National Aeronautics and Space Administration

# Moon to Mars Architecture Updates

**NASA Advisory Council, Human Exploration and Operations (NAC HEO)**


**Nujoud Merancy**

Deputy Associate Administrator

*Strategy and Architecture Office*

*Exploration Systems Development Mission Directorate*


*August 29, 2024*

# Agenda

## 2024 Progress and Milestones

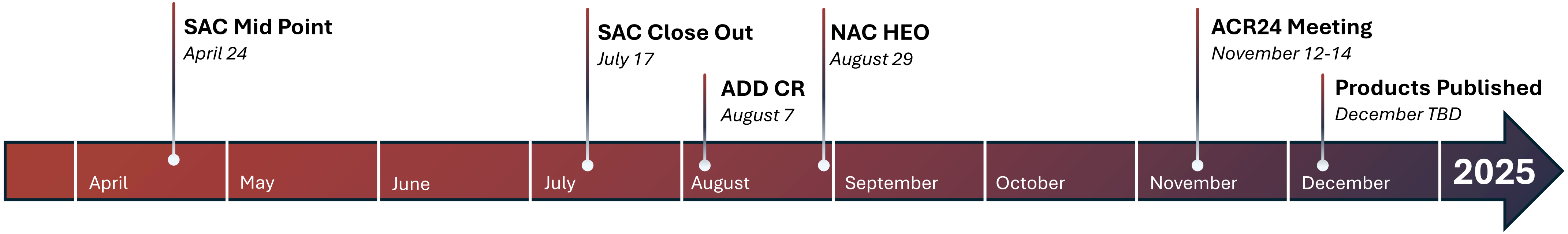
- Analysis Progress
- MBSE Environment

## Mid-Cycle White Papers

- Lunar Cargo
- Lunar Mobility

## Upcoming Milestones

# 2024 Progress and Milestones




- **Strategic Analysis Cycle (SAC) Task Highlights**
  - First year with cross-directorate-led tasks
  - 22 priority tasks reviewed, exclusive of team subtasks
  - Published two mid-cycle white papers
- **2024 Architecture Concept Review (ACR) Themes**
  - Integrated, collaborative analysis of tasks found to be a better approach
  - Continuing to refine stakeholder engagement points; identified areas to include additional contributing stakeholders
- **Two new elements have passed mission concept review and will be reviewed at the ACR24 meeting in November.**

# Analysis Progress



## Architecture Decisions

- Documents existing and proposed future architecture decisions
- Highlights the rationale and process for architecture decisions (e.g., flow-down impacts of driving decisions on later decisions)
- Features five new architecture decisions for formal consideration at this year's ACR

### Associated Segment(s)

Humans to Mars

## Technology Gaps

- Distinct from the Space Technology Mission Directorate's technology shortfalls, though there is overlap
- Identifies needed technologies and capabilities to realize future segments of the architecture
- Organizes gaps by associated sub-architecture and architecture segment

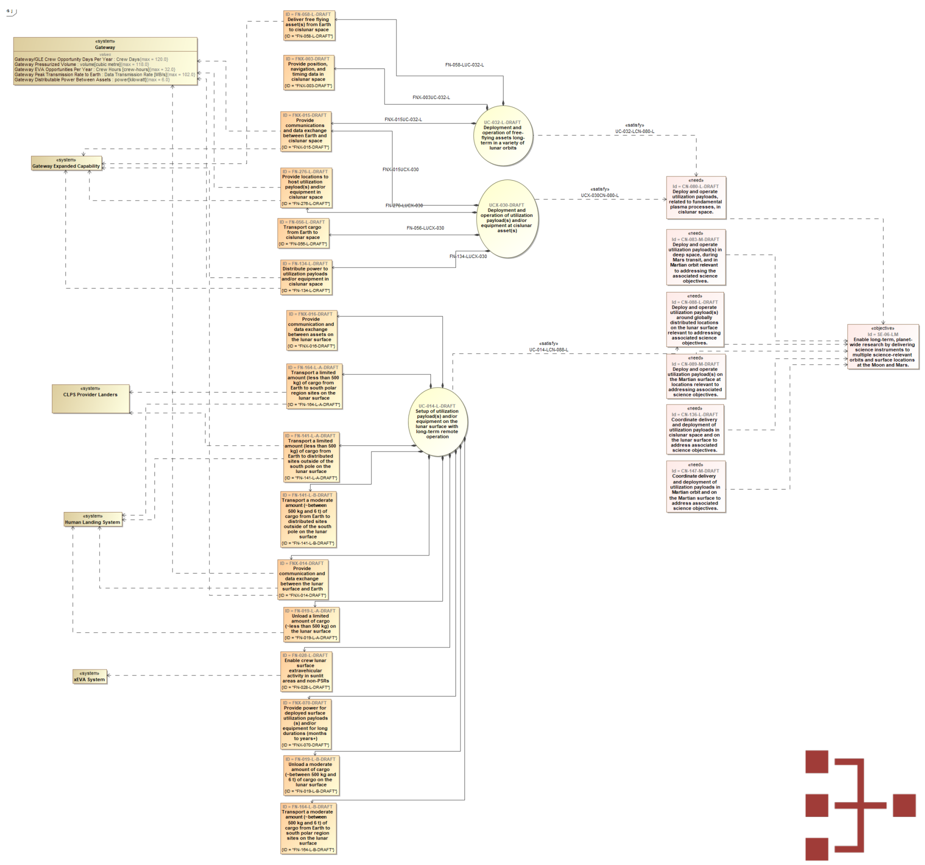
### Associated Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

# MBSE Environment



- NASA has migrated the decomposition of objectives into use cases and functions into an MBSE environment
- It offers a single source of truth for the architecture and will enable traceability from objectives down to requirements
- This tool will empower collaboration between the architecture team and the Moon to Mars Program Office and enhance understanding of architecture gaps through visualization

# Mid-Cycle White Papers


- SAC24 and element analysis indicated a greater challenge to two architectural gaps than previously communicated
    - Cargo lander demand aggregated across logistics, demonstration elements, and other systems
    - Surface cargo/element mobility demand relative to technology/system readiness
- **Given the scope and scale of forward demand, NASA published to out-of-cycle white papers in June to signal these future needs to industry and grow awareness across the NASA stakeholder community**
    - White paper content underwent development and review similar-to-nominal ACR process with informal ESDMD-led stakeholder review and comment period

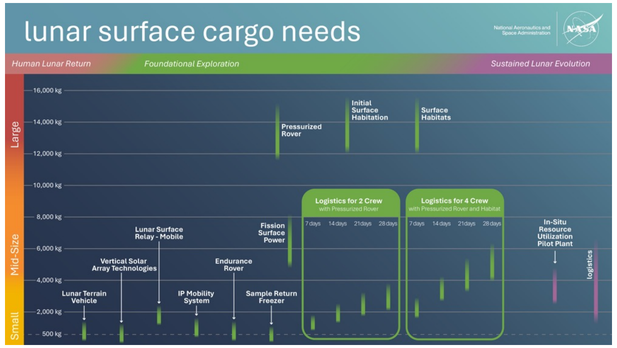
# Lunar Surface Cargo Background

- The architecture includes several surface cargo delivery or support functions, with some — but not all — needs current fulfilled by the Human Landing System (HLS), Human-class Delivery Lander (HDL), and Commercial Lunar Payload Services (CLPS)
- Analysis leading to and supporting the small cargo lander mission concept review (MCR) also revealed implications across the architecture strategy (e.g., available/contracted cargo capacity today versus aggregated future cargo demand)
- NASA allocated 17 functions to lunar surface cargo delivery in ADD Rev-A:
  - Nine identified as key; Eight identified as potential (*potential* reflects optional services that may be needed on some but not all landers)
  - **The ability to deliver cargo to the lunar surface is critical to the architecture**

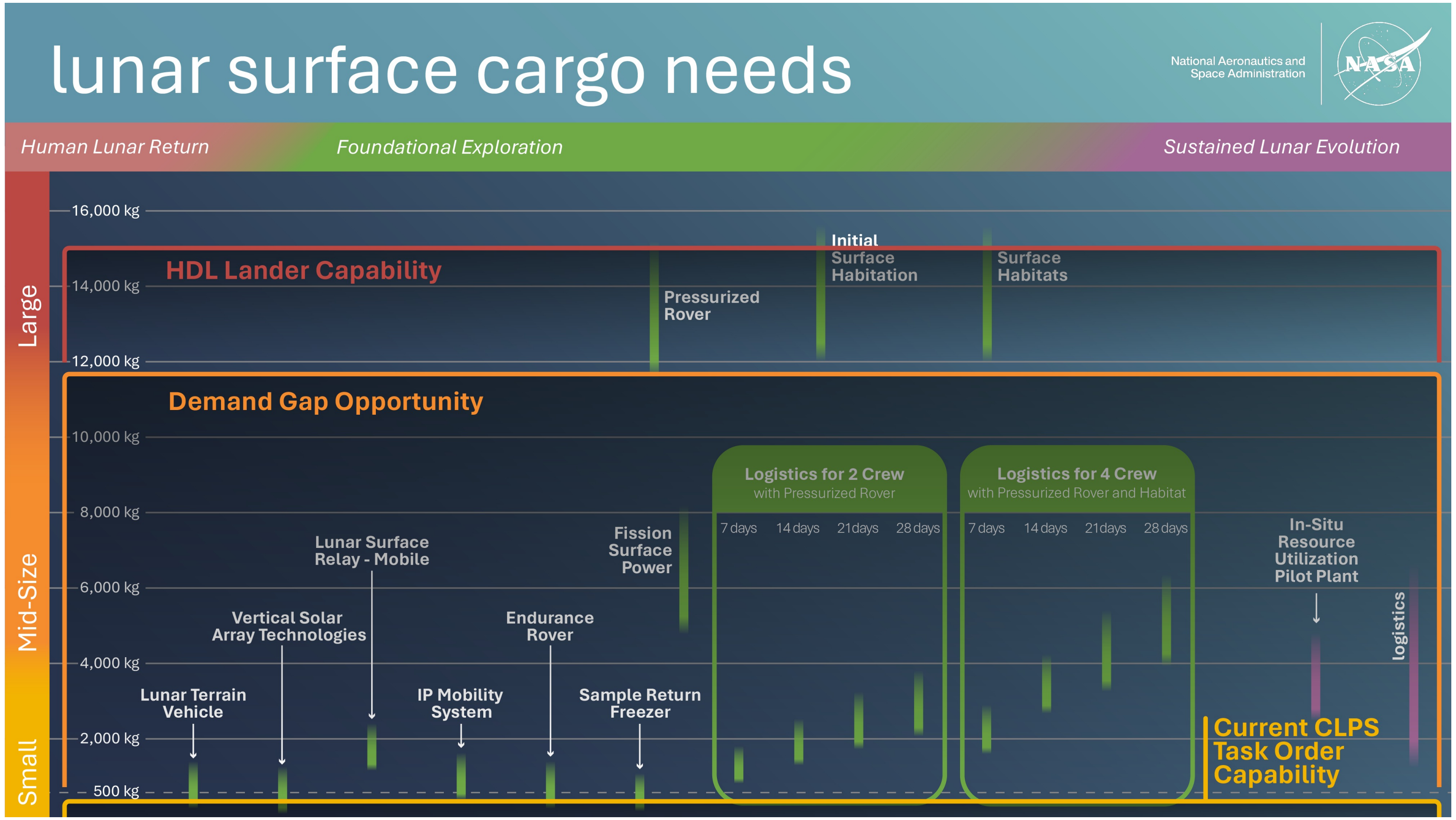
| Key | Potential | Lunar Surface Cargo Delivery Functions | |
|---|---|---|---|
| X | | FN-018-L | Transport cargo from Earth to the lunar surface |
| X | | FN-088-L | Provide precision landing for cargo transport to the lunar surface |
| X | | FN-122-L | Decommission surface delivery system(s) and/or surface asset(s) |
| X | | FN-126-L | Reduce blast ejecta |
| X | | FN-141-L | Deliver cargo(s) to distributed sites on the lunar surface |
| X | | FN-256-L | Provide physical and electronic safeguards for automated asset(s) operating near crew |
| X | | FN-257-L | Detect and avoid hazards during landing in darkness, high contrast, and long-shadowed lighting conditions in the presence of lunar dust and debris |
| X | | FN-277-L | Unload large utilization assets on the lunar surface |
| X | | FN-280-L | Deliver cargo(s) to south polar region sites on the lunar surface |
| | X | FN-066-L | Transport cargo from Earth to the far side of the lunar surface |
| | X | FN-123-L | Provide propellant/fluid transfer through common interface(s) between assets on the lunar surface (demonstration) |
| | X | FN-129-L | Transfer of propellant/fluids between assets on the lunar surface (demonstration) |
| | X | FN-139-L | Deploy (including setup, activation, and operation) science and/or monitoring utilization payload(s) on the lunar surface |
| | X | FN-144-L | Transport large exploration asset(s) from Earth to the lunar surface |
| | X | FN-148-L | Perform robotic manipulation of payloads, logistics, and/or equipment at multiple scales |
| | X | FN-254-L | Provide safety features, including shutoff, on robotic and/or autonomous system(s) |
| | X | FN-255-L | Robotic system(s) interaction with logistics carriers on the lunar surface |

**Architecture functions are intentionally decoupled from performance or demand to enable system analysis and trades**

# Lunar Surface Cargo Demand



Foundational Exploration

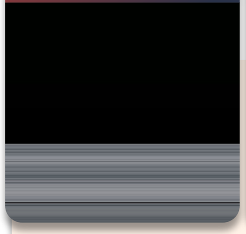



**NASA forecasts a cargo demand range of 2,500 to 10,000 kg per year for recurring logistics and some frequency of small to mid-size elements during Foundational Exploration segment**

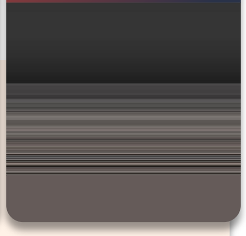
# Lunar Surface Cargo Capacity Estimates

| Lander Type | Mass Delivery Capability (t) | First Flight | Payload Class[1] | Maturity |
|---|---|---|---|---|
| US Industry - Current CLPS Task Orders | 0.07 – 0.475 for existing task orders | 2023-2025 | Class D | Phase D/E, SMD |
| HLS excess capability for co-manifested cargo[2] | *Proprietary* | 2025, 2027 | Class A, B, C | Phase B, ESDMD |
| HDL Cargo Lander | 0 - 12 or 15 t | 2029 | Class A, B, C | Phase A, ESDMD |
| ESA Argonaut Lander | 1.3 – 2 t | 2031 | Class A, B (TBC) | Pre-formulation |
| Mid-Sized lander (NASA Studies) | 2.5 – 13 t studied | 2031 | Class A, B, C | Concept studies |
| JAXA Lander | 3 - 4 t | Mid-2030s | TBD | Concept studies |
| Gov Assessment – US Industry growth | Up to 3.5t | TBD | TBD | Concept Studies |

SpaceX
Starship



Blue Origin
Blue Moon



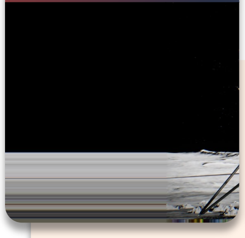
Human Landing System
*(HLS)*

SpaceX
Starship

Blue Origin
Mark 2 Cargo

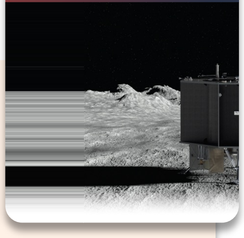
Human-Class Delivery Lander
*(HDL)*

Intuitive Machines
Nova-C



Firefly Aerospace
Blue Ghost

Draper
SERIES-2



Commercial Lunar Payload Services
*(provider list not comprehensive)*

**Notes:**
1. Classes as defined in NPR 8705.4A
2. Excess Capability is performance that is over and above the contractually required cargo/utilization delivery for human landing missions and is DRM and Provider dependent. Sensitivity to additional cargo mass is being discussed with providers.

**Current capabilities are not available from 500 kg to 12,000 kg, for which significant demand exists**

# Lunar Surface Cargo Capacity Estimates

- **Exploration of the lunar south pole region could cover significant distances**
  - The ability to deliver and deploy assets in multiple locations is likely of interest
  - Habitation, scientific, and infrastructure needs may not always be collocated


The Lunar South Pole Region Super-Imposed Over the Baltimore-Washington Metropolitan Area

- There is strategic benefit to enabling multiple cargo lander providers across both international partner and U.S. industry (e.g., through dissimilar redundancy)
  - Utilization payloads, technology demonstrations, and logistics delivery would benefit from the flexibility of a range of cargo delivery options
  - International Space Station lessons learned can be applied to a mixed cargo lander fleet approach
  - Small cargo lander capabilities can address a lower range of logistics needs and several potential utilization payloads needs

**Availability of a range of cargo provider types, scale, and accessibility has strategic benefits**

# Lunar Surface Cargo Key Takeaways


National Aeronautics and Space Administration

2024 Moon to Mars Architecture

white paper

Lunar Surface Cargo

**Introduction**

The exploration of the lunar surface, as described in NASA's Moon to Mars Architecture Definition Document (ADD), will require a wide variety of landed systems, including scientific instruments, habitats, mobility systems, infrastructure, and more. Given diverse cargo needs of varying size, mass, cadence, and operational needs, access to a range of cargo lander capabilities offers strategic benefit.

While current cargo lander development activities will contribute to meeting some cargo delivery demands, a substantial gap in lander capability remains. This paper characterizes lunar surface cargo delivery needs, compares those needs with current cargo lander capabilities, and outlines strategic considerations for fulfilling this architectural capability gap.

**Note:** *Cargo deliveries to Gateway are already instantiated in the Moon to Mars Architecture through the Gateway Logistics Element (GLE). GLE flights will supply Gateway with critical deliveries that maximize the length of crew stays on Gateway. While use of the Gateway as a logistics cache for lunar exploration could be considered, this paper does not attempt to speculate on concepts of operation. Instead, it specifically addresses architectural gaps for cargo deliveries to the lunar surface. The specific functions fulfilled by GLE may be found in Table 3-6 of ADD Revision A.*[1]

**Cargo Lander Architecture**

Lunar surface exploration will require the delivery of assets, equipment, and supplies to the lunar surface.[1] While some limited supplies and equipment may be delivered alongside crew on NASA's Human Landing System (HLS), the breadth and scale of logistical needs for deep space exploration require additional surface cargo lander capabilities.

NASA has developed a conceptual reference mission for cargo lander delivery that will be added to the ADD in revision B. This reference mission:

- Delivers non-offloaded and/or offloaded cargo to the lunar surface.
- Provides all services necessary to maintain cargo from in-space tra
surface until the cargo is either offloaded from the lander or in
services from the lander are no longer needed, in accordance wit
- Ensures successful landing at an accessible and useable locatio
precision.
- Establishes safe conditions on the lunar surface for the crew to a
- Verifies health and functionality of non-offloaded and/or offloade
- Performs any lander end-of-life operations — including potential
or other surface assets are not adversely affected by the lander a

As noted above, cargo deliveries will need support service interfac
to the surface. Service interfaces may support the offloading of carg
system interactions, and/or providing resources to the cargo, such
and/or thermal dissipation. Services may be needed from landing to
including before or after the cargo is offloaded to the surface.

Landers and cargo may also need additional, crew-focused lander
activity (EVA) touch interfaces to support crew interactions. Lastly, g
near a lander, landers must have the ability to safe itself after landing
a landers' vicinity.

2024 Moon to Mars Architecture Concept Review 1

**Key Takeaways**

- Foundational Exploration and Sustained Lunar Exploration segment goals require significant transportation of cargo to the lunar surface
- HDL is the only lander currently in the architecture that can deliver beyond 500 kg to the lunar surface
- NASA anticipates an aggregate demand for lunar surface cargo on the order of 2,000 to 10,000 kg per year
- To mitigate this capability gap, strategic considerations include engaging multiple providers across both international partners and industry over time, offering dissimilar redundancy
- Communication of cargo demand to the exploration community helps enable industry and international engagement

# Lunar Mobility Background

- The architecture includes several mobility functions, some of which are currently fulfilled by Lunar Terrain Vehicle (LTV) and Pressurized Rover (PR)
- Analysis leading to and supporting surface logistics, potential utility rover concepts, and initial surface habitation mission concept review (MCR) revealed implications across the architecture strategy:
  - Functional gaps and services not yet available for mobility of large uncrewed assets
  - Relocation and surface placement demand
  - Technological gaps in performance for mobility assets
  - Integrated architectural strategic considerations
- **Lunar surface mobility is allocated to 34 functions in ADD Rev-A**


**Mobility has a higher proportion of functions, which indicates a frequency of need previously not identified**

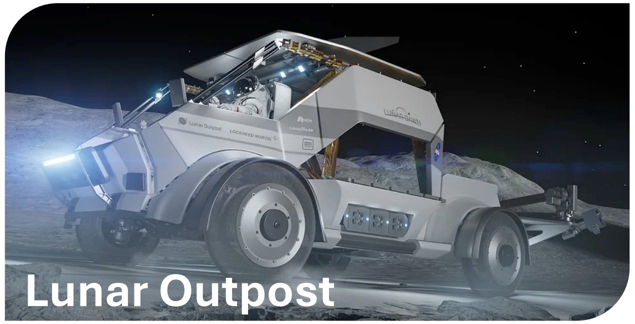
# Lunar Mobility Drivers and Capacity

- Demand for mobility is driven by integrated architectural operations:
  - Relocation out of lander shadows or engine blast range
  - Deployment to optimal solar points
  - Aggregation of logistics to point of use
  - Infrastructure deployment
- **Mobility mass demand ranges are similar to those of landed cargo demand**

| Mobility Asset | Mass Transport Capability (kg) | Launch Readiness | Maturity |
|---|---|---|---|
| Lunar Terrain Vehicle (uncrewed) | 800 kg (full performance)<br>1600 kg (reduced performance) | 2028 | Contracts awarded (pre-PDR) |
| JAXA Pressurized Rover | Cargo transport function not allocated | 2029 | Pre-SRR |

**Mobility capabilities are not available for cargo or assets greater than 1,600 kg; no mobility assets exist that can relocate large elements (e.g., initial surface habitat)**

Lunar Terrain Vehicle Concepts





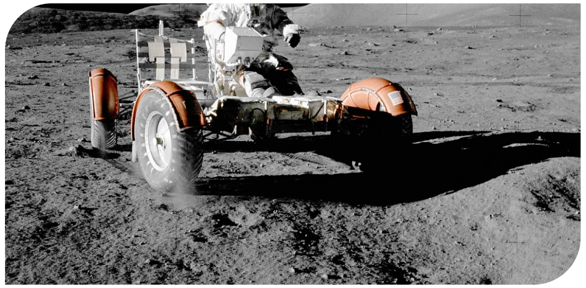
# Lunar Mobility: Historical Context

| | Apollo 11 | Apollo 12 | Apollo 14 | Apollo 15 | Apollo 16 | Apollo 17 | Total |
|---|---|---|---|---|---|---|---|
| **Mission Class** | G | H | H | J | J | J | --- |
| **Hours on surface** | 21.5 | 31.5 | 33.5 | 67 | 71 | 75 | 299.5 |
| **Number of EVAs** | 1 | 2 | 2 | 3 | 3 | 3 | 14 |
| **Mode of transportation** | Walking | Walking | Walking with MET | LRV | LRV | LRV | --- |
| **Approximate max distance from landing site** | 0.062 km | 0.45 km | 1.4 km | 4.7 km | 4.4 km | 7.5 km | 18.5 km |
| **Number of samples** | 58 | 69 | 227 | 370 | 731 | 741 | 2,196 |
| **Weight of samples (kg)** | 21.8 | 34.3 | 42.3 | 77.3 | 95.7 | 110.5 | 381.7 |
| **Mass of Tools and Sample Containers (kg)** | 22.85 | 29.17 | 43.07 | 50.29 | 53.03 | 45.69 | --- |

**Mission Classes**
G: The initial lunar landing mission
H: Precision manned lunar landing demonstration and systematic lunar exploration
J: Extensive scientific investigation of Moon on lunar surface and from lunar orbit

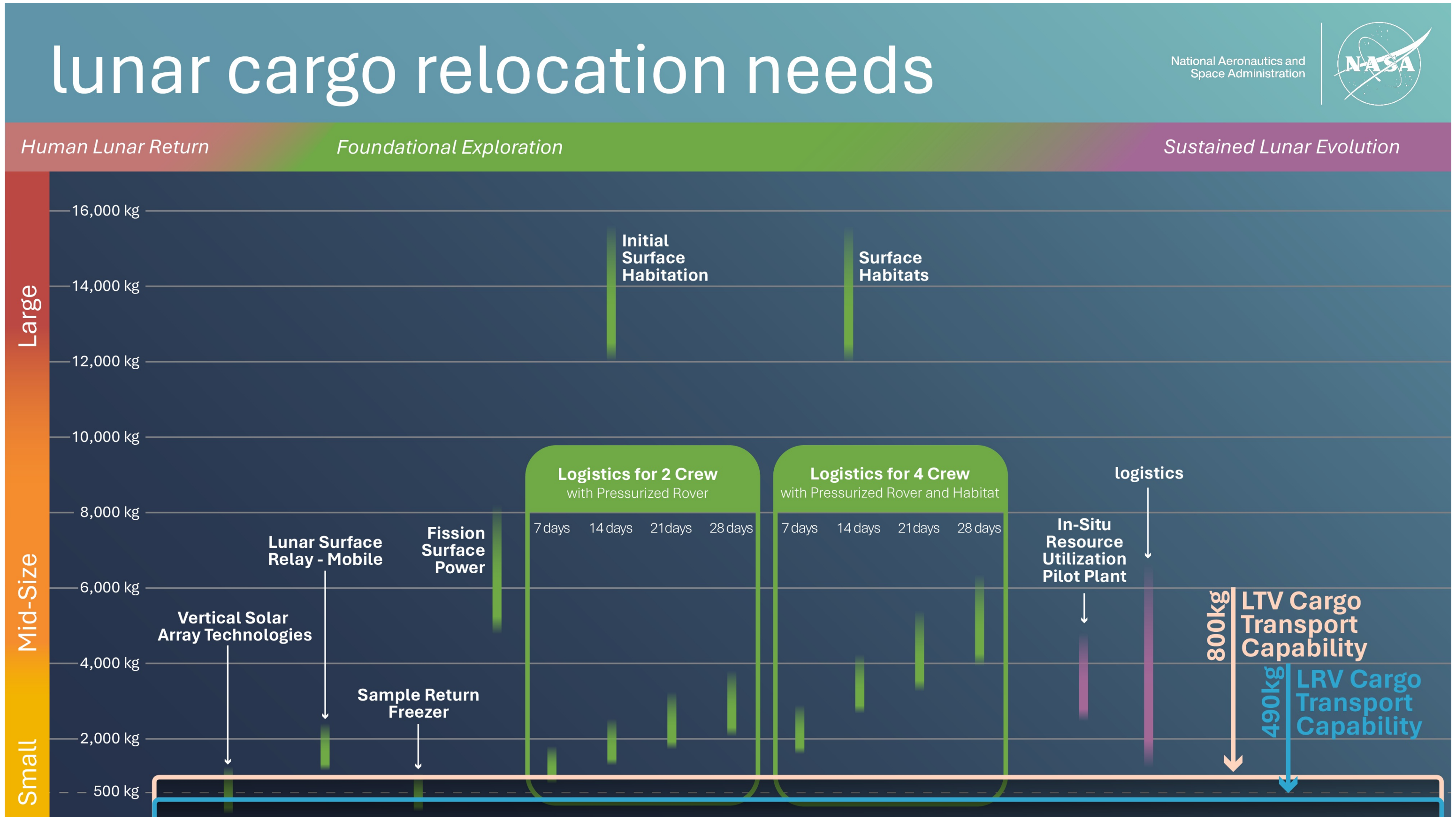
MET: Modular Equipment Transporter
LRV: Lunar Roving Vehicle

# Lunar Mobility Demand



**Apollo Era**
Lunar Roving Vehicle (LRV)

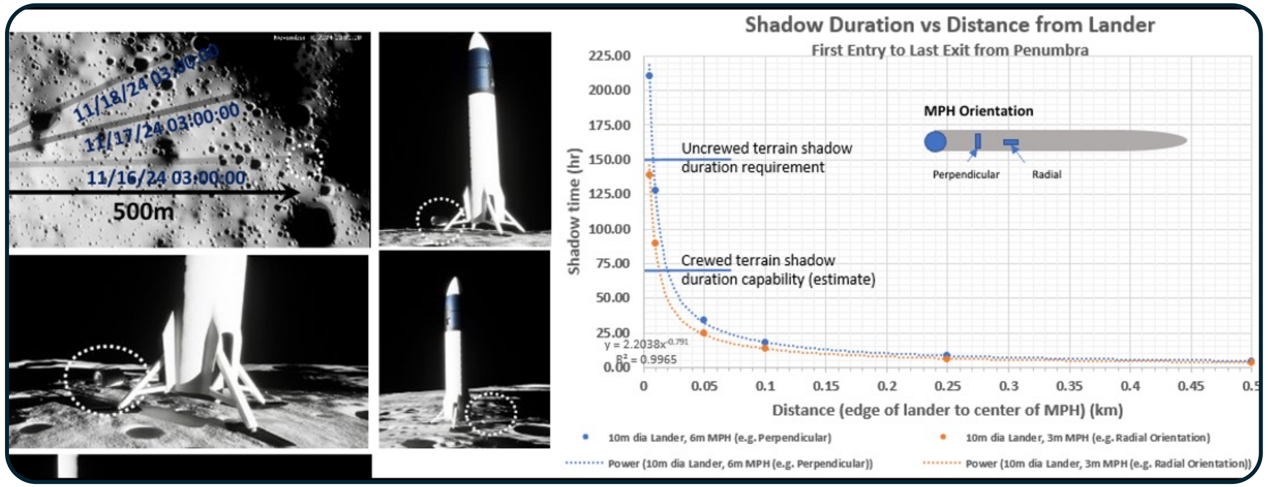
**Artemis Campaign**
Lunar Terrain Vehicle (LTV)

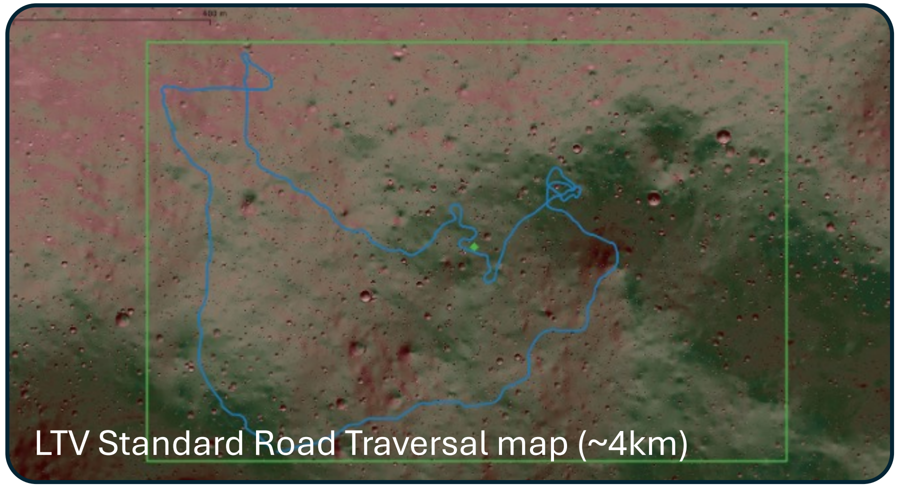



**Mobility payload mass demand forecasts range from 500 kg to 15,000 kg per asset during the Foundational Exploration segment**

# Lunar Mobility Range Demand

- Assessment of range per asset deployed could be driven by multiple factors:
  - Min relocation distance to avoid lander shadows >50m
  - Min relocation distance to avoid lander blast ejecta >1,000m
  - Relocation from potential lander sites to optimal/aggregate surface locations up to 5,000m
- Attempting multi-region mobility would require a capability of hundreds to thousands of kilometers



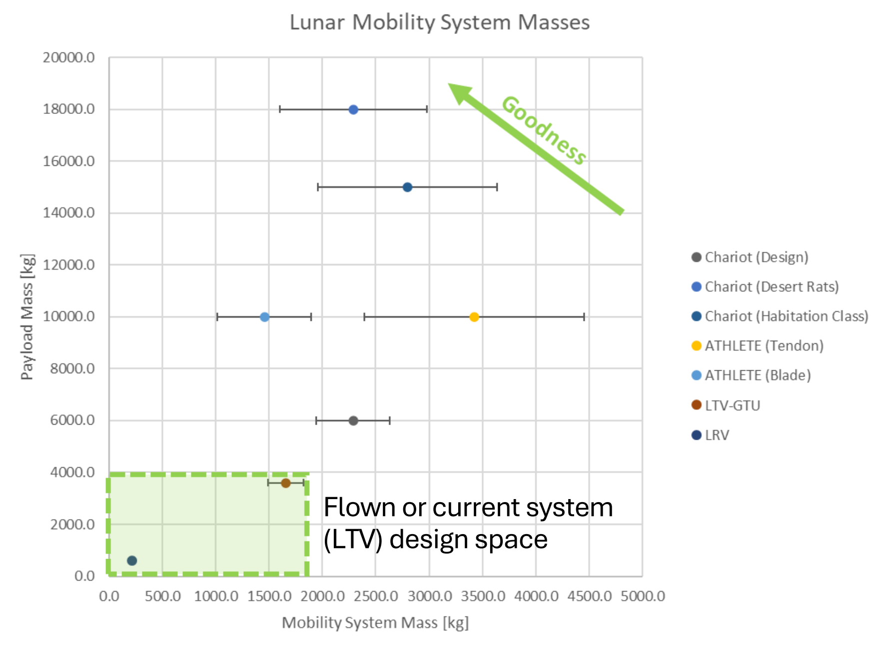




**Integrated architecture operations will necessitate non-trivial relocation and aggregation range demand for cargo and assets**

# Lunar Mobility Technology State

- Large scale mobility is not simply scaled up small-scale mobility:
  - Terramechanics considerations are crucial to mobility system design
  - Mobility systems (drivetrains) can weigh well over a metric ton
- Energy is one of the largest drivers of mobility design (i.e., understanding energy generation, storage, and night survival)
- Slope traversal can be exceedingly complex:
  - Analogous to driving a semi-truck up an unimproved mountain pass
  - Slopes more than 10 degrees are common at the lunar south pole region
- Mobility for moving items on the lunar surface must be resilient in the absence of crew and light

System vs. Payload Masses of Flown & Concept Mobility




**Significant technological gap exists between existing systems and actual mobility demand**

Architecture Updates

# Lunar Mobility Key Takeaways


National Aeronautics and Space Administration

2024 Moon to Mars Architecture

white paper

Lunar Mobility
Drivers and Needs

**Introduction**

NASA's new campaign of lunar exploration will see astronauts visiting sites of scientific or strategic interest across the lunar surface, with a particular focus on the lunar South Pole region.[1] After landing crew and cargo at these destinations, local mobility around landing sites will be key to movement of cargo, logistics, science payloads, and more to maximize exploration returns.

NASA's Moon to Mars Architecture Definition Document (ADD)[2] articulates the work needed to achieve the agency's human lunar exploration objectives by decomposing needs into use cases and functions. Ongoing analysis of lunar exploration needs reveals demands that will drive future concepts and elements.

Recent analysis of integrated surface operations has shown that the transportation of cargo on the surface from points of delivery to points of use will be particularly important. Exploration systems will often need to support deployment of cargo in close proximity to other surface infrastructure. This cargo can range from the crew logistics and consumables described in the 2023 "Lunar Logistics Drivers and Needs" white paper,[3] to science and technology demonstrations, to large-scale infrastructure that requires precision relocation.

The current defined mobility elements — the Lunar Terrain Vehicle (LTV) and Pressurized Rover (PR) — are primarily for crew transportation, with limited cargo mobility functions. Conversely, planned near-term robotic missions — such as those being delivered through the Commercial Lunar Payload Services (CLPS) program — provide only small-scale mobility. This paper describes the integrated cargo mobility drivers for consideration in future architecture and system studies, with a focus on the human lunar exploration architecture. Scientific and uncrewed, robotic missions could necessitate additional mobility needs beyond those discussed here.

The cadence, mass, and number of cargo lander deliveries will be timed to meet the operational needs of NASA's lunar architecture, based on factors including science objectives, lighting conditions, and safety considerations. In many cases, cargo offloading and manipulation will need to be conducted before the crew arrives at each landing location (point of origin) and then again at local lunar exploration and habitation sites (point of use). These exploration and habitation sites will li[...] landing location. This would require mobility capabilities to transport [...] full utilization within the architecture.

Current capabilities planned for lunar surface operations are limited [...] kg of cargo. However, fulfilling other key exploration objectives could [...] beyond of these planned capabilities, creating the need for additiona[...]

**Mobility Needs**

One of the largest drivers of mobility needs on the lunar surface is m[...] its point of use. Numerous factors drive cargo point of use, many of [...] landing sites (e.g., darkness caused by a lander's shadow, point of us[...] ejecta from lander plume surface interactions). These relocation d[...] factors:

- Separation from lander shadowing (tens of meters)
- Lander blast ejecta constraints (>1,000 m) due either to separati[...] infrastructure or lander ascent
- Support for aggregation of elements in ideal habitation zones fr[...] (up to 5,000 m)

For more insight into lunar lighting considerations, see the 2022 Moon [...] Selection" white paper.[4]

2024 Moon to Mars Architecture Concept Review

1

**Key Takeaways**

- Lunar exploration objectives require significant mobility of cargo and assets across the lunar surface from landing site to point of use at ranges of 5 to 5,000 m
- Currently, the surface mobility capability expressed in the architecture is limited to 800 kg; however, future mobility demands include aggregated logistics and larger elements as massive as 12,000 kg or more
- Large-scale mobility is not simply scaled up small-scale mobility; energy and environmental considerations are crucial to the design process
- Interoperability and autonomous or semi-autonomous capabilities on mobility systems enable mission planning flexibility and increase available crew utilization time

# Lunar Logistics and Mobility Solicitation


The Lunar South Pole Region Super-Imposed Over the Baltimore-Washington Metropolitan Area

- To meet the capability gaps identified in the mid-cycle white papers, NASA is preparing a request for proposals (RFP) seeking industry solutions for lunar logistics and mobility
- The RFP is in development and will be released as Appendix R of NASA's NextSTEP public-private partnership model
- NASA held an industry day on August 27 to answer questions from and facilitate conversations with industry
- **Ensuring a robust architecture means considering many solutions to gaps and embracing resiliency through redundancy**

# Summary and Upcoming Milestones

- Significant progress made implementing new Moon to Mars Architecture pre-formulation process
- Focus on architecture analysis and decision process in a digital environment to seamlessly integrate Lunar and Mars efforts
- Focused Foundational Exploration segment analysis identified key gaps in lunar surface logistics/cargo delivery and mobility needs

## Upcoming Milestones

**Architecture Concept Review (ACR)**
November 12–14, 2024

**ACR Product Release**
December 2024

**ACR Workshops**
February 11–13, 2025

**Sign up for Moon to Mars Architecture Updates**

National Aeronautics and Space Administration

nasa.gov/architecture

# Questions?

**NASA Advisory Council, Human Exploration and Operations (NAC HEO)**


**Nujoud Merancy**

Deputy Associate Administrator

*Strategy and Architecture Office*

*Exploration Systems Development Mission Directorate*


*August 29, 2024*