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 transit through landing on the lunar surface until the cargo is either offloaded from the lander or in an operational state where these services from the lander are no longer needed, in accordance with cargo lander provider agreements.
- Ensures successful landing at an accessible and useable location on the lunar surface with sufficient precision.
- Establishes safe conditions on the lunar surface for the crew to approach the lander.
- Verifies health and functionality of non-offloaded and/or offloaded cargo.
- Performs any lander end-of-life operations — including potential relocation — ensuring that the cargo or other surface assets are not adversely affected by the lander after landing operations.

As noted above, cargo deliveries will need support service interfaces to ensure safe delivery of cargo to the surface. Service interfaces may support the offloading of cargo, compatibility to surface mobility system interactions, and/or providing resources to the cargo, such as power, communications, data, and/or thermal dissipation. Services may be needed from landing to until the cargo is fully operational, including before or after the cargo is offloaded to the surface.

Landers and cargo may also need additional, crew-focused lander interfaces such as extravehicular activity (EVA) touch interfaces to support crew interactions. Lastly, given potential crew interaction at or near a lander, landers must have the ability to safe itself after landing so that crew are protected while in a landers' vicinity.

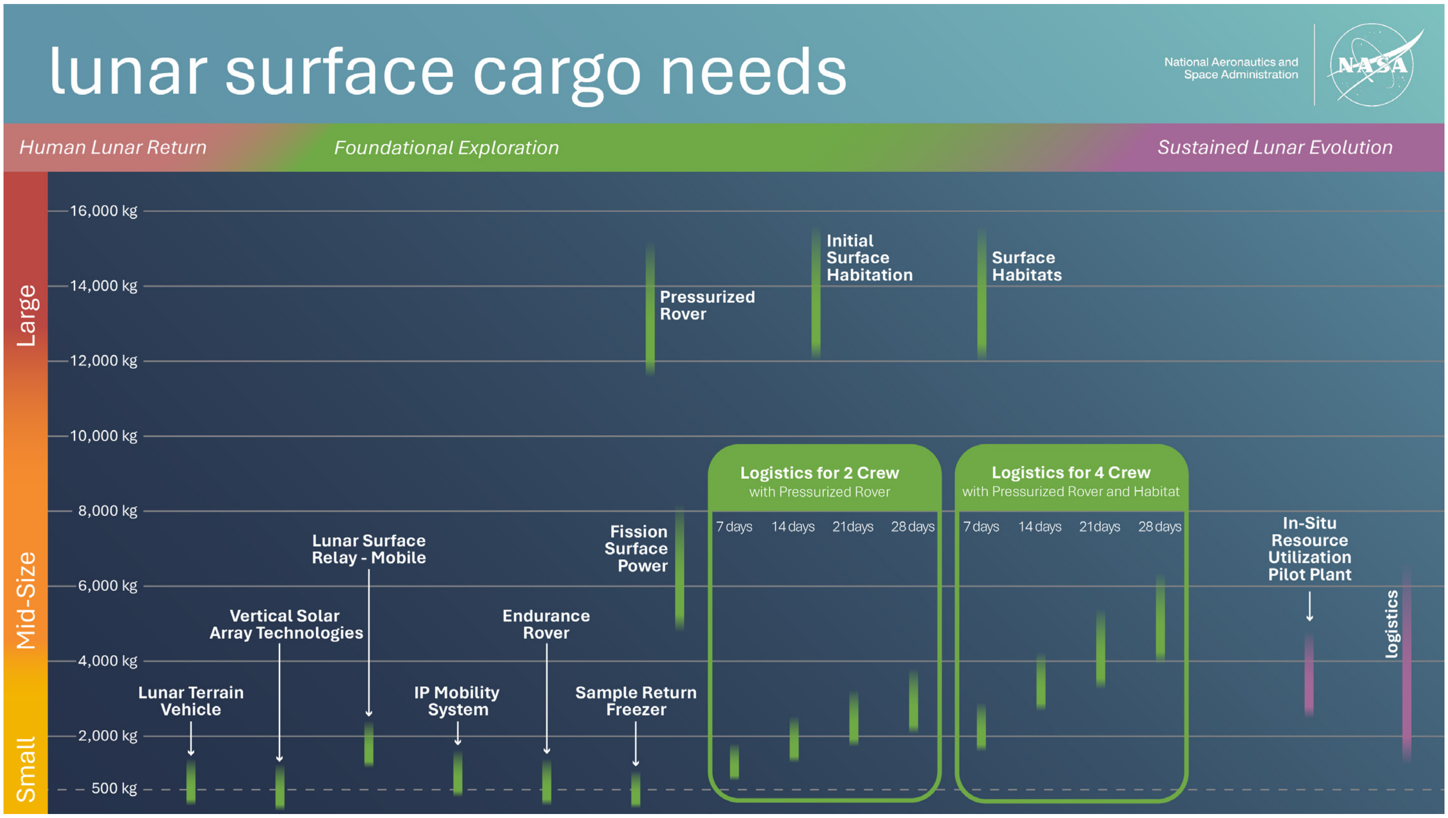

Figure 1: *Planned and potential cargo to the lunar surface. (NASA)*
Note: While contracts are in place for some cargo identified, this figure does not represent agency decisions to fly any item, nor does it reflect the order of flights for any of the items represented.

Lunar Surface Demand vs. Capability

Cargo Demand

To better understand the future demand for lunar landers and transportation systems, NASA assessed a representative sample of planned and potential future surface cargo. **Figure 1** reflects this assessment: each item is represented by a potential mass range and its notional alignment within an exploration campaign segment defined in the ADD.[1]

This cargo includes many one-time delivery missions for habitation, various types of mobility systems, power augmentation, communications relays, and freezers, among many other potential science and technology development payloads. These cargo deliveries — whether of a single item or in aggregate — would each come with a unique set of support service needs (e.g., offloading, manipulation, or surface mobility. For more insight into surface mobility, see the 2024 Moon to Mars Architecture “Lunar Mobility Drivers and Needs” white paper,[2] published concurrently to this paper).

Cargo needs also include recurring logistics delivery missions associated with projected crewed missions (assumed to occur on an annual basis). Logistics items include “food, water, air, spare parts, and other similar products required to sustain life, maintain systems, and allow for productive science and utilization activities.”[3]

While initial crewed missions using HLS vehicles will carry the logistics needed for short mission durations, future missions will utilize additional surface elements to expand mission duration, crew member size, and exploration capability (e.g., accessible range). **Figure 1** shows the approximate mass of logistics needed (including carriers) for a range of mission parameters.

To meet the annual crewed mission cadence, the associated logistics delivery for the duration and crew size will be required each year. For more insight on logistics needs, see the 2023 “Lunar Logistics Drivers and Needs” white paper.[3]

In aggregate, **NASA forecasts a cargo demand range of 2,500 to 10,000 kg per year** for annual recurring logistics and some frequency of small to large elements during the Foundational Exploration campaign segment. This includes occasional large cargo deliveries of up to 15,000 kg for elements like rovers or habitation modules.

These cargo deliveries are necessary to meet a variety of exploration, science, and technology development objectives and a robust future cargo delivery demand drives considerable cargo lander capability needs.

Cargo Lander Capability

To meet initial cargo delivery demands, NASA has contracted with U.S. industry for lander development through the Commercial Lunar Payload Services (CLPS) program[4] and the HLS program,[5] which includes crewed landers and cargo lander variants called Human-class Delivery Landers (HDL).[6] International partners, such as the European Space Agency

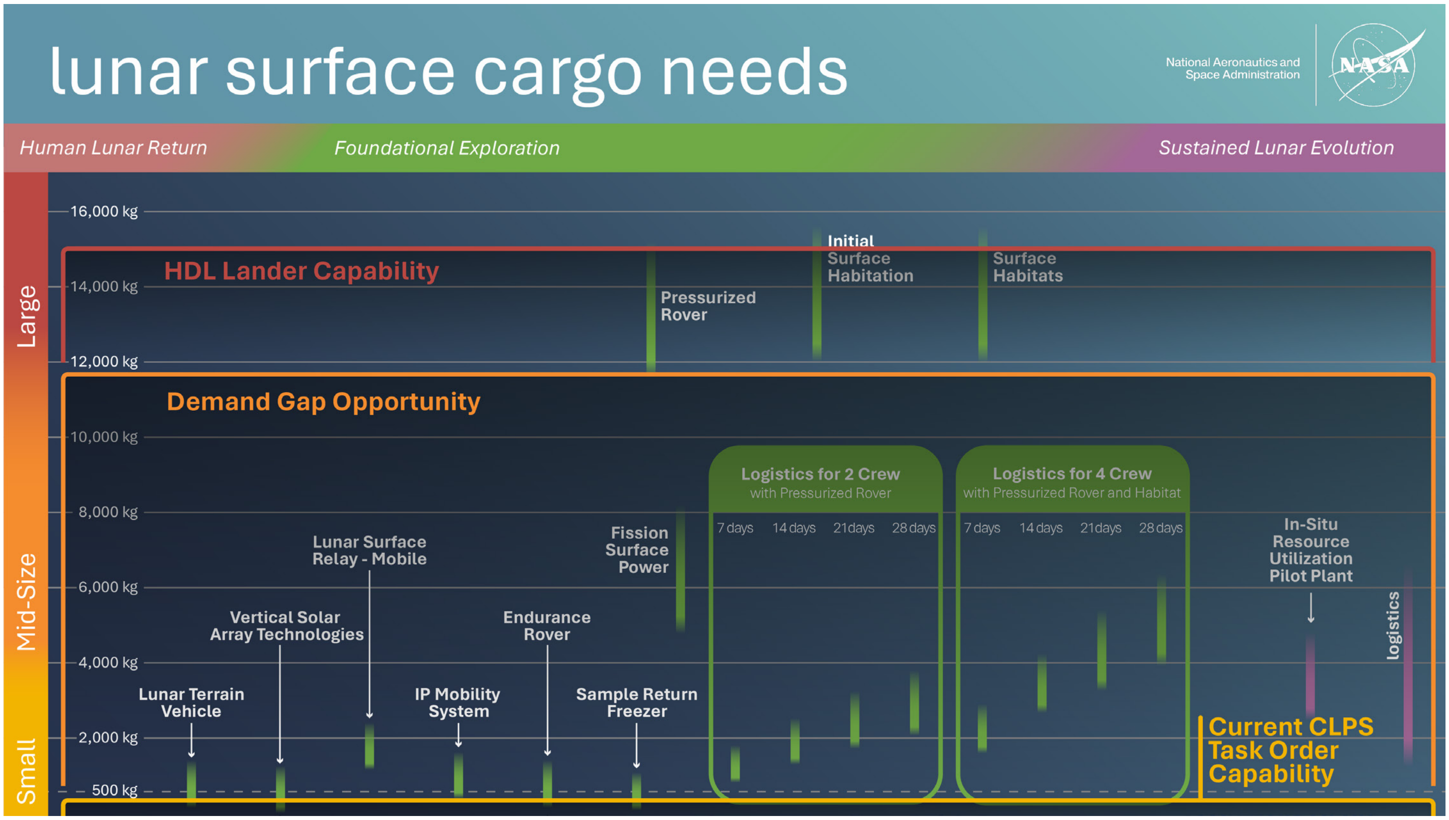

Figure 2: *Planned lander capability compared with lunar surface cargo demand. (NASA)*

(ESA) and Japan Aerospace Exploration Agency (JAXA), are working in collaboration with NASA on potential cargo delivery services.[7] **Table 1** reflects the latest planned and potential cargo lander capabilities.

Despite the capabilities currently in development, a gap in cargo lander delivery has been identified between 500 kg and 12,000 kg, for which significant demand exists. **Figure 2** illustrates the gap between planned lander capability and lunar surface cargo demand.

Strategic Cargo Considerations

Lunar exploration's dynamic mission parameters drive the need for a responsive cargo lander portfolio that covers a range of payloads of various shapes, sizes, and functions. The landers in this portfolio must also provide access to diverse locations across the lunar South Pole region to satisfy exploration objectives. **Figure 3** illustrates this diversity, showing potential landing and exploration regions superimposed over the Washington, DC, area.

Engaging multiple providers from both industry and international partners over time offers many strategic benefits. Leveraging provider diversity in a mixed cargo lander fleet approach addresses some key lessons learned from the International Space Station, including the need for dissimilar redundancy to avoid a situation in which any system becomes a single point of failure.[9] A range of cargo providers also gives NASA the flexibility to manifest cargo efficiently for utilization payloads, technology demonstrations, and logistics delivery.

In addition to the considerations listed above, NASA has identified additional capability gaps for lunar cargo and sample return. The capacity needed to achieve stated objectives greatly exceeds the return capability offered by existing elements. While this paper doesn't seek to address those specific concerns, ongoing NASA analysis is characterizing the driving needs and architectural constraints. Those will be published in an additional ACR24 white paper later this year.

Table 1: *Planned and Potential Cargo Landers*

Lander Type	Mass Delivery Capability (kg)	Provider
CLPS – Current Task Orders[4]	70 – 475	U.S.
HDL Cargo Lander[6]	0 – 12,000 or 15,000	U.S.
ESA Argonaut Lander*[7]	Up to 2,100	International
JAXA Cargo Lander Capability[8]	Under Study	International

**Note: Delivered mass represents cargo platform element + payload.*

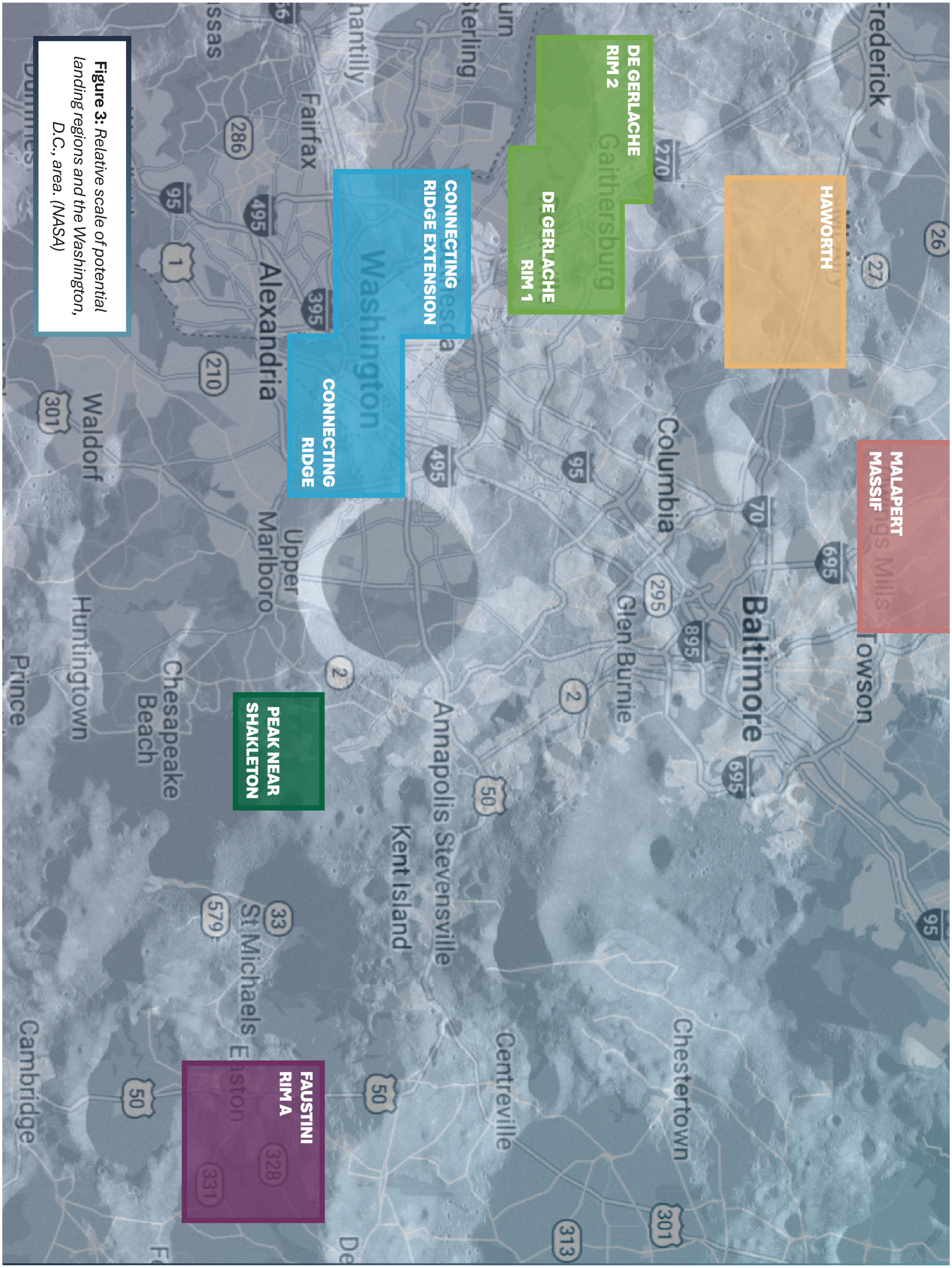

Figure 3: *Relative scale of potential landing regions and the Washington, D.C., area. (NASA)*

Summary

Given diverse cargo needs of varying size, mass, delivery cadence, and operational needs, a diverse portfolio of cargo lander capabilities will be necessary to achieve NASA's Moon to Mars Objectives. While current cargo lander development activities contribute to meeting the Human Lunar Return segment's cargo delivery needs, there is a substantial architectural gap in lander capability for the Foundational Exploration segment and beyond.

Both international partnerships and industry offer opportunities to create a mixed cargo lander fleet that fully meets cargo delivery demands, enables longer missions, sends more crew members to the surface, and empowers a larger exploration footprint. Encouraging the development of varied cargo lander concepts and capabilities will be key to establishing a long-term lunar presence for science and exploration.

More detail on architectural gaps for lunar cargo will be released at the close of the 2024 Architecture Concept Review Cycle, including in white papers on NASA's lunar surface strategy and cargo return needs.

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 expressed 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.

References

1. **ESDMD-001 Rev. A, Moon to Mars Architecture Definition Document (ADD)**
https://www.nasa.gov/wp-content/uploads/2024/01/rev-a-acr23-esdmd-001-m2madd.pdf?emrc=66576c36c8602
2. **Lunar Logistics Drivers and Needs, 2023 Moon to Mars Architecture White Paper**
https://www.nasa.gov/wp-content/uploads/2024/01/acr23-white-papers-compiled-v10.pdf?emrc=ca47b3
3. **Lunar Mobility Drivers and Needs, 2024 Moon to Mars Architecture White Paper**
https://www.nasa.gov/wp-content/uploads/2024/06/acr24-lunar-mobility-drivers-and-needs.pdf
4. **NASA CLPS Webpage**
https://www.nasa.gov/commercial-lunar-payload-services/
5. **NASA HLS Webpage**
https://www.nasa.gov/reference/human-landing-systems/
6. **NASA HDL Web Feature**
https://www.nasa.gov/directorates/esdmd/artemis-campaign-development-division/human-landing-system-program/work-underway-on-large-cargo-landers-for-nasas-artemis-moon-missions/
7. **ESA Argonaut Webpage**
https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Argonaut
8. **JAXA Briefing at the 2024 Humans to Mars Summit**
https://www.exploremars.org/wp-content/uploads/2024/05/0508_0840_-MOnoda_Going-Together.pdf
9. **International Space Station Lessons Learned for Space Exploration, September 2014**
https://www.nasa.gov/wp-content/uploads/2015/05/iss_lessons_learned.pdf