

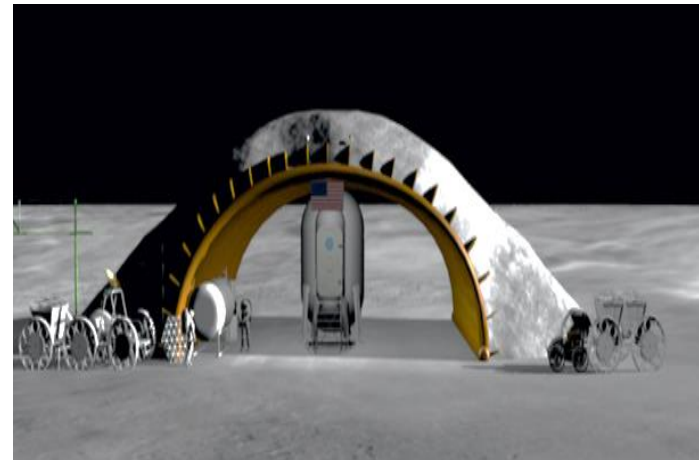
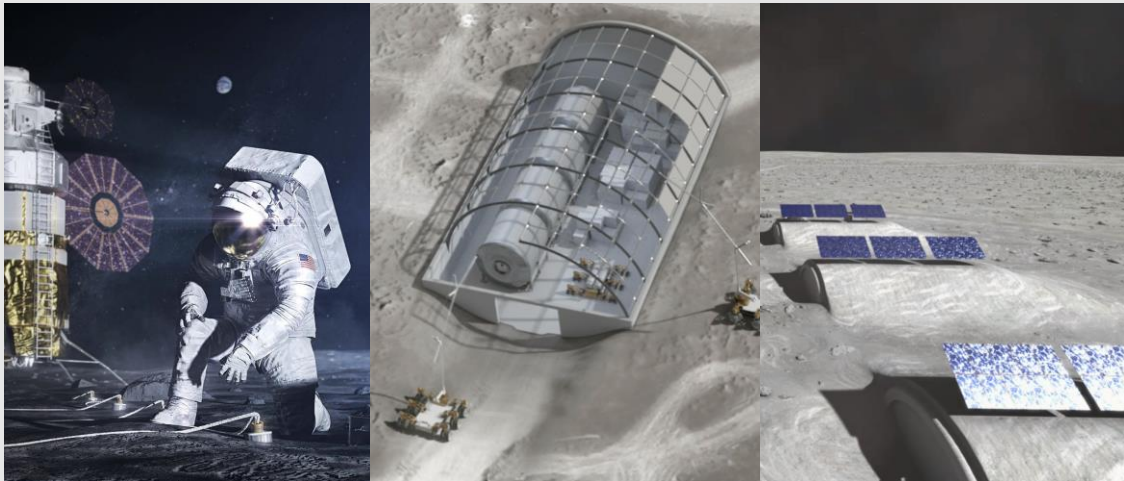


AIAA SciTech 2022: Design Analysis for Lunar Safe Haven Concepts

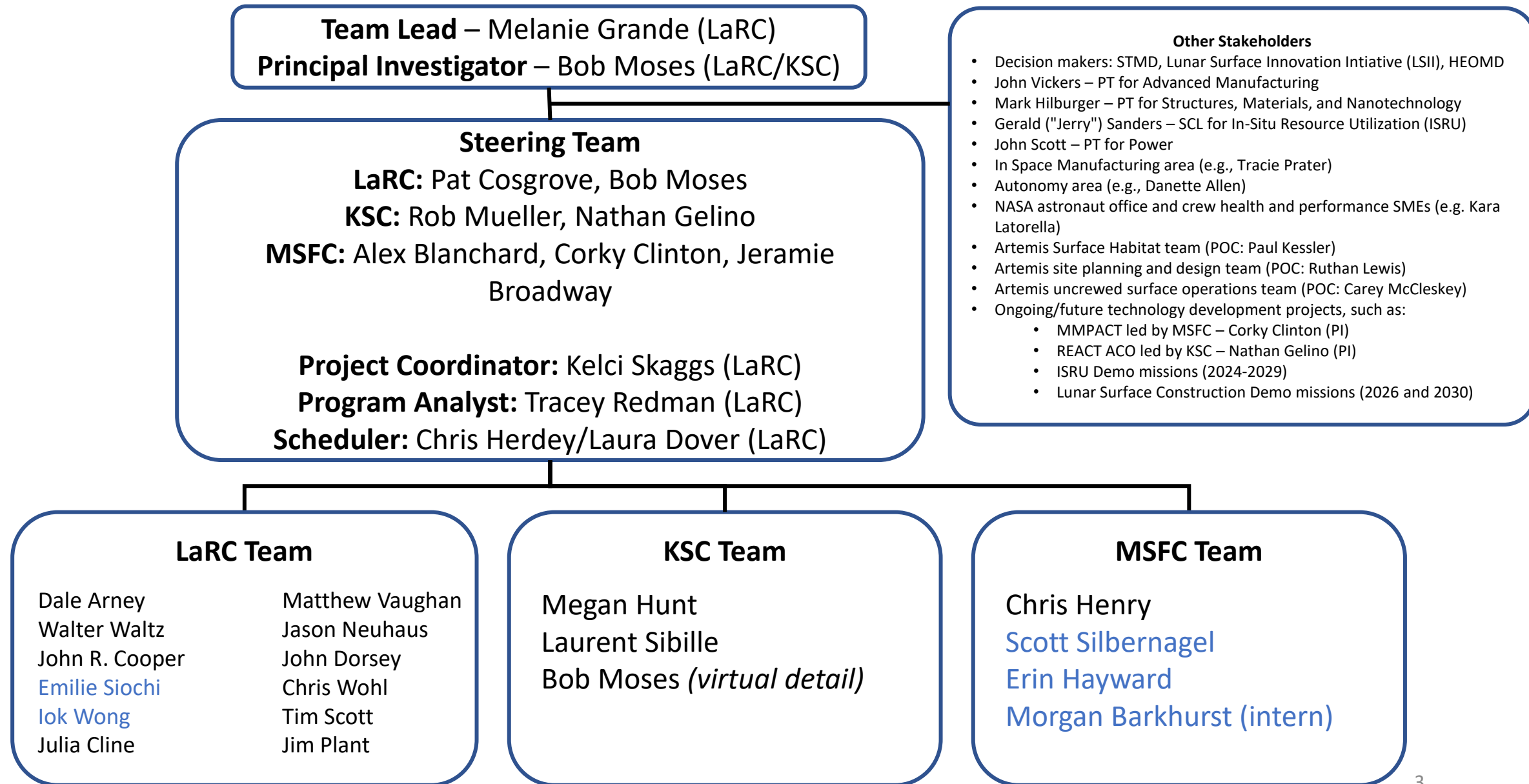
Erin Hayward, Iok Wong, Emilie Siochi, Scott Silbernagel, Morgan Barkhurst, Robert Moses, Walter Waltz, Melanie Grande

Lunar Safe Haven Seedling Study – Background

- NASA's Artemis program will include a “sustained” phase of lunar exploration, with **longer duration missions** and **focus on sustainability and extensibility** for Mars exploration
- To enable a sustainable human lunar presence, NASA must provide a **safe haven shelter to protect astronauts and equipment from radiation, thermal extremes, and micrometeoroids (MM)**.
- Development of a Safe Haven should include examination of NASA activities in **site preparation, excavation, regolith transfer, surface construction/assembly/deployment, autonomy, robotic servicing/repair, advanced manufacturing, and in situ resource utilization (ISRU)** for identifying the best approaches for implementing a safe haven shelter.
- HEOMD has declared development gaps in **TX6 06-38 Radiation Shielding**, and **TX12 12-07 Construction of Unpressurized Structure for Protection**; both of these gaps are the focus of the Lunar Safe Haven.



Who We Are



List of objectives (partial)

Protection

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 LSHC establishment and operations systems.

Operational

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

B2. Minimize need for crew involvement during establishment and sustained operations of the LSHC.

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

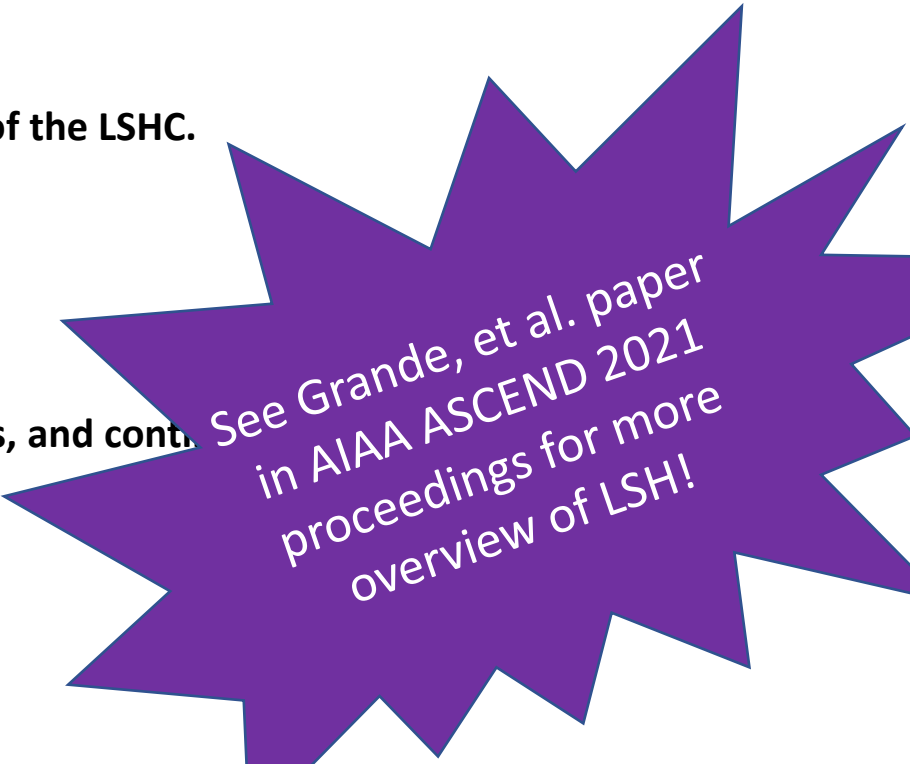
B4. Balance resiliency and robustness of LSH concept as a whole.

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

Programmatic

C1. Minimize investment costs.

C2. Maximize Mars extensibility.



See Grande, et al. paper
in AIAA ASCEND 2021
proceedings for more
overview of LSH!

Attributes – Objective A1

Objective A1: Minimize radiation exposure to crew.

POC: Erin Hayward

Decision Attributes

Measurement Guidance

1. Effective dose to crew from background radiation

Galactic Cosmic Rays (GCRs) are a constant background source of high energy particles that are difficult to shield from. Additionally, interactions with GCRs in regolith and shielding materials create secondary particles.

Career dose limits for crew are currently based on 95% confidence interval of <3% REID (risk of exposure induced death). REID is calculated from particle flux spectra at various locations in the body and accounts for crew age/gender; effective dose is a proxy for REID that is simpler to calculate to compare relative benefits of different shielding concepts.

The LSH shelter should minimize the contribution to career dose from background radiation, enabling longer stays on the moon, and consequently more trips into space per astronaut.

This attribute can be scored on a scale from -2 to +2, for example:

+2 – Earth-equivalent effective dose, or less than 0.015 mSv/day (7 m regolith equivalent)

+1 – Low level of effective dose, less than 0.1 mSv/day

0 – Moderately low level of effective dose, less than 0.25 mSv/day (3 m regolith equivalent)

-1 – Little to no protection, less than 0.5 mSv/day on average (same as standing on the surface with no protection)

-2 (Screening Criteria/does not meet requirements) – Increases the effective dose above background levels of radiation

In future studies with more developed concepts, a modeling tool such as OLTARIS can be used to estimate crew effective dose (inputs: ray trace of CAD model and design reference environment). For early-stage concept comparison, shielding effectiveness can be judged on slab geometry models with material composition and thickness as inputs.

Units: Sv (Sieverts), on a yearly basis.

Consider:

- How much incoming primary radiation does LSHC block?
- How much in situ generated radiation (neutrons in regolith) does LSHC prevent from being created?
- How much secondary scatter radiation does the shelter concept generate simply by existing?

2. Acute dose to crew during SPEs

Solar particle events (SPEs) are intense events that can cause acute radiation symptoms if crew is not protected. The LSH shelter should minimize the dose to crew during these events. Gray-Equivalent (Gy-Eq) to Blood Forming Organs is an appropriate proxy for this acute dose and can be calculated for different shielding concepts.

A “storm shelter” design may be appropriate, where the entire structure is not required to provide this level of shielding. Such shelter concepts sometimes require some amount of set-up time after a warning is given that an SPE is about to occur, or some may require the astronauts to access the shelter. It is expected that the advance warning would come 30 minutes before an SPE. All concepts should also be evaluated for the amount of set-up time required, if any, for any aspects of the concept that are involved in protecting the crew from SPEs—including any assembly, astronaut transfer, or other operations.

This attribute can be scored on a scale from -2 to +2, for example:

+2 – Dose is less than 50 mGy-Eq during SPEs AND shelter requires no set-up time

+1 – (Dose is 50 – 150 mGy-Eq AND shelter requires no setup) OR (Dose is less than 50 mGy-Eq AND shelter requires 1-30 minutes setup)

0 – (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)

-1 – Dose is 150 – 250 mGy-Eq AND shelter requires 1-30 minutes setup

-2 (Screening Criteria/does not meet requirements) – Dose is greater than 250 mGy-Eq OR shelter takes longer than 30 minutes setup

In future studies with more developed concepts, a modeling tool such as OLTARIS can be used to calculate the dose (similar to the previous attribute). The design reference environment is based on the proton spectra from the October 1989 event series. **SC:** Total gray equivalent to crew blood forming organs (BFO) must be less than 250 mGy-Eq.

Units: Gy-Eq (Gray Equivalent), on a per event basis. Gy-Eq takes into account the ability of different particles to cause deterministic effects, like acute radiation syndrome.

LSH Radiation Analysis - GCRs

Thickness (g/cm2)	Thickness (cm) of regolith	Effective Dose (mSv/day)	Notes
0	0	0.51 (.3 - .7 depending on solar)	
20	12	0.46	OK to get below dose limit for typical SPE
100	59	0.42	
200	118 ~= 1 m	0.34	
500	294 ~= 3 m (NO LOWER)	0.12	About equivalent to radiation workers on Earth (50 mSv/year Occupational Dose Limit)
1000	588 ~= 6 m (Good Enough)	0.08	
1200	705 ~= 7 m (Ideal)	0.015	About equal to Earth exposure
1500	~8-10 m	negligible	Infinite stay!!

- NASA Career dose is currently based on REID (<3%), which depends on age/gender of astronaut... international standard is 1 Sv == 1000 mSv
- Astronauts on ISS get a dose of ~200-300 mSv/yr

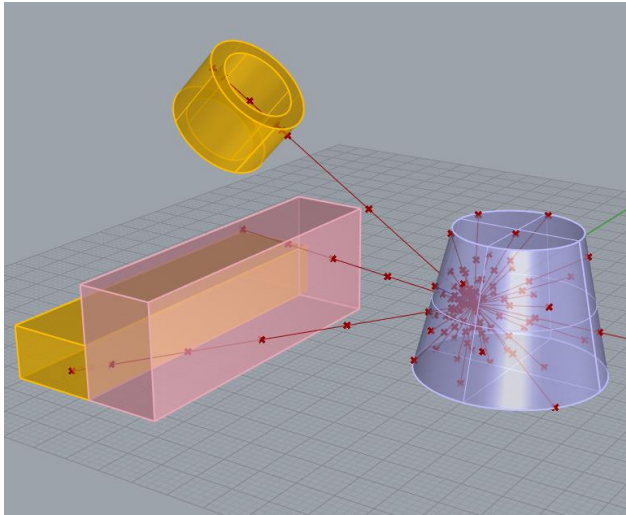
Note: these numbers are not exact calculations for any given concept; they are guidelines based on a number of calculations taken from the literature and OLTARIS! **Full lunar surface analysis with all materials and geometry should be run to get accurate dose numbers for any specific concept.**

LSH Radiation Analysis - SPEs

Calculation caveats: These numbers were run on a "sphere" in OLTARIS in Free Space for the 1989 event series. This model includes a human phantom (FAX) to calculate dose to BFO. So, these numbers should be *roughly* cut in half for the lunar surface, plus some contribution from albedo neutrons. They are meant to give an idea of the magnitude of protection,.

but full ray-trace geometries are required for realistic dose

The limit for dose to BFO is **250 mGy-Eq** per event (or 30 day rolling basis).



Thickness (g/cm2)	Thickness (cm) of regolith	Dose to BFO (mGy-Eq)
20	12.5	166
80	50 = 0.5m	43
160	100 == 1m	22
480	300 == 3m	2.8
1120	700 == 7m	0.05

Impact Protection

Protection needed from human made and natural hazards

- Micrometeoroids
- Localized meteor showers
- Secondary ejecta
- Plumes from landers
- Malfunctioning roving assets

What constitutes an impact that is structurally relevant?

What sort of maintenance schedule needs to be developed?

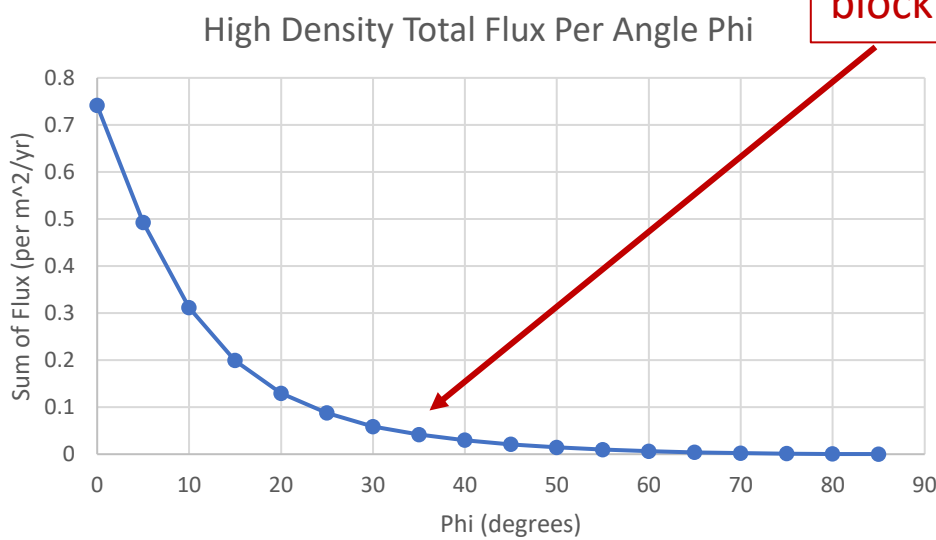


Detection ability... trades in sensitivity and timeliness of information

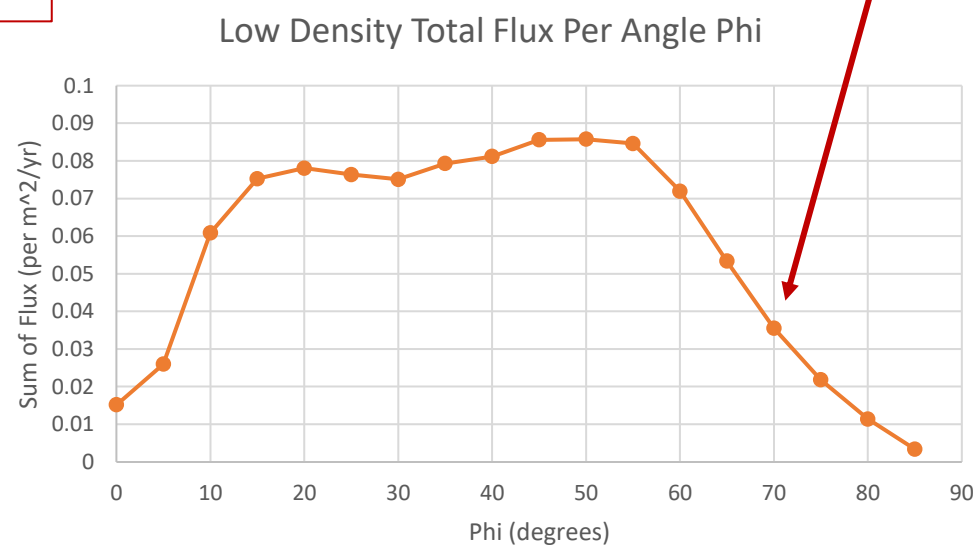
- Sensor net
- Cameras
- Crew

Micrometeoroid Protection

- Analyzed Meteoroid Engineering Model 3 (MEM 3) sporadic flux outputs at Lunar South Pole - does not include showers (which are localized events)
- High and low density meteoroid outputs from $10^{-6}g$ to $10g$
- Evaluated location of impacts with respect to angle from horizon



We can block **95%** of meteoroids if we block up to **phi = 35°**



Low-density flux more equally distributed

95% incoming low-density flux is **phi = 70°** or less

(Phi = angle from horizon)

Micrometeoroid Protection

Maintenance

As a first order approximation for the **Round Cake**, only roughly 10^{-4} cubic meters of regolith will be lost in 10 years.

High Density: Cake (7m)	Impacts/m ² /yr	Surface Area (m ²)	Years	Loss Per Impact (m ³)	Total Loss of Regolith (m ³)
	2.151	1996	10	6.463E-09	2.775E-04

Low Density: Cake (7m)	Impacts/m ² /yr	Surface Area (m ²)	Years	Loss Per Impact (m ³)	Total Loss of Regolith (m ³)
	1.021	1996	10	1.492E-08	3.04E-04

No maintenance schedules needed to replenish the loss of regolith from regular "background" meteors.

The same is true for the **Dome** design.

High Density: Twinkie (7m)	Impacts/m ² /yr	Surface Area (m ²)	Years	Loss Per Impact (m ³)	Total Loss of Regolith (m ³)
	2.151	3415	10	6.46278E-09	4.748E-04

Low Density: Twinkie (7m)	Impacts/m ² /yr	Surface Area (m ²)	Years	Loss Per Impact (m ³)	Total Loss of Regolith (m ³)
	1.021	3415	10	1.492E-08	5.20E-04

<http://keith.aa.washington.edu/craterdata/scaling/index.htm>

Worst Case

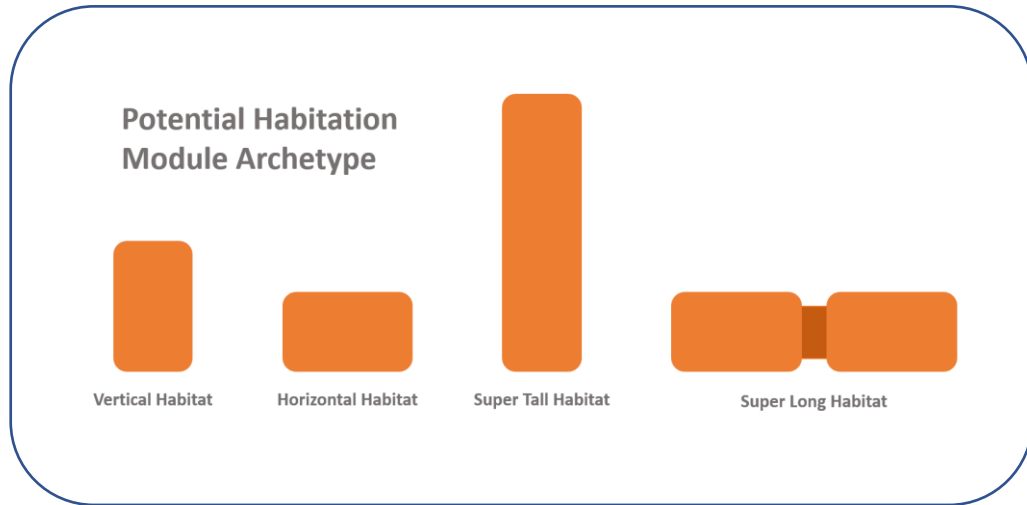
- Micrometeoroid impacts cause cratering that causes structural damage
- A crater causing 10% of regolith depth lost due to impact was chosen as a worst case scenario
- What impactor would cause 0.7m deep crater?

Lunar Crater	Meteoroid				Probability
Depth (m)	Angle to Normal	Velocity (km/s)	Diameter (m)	Energy (J)	Years until 1 Impact
0.7	0	80	0.052	8.43E+08	3.27E+13

One impact of that size will occur approximately every **trillion years** at this location.

Further analysis is needed to account for meteor showers. Meteor showers cause impactor flux to rise slightly above background levels for limited times, in specific locations.

LSH Key Footprint Dimensions

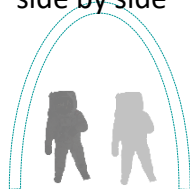


Space enough for
one EVA
astronaut



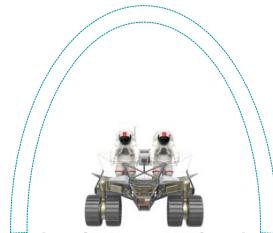
~1.7 M to 2.0 M

Space enough for
two EVA
astronauts walking
side by side



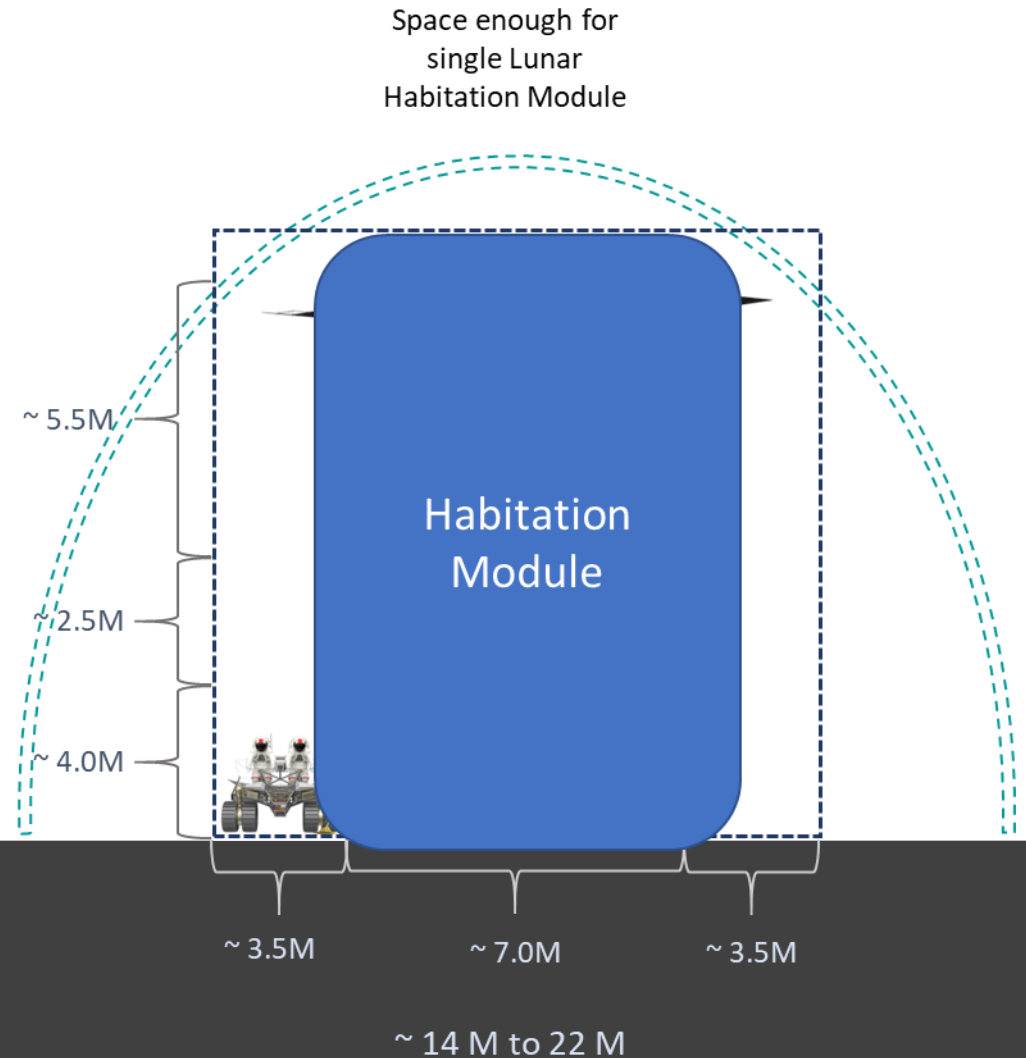
~3.5 M to 4.0 M

Space enough
for LTV access

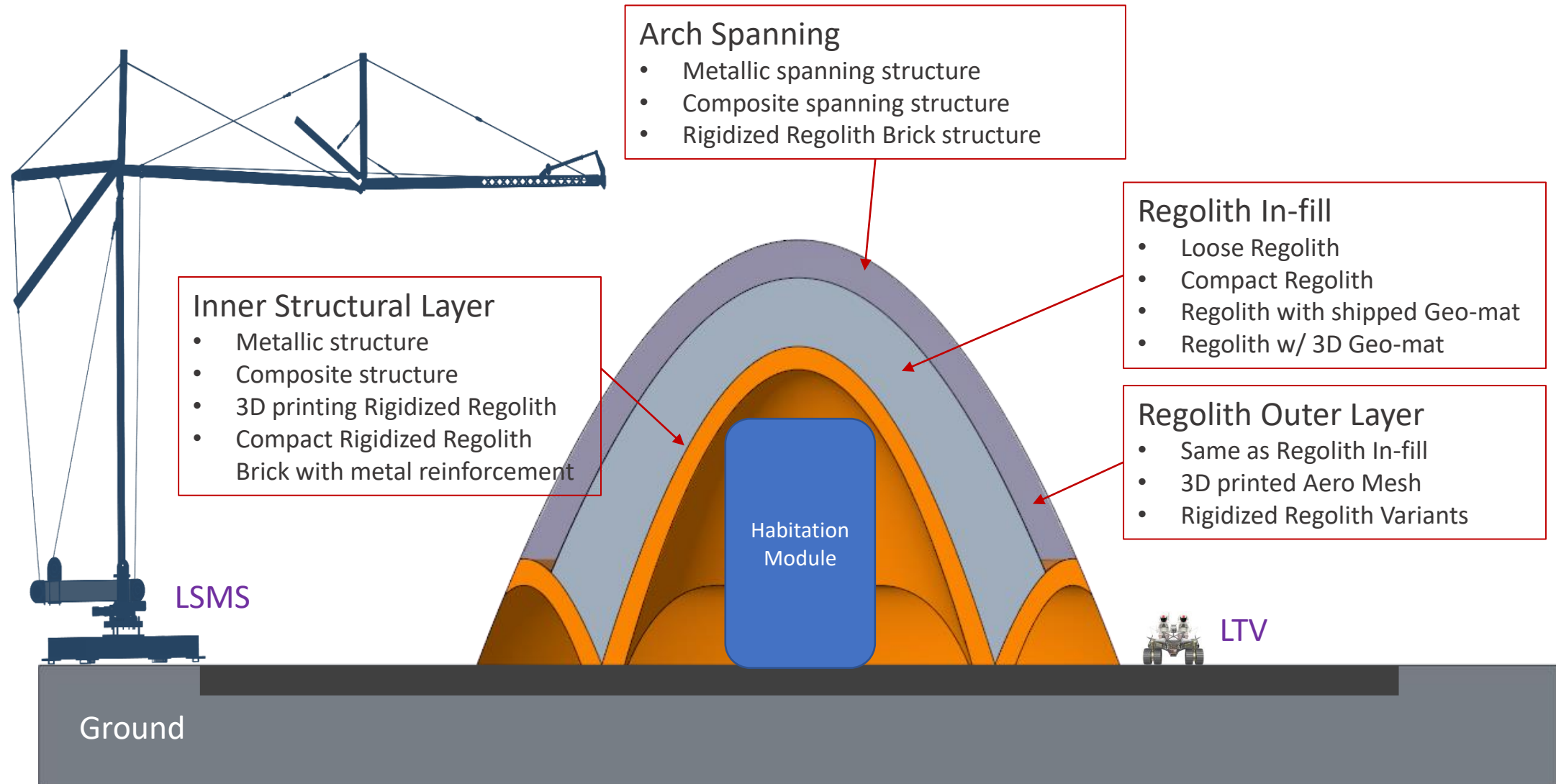


1.2M 3.2M 1.2M

~ 5.5 M to 6.5 M



Concept 1.1A



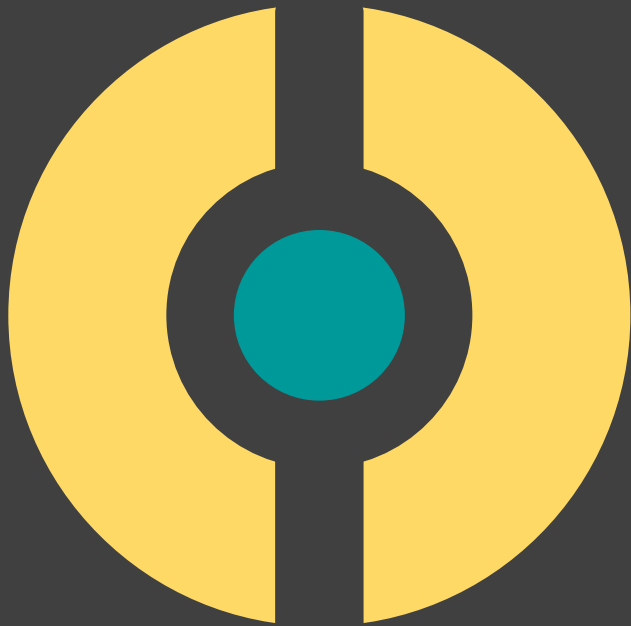
Potential Floor Plan Concepts for Single Habitat Shelter

Plan concepts with two means of egress and accessible space wide enough for two astronauts walking side by side. Additional width would be added to LTV passage connecting both egress to allow heavy equipment or large simple transportation.

Protective layer(s)

Access Space

Habitat



Basic Egress



Easy access for LTV



Easy access for LTV
with Better Protection

Concept 1.1B

Topping Options with Poly – Tank

(Fill with mass efficient shielding material such as Polyethylene from mission supporting packaging)

- Metallic spanning structure
- Composite spanning structure
- Multi – Layer Tensile Trampoline*

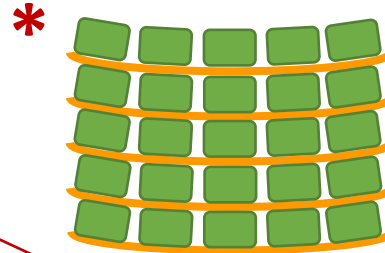


Food packaging waste is primarily PE, other plastics, and aluminum are all good GCR shields!

Even without further processing, trash bags can be repurposed for shielding.

Some up-mass are required to provide baseline protection until regular trash are being generated.

Available mass is roughly 0.3 kg/crew member/day.



Inner Structural Layer

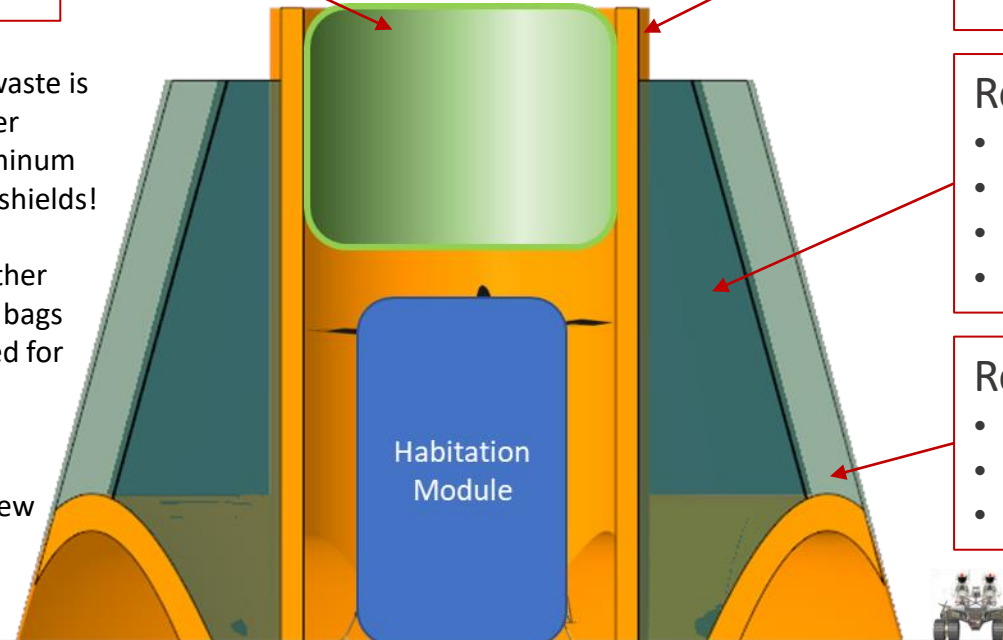
- Metallic structure
- Composite structure
- 3D printing Rigidized Regolith
- Compact Rigidized Regolith Brick with metal reinforcement

Regolith In-fill

- Loose Regolith
- Compact Regolith
- Regolith with shipped Geo-mat
- Regolith w/ 3D Geo-mat

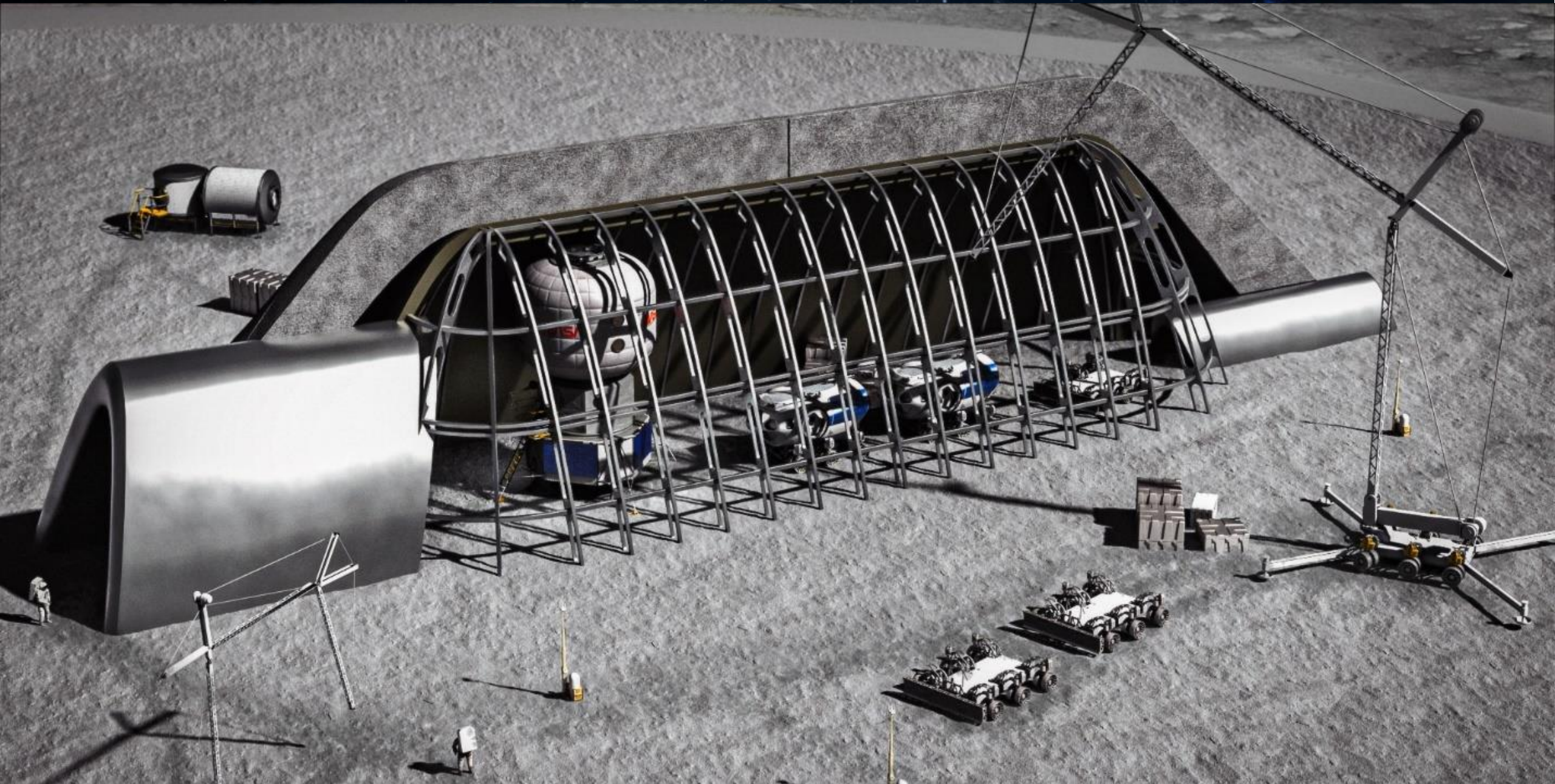
Regolith Outer Layer

- Same as Regolith In-fill
- 3D printed Aero Mesh
- Rigidized Regolith Variants

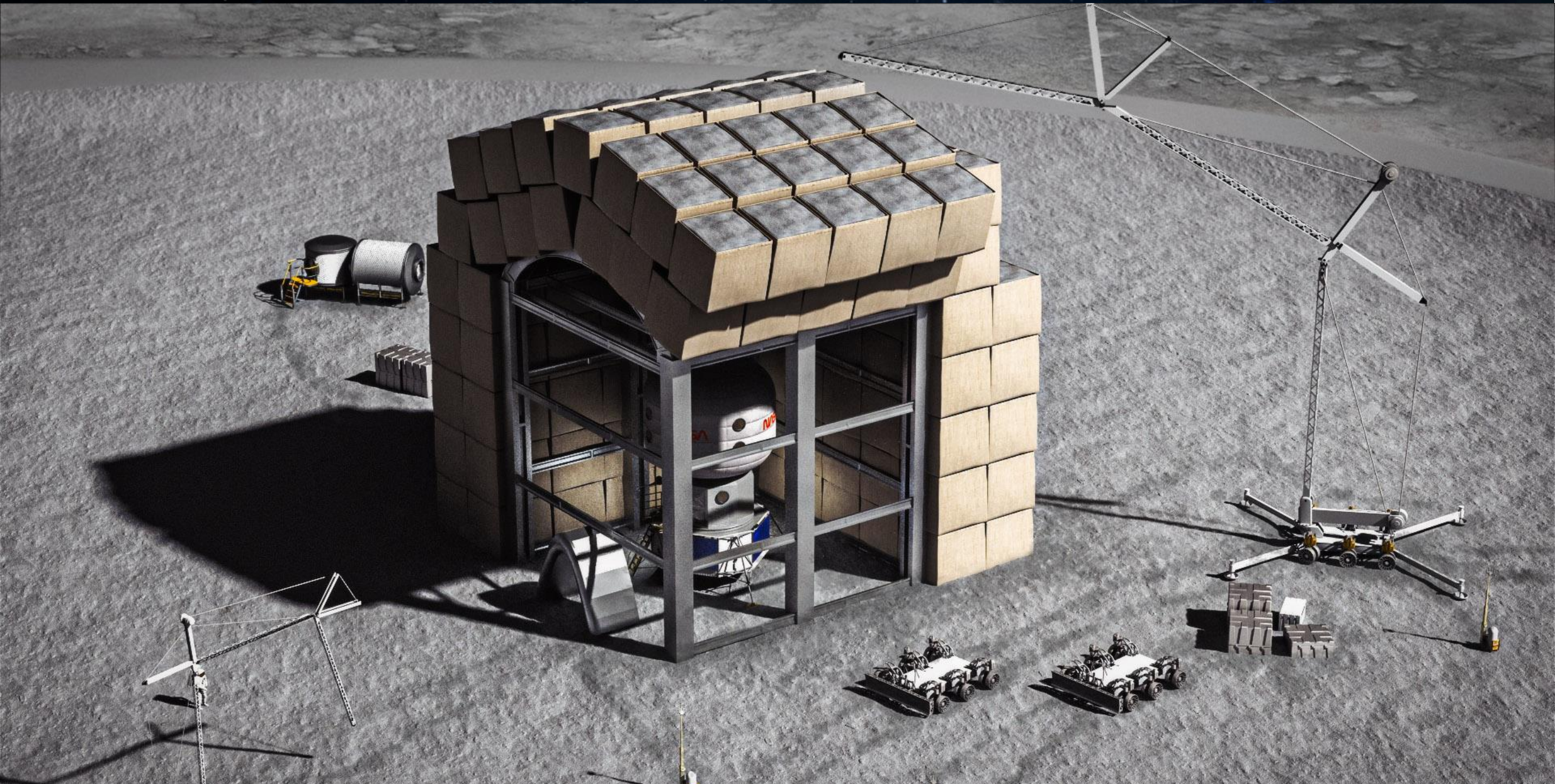


Ground

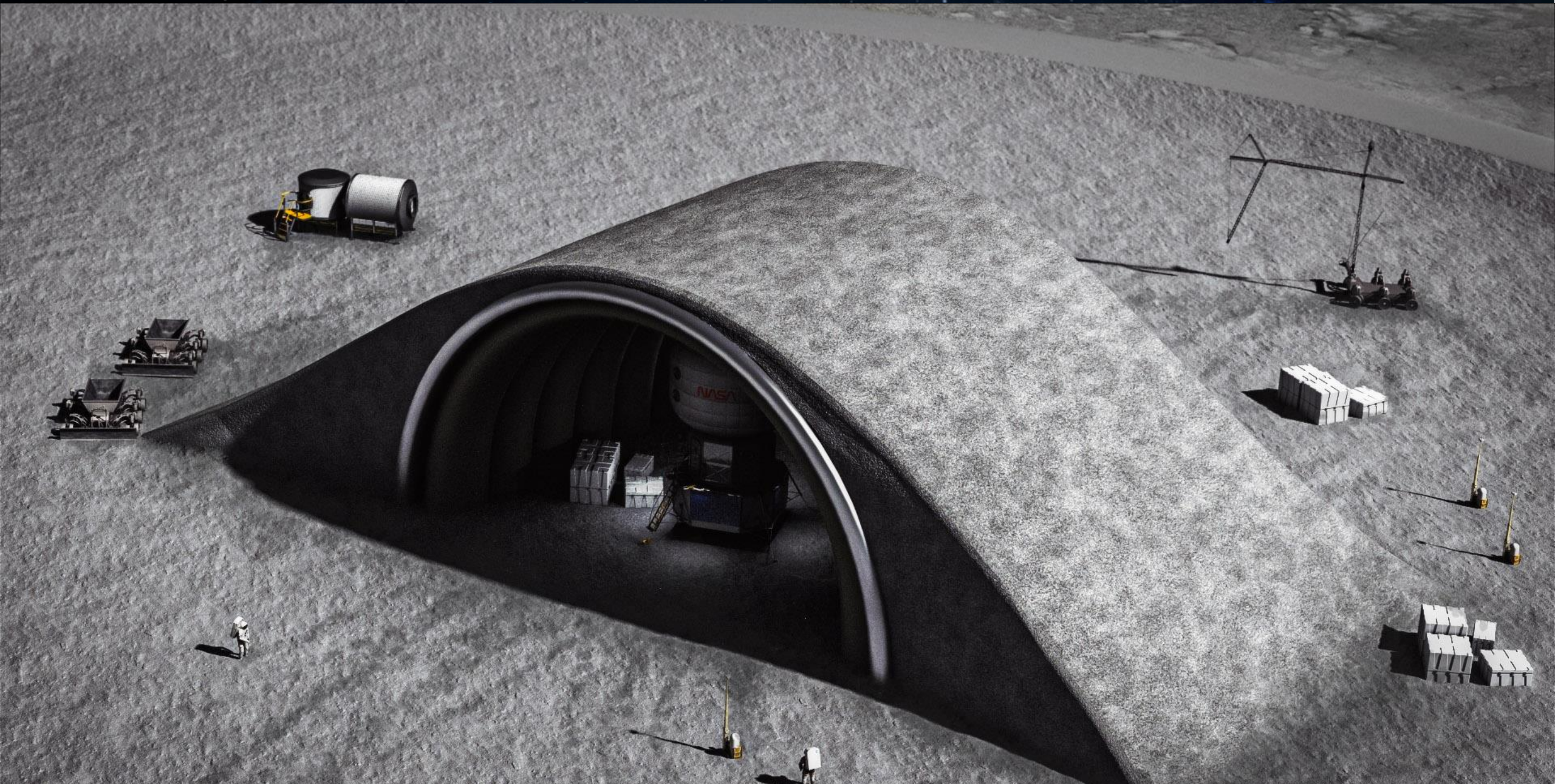
Concept 1.1A – Sized for more storage/habs



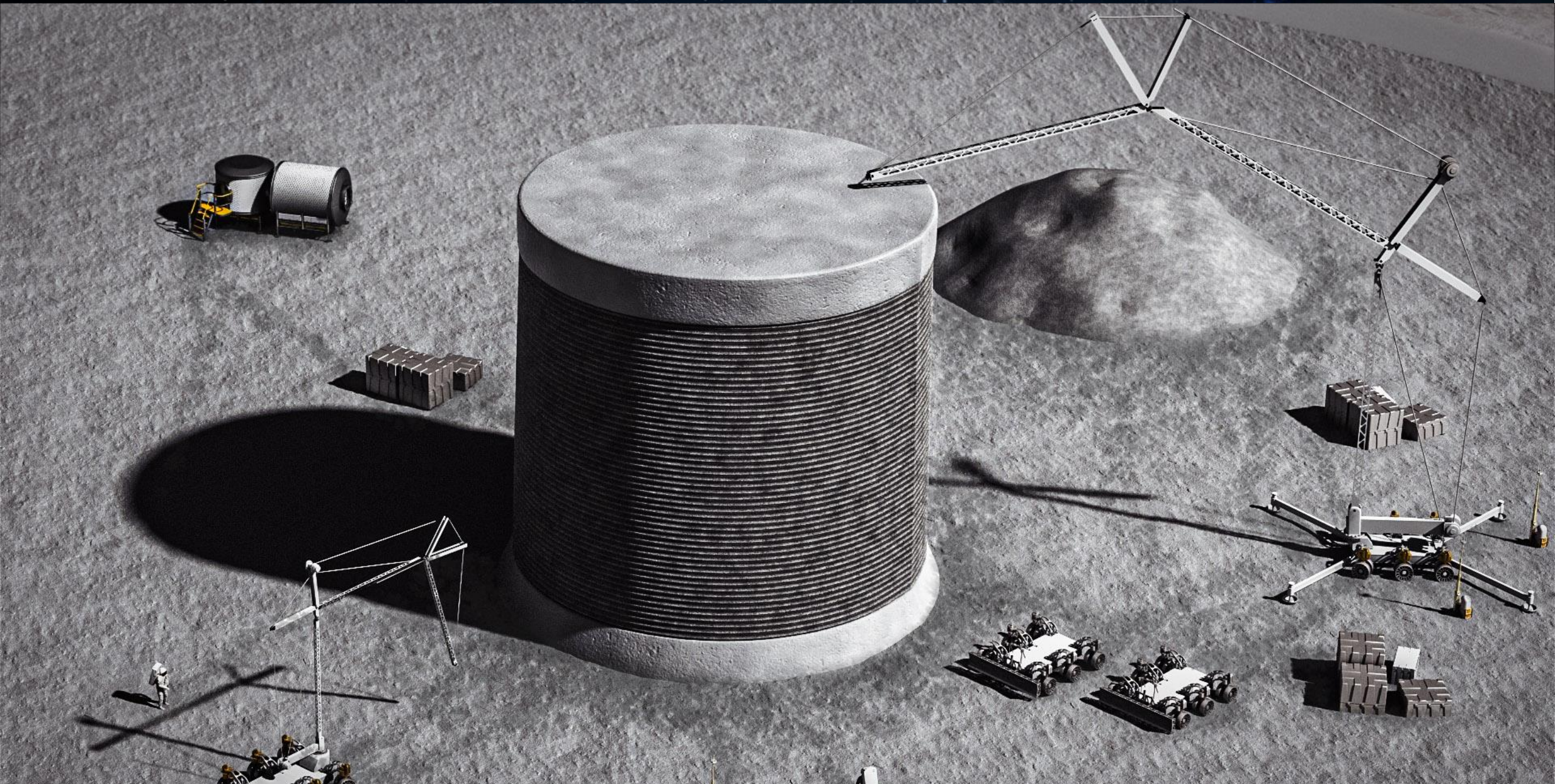
Additional Concepts



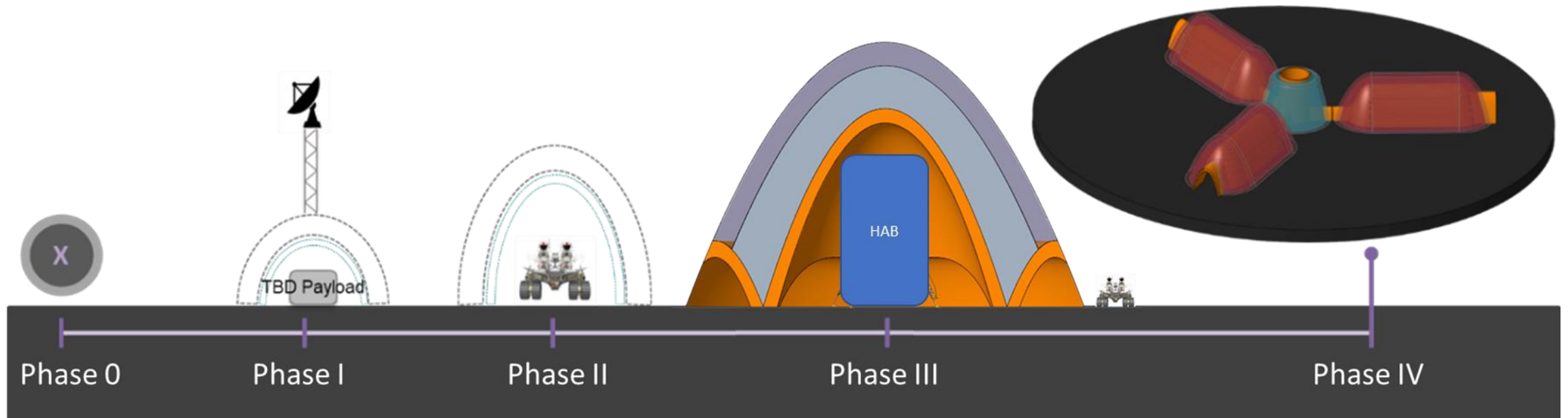
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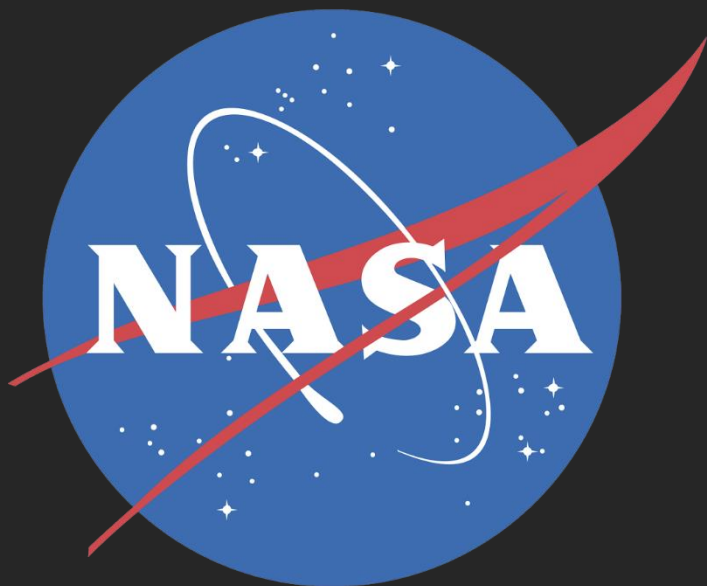


Additional Concepts



Possible LSH Development Phases





Thank you!

