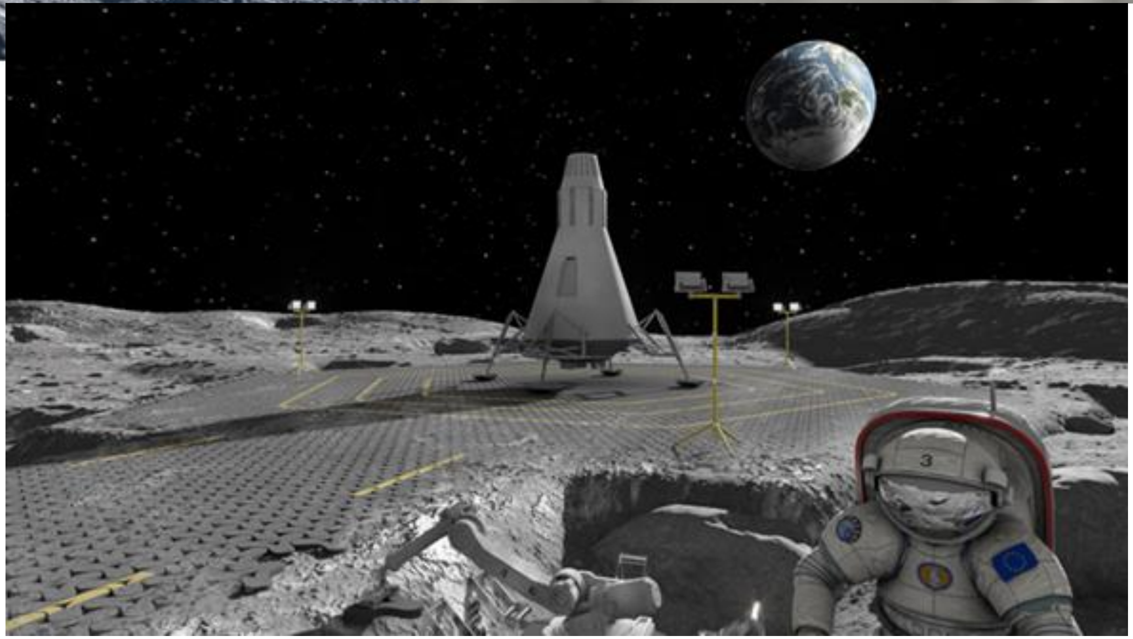
Where Are We – Extraterrestrial Construction



Vision of future Moon to Mars Planetary Autonomous Construction Technologies (MMPACT) Operations on the Moon. Image Courtesy of ICON Technologies



Concept of Outward Technologies Lunar Articulating Mirror Array (LAMA) Operating on the Lunar Surface. Image Courtesy of Outward Technologies



Vision of ESA's PAVER Concept of a Paved Road and Landing Pad Area Using Interlocking Triangular Pavers. Image from ESA

Where Are We – Extraterrestrial Construction

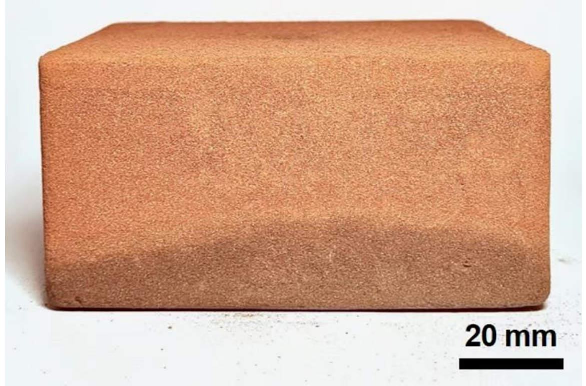
Chinese Plans for Lunar Construction

- China plans to start building a lunar base in about five years, kicking off with bricks made of moon soil.*
- China plans to send sample bricks made from various lunar soil simulants to the Tiangong space station to test durability in low Earth orbit conditions.*
- The Chang’e 8 mission around 2028 will deliver 14 instruments to the Moon. One of those instruments is slated to be a lander that uses solar energy to melt lunar soil into functional parts. *
- “Building stable and solid houses on the lunar surface was once a daunting problem that bewildered scientists worldwide”. **
- “Chinese scientists have long found 3D printing technology to be a solution to this conundrum”.**

A still from a video released by the China National Space Administration (CNSA). Caption and Image Copy from Space.com. (Image credit: China National Space Administration)

South Korea Extraterrestrial Construction Technology Development

- Korea Institute of Civil Engineering and Building Technology (KICT) has developed the capability, using microwave technology, to produce construction materials using the Moon's in-situ resources



Finished Microwave Brick. Korea Institute of Civil Engineering and Building Technology

* Source: South China Morning Post

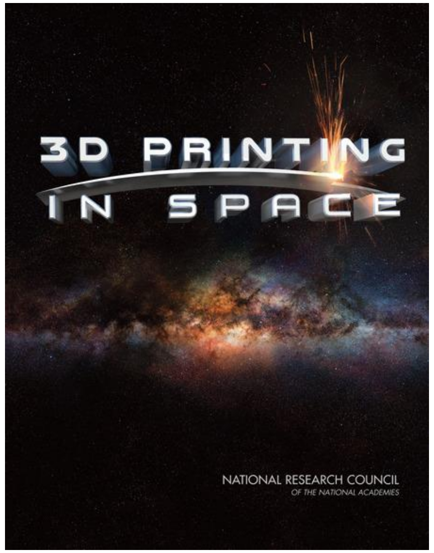
** Source: Chinese Global Television Network

In Space Manufacturing

Where Should We Be Going?

Where Should We Be Going

- In 2014 timeframe, the National Research Council of the National Academies Committee on Space-Based Additive Manufacturing, charged by Air Force Space Command, the Air Force Research Laboratory, and NASA's Space Technology Mission Directorate, conducted a review of in space manufacturing and published their findings and recommendations in "3D Printing in Space"
- Recommendations (paraphrased) included:
  - NASA and the Air Force should jointly cooperate to research, identify, develop, and gain consensus on standard qualification and certification methodologies for different applications.
  - Plans should include infrastructure for space-based additive-manufacturing, e.g. robotics, and even human presence.
  - Actual costs of the reproduction of components should not be the sole criterion for evaluation of benefits of additive manufacturing; criteria should also include the value of creating structures and functionalities not feasible before.
  - NASA should identify possible research projects in the short term (1-5 years) and medium term (5-10 years).
  - NASA should quickly identify any additive manufacturing experiments that it can develop and test aboard the ISS
  - NASA should define and validate an agency-level roadmap, with short- and longer-term goals for evaluating the possible advantages of additive manufacturing in space.
    - Developing goals for using the technology to assist the agency in meeting its key missions, covering all appropriate mission directorates, especially long-duration human spaceflight and planetary operations
    - Targeting the full technology-development life-cycle and insertion strategies through 2050
  - NASA should seek opportunities for cooperation/joint development with other organizations in space-based additive manufacturing, e.g. Air Force, ESA, JAXA, other foreign partners, and commercial firms.
- Challenges identified included the following: Materials development and characterization; Process modeling and control; Design tools and software; Machine qualification, certification, and standardization; Space environment; Part quality assurance, process verification, and functional validation executed in space
- The Committee recognized and emphasized that significant further development would be required to implement ISM, which would require government support.



Where Should We Be Going

Top 10 Ways ISS Is Helping NASA Get to Mars

1. Understanding how to manufacture items in space (3-D Printing)

As crews head to Mars, there may be items that are unanticipated or that break during the mission. Having the ability to manufacture new objects on demand while in space will greatly benefit missions. The 3-D Printing in Zero-G Technology Demonstration validates that a 3-D printer works normally in space. This is the first step towards establishing an on-demand machine shop in space, which is a critical enabling component for crewed missions to deep space.

Where Should We Be Going

- The In-space Servicing, Assembly, And Manufacturing Interagency Working Group Of The National Science & Technology Council released the In-space Servicing, Assembly, And Manufacturing (ISAM) National Strategy in April 2022
- The Strategy Established Six Goals:
  1. Advancing ISAM research and development
  2. Prioritizing the expansion of scalable infrastructure
  3. Accelerating the emerging ISAM commercial industry
  4. Promoting international collaboration and cooperation to achieve ISAM goals
  5. Prioritizing environmental sustainability as we move forward with ISAM capabilities
  6. Inspiring a diverse future workforce as a potential outcome of ISAM innovation.
- The Goals Address Three Challenges
  1. Improving coordination and collaboration both within the USG, as well as among the USG, academia, industry, and international partners
  2. Sending a clear and consistent demand signal to private industry in order to stimulate investment, mitigate risk, and address investor confidence
  3. Establishing and adopting ISAM standards to help promote growth.
     - Standards are nascent.
     - Development and adoption of ISAM standards regarding spacecraft modularity, standard interfaces, materials and manufacturing processes, and operational safety will facilitate the emergence of a market for ISAM services.
- The United States supports advancing the development of voluntary international standards, best practices, guidelines, and norms for ISAM activities.
- The United States Government will encourage international collaboration for responsible and interoperable ISAM capabilities among the global community of space-faring organizations, particularly among its allies and partners.

NASA's Moon to Mars Strategy and Objectives: Manufacturing and Construction Examples

Objective-based Approach – Architect from the Right - Stick with the Plan

LI-4L: Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-8L: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, needed for continuous human/robotic presence.

RT-5: Maintainability and Reuse: when practical, design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increase Earth independence.

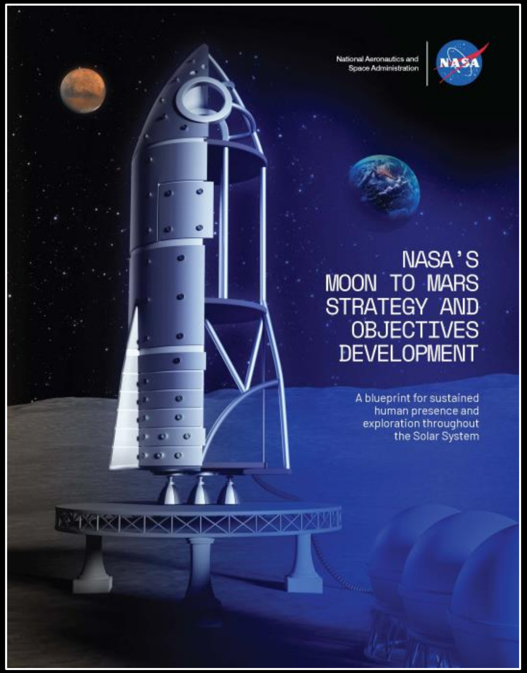
PPS-2LM: Advance understanding of physical systems and fundamental physics by utilizing the unique environments of the Moon, Mars, and deep space.

AS-6LM: Advance understanding of how physical systems and fundamental physical phenomena are affected by partial gravity, microgravity, and general environment of the Moon, Mars, and deep space.

TH-4LM: Develop in-space and surface habitation system(s) for crew to live in deep space for extended durations, enabling future missions to Mars.

OP-11LM: Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.

OP-12LM: Establish procedures and systems that will minimize the disturbance to the local environment and allow for reuse/recycling of material transported from Earth.



Example of Decomposition of NASA's Moon to Mars Objective from the Architecture Definition Document

- **Example Objective LI-04-L**: Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.
- **Characteristics and Needs**: Deploy and Operate autonomous construction and advanced manufacturing demonstration utilization payload(s) to the lunar surface
- **Use Cases**:
    - Deploy and set up autonomous construction and advanced manufacturing demonstration utilization payload(s)
    - Demonstrate autonomous construction techniques and regolith-based additive/subtractive manufacturing techniques
- **Functions:**
    - Regolith: Collect, Process, Refine, Store
    - Form scalable quantities of structures from lunar regolith
    - Manufacture (additive or subtractive) scalable quantities of item(s) from lunar regolith
    - Test product(s) from regolith processing and from additive/subtractive manufacturing demonstrations.

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide reference time/frequency generation on the lunar surface	FN-242-L			documentation of collected surface samples.			
Transport cargo from Earth to the lunar surface	FN-018-L	Deploy and set up autonomous construction demonstration utilization payload(s) on the lunar surface with long-term remote operation	UC-142-L	Deploy and operate autonomous construction demonstration utilization payload(s) to the lunar surface, including partial-scale demonstrations of regolith management and construction of structures, to demonstrate scalable capabilities and applications.	CN-162-L	Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.	LI-04-L
Conduct crew lunar surface extravehicular activity	FN-028-L						
Provide power for deployed surface asset(s)	FN-051-L						
Deploy (setup, activate, and operate) science and/or monitoring utilization payload(s) on the lunar surface	FN-139-L						
Deliver cargo(s) to south polar region sites on the lunar surface	FN-164-L						
Process and refine scalable quantities of in-situ resources on the lunar surface (demonstration)	FN-184-L	Demonstrate autonomous construction techniques, e.g., collection of regolith, processing regolith into feedstock, and regolith construction	UC-143-L				
Collect regolith at scale and subscale (demonstration)	FN-185-L						
Provide storage for collected regolith (demonstration)	FN-186-L						
Compact scalable quantities of lunar regolith (demonstration)	FN-188-L						
Form scalable quantities of structures from lunar regolith (demonstration)	FN-189-L						
Test product(s) from regolith processing (demonstration)	FN-205-L						
Transport cargo from Earth to the lunar surface	FN-018-L	Deploy and set up advanced manufacturing demonstration utilization payload(s) on the lunar surface with long-term remote operation	UC-144-L	Deploy and operate advanced manufacturing demonstration utilization payload(s) to the lunar surface, including scaled demonstration of additive/subtractive manufacturing techniques and inspection/certification processes, to demonstrate scalable capabilities and applications.	CN-163-L		
Conduct crew lunar surface extravehicular activity	FN-028-L						
Provide power for deployed surface asset(s)	FN-051-L						
Deploy (setup, activate, and operate) science and/or monitoring utilization payload(s) on the lunar surface	FN-139-L						
Deliver cargo(s) to south polar region sites on the lunar surface	FN-164-L						
Process and refine scalable quantities of in-situ resources on the lunar surface (demonstration)	FN-184-L	Demonstrate regolith based additive/subtractive manufacturing techniques	UC-145-L				
Collect regolith at scale and subscale (demonstration)	FN-185-L						
Provide storage for collected regolith (demonstration)	FN-186-L						
Manufacture (additive or subtractive) scalable quantities of item(s) from lunar regolith (demonstration)	FN-190-L						
Test product(s) from additive/subtractive manufacturing (demonstration)	FN-206-L						

Moon to Mars Architecture Definition Document (ESDMD-001) Page: 357 of 426

NASA Space Technology Mission Directorate: Advanced Manufacturing and Excavation, Construction, and Outfitting Technology Shortfalls and Rankings

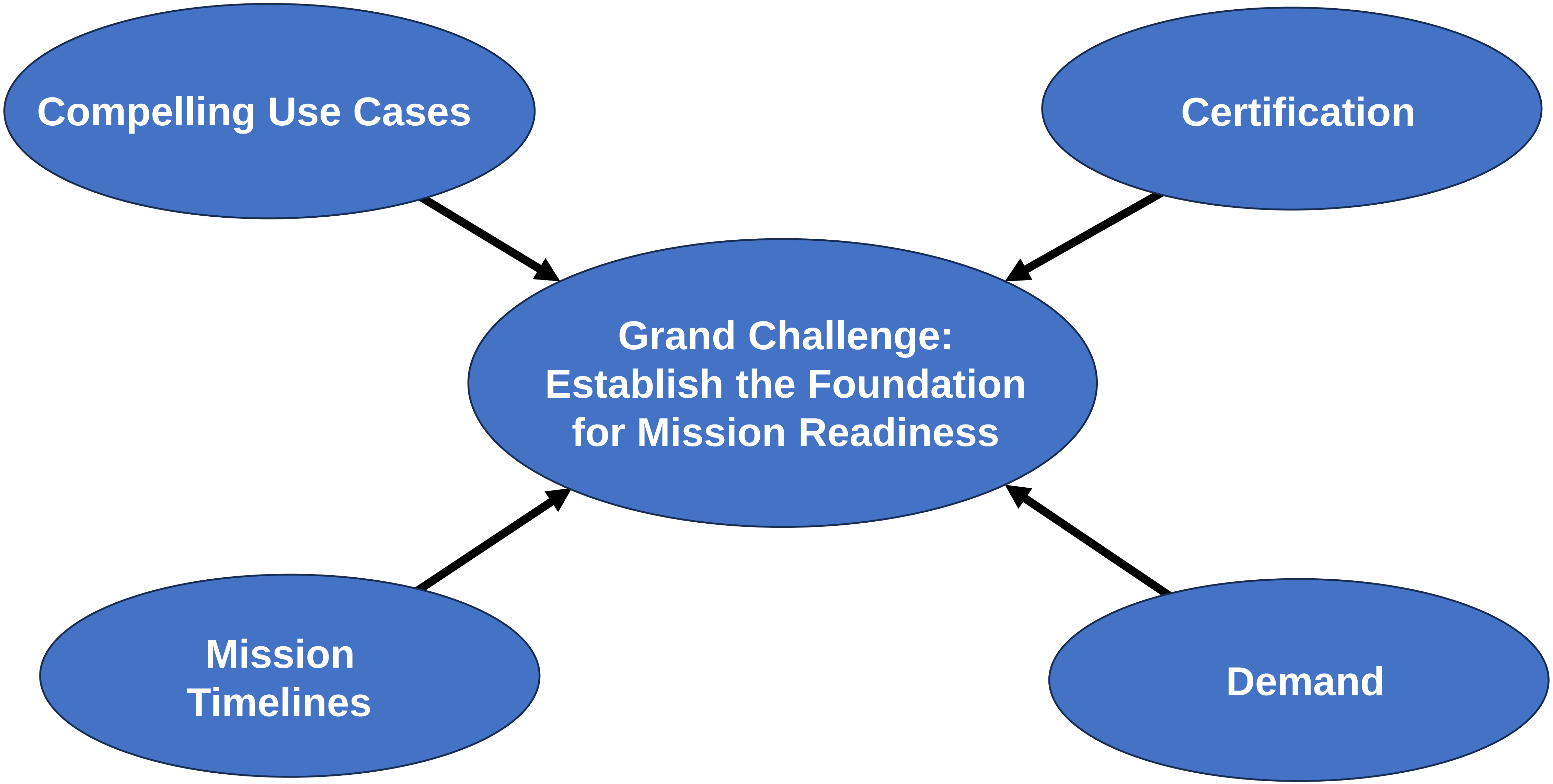
ADVANCED MANUFACTURING SHORTFALLS		
SHORTFALL NUMBER	SHORTFALL TITLE	RANKING
1485	In-Space and On-Surface Manufacturing of Parts/Products from Surface and Terrestrial Feedstocks	92
1486	In-Space and On-Surface NDE and Qualification of Components for Manufacturing, Assembly, and Construction	116
1487	In-Space and On-Surface Welding Technologies for Manufacturing, Assembly, and Construction	179
1489	In-Space and On-Surface Manufacturing from Recycled and Reused Materials and Components	172
1490	Additive Manufacturing for New and High-Performance Materials	145
1488	Additive Manufacturing for Propulsion	163
1491	Additive Manufacturing of Large-Scale Components	154
1492	Materials and Process Modeling for In-Space and On-Surface Manufacturing	170
1493	Computational Materials-Informed Qualification and Certification for In-Space and On-Surface Manufacturing	184
1494	Digital Transformation Technologies for Terrestrial, In-Space, On-Surface Manufacturing, and Operations	176
1496	In-Space and On-Surface New Materials, Manufacturing, Assembly, and Repair of Composite Structures	174
1495	Advanced Manufacturing for Improved Dimensional Control of Large-Scale Space Structures	171

EXCAVATION, CONSTRUCTION, AND OUTFITTING SHORTFALLS		
SHORTFALL NUMBER	SHORTFALL TITLE	RANKING
369	Excavation of granular (surface) regolith for ISRU commodities production	108
384	Excavation of hard/compacted/icy material	104
385	Regolith and resource delivery system	118
662	Robotic regolith manipulation and site preparation	102
617	On-surface robotic assembly of vertical structures	148
1400	On-surface robotic assembly of horizontal structures	159
425	On-Surface In-situ Construction of Vertical Structures	145
666	On-Surface In-situ Construction of Horizontal Structures	160
1480	On-surface Outfitting of Lunar Structures	138

THE CHALLENGE:

Establish the Foundation for Mission Readiness

Grand Challenge Integrates Challenge Elements To Exercise the Process for Mission Readiness



THE CHALLENGE: COMPELLING USE CASES

“Show me the ground truth”*

- “Ground Truth” could take the form of development and analyses of specific use cases (Makaya** and Moraguez***)
  - “To foster adoption of in-situ additive manufacturing, identification of the use case needs to be performed in close collaboration with the mission definition, to ensure that this capability is applied to the most relevant items”**
    - Cases where in-situ manufacturing/repair/recycling is inevitable **
    - Cases where the benefits at mission level (e.g. in terms of simplification of mission logistics, reduction of cost, increase of mission duration etc…) are clearly established” **
- “Ground Truth” could take the form of a risk-based approach as developed by Owens**** and Owens and de Weck*****.

DEVELOP COMPELLING USE CASES: A MULTI-PRONGED CHALLENGE TO THE IN-SPACE LASER PROCESSING COMMUNITY

* Private Communication. M. McDonald
** Private Communication. A. Makaya
*** MIT PhD Thesis. M. Moraguez
**** MIT PhD Thesis. A. Owens
***** Multiple papers by Owens and de Weck

THE CHALLENGE: CERTIFICATION

- The 2014 National Research Council's 3D Printing in Space report identified a key challenge to implementing in space manufacturing focused on "quality, verification, validation, and functional testing"
  - On-orbit manufacture of hardware will require techniques for part quality assurance, process verification, and functional validation that can be executed in space, either with or without human intervention.
  - This part-certification process has to be verified in space
- The 2022 In Space Servicing Assembly and Manufacturing (ISAM) National Strategy identified a similar challenge, stating that "Standards are nascent."
- Progress has been made in the development of standards, specifically NASA Standard 6030
  - "The purpose of this NASA Technical Standard is to define the minimum requirements for AM processes used for spaceflight systems, provide guidance and recommendations for tailoring this NASA Technical Standard for NASA non-crewed missions, and cover in-space AM operations"
- However, certification of products manufactured in space or on extraterrestrial surfaces lacks the benefits (e.g. access, mass and volume constraints), supporting infrastructure (e.g. power, robotics, human presence), and experience base that ground-based processes have.

"CERTIFICATION": A MULTI-FACETED CHALLENGE TO THE IN-SPACE LASER PROCESSING COMMUNITY: DEVELOP CONCENSUS ON EXTRATERRESTRIAL STANDARDIZATIONS REQUIRED AS A BASELINE FOR THE TECHNOLOGY DEMONSTRATION:

- **MATERIALS**
- **PROCESSES**
- **INSPECTION**
- **TESTING**

THE CHALLENGE: MISSION TIMELINES

- Attaining full acceptance and inclusion of the capability in mission plans enables the freedom to Design for Additive Manufacturing
- Examining mission timelines, a general estimate is that a decade or more lead time would be required for incorporation of “new” technologies.
- The rapid evolution of additive manufacturing for design and production of liquid rocket engine components is contrary to this timeline estimate.
  - The government (NASA) led the way in development of new materials; process development and demonstration; nondestructive inspection; specification and standards development; and hot fire testing.
  - A solid business case, cost and schedule savings, existed for industry to invest and to enable the rapidly accelerated adoption of this technology into the manufacturing mainstream.
- This scenario does not hold for in space manufacturing.
  - The experience base, infrastructure, exercising of specifications and standards, all factors noted previously, are nascent.
  - Return on investment is not so immediate or apparent.
  - The effort must be led by the government with a “consistent and reliable demand signal”
- For extraterrestrial construction, a commercial business case may be envisioned offering launch and landing operations services, as an example.

MISSION TIMELINES WILL REQUIRE DRAMATIC ACCELERATION OF CAPABILITIES. WILL THE TECHNOLOGY/PROCESS BE READY TO SUPPORT THE MISSION PLANNING DECISIONS?
A CHALLENGE TO THE IN-SPACE LASER PROCESSINGCOMMUNITY

THE CHALLENGE: DEMAND

- In the 2014 National Research Council's 3D Printing in Space report, the Committee recognized that significant further development would be required to implement ISM, which would require government support.
- The recent Office of Science Technology Policy (OSTP) Is Space Servicing, Assembly, and Manufacturing (ISAM) National Strategy identified a key challenge that the "private sector needs a demand signal"
  - The challenge "concerns the need for the private sector to receive consistent and reliable government demand signals that stimulate investment, mitigate risk, and create investor confidence".
  - "Robust commercial engagement, prudent planning, and stable funding are crucial to fully realize the potential impact of ISAM innovations"
- Low rankings of in space manufacturing and lunar surface construction technologies in NASA Space Technology Mission Directorate's 2024 Civil Space Shortfall Ranking, noted previously, do not send a positive or consistent and reliable government demand signal.

CONSISTENT AND RELIABLE GOVERNMENT DEMAND SIGNALS:

COLLABORATION BETWEEN DARPA AND NASA AMPLIFIES THE DEMAND SIGNAL FOR PRIVATE INDUSTRY.

THE GRAND CHALLENGE

- An intergovernmental In Space Laser Processing Technology Demonstration Initiative offers a tremendous opportunity to integrate and address these four Challenges by exercising the process and thereby advancing the state of readiness for in space manufacturing as a whole.
- Establish the rationale: logistics challenges; mass and volume savings; and/or risk reduction, as the foundation for specifically selected use cases, the analytical "ground truth."
- Through collaboration, establish the standardization requirements for the specifics for this use case, i.e. what requirements are to be placed on the materials, processes, {inspection}, and testing of products to be created in space.
- DARPA and NASA develop the comprehensive package for focused "whole of system" in space laser processing technology demonstration flight mission to establish the example for future In Space Manufacturing initiatives.

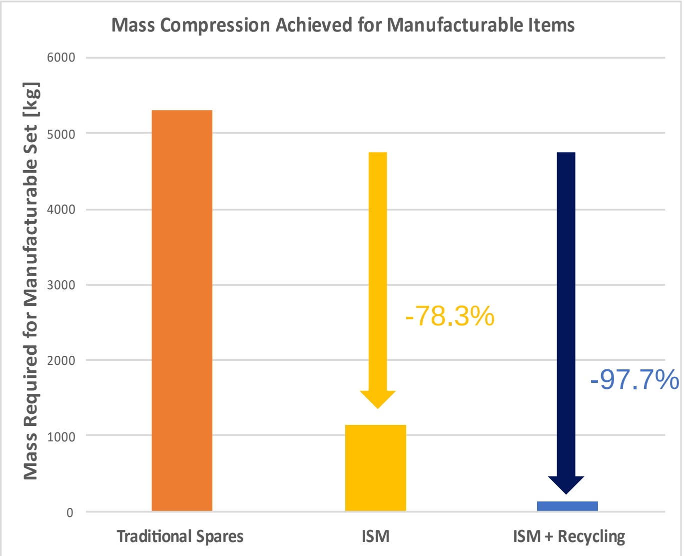
GRAND CHALLENGE: INTEGRATE AND SYSTEMATICALLY ADDRESS THE KEY CHALLENGE ELEMENTS TO CATALYZE AND ACCELERATE ADOPTION OF IN SPACE MANUFACTURING IN ADVANCE OF FUTURE DEEP SPACE EXPLORATION MISSIONS PLANNING DECISIONS.

Questions

BACK-UP

Recycling and Reuse

Fundamental Assumption: Payloads are designed to be maintainable/manufacturable with ISM systems

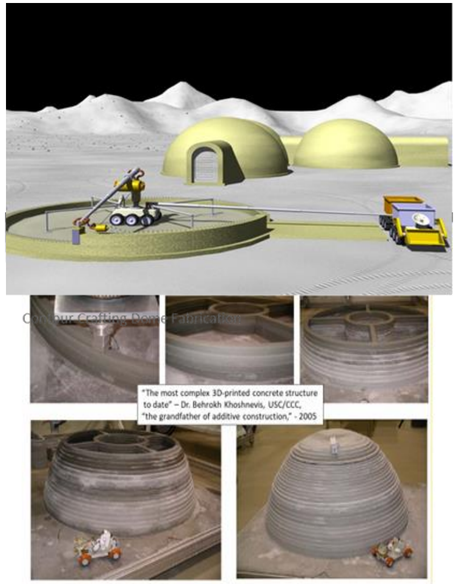


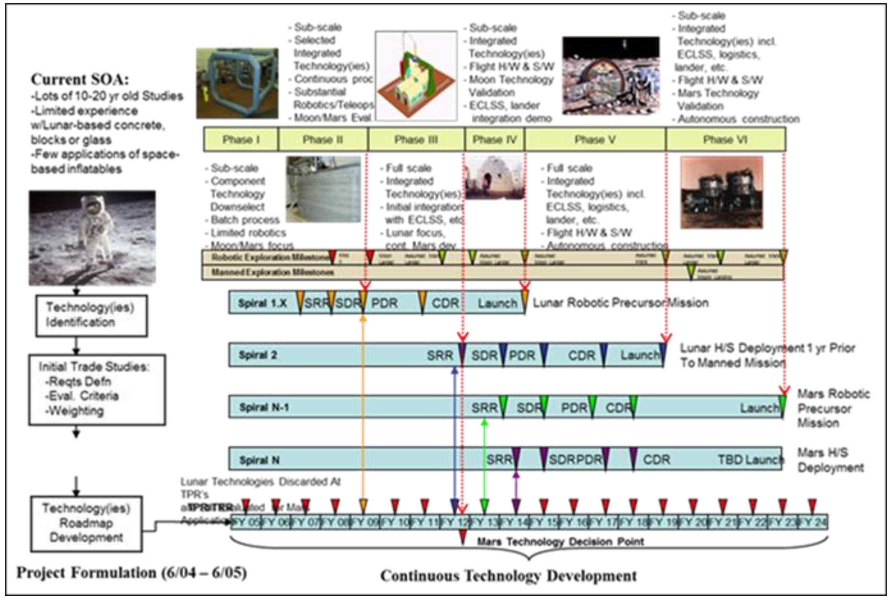
Andrew Owens and Olivier De Weck. "Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign", AIAA SPACE 2016, AIAA SPACE Forum, (AIAA 2016-5394)

How Did We Get Here: Extraterrestrial Construction

Administration/Agency Direction Created Cyclical Interest in Extraterrestrial Construction

- President George H. W. Bush “announced in July 1989 a project to send men back to the moon to set up a base there from which to launch a manned mission to Mars. President Bush predicted the base would be operational by the year 2005”. *
    - This plan was known as the Space Exploration Initiative (SEI).
    - Four years later, NASA closed the Office of Exploration charged with carrying out the SEI plans.
- NASA’s priorities changed in 2004 with the announcement of the Vision for Space Exploration (VSE) by President George W. Bush, which defined specific goals for the Agency. The first goal was to complete the International Space Station by 2010. The Space Shuttle was to be returned to flight as soon as possible with the chief purpose to help finish the ISS, and then be retired. The third goal was for America to return to the Moon as early as 2015, but no later than 2020 and use it as a steppingstone for more ambitious missions. **
- While goals and objectives of the In Situ Fabrication And Repair (ISFAR) technology development efforts were consistent with the longer-term goals of the VSE, all elements of ISFAR were subsequently terminated.





* James, B., “On Moon, Concrete Digs” New York Times, February 13, 1992.

** Press Release “President Bush Announces New Vision for Space Exploration Program” Space News, January 14, 2004.

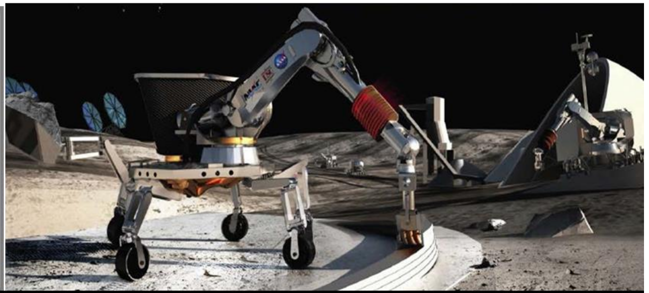
How Did We Get Here: Extraterrestrial Construction

Administration/Agency Direction Created Cyclical Interest in Extraterrestrial Construction

- In April 2010, President Barak Obama outlined a bold new course for NASA: “We are setting a course with specific and achievable milestones. Early in the next decade, a set of crewed flights will test and prove the systems required for exploration beyond low Earth orbit. And by 2025, we expect new spacecraft designed for long journeys to allow us to begin the first-ever crewed missions beyond the Moon into deep space. So, we’ll start -- we’ll start by sending astronauts to an asteroid for the first time in history. By the mid-2030s, I believe we can send humans to orbit Mars and return them safely to Earth”.*

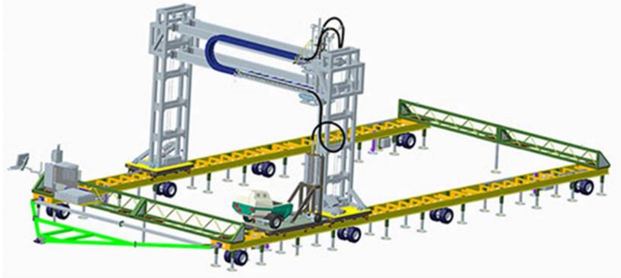
Additive Construction Dual Use Technology Projects For Planetary and Terrestrial Applications

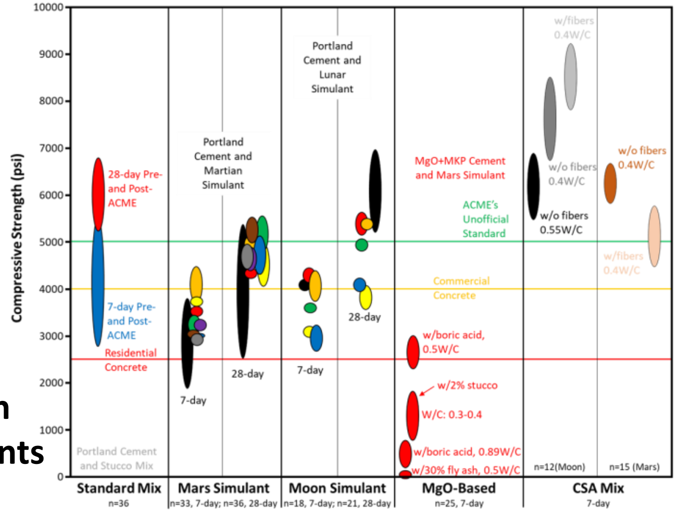
Additive Construction with Mobile Emplacement (ACME) NASA



Shared Vision: Capability to print custom-designed expeditionary (exploration) structures on-demand, in the field (extraterrestrial surface), using locally available materials (regolith).

Automated Construction of Expeditionary Structures (ACES) Construction Engineering Research Laboratory - Engineer Research and Development Center (CERL – ERDC)





Compression Test Results Using Various Binders with Lunar and Martian Simulants

ACES-3 Gantry and Supporting Systems at CERL-ERDC

*Obama, B., “21st Century Space Exploration: ‘The Next Chapter That We Can Write Together Here at NASA’" National Archives, Kennedy Space Center. April 15, 2010

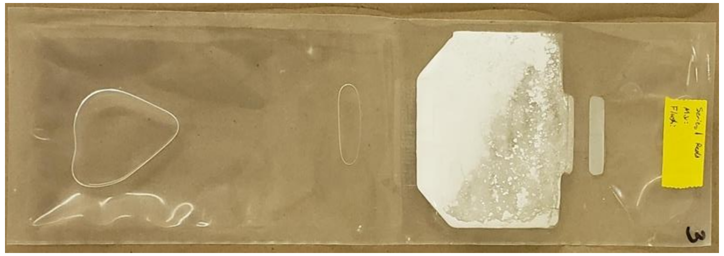


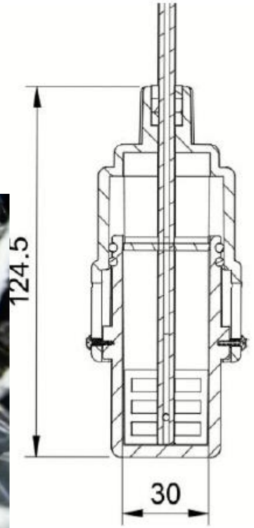



MICS and MASON teams have been collaborating on extraterrestrial concrete since 2020 to advance in-situ resource utilization and develop lunar and Martian binders







MICS *(Microgravity of Cement Solidification):*
Radlińska, Collins, Grugel, Littles, Edmunson, Fiske

MASON *(Material science on Solidification of cONcrete):*
Sperl, Schnellenbach-Held, Rattenbacher, Tell, Müller, Welsch

PennState Image Courtesy of Dr. Radlinska, and Peter Collins, PSU

How Did We Get Here: In Space Manufacturing

AM processes tested in μg

Year	Process	Material	Platform
1995	MJT	Silicone oil	Sounding rocket
1999	MEX	ABS	PFC
2002	MJT	Aqueous glycerol	PFC
2006	MJT	Aqueous glycerol	Drop tower
2007	DED	Aluminum 2319	PFC
2011	MEX	ABS	PFC
2013	MEX	ABS	PFC
2014	MEX	ABS	ISS
2016	MEX	PLA	ISS
2016	MEX	PLA	PFC
2016	MEX	PLA	PFC
2016	MEX	ABS	ISS
2016	DED	Aluminum alloy	PFC
2018	VPP	Alumina resin	PFC
2019	MEX	ULTEM 9085	ISS
2019	MEX	Biomaterial	ISS
2019	PBF	316L stainless steel	PFC
2019	PBF	Polystyrene	PFC
2020	PBF	Regolith simulant	Drop Tower
2020	MJT	Polystyrene suspension	Satellite

Note: ABS, acrylonitrile butadiene styrene; PLA, polylactic acid; CFR-PLA, carbon fiber-reinforced PLA.

From Hoffman and Elwany [19]

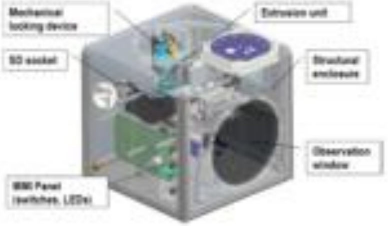
Principal Investigator Ken Cooper conducting first microgravity Additive Manufacturing pathfinder experiments on NASA's reduced gravity aircraft.

Flight-weight electron beam freeform fabrication (EBF3) system.

Astronaut Butch Wilmore holding ratchet handle. First part uploaded from ground and printed on ISS using the MIS 3DP printer

Refabricator – combined plastic materials recycler and printer – for Technology Demonstration on ISS. Image courtesy of Tethers Unlimited, Inc.

Made in Space (MIS) (Redwire) Additive Manufacturing Facility (AMF) installed in ISS ExPRESS Rack



Portable on-Board 3D Printer (P3DP) – overall architecture

Early Microgravity Additive Manufacturing Experiments Compiled by Hoffman and Elwany* with Added Photos and Graphics of Key AM Technology Demonstrations

* Hoffman and Elwany, "In-Space Additive Manufacturing: A Review," Journal of Manufacturing Science and Engineering, February 2023, Vol 145

How Did We Get Here: In Space Manufacturing

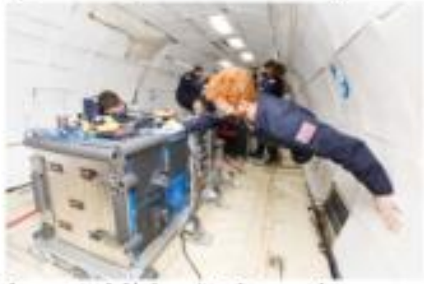
Turbine Ceramic Manufacturing Module (TCMM) Launched to ISS in 2020

Redwire Regolith Print (Modified AMF) Launched to ISS in 2021

Redwire Bioprinter EDU successful parabolic flight tests in 2024

2019 | 2020 | 2021 | 2022 | 2023 | 2024

Redwire Recycler Launched to ISS in 2019



Vulcan Additive/Subtractive Manufacturing of Polymers and Metals Parabolic Flight Test in 2021

MSTIC Autonomous Semiconductor Manufacturing Platform Launched to ISS in 2024

Additional Made in Space (Redwire) In Space Manufacturing Technology Demonstrations on ISS and Reduced Gravity Aircraft
Images Courtesy of Redwire

Development and Testing of Capabilities for On-Demand Spare Component Manufacturing

Techshot Fabrication Laboratory ground-based prototype for bound metal deposition. Image from Techshot, Inc.

Vulcan wire+arc hybrid additive manufacturing system from Made in Space, Inc.

Systems in development for future initial ISS demonstrations: 3D printing of metals

Adapting Metal AM for ISS and Lunar Surface

Environments (ISS and the lunar surface) impose unique constraints for manufacturing systems.

- Scale/scalability of hardware
  - Power (max power for ISS payload is 2kW)
  - Mass
  - Volume
- Safety (feedstock management, chip debris capture)
- Limited crew interaction
- Remote commanding
- Range of materials within processing capability
- Feedstock materials available, via beneficiation, on Moon
- Ability to produce complex features
- Surface finish
- Operation in reduced gravity
  - Physics of deposition
  - Impact on material quality
  - Management of heat in absence of natural convective cooling

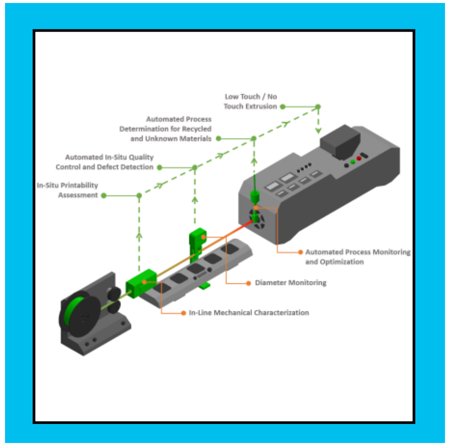
One of the pre-eminent ISM challenges is verification of parts produced on-orbit or on the lunar surface.

Recycling and Reuse (RnR)

The RnR project element develops materials and recycling technologies with the goal of creating an on-orbit ecosystem for repurposing waste products, such as packaging materials and defective components.

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

- Analyze historical waste streams and recycling technologies
- Development of “purpose-built” recyclable materials
- Development of in process monitoring technologies



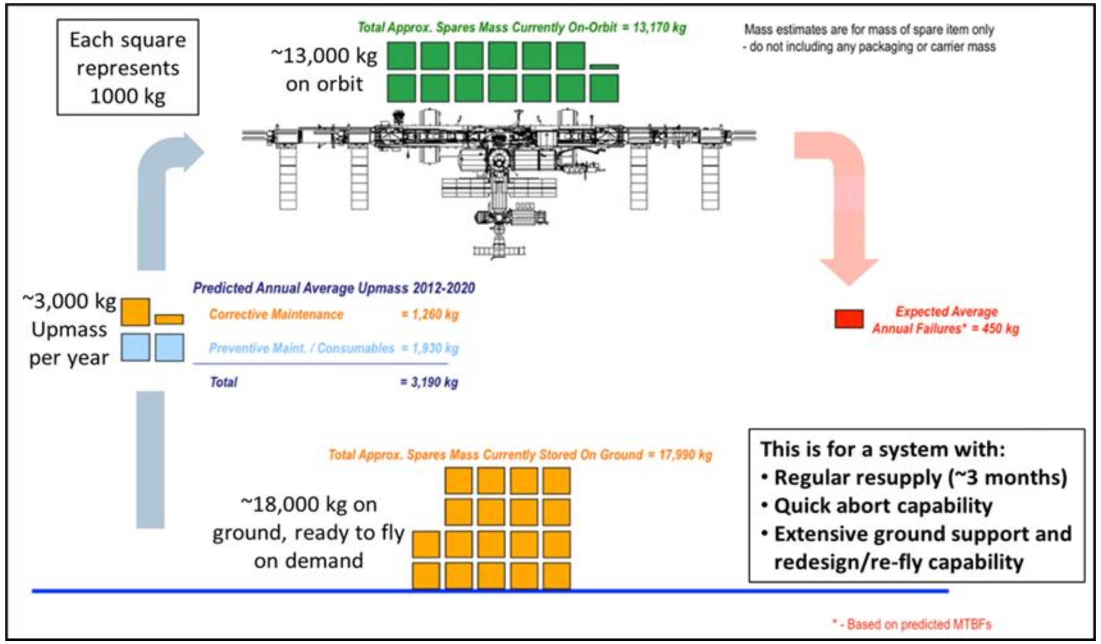
(LEFT) Thermally reversible packaging materials (which can also be used for 3D printing) and (RIGHT) in-process monitoring system for polymer filament production from Cornerstone Research Group (CRG). Images from CRG.

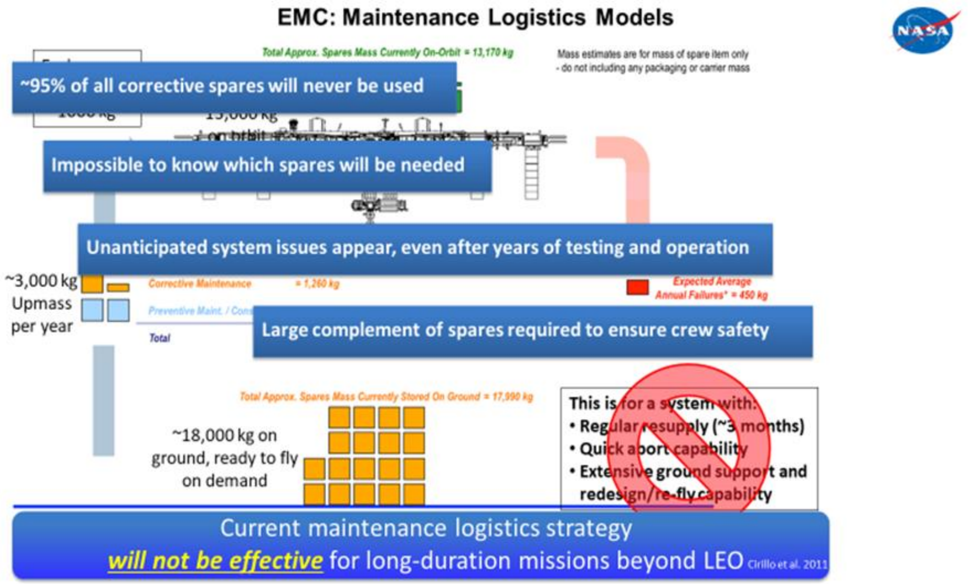
<u>Potential Areas for Future Exploration</u>

- Metals Recycling
- Sterilization and Sanitization Technologies
- Increased feedstock strength
- Validation and characterization of recycled feedstock
- In Situ Resource Extraction
- Cleaning Technologies (esp. food packaging)
- Disassembly of multi material products

Why: In Space Manufacturing

Evolvable Mars Campaign (EMC): Maintenance Logistics Models – Cirillo Analysis





Benefits from Incorporation of ISM

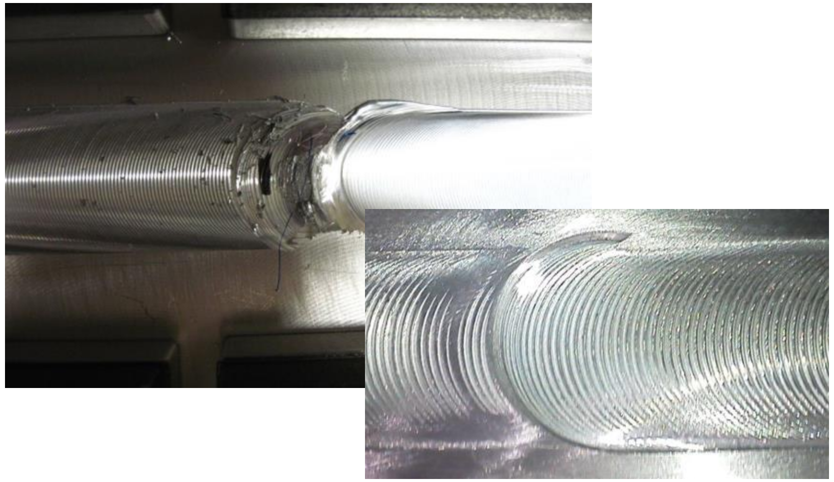
ISM offers the potential to:

- Significantly reduce maintenance logistics mass requirements
- Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements
- Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances
- Mitigate risks that are not covered by current approaches to maintainability

Why In-Space Manufacturing?

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

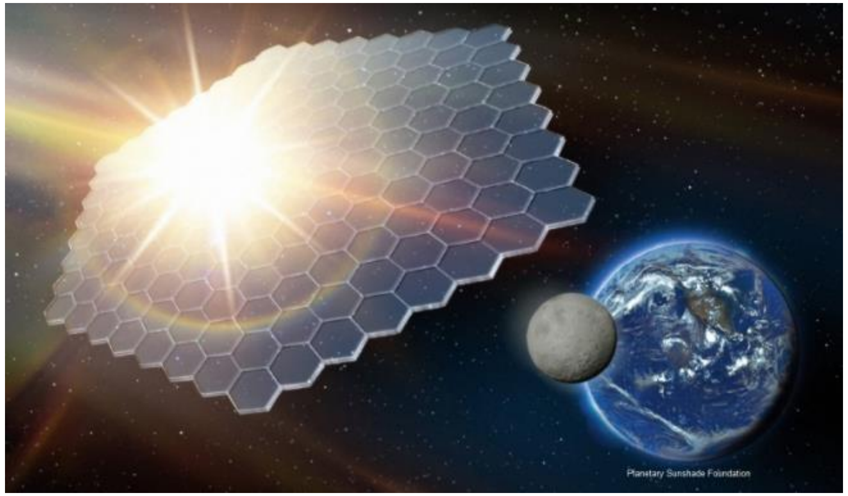
Reduce launch mass through in-situ resource use (image credit ICON) Moon to Mars Objectives



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

Recycling and Trash Management (image credit NASA)

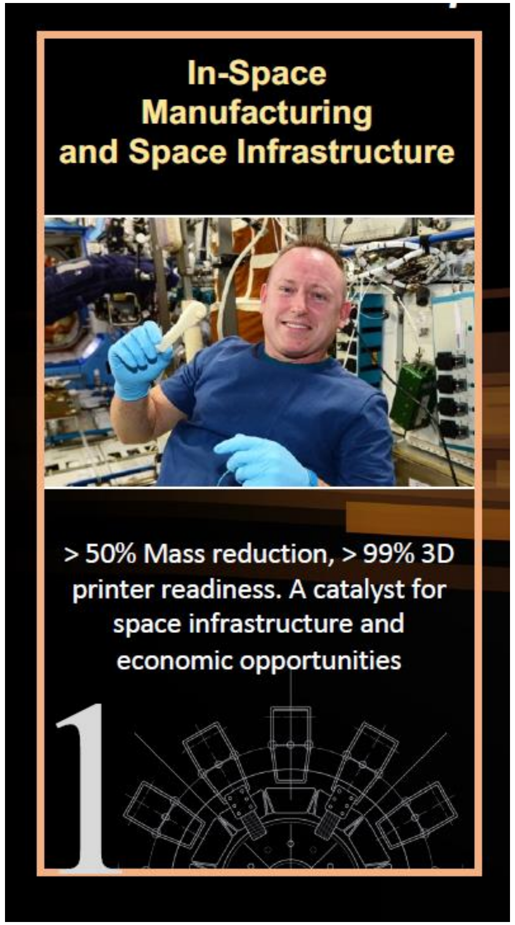
On-demand manufacturing of critical parts and tools (image credit NASA)



Build objects too big or fragile to launch

Bring → Recycle & Reuse → In-Situ Resource Utilization

ISM Addresses STMD Advanced Manufacturing Technology Shortfalls (“Gaps”)



Gap ID	Gap Title	ISM Portfolio Approach
1485	In-Space Manufacturing of Metals, Electronics, and Polymers (Spares, Repairs, New Parts)	GCD-funded project On-Demand Manufacturing of Electronics (ODME) is currently pursuing in-space manufacturing of sensors for astronaut health and semiconductors for use in space and terrestrially. ISM anticipates resumption of in-space fabrication of metallic and hybrid material components and structures in future fiscal years.
1487	In Space Welding and Large-Scale Additive Manufacturing	MSFC TIP, proposed ECI, and a DARPA NOM4D collaboration are developing in-space laser-based processing (e.g. welding and bending) to enable critical repairs and construction of large articles such as lunar towers or space-based storage tanks.
1489	Recycling and Reuse for In-Space Manufacturing	ISM plans to reintroduce a focus on space-based material recycling in FY25, to be followed by recycling of metallics.
1486	In Situ Qualification, Verification & Validation of Components for Manufacturing, Assembly, and Construction	ISM is utilizing NDE, structured light, and various other inspection techniques to verify and validate form, fit, and function of space-fabricated electronics, components, and structures.

Ref: Advanced Manufacturing Envision Future Priorities