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CONCEPT OF OPERATIONS FOR A DEMONSTRATION MISSION OF IN-SITU LUNAR REGOLITH BAG CONSTRUCTION FOR ARTEMIS MISSIONS (LUNAR BRICS)

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Abstract

LUNAR-BRICS (Lunar Robotically-Based Regolith Incorporated Constructions System) exploits regolith in-situ as a building material to fill Regolith Containment Units (RCUs) which are akin to terrestrial sandbags. This work is a pre-phase A concept of operations for a demonstration mission for a lunar surface robotic system that would serve as demonstration for the LUNAR-BRICS concept. The demonstration mission system is composed of an RCU production system and a multipurpose robotic arm from the MDA SKYMAKER™ lunar robotic arm line of products. Post landing the arm will perform a geological assessment of the surface, followed by extraction of regolith from the surface that would be transferred into the RCU production system. Filled RCUs would then be stacked and assembled to demonstrate and test the applicability of the technique to meet identified Moon-to-Mars (M2M) needs.

Keywords: Regolith, Artemis, robotic operations, in-situ resource utilization (ISRU)

Acronyms/Abbreviations

LUNAR BRICS	Lunar Robotically-Based Regolith Incorporated Construction System
RCU	Regolith Containment Units
ISRU	In-Situ Resource Utilization
LTV	Lunar Terrain Vehicle
LUV	Lunar Utility Vehicle
M2M	Moon to Mars
STMD	Space Technology Mission Directorate
TRL	Technology Readiness Level
MMOD	Micrometeoroids and Orbital Debris
PSR	Permanently Shadowed Regions

1. Mission Drivers

NASA’s crewed deep space exploration ambitions are to advance the goals of sustained infrastructure and commercial operations on planetary bodies – most notably the moon, with further aspirations towards Mars. The lunar Artemis base will employ a wide variety of technologies and architectures to facilitate this, with a range of commercial and government funded activities.

Robotic construction, maintenance, and repair have been identified as key aspects required to enable these activities, as the use of astronaut labour would be prohibitive (cost and human safety wise) given the breadth and depth of resources needed to support human activities on the lunar surface. In order to meet such an ambitious and complex goal, agencies such as NASA and the lunar community have conducted a series of community engagements, with the goal of developing a list of near-term priorities. Relevant to lunar construction, these include: structures such as landing pads and protective structures, technologies such as those to survive the lunar night, and methods for the recycle, reuse, and use of construction elements as well as the use of waste materials (e.g., tailings) (NASA, 2023). As the architecture of the Artemis base matures, technologies that can meet a wide variety of infrastructure needs will no doubt be among the first to be deployed on the lunar surface.

Use of regolith as a construction material has long been seen as key to a sustained presence on planetary bodies, most notably the moon. This approach greatly reduces the demand on transporting raw construction materials from Earth, and consequently the cost and logistics needed, and offers several attractive properties such as structural (Dotson, 2024), radiation shielding, and thermal insulation (Akisheva, 2021). A variety of ways to employ regolith have been conceived (G. Cesaretti, 2014) (Kai-tuo Wang, 2017) (S. L. Taylor, 2018), with corresponding advantages and disadvantages, however this work will focus on LUNAR-BRICS: the use of regolith filled bags (RCUs) – akin to terrestrial sandbags.

1.1. Use Cases for LUNAR BRICS

The advantage of RCUs originate from its compact form factor and modularity – one that can easily be robotically assembled to create structures of varying scales, geometries, and inherent complexities. RCUs shapes can also be tailored to the infrastructure need, such as for example slim and rectangular or long and tubular. This technology is seen as a "frontier" or temporary measure that could be quickly deployed before more permanent infrastructure is installed.. The following elements have been identified as applicable to the LUNAR BRIC architecture:

1.1.1. Sheltering and Shielding

A superadobe structure made of stacked RCUs can provide a physical protective layer to a wide variety of infrastructure elements. The lunar regolith contained within the RCU insulates and shields against radiation and micrometeorites, while the stackable form factor allows for the creation of vertical walls – desirable for compact surface structures. There are multiple infrastructure elements that would benefit from RCUs:

- Landing pad blast wall and/or skirting that would protect adjacent structures and mitigate ejected lunar regolith and debris.
- A garage, shed, or data center type building for any external hardware and lunar vehicles to be stored when not in use – possibly extending their operational lifetime.
- A protective layer around an inflatable infrastructure that can be employed as shielding and thermal insulation to survive the lunar night.
- A protective wall deployed next to the Fission Surface Power element, providing attenuation of the resulting neutron flux and reducing landed mass requirements of the delivered reactor.

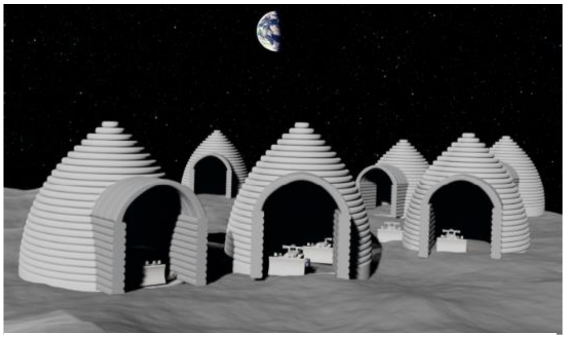
Figure 1: Superadobe concept on the moon (University of Arizona, 2024)

1.1.2. Paving

During the Apollo missions, lunar dust was found to be an insidious, highly abrasive and adherent material (Heiken, 1991) with detrimental long term health effects to astronauts (Pohlen, 2022). The best approach to mitigate the dust contamination on crewmembers during EVA would be to minimize direct contact to regolith and the mechanisms that generate dust plume creation, likely along vehicle tracks and walkways. RCUs can thus be deployed to create a surface for vehicles to operate without disturbing the underlying regolith.

1.1.3. Levelling and Foundations

Several construction concepts for the lunar surface could be deployed on top of a leveled foundation. Examples of this are the NASA AMES ARMADAS system (Gregg, 2024), which is another example of a modular, robotically deployed construction system.

1.1.4. Counterweights and Anchoring

As employed terrestrially, RCUs can provide a simple means to stabilise any wanted equipment or infrastructure. The reduced gravity environment (1/6th that of Earth) means that any mechanisms that rely on gravity for their operation or deployment could benefit from a simple, temporary anchor point. This includes the laying of cable or the use of guide wires for overhead infrastructure. Similarly, elements that terrestrially employ counterweights, such as cranes or elevators would benefit from ISRU-sourced ballast. Base weight for any fixed post could avoid unnecessary ground drilling.

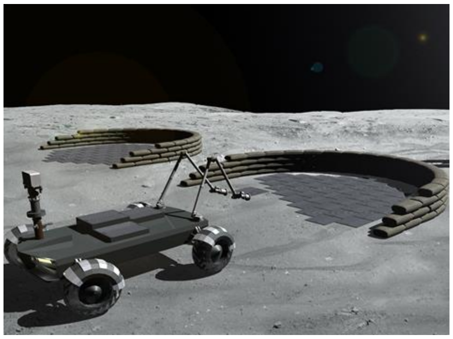

Figure 2: Rover with arms assembling RCUs (University of Arizona, 2024)

1.1.5. Robot Navigation and Astronaut Support

One concept for LUNAR BRICS employs electronics inside each RCUs to create a mesh network, facilitating communication across surface assets such as rovers, landers, and astronauts (Muniyasamy & Thangavelautham, 2024). Mesh networks provide increased redundancy and bandwidth, and the ability for localization of mobility platforms (e.g., rovers) and increased safety for astronaut EVAs (e.g., transmission of emergency beacon signals). RCUs can also be outfitted with simple technologies such as RFID tags or visible targets to provide local markers for guidance and navigation.

1.1.6. Environmental Monitoring

Similar to supporting communications infrastructure, RCUs outfitted with environmental sensors can provide a network of in situ measurements. This includes environmental properties such as radiation and temperature, as well as more transient properties such as seismographic measurements of lunar quakes and meteorite impacts. Environmental monitoring of multiple RCUs in a structure could provide valuable data. In the case of the superadobe a radiation heatmap of the building could be gathered to improve or detect off nominal situation easily.

1.2. How LUNAR BRICS meets Objectives for Moon to Mars

The LUNAR BRICS concept offers a low landed mass, easily constructable and versatile architecture for a wide range of Lunar surface applications for both government and commercial opportunities. LUNAR BRICS is also complementary to other ISRU architecture by having the possibility to use tailing as raw material. Overall this will meet several of the Moon-to-Mars objectives and Civil Space Shortfalls, making it a highly desirable technology to be explored for use in the Artemis architecture.

(a) LUNAR BRICS development will contribute to the achievement of M2M Objectives (NASA, 2023):

ESDMD #0601 Oxygen Extraction from Lunar Regolith	While not directed toward oxygen extraction, the LUNAR BRICS mission will demonstrate the use of a large quantity of preprocessed regolith ISRU.
ESDMD#0602 In-Situ Resource Identification, Characterization, and Mapping	LUNAR BRICS will analyse geotechnical properties of the lunar regolith and perform autonomous worksite mapping to determine area of interest for excavation and building location.
ESDMD #0605 Lunar Regolith Excavation, Manipulation, and Transportation	Probably the most valuable objectives as the LUNAR BRICS concept directly meet the those objectives by performing excavation, manipulation, and transportation of regolith for construction use.
ESDMD #0806 Payload Offloading, Handling, and Manipulation for Surface Assets	LUNAR BRICS will push the development of lunar robotic arm and tooling for the manipulation of payloads and allow them to gain flight-proven heritage.
ESDMD #1001 High-performance Actuators, Sensors, and Interfaces	LUNAR BRICS will push the development of robotic lunar arm and tooling and allow them to gain flight-proven heritage.

(b) LUNAR BRICS full architecture will achievement some of the M2M Objectives (NASA, 2023):

ESDMD #0301 Systems to Survive and Operate Through Extended Periods of Lunar Shadow	LUNAR BRICS will be used as a thermal battery and/or as thermal insulation for heated structures.
ESDMD #0805 Autonomous Surface Mobility and navigation	LUNAR BRICS smart RCUs will create a mesh network that will provide a navigation path and obstacle markers.
ESDMD #0306 Advanced Structures and Materials to Enable Mass-Efficient Habitats	Coupled with a pressurized element, LUNAR BRICS offers a low landed mass solution to protect habitats against radiation, micrometeorite impacts, and thermal fluctuations
ESDMD #0308 Radiation Countermeasures	LUNAR BRICS offers a cost effective solution for radiation mitigation and shielding for habitats and other critical infrastructure

(c) The LUNAR BRICS architecture offers several additional uses for government and commercial players for the achievement of some of their own M2M Objectives (NASA, 2023):

ESDMD #0901 Scalable Lunar Surface Power Generation Priority	LUNAR BRICS architecture could be used as a radiation protection element in reactors, thereby reducing landed mass

The architecture also can be traced to several other M2M items as well as Civilian Space Shortfall rankings, all of which can be found in Appendix A.

2. LUNAR BRICS Demonstration Mission Objectives

A complete production-level lunar construction system using RCUs would employ several high TRL elements that are already being developed for the Lunar surface (See Figure at right). These include: NASA's IPEX (Schuler, 2024) for excavation; NASA's LTV (NASA, Lunar Terrain Vehicle, 2025) or CSA's (LUV) (CSA, 2024) for transportation; and MDA SKYMAKER™ (MDA Space, 2025) for robotic manipulation. Currently, the development of an RCU manufacturing system, and manipulation of the RCUs, has the lowest TRL (TRL3) and is thus one of the elements being focused on for this demo mission.

The major advantage of RCU technology is that, while the regolith forms the largest mass component for construction, the properties of the bag material (e.g., coefficient of friction) determine much of the structural properties. Many of the properties of the RCUs can thus be tested terrestrially to reduce much of the risk ahead of deployment. What remains to be tested in lunar environment is how the filling of the RCUs can be accomplished, and that the RCUs can be manipulated efficiently (autonomously) for the purpose of construction.

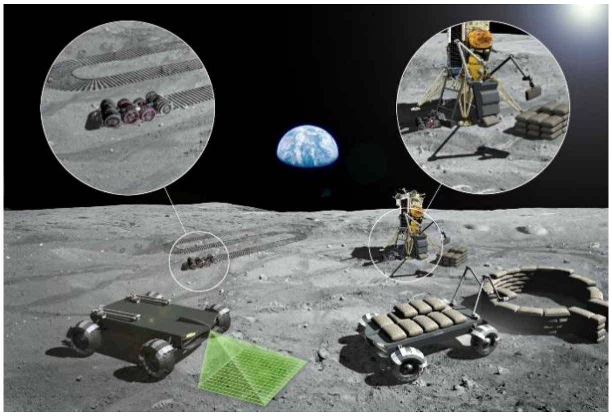

Figure 3: LUNAR BRICS render of a complete architecture (University of Arizona, 2024)

The initial step in achieving the deployment of a complete construction system such as LUNAR BRICS is thus a proposed demonstration mission (See Figure at left). The primary objectives of this would be:

1. Geotechnical preparation of the regolith for the purposes of construction – *Testing methods for the preparation of the supporting lunar regolith for RCU construction*
2. RCUs can be manufactured in situ on the lunar surface – *Can the regolith be efficiently integrated into an RCU under vacuum at 1/6th-g?*
3. RCUs can be robotically stacked – *Can the RCUs be manipulated and placed at 1/6th-g to enable a construction system?*
4. RCUs can be robotically unstacked – *Can RCU structures be decomposed to their constituent building blocks for reuse?*

The demo mission also has multiple secondary objectives including the following:

1. Geological and Geotechnical assessment of the regolith for the purposes of construction – *What can be gleaned about the properties of regolith from pre/peri/post robotic excavation?*
2. Environmental monitoring of the lunar surface / subsurface – *Can RCUs instrumented with sensors provide environmental monitoring?*
3. Robotic Autonomy Testbed – *Trialling different methods of autonomy for future RCU construction?*
4. Assessment of Constructed Structures – *Are the completed structures true to the original plan?*

3. Demonstration Mission Operational Factors

The LUNAR BRICS demonstration mission will land and operate on the lunar surface and thus must take all environmental factors and all LUNAR BRICS system interfaces into consideration. The following have been identified as key areas of focus which drive corresponding requirements for the system.

Environmental Factors

3.1. Lunar day/night

For landing location, the mission will avoid a PSR and aim for a continuously (south pole) or cyclic illumination, the mission concept is currently designed around this last one. Lunar day-night cycle last a full 29.53 earth day, meaning approximately 14 days of lunar night each cycle (Ahrens, 2020). While an absence of sunlight can easily be solved with floodlights, the more concerning issue comes from the power consumption required to keep the systems at operating temperature. With this in mind, the demo mission will begin at lunar sunrise and complete its objectives with margin before the end of the lunar day.

Key Interfaces

3.2. Lunar Regolith - Excavation

Loosely covering the surface of the moon, lunar regolith is made up of fine particles that are sharp and adhesive, infamously known to wear and damage mechanisms that get in contact with it. The robotic arm system will actively manipulate regolith to deliver regolith to the RCU production system.

3.3. Lunar Regolith – Construction Material

Also of note for the bagging process, loosely piled regolith has a relatively low bulk density of 30-40% (compared to the constituent material) however through mechanical compaction, values of 65-70% can be achieved (Colwell, 2007). This has two implications for LUNAR BRICS: Narrowing of regolith conveyances can cause the funnel mechanisms to become clogged and rendered unusable (Budzyn, 2023). Whereas regolith compaction within an RCU directly relates to structural properties and, as such, regolith within filled RCUs will be compacted to achieve improved structural performance and reduced settling post-construction.

3.4. Lander Integration

While the mission is relatively agnostic to lander selection, this mission concept is designed for the Intuitive Machine’s “NOVA-C” lander. This lander is 4.3m height and 1.6m diameter and is designed to carry a 130kg payload to the lunar surface (Intuitive-Machines, 2025). The lander geometry, specifically the placement of landing struts/pads, and payload deck, directly determine the MDA SKYMAKER™ robotic arm operational workspace.

4. System design

The present work seeks to investigate relative timings in order to better assess the operational feasibility of LUNAR BRICS, providing necessary inputs to a future complete LUNAR BRICS demonstration concept. For the purposes of this study, the architecture assumes a lander system that will provide power and communication to earth while in operation but will not directly participate in ISRU operations. Figure 4 illustrates a simplified view of the intended design of the demonstration mission that comprises a single robotic arm, a deployable bagging mechanism, and the filled RCUs.

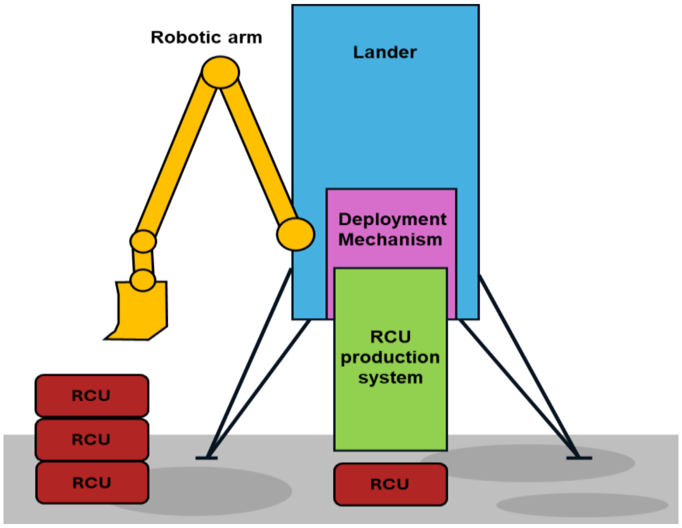

Figure 4: Graphical representation and identification of the

4.1. RCU Production System

Once deployed, the RCU production system will: (1) receive raw regolith from the robotic arm, (2) direct the regolith into an RCU, (3) seal the RCU and (4) deploy the completed RCU onto the lunar surface. The system will host 6-10 prefabricated RCU bags which will be filled in series. Each RCU will be monitored during filling to determine that the correct fill level is achieved and will be compacted via the use of a vibratory motor to maximize filled RCU density to achieve the required structural integrity. Deployment of the bag to the lunar surface by the RCU production system will be done in a manner to ensure robotic capture.

4.2. RCU

The current RCU concept is for dimensions of 0.4 m × 0.3 m × 0.2 m, yielding a mass of 30-35 kg (depending on achieved bulk density). Features for manipulation of the RCUs will be incorporated into the pre-fabricated units.

The RCU presents several challenges, most notably in the choice of bagging material and bag construction, as it shall:

- Sufficiently contain surface regolith with particle sizes down to 1 micron.
- Withstand the outward forces of not only its internal mass but support the mass of all RCUs stacked above it.
- Withstand the tension created when sealing the bag, as the tension is the primary factor in determining filled RCU structural properties (Bao, 2024).
- Withstand the effects of radiation and intense UV light present on the lunar surface for a minimum of 10 years.
- Withstand the effects of reasonable puncture from micrometeorites that can arise from 10 years of exposition.
- Outperform in launch mass reduction what would be the equivalent fully out-situ infrastructure solution: Meet a low bag mass requirement order to reduce cost of transiting empty RCUs to the lunar surface.
- Have an external coefficient of friction such that stacked RCUs will not slip once positioned.
- Have an internal coefficient of friction such that the unfilled RCUS can be opened for filling.

For this demonstration mission, Teflon impregnated Betacloth (on the inner surface), was selected.

A secondary objective of the LUNAR BRICS demonstration mission is to monitor the surface environment, and so RCUs could be outfitted with electronic sensors that transmit one or more of the following:

- Temperature
- Radiation
- Seismic events

4.3. Robotic Arm

The robotic arm performs two separate functions for the LUNAR BRICS demonstration mission: (1) excavation and collection of surface material (i.e., regolith) and (2) RCU placement. Furthermore, additional scientific measurements of the regolith sub-surface is considered to meet secondary objectives. The selected robotic arm is the lunar configuration of the MDA SKYMAKER™ commercial robotics, which is capable of excavation (using a removable scoop), and is able to position 70kg in a 1m workspace and 35kg in a 2.5 reach on the lunar surface. RCU placement will be achieved using a simple removable two-pronged tool, similar in design to a forklift, and that will interface with the filled RCUs along their long axis. **Error! Reference source not found.** illustrates the lunar configuration of the MDA SKYMAKER™ along with a test article design of an excavating bucket.

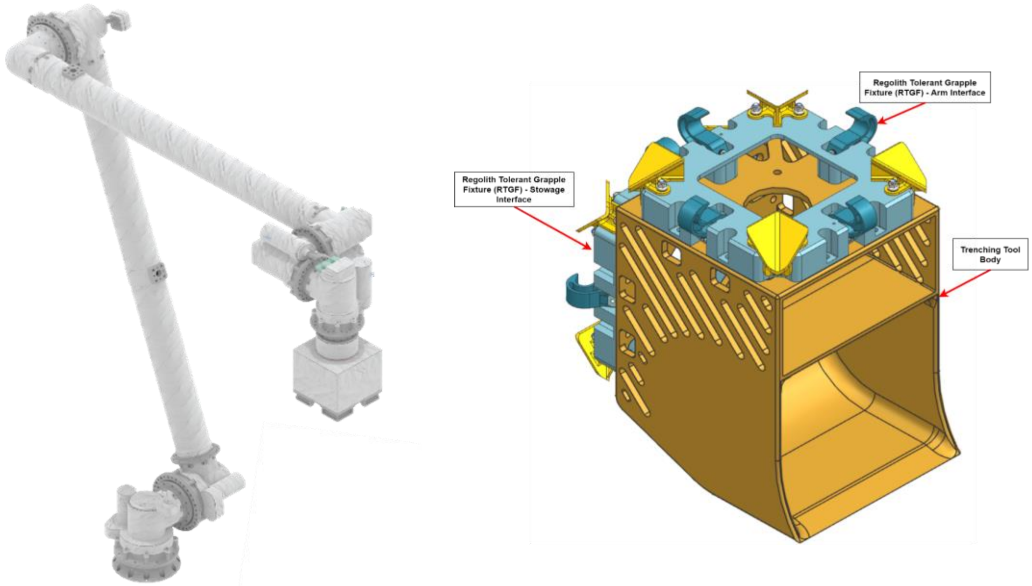

Figure 5: MDA SKYMAKER™ and excavating bucket tool

5. Mission Overview

5.1. System activity during transit and landing

During outbound cruise and landing, the LUNAR BRICS demonstration system will not perform any activities apart from periodic health monitoring.

5.2. Operations phases

The LUNAR BRICS demonstration mission has been decomposed into three phases labelled as: initialization, production, and analysis. The focus of the initialization focus is system deployment checkout of all hardware elements. This phase would also include a geotechnical assessment of the regolith workspace, which mimics terrestrial survey preconstruction. The production phase represents the core of the mission, where RCUs are filled (produced) and robotically positioned. The analysis phase will perform additional testing on the build structure and monitoring until end of mission. Details of each mission phase are provided below.

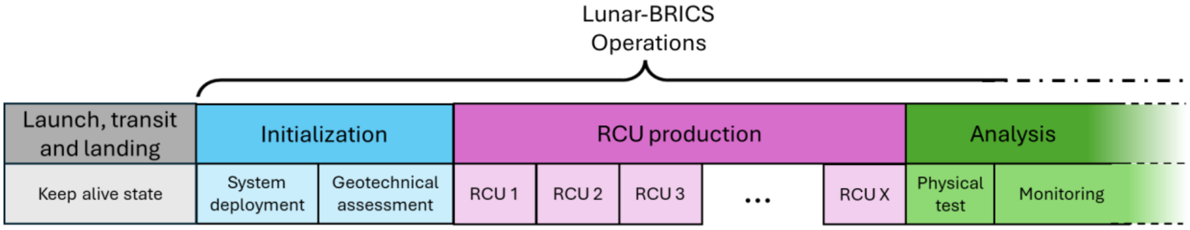

Figure 6: Mission phases

5.3. Initialisation Phase

The goals of the initialisation phase are (1) deploy all mechanisms; (2) perform functional checkouts of all mechanisms; (3) determine a baseline of operational telemetry.

5.3.1. System deployment

During system deployment, the robotic arm will go through a pre-heat and power-on sequence of each of its joints and associated controllers (Figure 7, panel 1). The arm will then be unstowed – releasing hold-down mechanisms and moving it from the launch position into the workspace (Figure 7, panel 2). A series of preplanned movements will then be performed - providing additional system checks at each of its joints. Deployment will continue with the RCU production system being lowered to the lunar surface (Figure 7, panel 3), with any one-time internal mechanisms (e.g., regolith hopper deployment) being activated. Internal system checks will be performed, and a complete visual inspection of the deployed systems will be undertaken through available camera views. At the end of this sub-phase, the system is ready to operate.

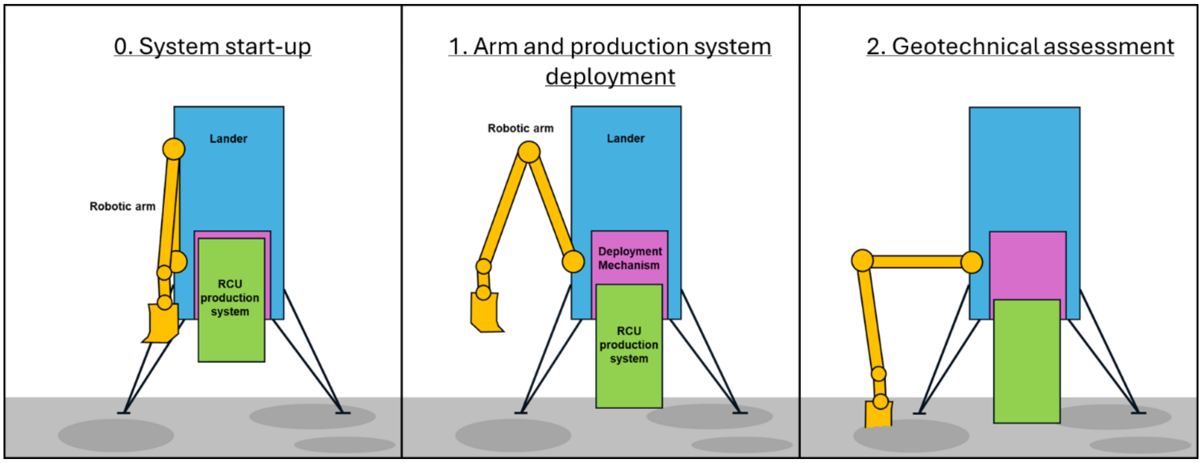

Figure 7: System deployment graphical steps

5.3.2. Geotechnical Assessment

Before commencing excavation, an assessment of the robotic workspace will be undertaken - identifying topological constraints of the terrain (Figure 8, panel 1). As an example, surface rock sizes will need to be identified, classifying obstacles into movable and unmovable categories. Following this, a measure of the surface bulk density would be made through use of a cone penetrometer, both preceding and following a regolith in situ compaction test (Figure 8, panel 2). This assessment will inform ground operators whowill create an optimal operations plan for the demonstration mission, including: excavation location(s); RCU construction location(s). At the end of this sub-phase, a complete operational worksite plan will be established (including risks and contingencies) and the first primary and first secondary objectives will be met.

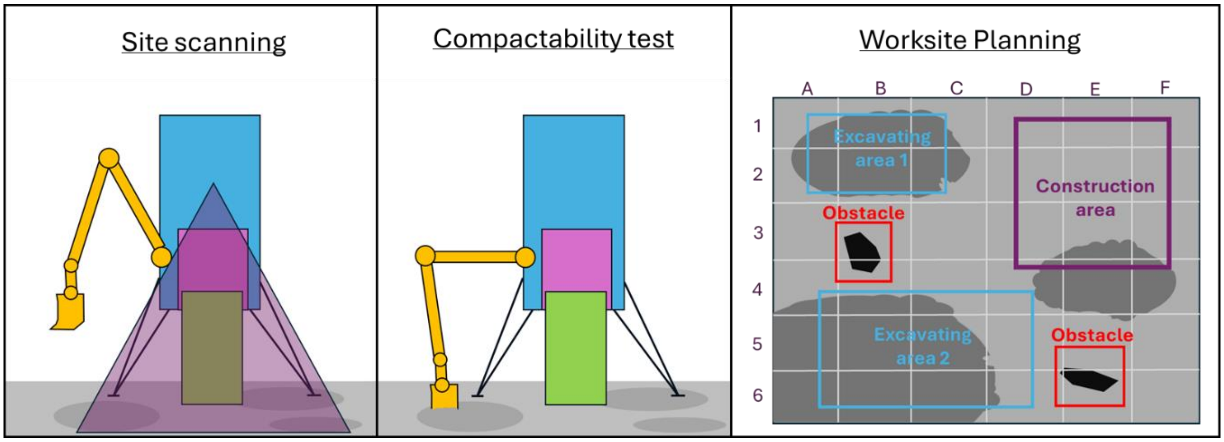

Figure 8: Geotechnical assessment graphical steps

5.4. RCU production

RCU production involves the full sequence of producing and placing an RCU into a stacked configuration - repeated until the deployment of all the RCUs has been conducted or the allocated time for this phase is exceeded (Figure 6). It is expected that the first RCU placements will be actively monitored and will involve potentially more operator responsibility. Placement of subsequent bags could then proceed in a semi- or fully-automatized way.

1. Prepare the RCU

The internal mechanism of the RCU production system will prepare each RCU by opening it and placing it under the regolith funnel in preparation for filling.

2. Excavating and Filling an RCU

If not already equipped, the arm will perform a tool changeout to equip the excavator bucket. The robotic arm will then excavate the predetermined location before emptying regolith from the excavator bucket into the hopper. The regolith is funnelled into the RCU where it is compacted with the induced vibration to maximize bulk density. The fill level of the RCU will be constantly monitored and will be coordinated with the robotic arm to ensure that the collection of regolith will cease once the predetermined volume / mass is achieved.

3. Sealing and Dispensing the RCU

The RCU will then be sealed, producing a semi-rigidized RCU. The bag will then be released and ejected down onto the lunar surface.

4. Robotic Positioning of the RCU

To use the appropriate bag manipulator end effector, the arm will perform a tool changeout. The robotic arm will then pick up the dispensed bag RCU, and position it in the desired location for construction. The RCUs will be notionally layered in a simple 3:2:1 configuration (from bottom to top), as a baseline construction demonstration. At the end of this sub-phase, the system will have met the second and third primary objective.

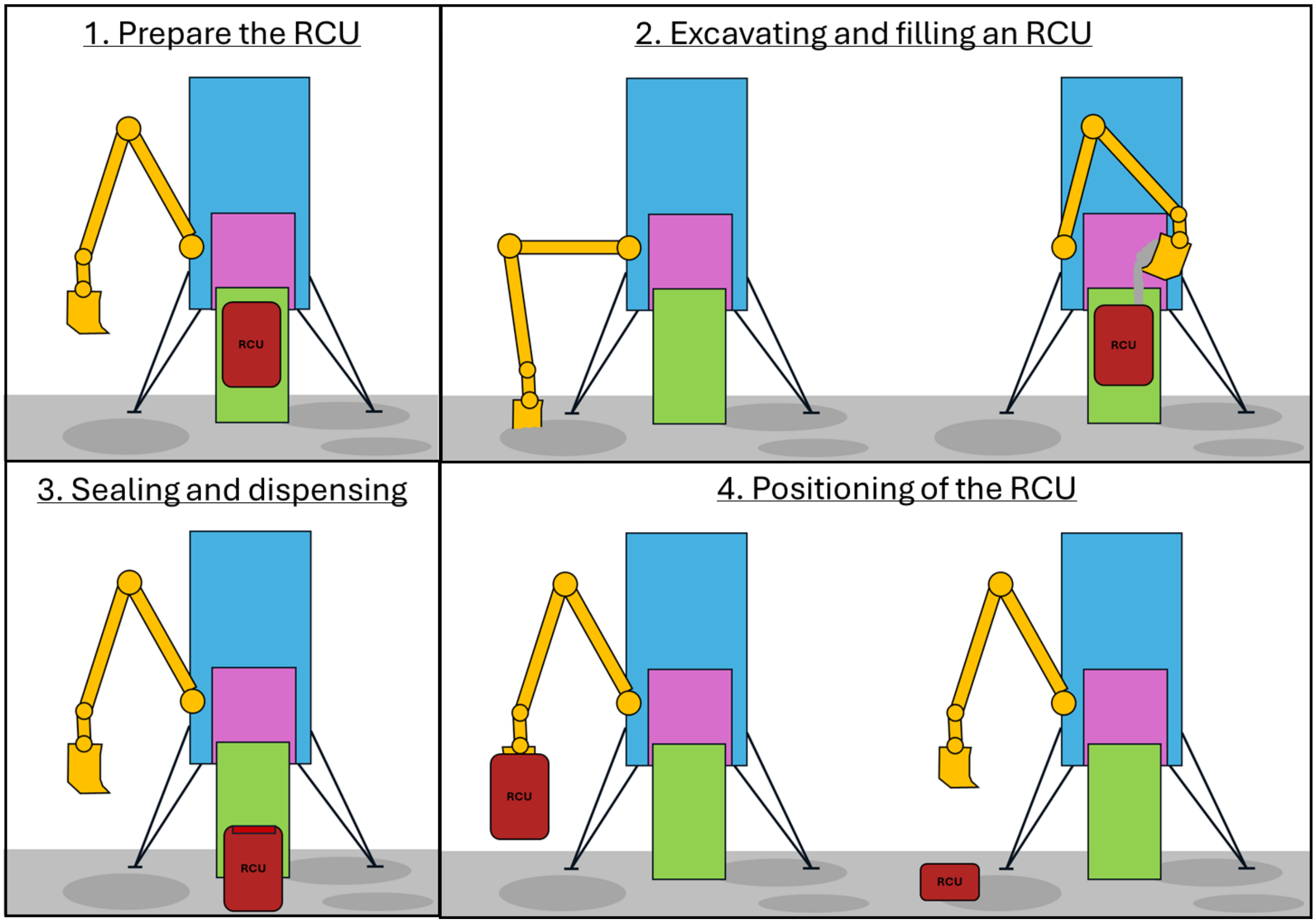

Figure 9: RCU production graphical steps

5.5. Analysis

The focus of this mission phase will be to demonstrate reutilisation of the RCUs by deconstruction and reconstruction of the stacked structure and to trial out a variety of autonomous algorithms for future consideration. This phase will also focus on environmental monitoring of RCU containing sensors while in different construction / deconstruction configurations.

5.5.1. Physical Tests

5.5.1.1. De-Construction and a Robotic Autonomy Testbed

The reuse of construction materials allows for RCUs to be deployed multiple times, as the needs of the Artemis base evolve. As such, the structures completed in the Production Phase will be deconstructed to demonstrate this. This has the advantage that the RCUs no longer require filling time. This activity dovetails with using the robotic workspace as a testbed for autonomy, to explore a wide variety of teleoperation, semi-autonomous and fully autonomous methods for construction (and deconstruction). This activity will fulfil primary objective four and secondary objective three.

5.5.1.2. Construction structural test

The structural integrity of a wall consisting of RCUs will be assessed and verified. This will be performed using optical means (e.g., stereoscopic cameras) to determine if the RCUs shift during assembly. Owing to the collective mass of the RCU structure, and the forces generated by the robotic arm, it is not possible to mechanically test the resulting structure. Multiple tests could provide valuable information, such as voluntarily perforate bags to see the low of stability of the wall and flow out of regolith. This will meet secondary objective four.

5.5.2. Monitoring

5.5.2.1. Environmental Monitoring

Monitoring of prolonged exposition of the RCUs will provide valuable data for radiation shielding, thermal monitoring, and (potentially) overall bag integrity. The monitoring should be realized for as long as possible to determine the life expectancy of the structure, and could also be used throughout the different construction operations.

6. Operational Timing

In order to assess the operational feasibility of the above concept of operations, timing was applied to each of the steps outlined above, in order to understand projected operations as a function of local (lunar) time of day.

Table 1:LUNAR-BRICS operational timing

			Start (h)	Duration (h)	End (h)	Lunar day
1. Initialization activities	**System deployment**		T=0	14.25	14.25	4%
	Geotechnical assessment		14.25	4.00	18.25	5%
2. Production	**RCU 1**	**1. Prepare the RCU**	18.25	0.08	18.33	5%
		2. Excavating and filling the RCU	18.33	5.20	23.53	7%
		2. Seal and dispensing the RCU	23.53	0.35	23.88	7%
		4. Positioning the RCU	23.88	1.50	25.38	7%
	RCU 2	**1. Prepare the RCU**	25.38	0.08	25.47	7%
		2. Excavating and filling the RCU	25.47	4.27	29.73	8%
		2. Seal and dispensing the RCU	29.73	0.28	30.02	8%
		4. Positioning the RCU	30.02	1.50	31.52	9%
	RCU 3		31.52	6.13	37.65	11%
	RCU 4		37.65	6.13	43.78	12%
	RCU 5		43.78	6.13	49.92	14%
	RCU 6		49.92	6.13	56.05	16%
	RCU 7		56.05	6.13	62.18	18%
	RCU 8		62.18	6.13	68.32	19%
	RCU 9		68.32	6.13	74.45	21%
	RCU 10		74.45	6.13	80.58	23%
3. Analysis	**Deconstruction and autonomy 1**		80.58	12.26	92.84	26%
	Deconstruction and autonomy 2		92.84	12.26	105.10	30%
	Deconstruction and autonomy 3		105.10	12.26	117.36	33%
	Wall structural test		117.36	1.00	118.36	33%
	Prolonged exposition monitoring		25.38	…	…	…

Timing was based on estimated MDA SKYMAKER™ performance for excavation and RCU placement. During the excavation and filling of the RCU, the robotic arm operation will be continuously excavating while the RCU production system will in parallel vibrate and allow the regolith to free flow in the RCU. Therefore, these two synchronous steps will make the full operation faster. In this estimation, RCU-1 steps are expected to be actively supervised by ground operators making them longer. The following bag production will be automated and will have a shorter time duration. Monitoring is considered to start at the time of RCU-1 completion (as their electronic sensor payload would be activated at that time).

7. Conclusions

The purpose of this paper was to establish a concept of operations along with an operations timeline to meet the objectives of a demonstration mission of the LUNAR BRICS concept, enabling future studies and concepts. This assessment shows that the main demonstration objectives of regolith manipulation and RCU production, manipulation and reuse could be completed within an estimated 33% of the lunar day, leaving an abundance of margin. Next steps include incorporation of additional scientific and geotechnical measurements, as well as incorporating higher fidelity estimates of operations

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Appendix

A. How does LUNAR BRICS tie into Artemis Architecture - Mapping LUNAR BRICS to M2M and Civilian Shortfall Rankings

NASA's Moon to Mars architecture outlines the Recurring Tennent, Objectives, Use Cases, and Functions required for the next 3 phases of lunar exploration. The LUNAR BRICS Architecture and demonstration mission ties into several of these as summarized below:

1. *Objectives, Recuring Tenants and Use Cases*

- Demonstrate industrial scale ISRU capabilities [LI-7]
- Demonstrate technologies supporting cislunar construction and manufacturing maximizing the use of in-situ resources [LI-9]
- Develop system(s) to allow crew to live on the lunar surface with scalability to continuous presence [TH-3]
- Develop in-space and surface habitation system [TH-4]
- 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-11]
- Maximize the resources available to future explorers [OP12]
- Maximizing crew time available for science and engineering activities [RT-4]
- Demonstrate advanced manufacturing and autonomous construction capabilities [LI-4]
- *UC-143-L: Demonstrate autonomous construction techniques, e.g., collection of regolith, processing regolith into feedstock, and regolith construction.*
- *UC-145-L: Demonstrate regolith-based additive/subtractive manufacturing techniques.*
- Provide precision landing for crew transport to the lunar surface [FN-T-401/2 L] (Landing Pads)
- Optimize operations between the team on Earth, crew members on orbit, and a Martian surface team [OP-2]
- Demonstrate the capability of integrated robotic systems to support and maximize the useful work performed by crewmembers [OP-9]
- Demonstrate the capability to operate robotic systems that are used to support crew members on the lunar or Martian surface, autonomously or remotely from the Earth [OP-10]
- Characterize the interaction of exploration systems and the deep space environment as it affect human health [HBS-3]
- Develop environmental monitoring [LI-10]
- Develop systems that monitor and maintain crew health and performance [TH-8]
- Providing highly Maintainable and Reusable systems [RT-5]
- *UC-142-L: Deploy and set up autonomous construction demonstration utilization payload(s) on the lunar surface with long-term remote operation.*

Source: NASA M2M ADD Rev B (NASA, 2023)

2. *Civilian Space Shortfalls*

- Survive and operate through the lunar night (Rank #1)
- Position, Navigation, and Timing (PNT) for InOrbit and Surface Applications (Rank #4)
- Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation (Rank #5)
- Environmental Monitoring for Habitation (Rank #7)
- Radiation Countermeasures (Crew and Habitat) (Rank #15)
- Radiation Monitoring and Modeling (Crew and Habitat) (Rank #16)
- High-Rate Communications Across The Lunar Surface (Rank #19)
- Power and Data Transfer in Dusty Environments (Rank #34)
- Extraction and separation of water from extraterrestrial surface material (Rank #53)
- Active Dust Mitigation Technologies for Diverse Applications (Rank #56)
- Space Situational Awareness (Rank #62)
- Extraction and separation of oxygen from extraterrestrial minerals (Rank #68)
- Micrometeoroid-Robust Protection of In-space Observatories (Rank #81)
- In-Space and On-Surface Manufacturing of Parts/Products from Surface and Terrestrial Feedstocks (Rank #92)

- Robotic regolith manipulation and site preparation (Rank #102)
- Modular design for in-space installation (Rank #109)
- Extraction and separation of metals/metalloids from extraterrestrial minerals (Rank #110)
- Regolith and resource delivery system (Rank #118)
- Remediation of Small Debris (Rank #123)
- Intelligent Robots for the Servicing, Assembly, and Outfitting of In-Space Assets and Industrial-Scale Surface Infrastructure (Rank #133)
- On-surface Outfitting of Lunar Structures (Rank #138)
- Distributed Avionics to Enable Improved Performance and SWaP Efficiency (Rank #140)
- Produce manufacturing and construction feedstock from extracted in-situ resources (Rank #142)
- On-Surface In-situ Construction of Vertical Structures (Ran #145)
- On-surface robotic assembly of vertical structures (Rank #148)
- Robotic Assembly and Construction of Modular Systems for Sustained In-Space Infrastructure (Rank #153)
- On-surface robotic assembly of horizontal structures (Rank #159)
- On-Surface In-situ Construction of Horizontal Structures (Rank #160)
- Autonomous Robotics for Sustained In-Space Manufacturing Operations (Rank #166)
- Extraction and separation of non-water volatile resources from Lunar regolith (Rank #169)
- Novel thermal technologies to improve environmental control of habitats (Rank #175)

Source: Civil Space Shortfall ranking (NASA, 2024)