

The background of the slide is a composite image of space exploration. On the left, a large, detailed view of the Moon's surface is shown, with a smaller, reddish planet (likely Mars) visible in the upper left. A rocket is depicted in the center, moving from left to right and leaving a bright blue trail of light. The sky is a deep blue with numerous white stars. In the bottom right, the silhouette of a person's head and shoulders is visible, looking towards the left. The overall theme is space exploration and technology.

EXPLORESpace TECH
TECHNOLOGY DRIVES EXPLORATION

NASA Advisory Council - Technology, Innovation, and Engineering Committee

John Vickers | Space Technology Mission Directorate | December 15, 2022

How We Explore... Lunar Construction Technology



Credit: ICON/BIG-Bjarke Ingels Group

Moon-to-Mars Planetary Autonomous Construction Technologies (MMPACT) Overview



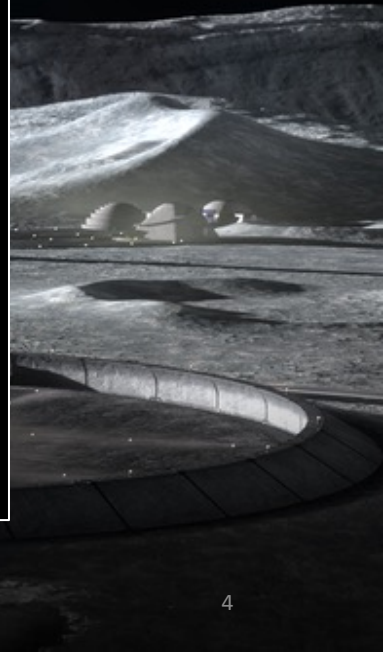
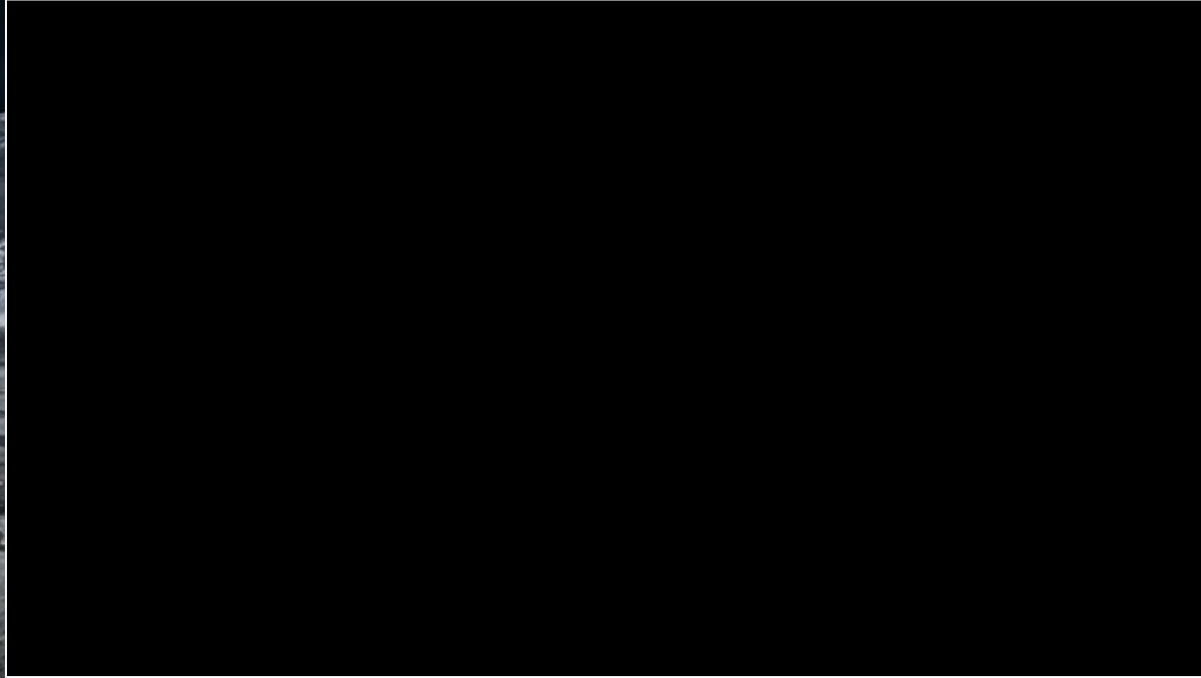
GOAL

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

- Develop and demonstrate additive construction capabilities for various structures as materials evolve from Earth-based to exclusively *In Situ* Resource Utilization (ISRU)-based
- Develop and demonstrate approaches for integrated sensors and process monitoring in support of *in situ* verification & validation of construction system and printed structures
- Test and evaluate materials from candidate processes for use in the lunar environment
- Validate that Earth-based regolith simulants and testing environments are sufficient analogs for lunar operations

ICON 3D Printing on the Moon and Beyond



100-home Community with Lennar



PROJECT OLYMPUS

ICON's vision for a sustained Lunar presence

ICON was awarded a Small Business Innovation Research Contract (SBIR) and Strategic Fund Increase (STRATFI) contract through the AFventures (Air Force) to develop "Project Olympus" the highly automated off-planet version of the Vulcan Printing System.

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Common Key Functional Requirements: Commercial, Military, Lunar Applications

- Long-distance communication, monitoring, and control
- Increased autonomy/automation of operations
- Increased transportability / mass reduction
- Expanded environmental range
- Design for field reparability
- Dust mitigation
- Shielding / ballistic protection
- Job-site mobility
- Off-foundation construction
- Multi-material printing & related control systems
- Improved user experience/ease of operation

The United States Marine Corps

Military Grade Equipment

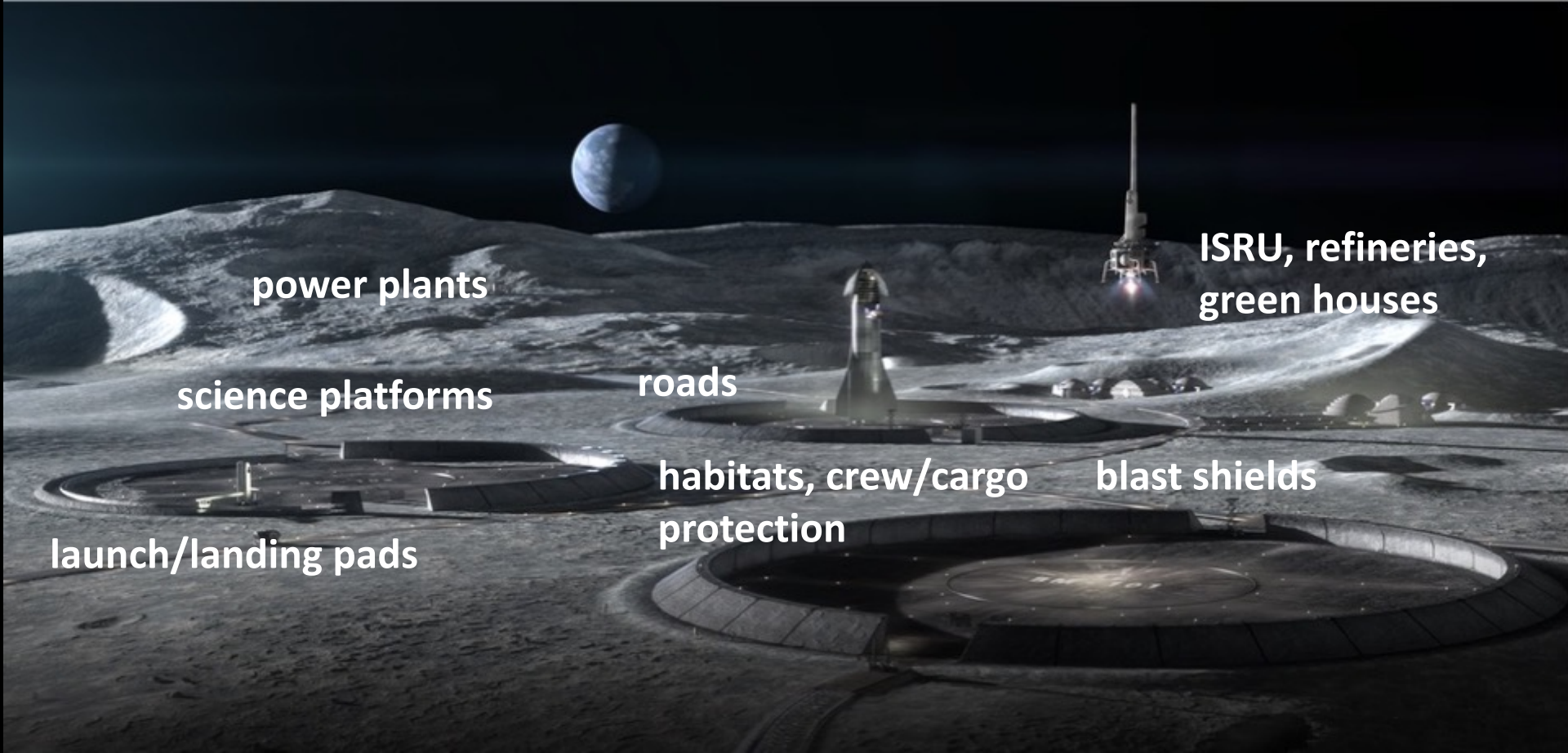
In partnership with U.S.M.C. and the Defense Innovation Unit, ICCO printed a large vehicle hide structure at Camp Pendleton without a foundation. The rugged and remote location with the Marines was not a problem for ICCO's equipment & team.

Date: July 2020
Speed: 36 hours print time
Size: 4 arches at 26" L x 13" W x 18" H
8 Marines trained



Building a Sustainable Presence on the Moon

What infrastructure are we going to need



power plants

science platforms

launch/landing pads

roads

habitats, crew/cargo
protection

blast shields

ISRU, refineries,
green houses

The Case for Lunar Surface Construction



RADIATION

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

METEOROID IMPACT

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

SEISMIC ACTIVITY

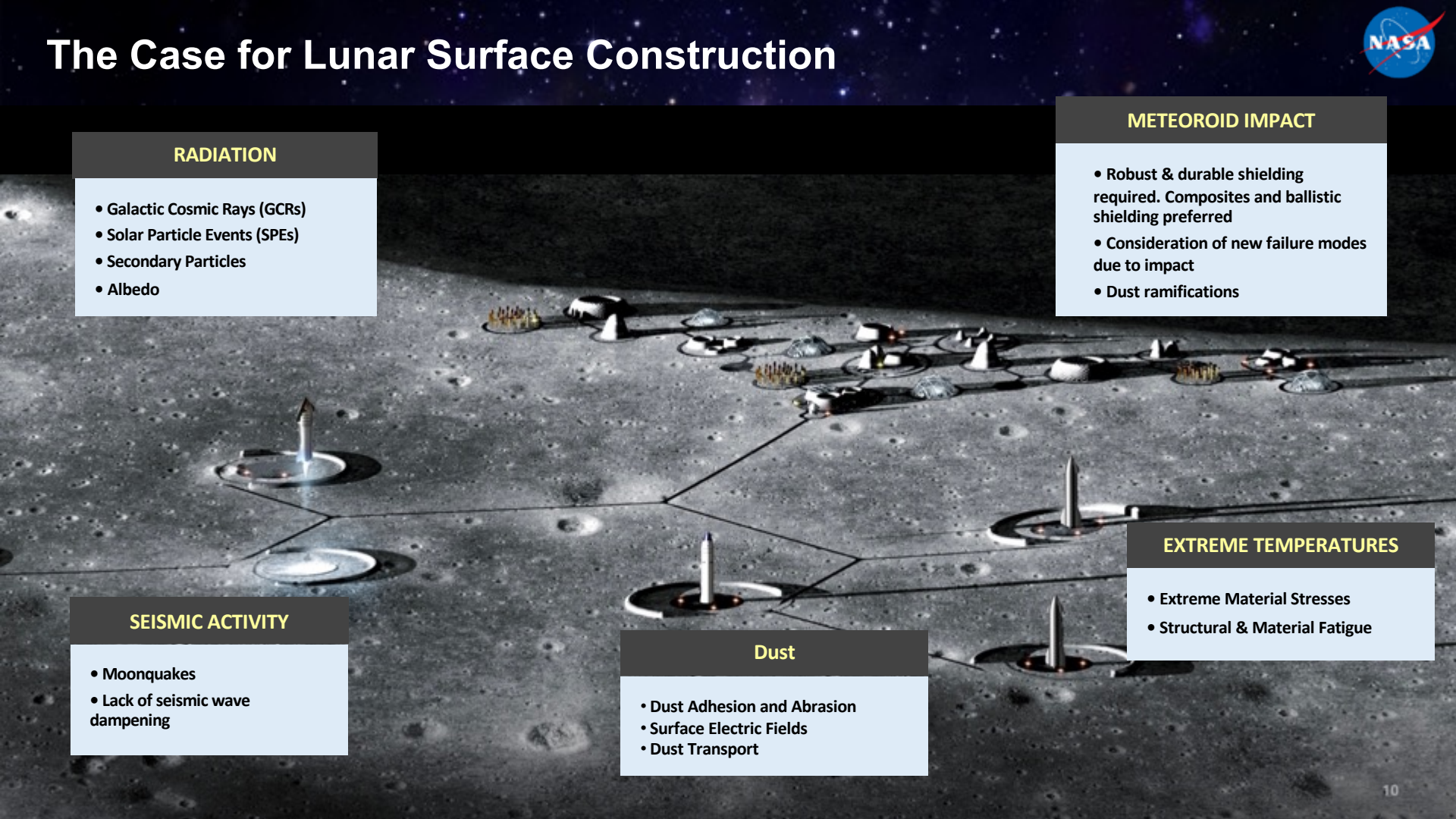
- Moonquakes
- Lack of seismic wave dampening

Dust

- Dust Adhesion and Abrasion
- Surface Electric Fields
- Dust Transport

EXTREME TEMPERATURES

- Extreme Material Stresses
- Structural & Material Fatigue

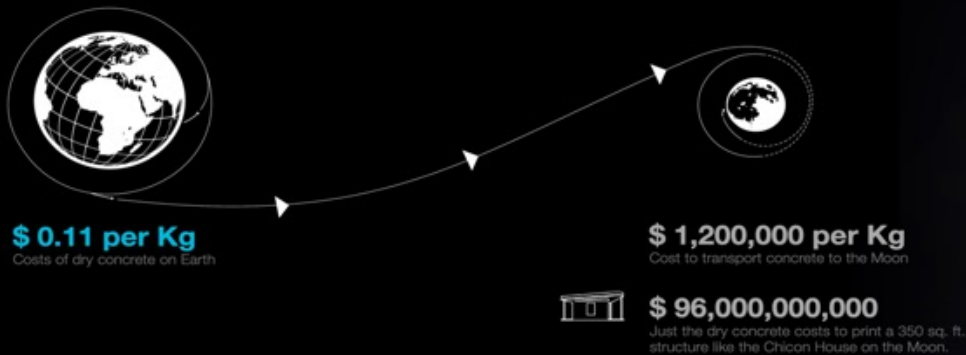


The Case for Lunar Surface Construction



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.



Source: Astrobotic Peregrine Lunar Lander Payload User's Guide:
https://customers.lan.nasa.gov/2019APRME-X000/pdf_files/Astrobotic%20Peregrine%20User's%20Guide%20v1%202018-10.pdf

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Lunar Construction Capability Development Roadmap

Phase 1:

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

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 of the first settlement

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

Demonstration Mission-1:

Proof of concept demonstration of material deposition technology from CLPS deck

Demonstration Mission-2:

Subscale lunar landing pad and vertical blast shield element construction demonstration using mobile construction

Qualification Mission-1: Operational full scale lunar landing pad and vertical blast shield. Construction technology ready for commercialization

Qualification Mission-2:

Autonomous ISRU consolidation into densified, full scale vertical infrastructure elements. Full on-demand construction capability

Initial Construction Technology Demonstration (DM-1) Concept



Initial Construction Technology Demonstration Mission (DM-1) Concept

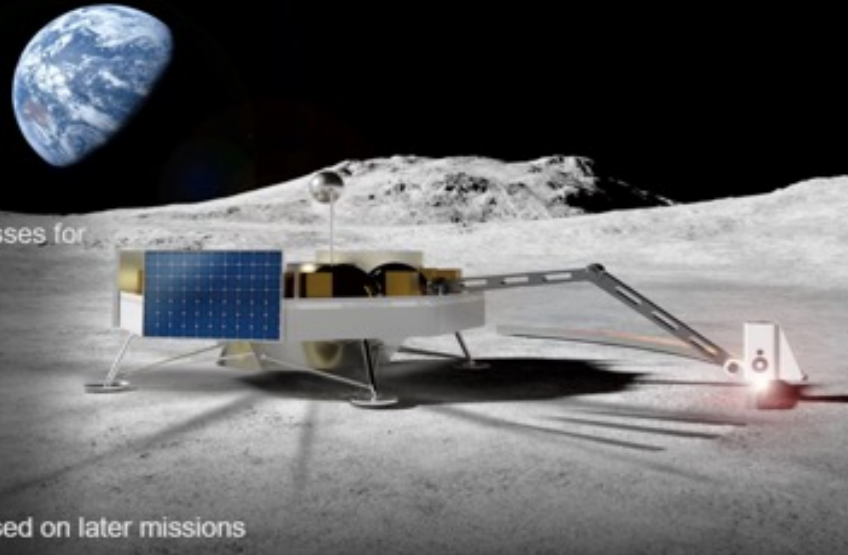


Objectives:

- Demonstrate a lander-based subscale "proof of concept" for selected construction technology utilizing in-situ resources
- Characterize local regolith and resulting regolith-based construction materials
- Demonstrate remote/autonomous operations
- Demonstrate operation of in-process and post-process monitoring instrumentation
- 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
- *Rationale: Must prove out initial construction concept in the lunar environment*

Outcomes

- **TRL 6** achieved for regolith consolidation into densified, subscale structural elements
- **TRL 9** for specific hardware and instrumentation to be used on later missions



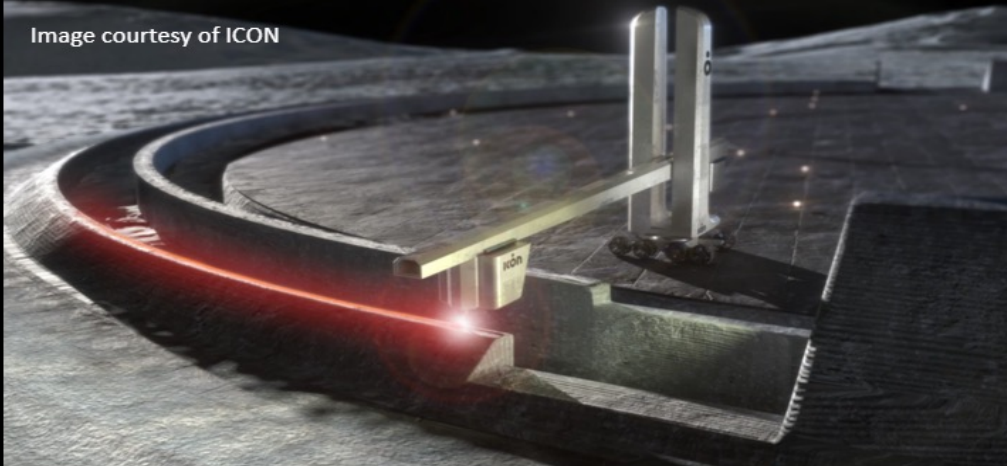
Autonomous Construction: Materials and Concepts for the Lunar Outpost



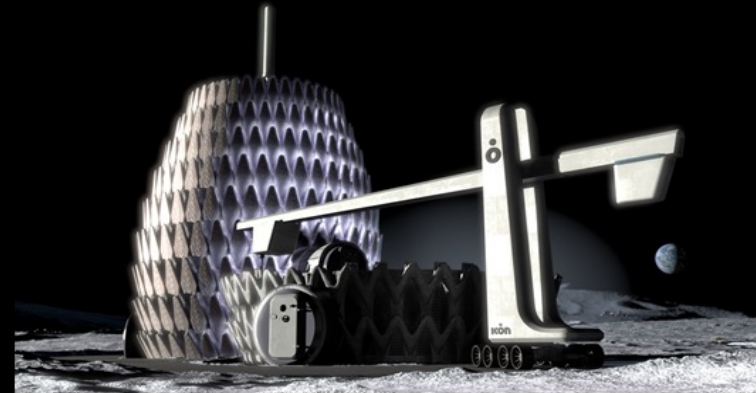
Regolith-based Materials and Processes:

- Cementitious
- Geopolymers/Polymers
- Thermosetting Materials
- Regolith Melting/Forming
- Laser Melting
- Microwave Sintering

Image courtesy of ICON



Bjarke Ingels Group Concept courtesy of ICON's Architecture Study



SEArch+ Concept courtesy of ICON's Architecture Study

Accomplishments

- **ICON Laser Melting**
 - Laser direct energy deposition process additively constructing a test specimen (brick) in atmosphere.
 - Process successfully transitioned to vacuum
 - All mechanical and thermal property characterization test articles delivered and in testing.
 - Established laser melting as baseline process for DM-1
- **ICON Molten Extrusion**
 - Controlled molten extrusion and cast samples under vacuum
 - Thermal profile established to achieve the same microstructure as the laser deposition system
- **Microwave Sintering**
 - Simulant brick sintered in atmosphere
 - Vacuum microwave sintered 5" square tile
- Developed highlands regolith simulant formulations using commercial sources (Colorado School of Mines and Washington Mills) as baseline materials common to all processes.
- Benchtop demonstration of a site preparation tool by KSC
- Completed selection of DM-1 primary instrumentation with LaRC
- Awarded Phase 3 SBIR to ICON for DM-1 flight hardware delivery



SBIR Phase III NASA, ICON Advance Lunar Construction Technology

SBIR Phase III Contract

- Approximate total value: \$57M
 - Base period with five options
- Includes Demonstration Mission 1 flight hardware, associated documentation, and option for lunar surface operations
- Base awarded at end of FY22

Addresses NASA's Needs

- Moon to Mars Objectives RT-2, RT-9, LI-4, LI-8, TH-3, TH-7, OP-1, OP-4, and OP-11
- NASA Strategic Plan Objective 2.2
- NASA Technology Taxonomy Areas 07.2.2, 07.2.3, 12.1.4, and 13.4.5

Goals for Demonstration Mission 1

- Proof of concept lunar construction technology demonstration
- Demonstrate in-situ resource utilization for the manufacture of construction materials
- First step to enable a sustainable human presence on the Moon

Key Milestones

- FY23
 - Deliver material down select samples
 - MCR charts/documentation
 - Ground test for robotic arm/thermal system in V20 DTVAC
 - Ground test for integrated laser system in V20
 - SRR charts/documentation
- FY24
 - Preliminary Design Review
- FY25
 - Critical Design Review
 - CLPS Interface Requirements Document
 - SIR charts/documentation
- FY26
 - Integrated payload flight acceptance testing
 - ADP/FRR charts/documentation
 - Deliver flight hardware

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 – Current Partners



NASA Centers

- MSFC
- LaRC
- KSC
- JPL

OGA Leveraging

Potential:

- Innovation Unit US Air Force (AF)

Contributing:

- AF Civil Engineering Center
- AF Special Operations Command
- Defense Innovation Unit
- Texas Air National Guard
- USAF

Public/Private Partnerships

- 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
- Space Exploration Architecture (SEArch+)
- Bjarke Ingels Group (BIG)
- Cislune
- Washington Mills
- Sioux Tribes

Technology Providers/ Contributing Partners: Academia

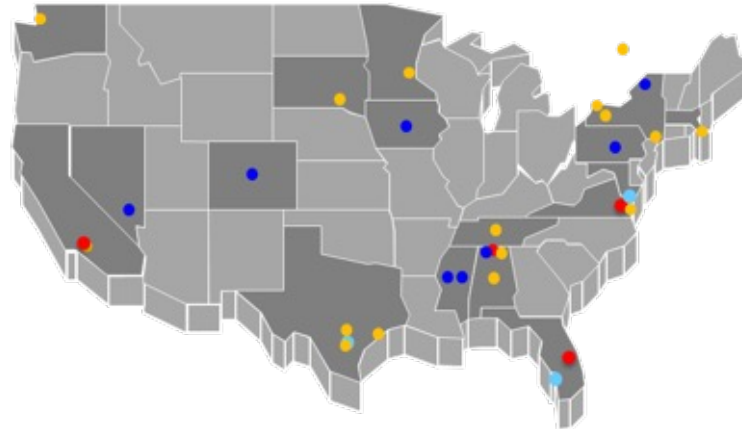
- Colorado School of Mines
- University of Texas in San Antonio
- Mississippi State University
- Pennsylvania State University
- University of Mississippi
- University of Nevada Las Vegas
- University of Alabama in Huntsville
- Clarkson University
- Iowa State University
- Crown College
- Sinte Gleska 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



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

MMPACT Science, Technology, Engineering, and Mathematics (STEM) Support



- MMPACT supported successful Cooperative Agreement (CAN) with Drake State Community and Technical College, a Minority Serving Institution (MSI)
 - Developed additive construction training curriculum certified for all 24 Alabama community colleges with support from MSFC and ICON subject matter experts
 - Procured and implemented robot arm for additive construction training using funds from Minority University Research and Education Project (MUREP) and Alabama State Legislature
 - Drake State leveraged this cooperative project to successfully compete for a 3-year MUREP Grant focused on STEM training: summer internships; STEM bootcamps; and teacher training.
- Implementing successful Drake State template in CAN with Sioux Tribes and Sinte Gleska University in South Dakota



- **MMPACT 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)**
- **MMPACT 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**
- **MMPACT's industry partners are expected to be commercially viable on the Moon in the 2030's**
- **Demonstrations begin with a CLPS proof-of-concept mission in 2026 (STMD)**
- **Many partnerships with members of industry and academia**
- **Technology Capability at the End State of the Current Scope of the Project**
 - **A flight-ready proof-of-concept technology demonstration for construction on the Moon**

Contributors

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- Quinn Otte – Radiance Technologies



MIMPACT

MOON TO

MARS PLANETARY AUTONOMOUS CONSTRUCTION TECHNOLOGY

