Assessing the Relocation of Artemis Lunar Surface Concepts

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***Abstract* — The National Aeronautics and Space Administration (NASA) has defined a functionally based Moon to Mars (M2M) architecture consisting initially of four key human exploration segments: human lunar return (HLR), foundational exploration (FE), sustained lunar evolution (SLE), and humans to Mars (H2M) [1]. These segments are portions of the architecture which represent a stepwise increase in complexity and achievement of M2M objectives. As systems are deployed during the FE segment, it may be desired or even necessary to relocate these elements on the lunar surface. While some Artemis elements under development, such as rovers, are being designed for mobility during both crewed and uncrewed/dormant periods, other element concepts do not currently carry a mobility capability. A team was assembled to establish a methodology for assessing the feasibility of relocating normally stationary elements. Such a capability could be applied locally or regionally, and might allow for re-purposing previously occupied terrain, expansion of exploration range, aggregation of habitation elements, or retiring systems at the end of their useful service life.**

The NASA team investigated the relocation trade space through defining a representative concept of operations and assessing possible system impacts. The team focused predominately on the relocation of medium and large surface habitat architectural concepts through surface-based traverses utilizing separable mobility platforms. A representative mobility platform model was placed through simulation to analyze the possible energy requirements and dynamic illumination impacts. Preliminary assessment indicated that element relocation might be achievable, however significant system and architectural-level

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risks still need to be quantified to properly evaluate the methodology. Future analysis will assist in determining what degree of element relocation provides the greatest benefit to achieving a sustained lunar presence.

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1. INTRODUCTION

As NASA and its international and commercial partners are set to return to the Moon and prepare for Mars exploration under Artemis, a quintessential question remains in connection to establishing a sustained, human lunar presence: Will a sustained presence consist of large, static base infrastructure, constantly nomadic expeditions, or a combination of both approaches? To begin qualitative and quantitative analysis of this question, NASA established a team to investigate approaches for the relocation of normally static lunar surface elements, such as surface habitation, during crewed missions. This relocation study was part of the 2023 strategic analysis cycle (SAC) that include studies to inform architectural-level trades and assessments while ensuring alignment with the guiding M2M objectives [1,2]. The study completed a cursory review of relevant M2M objectives, identified a trade space, captured applicable ground rules, assumptions, and constraints, identified a notional concept of operations (ConOps), narrowed focus to surface-based traverses, established likely modifications required for surface habitat concepts, and completed a first-order analysis of the energetics required for a surface-based relocation traverse. The steps in this process have helped to identify a methodology and tools that will allow further iteration of architectural concepts to determine the overall feasibility of foundational element relocation.

2. ELEMENT RELOCATION & M2M OBJECTIVES

An initial component of this study was to determine how NASA's Moon to Mars Objectives [1,2] support the capability of element relocation to fulfill the overall architecture. There are several objectives that are expected to drive the need for element relocation. Element relocation could have a positive impact on many science-related objectives by providing additional opportunities to explore multiple regions on the lunar surface. A few specific objectives that are expected to be positively impacted by element relocation as well as their rationale for inclusion can be seen in Table 1. These objectives largely relate to demonstrating the ability to move and perform activities at multiple regions on the lunar surface.

TABLE I:

MOON TO MARS OBJECTIVES POTENTIALLY POSITIVELY IMPACTED BY ELEMENT RELOCATION AND THEIR RATIONALE

M2M Objective	Expected Positive Impact with Element Relocation
SE-4: Return representative samples from multiple locations across the surface of the Moon and Mars, with sample mass commensurate with mission-specific science priorities.	Element relocation will allow for more sampling opportunities through the ability to access multiple locations across the lunar surface.
SE-6: Enable long-term, planet-wide research by delivering science instruments to multiple science-relevant orbits and surface locations at the Moon and Mars.	Element relocation is a step towards planet-wide research by enabling access to multiple locations across the lunar surface.
LI-6: Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.	Trade space options considered in this study demonstrate the mobility capabilities of some elements in architecture.
LI-7: Demonstrate industrial scale In-Situ Resource Utilization (ISRU) capabilities in support of continuous human lunar presence and a robust lunar economy.	Utilizing resources for element relocation, particularly for propulsive traverses, may incentivize growth of ISRU capabilities to an industrial scale.
TH-3: Develop system(s) to allow crew to explore, operate, and live on the lunar surface and in lunar orbit with scalability to continuous presence; conducting scientific and industrial utilization as well as Mars analog activities.	Element relocation can allow for opportunities to explore more of the lunar surface, while also enabling scalability through surface-based aggregation of habitable elements.
OP-3: Characterize accessible resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable use of resources on successive missions.	Element relocation can allow for more opportunities to explore, characterize, and analyze more of the lunar surface and its available resources.
OP-5: Operate surface mobility systems, e.g., extra-vehicular activity (EVA) suits, tools and vehicles.	Trade space options considered in this study demonstrate the potential to mobilize elements otherwise considered stationary/fixed.

In addition to the M2M objectives which may benefit positively from element relocation, there are similarly a few objectives expected to be negatively impacted, which are captured in Table 2.

TABLE II:

MOON TO MARS OBJECTIVES POTENTIALLY NEGATIVELY IMPACTED BY ELEMENT RELOCATION AND THEIR RATIONALE

M2M Objective	Expected Negative Impact with Element Relocation
SE-7: Preserve and protect representative features of special interest, including lunar permanently shadowed regions and the radio quiet far side as well as Martian recurring slope lineae, to enable future high-priority science investigations.	Element relocation might disturb additional sites on the surface when an element is relocated, forcing additional complexity, mass, and cost in order to mitigate disruption.
OP-12: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.	Element relocation might disturb additional sites on the surface when an element is relocated, forcing additional complexity, mass, and cost in order to mitigate disruption.

It should be noted that there are several M2M objectives in which element relocation could serve both as a detriment and benefit. Examples of these include several of the infrastructure objectives (LI) which are aimed at scaling an interoperable power, communications, position, navigation and timing, advanced manufacturing and construction, and ISRU infrastructure to see growth of a robust lunar economy (i.e., LI-1, LI-2, LI-3, LI-4, LI-7). Initial scaling of such capabilities may be challenged by the relocation of foundational elements by hindering the development of a centralized customer, yet the ability to relocate elements could also allow for further growth by providing opportunity for a greater number of providers and/or services. While the general observation was made that element relocation holds many benefits to the M2M objectives, the timing of when to introduce the capability in the progression from foundational exploration to sustained lunar evolution warrants further investigation.

3. TRADE SPACE

The trade space for element relocation was identified to consist of three major areas: the functional class of mobility platform, the platform options themselves, and the mass category of payload being transported. Two major functional classes of mobility (e.g., separable vs. integrated), six major mobility platform options, and three payload categories were identified to generally scope the trade space for element relocation (see Figure 1). Mobility platform options were further divided into surface mobility systems and propulsive mobility systems. Each of these areas were investigated leading to a selected trade scope for further assessment.

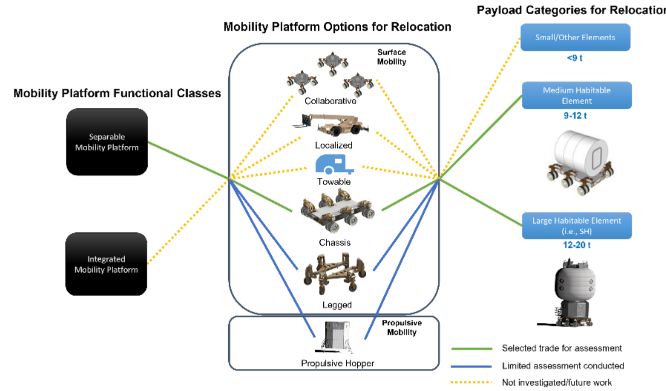

Figure 1. Element relocation trade space

Multiple elements are envisioned to operate on the lunar surface under Artemis. Current elements include: a pressurized rover (PR), a pressurized habitable volume that enables 2 crew to traverse the lunar surface for exploration; a lunar terrain vehicle (LTV), an unpressurized mobility system for crew transport similar to the Apollo lunar rover; exploration Extravehicular Activity (xEVA) suits, allowing crew to explore and interact directly with the lunar environment and exploration systems; and a human landing system (HLS), which delivers and returns crew to and from the lunar surface. Current concepts under consideration are various lunar surface habitats (SH), which can nominally support 2 crew for missions of up to 30 days. A notional example provided here is of a hybrid inflatable/metallic habitat (see Figures 2 & 3).

Figure 2. Artistic representation of Artemis reference elements and concepts (left to right: xEVA suits, SH, PR, LTV) (Credit: NASA)

Figure 3. Human Landing System - HLS (Credit: SpaceX)

A relocatable habitat is differentiated from other mobile habitable elements, such as the PR, in the intent to mobilize it between crewed missions, thereby allowing exploration of new regions and/or possibly extending the operational range of the PR, LTV, and exploration Extravehicular Activity (xEVA) suits. This study focused on the relocation of two classes of habitation elements as bounding cases for payload mass, volume, and center of gravity (CG) (see Figure 4). A medium-sized habitation element, considered to be similar to the existing Cygnus spacecraft, would be metallic module in a horizontal orientation. A large-sized habitation element, based upon NASA's current SH reference concept, would consist of a vertically oriented metallic barrel and a top-mounted multi-story inflatable section. Representative specifications for these elements are listed in Table 3.

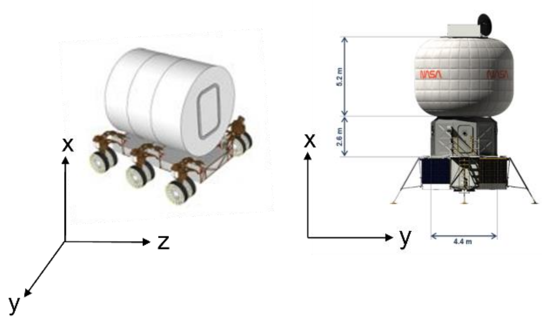

Figure 4. Medium (left) and large (right) habitation reference concepts considered in analysis.

TABLE III:
HABITATION REFERENCE CONCEPT SPECIFICATIONS FOR ANALYSIS

Element	Length (m)	Width/ Diameter (m)	Height (m)	Mass Range (t)	Center of Gravity (m)	Max Power Generation (kW)	Min Power Load (kW)	Min Power Energy Storage Duration (hr)
Medium	4.4	4.8	4.8	9-12	2.4	5.2	2	150
Large (SH)[1]	4.4	6.5	7.8	12-20	5.0	15.3	4.2	100

[1] *SH concept length is the equivalent diameter of metallic potion of the habitat with the width representative of the inflatable portion. Mass captures possible growth with outfitting and gradual inclusion of regenerative Environmental Control and Life Support Systems (ECLSS). CG range is estimated between 4.94 m and 5.01 m pending regenerative ECLSS outfitting and was taken to be 5m for the purpose of analysis.*

4. Mobility Platform Options

Historical assessments of lunar relocation options encompassed a variety of mechanical and operational platforms. Most can broadly be grouped into two categories defined by their method of locomotion – propulsive relocation systems and surface mobility systems. Surface mobility systems traverse across the lunar surface with wheels, tracks, or legs. Propulsive relocation systems ascend from their initial landing site and descend to their target relocation location using rocket engines, with the trajectory defined as either suborbital hops or a return to orbit.

Surface mobility systems can be further subdivided to include collaborative, localized, towable, legged, and chassis type systems. Collaborative robotic mobility platforms (i.e., multiple, load-bearing systems that aggregate to enable the relocation of a single element) were assumed to be subsets of either legged or chassis-based mobility platform variants and thus deferred for future study. Similarly, mobility platforms that may be tailored to more localized relocation (i.e., offloading from a lander and providing precise, surface-level emplacement) were thought to similarly decompose into either legged or chassis-based variants yet suited to short-duration traverses over relatively benign terrain. Towable platforms were eliminated from the initial study since massive payloads, such as habitats, would still require powered wheels to overcome bulldozing effects across unimproved lunar terrain. While these three mobility platform options were not investigated in this initial assessment, consideration may be given to these options for further analysis and iteration. Following consideration of the mobility platform trade space, further focus was given to propulsive hopper, legged, and chassis-based relocation methods.

A. Propulsive Hopper Platform

Propulsive flight and landing capability in the lunar environment is a prerequisite for any lunar mission, as is the ability to take off from the lunar surface for any crewed lunar mission. Large crew and cargo landers currently being developed for the Artemis program tend to conform to a 'single-stage lander' concept, unlike Apollo-era crew vehicles in which a separate ascent stage returned the crew to lunar orbit after their surface mission. These single-stage landers must be capable of loitering on the lunar surface, managing propellant, and re-lighting engines after over a month of standby. As hopping across the surface generally requires less performance than returning to orbit, there are potential opportunities to relocate equipment across the surface using a pre-existing delivery lander as opposed to a dedicated mobility asset.

Initial trade space construction, scoping, and investigation activities indicated that propulsive hopper relocation options presented some qualitative advantages compared to both surface mobility options from a payload perspective. Such advantages included: mitigating the need for new mobility platforms, eliminating offloading or attachment operations, and providing short-duration transits with fewer terrain limitations and greater possible relocation range. Despite the perceived advantages, the differences in operation and deployment compared to surface-based mobility systems were considered great enough that direct quantitative comparison would not be useful. Instead, a precursory analysis of the propellant requirements of a propulsive hopper was conducted.

Assessing a smooth spherical Moon, ΔVs needed for hopping range from 401 m/s to 1108 m/s for relocation between notional lunar south pole sites of interest. With a dry vehicle stack mass assumption of 15.7 t and a cryogenic hydrogen propulsion system, corresponding propellant masses to support hopping range from 2.7 t to 8.3 t.

Landing multiple tonnes of additional propellant on the lunar surface in addition to a habitation payload, storing it for multiple years, and maintaining the safety of that payload may be achievable with current technology, however it introduces significant complexity. To mitigate this, the hopper can be refueled prior to a relocation either on the surface or in orbit. Orbital refueling requires the hopper to carry enough propellant for an ascent to low lunar orbit (LLO) and rendezvous with a resupply vehicle. Regardless of the relocation distance, a propellant tanker must be launched to LLO carrying propellant for the hopper, necessitating additional launch vehicle and tanker acquisitions.

Surface refueling from a landed tanker has similarly high costs in launch vehicles and tankers, with additional requirements that the tanker be able to land on the lunar surface and that a method to transfer propellant between vehicles on the lunar surface exists. To avoid this cost and complexity, surface refueling architectures can instead utilize space-based resources (e.g., ISRU) for propellant without the need to ship multiple tons from Earth for each hop (see Table 4). Cryogenic propulsion systems, such as the hydrogen-oxygen system examined in this preliminary work, can make use of oxygen extracted from regolith as an oxidizer.

TABLE IV:

PROPELLANT ANALYSIS OF A PROPULSIVE HOPPER ENABLED BY ISRU

Threshold Lander Residual Propellant ISRU Case						
	Hop 1 (Site A to B)		**Hop 2 (Site B to C)**		**Total**	
Distance	43	km	91	km	134	km
ISRU O2	3000	kg	3000	kg	6000	kg
Req O2	4272	kg	5276	kg	9548	kg
Req H2	754	kg	931	kg	1685	kg
Residual	2026	kg	3207	kg	5233	kg
Savings	3797	kg	3000	kg	6797	kg

Even low-volume oxygen extraction that would be expected of early pilot plants may provide enough oxidizer to facilitate relocation after a few years of operation.

After initial scoping, propulsive relocation options were removed from the study's trade space. Opportunities exist for propulsive relocation options, especially when considering the impact of space resources on total propellant delivery requirements and may be subject to future study.

B. Legged Mobility Platform

Legged platforms are at a low technology readiness level with no relevant flown hardware, although testing on Earth has been extensively conducted since 2005. With each leg ending in a powered wheel, a legged platform is capable of both efficient 'rolling' traversal and 'walking' traversal when encountering terrain that would be otherwise impassible. The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE), developed by the Jet Propulsion Laboratory (JPL), is used as the basis for legged mobility platforms (see Figure 5). A Tri-ATHLETE consists of two independent robots equipped with three seven-degree-of-freedom articulating limbs each that can attach to a central pallet, forming a single six-limbed mobility platform. Two generations of ATHLETE, a lighter-weight but less functionally capable 'blade-type' with limbs constructed of metal 'blades' connected at the joints, and a heavier 'tendon-type' system that uses cables for articulation and to provide additional crane/winch functionality, are included in this study's trade space [3].

Figure 5. ATHLETE navigating natural terrain (Brian Wilcox, 2012) [4].

While there are distinct advantages to use of a legged mobility platform, resources did not allow for a detailed analysis in the current iteration of the element relocation study.

C. Chassis Mobility Platform

For this study, NASA's Chariot mobility chassis (see Figure 6) is used as the basis for rover-type surface mobility system sizing. Chariot is a mature NASA lunar mobility concept introduced in 2007 and used as the basis for government reference PR designs and human-in-the-loop testing [5]. The Chariot consists of a rigid chassis with six independently steerable wheel pods, each containing two wheels. Each wheel pod contains its own electric motor and active suspension. This design enables traversal over a variety of surface conditions, and enables 'crabbing', an operation where the vehicle is driven at an angle by rotating all its wheel pods. Active suspension control also allows for a degree of self-leveling, that is adjusting the height of wheels with respect to each other to alter the platform's, and therefore the payload's, attitude [5].

Figure 6. Chariot rover testing in Moses Lake, WA (Kevin Pratt, 2008)

5. SEPARABLE MOBILITY PLATFORMS

For this study, two functional classes of mobility were considered: integrated and separable. Integrated mobility platforms are permanently attached to the element, payload, or system as a monocoque design and thus necessitate being delivered with their parent element. Separable mobility platforms (SMPs) are considered detachable from their payload and could be delivered separately or de-coupled from their originally allocated element to allow re-use. The increased mass and complexity of integrated mobility may push the limits of delivery systems (i.e., launch vehicles and landers) and impose new constraints on the size and/or functionality of the element being transported. Conversely, using a SMP adds complexity with detachable interfaces but allows a single platform to possibly be used for multiple elements or purposes. These two approaches have their own set of advantages and disadvantages, which should be considered based on the specific requirements of the lunar mission.

A. Pros of Using a Separable Mobility Platform:

- Modularity and Customization: SMPs offer modularity, allowing for the independent design, development, and customization of the mobility system. This modularity facilitates flexibility in adapting the mobility platform to mission-specific needs and environments.

- Task-Specific Mobility: SMPs can be tailored to perform specific tasks on the lunar surface, such as sample collection, scientific exploration, resource utilization, logistics ferrying, all in addition to moving elements between locations (see Figure 7). This specialization can enhance the effectiveness and efficiency of lunar missions.

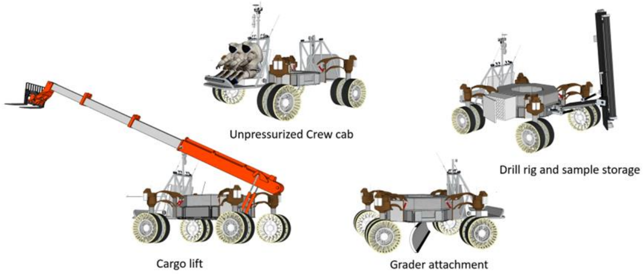

Figure 7. Examples of task-specific configurations achieved through modular attachment of equipment.

- Scalability: SMPs can be scaled up or down based on mission requirements (see Figure 8). The same mobility platform can be configured for different vehicles or even for larger payloads, optimizing resource utilization.

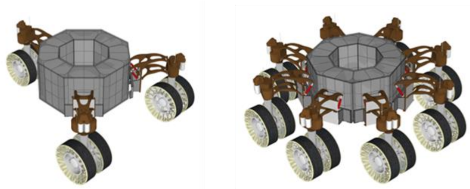

Figure 8. Example of a configurable modular mobility platform configured for light (left) and heavy (right) payloads.

- Redundancy and Mission Reliability: Separating the mobility system from the primary vehicle adds redundancy. If the primary mobility system encounters issues, it can be separated from the payload element and replaced by a second SMP, enhancing mission reliability.

- Ease of Maintenance: SMPs can be designed for easier access and maintenance. This facilitates quicker repairs or replacements of mobility components, minimizing downtime.

- Payload Flexibility: SMPs can be configured with a common interface to accommodate various payloads or scientific instruments, making it easier to transport and deploy equipment on the lunar surface.

- Technological Innovation: SMPs provide opportunities for research and innovation in mobility technologies. Researchers can focus more on improving mobility efficiency, autonomy, and sustainability without constraints imposed by systems which are initially integrated at deployment. As mobility system technology evolves, the older SMP can be swapped out with a better model.

B. Cons of Using a Separable Mobility Platform:

- Complexity: The use of an SMP adds complexity to mission planning, integration with other surface elements, and operations. It requires additional components, interfaces, and coordination and may require additional launches, albeit each delivering more functional sub-elements.
- Mass and Volume: SMPs can increase the mass and volume of the lunar vehicle. Some equipment redundancies may exist to allow each sub-element to operate independently. Operating a heavier vehicle may present challenges, especially in terms of energy for locomotion, etc.
- Cost: Developing and integrating an SMP can increase mission costs. The development and testing of a separate mobility platform may require a substantial investment unless the single unit can replace multiple integrated subsystems.
- Integration Challenges: Integrating an SMP with the primary vehicle and its systems can be technically challenging. Compatibility issues may arise, and the coordination of multiple subsystems may be complex, possibly requiring ancillary support systems (i.e., cranes, davits, etc.) to complete.
- Testing Complexity: Testing and validating the interaction between the SMP and the lunar vehicle's systems can be more complex, requiring additional time and resources.
- Mission-Specific Design: Designing an SMP for a specific mission may limit its versatility for future missions, potentially reducing its cost-effectiveness in the long term.
- Resource Utilization: Deploying an SMP consumes valuable resources, including power, communications bandwidth, and engineering effort.

Using a SMP offers flexibility, specialization, and redundancy but comes with added complexity, cost, and integration challenges. The decision to use SMP or integrated mobility functionality should be made after careful consideration of mission objectives, available resources, and technical constraints. Each approach has its merits and drawbacks, and the choice should align with the specific needs and goals of the architecture. Upon investigating this area of the trade space, the study set an initial focus on an SMP-based architecture to aid in separately assessing the needed functional capabilities of a mobility system and the relocatable payload (i.e., habitat).

6. GROUND RULES, ASSUMPTIONS, AND CONSTRAINTS (GRA&CS)

GRA&Cs were applied to further define the trade space's boundaries. Ground rules are unchangeable architecture-level factors applied broadly across trade studies. Assumptions are study-specific factors derived from engineering judgement which could change in future iterations of analysis. Constraints are study-specific bounds derived from analysis and less likely to change in future iterative analysis. Table 5 on page 8 identifies some of the GRA&Cs that were applied to this study.

7. CONCEPT OF OPERATIONS (CONOPS)

To aid the relocation assessment, a generalized concept of operations was formulated for surface-based relocation methods and considered to be agnostic of the mobility platform chosen (see Figure 9).

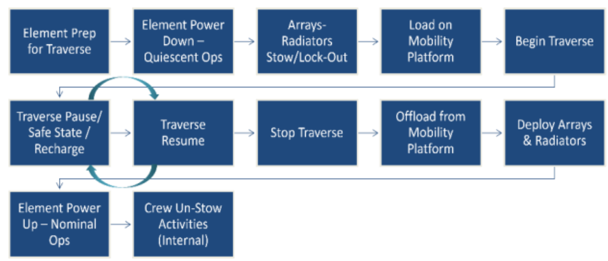

Figure 9. Generalized ConOps for surface-based element relocation.

This ConOps details a few critical steps as follows:

- Element Preparation for Traverse: It is considered that certain systems will need to be specially configured and/or safed to support the likely vibrational loads and variable terrain-induced angles encountered during a surface-based traverse. Preparing the relocatable element for traverse may include crew-based activities prior to crew departure and/or automated or commanded activities.
- Element Power Down – Quiescent Ops: In alignment with the assumption that relocatable elements will be self-sufficient throughout the traverse, it is expected that the element will be powered down to minimal, quiescent operational loads for power and thermal management.
- Arrays-Radiators Stow/Lock-Out: This step protects for stowage and securing of deployed systems which may not withstand traverse operational loads. Such systems may re-deploy during pauses along the traverse as required.
- Load on Mobility Platform: Assuming a SMP architecture, the relocatable element will need to undergo a loading/emplacement operation allowing connection to the mobility platform. This operation could be completed through numerous different methods to include cranes, davits, or mobility systems that are capable of self-loading. This step may be performed earlier in the sequence or may be omitted if relocatable element remains affixed to its mobility platform from a previous traverse.

TABLE V:

GRA&CS APPLIED TO THE ELEMENT RELOCATION STUDY

GR/A/C[1]	Text	Notes
GR	Delivered relocatable elements will adhere to Human-class Delivery Lander (HDL) mass & volumetric delivery constraints.	Should relocatable elements be integrated with mobility platforms, they must conform to current HDL delivery constraints (12 t threshold, 15 t goal) [6].
A	Relocation of elements to new operational and/or hibernation locations will nominally occur between crewed surface missions.	In alignment with definition of a relocatable element and differentiating from mobility elements used during a crewed mission.
A	Habitable relocation elements will nominally remain fixed/stationary during crewed missions.	Does not preclude contingency relocation during crewed operations if it can be supported (i.e., the habitable element remains attached to its relocation platform).
A	Relocatable elements will be considered self-sufficient payloads during the relocation process for a set duration.	While sharing of power, data, comms, etc. may lead to some efficiencies between a relocatable element and its mobility platform, the relocatable element should be considered entirely self-sufficient for initial analysis. The duration of self-sufficiency for energy storage should align with current darkness survival durations and minimal power loads.
A	Other mobility assets (i.e., LTV, PR) may be assumed to be present for relocation with analysis capturing their assumed roles if relevant.	Given currently assumed elements supporting the HLR and FE segments of lunar exploration, LTV and PR will be present and may be leverage in support of relocation operations if warranted.
A	Relocatable elements will minimize the use of deployed hardware during traverses.	Arrays, radiators, and other deployed items are likely to add additional constraints on traverse conditions as well as face additional loading and dust accumulation risks and can be assumed to stow and re-deploy for traverse.
C	Four representative masses will be used for this study to capture the two major payload mass categories: 10 t, 12 t, 15 t, and 20 t.	Two primary elements are in consideration for assessing the benefits & risks of relocation: a large habitat (SH) that could approach 20 t after outfitting and a medium-sized habitat that could fall in a 9-12 t range. The representative masses chosen encompass several architectural concepts in-trade.
C	Capabilities for offloading and emplacing relocatable elements onto separable mobility platforms can be assumed to be available independent of the relocatable element, but must be documented.	Identified needed capabilities is an output of this study while focusing on the feasibility of tailoring elements to allow relocation and the degree to which certain masses and geometries can be relocated on the lunar surface. Design of offload systems should be considered, with assumptions documented, but will not be a product of this study.
C	Surface traverses of relocatable elements will be completed so as to minimize exposure to darkness while respecting a maximum slope steepness and a minimum communication window.	This will aid navigation/hazard avoidance and provide opportunity for solar-based recharge as required. Communication can be direct-to-Earth (DTE) or relayed via Gateway.
C	Surface traverses of relocatable elements will not exceed the time between missions (~11 months).	Assumes up to a 1-month mission once a year.
C	Traverse paths will not exceed slopes of 20 degrees.	Based on current understanding of system stability. Likely to become more constraining as the understanding of involved systems evolves.

1. All existing Artemis GRA&Cs still apply to relocatable habitation elements. To avoid unnecessary duplication of parent GRA&Cs, only the GRA&Cs that are unique to element relocation will be documented.

- Begin Traverse/Pause/Resume/Stop: Four segments of the ConOps outline actual traverse operations and entail: first motion; pausing for system recharge, terrain assessment, contingencies, or illumination; resumption of the traverse after a pause; and final emplacement/stopping of the traverse. The number of pauses that may be necessary during a traverse are to be analyzed. Note that during a traverse pause, it may be required to re-deploy arrays and radiators for system recharge and thermal control.
- Offload from Mobility Platform: An optional action assuming needed re-use of the SMP or desire for permanent element emplacement in a new location.
- Deploy Arrays & Radiators: This step will be needed after a set period of time to allow for full power generation, thermal control, communications, and other such capabilities to facilitate post-relocation operations.
- Element Power-Up: Upon completion of the traverse, the element may resume normal operational power, thermal, and other system loads. This step serves as verification that all necessary crew and habitation systems can successfully operate following the relocation before a commitment is made to deliver crew to the new location.
- Crew Un-Stow Activities: This step signifies the final step during crew arrival and results in internal reconfiguration that may be required to ensure an appropriate work environment for a stationary element.

8. SYSTEM SIZING

A. Mobility Element Sizing

While some benefits of SMP warrant further investigation, a chassis-based platform was chosen as a representative mobility element design that could support lunar traverse analysis while leveraging existing models. Chariot-derived data and a CAD model of the chassis, shown in Figure 10, were used to initially size the mobility element to support up to 10 t of payload, the median mass for the medium-sized habitat element. To accommodate payloads over 10t, the mass of the mobility element is increased. Table 6 provides a breakdown of the mobility element subsystem masses. The total mass of the system is ~2,300 kg and has an overall predicted mass of ~2,800 kg after accounting for potential mass growth. Table 6 breaks down some of the high-level design constraints and parameters of the mobility element.

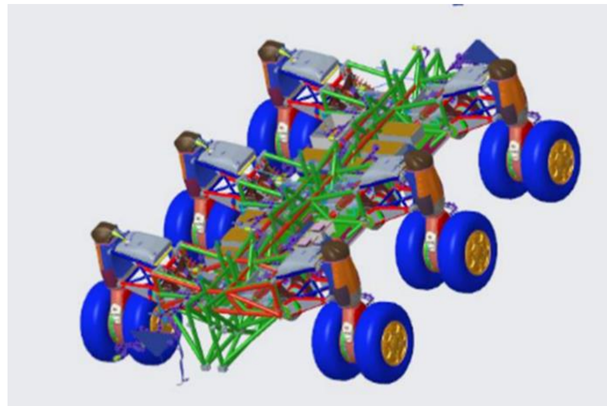

Figure 10. Chariot-derived Mobility Element CAD Model.

TABLE VI:

MOBILITY ELEMENT DESIGN CONSTRAINTS AND PARAMETERS

Design Constraints/Parameters	
Element Lifetime	10 yrs
Destination	Moon
Length	4.2 m
Width	3.5 m
Height	1.2 m
Ground Clearance	0.5 m
Wheel Diameter, 10-15t Payload	0.7 m
Wheel Diameter, 15-20t Payload	1.0 m
Wheel Width (wheel pairs)	0.66 m
Max Speed (no payload)	15 kph
Max Speed (all Payloads)	4 kph
Max Driving Distance Per Charge	50 km
Slope Limit (uphill/downhill)	20
Energy Generation	Solar
Thermal Control	Radiators, Heat Sinks
Overall Mass	2800 kg

B. Habitation System Sizing

In reviewing the current SH government reference concept, a total of four notable design modifications were identified in the areas of power, thermal control, and structure based on this analysis. Re-deployable arrays and radiator panel functionality would likely be needed to minimize oscillatory loading, fatigue, and dust accumulation during relocation. Roll-out Solar Arrays (ROSA) or similar, capable of multiple cycles, would be needed to accommodate stowage during surface traverses and re-deployment upon relocation or during pauses in the traverse. To maintain heat rejection during relocation, a small and fixed radiator panel would be added to the zenith of the habitat structure, thereby reducing some of the deployable radiator area and associated complexities. Structurally, a relocatable habitat is assumed to be capable of emplacement on the lunar surface to enable mobility platform reuse. The addition of a surface standoff system/deployable legs provides this capability. Additional modification of lift points and/or structural enhancements to allow lander offload are also envisioned. While the interface of a habitat to its delivery lander may also necessitate modification, the current assessment assumed a common interface design for a mobility platform and lander could be architected. Collectively, needed modifications were estimated to add ~650 kg of mass with growth allowances and margin to the baseline surface habitat design (see Table 7). This mass growth for a conceptual element, while exceeding the 12 t human-class delivery lander (HDL) threshold, falls within the 15 t delivery target.

TABLE VII:

MASS CHANGES TO BASELINE SURFACE HABITATION REQUIRED TO ACCOMMODATE RELOCATION

Category	Basic Mass (kg)	Predicted Mass w/MGA (kg)	Gross Mass w/Margin (kg)
Power Deltas	+130	+150	
Thermal Deltas	-20	-30	
Structure Deltas	+240	+280	
SH Baseline (12mt)	8600	10000	11850
Relocatable SH Baseline	8950	10400	12500

9. TRAVERSE ROUTE ANALYSIS

Following initial sizing activities, two analyses were conducted to evaluate both the energy usage for a chassis-based mobility platform and the energy balance of habitation energy storage systems.

A. Lunar Traverse Modeling and Simulation

To further assess the feasibility of element relocation, four mass classes of notional habitat payloads (10, 12, 15, and 20 t) were evaluated using a Johnson Space Center (JSC)-developed physics-based rover simulation built in the Trick Simulation Environment [7]. This simulation includes lunar terramechanics modeling [8-10] and was utilized to calculate the energetics of a revised chassis model based upon the NASA Chariot government reference mobility concept [4]. Several traverses between representative Artemis proposed landing regions were simulated [11]. Notional traverse routes were generated using a blended cost raster. Weighting was applied to three criteria (slope, average solar illumination, and DTE communication availability) and then a least-cost algorithm calculated the traverse paths between sets of desired locations.

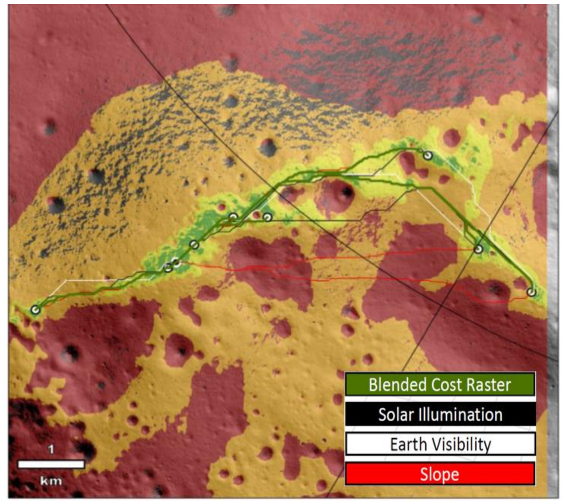

Figure 11. Example traverse paths generated through least-cost-path models, considering a suite of individual factors as well as a weighted, blended raster. These traverses were generated to connect several points of favorable average solar illumination within a candidate region [11]. The longer traverses analyzed in this study were derived using a similar approach.

Figure 11 highlights the impact the individual criteria have on the calculated traverse paths. Each path is colored according to the individual criteria, or a weighting of all three is used for the blended cost raster, which was utilized to create the traverse. Considering only slope (the red traverse lines) results in different paths across the surface as opposed to considering only Earth visibility (the white traverse lines). The lighting in this analysis was averaged over an 18-year cycle, useful to identify areas of frequent light but also of heavy darkness. Season-specific conditions such as the deep, sustained shadows of the lunar south pole winter periods (see Figure 12) will be addressed in further studies.

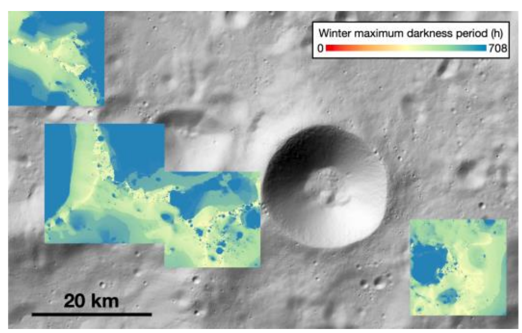

Figure 12. Periods of maximum continuous shadow during lunar south pole winter over the Artemis III candidate landing regions, at a height of 2 meters above the surface.

Thus, for each notional traverse route, a dynamic lighting analysis was also performed to supplement the average lighting analysis. These dynamic analyses map out the lighting conditions during a particular epoch to identify areas with relatively high fractional solar visibility that would support a stationary dwell to replenish energy reserves or while awaiting favorable lighting conditions to proceed to the next hibernation point.

For a rover to successfully drive one of the generated least cost paths, times of traverse and times of dwell, or stopping, at high solar visibility locations are necessary. As mentioned previously, for each traverse calculated from the blended cost raster, a lighting analysis was performed [12]. The left plot in Figure 13 shows lighting conditions along one of the generated traverses. In this plot, color represents light (fraction of solar flux) available at 10 m above the surface with blue indicating shadow and red indicating light is available. Additionally, the X-axis is days since a chosen epoch in 2030, and the Y-axis is distance along the traverse. Thus, the plot represents lighting at each point along one traverse over time. This information enables the selection of a trip through the shadows by tracing a line from 0 km to the full distance, minimizing time spent in shadow. The underlying traverse across the lunar surface remains unchanged; however, the chosen trip determines velocity and timing. The pink line on the left plot in Figure 13 shows the trip chosen based solely on this lighting data. Note that the traverse path on the surface of the Moon is the same for any selected trip. Note also that a horizontal line indicates a dwell, or stationary pause in the trip, since distance is not changing. Clearly, it is possible to have chosen slightly different trips through the shadows, but the available lighting does constrain the options.

Simulated traverses between candidate Artemis III regions for the four classes of notional payload mass were allowed an unconstrained energy storage to better determine the traverse energy costs and begin assessing energy storage needs. Since dwell, or stopped, times have no impact on motor energetics, the traverse was simulated end-to-end without stopping. The calculated energetics from the rover simulation were matched to the traverse using distance from the starting location. The right plot in Figure 13 shows these cumulative energy calculations for the same traverse as the one shown in the lighting analysis. Note that housekeeping loads, such as energy to power lights or keep the rover warm, are not included in the energy calculations presented in Figure 13. Additionally, color on this plot provides the time until shadow (still assuming 10 m above the surface) at each point along the traverse. Redder colors indicate that if the rover remains at that location along the traverse, shadow is expected within the specified number of hours. The colorbar has a maximum value of 48 hours, to indicate that the rover would have at least two full days of light in that location. However, lighting along the rest of the traverse must still be considered for the rover to arrive at its destination alive.

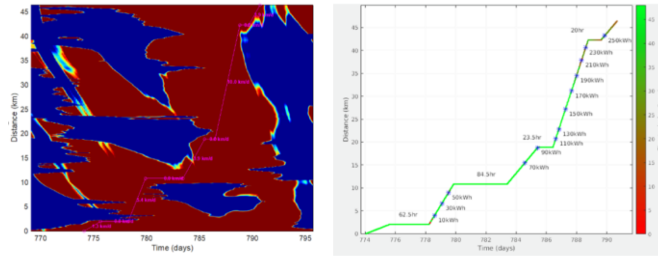

Figure 13. Example illumination matrix traverse analysis for 10 t habitat from Site A to Site B. Horizontal sections represent pauses over sunlit terrain.

For future SAC studies, the habitation energy storage capacity and the associated power architecture recharge times will be taken into account to iterate on these traverses. Factors such as traverse and dwell timing, as well as traverse starting epoch can be modified to achieve more optimal traverses. Further assessment on power augmentation needs and alternate traverse routes will be conducted as a lead-in to SAC24.

In addition to assessing illumination and energetics associated with these traverses, two habitat centers of gravity (CG) heights of 2.4 m and 5 m were assessed for stability over the varied terrain and slopes. Stability issues were discovered for the 5 m CG habitat traversing at 1 m/s (~3.6 km/hr), requiring further investigation of possible mitigations. Leading into and throughout the SAC24 cycle, the initial energetics and stability assessments will be iterated. Energy storage constraints based upon current habitation power architectures will be fielded to identify additional traverses as well as whether supplemental energy may be required at what waypoints to close each traverse. This will be worked in parallel to assessing traverse speeds and stability for various habitat CGs. Final assessment will likely include a comparison of localized traverses within a region and the associated risk mitigations and architectural impacts.

B. Habitation Energy Balance for Lunar Traverse

Energy balance calculations were needed to better assess habitat energy storage during different lunar traverse segments and to better utilize the lighting during the dwell periods, when the habitat is stationary and charging. The energy storage assessed during the period of traverse and dwell were assumed to be internal to the habitation elements considered.

TABLE VIII:
TRAVERSAL ENERGY BALANCE ANALYSIS

HABITATION ENERGY BALANCE							
TRANSITION STATUS		MEDIUM HABITAT		LARGE HABITAT			
				BATTERY-BASED ARCHITECTURE		RFC-BASED ARCHITECTURE	
Activity	Time (hrs)	Charge (%)	Remaining Charge (hrs)	Charge (%)	Remaining Charge (hrs)	Charge (%)	Remaining Charge (hrs)
SITE A to B							
Moving	38	75%	113	63%	63	63%	63
Stationary	63	100%	150	100%	100	100%	100
Moving	40	74%	111	61%	61	61%	61
Stationary	85	100%	150	100%	100	100%	100
Moving	50	67%	101	51%	51	51%	51
Stationary	24	91%	136	98%	98	72%	72
Moving	57	53%	79	41%	41	15%	15
Stationary	20	73%	109	81%	81	34%	34
Moving	25	56%	84	56%	56	8%	8
SITE B to A							
Moving	143	5%	7	-43%	-43	-43%	-43
Stationary	19	23%	35	-6%	-6	-26%	-26
Moving	46	8%	11	34%	34	-6%	-6
Stationary	39	46%	69	100%	100	29%	29
Moving	60	6%	9	40%	40	89%	89
Stationary	22	28%	41	83%	83	100%	100
Moving	38	2%	3	45%	45	62%	62
SITE A to C							
Moving	50	67%	101	50.5%	51	50.5%	51
Stationary	94	100%	150	100%	100	100%	100
Moving	137	9%	14	0%	-40	0%	-37
Stationary	110	100%	150	100%	100	100%	100
Moving	144	4%	6	0%	-44	0%	-44
Stationary	439	100%	150	100%	100	100%	100
Moving	371	0%	-221	0%	-271	0%	-271
SITE C to A							
Moving	101	33%	49	-1%	-1	-1%	-1
Stationary	50	83%	124	99%	99	44%	44
Moving	200	0%	-50	0%	-100	0%	-100
Stationary	74	74%	110	100%	100	67%	67
Moving	93	38%	57	7%	7	7%	7

The analysis only included energy balances for traverses between representative sites: Site A and Sites B/C. Based on this energy balance assessment, the team may be able to implement complete traverse and dwell periods and refine the calculation methods for future analysis.

Habitation energy storage was not utilized for the mobility operations (i.e., the mobility system and habitat were considered to have their own energy storage systems). Each system would be charged or discharged according to their individual capacities/characteristics. For the medium mass habitat, the storage capacity was baselined as 150 hours to depletion with a recharge time of 100 hours considering a battery-based architecture. For the larger habitat, or SH, 100 hours of energy storage was assumed with two different architectures considered: a) a battery-based architecture requiring 50 hours to recharge, and b) a Regenerative Fuel Cell (RFC)-based architecture requiring 110 hours to recharge. Based on the energy storage capacity, recharge time, traverse, and dwell time, an energy balance assessment was performed.

For simplicity, depletion and recharging time were assumed to be linear from 0 to 100 percent. The energy storage systems were assumed to only support the internal operations of the habitats at the power loads identified in Table 3 and not protect for power transfer to the mobility system. The traverse and dwell durations were aligned with the traverse analysis [12].

This cursory analysis suggested that only a traverse from Site A to B could be accomplished for both habitation concepts. Only the medium-sized habitat could support a return traverse back from Site B to A, although as little as a 5% state of charge would be encountered on the first leg. No other traverses would close under the current assumptions and architecture without possible re-adjustments to either traverse durations or dwell periods for recharge (see Table 8). No margin was included in this initial assessment but will need to be considered in future work.

10. Interim Conclusions

A. The Risks

Energy storage, and associated illumination, coupled with challenging terrain between regions make foundational element relocation complex, risky, and most likely needing supplemental elements or functionality to close with acceptable risk tolerance. The degree of needed supplementation is still being quantified, but this initial methodology suggests that supplemental power, particularly energy storage, or significant changes to the assumed power generation architecture may be needed.

B. Top 5 Risks/Concerns:

- Loss of habitable element – Relocation of an element not primarily designed for frequent mobility increases likelihood of loss (e.g., getting stuck, tipping-over, etc.)
- Energy storage capabilities – Energy storage (particularly for battery-based architectures) is one of the largest mass drivers. Initial assessments show neither habitat concept can survive outside of a highly illuminated hibernation point without supplemental power or a significant, nearly double, upsize of energy storage, necessitating a return trip to a hibernation point before lunar winter.
- Overall complexity/Additional elements needed – The current ConOps calls for the offload of an element from a lander onto a common SMP or accepting higher delivery mass/volume with an integrated mobility platform. Concerns over energy storage, continuity of communications, and ability to remain at alternate, less-illuminated hibernation points may dictate adding supplemental power, communications relays, etc.

- Unknown vehicle dynamics – Variability of terrain that is not fully understood (i.e., limited highlands-based sampling to inform terramechanics models, current remote sensing resolution, etc.) could impart unknown impulsive and resonant loads to structure. More ground-truth in the south pole region is needed to enhance modeling.

- Energy generation capabilities – The baseline assumption includes stowage & re-deployment of solar arrays. This approach has a low Technology Readiness Level (TRL) and cycles in a dusty, low-gravity environment are largely unknown and undemonstrated. Vertical Solar Array Technology (VSAT) advancements may help buy down this risk. Alternate power generation approaches (i.e., conformal arrays that stay deployed, a mix of small fixed & large deployable arrays, etc.) may mitigate, but these are also lower TRL, possibly higher mass, and/or come with increased system complexity.

C. The Benefits

Relocation of normally fixed elements is likely required to reach the sustained lunar evolution segment; enabling offload of large payloads for lander reuse and possibly mitigating plume impingement prior to the construction of improved landing or launch surfaces. Relocation of other habitable volumes likely increases exploration range/area and increases safe haven opportunities, although the degree of improvement over an HLS sortie to a new location hasn't been quantified.

D. Top 5 Benefits/Opportunities:

- Increased exploration/utilization area – Relocation of additional habitable elements beyond HLS & PR can expand the area of exploration to other lunar regions.

- Leans forward to sustained presence – Lander offload and relocation of large payloads and habitation elements enables lander reuse, disposal of expired or failed systems to better utilize limited preferred locations, and aids modular build-up of habitable bases mitigating the need for EVA between habitable elements (assuming a surface docking capability).

- Provides landing site flexibility – Provides a possible opportunity to relocate habitation elements to a different landing site due to launch/orbital delays, pending lighting constraints, etc.

- Provides for optimal placement – Given very limited locations of optimal illumination coupled with landing ellipse uncertainties, relocation can ensure emplacement in an ideal location and also allow for alternate placements due to other element shadowing, plume impingement, etc.

- Provides some exploration redundancy – Adding mobility to foundational elements could provide additional habitable safe-haven capability without having to fully constrain to EVA walk-back or mobility exploration distance limitations from a habitable element.

11. FUTURE WORK

This work represents a high-level investigation of surface traverse viability for habitation and corresponding massive payloads. To gain an in-depth understanding of these traverses, further analysis is needed – particularly examining energy storage and recharge constraints for the payloads. Tuning of traverse route planning for payload survival, which is not possible for all payloads in all traverses examined, may reveal additional challenges to be addressed by modifications to the power generation, storage, and thermal control architectures. Additionally, further investigation into alternatives for these sub-systems, both on individual elements and across the architecture, may significantly impact traverse viability by reducing cycling of deployable systems or offloading functionality to distributed platforms.

Additionally, there is significant interest in exploring shorter-ranged, localized mobility scenarios. Even in an architecture that does not incorporate long-range traverses or exploration of multiple sites, the ability to pick up an element and move it away from its delivery vehicle or to a better-illuminated location offers opportunities for element reuse and increased survivability. Understanding the required systems for localized relocation and how they compare to long-range mobility platforms will allow for more effective scoping of evolvable exploration campaigns.

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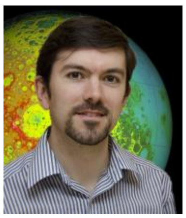

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