National Aeronautics and Space Administration

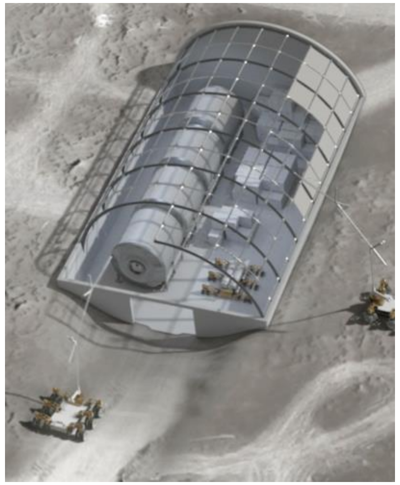
Lunar Safe Haven Seedling Study
Overview for LSIC Excavation and Construction Focus Group

Dr. Bob Moses, Melanie Grande | Lunar Safe Haven Seedling Study | 04.30.2021

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.


Source: NASA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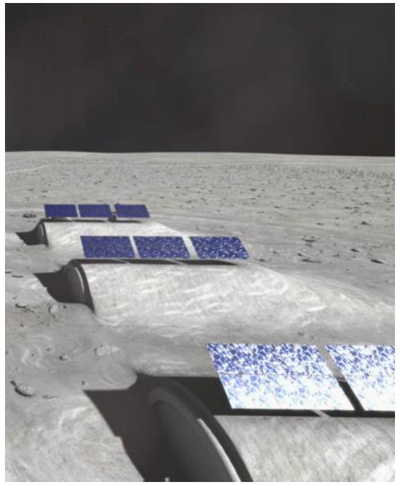
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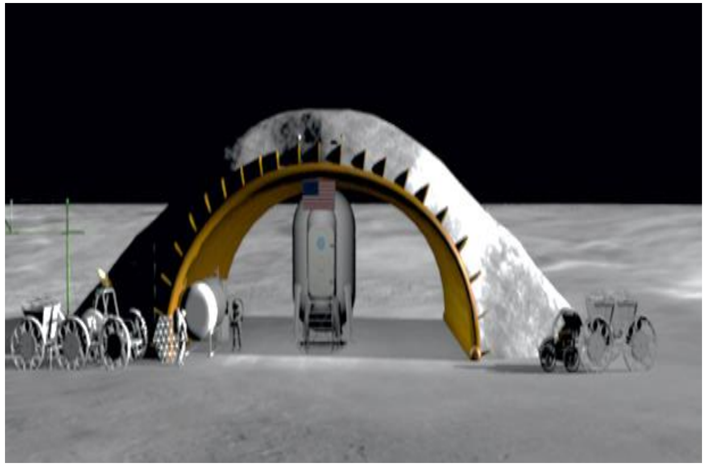

Source: NASA

Game-Changing Nature of a Lunar Safe Haven

- **The Lunar Safe Haven Study is leveraging the substantial work of the Artemis program, such as the progress in habitat and rover development**
  - We are choosing to define "Lunar Safe Haven" to mean a continuous strategy for protection of crew and exploration systems
- **The Lunar Safe Haven concept is "game changing" because it provides:**
  - Shielding for crew to a degree that cannot be done via delivery from Earth, given constraints/costs of landing systems
  - Protection with access, which directly burying habitats wouldn't allow
  - Shielding for electronics that can be a game-changer for autonomy, avionics, and communications—e.g., by **extending their lifetime** and reducing rad-hardening and thermal control requirements
  - Protective shelter for mobile assets and potentially an area for servicing, both of which **will extend their lifetime**
  - **Scalability**, if various sizes of safe haven shelters are possible
  - **Evolvability**, if the safe haven concept is able to change and respond to new scenarios over time

Study Approach

- **Ultimate Goal: The trade study and identification of both high-level and derived, system-level requirements will provide a path to future technology investments plus synergy with existing and proposed programs**
- **A multi-center team (LaRC, MSFC, and KSC) with a Steering Team consisting of two SMEs from each center**
- **One-year effort in FY21 sponsored by STMD Game Changing Developments**
- **Content areas for seedling trade study will include, but are not limited to:**
    1. Site preparation and shelter preparation (e.g. deployment, assembly, and/or construction)
    2. Protection of crew and surface systems (i.e. from radiation, thermal extremes, micrometeoroid strikes)
    3. System / structural verification
    4. System maintenance for long duration use
- **Data will be collected from other NASA projects, OGA's, industry, and academia on concept options and state of technology maturity**

Study Scope and Progress

- **3 Main Deliverables:**
  1. Identify **high-level requirements** for synergy with the Artemis program
  2. Define several safe haven shelter concepts and conduct a **comprehensive trade study**
  3. Derive **system-level requirements** for 1-2 chosen safe haven concepts, including requirements for surface radiation shielding, thermal extremes, and micrometeoroids
- **Current status:**
  - Level Zero Requirements **– Completed**
  - Functional Decomposition and Ground Rules & Assumptions (GR&A) **– Completed**
  - Decision Objectives and Attributes, to assess concept alternatives **– Completed**
  - Concept generation of alternatives **– Completed**
  - Concept evaluation and down-select **– Coming in May**

Concept Alternatives

Concept Generation Process

- **The LSH team defined three morphological matrices for each system group with a large number of alternatives**
  - System groups: Shelter Physical Design, Establishment Systems, Sustained Operations Systems
- **Each concept combination of alternatives will be evaluated based on identified decision attributes to quantify how well each concept satisfies the main objectives**
  - Ultimately 1-2 concepts will be down-selected based on attribute scores

For the Shelter, we used the Physical Architecture method:

- One **parameter** per row
- Brainstormed to put one **parameter setting alternative** per column

For the Establishment and Sustained Ops systems, we used the Function Decomposition method:

- One **function** per row
- Brainstorm to put one **alternative for "means to achieve the function"** per column

Morphological Matrix – Shelter Design

Shelter protection	Idea 1	Idea 2	Idea 3	
Shelter structure	Idea 1	Idea 2	Idea 3	Idea 4
Shelter size/dimensions	Idea 1	Idea 2		
Shelter shape	Idea 1	Idea 2		
…				

Morphological Matrix – Establishment Systems

Transport LSH systems	Idea 1	Idea 2	Idea 3	
Survey the location	Idea 1	Idea 2	Idea 3	Idea 4
Emplace, assemble, and/or construct the LSHC shelter	Idea 1	Idea 2		
…				

Sample LSH Concepts – Physical Shelter Design

A concept combination is made up of at least one alternative in each row, and it includes a design (selection) for the physical shelter + establishment systems + sustained operations systems.

Parameters - SHELTER	Alternative 1	Alternative 2	Alternative 3
1. Shelter protection	Regolith, bulk covering	Layered polyethylene and regolith	
2. Shelter structure	Inner metal structure delivered from Earth		Inflatable beams/form work, which could be empty or filled with water or gas, e.g. Vectran
3. Shelter size/dimensions	Accommodates all crew because big enough just for Surface Habitat (SH)		
4. Shelter shape			
4A. grade level	level with the grade		
4B. plan profile (i.e. from aerial view)	rectangular		
4C. section profile (i.e. view normal from the ground)	dome (circular, parabolic, or egg), for example: Quonset hut half cylinder, vertical arch, or geodesic dome		
4D. means of ingress/egress	two open sides		
4E. number of stories	single story		
5. Dust management within (or under the footprint of) the shelter	Stabilized regolith (binder/epoxy mixed in) to develop floors and pathways under footprint of shelter		
6. Thermal management/ protection	• Thick enough regolith shielding causes controlled/ constant thermal environment • Low CTE materials for shelter structure • Sunshades (e.g. at door/openings)		

Green cells = fixed variables

White cells = will vary between Alternatives

Sample LSH Concepts – Establishment Systems

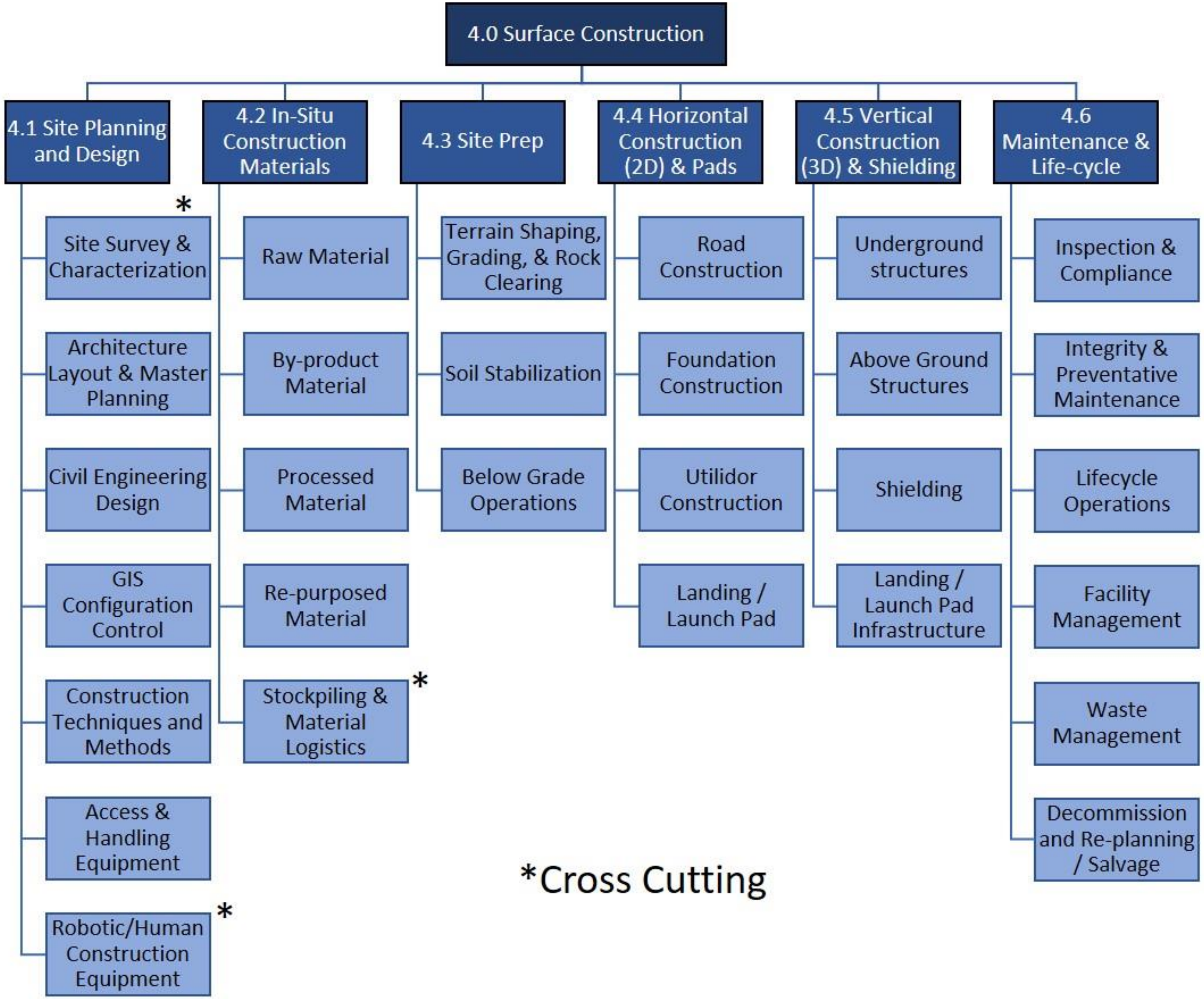
Functions - ESTABLISHMENT SYSTEMS	Alternative 1 *(continued)*	Alternative 4	Alternative 5
1. Transport LSH systems from lander off-loading site to establishment site	Crane with appropriate implements, such as LSMS on wheels, which can pick up cargo and transport it		
1. Degree of Autonomy*	Completely autonomous		
2. Prepare the site for installment of the shelter			
2A. Remove rocks; Grade (level) the site; Build foundation (if needed)	RASSOR, an excavation robot used to clear area of rocks and level the site	LTV 2 (copy) with an attachment of a hoe/claw	Backhoe
2B. Rough compact the site and stabilize the surface of the compacted area	Compactor/Roller (has a smooth wheel roller to compact shallow layers of soil)	LTV 2 (copy) with an attachment of a Compactor/Roller (has a smooth wheel roller to compact shallow layers of soil)	
2C. Verify compaction and grading	Verification sensors and imaging equipment built in to the Establishment rovers		
2D. Transfer bulk regolith; Stockpile construction feedstock	Crane with appropriate implements, such as LSMS on wheels	LTV 2 (copy) with an attachment of a loader + dump truck-style container	Dump Truck + Loader
2. Degree of Autonomy*	Completely autonomous		
3. Emplace, assemble, and/or construct the shelter			
5A. Deploy the LSHC systems	Deployment of structure delivered from Earth		
5B. Accept construction materials at the installment site	Dedicated area to pile up regolith		
5C. Process construction materials	Use bulk regolith, remove large rocks (no additional processing? TBR)		
5D. Construct/ assemble shelter structure and protection	Multiple assembly/construction agents	LTV 2 (copy) with robotic arms to do assembly, plugging stuff in, moving things around	
5. Degree of Autonomy*	Completely autonomous		
4. Receive distributed power from the Artemis surface power source	• Rovers drive over to the surface power source when needed • Wireless charging • Onboard batteries for power storage		
5. Manage/remove lunar dust for individual LSHC systems (not Artemis systems inside the shelter)	Combination of surface coatings to resist dust/abrasion and electrodynamic dust shield		

Functional Capabilities WBS – Surface Construction

Consistent with Construction Industry Terminology

Rob Mueller presented this WBS at a previous LSIC E&C FG Meeting

Moses & Mueller, "Requirements Development Framework for Lunar In-Situ Surface Construction of Infrastructure," ASCE Earth & Space Conference, 19-23 April 2021, Seattle, Washington



Functional Capabilities to be Addressed / Considered

- **Deploy Location Determination Reference Systems**
  - Reverse-Ephemeris Satellite Suite
  - Ground Beacons
- **Preposition Related Equipment on the Lunar Surface**
- **Site survey**
  - Topography
  - Geology
- **Site preparation**
  - Rock removal
  - Grading
  - Stabilization/compaction
  - Verify compaction
- **Foundation construction/emplacement (i.e., horizontal / footer / slab)**
  - Verify surface stabilization
  - Verify structural performance
- **Off-loading any Earth-manufactured LSH components/equipment from Lander(s) (i.e., trusses may be manufactured in situ and aligned tightly so that panels are not needed)**
- **Transportation of LSH components from landing site to construction site**
- **Assembly/Construction of LSH Structural Elements**
- **Deployment of service cables through structural "wall" with length available both "inside" (underneath/shadow of) and outside the LSH "final" configuration footprint**
- **Emplacement of shielding material overtop LSH (sub)structure**
- **Connection of (external) services as needed (such as power, communications, ECLSS, …)**
- **V&V and other check out of the structure and monitoring systems**

Concepts of Operations

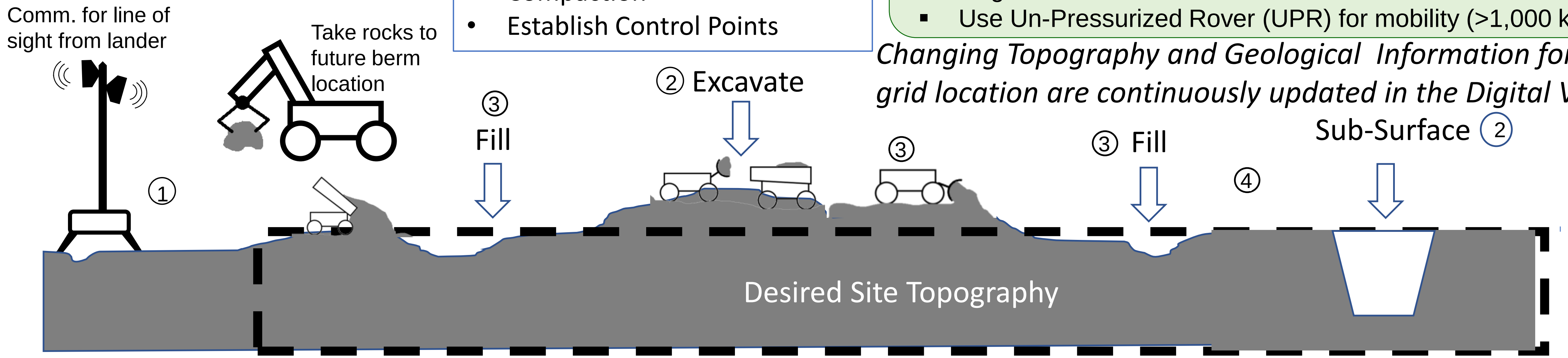
Concept of Operations : WBS 4.3 – Site Preparation

- Site preparation
  - Rock removal
  - Grading
  - Stabilization/compaction
  - Verify compaction

Site Preparation Examples Include:
- Obstacle/Rock Clearing
- Bad Material Removal
- Establish Rough Grade
- Grade Fill and Cut Ops
- Compaction
- Establish Control Points

Primary Implements of Interest for Site Prep:
- Rock Removal
- Dozer Blade
- Load Haul Dump (LHD) Excavator
- Compactor
- Regolith Stabilization
- Use Un-Pressurized Rover (UPR) for mobility (>1,000 kg cargo)

Changing Topography and Geological Information for each grid location are continuously updated in the Digital Village



⓪ Install control points and continuously assess desired states

① Deploy Un-pressurized Rover (UPR) with implements for rock removal, load, haul, dump, grade, stabilize surface

② Excavate high areas, load, haul (trench for subsurface structures, if desired)

③ Dump regolith in depressions, to create a level site and rough grade the site

④ Rough compact the site and stabilize the surface of the compacted area

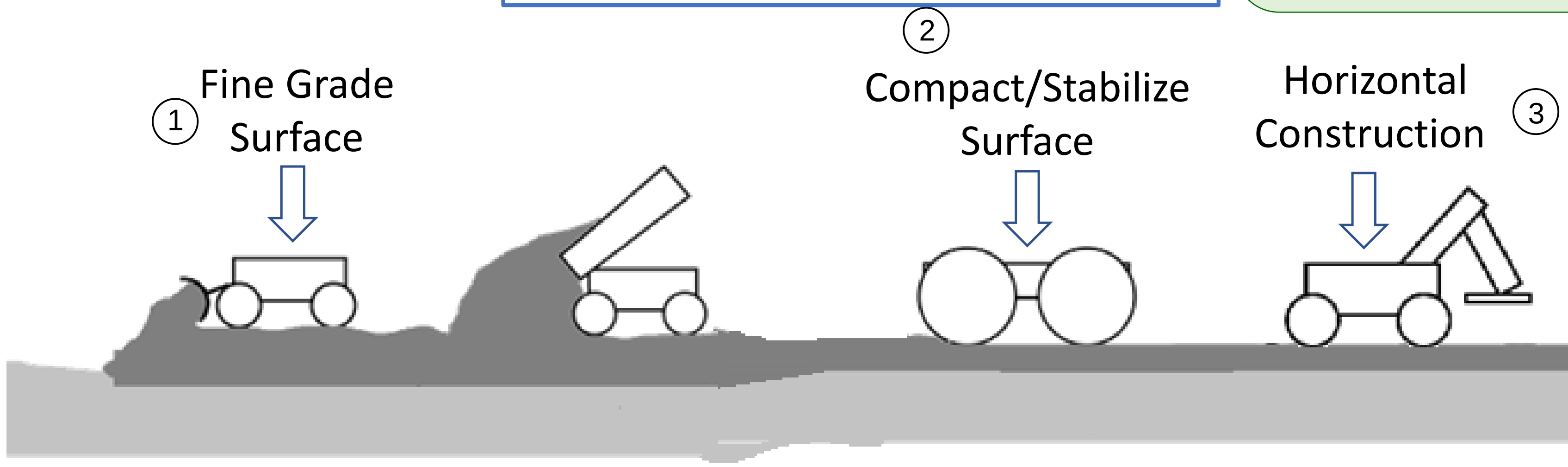
⑤ Stockpile construction feedstock pile and stage required construction equipment

Concept of Operations : WBS 4.4 - Horizontal Construction

- Foundation construction/ emplacement (i.e., horizontal / footer / slab)
  - Verify surface stabilization
  - Verify structural performance

Horizontal Construction Elements Include:
- Launch and landing pads
- Roads
- Dust free zones
- Foundations
- Thermal wadis
- General purpose pads

Primary systems/functions of Interest:
- Specialized Construction Implements/Systems
- Surface preparation systems
- Verification of structure
- Use Un-Pressurized Rover (UPR) for mobility (>1,000 kg cargo)
- **Additional Power if making bricks / pavers / sintering / molten regolith printing**



Changing Topography and Geological Information for each grid location are continuously updated in the Digital Village

1. Bring surface to final grade
2. Complete surface preparation operations such as compaction and stabilization surface
3. Perform specialized construction operations
4. Verify as-built configuration and performance of surface and structures (not shown)

Concept of Operations : WBS 4.5 – Vertical Construction

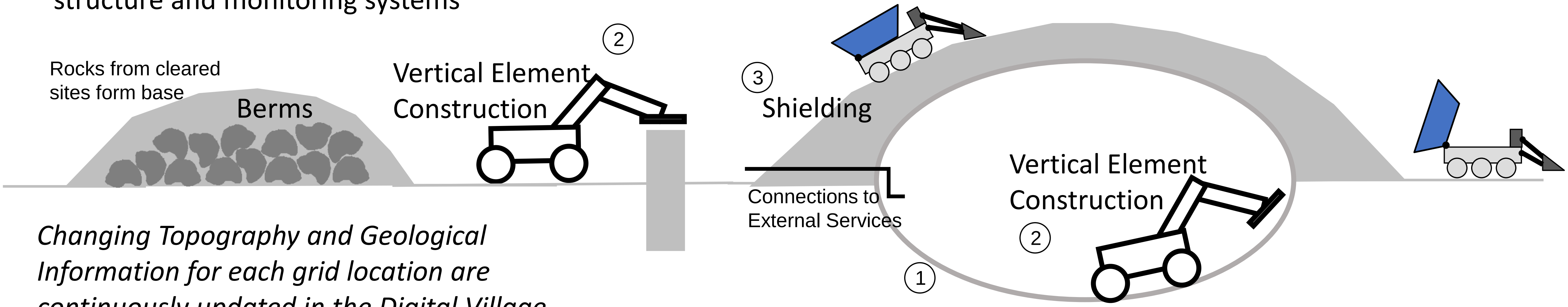
- Emplacement of shielding material overtop LSH (sub)structure
- Connection of (external) services as needed (such as power, communications, ECLSS, …)
- V&V and other check out of the structure and monitoring systems

Vertical Construction Elements include:

- Blast Protection
- Radiation Shielding (Nuclear Reactor and Space Radiation)
- Unpressurized Hangars
- Pressurized Habitats
- Sun Shades for Thermal Control
- Solar Power Farm

Primary systems/functions of Interest:

- Specialized Construction Implements/Systems
- Verification of structure
- Use Un-Pressurized Rover (UPR) for mobility (>1,000 kg cargo)
- **Additional Power if making bricks / pavers / sintering / molten regolith printing**



Changing Topography and Geological Information for each grid location are continuously updated in the Digital Village

1. Excavate & trenching (previously shown)
2. Structural (vertical element) construction (not shown – requires other systems currently not shown)
3. Transfer bulk regolith & bury support (“roof”) structure

Potential Collaboration

Potential Collaboration between LSH and LSIC FGs

- **Challenges and barriers**
  - Limited opportunity for demonstrations
  - Low Technology Maturity Level (TRL) of certain construction technologies
  - Autonomy capabilities need to be matured
  - Power supply for construction (e.g., sintering)
  - Amount of regolith to be moved
  - Electrostatic environment (lunar surface is very charged, so electrostatic discharge is a risk to electronic systems)
  - Limitations of material survivability in lunar environment
  - Cargo delivery mass constraints
  - Etc.

How do you see the LSIC FG helping to address these?

Back-Up

Sample LSH Concept #1 – Sustained Operations Systems

SUSTAINED OPS SYSTEMS	Alternative 1
1. Maintain successful operation of the LSHC	
1A. Identify and respond to anomalies during the establishment of the shelter; Fix anomalies	LTV 2 (copy), with sensors/ imaging equipment specifically for construction
1B. Inspect and verify that the establishment of the shelter has completed successfully, and confirm operational readiness	LTV 2 (copy), with sensors/ imaging equipment specifically for construction
1C. Provide continuous health monitoring and fault identification the LSHC operations	imbedded sensors and digital twin
1D. Provide appropriate audits to verify operational readiness during LSHC operations	send rover to perform inspection + diagnostics
1E. Identify and respond to anomalies during operations lasting up to 10 (TBR) years	*Implement all anomaly type + response options listed in matrix*
1F. Perform repairs of systems	shared servicing robot (e.g. lunar rover also used for other surface systems)
1G. Support tool changes during repairs and operations	TBD
1. Degree of Autonomy*	Completely autonomous
2. Manage waste and trash, including waste from construction, maintenance, and operations (i.e., logistics wrappers and general trash)	Sort, separate, and classify waste types (e.g. using RFID system)
2. Manage waste and trash, including waste from construction, maintenance, and operations (i.e., logistics wrappers and general trash)	Areas to stage/store trash for pickup, transfer, and processing and/or disposal
2. Manage waste and trash, including waste from construction, maintenance, and operations (i.e., logistics wrappers and general trash)	In-space recycling of polymers
2. Manage waste and trash, including waste from construction, maintenance, and operations (i.e., logistics wrappers and general trash)	Waste collection system (e.g rover/WALL-E or LTV copy)
2. Manage waste and trash, including waste from construction, maintenance, and operations (i.e., logistics wrappers and general trash)	Design strategy to maximize reusability or repurposing (different than salvaging, focus on refurbishment)
3. Monitor the lunar environment to provide information on space weather conditions, radiation, seismic activity, and other conditions relevant to protection of crew and surface systems	
3A. how/where you do the monitoring	Continuous sensor array on lunar surface and/or orbit to monitor for dangerous conditions
3B. what monitoring is being performed	Combination: mass spectrometer, seismometer, radiation monitors, dust monitor, space weather sensors
4. Receive distributed power from the Artemis surface power source	Can use the same/similar or different means as listed under the Establishment systems!
5. Communicate and provide sufficient command and data handling with other surface systems	Can use the same/similar or different means as listed under the Establishment systems!
6. Provide sufficient illumination for operations of the LSHC based on conditions at the lunar South Pole	Can use the same/similar or different means as listed under the Establishment systems!
7. Manage/remove lunar dust for individual LSHC systems (not Artemis systems inside the shelter)	Can use the same/similar or different means as listed under the Establishment systems!
8. Manage thermal control for individual LSHC systems (not Artemis systems inside the shelter)	Can use the same/similar or different means as listed under the Establishment systems!

Level Zero Requirements (1/2)

1. The Lunar Safe Haven Concept (LSHC) ***shall*** shield crew, electronics (such as computers providing command and control of autonomous systems), and other exploration and habitation systems that require radiation shielding as defined by HEOMD for at least 10 (TBR) years without exceeding the proxy dose limits for crew and electronics. [Functional]
2. The LSHC ***shall*** protect crew, electronics, and other exploration and habitation systems that require protection as defined by HEOMD from the hazards of the lunar environment—including but not limited to micrometeoroid impacts, thermal loads, seismic activity, electrical charging, dust, vacuum, and the sun—for at least 10 (TBR) years. [Functional]
3. The LSHC ***shall*** protect crew, electronics, and other exploration and habitation systems that require protection as defined by HEOMD from the impacts and damage from other external assets that could cause collisions or ejecta for at least 10 (TBR) years. [Functional]
4. The LSHC ***shall not*** negatively impact the crew performance, habitability, and safety requirements derived from NASA-3001 for crew—as defined in HSI requirements documents of the lunar exploration systems to be used by HEOMD—and for proximal EVA. [Technical]

Note: 10 years operational duration will include any maintenance/repair.

Level Zero Requirements (2/2)

5. The LSHC shall not negatively impact functionality nor negatively impact deployment and placement of heritage exploration habitation systems selected by HEOMD that require protection and shielding. [Technical]

Note: L-0 Req. #5 was written with the intent to rule out any concepts that would expose habitats directly to regolith, such as by burying.

6. The LSH concept ***shall*** utilize in situ resources, including both natural and repurposed resources. [Technical]
7. The LSH concept ***shall*** identify and define the surface equipment concepts necessary to emplace, assemble, and/or construct the safe haven shelter. [Programmatic]
8. The technologies included in the LSH concept ***shall*** be be ready to be deployed and operational on the lunar surface by 2026 (TBR), according to the Artemis Program. [Programmatic]
9. The Lunar Safe Haven ***shall*** be compatible with NASA's lunar lander systems to be selected by HEOMD. [Programmatic]

Functional Decomposition – Shelter (As of 2/23)

The Lunar Safe Haven Concept (LSHC) will consist collectively of: (A) a shelter, (B) systems to establish the shelter (whether via emplacement, assembly, construction, and/or manufacturing), and (C) systems to perform and maintain general operations of the shelter.

(A) The functions of the LSHC shelter must be to:

1) Store the crew and some amount of electronics and other exploration and habitation systems, including:
    a) Allow shipping and receiving (in and out)
2) Protect from radiation for at least 10 years without exceeding the proxy dose limits for crew and electronics, including: [Mapped to L-0 Req. 1]
    a) Protect the crew
    b) Protect some amount of electronics and other exploration systems
3) Protect from the hazards of the lunar environment—including but not limited to micrometeoroid impacts, thermal loads, seismic activity, electrical charging, dust, vacuum, and the sun—for at least 10 *(TBR)* years, including: [Mapped to L-0 Req. 2]
    a) Protect the crew
    b) Protect some amount of electronics and other exploration systems
4) Protect from the impacts and damage from other external assets that could cause collisions or ejecta for at least 10 *(TBR)* years, including: [Mapped to L-0 Req. 3]
    a) Protect the crew
    b) Protect some amount of electronics and other exploration systems

In addition, options for the shelter might include:

1) Provide a protected area for servicing systems
2) Manage/remove lunar dust for individual LSHC systems *(not Artemis systems inside the shelter).*

Functional Decomposition – Establishment Systems (As of 2/23)

According to Level Zero Requirement 7, the LSHC shall identify the concepts needed to emplace, assemble, and/or construct the LSHC shelter on the lunar surface. Collectively, the systems that will be identified in the emplacement/assembly/construction trade space will be known as the "LSHC establishment systems". The list below represents the functions of the establishment systems that *might* be included—but are not required—to satisfy Level Zero Requirement 7.

(B) The functions of the LSHC establishment systems might be to:

1) Transport LSH systems from lander off-loading site to the establishment site
2) Deploy Location Determination Reference Systems
3) Survey the installment location
4) Prepare the site for installment of the LSHC shelter
5) Emplace, assemble, and/or construct the LSHC shelter, including:
   a) Deploy the LSHC systems
   b) Accept construction materials at the installment site
   c) Process construction materials
   d) Construct shelter structure
   e) Install equipment

Some functions are subsequently broken down into lower-level functions

Continued:

5) Receive distributed power from the Artemis surface power source, ***OR*** generate power independently
6) Communicate and provide sufficient command and data handling with other surface systems, including:
   a) Send and receive data to/from LSHC and other Artemis systems on the lunar surface
   b) Manage algorithms for autonomy
   c) Distribute commands among agents
   d) Connect to and accept internet from the Artemis Base Camp elements
7) Manage/remove lunar dust for individual LSHC systems *(not Artemis systems inside the shelter)*, including:
8) Manage thermal control for individual LSHC systems *(not Artemis systems inside the shelter)*

Functional Decomposition – Operations Systems (As of 2/23)

According to Level Zero Requirements 1-3, the LSHC shelter shall operate for at least 10 years. Collectively, the systems that will be identified in the maintenance/repair trade space will be known as the "LSHC operations systems". The list below represents the functions of the operations systems that might be included—but are not required—to satisfy the Level Zero Requirements 1-3.

(C) The functions of the LSHC <u>sustained operations systems</u> might be to:

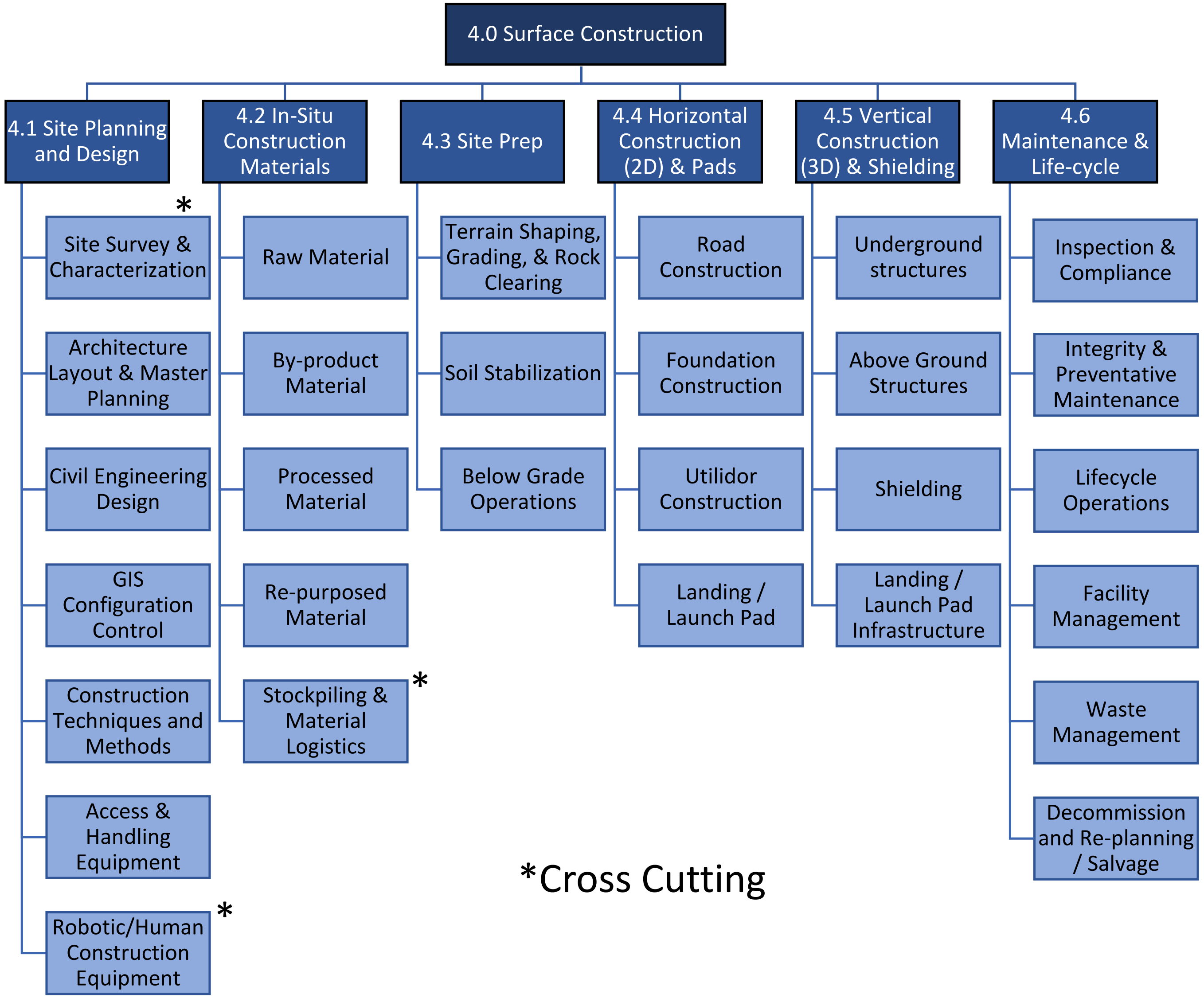
1) Maintain successful operation of the LSHC, including:
   a) Identify and respond to anomalies during the establishment of the shelter
   b) Inspect and verify that the establishment of the shelter has completed successfully, and confirm operational readiness
   c) Provide continuous health monitoring and fault identification the LSHC operations
   d) Provide appropriate audits to verify operational readiness during LSHC operations
   e) Identify and respond to anomalies during operations lasting up to TBD years
   f) Perform maintenance and repairs of LSHC systems
   g) Support tool changes during repairs and operations
2) Manage waste and trash, including waste from construction, maintenance, and operations (i.e., logistics wrappers and general trash).
3) Monitor the lunar environment to provide information on space weather conditions, radiation, seismic activity, and other conditions relevant to protection of crew and surface systems.

Continued:

4) Receive distributed power from the Artemis surface power source, OR generate power independently
5) Communicate and provide sufficient command and data handling with other surface systems
6) Manage/remove lunar dust for individual LSHC systems (not Artemis systems inside the shelter), including:
7) Manage thermal control for individual LSHC systems (not Artemis systems inside the shelter)

#4-7 are the same functions as for Establishment Systems

Functional Capabilities WBS – Surface Construction



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