



Make It – Don't Take It: NASA's Vision for Extraterrestrial Manufacturing and Construction
2023 Ohio State Materials and Manufacturing Conference
May 10, 2023
R. G. Clinton Jr., PhD, Principal Investigator, MMPACT Project

AGENDA



- NASA's Moon to Mars Exploration Strategy Overview
- Artemis
- NASA's Space Technology Mission Directorate (STMD): Technology Drives Exploration
- Excavation, Construction and Outfitting Focal Area Summary
- Moon to Mars Planetary Autonomous Construction Technology (MMPACT) Project Overview
- Advanced Manufacturing Focal Area Overview
- In Space Manufacturing Portfolio
- Summary

NASA's Moon to Mars Exploration Strategy



- NASA's Moon to Mars Strategy and Objectives Development document is available online at:

<https://go.nasa.gov/3zzSNhp>

- There are multiple resources available to provide additional information on the background and development of the strategy:
 - Architecture Definition Document
 - NASA's Moon to Mars Architecture: A Summary of the 2022 Architecture Concept Review
 - Architecture Concept Review 2022 White papers:
 - [Systems Analysis of Architecture Drivers](#)
 - [Why NRHO: The Artemis Orbit](#)
 - [Why Artemis will Focus on the Lunar South Polar Region](#)
 - [Gateway: The Cislunar Springboard for International and Sustainable Human Deep Space Exploration](#)
 - [Mars-Forward Capabilities to be Tested at the Moon](#)
 - [Mars Transportation](#)
 - https://www.nasa.gov/sites/default/files/atoms/files/acr22-wp-why_nrho-the-artemis-orbit.pdf



Moon to Mars Strategy: 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.



Artemis: Landing Humans On the Moon



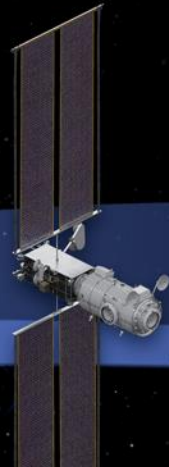
Lunar Reconnaissance Orbiter: Continued surface and landing site investigation



Artemis I: First human spacecraft to the Moon in the 21st century



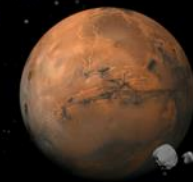
Artemis II: First humans to orbit the Moon and rendezvous in deep space in the 21st Century



Gateway begins science operations with launch of Power and Propulsion Element and Habitation and Logistics Outpost



Artemis III-V: Deep space crew missions; cislunar buildup and initial crew demonstration landing with Human Landing System



Early South Pole Robotic Landings
Science and technology payloads delivered by Commercial Lunar Payload Services providers

Volatiles Investigating Polar Exploration Rover
First mobility-enhanced lunar volatiles survey

Uncrewed HLS Demonstration

Humans on the Moon - 21st Century
First crew expedition to the lunar surface

LUNAR SOUTH POLE TARGET SITE

Artemis Base Camp Buildup

First lunar surface expedition through Gateway; external robotic system added to Gateway; Lunar Terrain Vehicle delivered to the surface

Sustainable operations with crew landing services; Gateway enhancements with refueling capability, additional communications, and viewing capabilities

Pressurized rover delivered for greater exploration range on the surface; Gateway enables longer missions

Surface habitat delivered, allowing up to four crew on the surface for longer periods of time leveraging extracted resources. Mars mission simulations continue with orbital and surface assets.

Lunar Terrain Vehicle (LTV)

Crew Landing Services

Pressurized Rover

Fission Surface Power

ISRU Pilot Plant

Surface Habitat

SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION

MULTIPLE SCIENCE AND CARGO PAYLOADS | U.S. GOVERNMENT, INDUSTRY, AND INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

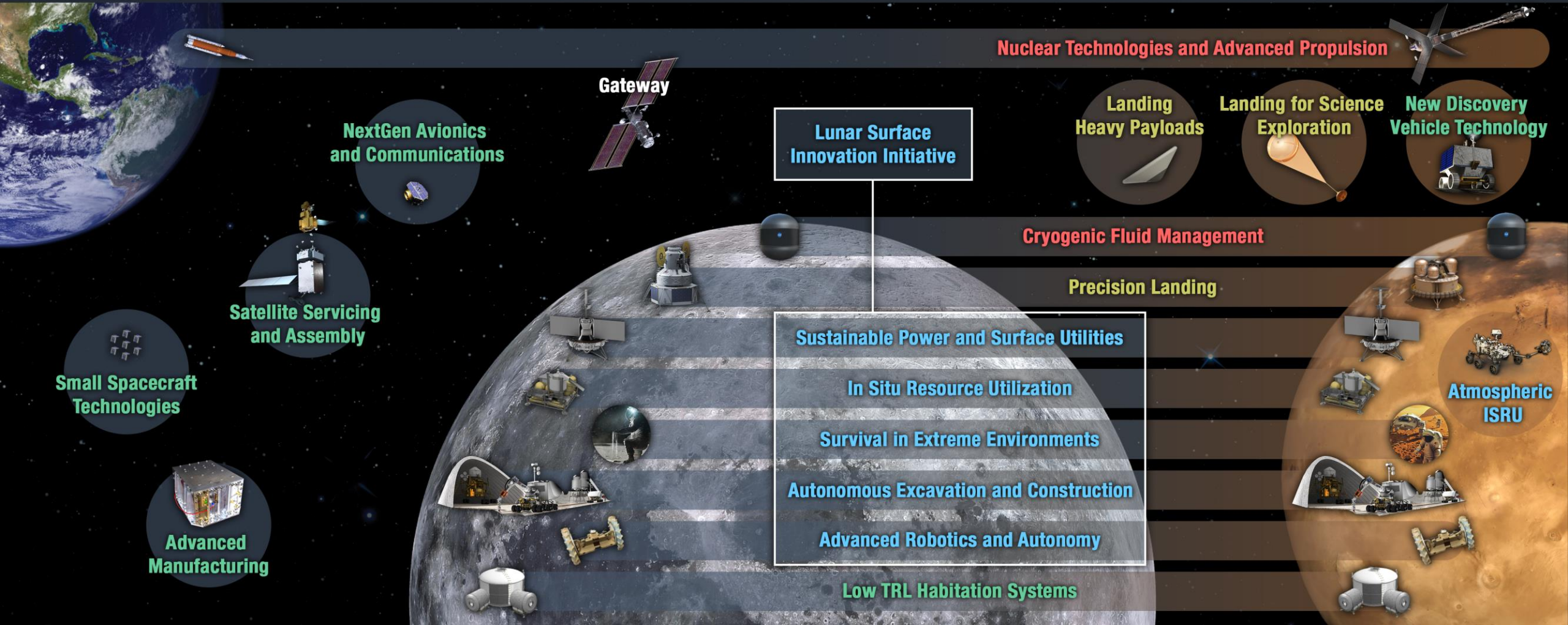
TECHNOLOGY DRIVES EXPLORATION

Rapid, Safe, and Efficient
Space Transportation

Expanded Access to Diverse
Surface Destinations

Sustainable Living and Working
Farther from Earth

Transformative Missions
and Discoveries



2020

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203X

Inclusive Strategic Technology Planning

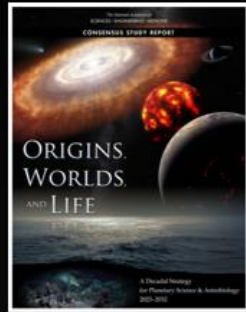


Strategic Technology Architecture Roundtable (STAR) Process

In order to achieve the NASA Strategic Objective led by the Space Technology Mission Directorate, the STAR process was implemented to bring together the various inputs from stakeholders to produce a set of gaps that can be closed through STMD investments.



Draws directly on Artemis architectures and Science Mission Directorate Decadal to identify technology gaps.



Industry Partners' participation is obtained through Requests for Information (RFIs) to validate envisioned futures, the current state of the art and the gaps between those two.



STAR process inclusive of Center Chief Technologists, ESDMD and SMD Representation.

Maps to OTPS Taxonomy.

STMD Strategic Framework describes the STMD investment priority strategy. Strategic Technology Framework aligned to Agency Moon to Mars Strategy along with Agency Strategic Capability Leads (SCLs) and Principal Technologists (PTs).



STAR



Envisioned Future Priorities

PPBE Process

STARPort is the database of all Capability Area gaps for both STMD and ESDMD. Envisioned Future Priorities (EFPs) are written by SCL/PTs to show the future state envisioned and suggested path forward to inform Planning, Programming, Budgeting, and Execution (PPBE) process.

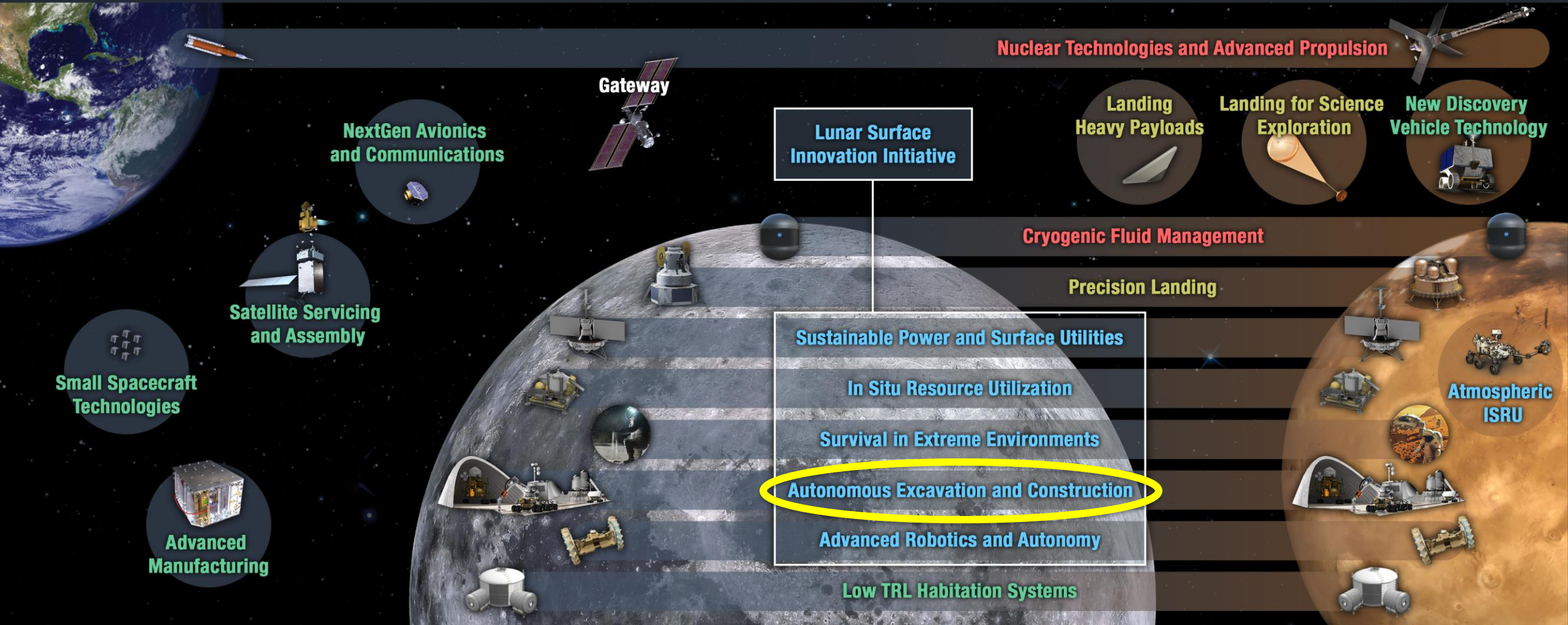
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Autonomous Lunar Excavation, Construction, & Outfitting

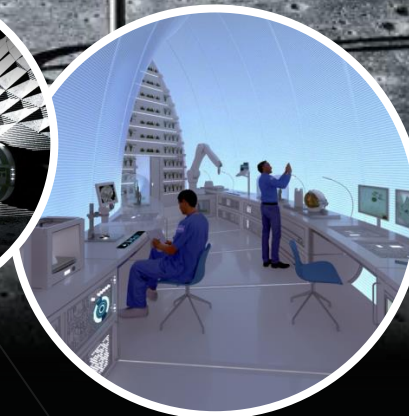
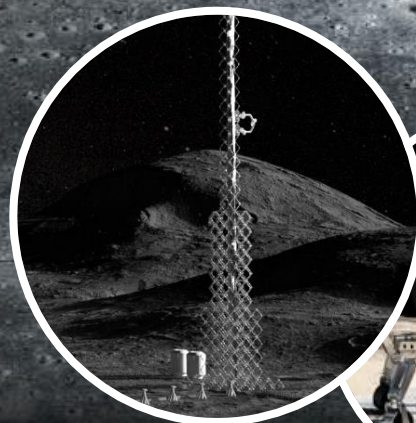
targeting towers, roads, landing pads, and habitable buildings utilizing in-situ resources

Updated



Excavation for ISRU-based Resource Production

- Ice mining & regolith extraction for 100s to 1000s metric tons of commodities per year
- Regolith for production of construction materials
 - 100s to 1000s metric tons of regolith-based feedstock for construction projects
 - 10s to 100s metric tons of metals and binders



Regolith Manipulation & Site Preparation

- Site preparation: obstacle clearing, leveling, compacting & trenching
- Bulk regolith manipulation for berms and overburden
- Foundations for large infrastructure elements

Construction and Outfitting

- Assembly of tall towers for solar power generation, communications, navigation
- Landing pad construction for CLPS and human lander systems
- Unpressurized structure evolving to single and then multi-level pressurized habitats
- Outfitting for data, power & ECLSS systems
- 100-m-diameter landing pads, 100s km of roads, 1000s m³ habitable pressurized volume

Commercial ECO Capabilities for Sustainable Infrastructure & Economy

- Commercial capabilities to construct tall towers, landing facilities, roads, and habitable structures
- Fully outfitted facilities and buildings to support a permanent lunar settlement and vibrant space economy
- Capabilities extensible to future ESDMD, SMD and Mars missions

Surface Construction

Capability Description, Outcomes, State of the Art, and Technology Gaps (Class III)

Capability Description:

- **Class II:** Assembly of components into built-up structures (e.g., Earth-sourced or ISRU-based truss, panel, paver, bricks); deployment of human-rated preassembled or inflatable structures
- **Class III:** In-situ additive construction (e.g., 3D printed regolith-based construction)
- In-situ testing and inspection techniques for certification (material and structural)
- Structural enhancement and repair
- Construction Systems: design for lunar survivability, reliability, and maintenance

Outcomes

- Towers (50+ m tall for Power and Communication)
- 10s km of roads
- 100-m-diameter launch/landing pads (LLPs)
- Blast containment shield (BCS)– 7m-tall, 100s m long
- Shelters & habitats (1000s m³ volume) to provide asset and crew protection (thermal, radiation, etc.)

SoA: Extraterrestrial surface construction has never been attempted. Terrestrial prototypes at low TRL.

Technology Gaps (Class III)

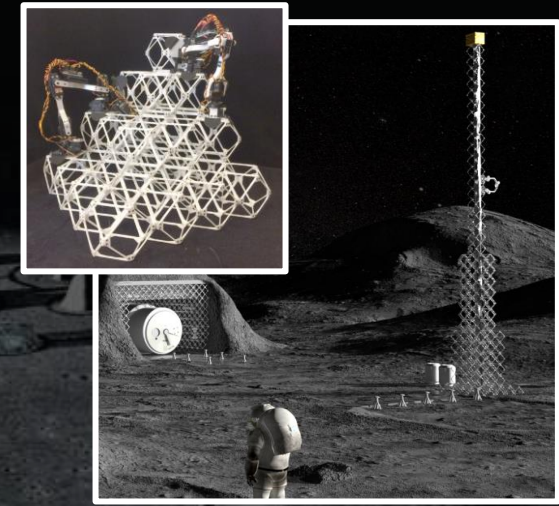
- Deposition of print material in low-pressure environment while controlling porosity
- High-temperature materials for LLPs
- LLP Paver joining
- Surface stabilization, Foundations, and Anchors
- Repair technologies
- Process inspection and control
- In-situ V&V of construction materials



Terrestrial printing of cementitious material



Class II: Assembly & Deployables



Class III: In-situ Construction Process Development

Laser melting in vacuum



Microwave sintering in vacuum



Molten extrusion in vacuum



Excavation for ISRU

Capability Description, Outcomes, and Technology Gaps

Capability Description

- Autonomous resource excavation and delivery to ISRU plant –1000s t/year
- Distance traveled with repeated trafficking – 1000s km/year
- Recharging – 100s times (assuming no on-board PV charging)
- Operational Life – 5 years
- Reliability and Repair – MTBF = 10 lunar days, MTTR = <2 hrs

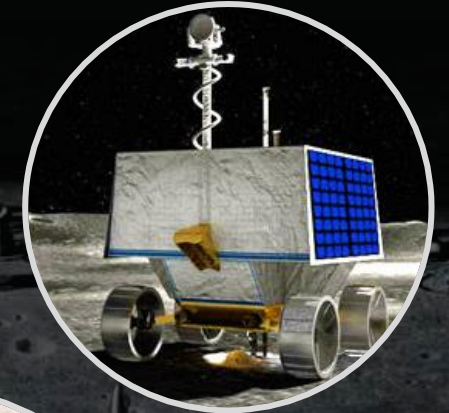
Outcomes

- Regolith for O₂
- Icy Regolith for H₂O and volatiles - hydrogen, carbon oxides, hydrocarbons, and ammonia
- Regolith for ISRU-based construction feedstocks and binders – Metals, Silicon, Slag

Technology Gaps

- Multi-functional low mass rugged robotic platforms for regolith excavation and delivery
- Modularity and interfaces for reconfigurability and repairability
- Autonomy for high throughput and cooperative operations
- Lunar survivability, reliability, and repair
 - Survive multiple lunar nights or shadowed regions
 - Wear-resistant materials and wear characterization
 - Long-life lubricants, motors, avionics
 - Dust mitigation for actuators, seals, joints, mechanisms; Dust-tolerant thermal control system
 - Autonomous maintenance and repair
 - Health and Fault management
- Regolith flow/interaction with implements (simulation and test)
- Scale-up from pilot scale (10mT) to initial commercial scale (1000mT/yr)
- End-to-end system demonstrations that lead to lunar demo, need time on equipment

ISRU resource prospecting and geotechnical characterization (ISRU dependency)



Resource excavation and delivery



Regolith Manipulation and Site Preparation

Capability Description, Outcomes, and Technology Gaps

Capability Description - Similar Capabilities as Excavation for ISRU, plus...

- Site survey – geotechnical, topography
- Load, Haul, Dump
- Bulk regolith manipulation – berms, piles, overburden, and gravel
- Level, grade, and compact
- Rock removal and gathering
- Trenching and burying

Outcomes

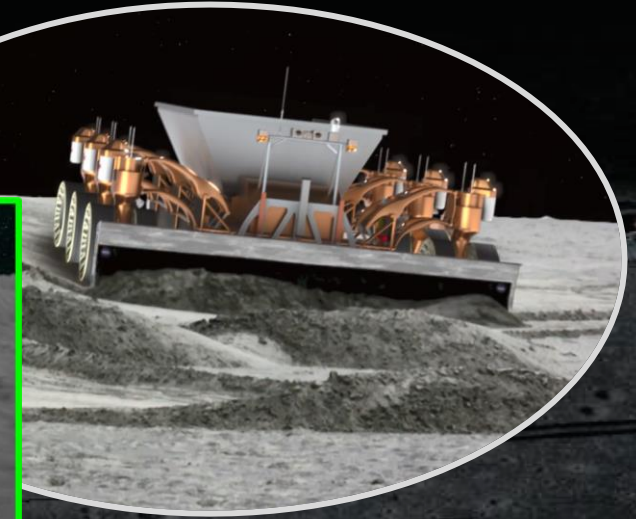
- Site preparation for construction - 1000s of m² of prepared surface
- Provide bulk regolith berms and overburden for shielding
- gravel surfaces for dust mitigation

Technology Gaps

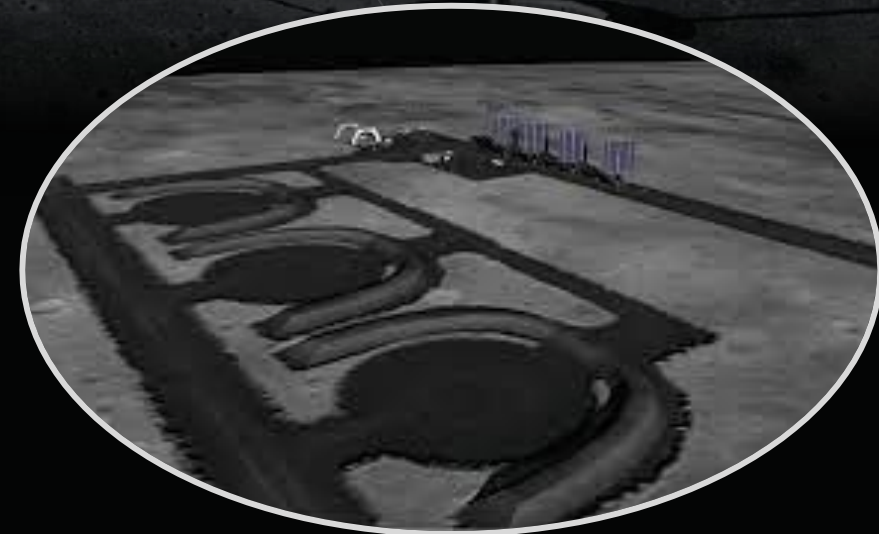
- Site survey – geotechnical, topography
- Implements and Systems: excavation, haul, dump, rock handling, grading, leveling, compaction, berm building, trenching
- Site prep inspection techniques and sensor systems
- Feasibility testing for regolith manipulation and system development leading to lunar surface demo
- System scale-up to initial commercial scale; 100's m² areas, 10,000's mT regolith moved
- *Additional shared gaps listed for Excavation for ISRU*

Leveling and grading

STTR Ph1 Site Prep System Study –
Astroport Space Technologies, Inc.



Early-phase infrastructure



Outfitting

Capability Description, Outcomes, and Technology Gaps

Outfitting Capability Description

Capability Description

- The process by which a structure is transformed into a useable system by in-situ installation of subsystems.
 - Subsystem installation
 - In-situ testing/validation and inspection techniques with associated metrology
 - Structural repair and enhancement

Outcomes (affects most systems that are not landed in operational self-contained state)

- Power, Lighting, Data & Communications distributed through system
- Fluids & Gasses (ISRU products) managed and stored.
- ECLSS
- Hatches and Penetrations
- Interior Furnishing

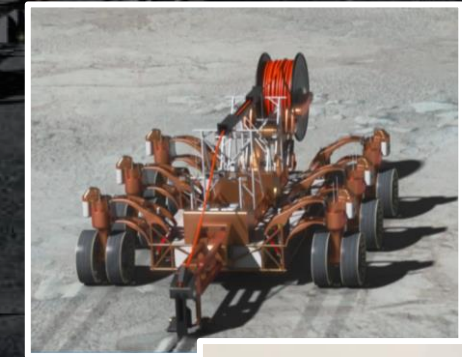
Technology Gaps

- Architectural and ConOps studies
- Outfitting requirements and standards
- Robotic outfitting technologies for installation of lighting, harnesses, beacons, sensors, fluid systems, HVAC, etc.
- Design of pressure vessel connections/seals with penetrations
- Common interface definition
- Inspection methods & repairs
- Utility corridor design
- Autonomy for complex outfitting and inspection tasks

Apollo 14: Setting up long duration experiments.

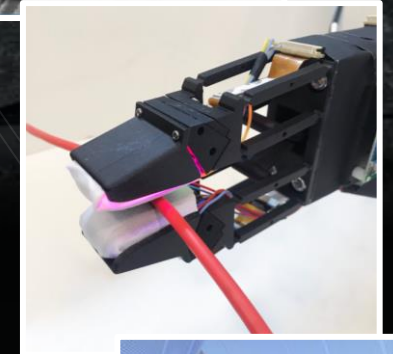


Wiring harness for Instruments, beacons, etc.

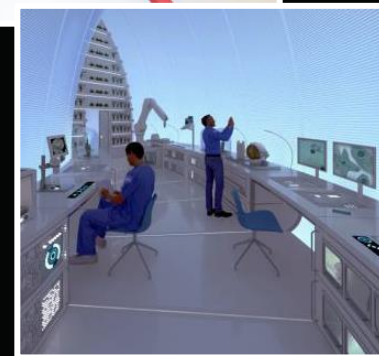


Trenching and cable laying

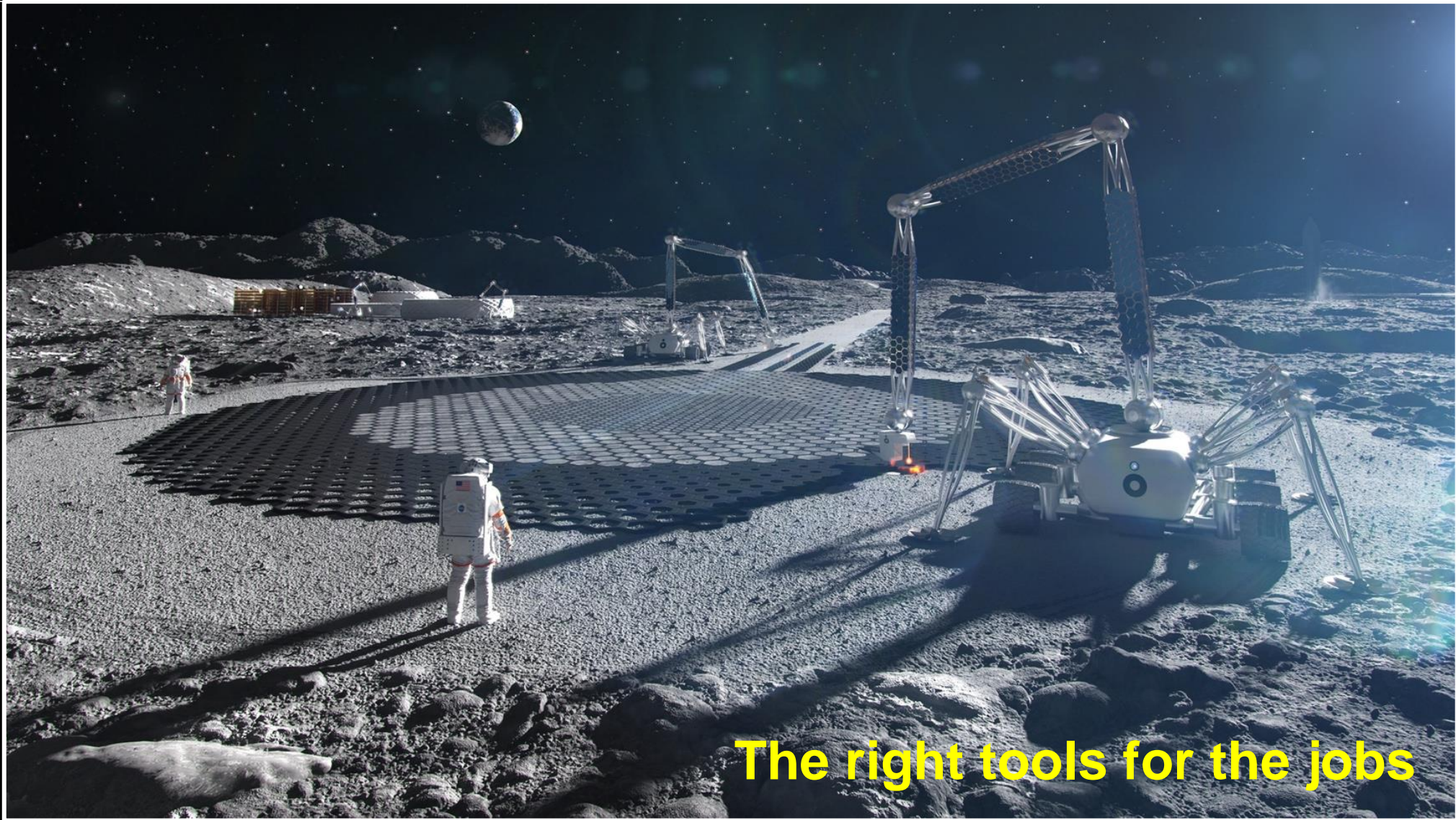
Cable handling



Outfitted facility



How We Explore... Lunar Construction Technology



The right tools for the jobs

GRAND VISION

- **MIMPACT will enable the development of a lunar economy by providing an on-demand construction capability for multiple infrastructure elements (habitats, launch/landing pads, roads, blast shields, and other structures)**
- **MIMPACT will enable sustainable human presence on the Moon**
 - **Customization of infrastructure based on application**
 - **Construction of a suitable location for new crew members, new rovers/spacecraft, or facilities based on need**
- **MIMPACT's industry partner is expected to be commercially viable on the Moon in the 2030's or potentially earlier**
- **Demonstrations begin with a CLPS proof-of-concept mission (STMD)**
- **Partnerships with other NASA Centers and members of industry and academia**
- **Technology Capability at the End State of Phase II of the Project:**
 - **A flight-ready proof-of-concept technology demonstration for construction on the Moon**

WHY- The Case for Lunar Surface Construction: PROTECTION

Lunar ISRU-based infrastructure provides protection from a variety of environmental hazards.

RADIATION

- Galactic Cosmic Rays (GCRs)
- Solar Particle Events (SPEs)
- Secondary Particles
- Albedo



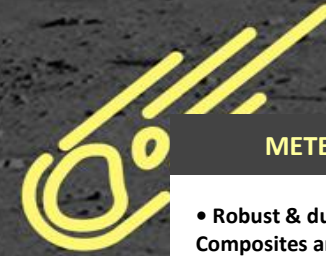
SEISMIC ACTIVITY

- Deep Moonquakes lasting hours, even days
- Seismic Effects of Meteor Impacts



METEOROID IMPACT

- Robust & durable shielding required. Composites and ballistic shielding preferred.
- Consideration of new failure modes due to impact
- Dust ramifications



EXTREME TEMPERATURES

- Extreme Material Stresses
- Structural & Material Fatigue



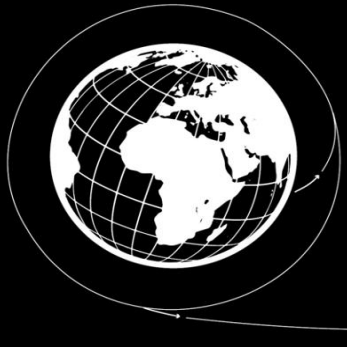
Image courtesy of SEARCh+

WHY- The Case for Lunar Surface Construction: COST

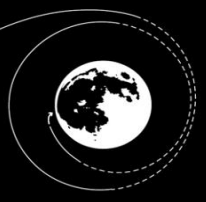


Rockets are not *efficient* movers of building materials.

Even with commercial space flight dramatically dropping the launch costs to all-time historic lows, flying pre-built structures doesn't make financial sense. Even flying building materials from Earth to the Moon is costs prohibitive.



\$ 0.11 per Kg
Costs of dry concrete on Earth



\$ 1,200,000 per Kg
Cost to transport concrete to the Moon



\$ 96,000,000,000
Just the dry concrete costs to print a 350 sq. ft. structure like the Chicon House on the Moon.

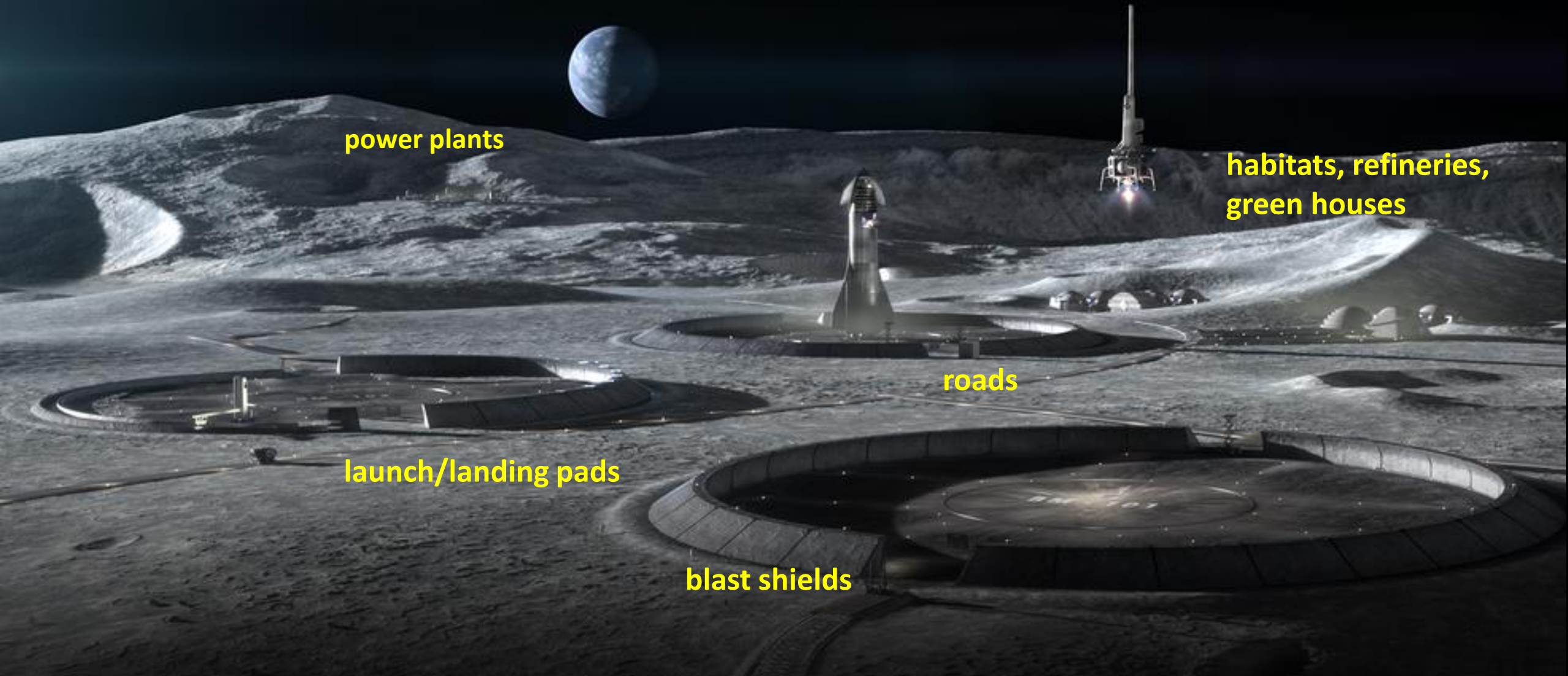


Image courtesy of ICON

Source: Astrobotic Peregrine Lunar Lander Payload User's Guide:
https://explorers.larc.nasa.gov/2019APSMEX/MO/pdf_files/Astrobotic%20-%20Payload%20User%20Guide%20v3%202018-10.pdf

Building a Sustainable Presence on the Moon

- What infrastructure are we going to need?



power plants

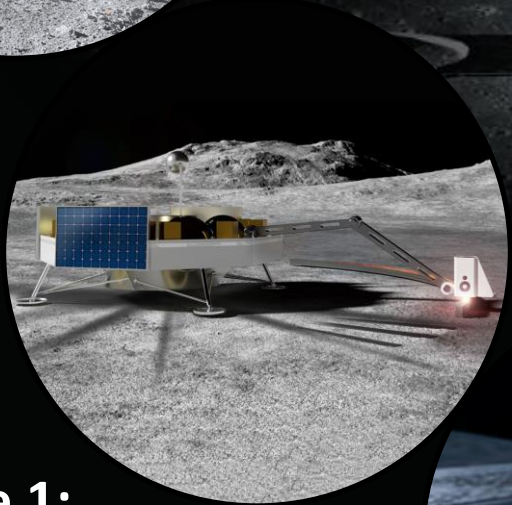
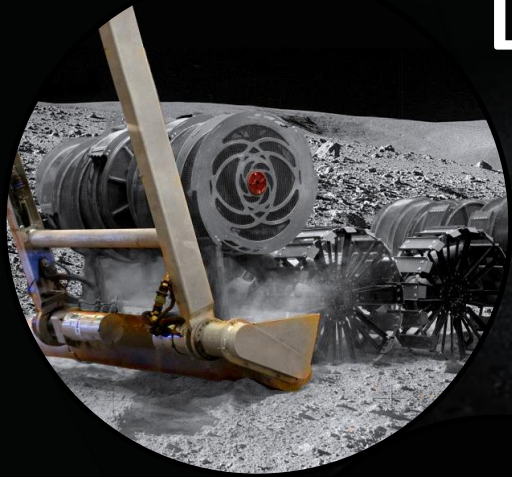
habitats, refineries,
green houses

roads

launch/landing pads

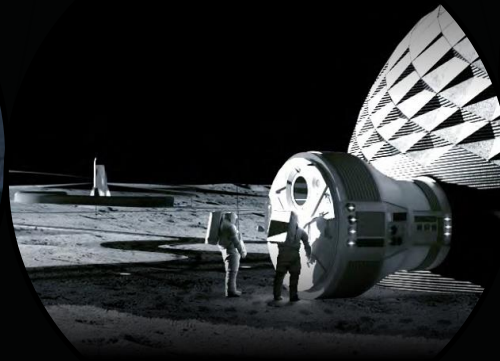
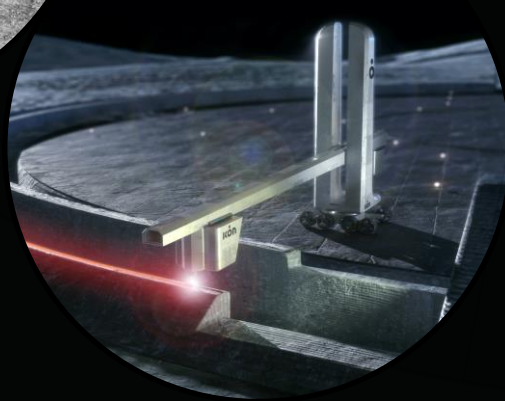
blast shields

Lunar Construction Capability Development Roadmap



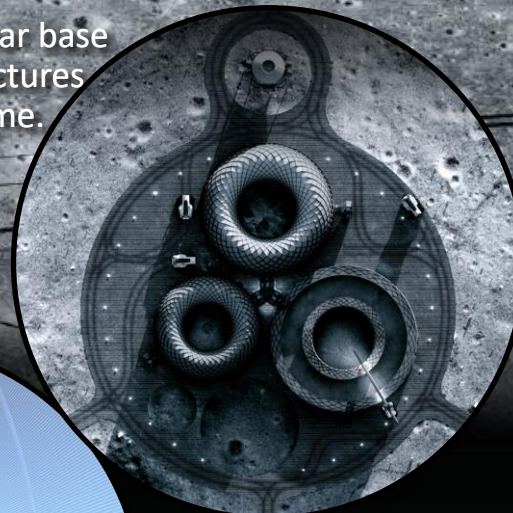
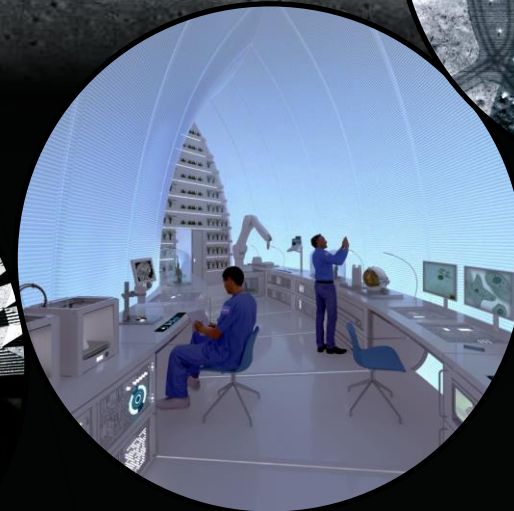
Phase 1:

Develop & demonstrate excavation & construction capabilities for on-demand fabrication of critical lunar infrastructure such as landing pads, structures, habitats, roadways, blast walls, etc.



Phase 2: Establish lunar infrastructure construction capability with the initial base habitat design structures.

Phase 4: Complete build-out of the lunar base per the master plan and add additional structures as strategic expansion needs change over time.



Phase 3: Build the lunar base according to master plan to support the planned population size of the first permanent settlement (lunar outpost).

Space Tech Lunar Surface Demonstration Strategy

ISRU, power, excavation, and construction utilizing cross-cutting technologies

Reconnaissance, Prospecting, Sampling

Resource Acquisition & Processing

Pilot Consumable Production

Sub-system demonstrations:
Investigate, sample, and analyze the environment for mining and utilization.

Follow the natural resources:
Demonstrations of systems for extraction and processing of raw materials for future mission consumables production and storage.

Sustainable exploration:
Scalable pilot systems demonstrating production of consumables from in-situ resources in order to better support sustained human presence.



Oxygen extraction ground demo

IM-2

PRIME, Hopper, LTE Demos



VIPER (SMD)

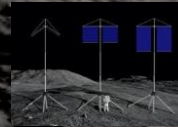


CT-1

ISRU O2 Demo



ISRU Pilot Excavator



Surface Power Demo (VSAT, RFC)

Construction Demo 1



CT-2

ISRU Subscale Demo



Construction Demo 2



Fission Surface Power

ISRU Pilot System*

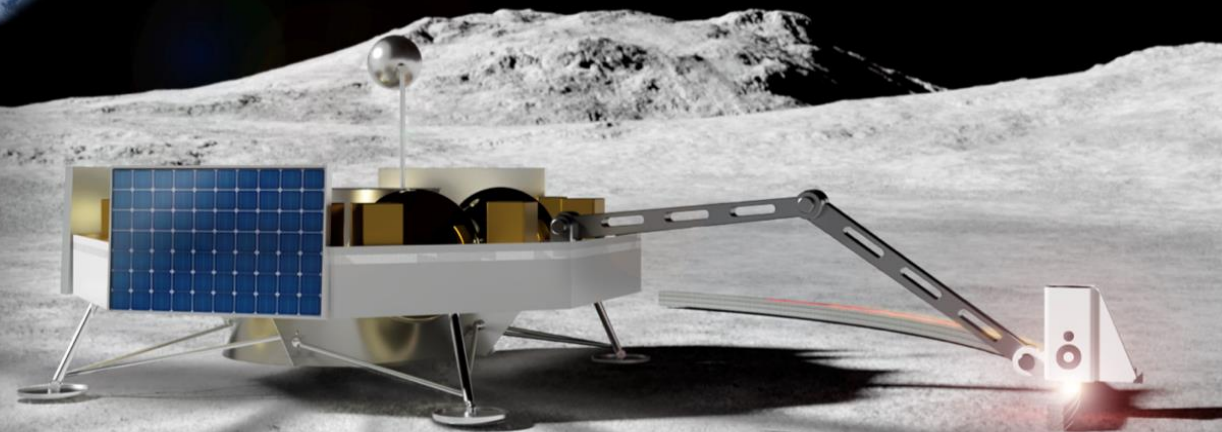


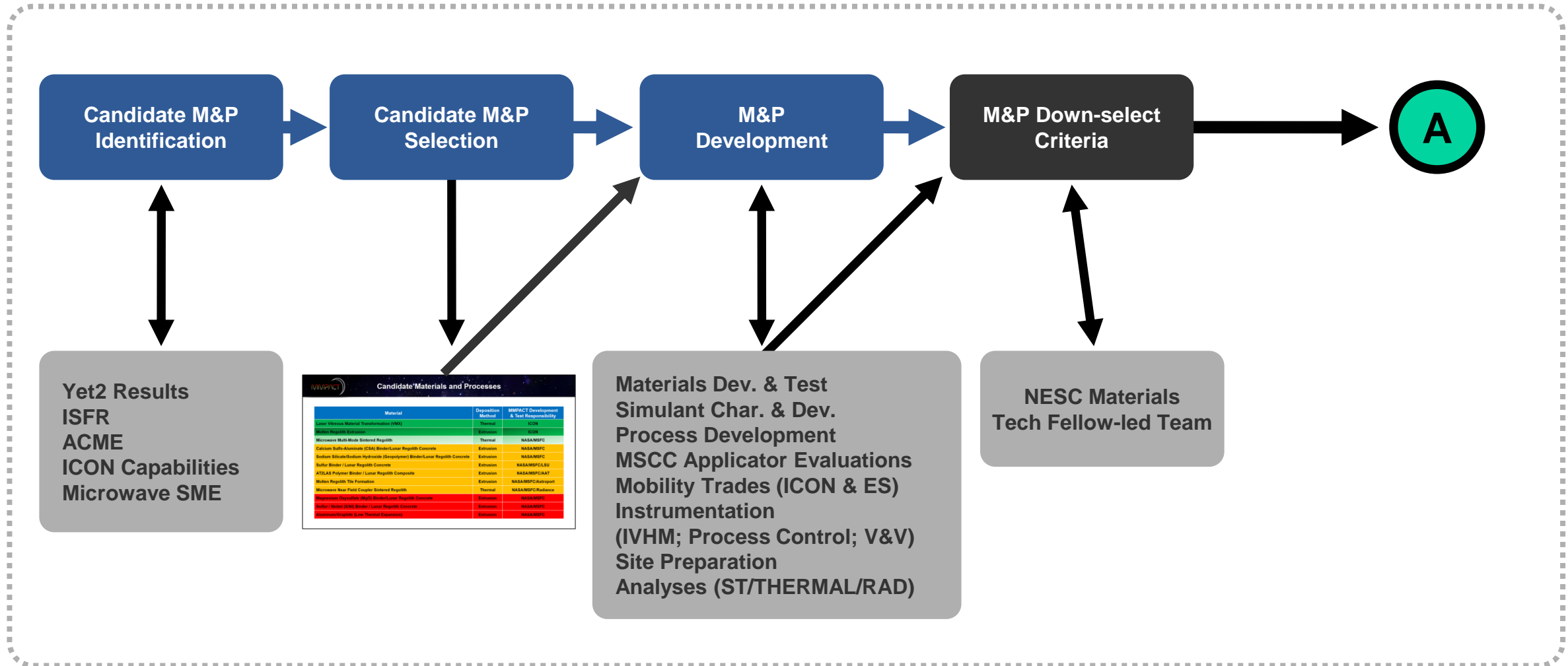
* ISRU Pilot Plant demo will use Fission Surface Power



Early Construction Technology Demonstration Mission

- **Mission success is defined as:**
The ability to emplace a structural element with an observed material characteristic
- **Level 1 Requirements**
 - The system shall demonstrate lunar construction for future missions
 - The system shall additively construct structures using in-situ resources on the lunar surface
 - The system shall implement both autonomy and remote operations to carry out its tasks

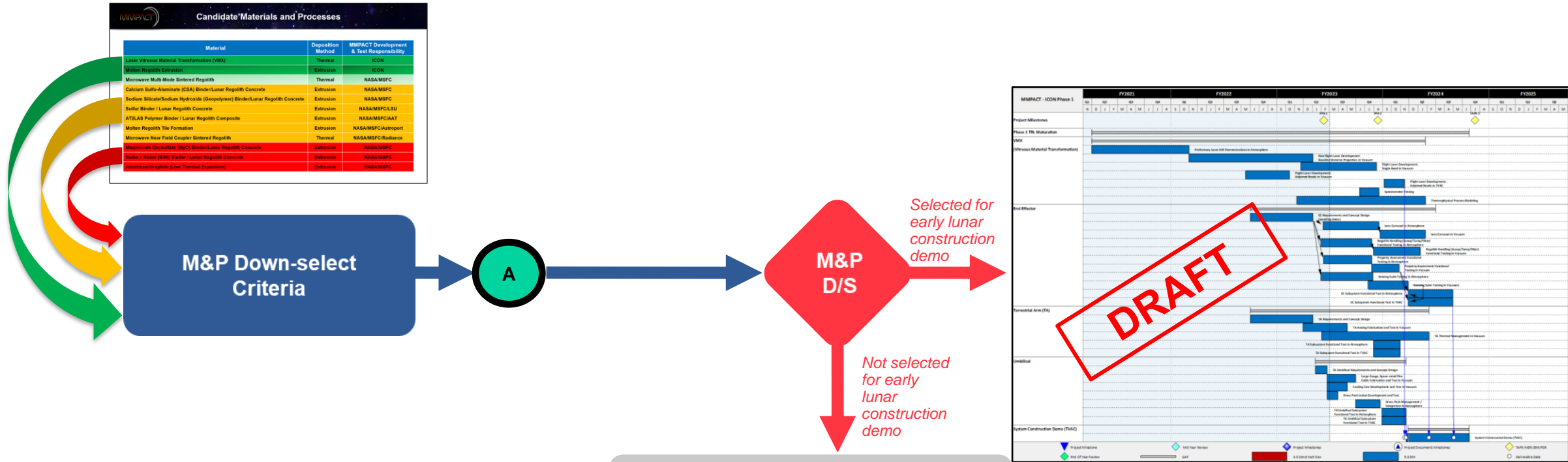






Candidate Materials and Processes

| Material | Deposition Method | MIMPACT Development & Test Responsibility |
|--|-------------------|---|
| Laser Vitreous Material Transformation (VMX) | Thermal | ICON |
| Molten Regolith Extrusion | Extrusion | ICON |
| Microwave Multi-Mode Sintered Regolith | Thermal | NASA/MSFC |
| Calcium Sulfo-Aluminate (CSA) Binder/Lunar Regolith Concrete | Extrusion | NASA/MSFC |
| Sodium Silicate/Sodium Hydroxide (Geopolymer) Binder/Lunar Regolith Concrete | Extrusion | NASA/MSFC |
| Sulfur Binder / Lunar Regolith Concrete | Extrusion | NASA/MSFC/LSU |
| AT2LAS Polymer Binder / Lunar Regolith Composite | Extrusion | NASA/MSFC/AAT |
| Molten Regolith Tile Formation | Extrusion | NASA/MSFC/Astroport |
| Microwave Near Field Coupler Sintered Regolith | Thermal | NASA/MSFC/Radiance |
| Magnesium Oxysulfate (MgO) Binder/Lunar Regolith Concrete | Extrusion | NASA/MSFC |
| Sulfur / Nickel (S/Ni) Binder / Lunar Regolith Concrete | Extrusion | NASA/MSFC |
| Aluminum/Graphite (Low Thermal Expansion) | Extrusion | NASA/MSFC |



Selected M&P Development for Risk Mitigation:

- Back-up for early lunar construction demo
- Achieve TRL 6 for second lunar construction demo
- Provide additional construction capabilities and materials for different infrastructure elements/applications (habitats, roads, etc.)

Test Matrix for Selection of Demonstration Mission One (DM-1) Material/Process

| | | | | |
|---|---------|--------------|---|--------|
| Compression Strength | Mortar | ASTM C0109 | Standard Test Method for Compressive Strength of Hydraulic Cement Mortars | STP |
| | Ceramic | ASTM C1424 | Standard Test Method for Monotonic Compressive Strength of Advanced Ceramics at Ambient Temperature | STP |
| Compression at Cold Temperature (lunar night) | Mortar | ASTM C0109 | Standard Test Method for Compressive Strength of Hydraulic Cement Mortars | -192°C |
| | Ceramic | ASTM C1424 | Standard Test Method for Monotonic Compressive Strength of Advanced Ceramics at Ambient Temperature | -192°C |
| Compression at Elevated Temperature (lunar day) | Mortar | ASTM C0109 | Standard Test Method for Compressive Strength of Hydraulic Cement Mortars | 57°C |
| | Ceramic | ASTM C1424 | Standard Test Method for Monotonic Compressive Strength of Advanced Ceramics at Ambient Temperature | 57°C |
| Compression After Thermal Cycling Under Vacuum² | Mortar | ASTM C0109 | Standard Test Method for Compressive Strength of Hydraulic Cement Mortars | STP |
| | Ceramic | ASTM C1424 | Standard Test Method for Monotonic Compressive Strength of Advanced Ceramics at Ambient Temperature | STP |
| Layer to Layer Adhesion | Both | ASTM C297 | Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions | STP |
| 4 Point Bend Flexural Test | Mortar | ASTM C78 | Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) | STP |
| | Ceramic | ASTM C1161 | Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature | STP |
| Ablation³ | Both | EM40-OWI-013 | EM40 Non-Metallics & Advanced Manufacturing Division Plasma Torch Test Facility Operation Procedure | TBD |

1All test specimens will have more than 1 horizontal layer, with the knitline(s) perpendicular to the loading axis.

2One thermal cycle is defined as room temperature to -192°C, -192°C to 57°C, 57°C to -192°C and back to room temperature. Vacuum level used will be 10⁻⁴ to 10⁻³.

3Two configurations of ablation specimens will be tested: an as-built surface facing the plasma torch and a machined surface facing the plasma torch.

- Pathfinders conducted at both KSRE and PTTF
 - X-ray/Computed tomography
 - Microscopy
 - Thermal cycling
 - CTE
 - Compression & tension
 - Ablation – heat flux selected based on lander data and expected simulant melt temperature
- Specimen configuration determined
- Material preparation process documented
 - CSM-LHT-1G simulant
 - 10^{-3} torr (exception: mortar)
- Testing and inspection methods documented
- All material processes, specimen preparation, testing, and inspection procedures presented to and approved by the MIMPACT Engineering Control Board

Results for ICON Laser VMX Material

Thermal (PTTF ablation)

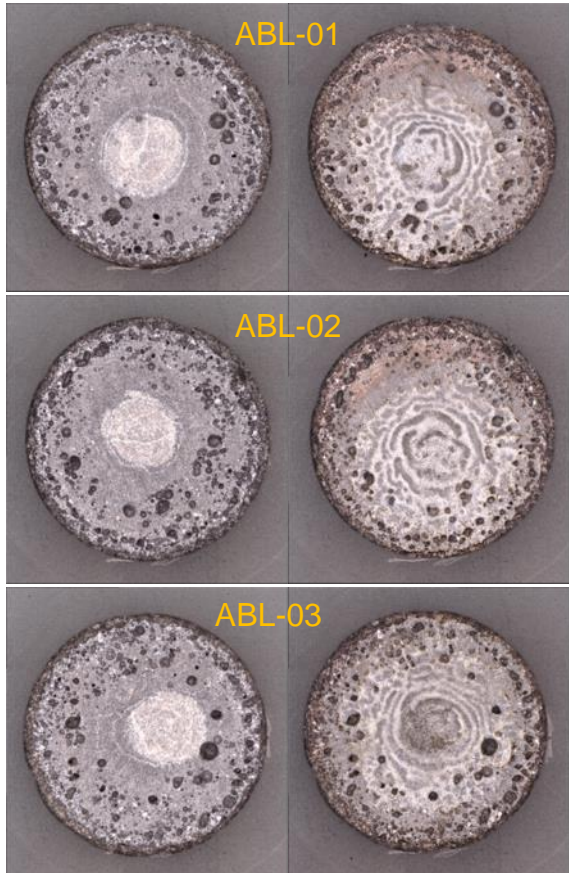
- Each specimen 1 in thick
- Heat flux 3 MW/m² (~264 BTU/ft²-sec), 5 sec duration

| Specimen Number | Pretest Mass (g) | Post Test Mass (g) | Weight Loss (grams) | Weight Loss (%) | MDR (μm/s) | Max. Backside Temp. °F |
|-----------------|------------------|--------------------|---------------------|-----------------|------------|------------------------|
| 01 | 51.5905 | 51.5587 | 0.0318 | 0.06% | 5.1 | 279 |
| 02 | 50.4325 | 50.4103 | 0.0222 | 0.04% | 5.1 | 144 |
| 03 | 49.6280 | 49.6013 | 0.0267 | 0.05% | 0.0 | 157 |
| 04 | 49.5035 | 49.4813 | 0.0222 | 0.04% | 15.2 | 209 |
| 05 | 48.3913 | 48.3484 | 0.0429 | 0.09% | 0.0 | 213 |
| 06 | 50.0569 | 49.9962 | 0.0607 | 0.12% | 0.0 | 194 |

Extensive details are provided in the MMPACT DS Report

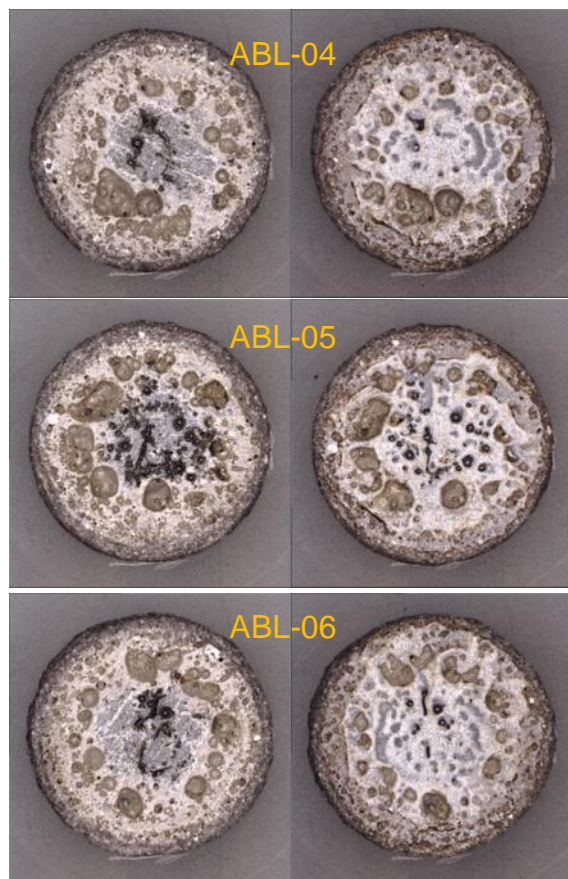
Machined

Pre-test Post-test



As-fabricated

Pre-test Post-test

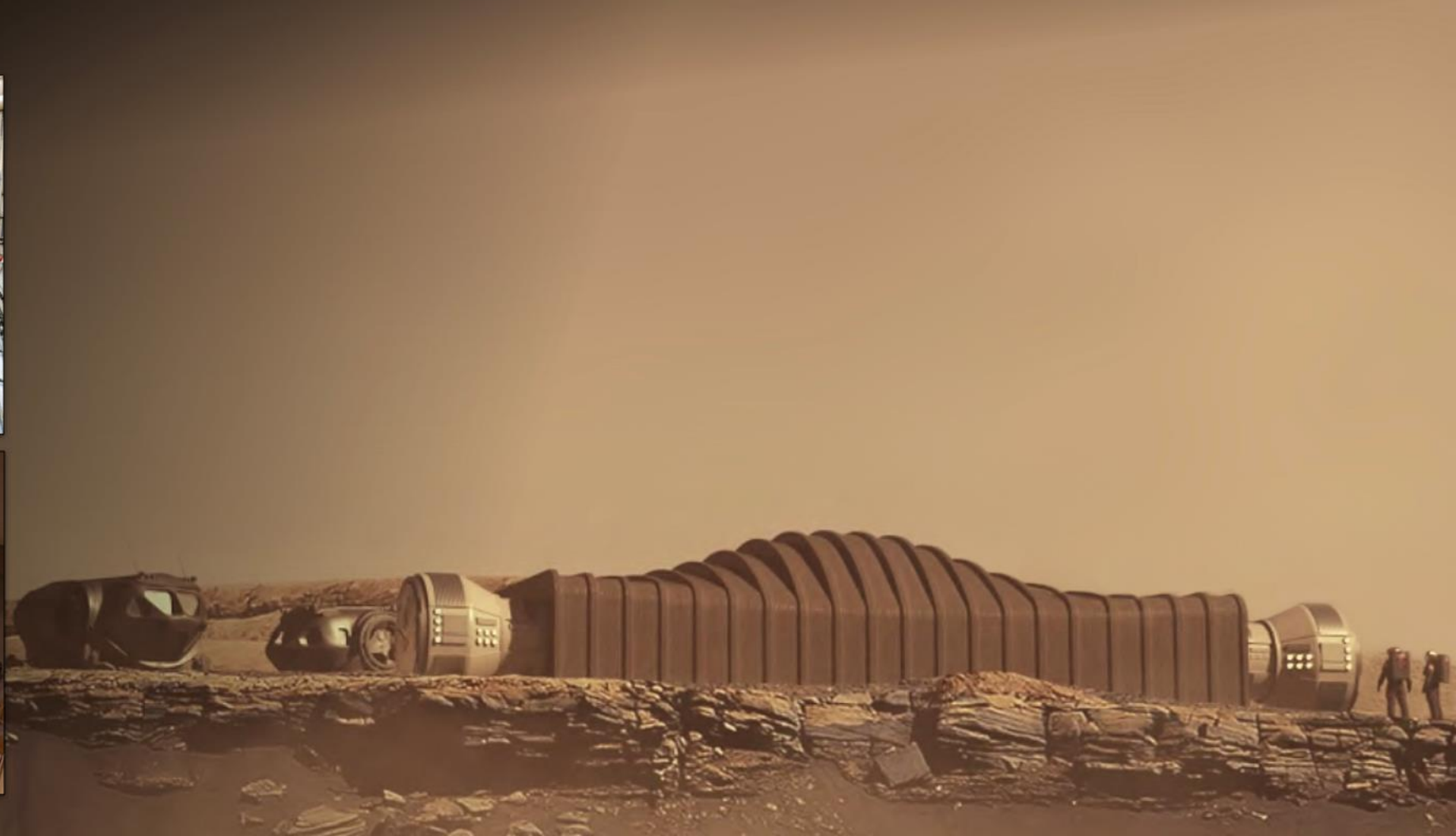


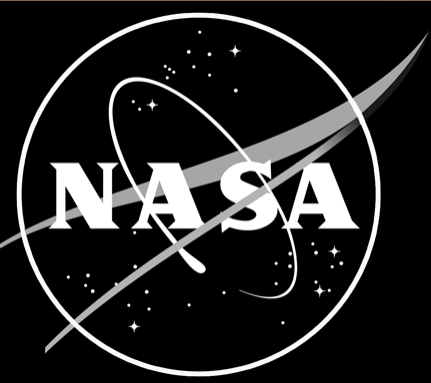
- **Laser Vitreous Material Transformation (VMX) selected as baseline for early lunar construction demonstration**
 - Capability for both horizontal and vertical construction – process versatility
 - Most mature among the candidate processes/materials – process maturity
 - No construction materials required to be launched – process efficiency/launch mass and cost reduction
 - Sample size to date limited by the size of the vacuum chamber
 - Large scale capability demonstrated in atmosphere
 - Early physics models correlated well with empirical observations of glass ceramic material production
 - Demonstration at scale in simulated lunar environment (temperature and vacuum) to be conducted in V20 to validate performance/properties
 - Process is extensible to structures at scale on the lunar surface

Laser VMX enables true on-demand infrastructure capability

CHAPEA / Mars Dune Alpha

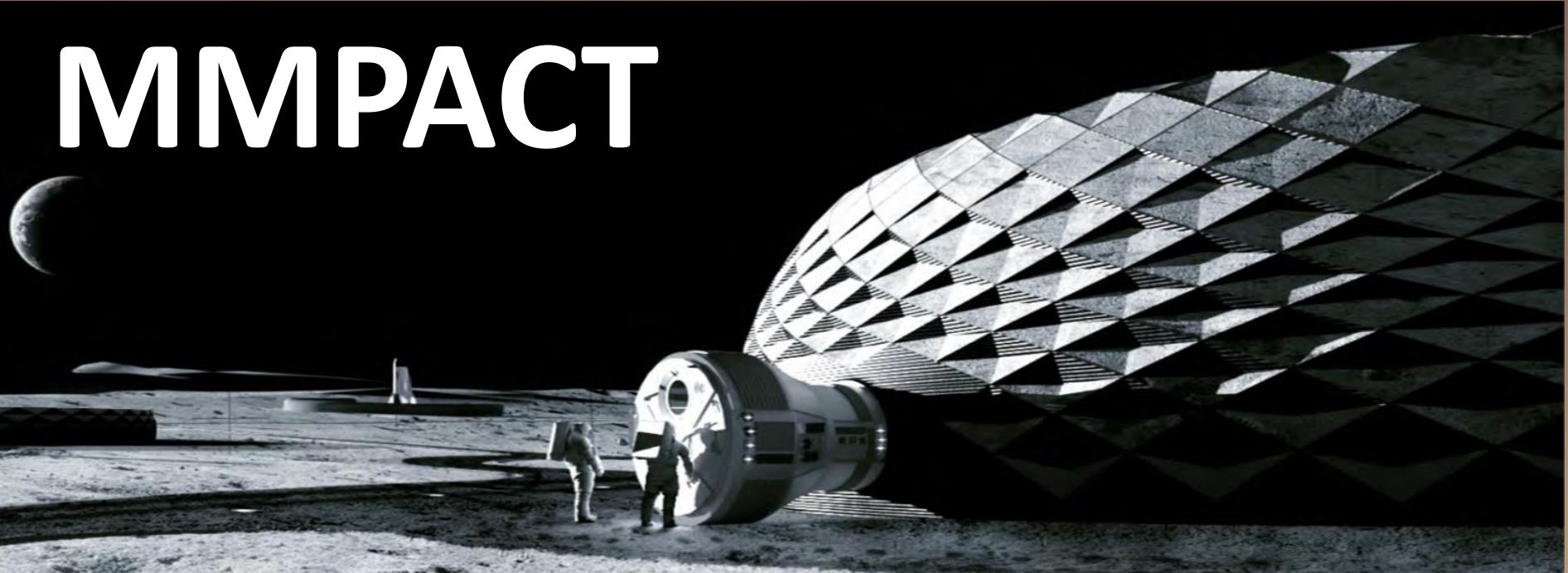
To prepare for long-duration missions to Mars, ICON constructed a Martian analog habitat designed by BIG at Johnson Space Center. The 1,700 ft² structure will be home to four crew members in year-long missions as part of the Crew Health and performance Exploration Analog (CHAPEA) program beginning in 2022.





MMPACT

MOON TO



MARS PLANETARY AUTONOMOUS CONSTRUCTION TECHNOLOGY



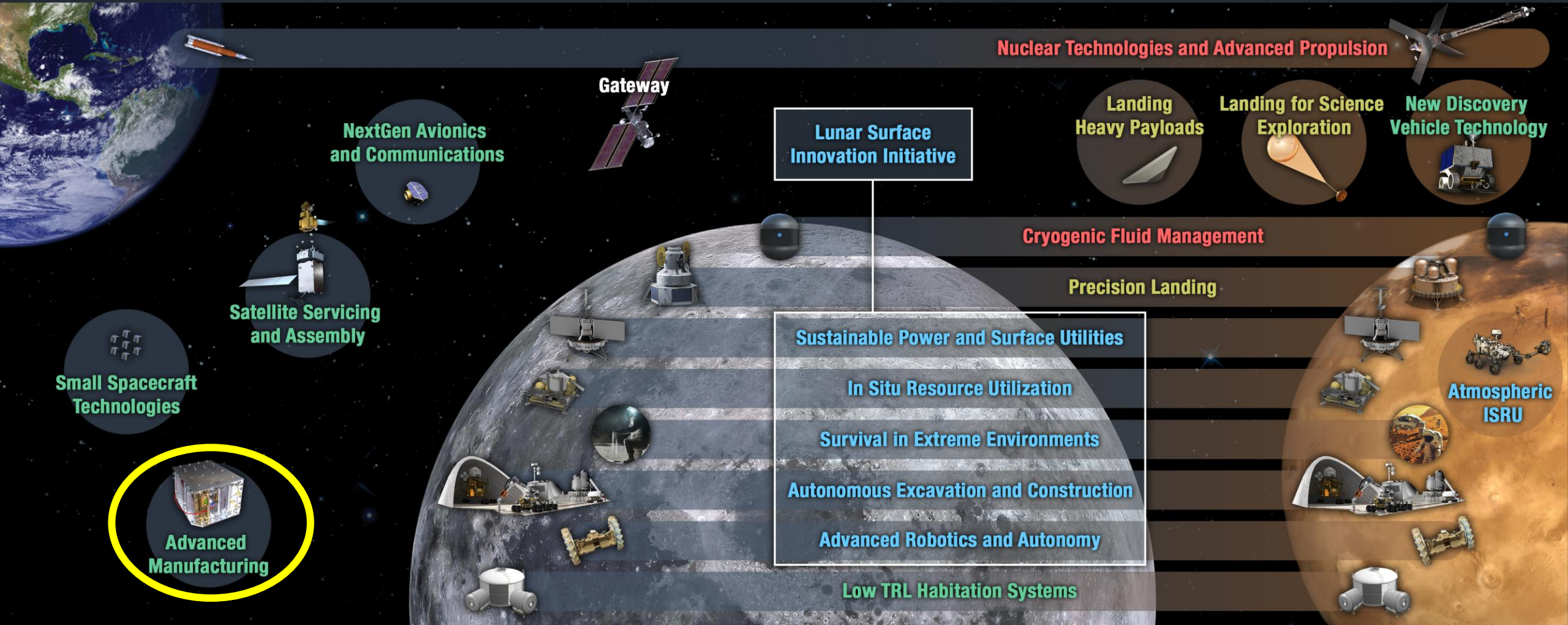
TECHNOLOGY DRIVES EXPLORATION

Rapid, Safe, and Efficient
Space Transportation

Expanded Access to Diverse
Surface Destinations

Sustainable Living and Working
Farther from Earth

Transformative Missions
and Discoveries



2020

GO | LAND | LIVE | EXPLORE

203X



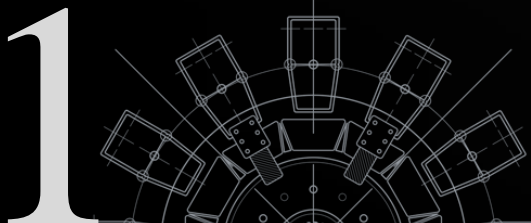
EXPLORE: Develop technologies supporting emerging space industries

Priorities - Targeted advanced manufacturing outcomes aligned with space industry trends that will shape the course of research and development over many years

In-Space Manufacturing and Space Infrastructure



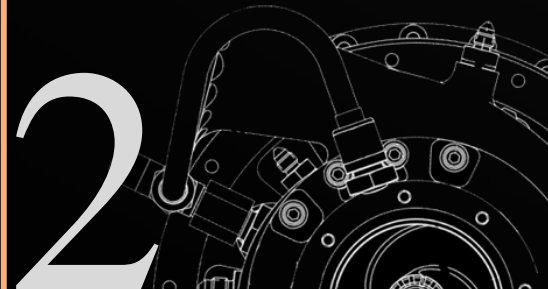
> 50% Mass reduction, > 99% 3D printer readiness. A catalyst for space infrastructure and economic opportunities



3D Printing / Additive Manufacturing



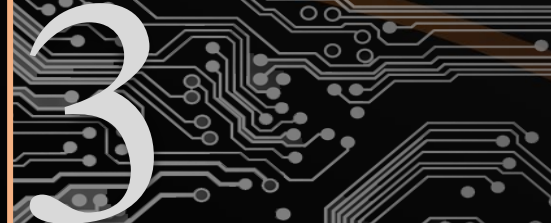
>50% Cost reduction, 12 months instead of five years, Parts reduction >100 to 1



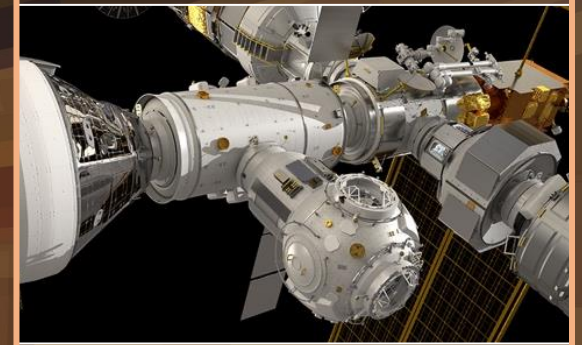
Digital Transformation Digital Twins and Artificial Intelligence



>50% of physical resources replaced with virtual
More intelligent and more accurate predictions and capabilities



Lightweight Composite Spacecraft

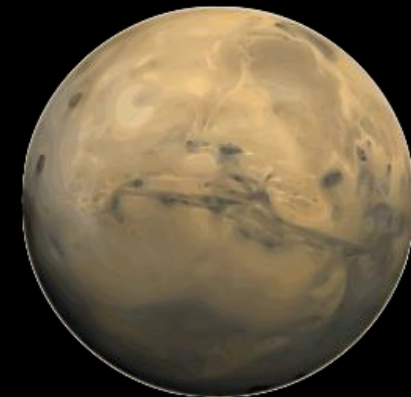


30% - 50% Mass reduction, More payload, equipment, and experiments





Phase II for ISM: On-Surface sustainable Habitats

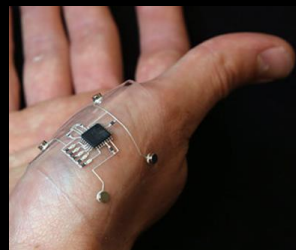


Focus on making living and working in space sustainable, reducing Operations cost.

- Metal Manufacturing for Life Support Systems
- Outfitting for Habitats
- Environmental and health sensors
- Energy Storage
- Medical devices
- Food and Pharma
- Modular Excursion Devices
- Textiles



Heat Exchangers



Wearable Disposable Flexible Sensors



Modular Excursion Devices



On Demand Farming Tools



On Demand Shoes



On Demand Cast



Fasteners and Tools



Food for Space

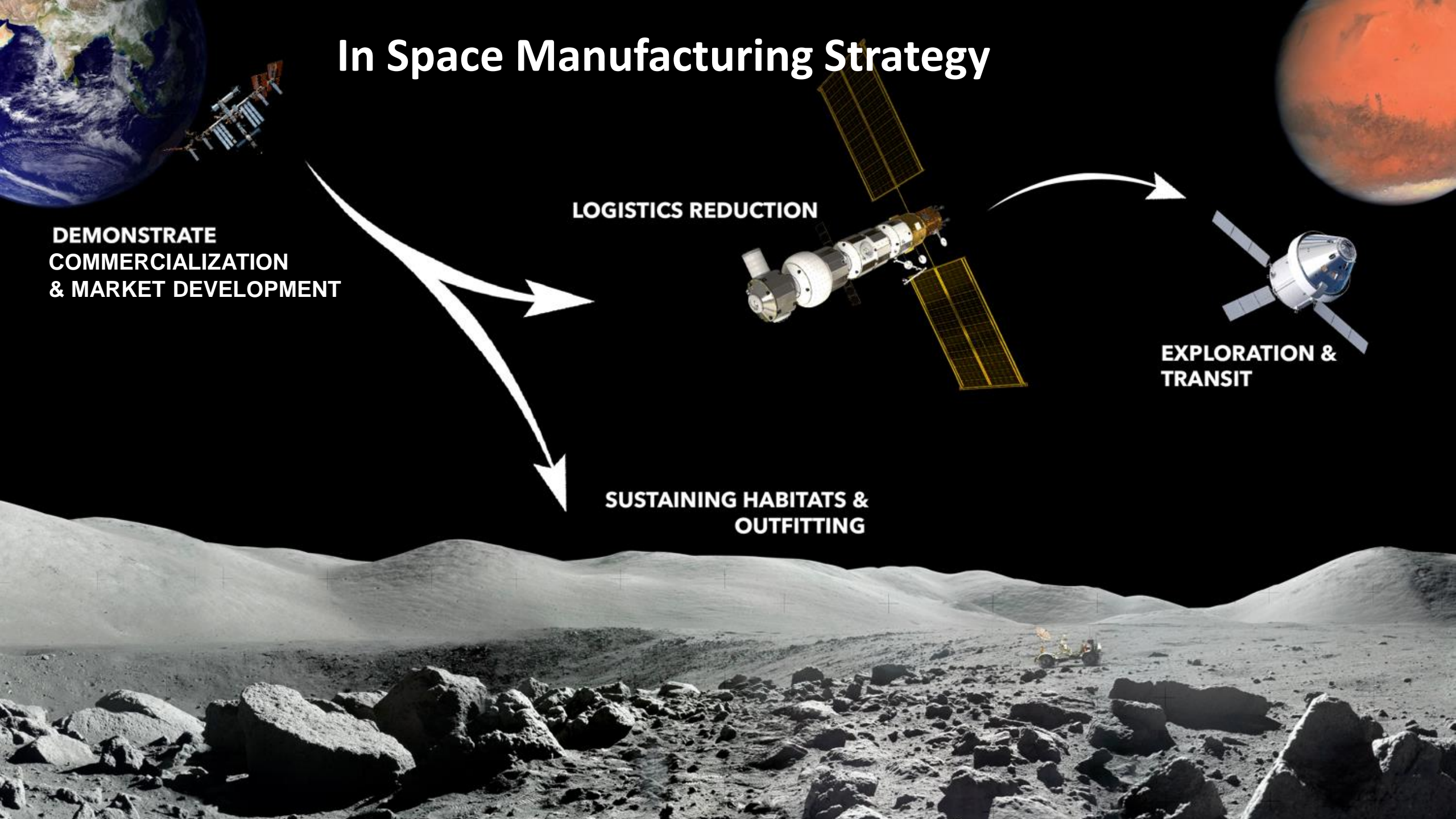
In Space Manufacturing Strategy

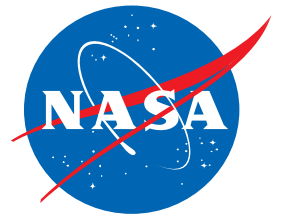
**DEMONSTRATE
COMMERCIALIZATION
& MARKET DEVELOPMENT**

LOGISTICS REDUCTION

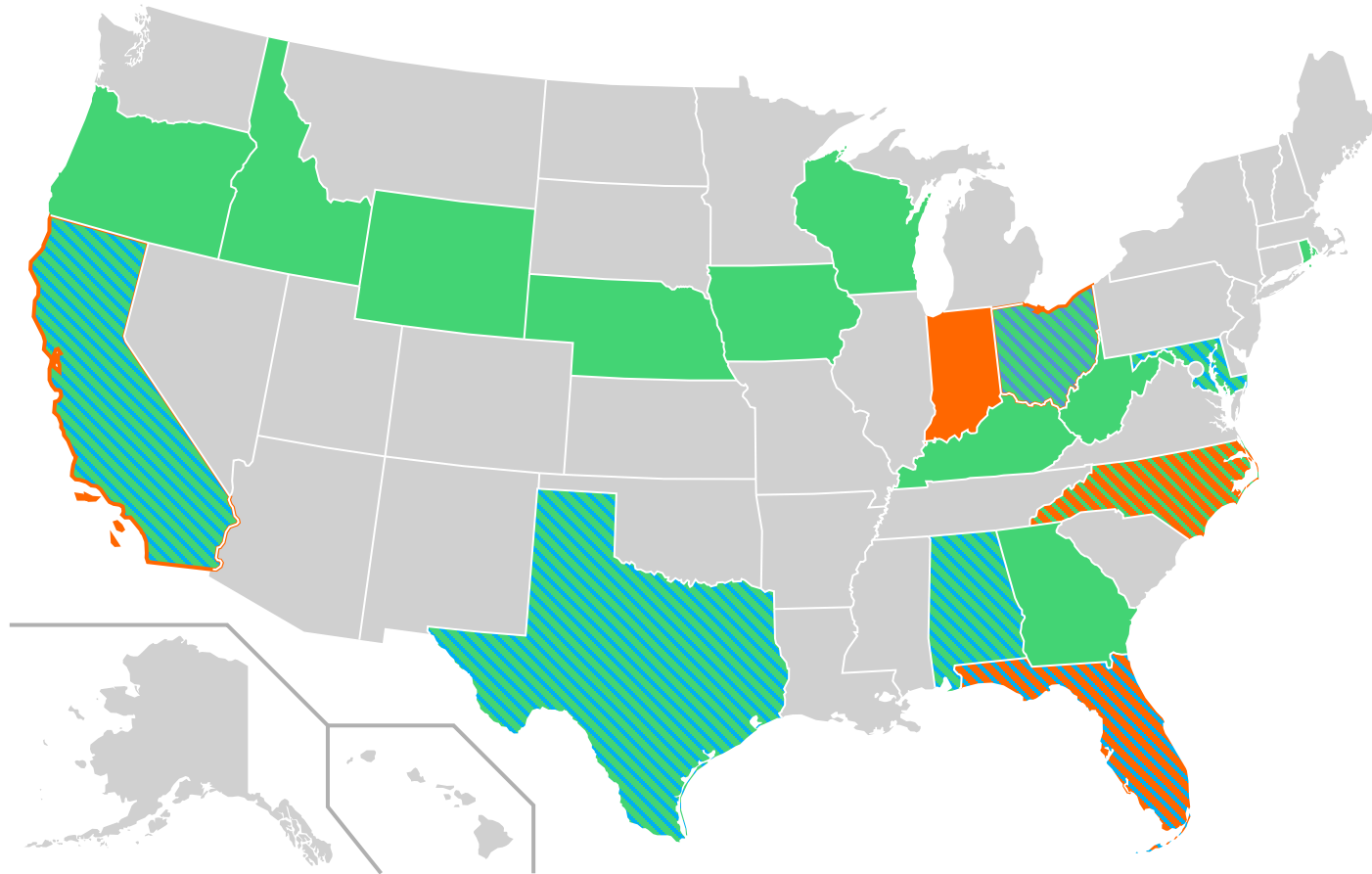
**EXPLORATION &
TRANSIT**

**SUSTAINING HABITATS &
OUTFITTING**





Partnerships'/Collaborators



Academic

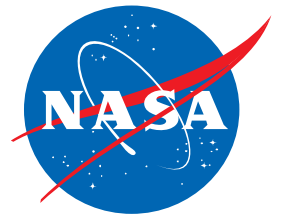
- University of Louisville
- University of California Berkley
- University of Nebraska
- University of Alabama Huntsville
- Appalachian State
- Auburn University
- Boise State
- Georgia Tech
- California Tech
- Iowa State University
- University of Miami
- Florida A&M University

NASA Centers

- Oregon State
- Marshall Space Flight Center
- Ames Research Center
- Johnson Space Center
- Kennedy Space Center
- Goddard Space Flight Center
- University Research Center
- Jet Propulsion Laboratory
- Glenn Research Center

Industry

- Techshot
- Redwire Space
- Cornerstone Research Group
- NextFlex
- nScript
- Multi3D
- LambdaVision
- Faraday Incorporated

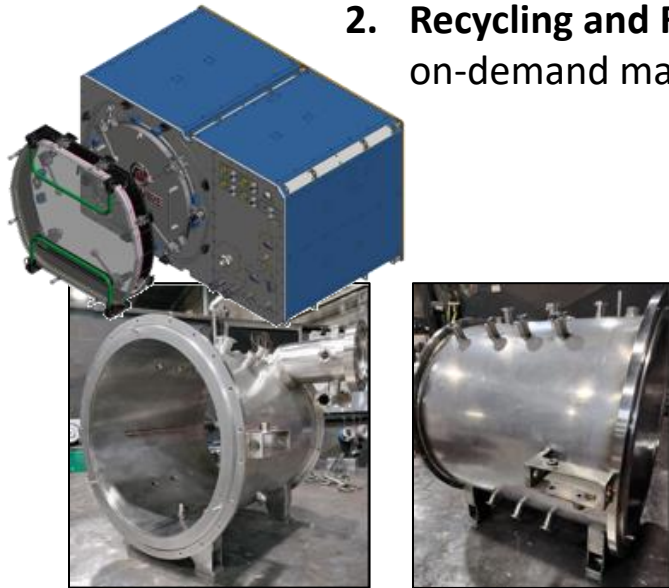


On Demand Manufacturing Of Multi-materials

Goal: Demonstrate metals additive manufacturing in microgravity and characterize the impact of microgravity.

Sub Projects:

1. **Outfitting:** Develop the capability to manufacture on-demand utilities, furnishings, tools, etc. for off-earth habitation including the use of In-Situ Resources.
2. **Recycling and Reuse:** Develop the capability to recycle and reuse materials into useable feedstocks for in-space, on-demand manufacturing.



CAD of Revised furnace module (top). Furnace module hotzone during manufacturing. Image courtesy of Techshot a Redwire company (bottom).



Space Suit Wrist Disconnect manufactured by FabLab. Image courtesy of Techshot a Redwire company.

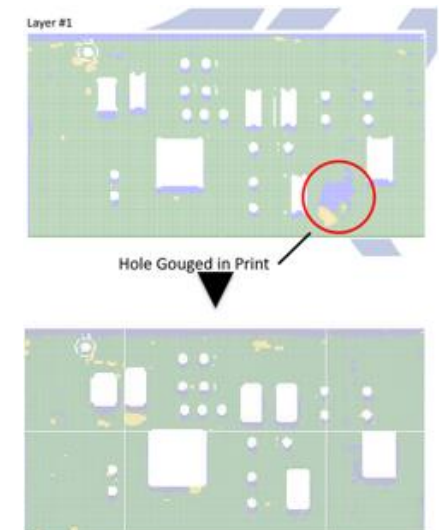
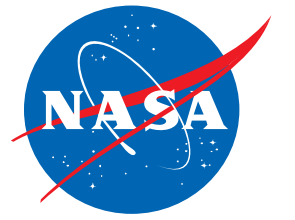


Illustration of inspection and remediation. Image courtesy of Techshot a Redwire company.



Overview of FabLab

Print Module

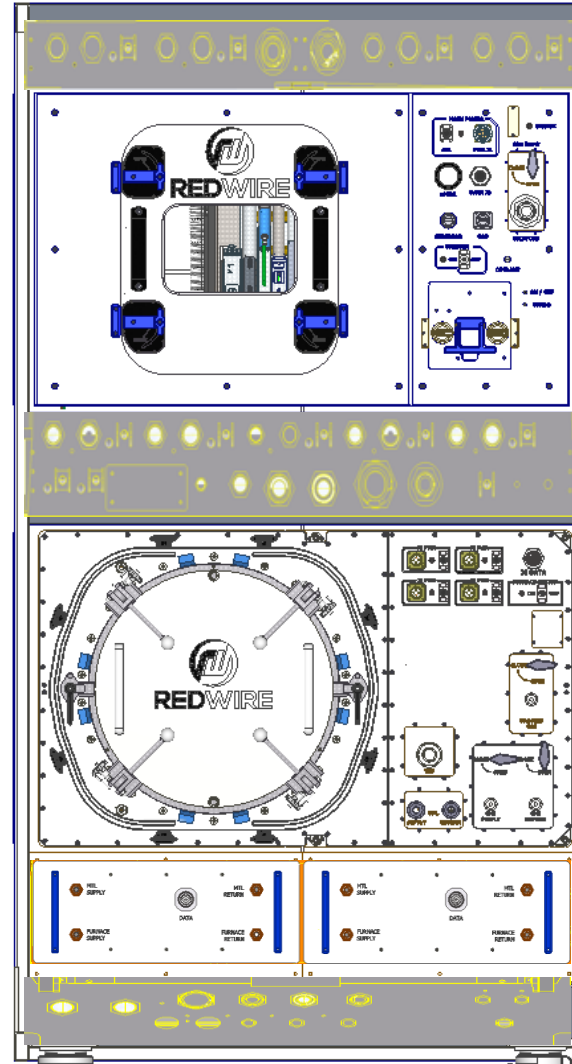
- Advanced Toolplate:
 - Printing of Metal and Polymer Parts
 - Finish Milling
- Inspection Subsystem
 - Defect Detection and Remediation
- Environmental Control
 - FOD capture system
- Electronics Manufacturing
 - Smart Pumps, Directed Energy, Pick and Place, etc.
- Avionics and Control

Furnace Module

- Sintering of Metal Parts
- Brazing of Assemblies
- Avionics and Controls

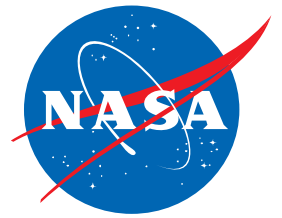
Process Gas Drawer

- Provides Argon to Furnace Module



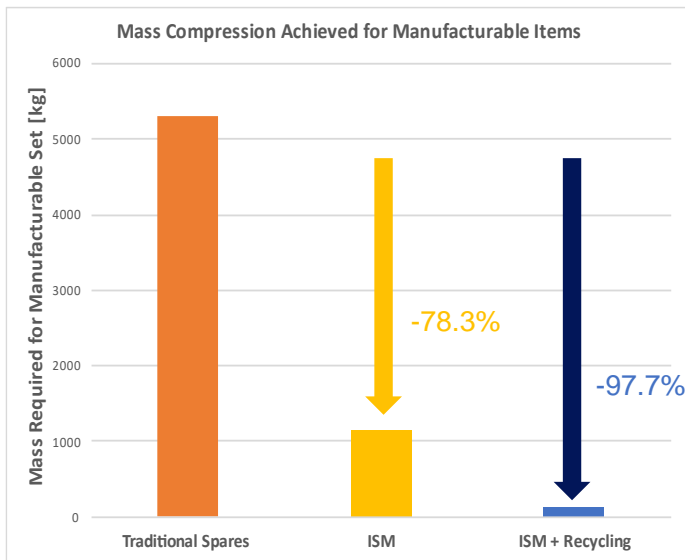
Full Payload

- 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



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)

CRG
Introducing CRG's **Reclaimable Packaging**

A material technology designed to allow for reclamation and reuse of traditionally disposable packaging materials. Traditional packaging materials are significantly degraded when recycled, making them unusable or only suitable for low-value applications. CRG's reclaimable packaging doesn't degrade, even after multiple reuses, making it ideal for circular packaging economies and in-situ resource utilization needs while reducing the need for virgin packaging manufacturing.

With its unique properties, CRG's reclaimable packaging can be adapted for many industrial and commercial applications

- Strong and Lightweight**
Foam and film materials satisfy packaging application requirements in regards to strength, weight, and protective properties
- Facilitates Resource Utilization**
Allows for reuse and redeployment of on-site resources after satisfying the initial use case for the application
- Various Source Material Options**
Source materials can be varied from other packaging materials, plastic bags, foam, films, and other polymeric materials
- Reusable Materials**
PE foam and film materials proven reclaimable for fused filament fabrication without material property degradation
- Promotes Circular Economy**
Process encourages the reutilization of used packaging material in the commercial or industrial setting
- Customizable Fabrication**
Reclaimed material is suitable for various fabrication methods such as 3D printing, injection molding, compression molding, etc.

Increase In-Situ Resource Utilization
via reclamation of packaging materials for various fabrication processes:

- Polymer Foam and Film**
 - RVT Foam
 - RVT Film
- Fabrication Materials**
 - Extruded Filament
 - Pellets
- New Parts**
 - Additive Manufacturing
 - Injection Molding
 - Compression Molding

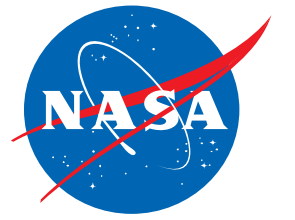
Use & Reclamation → **Reprocess** → **Reuse**

Reclaimable Packaging Production Status:

- Technology Readiness Level: ██████████
- Manufacturing Readiness Level: ██████████
- Certifications: NASA 6001
- Testing: Various ASTM Characterization Testing

Interested in CRG's reclaimable packaging material?
Contact us at ventures@crgrp.com

CRG
www.crgrp.com



Outfitting



Image Credit: ICON

CHAPEA

Provided 3D printer and scanner for crew analogue

Goal: Understand crew interaction with manufacturing systems.

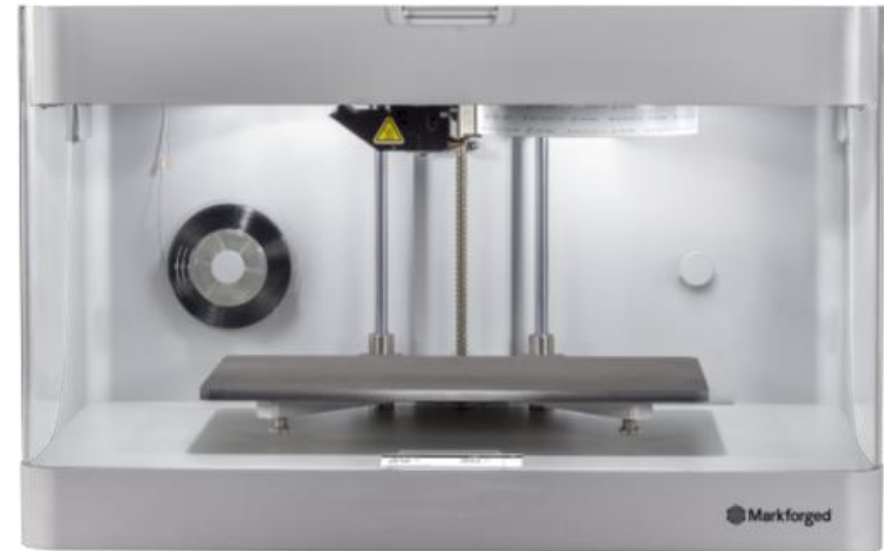
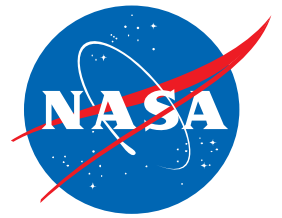
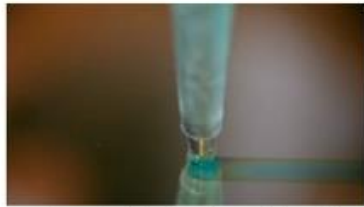


Image Credit: Markforged

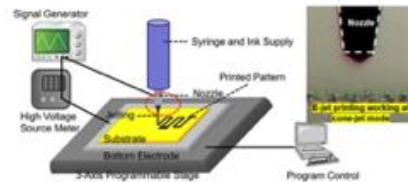


On Demand Manufacturing Of Electronics

Goal: Develop and demonstrate on demand printing of electronics in microgravity and characterize the impact of microgravity.



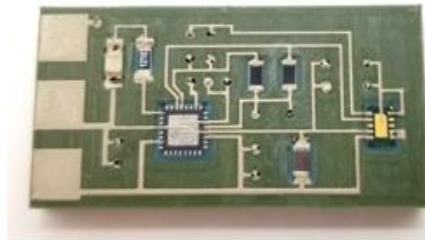
Faraday Electrodeposition of Covetic Copper



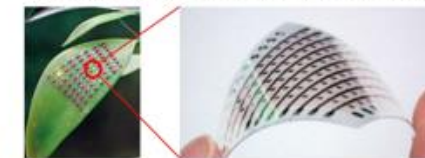
Electrohydrodynamic Ink Jet Printer



Iowa State Parabolic Flight



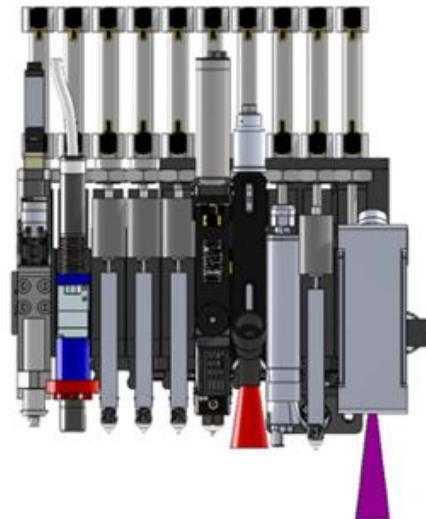
Printed CO2 Sensor (ODME ISS Demo)



University of Illinois Plant Growth Sensor



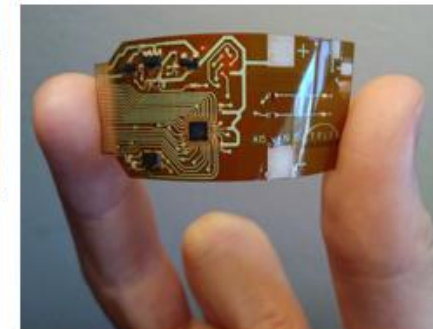
TechShot FabLab Multi-material 3D Printer for ISS Demo



FabLab Advanced Toolplate with Newly Developed Deposition Tech



RF Power Harvesting Antennas- UAH



NextFlex Wireless Flexible Sensor Board

1 In Space Manufacturing and Space Infrastructure

Motivation/State of the Art

- Aligned with STMD Strategic Framework and Moon to Mars Objectives
- In-space Servicing Assembly and Manufacturing (ISAM) strategy
- The Post-ISS Plan: Commercial demand for in-space manufacturing
- The current logistics model is unsustainable for long duration space missions
- 3D Printer GCD tech demo on-board ISS in 2014

Next Steps, Future Focus Areas and Investments

- STMD GCD ISM project (FabLab prototype testing)
- ISS microgravity materials science research (SMD BPS)
- ISS commercial In Space Production Applications (InSPA)
- ISS National Lab/CASIS In-orbit materials/manufacturing
- NASA OSAM-1 and OSAM-2
- Announcement of Collaboration Opportunity & Partnership Proposals to Advance Tipping Point Technologies
- On-demand manufacturing of metals, electronic components, recycling, and reuse
- ISRU-derived materials for feedstocks (e.g., Al, Si) for lunar surface manufacturing
- Certification is a top challenge - Physics-based models to predict processing and material properties
- ISAM - welding in space, recycling and reuse, large scale additive manufacturing
- Maximize use of ISS for demonstration





www.nasa.gov/spacetech

ECO Mapping to M2M Blueprint Objectives **New**

| M2M Obj. | Description | <p>DEMONSTRATE: Deploy an initial capability to enable system maturation and future industry growth in alignment with architecture objectives.</p> <p>DEVELOP: Design, build, and deploy a system, ready to be operated by the user, to fully meet architectural objectives.</p> | Regolith Excavation /Delivery | Regolith Manipulation and Site Prep | Assembly, Construction, Outfitting |
|----------|--|--|-------------------------------|-------------------------------------|------------------------------------|
| LI-1 | Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels | | x | x | x |
| LI-2 | Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs | | x | x | x |
| LI-4 | Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy | | x | x | x |
| LI-6 | Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy | | | x | x |
| LI-7 | Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy. | | x | | |
| LI-8 | Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence. | | x | x | x |
| MI-4 | Develop Mars ISRU capabilities to support an initial human Mars exploration campaign. | | x | | |
| OP-11 | Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth. | | x | | x |
| TH-3 | Develop system(s) to allow crew to explore, operate, and live on the lunar surface and in lunar orbit with scalability to continuous presence; conducting scientific and industrial utilization as well as Mars analog activities. | | x | x | x |
| RT-2 | Industry collaboration | | x | x | x |
| RT-4 | Crew Time: maximize crew time available for science and engineering activities | | | | x |
| RT-9 | Commerce and Space Development | | x | x | x |

Thermal Schedule Applied to Each Layer:

- **Power Ramp Up.** Ramping up slowly from a low power to the final peak power reduces explosive loss of mass in the layer due to recoil pressure (and also reduces the dust that adheres to the laser glass or lens)
- **Peak Power Hold.** Using the laser we “dwell at the soak temperature” by maintaining a power level and rescanning the surface for the requisite length of time. This allows the layer to take on a homogenous, de-gassed amorphous phase.
- **Power Ramp Down.** Ramping power down stops the layer from quenching out and freezing in an amorphous state - a high level of nucleation and limited crystal growth is promoted. The material microstructure continues to change as the next several layers are added.

Vertical Building Strategy:

- **The Thermal Schedule for each layer is different as you build up.** We ended up using two different “layer recipes,” one for “slab layers” to avoid large defects in the base and one for “sample layers.”

Other Findings:

- Some compaction is important to make the powder layer consistent in density, but there is a point of diminishing returns
- Thinner layers produce a better microstructure (lower thermal gradient), but it means building slower.

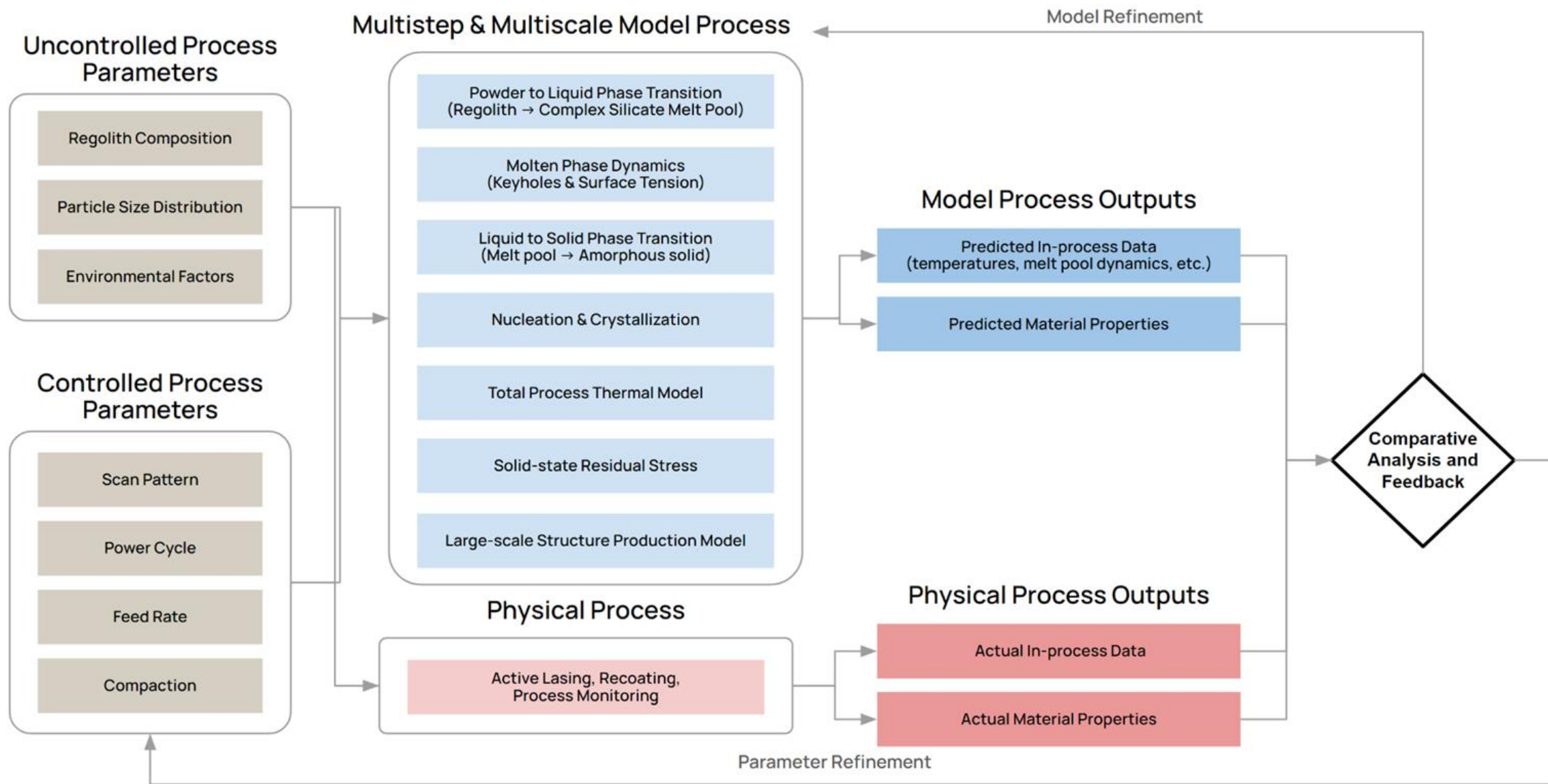


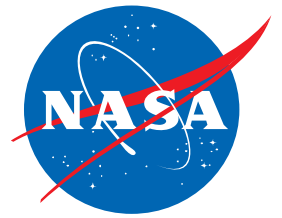
Lessons learned over 1.5 years of point laser VMX development enabled the transition to the bar laser to produce a similar material in 2 months.

- In the point laser test fixture, the commanded power is applied to the 0.6mm laser spot that is translated in x and y directions using the galvo head. At small sample sizes with a small cross-sectional area, it is easy to bulk melt the entirety of a layer to degas and homogenize the material without inducing keyholing/surface texture.
- At larger sizes, it is difficult to achieve homogenous heating over a significant area with a 1-D object (the laser spot). A bar or rectangular laser, only scanned in one dimension, is a superior choice for our application. Fortunately, that is exactly the type of laser we had already ordered.



Laser Process Modeling

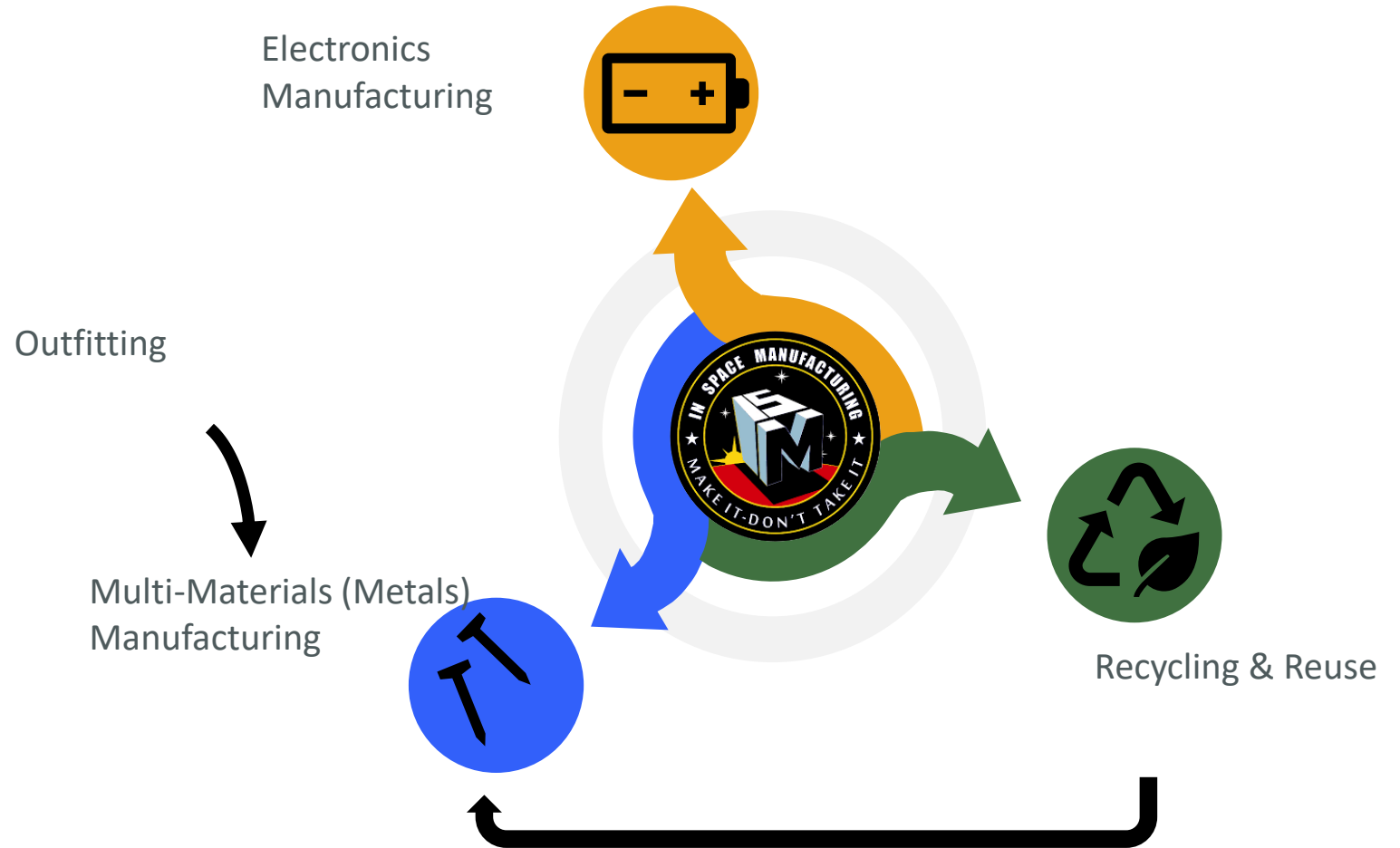




Portfolio Overview

Focus on making living and working in space sustainable, reducing Operations cost.

- Metal/Multi-Material Manufacturing
- Outfitting for Habitats
- Environmental and Health Sensors
- Energy Storage
- Medical Devices
- Food and Pharma
- Modular Excursion Devices
- Textiles





Phase I for ISM - Develop a Space Economy



In Space Manufacturing Vs In Space Construction:

Construction is focused on the process of building facilities and infrastructure.

Manufacturing is focused on creating goods (e.g. textiles, tools, furniture, etc)



Use microgravity environment to manufacture goods for Government and Commercial Uses

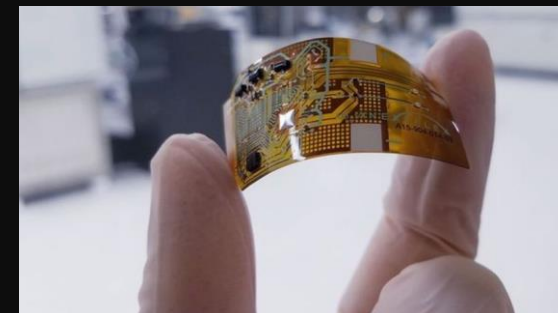
- ISS, Commercial Space Stations, Lunar gateway
- Technology Focus on printing Metals, Electronics, and Logistics Reduction (e.g. Recycling)



**ISS Demo – Fablab
Manufactures both
Metal and electronic
components on orbit**



**Redwire
Regolith Print
Wins Popular
Science 2021
Best of What's
New Award**



**Printable and wearable
biosensors**