In Space and For Space Additive Manufacturing - Then and Now - An Overview AND Moon to Mars Planetary Autonomous Construction Technology (MMPACT) Project Overview

Manufacturing Problem Prevention Program

Aerospace Corp. October 17, 2023

R. G. Clinton Jr., PhD, Principal Investigator, MMPACT Project, NASA MSFC

AGENDA

- NASA’s Moon to Mars Exploration Strategy – Key Manufacturing and Construction Objectives
- NASA’s Space Technology Mission Directorate (STMD): Technology Drives Exploration – Advanced Manufacturing
  - In Space Manufacturing – Then and Now Overview
  - Additive Manufacturing FOR Space – Propulsion Revolution At MSFC Overview
- Lunar Surface Innovation Initiative (LSII)
  - Moon to Mars Planetary Autonomous Construction Technology (MMPACT) Project Overview
- Summary

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.

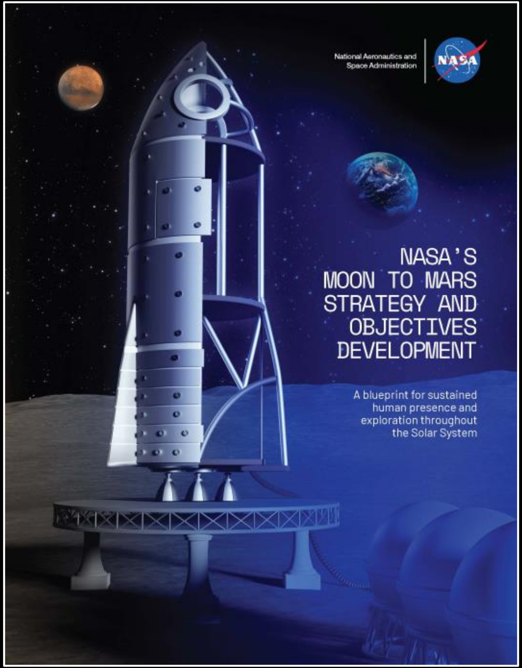
PPS-2LM: Advance understanding of physical systems and fundamental physics by utilizing the unique environments of the Moon, Mars, and deep space.

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.

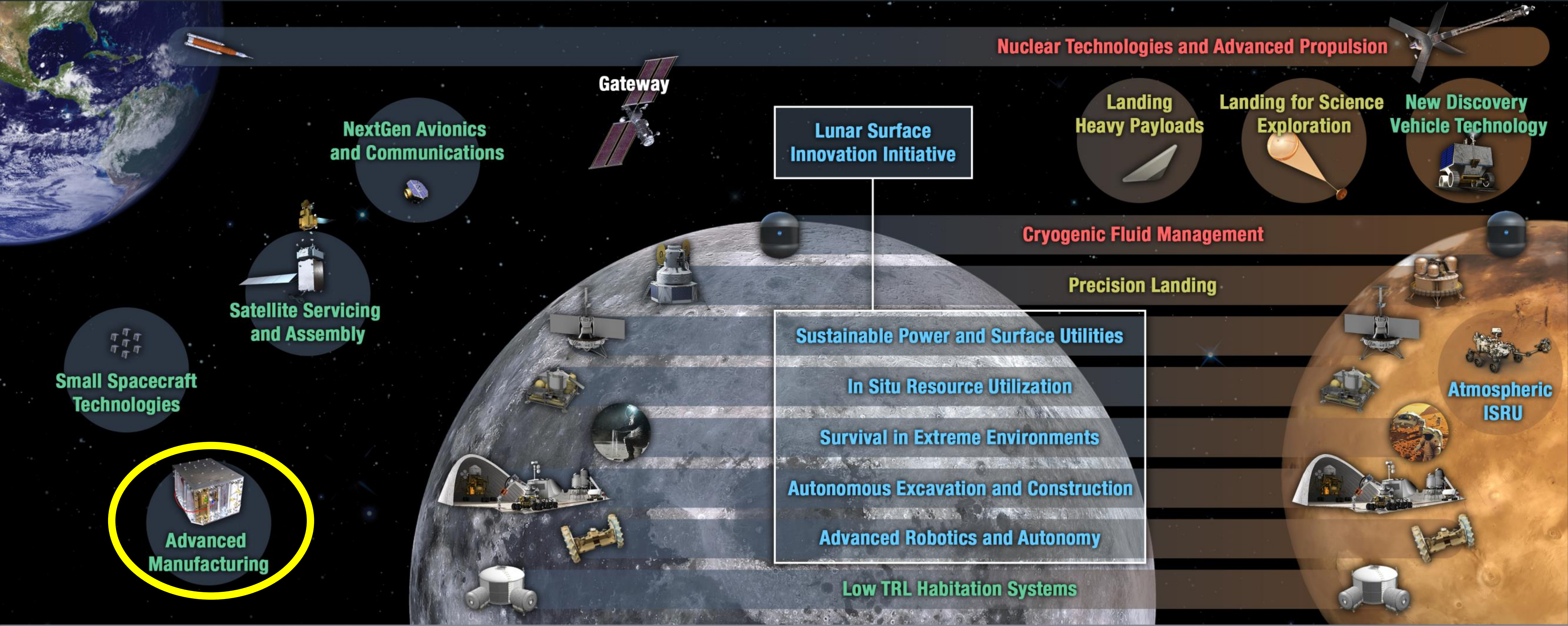
OP-12LM: Establish procedures and systems that will minimize the disturbance to the local environment and allow for reuse/recycling of material transported from Earth.



In Situ Fabrication and Repair Program Element– circa 2004

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

1

3D Printing / Additive Manufacturing

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

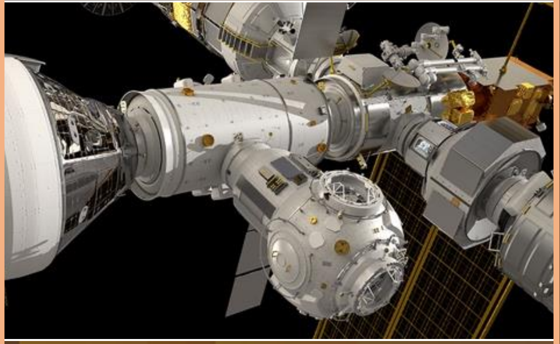
2

Digital Transformation Digital Twins and Artificial Intelligence

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

3

Lightweight Composite Spacecraft



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

4

In-space Manufacturing Exploration Technology Development Roadmap

Earth-based

Ground Analogs

- **Multiple FDM Zero-G parabolic flights (1999-2013)**
- **System Studies & ground Tests for Multiple Materials & Technologies**
- **Verification & Cert. Process development**
- **Material & Printer Characterization Database**
- **Autonomous Process Dev.**
- ***Additive Construction: Simulant Dev. &Ground***

Demos: Ground & ISS

3D Print Tech Demo

2014

- **In-space:3D Print: First Plastic Printer on ISS Tech Demo**
- **NIAC Contour Crafting**
- **NIAC Printable Spacecraft**
- **Small Sat in a Day**
- **AF/NASA Space-based Additive NRC Study**
- **ISRU Phase II SBIRs**
- **Ionic Liquids**
- **Printable Electronics**

Recycler

Utilization Testing AMF

Fab Lab

Metal Printing

Self-repair/ replicate

Digital Mfctr.

External In-space Mfctr

2015 - 2017

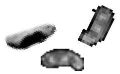
- ***3D Print Demo ABS Ops***
- ***Add. Mfctr. Facility Ultem Ops (AMF)***
- ***In-space***
- ***Utilization Catalogue Part Cert & Testing***
- ***Recycler Demo***
- ***NASA/DARPA External In-space BAA Demo***
- ***In-space Material Database***
- ***Future Engineer STEM Challenge(s)***

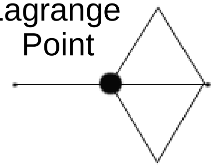
2018 - 2024

ISS: “Fab Lab” *Utilization/Facility Focus*

- Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
- Embedded Electronics Tech Demo
- Metal Demo Options
- ***ACME Ground Demos***
- STMD External In Space Manufacturing and Assembly Demo

Exploration





2025-35

Cislunar, Lagrange FabLabs

- Robotic/Remote Missions
- ***Provision feedstock***
- ***Evolve to utilizing in situ materials (natural resources, synthetic biology)***
- ***Product: Ability to produce, repair, and recycle parts & structures on demand; i.e.. “living off the land”***
- Autonomous final milling to specification

2035+

Planetary Surfaces Points Fab

- Transport vehicle and sites need Fab capability
- ***Additive Construction & Repair of large structures***

Mars Multi-Material Fab Lab

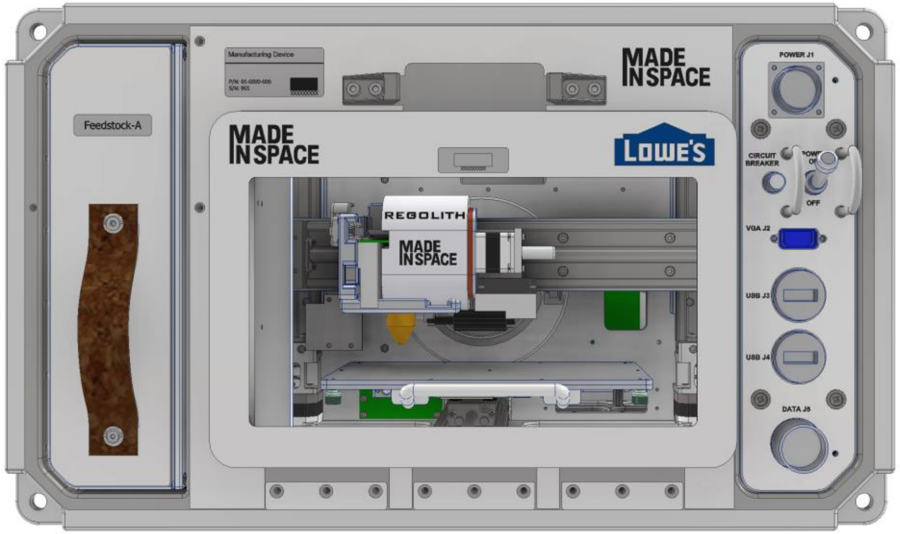
- ***Provision & Utilize in situ resources for feedstock***
- ***FabLab: Provides on-demand manufacturing of structures, electronics, & parts utilizing in-situ and ex-situ (renewable) resources.*** Includes ability to inspect, recycle/reclaim, and post-process as needed autonomously to ultimately provide self-sustainment at remote destinations.

****Green text indicates ISM/ISRU collaboration***

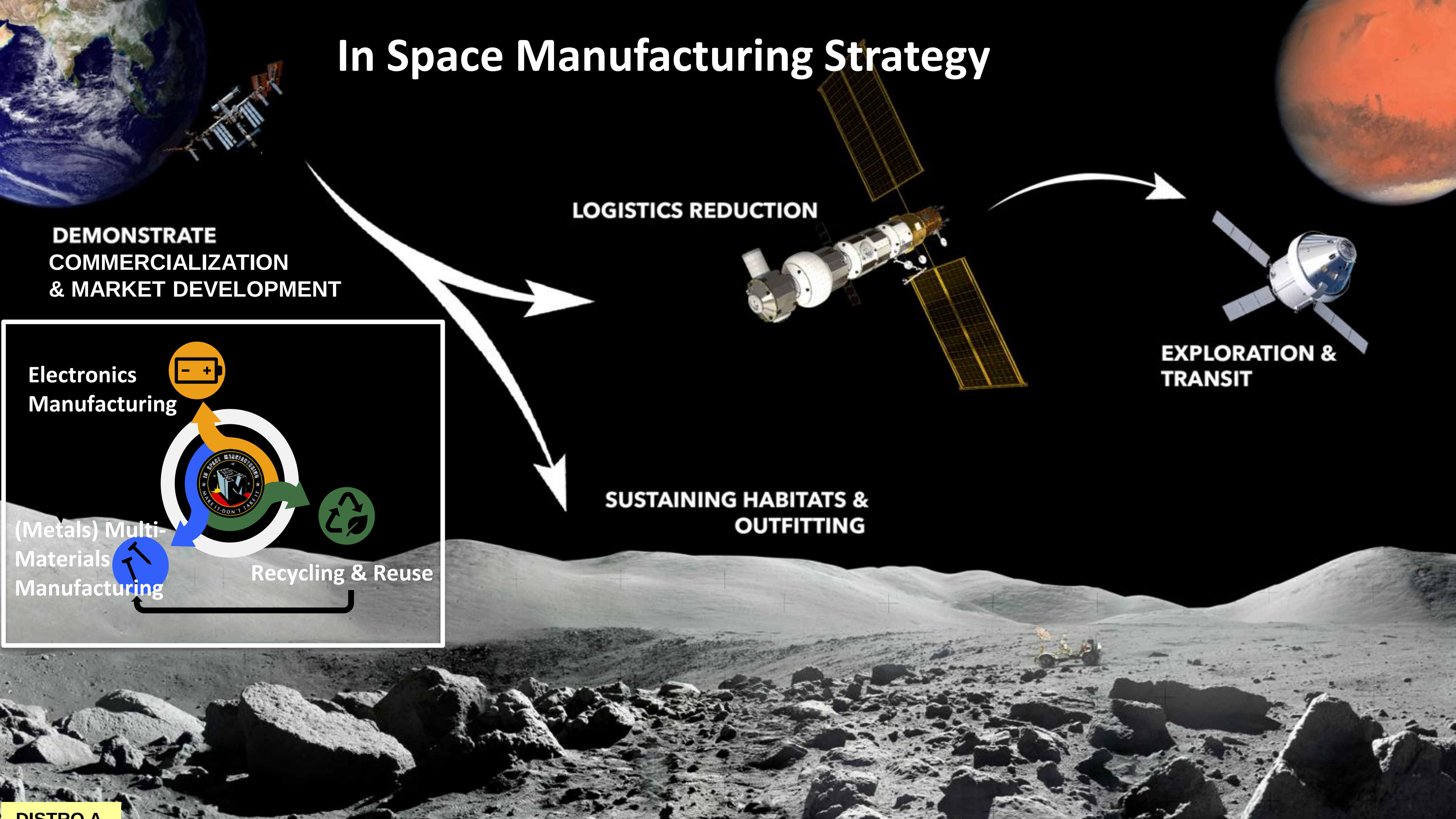
ISS Serves as a Key Exploration Test-bed for the Required Technology Maturation & Demonstrations

Vision for In Space Manufacturing

Goal: Demonstrate additive manufacturing using polymeric and metallic materials on ISS and characterize the impact of microgravity.



In Space Manufacturing Strategy



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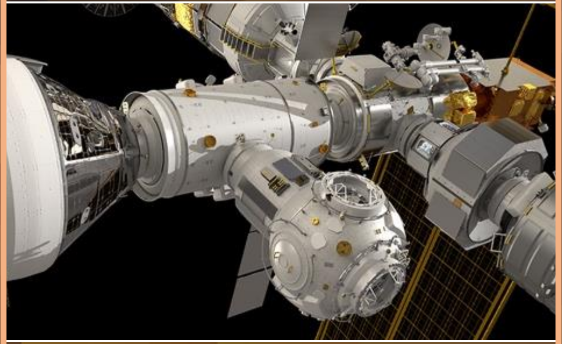

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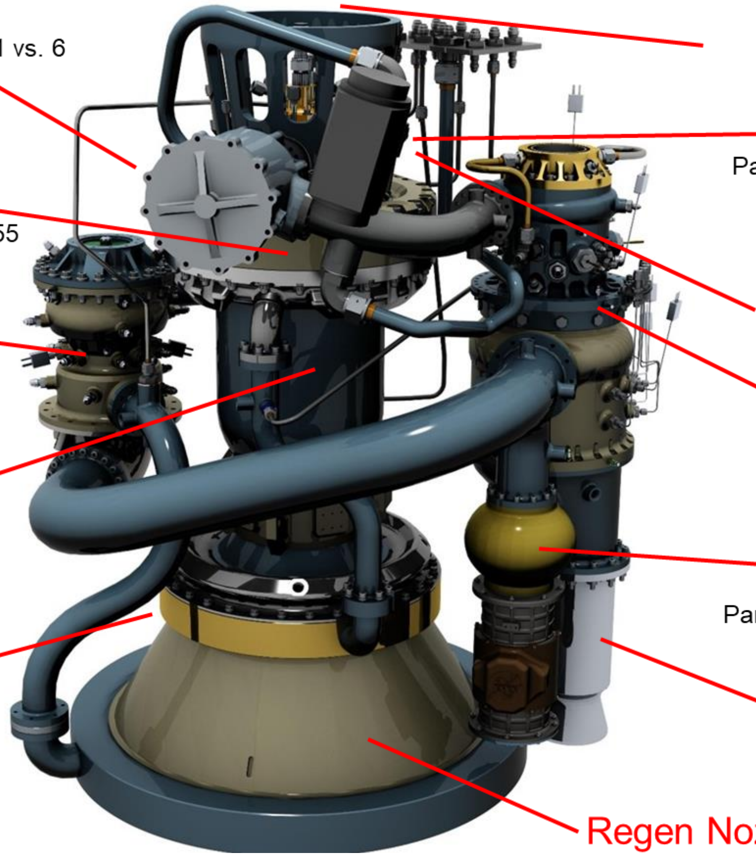
Transforming Liquid Propulsion Systems DDT&E with AM

Project Objectives

- **Reduce the cost and schedule required for new engine development and demonstrate it through a complete development cycle.**
  - Prototype engine in less than 2.5 years.
  - Use additive manufacturing to reduce part cost, fabrication time, and overall part count.
  - Adopt Lean Development approach.
    - Focus on fundamental/quick turn analysis to reduce labor time and cost and move to first development unit
    - Get hardware into test fast so that test data can be used to influence/refine the design
- **Advance the TRL of additive manufactured parts through component and engine testing.**



Low Cost Upper Stage-Class Propulsion (LCUSP) Overview

Project Description:

- **Developed Selective Laser Melting (SLM) of GRCop-84 and**
- **Developed Electron Beam Free Form Fabrication (EBF^3) with Nickel Alloy Inconel 625 to**
- **Produced a rocket combustion chamber significantly faster & at a lower cost.**
- **Combustion chamber was designed, fabricated, and then hot-fire tested successfully at MSFC East Test Area.**

Team: **Multi-center -- MSFC, GRC & LaRC**

Next Steps: **RAMPT, Significant commercial investments and supply chain established.**

Ultimate Goal: **Transition capability to industry.**

Rapid Analysis Manufacturing Propulsion Technology (RAMPT) Overview

Science & Technology Office

NASA

Description:

- Develop and advance large-scale light weight manufacturing techniques and analysis capabilities
- Implement them to reduce design and fabrication cycles for regenerative-cooled liquid rocket engine components.

Goals:

- Reduce design, fabrication, assembly schedules (60%)
- Reduce parts, increased reliability, significant weight reduction (70%).

Team: Multi-center -- MSFC, GRC, ARC, & LaRC

RAMPT partnered with industry through public-private partnerships to design and manufacture component parts

Bimetallic Deposited Manifolds Vendor Development and Optimization

- Develops commercial supply chain
- Reduces Cost

3D printed Copper Chamber (derived from LCUSP Program)

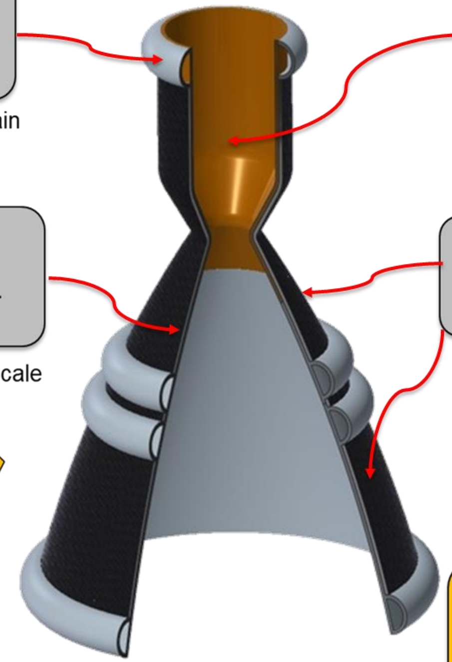
- Proven Technology
- Advances Commercial Supply Chain

Integrated Large Scale Freeform Manufacturing Freeform Deposition Regen-Cooled Nozzle

- Rapid Fabrication for Increased Scale
- Reduces cost and schedule
- Removes all joints
- Increases reliability
- Reduces complexity

Composite Overwrap Thrust Chamber Assembly

- Significant weight reduction (70%)
- Reduces overall cost and schedule
- Increased performance



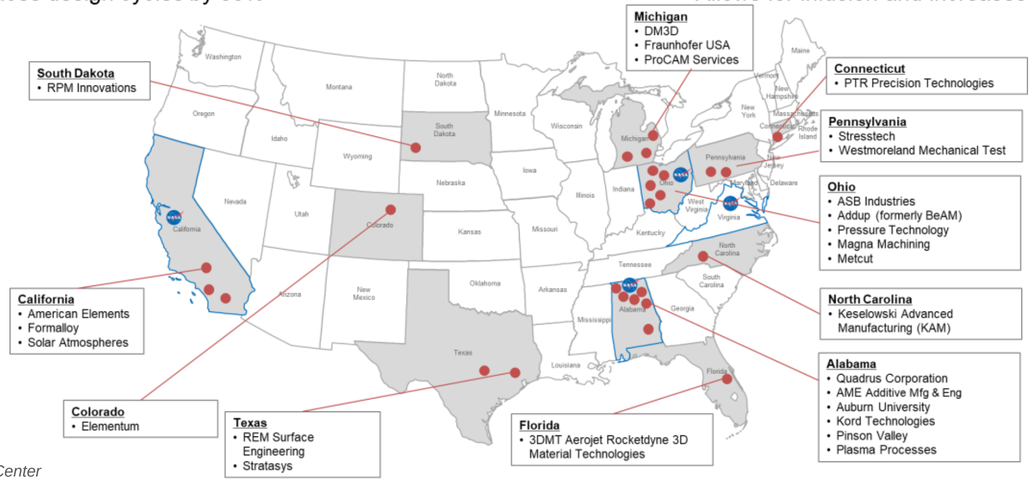
Thrust Chamber Assembly

Design and Process Modeling Tools Enable an Integrated Optimized Design

- Reduces design cycles by 60%

Demonstrate Subscale and Large Scale Hot Fire testing of Multi-material Chamber

- Allows for infusion and increases TRL



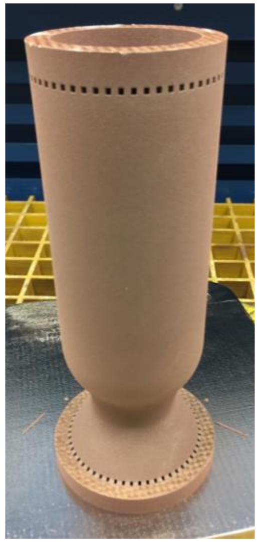
Project Description:

- The ORCA project builds upon the successful evolution of additive manufacturing (AM) core technology under the LCUSP and RAMPT projects for liquid rocket components
- ORCA provides high payoff optimized performance technologies and enabling materials in AM for: Combustion Chambers, Injectors, Nozzles, and Turbomachinery.

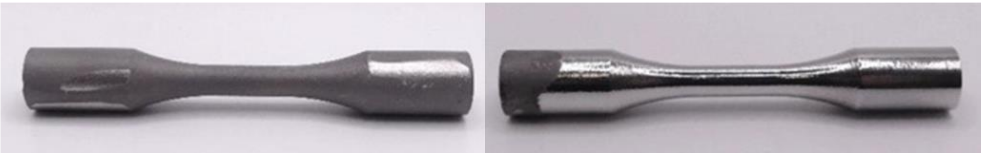
ORCA areas of focus:

1) Evolution of enabling materials for high performance and extreme environments for large scale propulsion applications (Ox-rich, H2 Compatibility, High Conductivity, Composite)
2) Advanced development of additive post-processing surface enhancement/polishing techniques for internal surfaces to improve flow performance and repeatable mechanical properties across multiple components (>20% performance increase)
3) Advanced materials and process modeling and validation allowing for First Time Thru and repeatable part fabrication further enabling an additive digital model twin.

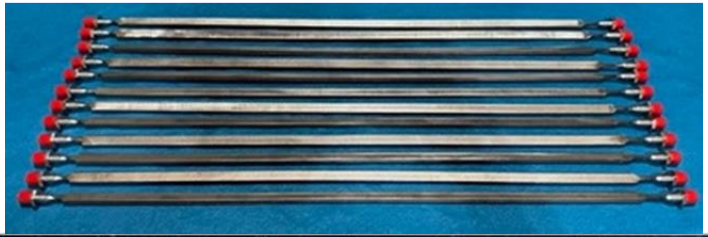
Team: Multi-center -- MSFC, GRC, ARC, & LaRC



Dry Electropolishing HCF Samples (Haynes 214)



Internal Polishing Tube Specimens



LP-DED Bimetallic Combustion Chamber

Long Life Additive Manufacturing Assembly (LLAMA) - Overview

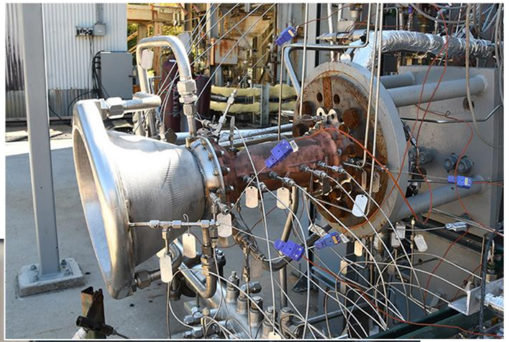
Goals:

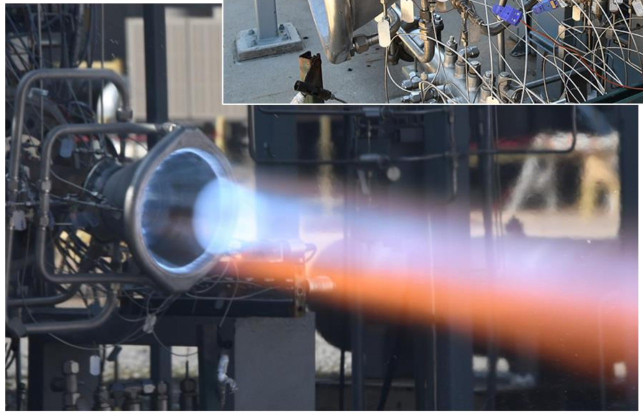
- Complete rapid fabrication and testing of a lander concept thrust chamber with the
- Demonstrate **high duty cycle** and **high performance** while **understanding throttling capabilities**.
- Perform hot-fire testing meeting a minimum of **50 starts** that **targets mid-throttling level capabilities** for lander technology.
- Complete destructive evaluation of chamber following testing to determine material performance and reporting for characterization of material.

Deliverables:

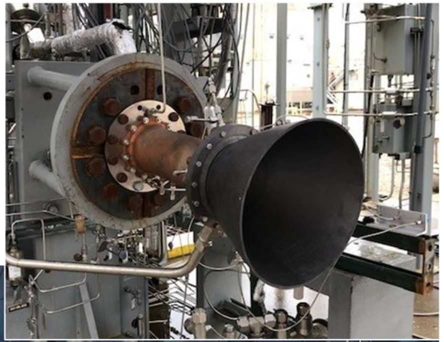
- Fabrication of GRCop42 lander class chamber and injector. (7k lb_f thrust level)
- Design and fabrication of two high temperature composite nozzles.
- Demonstrate 25 cycles by hot-fire tests in 30 days within seven months of ATP. (chamber only)
- Demonstrate additional 25 cycles by hot-fire tests. (chamber and composite nozzle)
- Material performance and characterization by destructive evaluation of chamber post hot-fire tests.

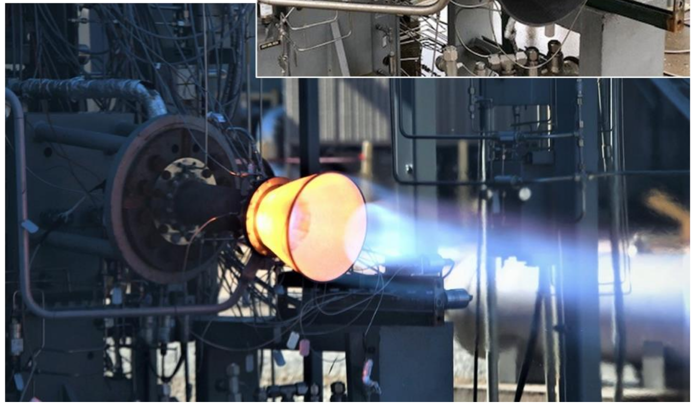
7k-lb_f GRCop-42 chamber and HR-1 regeneratively cooled nozzle





7k-lb_f GRCop-42 chamber and Composite Nozzle





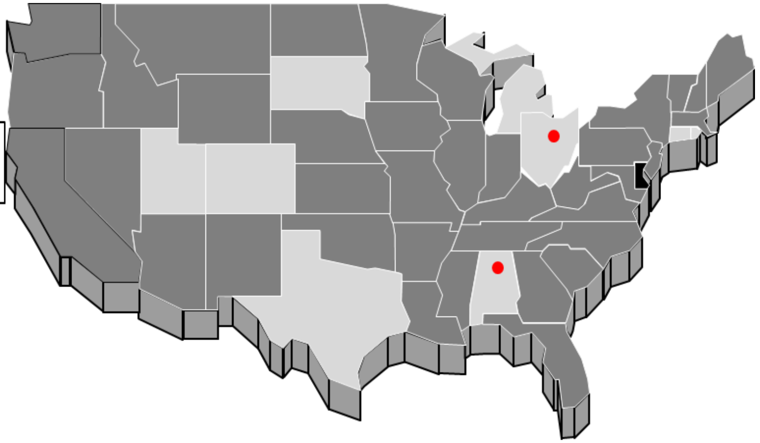
Support Vendors
- Additive Manufacturing and Engineering (AME)
- Carbon Carbon Advanced Technologies (C-CAT)
- G.E Aviation
- Maximus Welding
- NamPros
- Northrup Grumman Innovation Systems (NGIS)
- ProCAM Services
- PTR Precision Technologies
- Plasma Processes
- Pressure Technologies (PTI)

NASA Centers
- GRC
- MSFC

Public/Private Partnerships
- RPM Innovations (RPMI)

Academia
- University of Alabama Huntsville

SBIR
- Elementum 3D
- REM Surface Engineering



Refractory Alloy Additive Manufacturing Build Optimization (RAAMBO)- Overview

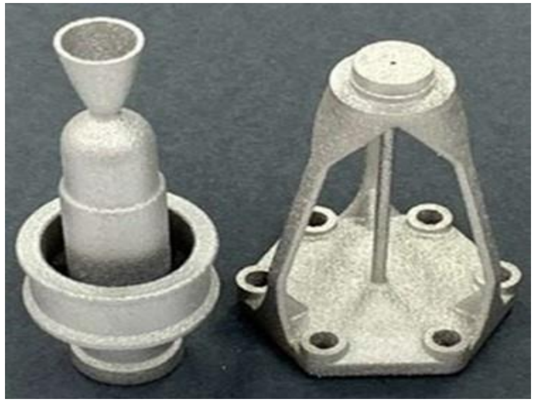
Project Description:

- Advance additive manufactured (AM) refractory alloys technology readiness level (TRL)
- Develop methods/materials to generate propulsion components with an integrated computational materials engineering approach and
- Test under prototypic sustained high temperature operating environments.
- AM of refractory alloys enables higher temperature performance with reduction in cost over traditional manufacturing methods.
- Component designs are optimized for AM to improve performance while reducing mass, production risks, cost, and lead time.
- RAAMBO will increase the technology readiness level of AM refractory alloys for propulsion components from a TRL3 to a TRL6.

RAAMBO areas of focus:

1) Enable additive manufacture (AM) of refractory metal components.
2) Advance material options, develop feedstocks and parameters, optimize heat treatments, utilize novel inspection methods, characterization, and testing.

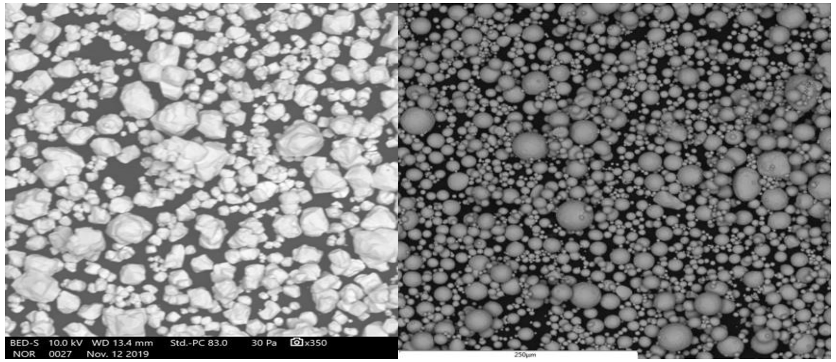
<u>Team:</u> Multi-center -- MSFC, GRC & ARC



AM C103 Green Propulsion Thruster and Stand-Off.

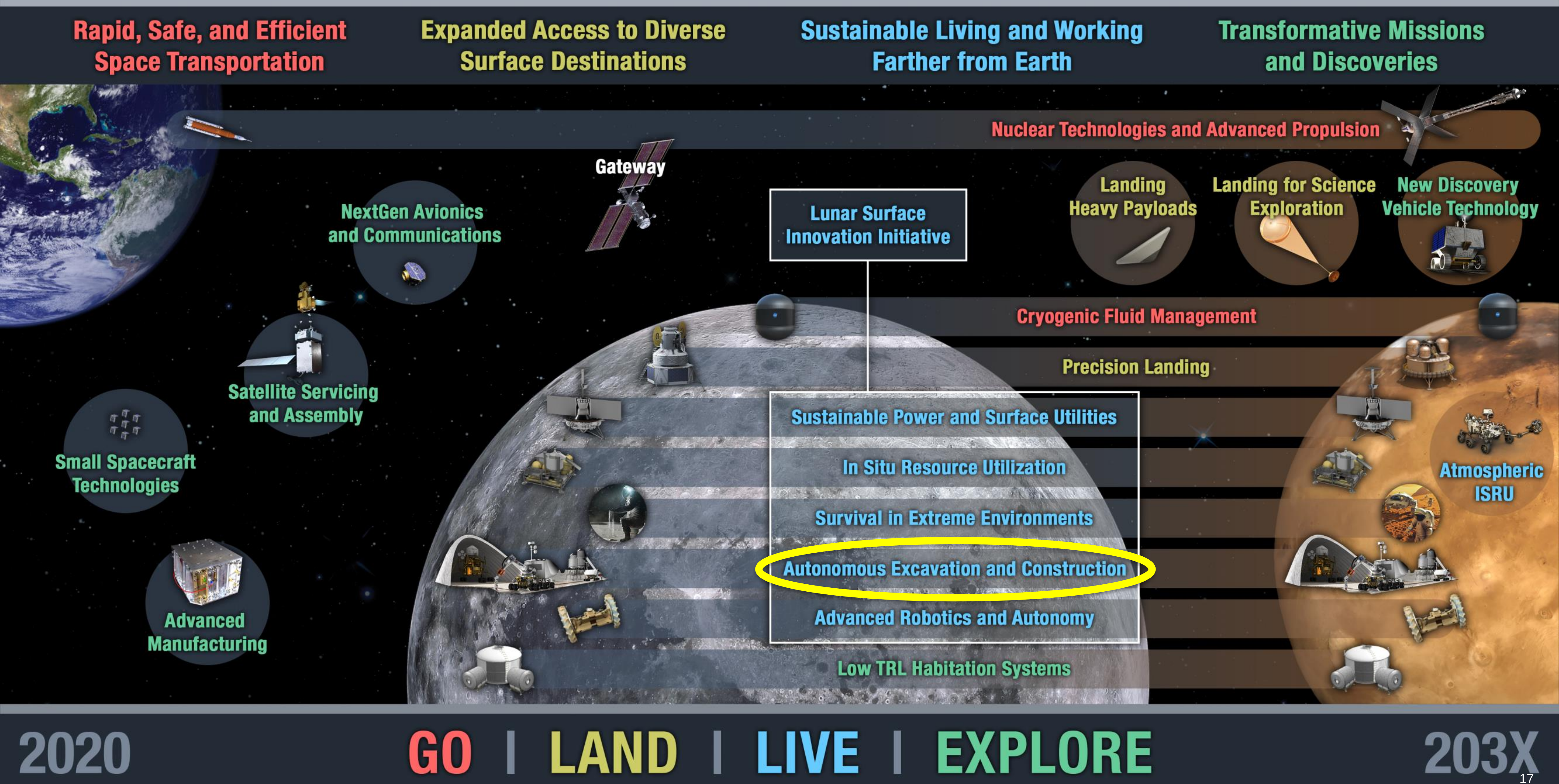
AM W NTP Fuel Clad.

Thruster hot-fire test.

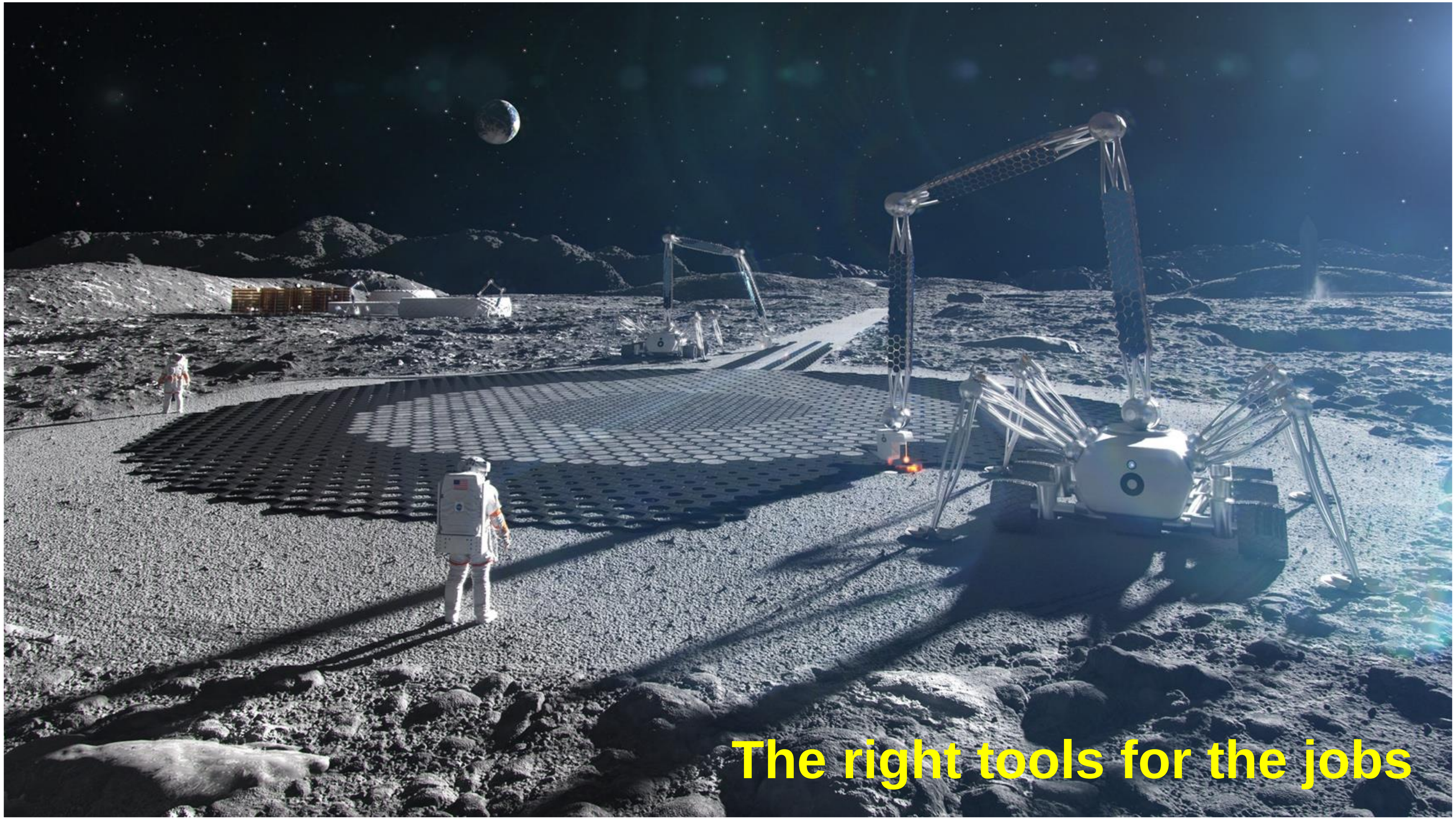


Angular W & spherical C103 powders comparison.

TECHNOLOGY DRIVES EXPLORATION



How We Explore… Lunar Construction Technology



Credit: ICON/BIG-Bjarke Ingels Group

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.

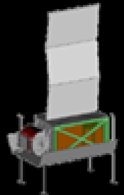
Sustainable exploration:
Scalable pilot systems demonstrating production of consumables from in-situ resources in order to better support sustained human presence.

Oxygen extraction ground demo

CT-1

ISRU O2 Demo

CT-2



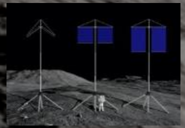
Fission Surface Power

IM-2

PRIME, Hopper, LTE Demos

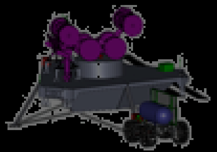
VIPER (SMD)

ISRU Pilot Excavator



Surface Power Demo (VSAT, RFC)

ISRU Subscale Demo



Construction Demo 1

Construction Demo 2

ISRU Pilot System*

* ISRU Pilot Plant demo will use Fission Surface Power

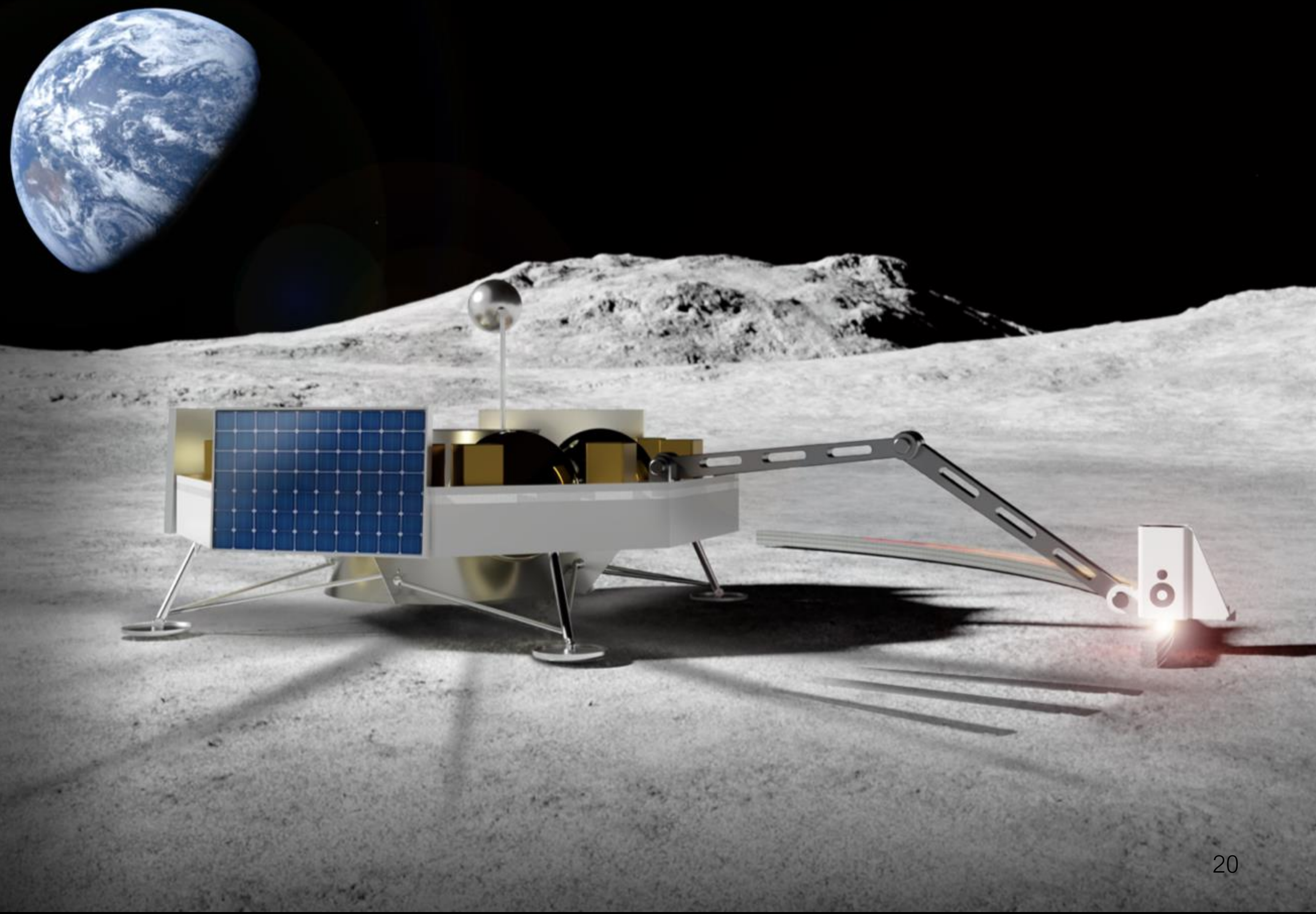
Moon-to-Mars Planetary Autonomous Construction Technologies (MMPACT) Initial Construction Technology Demonstration Concept

Goal

Develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure on the lunar surface via construction of landing pads, habitats, shelters, roadways, and blast shields using lunar regolith-based materials.

Objectives:

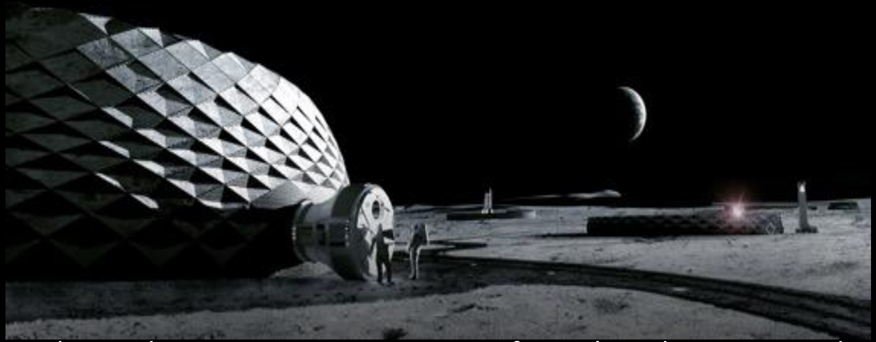
- Demonstrate “proof of concept” for downselected construction technology utilizing ISRU materials at small scale from lander base
- Characterize ISRU and ISRU-based materials
- Demonstrate remote/autonomous operations
- Demonstrate instrumentation operations
- Validate that Earth-based development and testing are sufficient analogs for lunar operations
- Anchor analytical models
- Address technology gaps and inform construction processes for future construction of functional infrastructure elements



Materials and Concepts for the Lunar Outpost

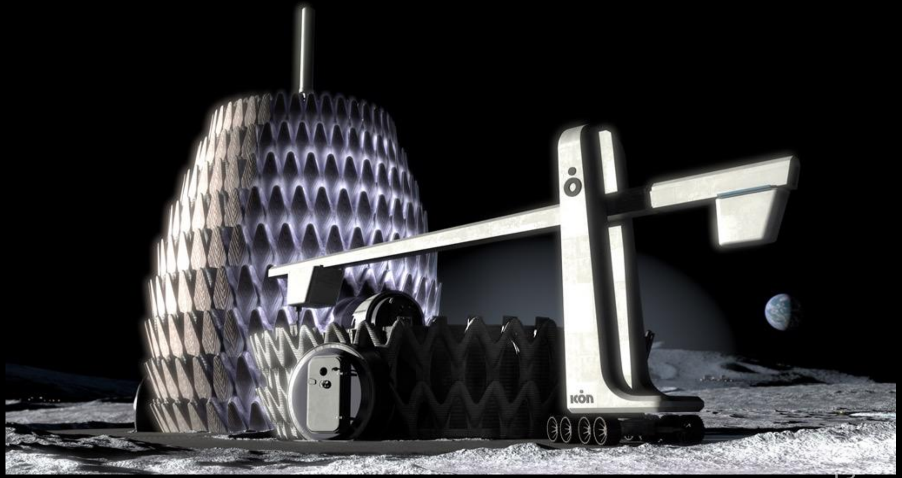
Regolith-based Materials and Processes:

- Cementitious
- Geopolymers/Polymers
- Thermosetting materials
- Regolith Melting/Forming
- Laser sintered
- Microwave sintered



Bjarke Ingels Group Concept courtesy of ICON's Architecture Study

Image courtesy of ICON

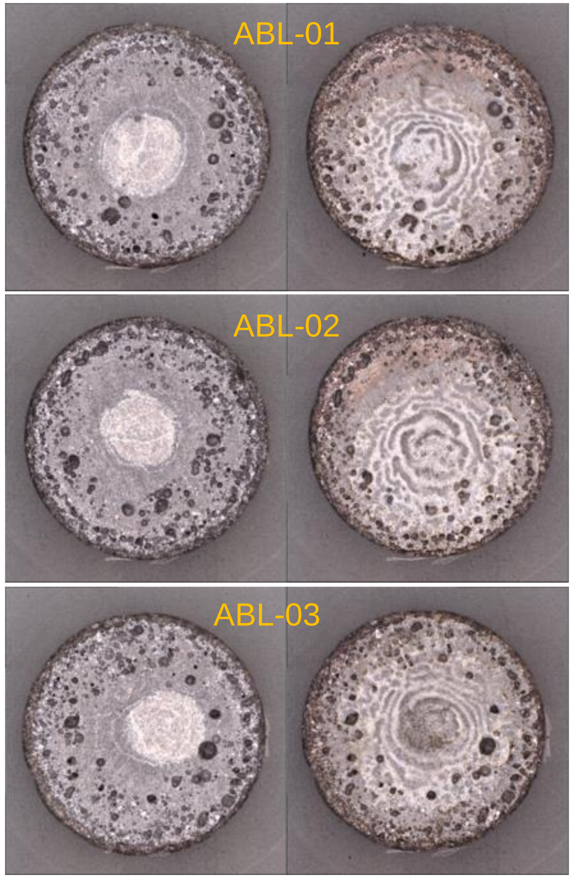


SEArch+ Concept courtesy of ICON's Architecture Study

PTTF Images

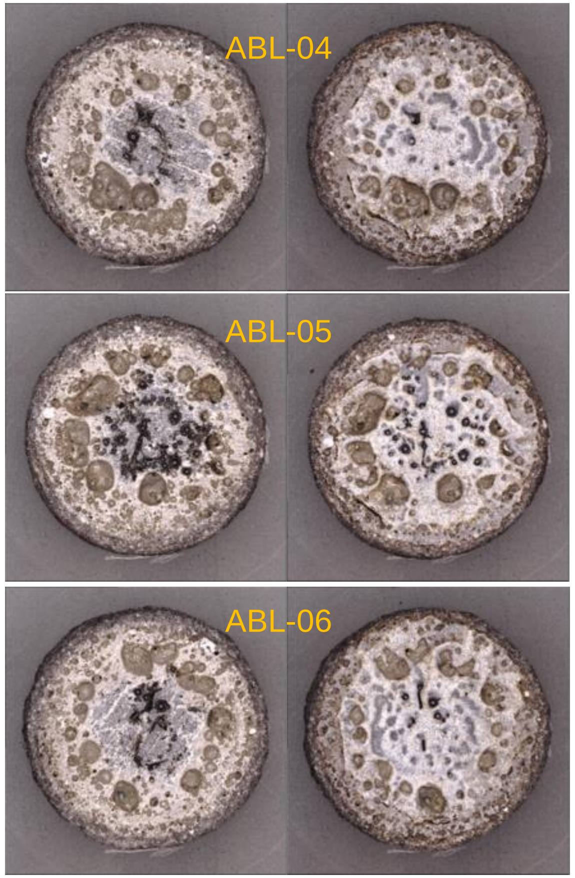
Machined

Pre-test | Post-test

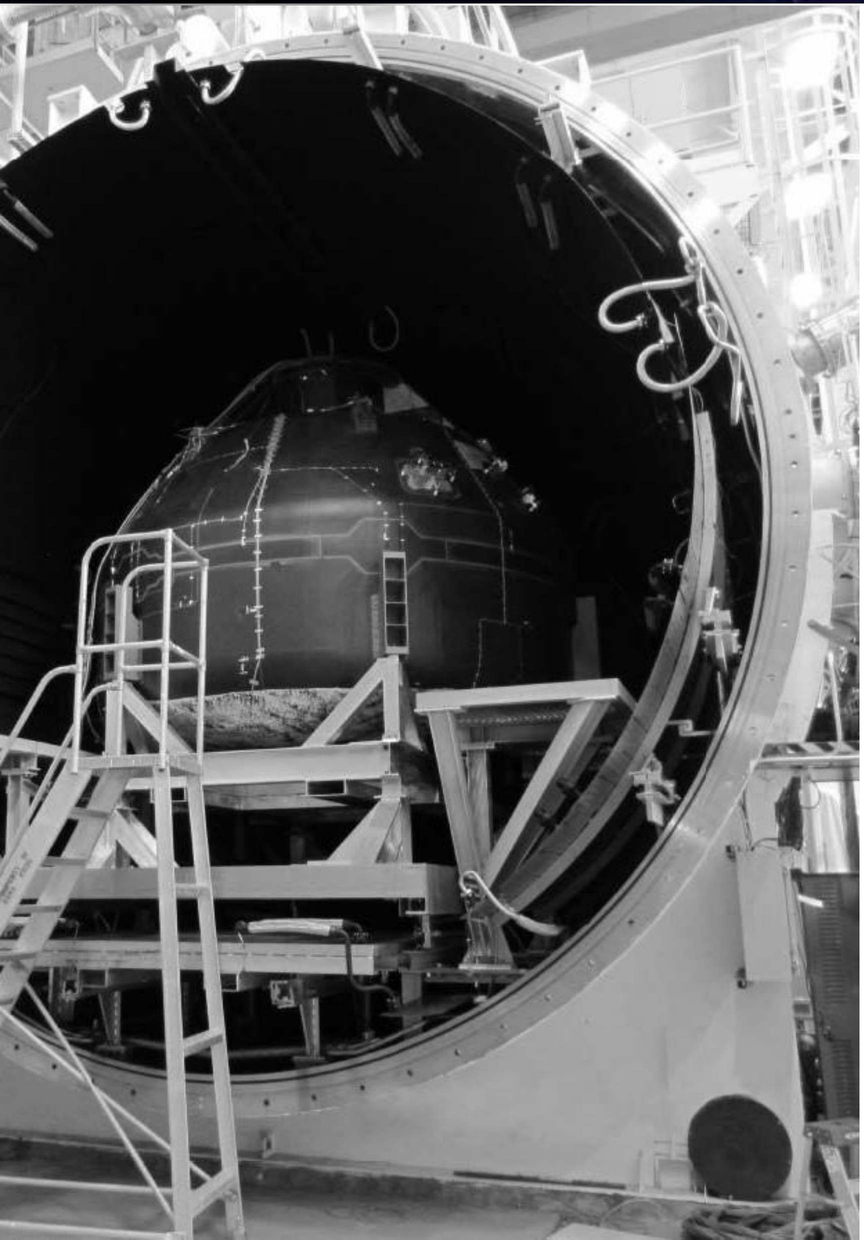


As-fabricated

Pre-test | Post-test



Next Steps Towards a Demonstration Mission Testing in a Simulated Lunar Environment



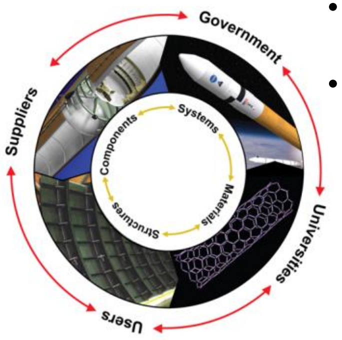
- MSFC has a large (20 ft. diameter by 28 ft. depth) Thermal Vacuum Chamber (TVAC) called V20.
- It is being outfitted with a regolith bed for "dirty" operations
- V20 dirty vacuum chamber at MSFC is an excellent lunar environment analog
- V20 testing still differs from the actual lunar surface in many ways:
  - Simulant vs. Regolith
  - Earth vs. Lunar Gravity
  - Soft vs. Hard Vacuum
- Development system tests are planned
  - Thermal and kinematic testing of terrestrial robot arm (Fall 2023)
  - Development system – simulation of proof of concept mission (Summer 2024)
    - System functionality
    - Material test articles
    - Demonstration article
    - Instrumentation
    - Site preparation
    - Process model anchor data

Current Mission Partnerships

NASA Centers
- MSFC
- LaRC
- KSC
- JPL

OGA Leveraging
- AF Civil Engineering Center
- Defense Innovation Unit (In Discussions)

Initial STRATFI ICON Phase 2 SBIR Partners:
- AF Civil Engineering Center
- AF Special Operations Command (AFWERX)
- USAF
- Defense Innovation Unit
- Texas Air National Guard

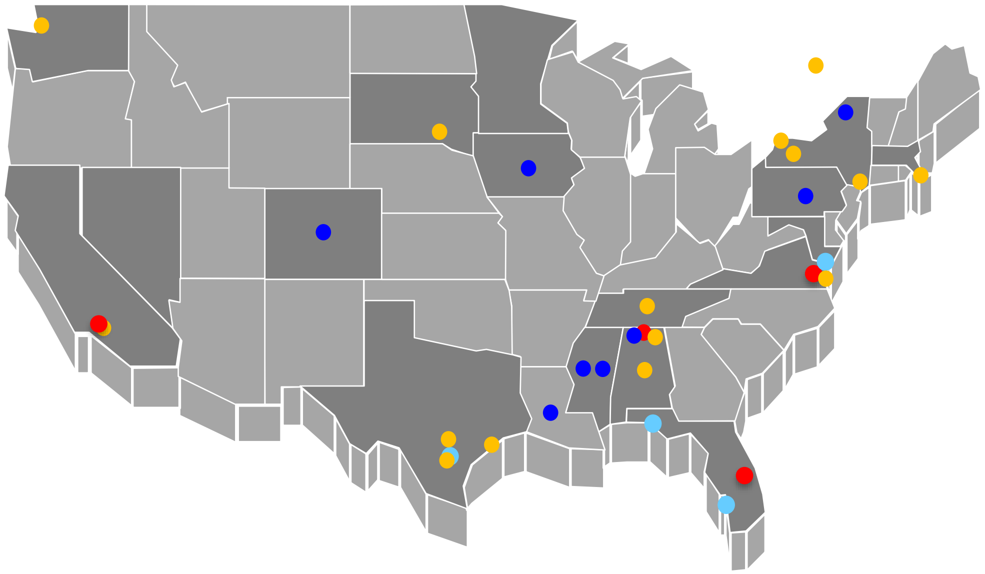


Public/Private Partnerships/Contract
- ICON Build
- Dr. Holly Shulman
- Radiance Technologies
- RW Bruce Associates, LLC
- Blue Origin
- Jacobs Space Exploration Group
- JP Gerling
- Microwave Properties North
- Southeastern Universities Research Association
- Southern Research Engineering/Kratos
- Bjarke Ingels Group (BIG)
- Cislune
- Washington Mills
- Texas Research Institute (Austin)
- Astroport

Technology Providers/ Contributing Partners: Academia
- Colorado School of Mines
- University of Texas in San Antonio
- Mississippi State University
- Pennsylvania State University
- University of Mississippi
- University of Alabama in Huntsville
- Clarkson University
- Iowa State University
- Louisiana State University
- Alfred University
- Sinte Gleska University
- Drake State

SBIR/STTR
- Construction Scale Additive Manufacturing Solution
- Millimeter Wave Camera
- High Efficiency Sintering via Beneficiation of the Building Material

Potential Customer
- Artemis
- Commercial



Collaborative multidisciplinary partnerships to leverage fiscal resources, ideas, knowledge & expertise.

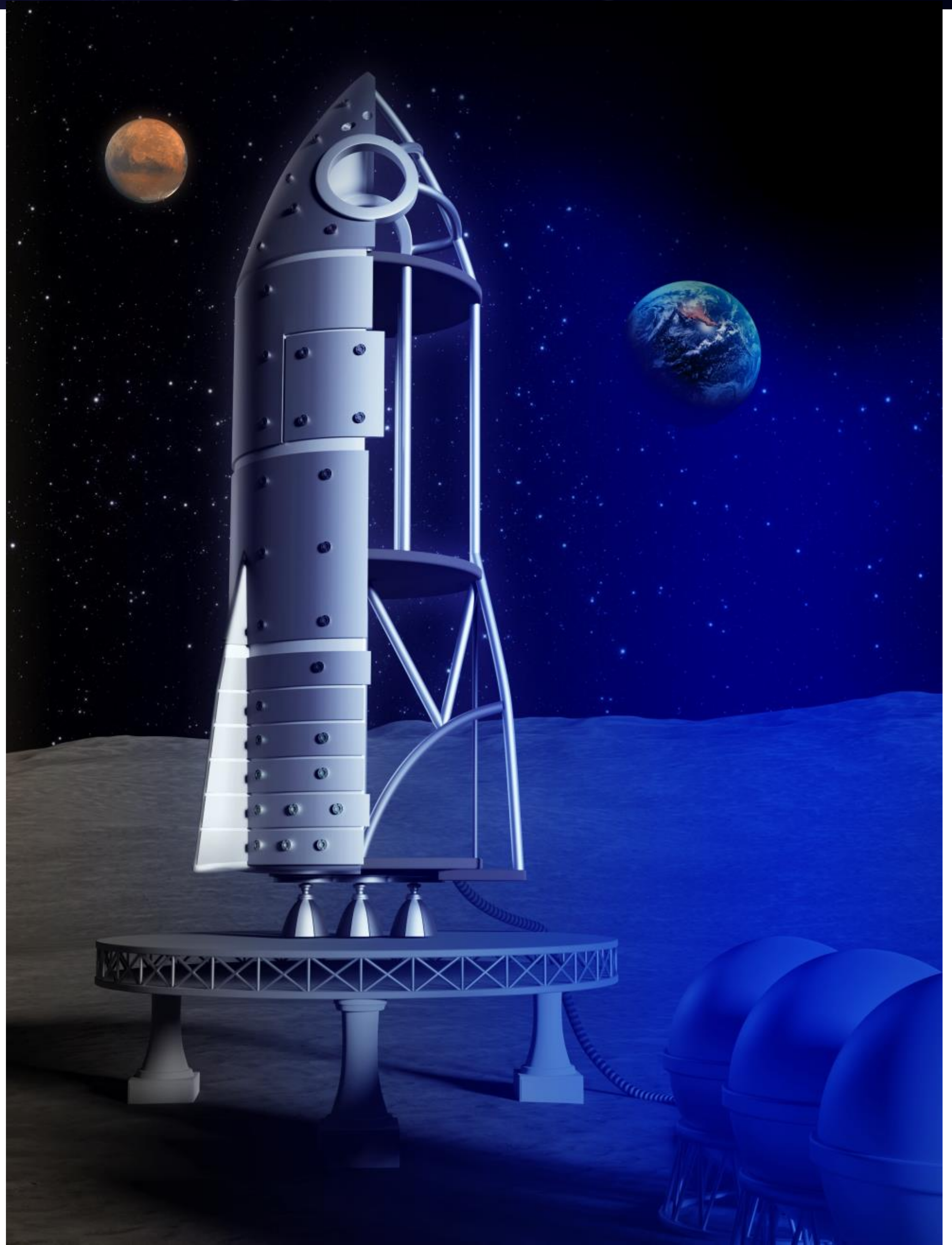
MMPACT

MOON TO MARS PLANETARY AUTONOMOUS CONSTRUCTION TECHNOLOGY

Extraterrestrial Construction and In Space Manufacturing Summary

- NASA has developed its Moon to Mars Strategy and Objectives
- Multiple resources are available to provide additional information on the background and development of the strategy:
  - https://go.nasa.gov/3zzSNhp
  - https://www.nasa.gov/feature/nasa-details-strategy-behind-blueprint-for-moon-to-mars-exploration
  - https://www.nasa.gov/sites/default/files/atoms/files/acr22-wp-why_nrho-the-artemis-orbit.pdf
- Advanced manufacturing and autonomous surface construction are specified as key objectives for demonstration:
  - 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.
- **We have a lot of work to do to demonstrate and to institutionalize these capabilities.**

DON'T LEAVE HOME (EARTH) WITHOUT THEM



www.nasa.gov/spacetech

QUESTIONS

DISTRO A.