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NASA's Moon-to-Mars Planetary Autonomous Construction Technology Project: Overview and Status

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Abstract

NASA plans to land the first woman and next man on the Moon by 2025 through the initial Artemis missions. NASA and its international partners plan to establish a sustainable long-term presence on the lunar surface and build up infrastructure in the subsequent Artemis missions. The Lunar Surface Innovation Initiative (LSII), within NASA's Space Technology Mission Directorate, aims to spur the creation of novel technologies needed for lunar surface exploration and accelerate the technology readiness of key systems and components. The primary thrust areas of LSII include sustainable power; dust mitigation; in-situ resource utilization; surface excavation, construction, and outfitting; and extreme access/extreme environments.

The Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project was initiated to address the lunar surface construction thrust area of LSII. The goal of the MMPACT project is to 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, berms and blast shields using lunar regolith-based materials. The MMPACT project is leveraging technology derived from NASA's 3D Printed Mars Habitat Challenge along with contributions from other Government agencies, and multiple partners within industry and academia. The MMPACT project is comprised of three interrelated elements, construction hardware and process development; feedstock materials development; and microwave structure construction capabilities. These elements are working together to address the multiple challenges of infrastructure construction on the surface of the Moon including increased autonomy of operations, hardware operation and manufacturing under lunar environmental conditions, long-duration operation of mechanisms and parts, scale of construction activities, and material and construction requirements and standards.

This presentation will summarize the status of development activities in each of the three elements, including testing of the various candidate materials, preliminary design concepts for future lunar infrastructure elements, and the vision for future technology demonstrations on the lunar surface. These demonstrations, targeting the mid-to-late 2020's, are expected to enable landing pad construction and habitat construction resulting in commercial capabilities early in the next decade.

Keywords: lunar infrastructure, additive construction, regolith processing

1.0 Introduction

NASA's Space Technology Mission Directorate (STMD) is supporting Artemis through the development of key technologies and capabilities for deep space exploration. Figure 1 provides an overview of the investments that STMD is making in the four thrust areas, GO, LAND, LIVE, and EXPLORE, which are color-coded as are the associated technologies. The Lunar Surface Innovation Initiative (LSII) comprises the majority of the LIVE thrust area. Within LSII is the focal area of Excavation, Construction, and Outfitting (ECO). NASA's Marshall Space Flight Center formulated the Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project to address the lunar surface construction thrust area of LSII, specifically the ECO focal area, in partnership with other Government organizations, multiple academic institutions, industry organizations, and the Jet Propulsion Laboratory, Kennedy Space Center and Langley Research Center. The goal of the MMPACT project is to develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure on the lunar surface00 via construction of landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith-based materials. [0] This paper provides an overview of the formulation, execution, and vision of the MMPACT project and the status of the multiple efforts.

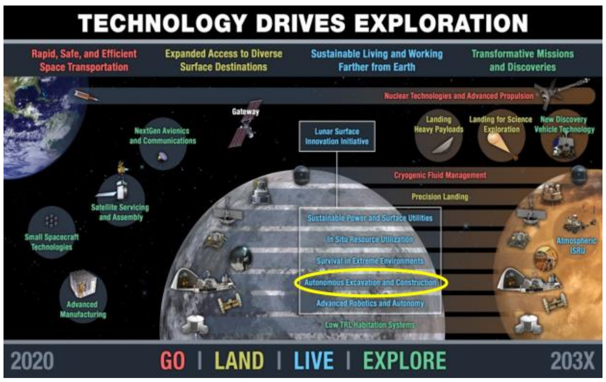


Fig. 1. Space Technology Mission Directorate's technology thrust areas supporting exploration and the Lunar Surface Innovation Initiative focal areas.

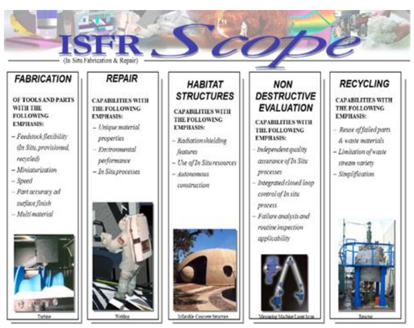


Fig. 2. (Above left) Principal Investigator Ken Cooper conducting first microgravity Additive Manufacturing pathfinder- experiments on NASA's reduced gravity aircraft. Fig. 3. (Above right) Technology development focal areas of the In Situ Fabrication and Repair (ISFAR) Program.

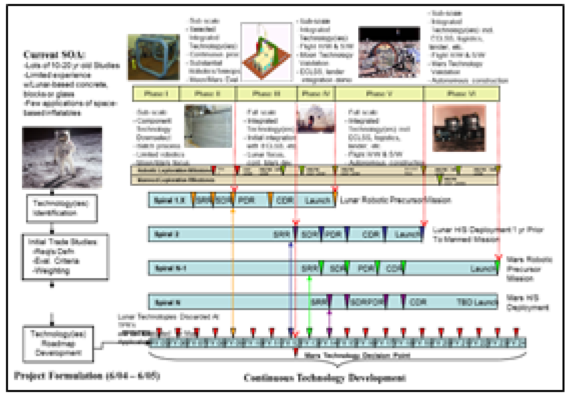


Fig. 4. MSFC Habitat structures capability development roadmap from ISFAR Program Element, 2004.

2.0 Additive Construction for Extraterrestrial

2.1 First Microgravity Additive Manufacturing Experiments

Interest at NASA's Marshall Space Flight Center (MSFC) in off-world additive manufacturing and subsequently in additive construction can be traced to the first "proof of concept" experiment in additive manufacturing in a reduced gravity environment in 1999. This first experiment was to assess whether a Stratasys Fused Deposition Modeler (FDM) would function in a microgravity environment on NASA's KC-135 reduced-gravity flights (Figure 2). The initial experiment results indicated that additive manufacturing using the FDM was feasible in the microgravity environment [0] and the final report recommended that "further testing be granted in a full microgravity setting, i.e. aboard the space shuttle or space station" [0]. However, funding for further development and testing was not available in the following years.

2.2 Initial Extraterrestrial Additive Construction Development: In Situ Fabrication and Repair (ISFAR)

In 2004, NASA's Office of Biological and Physical Research (OBPR) restructured its portfolio to increase focus on support for exploration. In response to the change in focus, the Exploration Science and Technology Division at MSFC formulated and recommended the establishment of the In Situ Fabrication and Repair (ISFAR) Program Element and the In Situ Resource Utilization (ISRU) Program. Element. A synopsis of the key elements of ISFAR is provided in Figure 3. An element focused on extraterrestrial habitat structures construction using lunar regolith was established within the ISFAR Program Element. The Lunar Concrete Crafting (LCC)

Technology Roadmap formulated for ISFAR is shown in Figure 4. Unfortunately, these Program Elements were short-lived, as Agency priorities changed in 2005. However, prior to these Program Elements being terminated, MSFC gained valuable experience in "printing" with lunar regolith simulant-based concrete [0].

2.3 Additive Construction for Expeditionary Structures (ACES) and Additive Construction using Mobile Emplacement (ACME)

In 2014, MSFC again had the opportunity to partner with Prof. Khoshnevis, who had developed the nozzle for the Lunar Contour Crafting element of ISFAR previously noted. This partnership expanded to include U. S. Army Corps of Engineers on additive construction technology development. Through a series of discussions with representatives of the Corps of Engineers Construction Engineering Research Laboratory – Engineer Research and Development Center (CERL-ERDC), and NASA's Kennedy Space Center (KSC), a dual-use additive construction technology was formulated. The project was jointly supported by NASA's STMD for Additive Construction with Mobile Emplacement (ACME) and CERL-ERDC for Automated Construction of Expeditionary Structures (ACES). Development work began in 2015. The projects shared a common vision. The CERL-ERDC version of the vision was, "capability to print custom designed expeditionary structures on-demand, in the field, using locally available materials." With only minor modification, the NASA vision was "capability to print custom designed exploration structures on-demand, on extraterrestrial surfaces, using locally available materials (or regolith)" [0]. Work continued for 3 years. MSFC upgraded the initial gantry-styled printer was to a true "3-D" laboratory-scale system, including a mixer, pump and accumulator and worked extensively on process parameter development. Fabrication of the dry goods storage and delivery subsystem and the liquid storage subsystem was completed by KSC. Finally, scale up from the laboratory system to a full scale gantry printer capable of printing a 16' X 32' "B-hut" structure was completed and delivered to the U. S. Army Corps of Engineers CERL-ERDC. The full-scale system at CERL-ERDC is shown in Figure 5, with the gantry system in mid-frame and the dry goods and liquids storage and delivery subsystems in the upper right of the figure. Additional information on project development activities can be found in references [0,0,0,0].

Fig. 5: The full-scale system at CERL-ERDC

3.0 Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) Project Formulation

3.1 NASA's 3D-Printed Mars Habitat Centennial Challenge

NASA's 3D-printed Mars habitat challenge was a competition to design and print habitats that could house humans as they live and work in space and here on Earth. It was conducted in three phases. Phase 1 was the design competition, which was completed in September 2015. Phase 2 was the structural member competition, which was completed in September 2017. Phase 3 was the habitat construction competition, which was completed in May 2019. The Challenge sought to identify commercial entities developing state-of-the-art capabilities for large-scale additive manufacturing, who are also committed to developing in-situ planetary surface construction capabilities. ACES/ACME team members served as judges for the 3D-Printed Mars Habitat Challenge and were introduced to Space Exploration Architecture (SEArch+) and ICON Technology, a construction technology start-up out of Austin Texas. SEArch+ was a winner of two of the design competition phases and ICON Technologies was a Phase 3 finalist in the habitat construction competition. After the conclusion of the competition, both organizations contacted MSFC to discuss opportunities to continue the habitat design and construction technology development. In the same time period, NASA's Space Technology Mission Directorate was standing up the Lunar Surface Innovation Initiative (LSII) under the leadership of Niki Werkheiser. The LSII was created to "spur the creation of novel technologies needed for lunar surface exploration and accelerate the technology readiness of key systems and components." [9]

The fortunate confluence of events led to a partnership among MSFC, SEArch+, and ICON Technologies. Each organization had multiple interests in advancing the autonomous construction technologies. In 2019, SEArch+ conducted a "Venn diagram" exercise to identify common goals and areas of shared interest for Earth and space development, particularly as they relate to large-scale additive manufacturing. Multiple topics identified by SEArch+ aligned with existing areas of co-development between ICON and NASA, as well as ICON's work with the Department of Defense (DoD). Based on this initial exercise of identifying areas of shared development between terrestrial and in-space additive manufacturing, ICON in collaboration with NASA developed a set of functional hardware and system requirements for autonomous in-space additive construction. These efforts created the foundation for the MMPACT project, as described in more detail in the following section.

3.2 SEArch+ Venn Diagrams via ICON

A critical part of refining requirements and scope of MMPACT were to identify opportunities for co-development of technologies benefiting both Earth and Space. The rationale for co-development was to align and onboard multiple diverse stakeholders in support of lunar exploration while supporting a return on investment for Earth-based architectural design and construction. The design and construction of Lunar or Martian surface habitats which operate within limited means and resources at scale will have immense promise to return knowledge and provide feedback for Earth construction that must also begin to act as though materials, energy, and resources were limited [10].

Additive manufacturing using in situ planetary materials is one of many habitation construction technologies which are concurrently being developed for large scale projects on Earth. There are of course significant environmental and operational differences between Earth and Space construction, and historic separation of the aerospace and earth building and construction industries have created a difficulty in creating a common lexicon, ontology, or methodology between the sectors. However as aerospace progresses towards expanding interest particularly in surface construction systems there are also several opportunities to share common knowledge.

In order to assess the potential for realistic construction technology co-development (as opposed to technology transfer) [11], a series of "Venn-diagram" exercises were undertaken by SEArch+, ICON, and NASA to find opportunities for synergies. SEArch+ led in developing common terminology around the areas of *construction means and methods, material innovation, sustainability,* and *human factors,* towards the development of a set of "comparative requirements." These comparative requirements established in more detail the structural and spatial goals for both equipment and building for Earth, Lunar, and Mars environment and mission scenarios. **(See Figure 6)** Particular attention was paid to established Earth guidelines surrounding both structural and habitation requirements and the need to develop similar frameworks for surface habitats. These requirements were compared for their common goals or divergence, then linked to targeting which technologies would be most critical among a series of interdependent systems. The resultant choice of system requirements could be considered a productive compromise in which, while systems were not entirely the same, lessons learned between collaborators supported parallel goals on both sides (10).

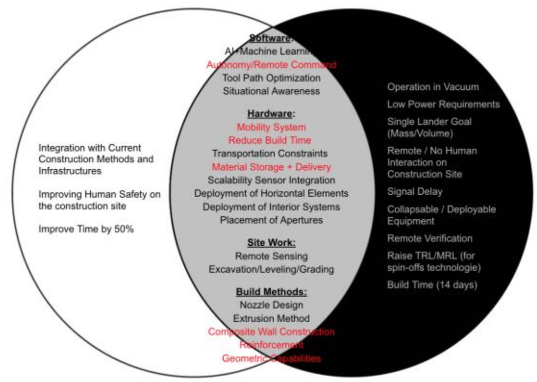


Figure 6. Exemplar Venn Diagram: Construction Means and Methods: Technology Drivers

3.3 ICON/Venn

As a leader in large-scale additive manufacturing solutions, ICON has identified shared technology development goals applicable to the global residential construction market, the Air Force/Department of Defense (DoD), and in space for the purposes of autonomous in situ surface construction on the Moon and Mars. Large-scale additive construction is uniquely suited for both earth and space applications in that it enables construction of many types and varieties of structures (i.e. horizontal and vertical construction) on-demand and in variable settings using local materials. In 2020 ICON was awarded a SBIR Strategic Fund Increase (STRATFI) contract through the AFVentures managed "Open Topic" process to advance the development of its 3D printing technology, advanced materials and software. Through additional support from NASA, ICON continues to mature off-Earth applications for potential use for sustainable lunar missions and develop technology with shared agency benefits for Earth and space. As of present ICON has delivered 24 completed homes, 10 of which were completed using remote teleoperations between Texas and Mexico, 4 of which were sold at market rates in Austin, and 7 of which are currently occupied by formerly homeless individuals. ICON has also completed 5 3D-printed structures for the DoD, including the largest 3D-printed Barracks structure in North America.

In 2020 ICON leveraged the shared technology development goals for residential construction, for construction applications desired by the Air Force / DoD, and NASA to create specific and differentiated functional requirements for in-space construction on the Moon and Mars, in addition to identifying areas of shared technology co-development between sectors. Requirements for each system's communication and monitoring capabilities, baseline autonomy capabilities, usability, reliability, repairability and maintenance, transportation and mobility were each thoroughly considered for similarities and differences. Key differences included: the requirement for fully autonomous capabilities for off-world robotic construction (i.e. zero on-site operators), the need to withstand and operate in a Lunar environment with harsh temperature differentials (-175 degrees Celsius – 127 degrees Celsius). The system architecture and form factor for the Lunar deposition system will vary from ICON's terrestrial gantry-based printer and autonomous material delivery system, as will the material handling and processing system itself.

The requirements definition gave way to suggested areas of mutual collaboration between ICON, NASA, and the DoD, including: goals for measuring the reliability and repairability of hardware and technology systems, development of long-rang communication systems, monitoring and control systems, autonomous mobility within variable sites, dust mitigation strategies, projectile shielding strategies (against micrometeorites, bullets, shrapnel, blasts, etc.), advanced software controls, construction software platforms and building information modeling (BIM) systems, remote teleoperations, off-foundation printing and/or autonomous foundation delivery, as well as advanced autonomy capabilities for site preparation (excavation, leveling, compacting, etc). Areas of collaboration identified between ICON and NASA alone included: autonomous capabilities for surface construction, the development of transportation and payload requirements, hardware system architecture and requirements, Lunar power requirements, materials science for regolith-based print mediums, regolith material harvesting, excavation, handling, as well as feedstock delivery systems.

3.4 Architectural Design Concepts by ICON

Project Olympus is ICON's multi-year initiative to develop an autonomous, large-scale construction system capable of manufacturing horizontal and vertical structures on the Moon and eventually Mars. Project Olympus introduces design schematics for critical surface infrastructure necessary to realize a permanent Moon base, and envisions the construction of durable, self-maintaining, and resilient surface structures enabled by advanced 3D-printing technologies. ICON employed SEArch+ and the Bjarke Ingels Group (BIG) to develop design schematics for mission-critical surface construction elements for a permanent lunar base. The design process was informed by discussions with key ICON engineers and NASA collaborators. The exchange not only ensured the constructability of designs according to known hardware constraints and material processing limitations, but also enabled the architectural process to influence and shape hardware requirements as they were being defined. Within this study SEArch+ developed landing pad concepts and BIG developed a foundational habitat design as well as the master plan for a permanent Lunar base.

Olympus is ICON's autonomous, large-scale construction system capable of delivering a high variety of surface infrastructure elements. ICON's hardware and technology development goals are to develop, deliver, and demonstrate on-demand capabilities for critical surface infrastructure on the lunar surface—including landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith. As a part of the MMPACT program, ICON and NASA are evaluating multiple additive construction technologies, materials, and construction element forms.

4.0 Construction Capabilities Development

4.1 Materials

The only way to enable a sustainable human presence on the Moon, or any other planetary surface, is to develop the capability to produce construction materials from in-situ resources. Lunar resources include the minerals on the lunar surface, such as feldspar, olivine, pyroxene, and ilmenite; volatile deposits in the Permanently Shadowed Regions of the lunar north and south poles; volatiles captured in the igneous rocks on the surface as a result of igneous processes; and volatiles emplaced in the surface materials through approximately 4.5 billion years of solar wind and comet/asteroid bombardment.

Silicate minerals (i.e., feldspar, olivine, and pyroxene) dominate the mineralogical makeup of the lunar surface. From these minerals, the elements Ca, Al, Si, O, Mg, and Fe can be extracted (along with other elements in lower abundance). These "major elements", in addition to sulfur available on the lunar surface and in the mineral troilite, can provide the elements required to manufacture feedstock for cements, such as calcium sulfo-aluminate and magnesium oxysulfate, that could one day be mixed with in-situ regolith and emplaced on the lunar surface to construct infrastructure elements.

Alternatively, regolith, as found in-situ, can be transformed into a construction material. Sintering regolith particles, the vast majority of which are 1mm in size or less [0], can form a solid material strong enough for building. Melting and cooling regolith also allows production of a strong solid material, particularly if that material is cooled at a controlled rate to allow formation of a glass ceramic material instead of a brittle glass material.

The MMPACT project is investigating, and creating, construction materials that can be made from lunar in-situ resources. The team is using cement binder, sintering, and melting methods that can be produced from regolith, or are composed of regolith. To test and evaluate these candidate processes, the MMPACT project created its own lunar highlands regolith simulant due to the lack of significant quantities of high-quality highlands simulant. This simulant is being produced by the Colorado School of Mines and is based on the CSM highlands simulant CSM-LHT-1. The CSM highlands simulant has been modified by incorporating glassy constituents manufactured by Washington Mills and adding commercial augite to achieve the appropriate geochemistry. The resulting simulant, named CSM-LHT-1G, has been characterized by numerous entities, including ICON, MSFC, and JPL; the data indicates the appropriate constituents and at the appropriate mass fractions have been achieved. Production of the final batches of this highlands simulant are ongoing as of the writing of this paper.

4.2.1 Cementitious Materials Development

Since the beginning of the MMPACT project, there has been a concerted effort to develop ISRU-based binder materials that can be extracted from lunar regolith and mixed with the regolith and ISRU-based water to form lunar concretes. For operations on the lunar surface, it is envisioned that the binder raw materials would be extracted by the ISRU community from lunar regolith using any one of several available techniques and provided to MMPACT for storage. Multiple candidate materials have been evaluated, which are summarized in the following sections.

4.2.1.1 Magnesium Oxysulfate (MOS) Binder/Lunar Regolith Concrete

The typical binder composition for this material is $5Mg(OH)\ 2MgSO_4\ 7H_20$ with a small (1-2 wt%) of boric acid as a set retardant, as it is a rapid-set material. Anticipated mix is 30% binder, 70% regolith. The binder decomposes at ~1124 deg C with many phase changes. These materials would be mixed/reacted in several steps to obtain the required compounds (MgO, MgSO4, H2O), mixed as a binder, then mixed with lunar regolith and set retardant.

4.2.1.2 Calcium Sulfo-Aluminate (CSA) Binder/Lunar Regolith Concrete

The typical binder composition is $Ca_6Al_2(SO_4)_3(OH)_{12}\ 26H_20$ with a small (2-4 wt/%) of citric acid as a set retardant, as it is a rapid set material. Anticipated mix is 30% binder, 70% regolith. These materials would be mixed/reacted in several steps to obtain the required compounds ($Ca_6Al_2(SO_4)_3(OH)_{12}$, H2O), mixed as a binder, then mixed with lunar regolith and set retardant.

4.2.1.3 Sodium Silicate/Sodium Hydroxide (geopolymer) Binder/Lunar Regolith Concrete

The typical binder composition is of the form $Na_2O)_x{\cdot}(SiO_2)_y$. Anticipated mix is 30% binder, 70% regolith. The binder decomposes at ~1100 deg C with many phase changes. These materials would be mixed/reacted in several steps to obtain the required compounds (NaSi, NaOH, H2O), mixed as a binder, then mixed with lunar regolith.

4.2.1.4 Sulfur/Nickel (S/Ni) Binder/Lunar Regolith Concrete

Sulfur has been investigated as a planetary concrete binder for many years. The two main drawbacks to sulfur include a low melting point and sublimation of the sulfur in the vacuum of space. Recent research by the MMPACT team has led to the idea of alloying the sulfur with nickel to raise the melt temperature and stabilize/reduce sublimation. The typical binder composition would be Sulfur alloyed with 3-4% Nickel to elevate the melt temperature of the alloy. Anticipated mix is 45% binder, 55% regolith. The binder decomposes/melts at ~115 deg C, meaning that it could soften again in the lunar environment without protection. Additions of small amounts of nickel are expected to raise the melt temperature of the alloy, but two cooling curve experiments to date have not confirmed this hypothesis. These materials would be mixed/reacted in several steps to obtain the required recipe, mixed as a binder, then mixed with lunar regolith in a heated mixer.

4.2.2 Cementitious Material Deposition Process

The materials would be transported via conveyor or other technique into a progressive cavity pump. The pump would push the concrete mix through a hose and nozzle, presumably in an Environmental Enclosure that would be pressure and temperature controlled for reduction of porosity. The print would be monitored during processing, using electrical impedance, backscatter x-ray, or other techniques for real-time void detection. Upon completion of printing, the concrete would be cleaned out of the system and placed into a washout pit (also in the enclosure). Post-cure characterization may be performed using a Schmidt hammer (hardness, compressive strength), backscatter x-ray (void detection), or other techniques. Estimated power varies slightly from material to material, but falls in the range of ~1.0 – 2.0 kW, with the exception of the Sulfur/Nickel binder lunar regolith concrete, which requires higher power (1.5 - 2.5 kW) due to the requirement to maintain the sulfur in a molten state from mixing through extrusion. Complexity also varies by material composition, the Magnesium Oxysulfate and the Calcium Sulfo-Aluminate are estimated as moderate. Complexity of the geopolymer binder and the sulfur/nickel binder lunar concrete materials is estimated as slightly higher than moderate due to the heating requirements. It should be noted that every cementitious process described here is performed on Earth routinely in the Additive Construction industry.

4.2.3 Current Cementitious Materials Test Activities

An internal downselect process in December 2021 resulted in the geopolymer concrete and sulfur concrete variations being removed from consideration for the DM-1 mission, planned for December 2026. These materials will continue to be evaluated for possible application to a subsequent DM-2 mission, but it was determined that the Technology Readiness Levels (TRLs) were too low to consider for DM-1.

Meanwhile, a detailed test program was undertaken to characterize the behavior/performance of these concretes. For the sake of brevity, only the results for the CSA concrete will be reported here, including:

- "Recipe" development to optimize compressive strength and set time while maintaining a previously optimized material viscosity of 9-15 Pascal-seconds (Pa*s).
- Reduced pressure integrity testing consisting of curing samples at various pressures between 1.0 atmosphere (atm) and 0.4 atm and assessing effects on compressive strength
- Early set performance testing consisting of both Vicat Penetrometer Testing to determine consistency and initial/final set times, and Flow Table Testing to evaluate workability, consistency, cohesiveness, and the proneness to segregation.

Previous testing at MSFC [0] on 3D printing of Ordinary Portland Cement (OPC)-based concretes yielded an optimum concrete viscosity of 9-15 Pa*s and this was the target for the planetary concrete as well. A series of experiments were performed in late 2021 with Royal White Cement (RWC) Calcium Sulfo-Aluminate (CSA cement, Deltion OB1-A Lunar Highlands Regolith Simulant, Jungbunzlauer Citric Acid (as set retardant), and industrial-grade water resulted in an optimized "recipe" with a water/cement ratio of 0.37 and a 49:51 ratio of lunar regolith to CSA cement. Set retardant was optimized at 1.02% of CSA cement mass to yield a working time of about 1 hour, with a time margin of 50% to allow for unforeseen circumstances. This mix yielded an average compressive strength of just over 7,500 pounds per square inch (psi).

It is anticipated that curing of a concrete using a water-based binder in the reduced pressure of the Moon or Mars would result in significant porosity and reduced structural integrity. One idea to mitigate this problem has been the use of a deployable Environmental Enclosure on the surface to house both a printer and the structure being printed at a pressure as low as possible while still maintaining structural integrity. To determine the structural requirements of such an Enclosure, our team embarked on a series of Reduced Pressure Integrity Tests. In these tests, samples were cast and tamped into 2" cube molds in accordance with ASTM-C109 and immediately placed into a bell jar. The samples would cure for 2 days in the bell jar at a pre-determined pressure (between 1.0 atm and 0.4 atm, at 0.1 atm intervals) and 5 days at ambient and were compression tested (also per ASTM C-109) after 7 days total cure. Nine samples were tested for each pressure level and the results are shown in Figure 7.

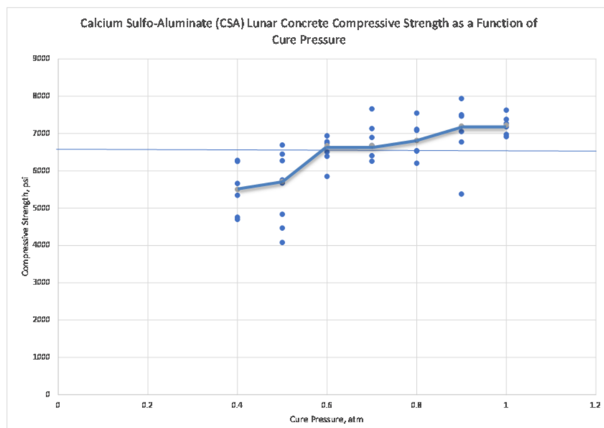


Fig. 7. Calcium Sulfo-Aluminate (CSA) Lunar Concrete Compressive Strength as a Function of Cure Pressure

It can be seen in Figure 7 that the compressive strength decreases as the cure pressure decreases and these results were not unexpected. The horizontal line represents 90% of the nominal compressive strength at 1.0 atm. This 90% value was used as the cut-off line to determine at what pressure the Environmental Enclosure should operate. At the 90% strength line, the cure pressure was ~0.6 atm and this pressure became the driving requirement for the design of the Environmental Enclosure, which is still in work.

To fully understand and predict behavior as a 3D print material, it was also important to quantify early-set characteristics. This was performed using a combination of Vicat Penetrometry (in accordance with ASTM C-191) and the Flow Method in accordance with ASTM C230 and ASTM C1437. The results of these tests are shown in Figure 8 for the CSA lunar concrete.

The data reflects the non-Newtonian nature of concrete and the ability of this mix to be used for 3D printing. Note that the flowability (pumpability) remains high for up to 2 hours even as the penetrometer data shows the concrete is setting up. This data also indicates, even with about a 50% margin, the open time (time between layers) of up to an hour which is necessary for printing larger structures or multiple structures simultaneously.

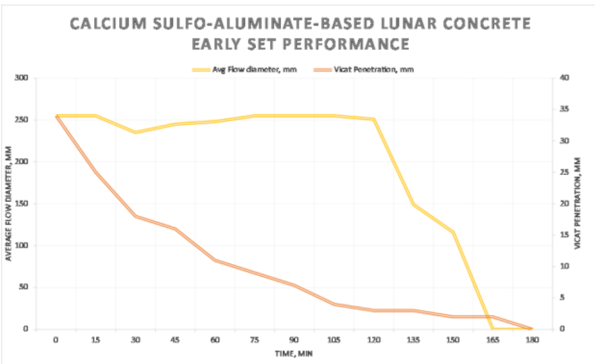


Fig. 8. Calcium Sulfo-Aluminate (CSA) Lunar Concrete Vicat Penetrometer and Flow Table Data during Early Set

4.2.4 Future Cementitious Materials Team Activities

The Cementitious Materials Team at MSFC is preparing samples for the upcoming DM-1 mission deposition materials/technology downselect later in 2022. The planned testing is discussed in Section 5.0.

In addition, testing of a prototype Environmental Enclosure will soon be tested and the team continues to develop monitoring equipment for cementitious materials processes including electrical impedance measurements as a real-time void detection device and a rebound (Schmidt) hammer as a way of characterizing finished structure hardness and/or compressive strength.

4.3 Microwave Structures Construction Capabilities Development

Another processing method MMPACT is pursuing is utilization of microwaves to heat and sinter the regolith into infrastructure. Brickmaking was pursued for a short time, but development has been delayed to future missions due to the complicated conops for ISRU joining. Multimode (MM) and Near Field Coupler (NFC) are applicators currently being focused on for development. These applicators are more of an additively manufacturing or paving approach and will be employed to build up layers above grade after the site has been prepared. For flight, a solid state microwave source has been baselined. Wave guide or transmission line will transmit the energy form the source to the applicator. A microwave imager was baselined to inspect for rocks subsurface, monitor the sintering process, obtain dimension tolerances, measure dielectric constant, and characterize detectable porosity and cracks.

4.3.1 The Multimode

This method allows top-down heating of regolith on the lunar surface, with translation to cover large areas for paving via microwave sintering. The multimode application of microwave energy allows better mixing of the electric field for more uniform heating. See Figure 9 for Multimode experimental setup. Designed experiments are focused on optimizing the energy input for microwave sintering control, with imaging and optical pyrometry for fast feedback temperature measurement. After the first pass with the multimode applicator, the next layer of regolith will be added with a robotic arm, potentially with an ISRU composition to facilitate bonding with the sintered layer below, similar to the 3D printing binder jet method.

High temperature dielectric properties are used to guide the engineering design. For the lunar Highlands, a hybrid microwave approach is indicated with the use of radiant heat to elevate the surface temperature. Once the surface is heated, regolith readily absorbs microwave energy to sinter. There are many options for the hybrid design with TRLs as high as 7. The method selected for DM1 is the use of external non-consumable susceptors which quickly radiate to preheat the regolith surface. See Figure 10 showing susceptor array and initial experiment results in Figure 11.

Fig. 9. Experimental set up showing the multimode applicator on top and a powder bed below, simulating the microwave paving method.

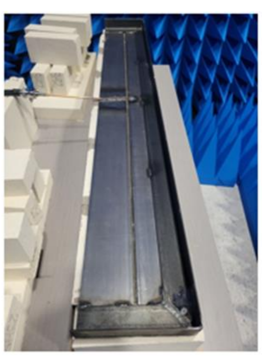
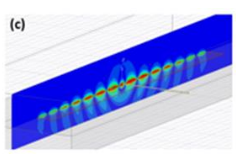

Fig. 10. (Left) Susceptor array used to supply radiant energy to concentrate microwave heating on regolith surface.
Fig. 11. (Right) First high vacuum microwave sintering result showing solid sintered CSM-LHT-1G tile removed from the top of the powder bed.

4.3.2 The Near Field Coupler

The Near-Field Coupler is another microwave applicator used for paving processes, used by translating the applicator over a site-prepped surface [0]. By using a planar applicator that creates a near field as opposed to an antenna radiator, energy is constrained to the first several centimeters of a surface. This is expected to increase energy efficiency by reducing energy lost to non-target areas. See Figures 12, 13, and 14.

Experiments are currently focused on optimizing the energy input for microwave sintering control, with infrared imaging for temperature measurement. After the first pass with the near-field coupler, site prep will be repeated and the applicator will make another pass to create layers of sintered material.

The Near-field coupler testing is not planning to use any microwave susceptors, and the simulant bed is designed to sufficiently mimic an infinitely large volume of material. Process parameters for experimentation are being guided by dielectric properties of the CSM simulant provided by JPL, as well as Thermo Gravimetric Analysis provided by NASA.

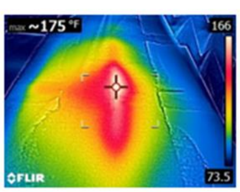


Fig. 12. (Left) Prototype steel NFC, resting on top of the firebrick simulant bed for low-power, open-air testing. Fig. 13. (Top right) Near-Field Coupler's electromagnetic field map modeled in HFSS.
Fig. 14. (Bottom right) Proof-of-concept low-power testing with the steel NFC showing predictable heating patterns.

Plates are being generated from both of these processes for sectioning into tensile, compression, and ablation test samples. The properties obtained from the testing along with conops and energy efficiency will be used to select among the two applicators.

After downselect between the applicators, a 4’x4’x 4” subelement would be fabricated in a 20’ diameter vacuum chamber. This information would feed the design for the engineering unit and subsequent tqualification and flight systems.

4.4 Process Development, Molten Regolith Extrusion

ICON is in development of a molten regolith extrusion system, capable of casting molten regolith in molds, and also extruding beads of molten regolith adjacent to one another, and vertically on top of one another. Though molten extrusion is quite common terrestrially, ICON’s molten regolith extrusion system is capable of thermal vacuum operation. Shown below in Figure 15, by tightly controlling the temperature in each zone of the reaction chamber, extrusion can be started, rate controlled, and stopped.

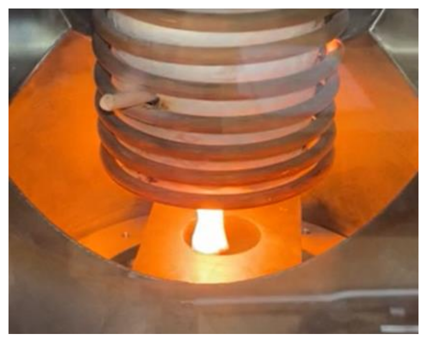


Fig. 15. Controlled molten extrusion under vacuum from ICON’s molten regolith extrusion system.

This system is still under development and has remaining operational challenges, however, once complete, it will be capable of operating with a wide range of input materials, and will be the likely choice for casting ingots, bricks, and tiles using waste-slag from molten regolith electrolysis systems. The ability to consume and deposit molten materials from other processes, this system can make use of these byproducts and embodied energy for use in robotic additive construction. The resulting material, shown below in Figure 16 has mechanical properties favorable for various intended uses.

Fig. 16. Vacuum-cast specimens, using ICON's molten regolith extrusion system.

4.5 Process Development, Regolith Laser Direct Energy Deposition

ICON has developed a system for producing consolidated structural elements from raw amorphous lunar regolith simulant using a custom laser directed energy deposition system. The vacuum-processing laser DED system, shown below in Figure 17, has primarily been developed using powder-bed support for structures, building layer by layer, the concept is adaptable to additively constructing (printing) structures without the need for a powder bed to support the part.

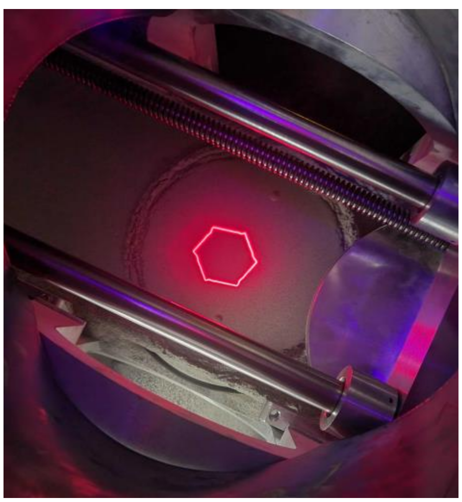


Fig. 17. ICON's terrestrial vacuum laser direct energy deposition testbed.

The laboratory systems have built "human scale" parts for construction in atmospheric conditions as well as in vacuum. Capable of supporting both Mare and Highlands simulants, process parameters are set such that the resulting material is as robust as possible. For instance, compressive strengths of more than 4,000 psi have been achieved with raw lunar highlands simulant (CSM-LHT-1g), requiring no external beneficiation or "brought" materials.

ICON believes the flexibility of this system in the ability to control power, scan rate, angle of incidence and many other parameters makes this system incredibly robust. The prototype systems have also demonstrated the ability to weld cast bricks and tiles. Shown in Figure 18 is an in-process snapshot of a single layer, eventually consolidated into a brick-like structure, Figures 19 and 20.

Fig. 18: Laser direct energy deposition process building a layer of a test specimen (brick).

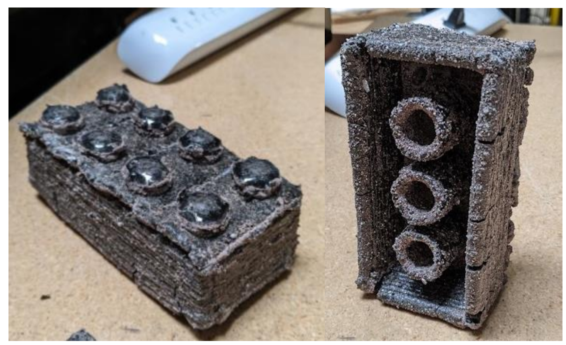


Fig. 19 and 20. Laser direct energy deposition, additively constructed test specimen (brick).

Future development on the system will reduce defects using in-process monitoring and adaptation, as well as increased fidelity and resolution of the resulting structural elements.

5.0 Material and Process Downselect

The goal of the down-select test campaign is to use material testing and operations assessments to inform a data-based selection the material deposition process that will be used for the candidate initial MMPACT Technology Demonstration Mission (DM-1). A primary material/process will be selected and risk reduction back-up materials will be prioritized from among the candidate technologies to focus efforts and resources into developing a successful DM-1 capability. For materials testing, lunar highlands simulant is used to make test specimens that are multi-layered. A relevant environment – according to each technology's concept of operations, or CONOPs – is used during fabrication.

All but one of the candidate technologies are fabricating specimens in vacuum (threshold no greater than 10-3 Torr at this time). The cementitious material development proposes implementation of an enclosure that maintains Earth-like temperature and pressure. All technologies, however, will use the same lunar simulant to fabricate test specimens. Materials testing includes responses to mechanical loads (compression, tension and bending), thermal loads (plasma torch) and combined-effects such as compression after thermal cycling in vacuum, all of which are intended to represent some of the conditions of a lunar landing pad. The MMPACT project enlisted the assistance of a NASA Engineering Safety Center (NESC) – led team to: (1) review candidate materials and associated processes: (2) review, evaluate and recommend appropriate mechanical and thermal property tests; review and integrate requirements and CONOPS factors; (3) review and integrate requirements and CONOPS factors; and (4) provide a comprehensive set of down selection criteria. [0] CONOPS factors are used to grade a technology's ability to meet limitations driven by Commercial Lunar Payload Services (CLPS) vendors and the lunar environment. Two prime examples are payload mass restrictions and absence of light during Lunar night. The CONOPS assessments and material test results will be used to grade each technology before a final selection of primary and prioritized secondary processes (as back-ups) is made. Test article fabrication has begun and final selection will be accomplished by the end of the first quarter of FY23.

6.0 Lunar Construction Hardware Development

ICON's Project Olympus mobile robotic construction system is under development. Focusing on the print processes primarily, the team has designed terrestrial analog tool heads for thermal vacuum testing. The current focus is on process tool heads that will be capable of operation in large dirty thermal vacuum chambers. For tool head manipulation and articulation, ICON's terrestrial system "mission brassboard" robotic manipulator consists of six custom built serially configured robotic joints. Full kinematic control of the manipulator will be integrated with ICON's robotic system control suite, including temperature control and system health monitoring. The testing of our process tool heads and robotic manipulator will inform a lunar-optimized variant for substantial mass and energy savings. ICON's process tool head under development will leverage one or more additive construction processes such as laser directed energy deposition, and will also house various sensors for work area manipulation, site curation, and material deposition. Additionally, the tool head is capable of housing instruments such as visible light and thermal cameras for perception of the environment. A scoop and basic sieve functionality is also included, with positioning handled by the robotic manipulator.

7.0 Planning for Lunar Construction Technology Demonstration Mission – 1 (DM-1)

The current Space Technology Mission Directorate planning targets a no earlier than date of late 2026 for the initial lunar surface construction technology demonstration. The MMPACT project is a candidate for that mission and is working towards a readiness date that is consistent with the STMD plans. If selected for this mission, or a subsequent flight, the goal of the mission will be proof of concept for the selected material deposition system. The objectives of this initial mission are as follows:

- Demonstrate the selected construction technique utilizing ISRU materials at small scale from lander base
- Demonstrate remote/autonomous operations
- Demonstrate instrumentation for systems health monitoring; process monitoring and control; and post-process material inspection
- Validate (or refute) that (a) Earth-based lunar highlands simulant and (b) testing in a simulated lunar environment in a thermal vacuum chamber are sufficient analogs for lunar operations
- Anchor analytical models using information generated during the mission

Results from this initial technology demonstration are critical to inform future construction demonstrations and to characterize ISRU-based materials and construction processes for future autonomous construction of functional infrastructure elements.

The construction payload will be delivered to the lunar surface by a Commercial Lunar Payload Service (CLPS) lander and, as currently envisioned, will target the South Pole region of the Moon. A preliminary concept of the DM-1 lander/construction payload system is shown in Figure 21.

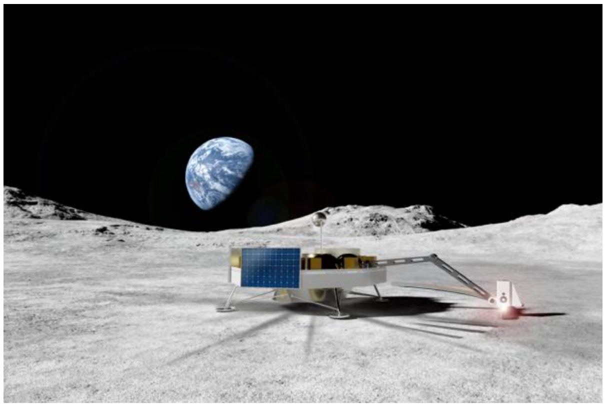


Fig. 21. Preliminary concept of the DM-1 MMPACT surface construction system operating from the deck of a CLPS lander on the Moon.

8.0 Notional Lunar Construction Capability Development Roadmap

Looking beyond the DM-1 mission, additional construction technology demonstration and qualification missions are envisioned to mature the capabilities in a phased approach. A graphical representation of this phased development is shown in Figure 22. The next candidate mission, lunar surface construction technology demonstration mission two (DM-2), would represent a significant step forward in the capability development. The DM-2 mission would focus on the construction of a subscale landing pad and blast shield section, to assess both horizontal and vertical construction capabilities. The additive construction system would be mobile and work on the surface rather than from the deck of the lander. The mobile system would need to interface with the excavator system for the transfer and conveyance of the regolith feedstock material and co-location for site preparation. In addition, for these larger and more complex infrastructure builds, additional capabilities will be required from other STMD projects, such as surface power, communications and navigation, as well as a scaled up excavation and site preparation system. Instrumentation would be leveraged from the DM-1 mission and expanded to meet the challenges of the larger construction capability to include in-process feedback and controls and post process material inspection. It is a goal of DM-2 to be able to assess the mechanical capabilities and thermal performance of the printed lunar materials. This is critical to be able to understand whether the Earth-based regolith simulant materials and the processes developed and tested in a simulated lunar environment (thermal vacuum chamber) are sufficient analogs for actual lunar operations and to ensure that the material can withstand the operational environment for an actual full scale landing pad.

The third mission in the notional lunar construction capability development requires additional scale up of the systems. This mission is referred to as the lunar surface construction technology Qualification Mission One, (QM-1). The targeted infrastructure elements would be an operational landing pad and blast shield. While no requirements for the landing pad dimensions have been established, it is envisioned that a pad on the order of 50 meters in diameter would be the target with additional consolidated apron and full perimeter blast shield. Further, a subscale vertical element, an unpressurized lunar shelter, would be an additional goal of this mission. The full suite of complementary capabilities for long duration operation of the lunar construction system would be necessary to create infrastructure of this scale and complexity. Upon successful completion of this mission, the construction technology for horizontal infrastructure elements would have achieved a Technology Readiness Level of 9 and be ready for commercialization.

The fourth and final mission in the envisioned construction capability development series would be Qualification Mission Two (QM-2). The focus of this mission would be to qualify the system for full scale habitat construction. Early architectural concepts for such habitats were developed for ICON by Space Exploration Architecture (SEArch+) and the Bjarke Ingels Group (BIG) as described in Section 3.4. Another possibility would be to produce a large unpressurized lunar shelter similar to the Lunar Safe Haven studied by a team led by the Langley Research Center. [0]. For this mission, the full complement of ancillary capabilities used for the QM-1 mission would be expected to be available to support the construction effort for this large vertical infrastructure element. Upon successful completion of this structure, the construction system for vertical infrastructure elements would have achieved a Technology Readiness Level of 9 and be ready for commercialization.

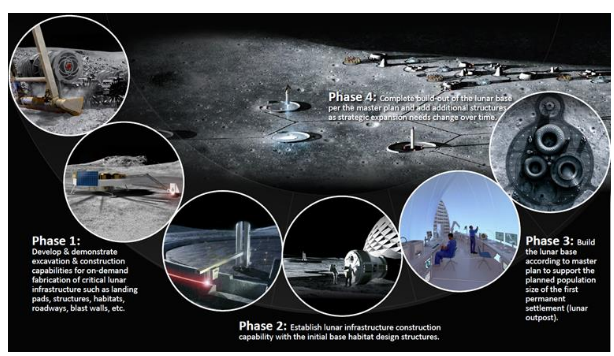


Fig. 22. Notional phased lunar construction capability development roadmap.

9.0 Summary

Through the Artemis missions, NASA and its international partners plan to establish a sustainable presence on the lunar surface. The initial Artemis missions will lead to landing the first woman and next man on the Moon by late 2025. To establish a sustainable long-term presence on the lunar surface, critical infrastructure elements and capabilities must be emplaced by subsequent missions. NASA's Space Technology Mission Directorate is investing in technologies in four key thrust areas that support Artemis. The Lunar Surface Innovation Initiative (LSII) is one of the four key thrust areas and includes developments in the following technologies: sustainable power; dust mitigation; in-situ resource utilization; surface excavation, construction, and outfitting; and extreme access/extreme environments.

The Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project was initiated to address the lunar surface construction thrust area, with the goal of developing, delivering, and demonstrating on-demand capabilities to protect astronauts and create infrastructure on the lunar surface via construction of landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith-based materials. The MMPACT project is partnered with other Government agencies, and multiple industry and academic organizations in this technology development initiative. MMPACT is evaluating several processes, all of which utilize only materials that can be found on the Moon to avoid the extremely expensive transportation costs to launch building materials to the Moon. The cementitious material candidates have been reduced to only one, the calcium sulfo-aluminate binder (with regolith as the feedstock/aggregate), through internal evaluations. The laser sintering and molten regolith extrusion processes along with two microwave applicator options also remain as candidates for DM-1. Materials produced using these processes will undergo mechanical testing and thermal performance testing per the tailored NESC-developed down-selection test matrix. A selection is expected late in the first quarter of FY23. In addition, ICON is developing a robot arm that is scheduled for testing in the large MSFC "dirty" thermal vacuum chamber (TVAC) in the second quarter of FY23. A test of the selected materials deposition process in the same TVAC is scheduled for later in the year. If selected for flight, the MMPACT team will continue the design, development, and testing through the preliminary and critical design reviews and deliver the payload to the CLPS provider according to the schedule established by the Space Technology Mission Directorate.

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