Protecting Crew and Surface Systems with a Long-Duration Lunar Safe Haven

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STMD Game Changing Developments (GCD) Program

Lunar Safe Haven (LSH) Seedling Study Overview

Objective: Ensuring astronauts and their equipment are safe on the lunar surface

Deliverables:

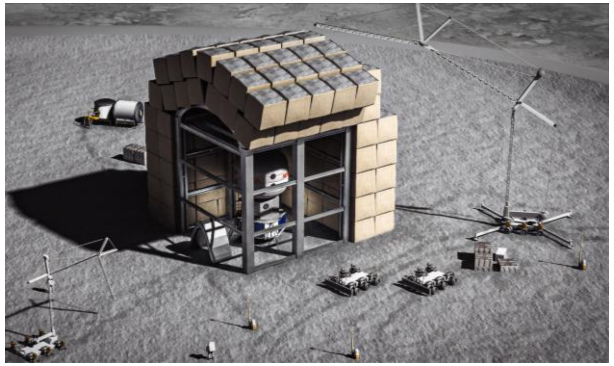
1. Level Zero lunar construction requirements for a safe haven shelter
2. Trade Study of several concepts and identify current mission assets that could be used or leveraged

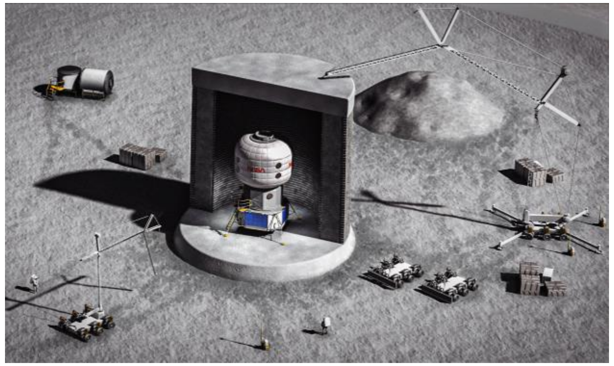
Outcomes:

1. The Lunar Safe Haven (LSH) Seedling Study has identified and evaluated high-value concepts that can be achieved in either the near-term (higher-TRLs) or long-term (lower-TRLs)
2. NASA and others can use the final recommended LSH concept and the decision analysis framework to:
   a) Provide a path to future technology investments, and promote synergy with existing and proposed programs
   b) Compare future concepts
3. Recommendations by the LSH Seedling Study are based on contributions from a multi-center team (LaRC, MSFC, and KSC)
4. Data has been collected from other NASA projects, OGA's, industry, and academia on concept options and state of technology maturity

Background

- **In order to enable sustainable presence (~10 years) on the Moon, we must provide better protection for crew and surface systems from radiation, thermal extremes, and micrometeoroids (MM)**
- **The Lunar Safe Haven is a game changing concept including a protective shelter, site preparation/construction/ assembly systems, and maintenance systems**
  - With recent technology advancements, it is now **reasonably achievable** using in situ resource utilization (ISRU) and autonomous robotics
  - **Protection for crew with access** is possible to a level that mission architectures have been unable to provide to date
  - **Protection for surface systems** extends their lifetime, provides an area for servicing/maintenance, and potentially reduces rad-hardening and thermal control requirements
  - The LSH concept is **scalable and evolvable**, able to respond to various mission scenarios
- **The Lunar Safe Haven Study is leveraging the substantial work of the Artemis program, such as the progress in habitat and rover development**





Images Source: NASA/LaRC

Requirements, Assumptions, and Common Features

- **Level Zero Requirements were developed by the LSH team to be synergistic with the NASA Artemis Plan and guide the trade study from a high level, including principles such as:**
  - Protection is needed for crew and surface systems from radiation, micrometeoroid strikes, and the thermal environment on the lunar surface
  - Construction/assembly of a shelter needs to leverage as much as possible existing or high-TRL systems to support the activity in the late 2020s/early 2030s
- **Based on the Level Zero Requirements, the team developed more in-depth Ground Rules & Assumptions (GR&A)**
  - GR&A assumed limited systems/infrastructure would be already present at Artemis Base Camp (ABC) for use in LSH operations
- **Next, several parameters were described for the baseline design that were constant across all concept alternatives:**
  - **Site Preparation:** Small rovers should be used for soil analysis, resource assessment, and site mapping
  - **Power:** LSH systems must drive to and connect to the Artemis Base Camp (ABC) surface power source, such as via wireless charging

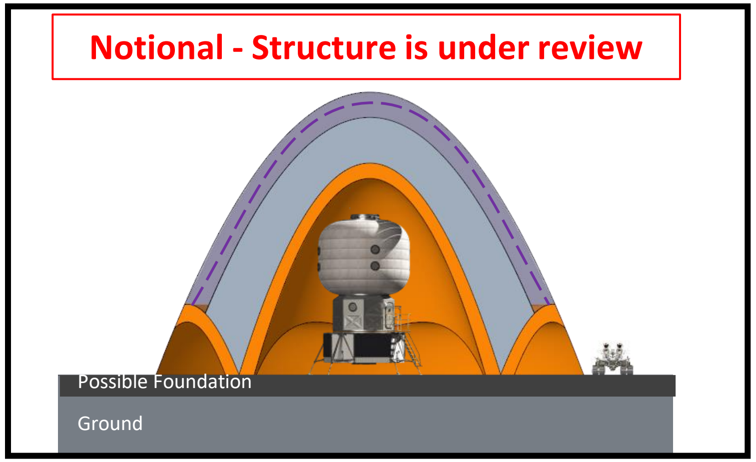
Overview of Modeling and Takeaways

- **The Lunar Safe Haven study included initial environmental effects modeling as well as substantial input from SMEs to develop ground rules and requirements for protection of crew and surface systems**
- **While specific Artemis requirements for radiation dosage have not been defined, substantial NASA experience in space environmental effects and crew health can guide recommendations for radiation protection**
  - **Galactic Cosmic Rays (GCR)** are a constant background source of radiation that impact long-term crew health
    - **Threshold**: Moderately low level of effective dose, <0.25 mSv/day (equivalent to 3 m regolith covering)
    - **Goal**: Earth-equivalent effective dose, <0.015 mSv/day (equivalent to 7 m regolith covering)
  - **Solar Particle Events (SPEs)** can cause acute radiation sickness and must be protected against
    - **Threshold**: (Dose is 150 – 250 mGy-Eq AND shelter requires no setup) **OR** (Dose is 50 – 150 mGy-Eq AND shelter requires 1-30 minutes setup)
    - **Goal**: Dose is less than 50 mGy-Eq during SPEs AND shelter requires no set-up time
- **Micrometeoroid impacts at the lunar south pole will mostly be fine-grained particles (mass 10^{-6} to 10^{-4} g), resulting in regolith on the order of 100 cm^3 lost from the LSH shelter protective shield over 10 years**
  - Further analysis is needed to account for meteor showers
- **From an initial look at the thermal environment, the LSH will protect assets from thermal swings, but the habitat will be essentially put in a man-made permanently shadowed region, which stays cold through the lunar day and night cycle**
  - Extra power may be required to keep systems warm enough to function

Concept Generation Overview

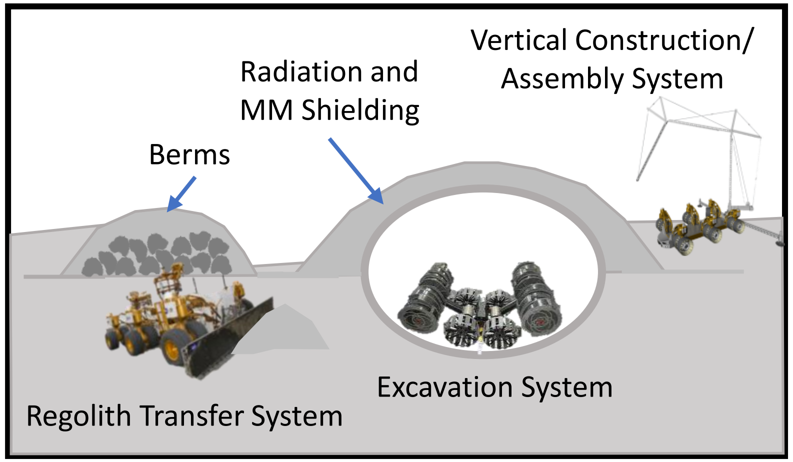
- **Concept Generation was the next step after outlining the scope via the LSH's GR&A and common features**
- **Each LSH concept includes 3 system groups:**
  – Physical shelter design
  – Establishment Systems (Site Preparation/Excavation + Construction/Assembly/Deployment)
  – Maintenance Systems
- **A single "Baseline" concept was established to which other alternatives could be compared and the impact of changes could be evaluated**
  – The Baseline does NOT necessarily represent our preferred option, but it does represent a reasonable solution

Physical Shelter Design (Baseline)



Images Source: NASA

Establishment Systems (Baseline)



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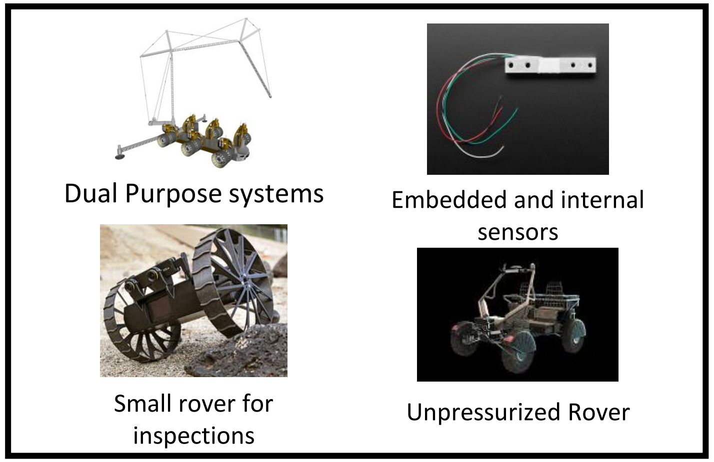
Maintenance Systems (Baseline)



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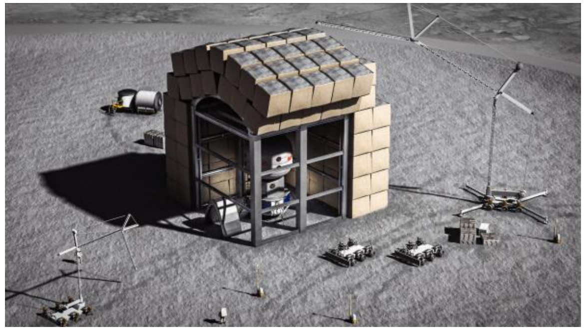
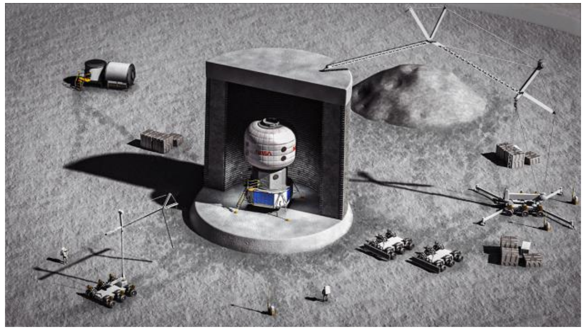
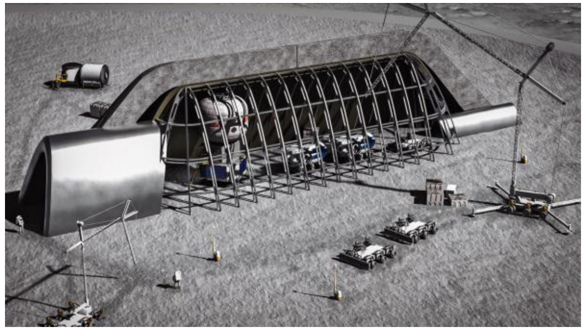
Concept Generation Results (1/2)

- **15 different concepts were defined by the team**
  - Many alternatives were identified during brainstorming, but the team prioritized evaluation of 15 that were representative and also considered reasonably achievable within the 2020s or 2030s
  - Each concept after the Baseline (Concept 1.1) is a slight variation, where only one main design characteristic has been changed
- **Concepts 1.1-2.4 – Change Shelter Structure and Construction Method**
  - Baseline: bulk regolith, and inner metallic structure delivered from Earth
  - Alternatives: regolith sandbags, whipple shield, inner metal structure scavenged from landers, inflatable beams, 3D printed regolith cement walls, sintered regolith walls
- **Concepts 3.1-3.2 – Change Establishment Systems**
  - Baseline: Combination of LSMS, RASSOR, Chariot, LANCE, Compactor, Inspection Rover, and Rover with Robotic Arm
  - Alternatives: LTV copies, loader and dump truck combination

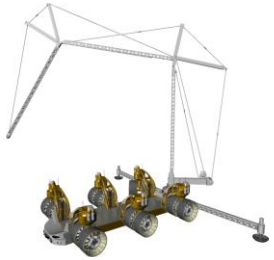


Images Source: NASA/LaRC

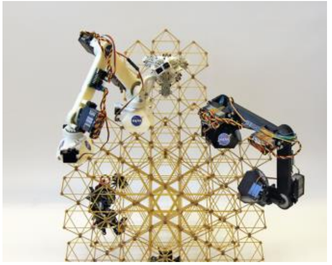
Concept Generation Results (2/2)

- **Concept 4.1 – Change Crew Involvement for LSH Sustained Operations**
  - Baseline: robotics and/or sensors perform inspection and diagnostics
  - Alternative: crew performs manual inspections during crewed surface missions
- **Concepts 4.2-4.3 – Change Degree of Autonomy**
  - Baseline: Semi-autonomous with crew supervision
  - Alternatives: fully autonomous, human operated/lower level of autonomy
- **Concepts 5.1-5.2 – Change Shelter Size and Dimensions**
  - Baseline: Single shelter just big enough for the Foundation Surface Habitat (FSH)
  - Alternatives: single shelter with space for the FSH ***plus*** other vehicles/equipment, multiple shelters of various sizes



LSMS on Chariot chassis to move rocks and lift trusses into place

Image source: NASA



Mobile robots to assemble trusses (e.g., ARMADAS)

Image source: NASA

RASSOR, LANCE, and LSMS work together to pile regolith on top of shelter and form berms

Images source: NASA

Compactor on Chariot for rough compaction and grading

Small rover (e.g., A-PUFFER) for surveying, inspection, and V&V

Images source: NASA

Concept Evaluation using Decision Analysis Method

Purpose: Characterize the Lunar Safe Haven trade space by quantifying the benefits, costs, and risks for each concept alternative, which together represents value to stakeholders

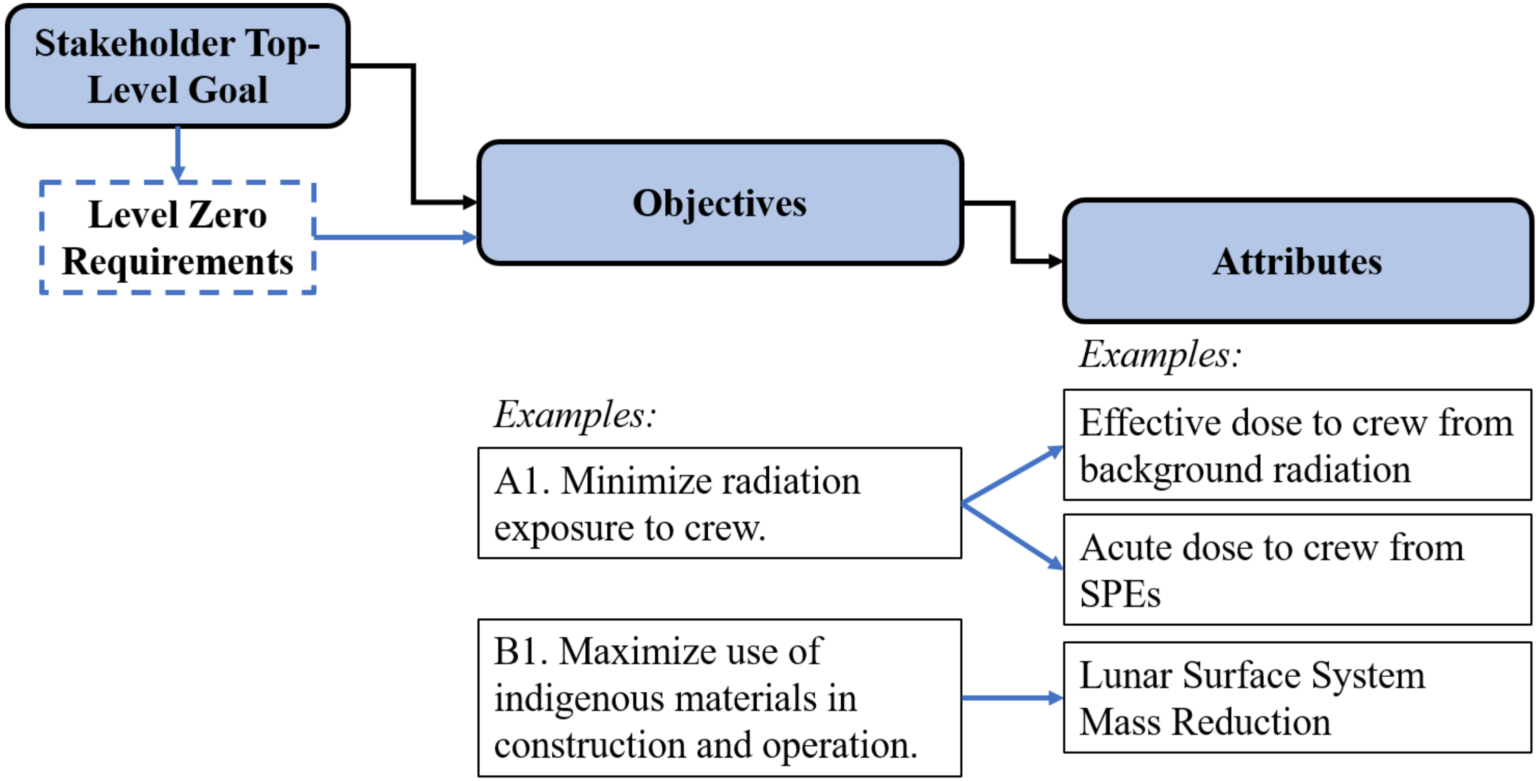
Method:

<u>A) Identification of Objectives:</u>

Definition: Define what you hope to achieve to meet the goal

<u>B) Attribute Selection:</u>

Definition: Measure that enables trade-offs between achieving relatively more or less on a given objective



LSH Objectives

Environmental

A1. Minimize radiation exposure to crew.

A2. Maximize energy absorption capability of the shelter from impacts for crew and other exploration systems, including impacts from micrometeoroids, the movements of external assets (e.g., mobility systems), and any resulting ejecta.

A3. Minimize accumulation of dust (fine and coarse) on LSH establishment and maintenance systems.

Operational

B1. Maximize use of indigenous materials in construction and maintenance.

B2. Minimize need for crew involvement during establishment and maintenance of the LSH.

B3. Maximize evolvability of the LSH establishment and maintenance concept.

B4. Balance resiliency and robustness of LSH concept as a whole.

B5. Maximizes available storage for exploration systems, science equipment, consumables, and contingency spares.

Programmatic

C1. Minimize investment costs.

C2. Maximize Mars extensibility.

LSH Decision Attributes

Category	LSH Attributes
Environmental	Effective dose to crew from background
	Acute dose to crew during SPEs
	Micrometeoroid (MM) Impact Protection Probability
	Sensitivity of Damage Detection Systems
	Protection against impact from external assets
	Architectural Dust Mitigation
Operational	Lunar Surface System Mass Reduction
	Maintenance Need from Crew
	Training Need for Crew
	Degree of Autonomy
	Crew Situational Awareness

Category	LSH Attributes cont'd
Operational (cont'd)	Evolvability Composite Score
	Fault/Degradation Identification
	Resiliency
	Complexity
	Long Term Utility
	Space Management
Programmatic	Total Lunar Safe Haven Architecture Investment
	Technology Maturation Investment
	Regolith as a Shielding Material
	Autonomous Emplacement
	Scalability for Mars

LSH Decision Attributes Results

- **Sub-teams approached different sets of concepts, defined additional details, and evaluated the decision attributes**
- **Each attribute was evaluated on a scale from -2 to +2**
  - Most attributes were defined where the Baseline Concept's score = 0, and the other concepts are evaluated in comparison to the baseline (i.e., better = +2, worse = -2)
  - *Note*: "Evolvability" was defined with 3 scenarios, where each scenario scored from -2 to +2, resulting in max score of +6
- **The "Ideal" column shows the maximum possible scores for each attribute, for reference**
  - A perfectly "ideal" concept may not be possible, but the maximum scores are a generally good indicator of where concepts might be able to be improved in future studies
- **Steering Team's priorities for attributes were used to develop swing weights to get a weighted sum of scores**
  - Weighted sums of the scores and the raw scores are guiding the down-select of the concepts *(Still in progress)*

Sample Table

	Concept Alternative #: Descriptive Concept Name:	Swing Weight	1.1A Baseline	2.1 Scavenged from Landers	2.2 Inflatable Beams	"Ideal"
Category	**Attribute**	**Value**	**Value**	**Value**	**Value**	**Value**
A.	Effective dose to crew from background	0.08	2	2	0	2
B.	Lunar Surface System Mass Reduction	0.09	0	1	-1	2
C.	Total Lunar Safe Haven Architecture Investment	0.10	0	2	0	2
	Un-Weighted Sum:		**10**	**8**	**1**	**36**
	Weighted Sum:		**0.37**	**0.33**	**-0.27**	**1.638**

SAMPLE: Concepts 2.1-2.4 – Change Shelter Structure Material

Impact on Decision Attributes

Category	Concept Alternative #: / Descriptive Concept Name:	Swing Weight	1.1A Baseline	2.1 Scavenged from Landers	2.2 Inflatable Beams	2.3 3D Printed Cement Structure	2.4 Sintered Regolith Structure	"Ideal"
Category	Attribute	Value	Value	Value	Value	Value	Value	Value
A. Environmental	Effective dose to crew from background	0.08	2	2	0	0	0	2
	Acute dose to crew during SPEs	0.00	2	2	2	2	2	2
	Micrometeoroid (MM) Impact Protection Probability	0.00	2	2	2	2	2	2
	Sensitivity of Damage Detection Systems	0.00	-1	-1	-1	-1	-1	2
	Protection against impact from external assets	0.00	1	1	1	1	1	2
	Architectural Dust Mitigation	0.00	-1	-1	-1	-1	-1	2
B. Operational	Lunar Surface System Mass Reduction	0.10	0	1	-1	-2	0	2
	Training Need	0.04	0	-2	-1	0	0	2
	Evolvability Composite Score	0.06	0	2	-3	-3	6	<u>6</u>
	Complexity	0.06	1	-2	0	-1	-1	2
	Long Term Utility	0.04	1	1	1	1	2	2
	Space Management	0.03	0	0	0	0	0	2
C. Programmatic	Total Lunar Safe Haven Architecture Investment	0.10	0	2	0	-2	2	2
	Technology Maturation Investment	0.10	0	-2	-1	-1	-1	2
	Regolith as a Shielding Material	0.03	2	2	2	1	1	2
	Autonomous Emplacement	0.05	1	1	1	1	1	2
	<u>Un-Weighted Sum:</u>		**10**	**8**	**1**	**-3**	**13**	**36**
	<u>Weighted Sum:</u>		**0.37**	**0.33**	**-0.27**	**-0.63**	**0.57**	**1.638**

The Concept 1.1A/Baseline will be discussed further on the next slide.

The attributes allowed the team to:

- ***Both think through and quantify*** **the benefits, costs, and risks that together represent value to stakeholders**
- **Understand concepts have both pros and cons**
- **Get an overall score (sum) to compare concepts**

LSH Recommendation

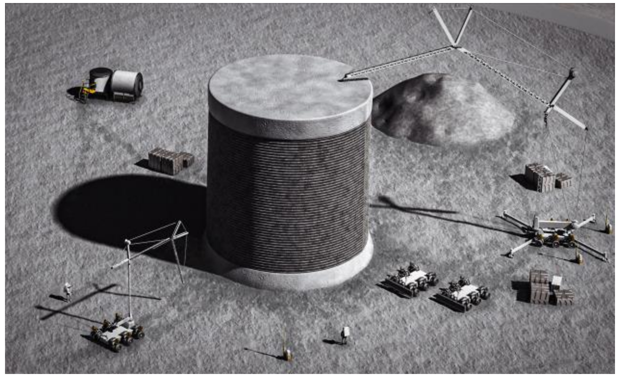
- **Most LSH concepts reflected significant value for NASA stakeholders, but a concept needed to be down-selected that leverages the <u>most existing or high-TRL systems</u> to support lunar operations in the late 2020s/early 2030s**
- **The LSH Seedling Study recommends the Baseline Concept (1.1A) since it is high-value and high-TRL**
  - Metallic or composite structure delivered from Earth, assembled on lunar surface
  - Simple structure is covered in bulk regolith *(example geometry shown in images, not final structural design!)*
  - Low- to Mid-level of autonomy
  - Existing construction & maintenance systems, incl. LSMS, RASSOR, Chariot, LANCE, and A-PUFFER
- **Two other of the top-scoring concepts are recommended as evolvability pathways**

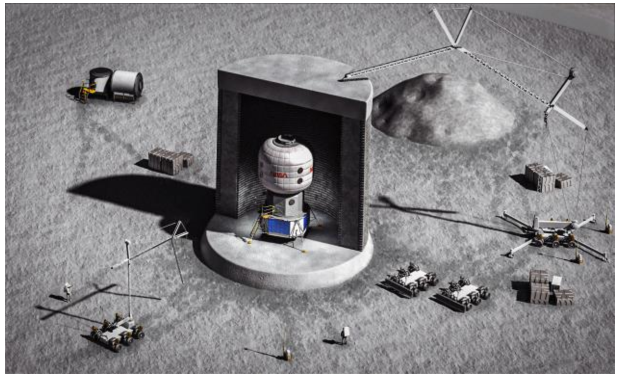
Images Source: NASA/LaRC

Evolvability of the LSH is Recommended Across Two Pathways

Construction Pathway: Sintered Regolith Structure

- LSH Concept 2.4
- Sintering represents a high-value concept that maximizes use of ISRU, reduces the mass delivered from Earth, and is evolvable to many mission scenarios
- Sintering is currently low-TRL, so continued technology investment and demonstrations are needed
- Remaining challenges also includes power availability





Images Source: NASA/LaRC

Autonomy Pathway: Advanced Levels of Autonomy

- LSH Concept 4.2
- LSH results showed that concepts with increasingly higher levels of autonomy have very high value (amongst top-scoring concepts)
- Advance capability over time through technology investment, demonstrations, and validation on the surface
- Autonomy is required for crewed Mars missions and should be validated on the lunar surface

Lunar Safe Haven Study Takeaways

1. **Lunar Safe Haven offers a remedy for crew health hazards including GCR and SPE radiation effects that mission architectures have been unable to provide to date (ref: AIAA-2018-5360)**
2. **We have evaluated both near-term and far-term concepts from an architecture level using rigorous systems analysis and mission planning using NASA's Artemis plan as the framework**
   – The LSH Study's selected reference concept and decision framework are tools that NASA and others can use to assess/compare future ideas
3. **We have examined cross-cutting capabilities in excavation, construction, ISRU, and autonomy**
   – Architecture was designed to utilize ISRU to varying degrees
4. **Lunar surface excavation, construction, and ISRU capabilities and current and planned equipment concepts suggest that implementing the GCR shielding necessary for long crew stays on the Moon and Mars is <u>reasonably achievable</u>**
   – We evaluated the TRLs and capability levels required for the construction concepts proposed
   – We identified recommendations and requirements for future concepts and mission planning, for example: 3–7 m of regolith thickness is recommended for radiation protection, which will require approx. 3–3.5 t of construction equipment delivered to surface (not including excavation/ISRU equipment nor added structural mass)
5. **The multi-center collaboration during the Study resulted in skills development and a build-up of interest/excitement in lunar construction**