National Aeronautics and Space Administration

NASA

# Assessing the Relocation of Artemis Lunar Surface Concepts

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STRATEGY AND ARCHITECTURE OFFICE

EXPLORATION SYSTEMS DEVELOPMENT MISSION DIRECTORATE

# Why Relocation?

Relocation:
*"Ability to move normally stationary surface elements from one operational location to another"*

**Human Lunar Return**

Initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization (science, etc.) on and around the Moon.

**Foundational Exploration**

**Expansion of lunar capabilities**, systems, and operations **supporting complex orbital and surface missions** to conduct utilization (science, etc.) and Mars-forward precursor missions.

**Sustained Lunar Evolution**

Enabling capabilities, systems, and operations to support regional and global utilization (science, etc.), economic opportunity, and a steady cadence of human presence on and around the Moon.

**Humans to Mars**

Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (science, etc.) on Mars and continued exploration.

- **Moon-to-Mars (M2M) objectives suggest relocation has an overall positive impact by providing additional opportunity to explore multiple regions or for infrastructure growth**
  - 7 positively impacted objectives: SE-4, SE-6, LI-6, LI-7, TH-3, OP-3, OP-5
  - 2 negatively impacted objectives: SE-7, OP-12
- **Functions enabled by relocation in the 2023 Architecture Definition Document (ADD), Rev A:**
  - FN-020-L: Reposition cargo on the lunar surface
  - FN-124-L: Docking/berthing between pressurized assets on the lunar surface
  - FN-178-L: Transport cargo on the lunar surface between landing location and surface assets

More at: nasa.gov/moontomarsarchitecture/

# The Team – Co-Authors

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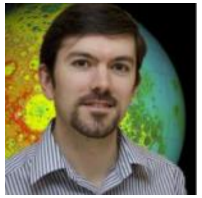

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# A Relocation Precedent…

Haley VI Station – Credit: British Antarctic Survey (BAS)

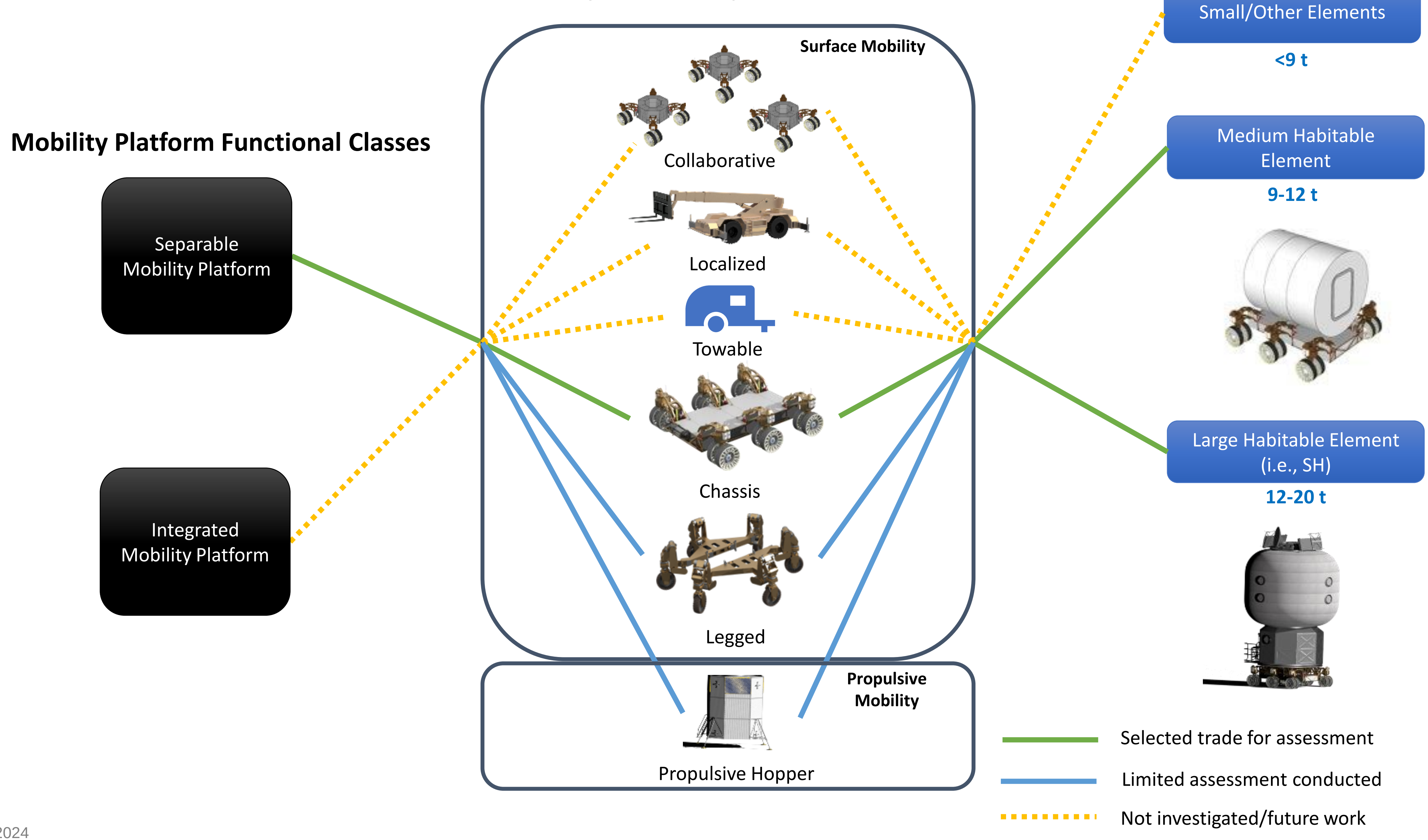
Apollo 14 – Credit: NASA


Artemis I – Credit: NASA

# The Relocation Trade Space

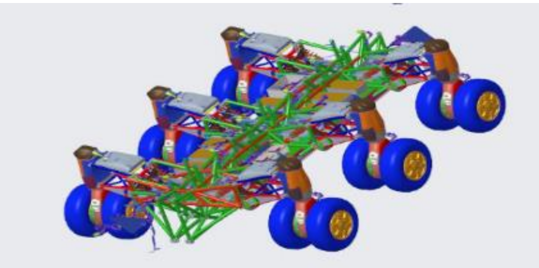
## Payload Categories for Relocation

## Mobility Platform Options for Relocation



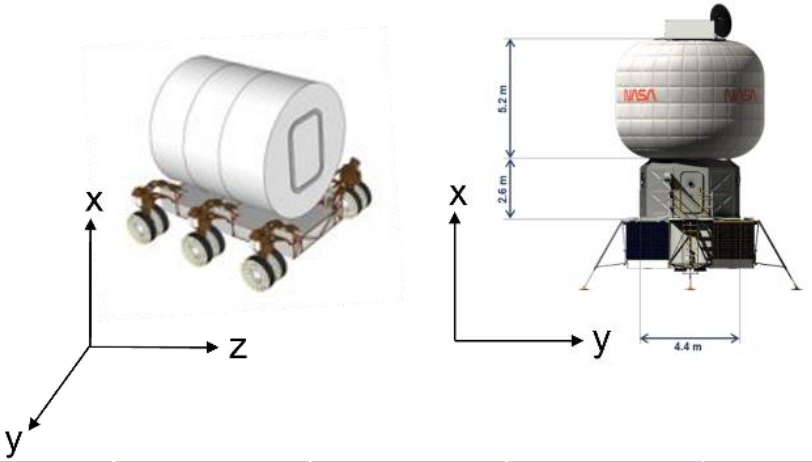
# Selected Trade Space in Pictures & Numbers

## Chariot-derived Separable Chassis



| 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** |

## Medium & Large Habitation Bookends



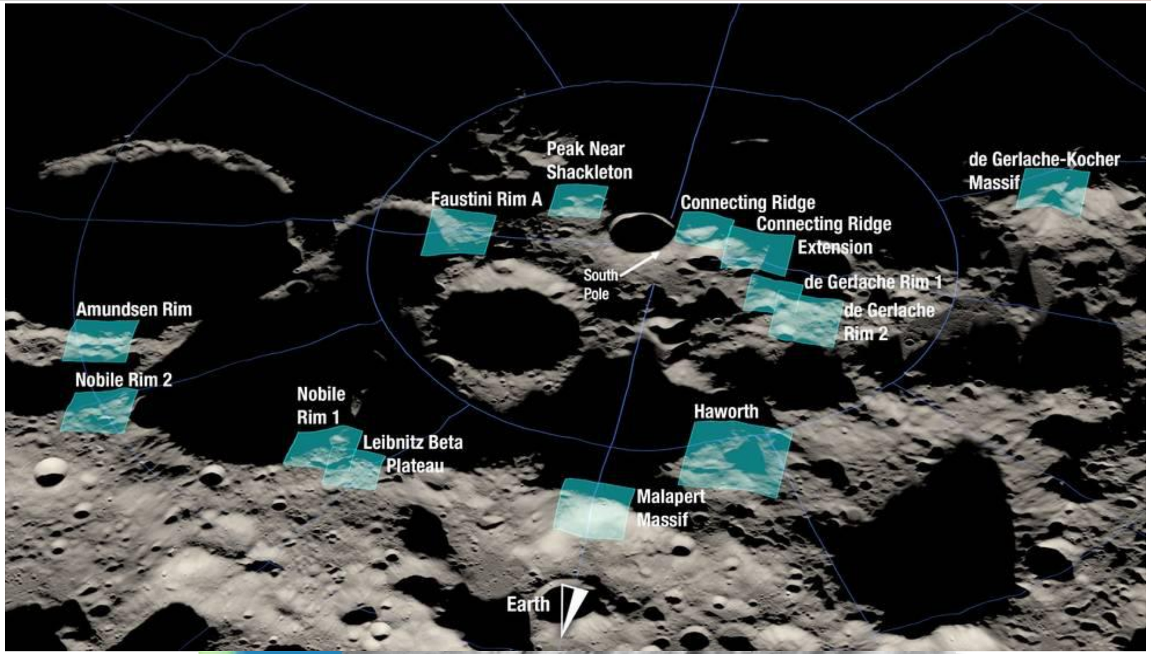

| Habitation Element | Length (m) | Width/ Dia (m) | Height (m) | Mass Range (t) | Center of Gravity (m) | Energy Storage (hr) |
|---|---|---|---|---|---|---|
| **Medium** | 4.4 | 4.8 | 4.8 | 9-12 | 2.4 | **150** |
| **Large** | 4.4 | 6.5 | 7.8 | 12-20 | 5.0 | **100** |

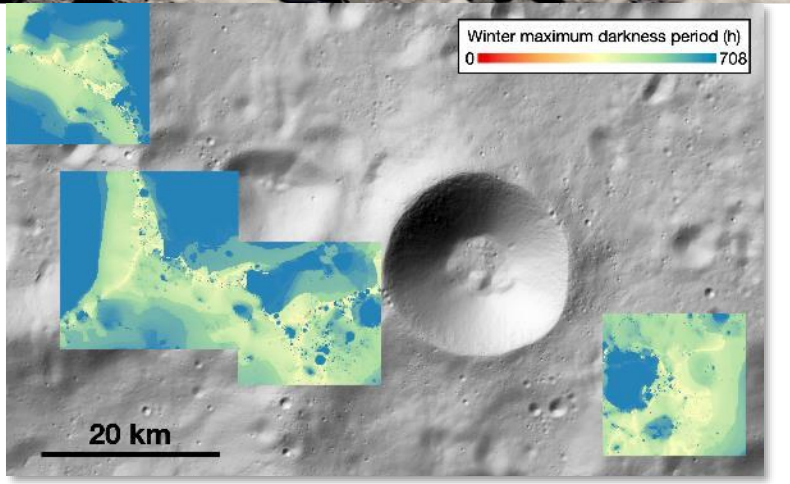
## Mass Penalties for Relocatable Habitat Design

- Re-deployable Arrays → Power Deltas
- Fixed Radiator Panel Offset → Thermal Deltas
- Standoffs & Lift Points → Structure Deltas

| 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** |

# Reference Regions, Ground Rules, Assumptions, & Constraints



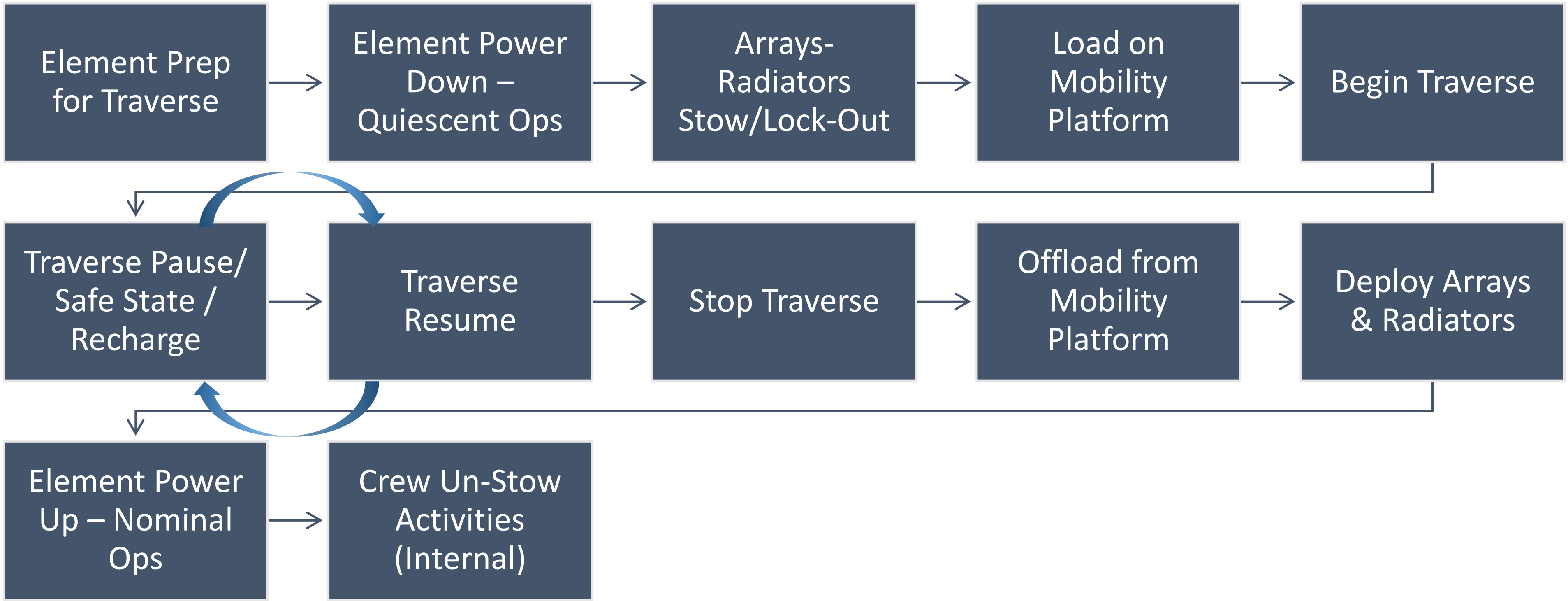




Maximum continuous shadowing over Artemis III candidate regions at 2m

- GR: Relocatable elements will adhere to Human-class Delivery Lander (HDL) mass & volume constraints (12t threshold, 15t goal)
- A: Relocation occurs between crewed missions (i.e., uncrewed)
- A: Relocatable habitation elements remain fixed during crewed missions
- A: Relocatable elements considered self-sufficient during relocation
- A: Relocatable elements will minimize use of deployed hardware
- C: Representative masses of 10, 12, 15, & 20 t will be analyzed
- C: Offloading and emplacement capabilities not evaluated
- C: Relocation will minimize exposure to darkness
- C: Traverse paths will not exceed 20-degree slopes

**Definitions:**
Ground Rule (GR) – Unchanging, architecture-level
Assumption (A) – Study-specific, judgment-based & can change
Constraint (C) – Study specific, analysis-based, may change

# Surface Traverse Concept of Operations

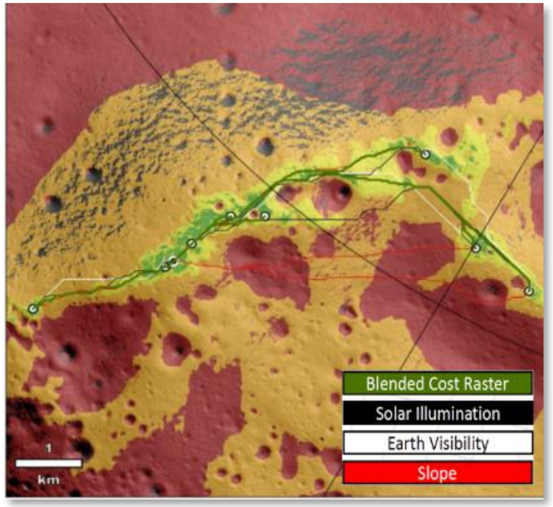



- Steps include load/offload from separable mobility platform
  - Duration of process may drive additional deployment of arrays/radiators, etc. prior to traverse
  - Complexity of load/offload operation may drive decoupling with traverse
- Multiple starts & stops presumed and validated through illumination analysis
- Duration for array/radiator deployment not included for this initial analysis

# Traverse Route Analysis Process

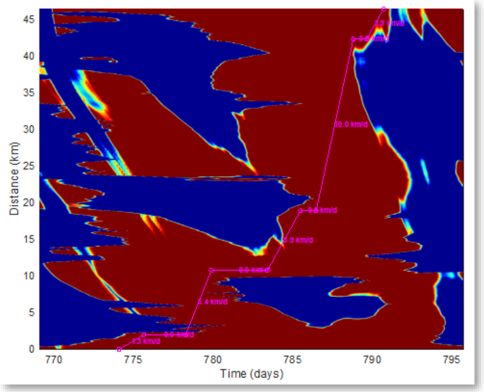
A traverse is created via blended cost raster (slope, solar illumination, communications availability)

EX: Site A to Site B




Path Illumination Matrix (PIM) is used to determine a path through the shadows for a given epoch

PIM is used to determine timing, velocities, and stopping points to finish the traverse within habitat energy constraints



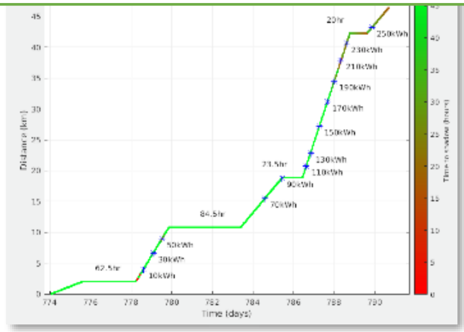

Traverse path is an input to a physics-based rover simulation for different vehicle weight classes

For each weight class, simulated driving the traverse path and output energetics

*Independent of the traverse timing from PIM

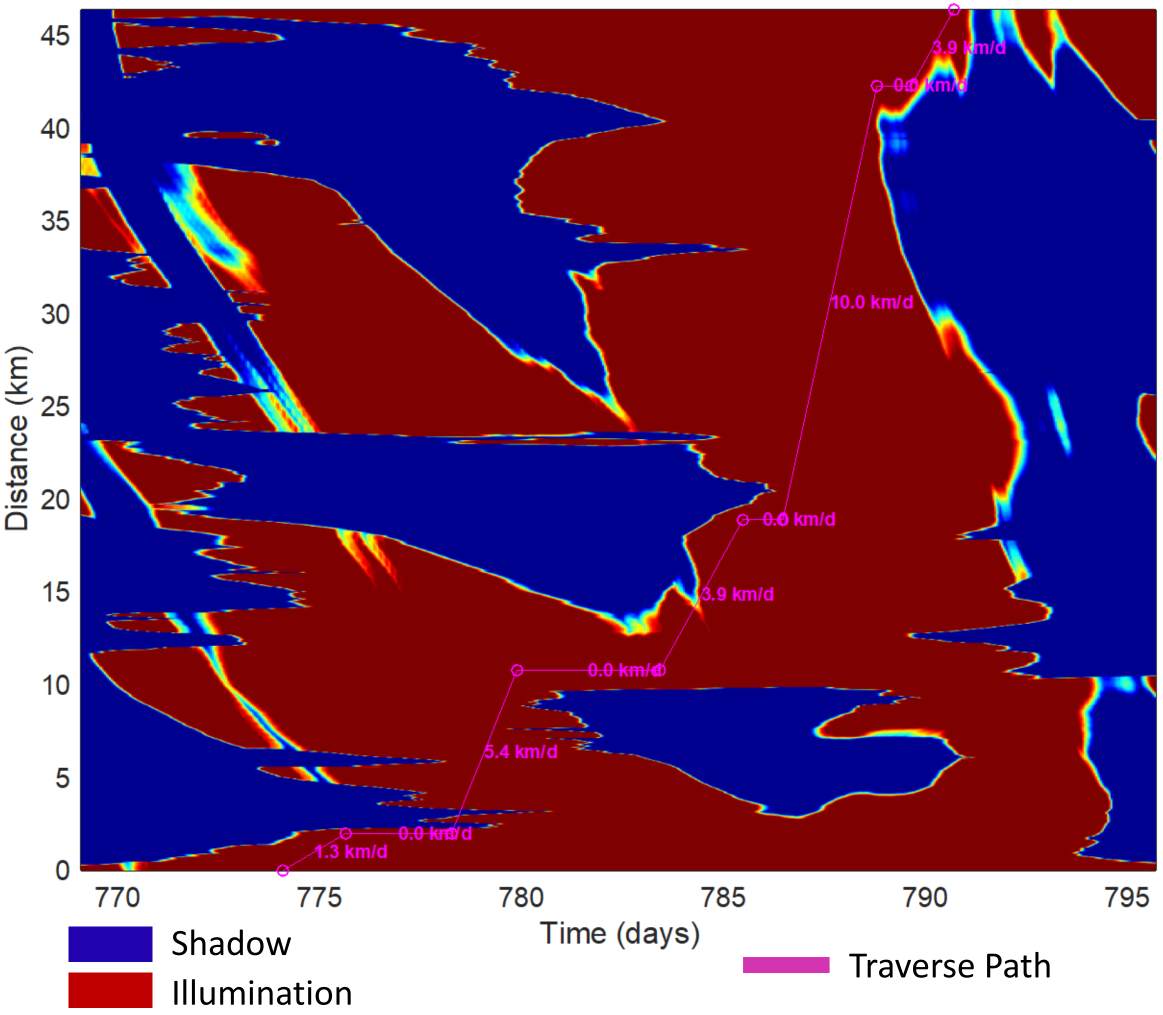
Energetics data overlaid on Time to Shadow plots

- Energetics data is lined up with the path based on distance traveled from start
- Thus, we can determine energy expenditure based on chosen path through the shadows

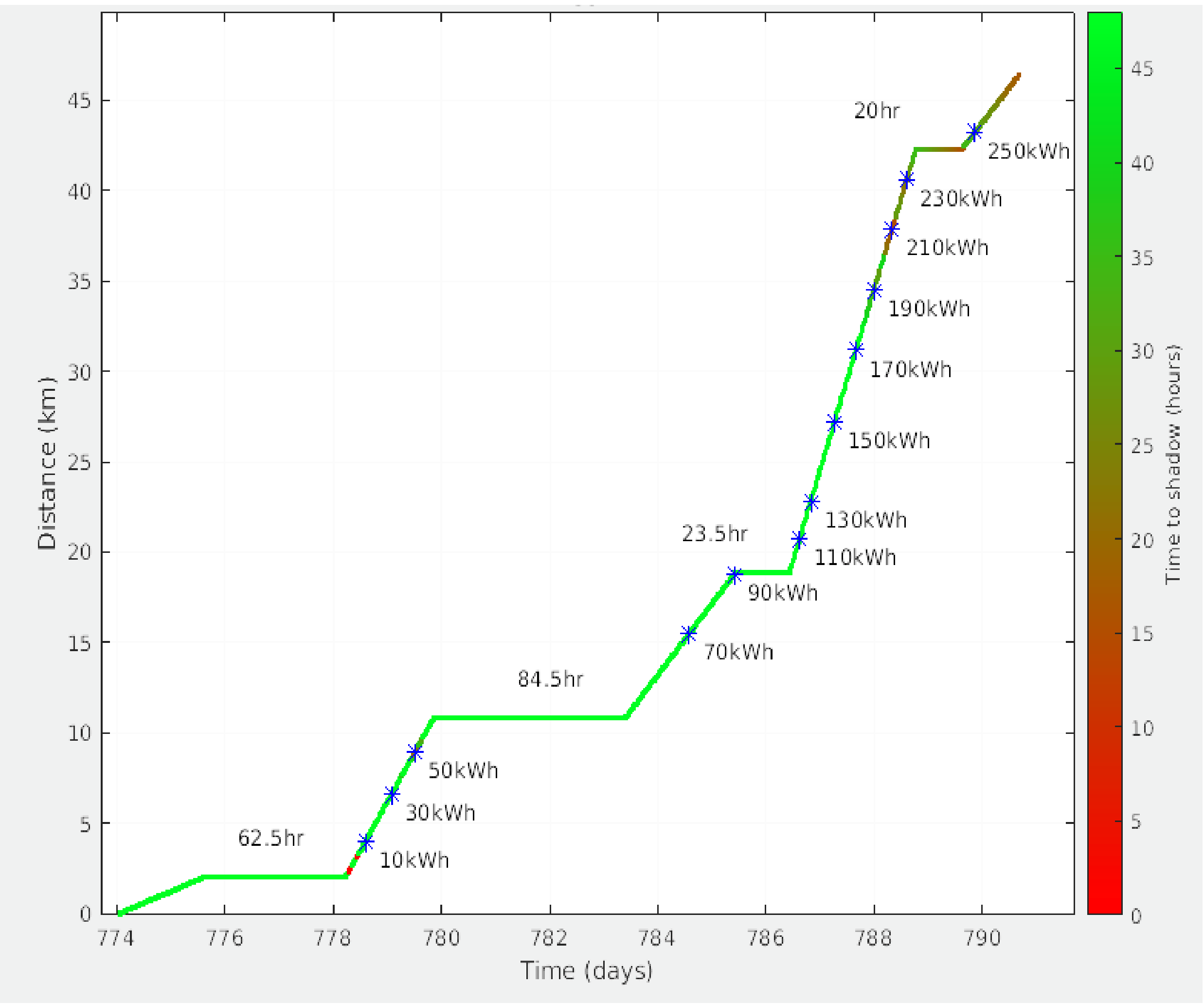


# Traverse Route Analysis (Site A to B example)

## Path Illumination Matrix (PIM) @ 10 m elevation




## Energetics & Time-to-Shadow



# Energetics Assessment

- **Simulated traverses ran unconstrained to identify energy costs**
  - Lunar terramechanics modeling basis with modified NASA Chariot government reference concept mobility platform
  - 3.6 km/hr (1 m/s) commanded speed – challenging for higher mass payloads
  - Traverses also investigated effects of hotel/housekeeping loads
- **Habitation energy balance ran independent of mobility**
  - 150 hr energy storage for medium habitat, 100 hr for large
  - Large habitat considered two power architectures, different recharge times
  - No margins applied
  - Only 1 non-optimized traverse duration ‘closed’, warranting further investigation

**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 |

# Summary

- **Element relocation necessitates deeper focus on:**
  - Energetics – Balance of energy needs, recharge opportunities, and traverse paths
  - Timing – Balance of dynamic illumination, terrain, and achievable speeds
  - Risk Posture – Margins will make above ‘balance’ more challenging, but needed to protect elements
- **Approach & findings may be applicable to relocation of other large, non-habitation elements**

**Risks**

- **Loss of habitable element**
  - Getting stuck, tipping over
- **Energy storage capabilities**
  - Among largest mass drivers
- **Overall complexity/additional elements**
  - Highly integrated activity
  - Increased delivery mass
- **Unknown vehicle dynamics**
  - Ground-truth of terrain & variability unavailable
- **Energy generation capabilities**
  - Re-deployable systems & dust tolerance

**Benefits**

- **Increased exploration/utilization area**
  - Expands habitation to additional regions
- **Forward leaning to sustained presence**
  - Applicability to scaling & aggregation
- **Landing site flexibility**
  - Adds flexibility for arriving vehicles
- **Allows optimal emplacement**
  - Greater position than through landing alone
- **Some exploration redundancy**
  - Mobilized safe-haven capability

# Future Work

- **Further traverse & energy balance optimization**
  - This work represents a single iteration, additional needed for increased confidence
  - A second iteration indicates possibility for improved payload energy management
- **Sub-system and architectural optimization**
  - Identifies possible technology development needs (conformal arrays, increased dust tolerance, etc.) that may reduce complexity & mass
  - Need to understand architectural return on investment
- **Localized mobility investigation**
  - Leverage approach to short-duration/limited use relocation (i.e., intra-regional)
  - Compare benefit and risks of intra vs. multi-regional relocation

Thank you!

# Back-up

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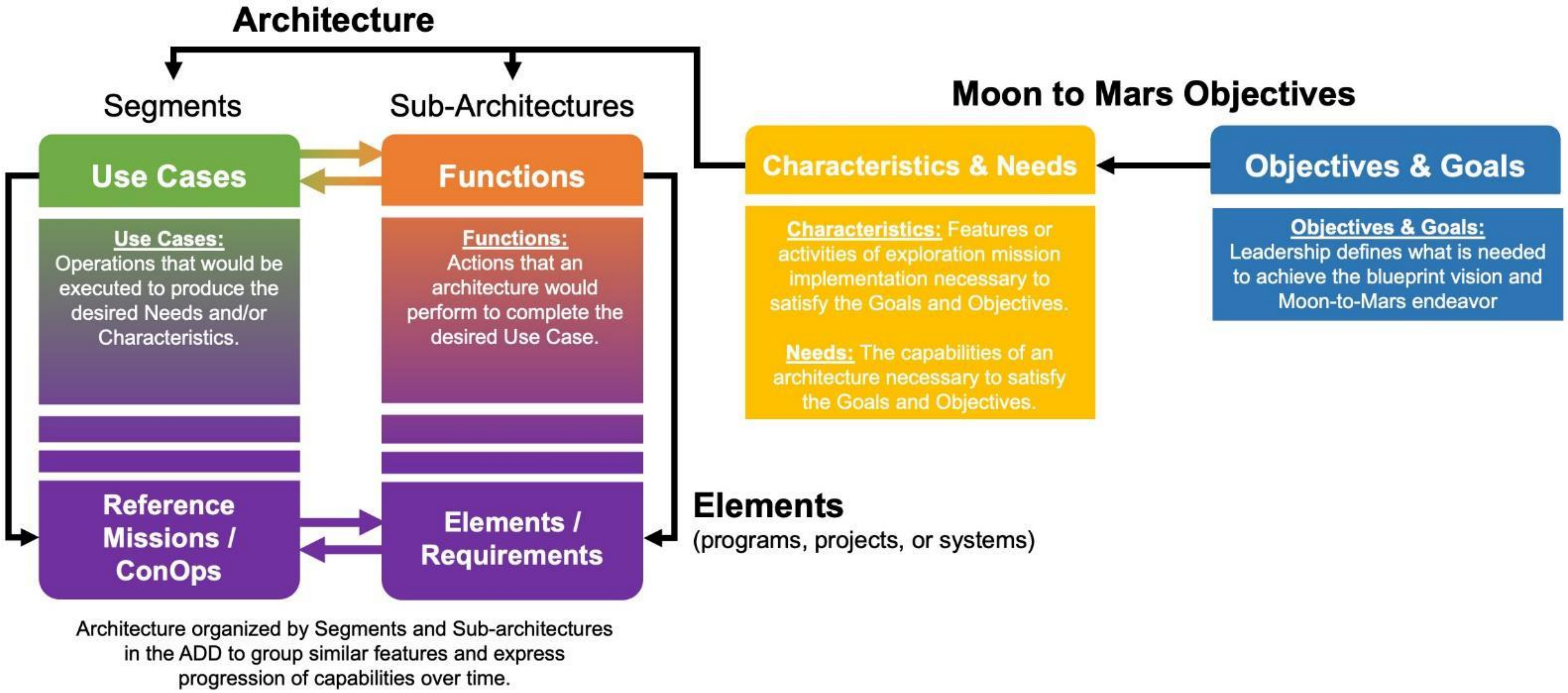
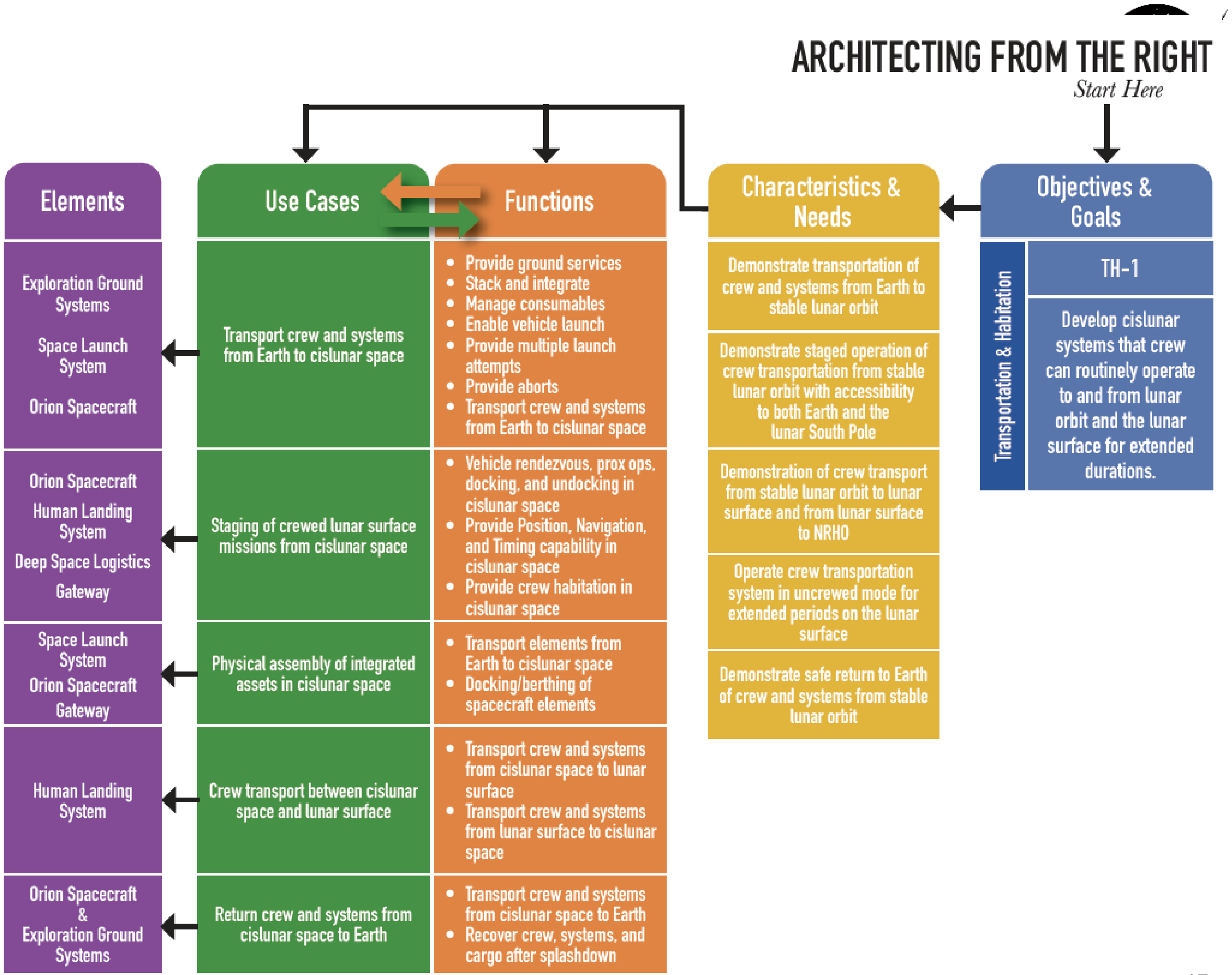
# Architecting from the Right




The Architecture process requires a decomposition of Moon-to-Mars Objectives to element Functions and mission Use Cases to complete the process of "architecting from the right." This establishes the relationship of executing programs and projects to the driving goals and objectives.

# Example Objective Decomposition

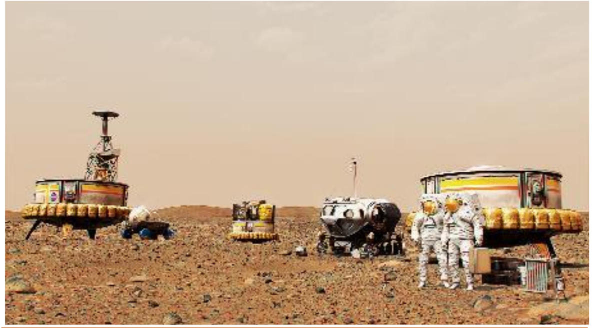
Example of the full distillation of the Objectives into lunar-specific Use Cases, Functions, and Elements for the *Human Lunar Return* segment using one of 12 Transportation and Habitation Objectives.



# Executing from the Left: Segments and Sub-architectures

**Segment:** A portion of the architecture, identified by one or more notional missions or integrated use cases, illustrating the interaction, relationships, and connections of the sub-architectures through progressively increasing operational complexity and objective satisfaction.



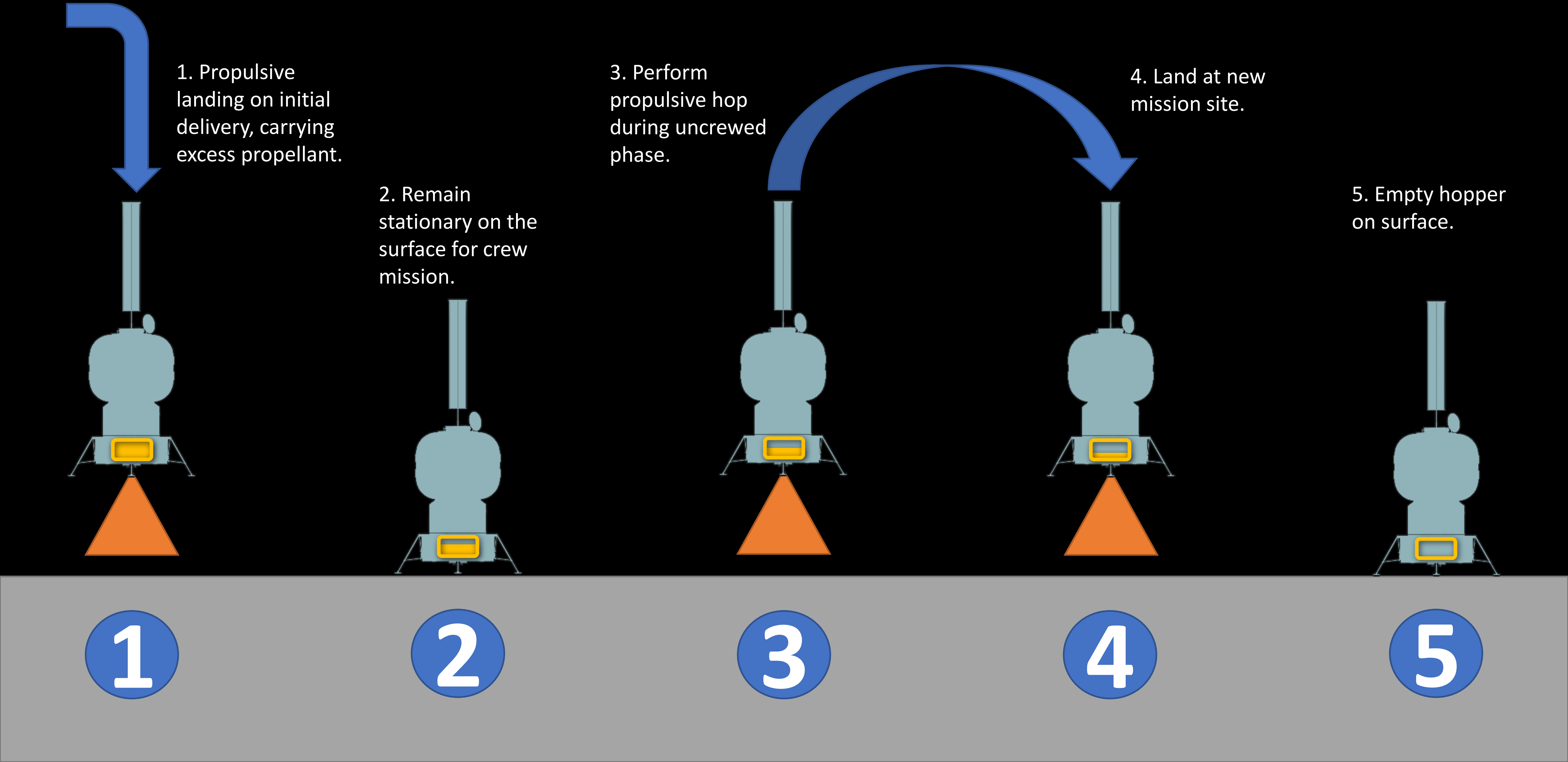



| Human Lunar Return | Foundational Exploration | Sustained Lunar Evolution | Humans to Mars |
|---|---|---|---|
| Initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization (science, etc.) on and around the Moon. | Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (science, etc.) and Mars-forward precursor missions. | Enabling capabilities, systems, and operations to support regional and global utilization (science, etc.), economic opportunity, and a steady cadence of human presence on and around the Moon. | Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (science, etc.) on Mars and continued exploration. |
| **Focus for ACR 22** | | | **Focus for ACR 23** |

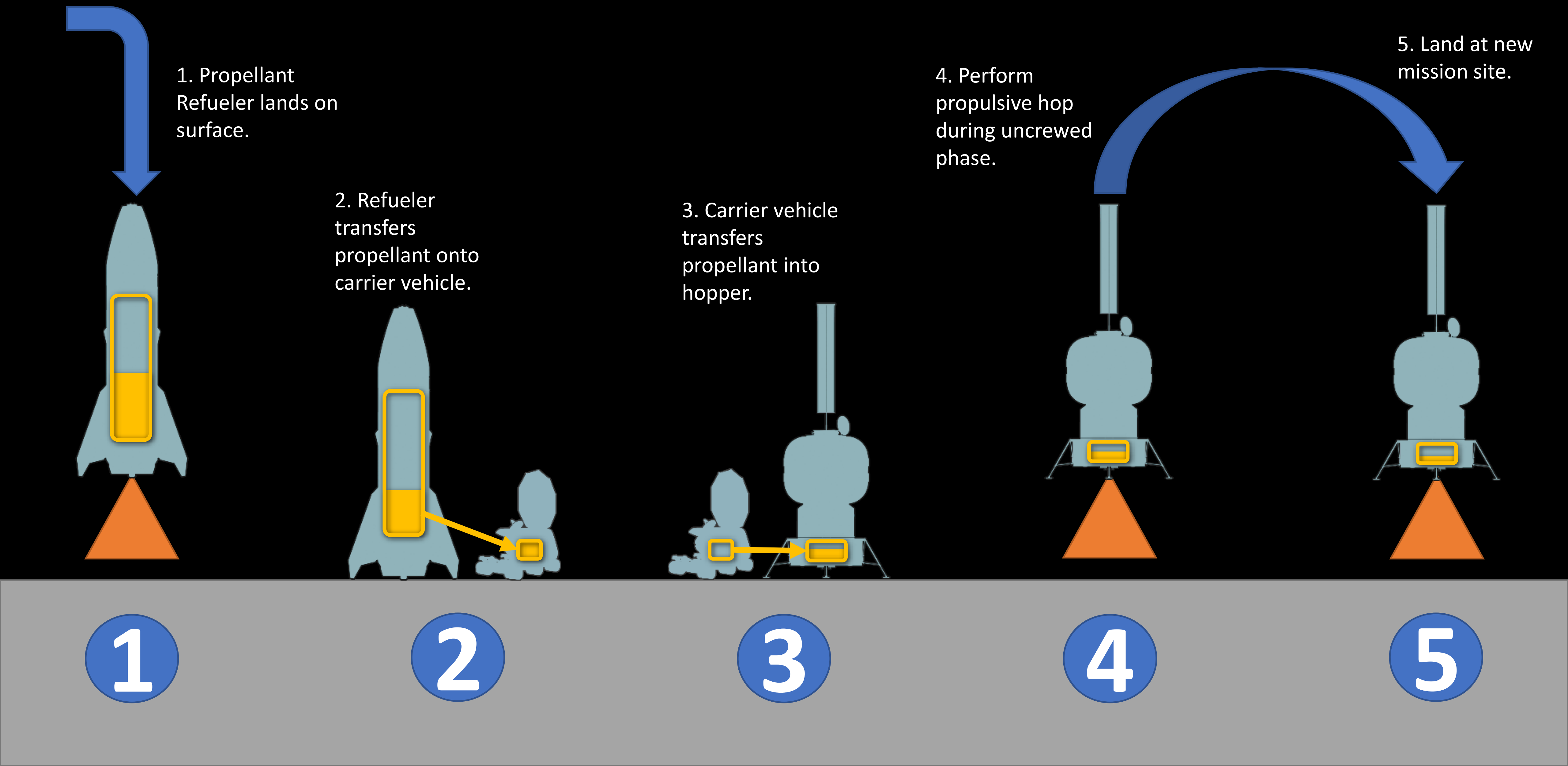
**Sub-architecture:** A group of tightly-coupled systems, functions, and capabilities that perform together to accomplish architecture objectives.

Communication, Positioning, Navigation, and Timing • Habitation • Human Systems • Logistics • Mobility Systems • Power • Transportation • Utilization Systems

# Propulsive Hopper – Residual Propellant



# Propulsive Hopper – Surface Refueling (Non-ISRU)



# Propulsive Hopper & ISRU Impacts

- **Propulsive Hop Assumptions:**
  - Smooth, spherical Moon
  - LOX/Hydrogen propulsion system
  - Dry stack mass of 15.7 t
  - Delta-v range: 401 m/s to 1108 m/s between sites of interest
- **ISRU**
  - Oxygen production presents significant opportunities to lower landed mass
    - LOX/LH2 engines operate at ratios of 6:1
    - Assumed ISRU pilot plant production rate is ~1000kg/year
    - With 3-4 years between missions, a significant amount of required residual mass can be replaced with ISRU, lowering propellant costs across all phases
    - Less significant changes for Large Lander cases, as saved propellant is proportionally small compared to vehicle mass

**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 |

- **Mars**
  - Surface propellant storage and transfer is Mars-forward technology
    - Technology demonstration of long-term cryogenic storage, propellant transfer vehicle, and robotic umbilical interfaces