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Lunar Surface Cargo Offloading Concepts

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A sustainable presence on the lunar surface will serve as a vital training ground and technology demonstration test site in preparation for future human missions to Mars. Robotic lunar surface campaigns will focus on the exploration of resources providing information on the availability and extraction of usable resources, such as oxygen and water, and prepare the surface for a sustained human presence. Landers, outfitted with sensor packages, will be used to conduct risk-reduction activities and aid in the development of technologies prior to the crewed lunar missions that drive the need to for a logistics supply chain that requires offloading.

A series of landers will be required on other planetary surfaces to build up the capabilities, capitalizing on those resources, required for sustained human presence. In each of those landers will be cargo including ascent vehicles, habitats, supplies, science packages, spare parts, fluids commodities for fuel and life support, and others varying in volume and ranging from mass in hundreds of kilograms to an estimated 6-14 metric tons to support Human Landing Systems and surface logistics requirements. This paper will examine the challenge of offloading examples of these cargo elements from different categories of landers on the lunar surface using a variety of methodologies. Challenges on the lunar surface arise with the conditions present (thermal, lighting, communications, regolith consistency), the desire to minimize mass of all landed systems, the desire to perform much of the activities with limited to minimal human interaction, and the overall configuration of the landers that are responsible for landing the cargo.

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Nomenclature

ATHLETE= All-Terrain Hex-Legged Extra-Terrestrial Explorer
CLPS = Commercial Lunar Payload Services
GER = Global Exploration Roadmap
HLS = Human Landing System
ISECG = International Space Exploration Coordination Group
ISS = International Space Station
LETS = Lunar Exporation Transportation Services
LORI = Large ORU Robotic Interface
LSMS = Lunar Surface Manipulator System
LTV = Lunar Terrain Vehicle
mt = metric tons
NASA = National Aeronautics and Space Administration
NextSTEP= Next Space Technologies for Exploration Partnerships
ORU = Orbital Replacement Unit
SORI = Small ORU Robotic Interface

I. Introduction

The lunar surface holds valuable resources that supports space exploration activities and provides scientific information about the Earth. A sustainable presence on the lunar surface will serve as a vital training ground and technology demonstration test site in preparation for future human missions to Mars. Robotic lunar surface campaigns will focus on the exploration of resources providing information on the availability and extraction of usable resources, such as oxygen and water, and prepare the surface for a sustained human presence. Landers, outfitted with sensor packages, will be used to conduct risk-reduction activities and aid in the development of technologies prior to the crewed lunar missions that drive the need to for a logistics supply chain that requires offloading.

A series of landers will be required on other planetary surfaces to build up the capabilities, capitalizing on those resources, required for sustained human presence. In each of those landers will be cargo including ascent vehicles, habitats, supplies, science packages, spare parts, fluids commodities for fuel and life support, and more. On Earth, cargo loading/unloading is something that is performed at an unprecedented level today as cargo transportation and offloading are inherent in the global economy. The challenge on other surfaces arises with the conditions present (thermal, lighting, communications, regolith consistency), the desire to minimize the mass of all landed systems, the desire to perform much of the activities with limited to minimal human interaction to save on crew/operator time, and the overall configuration of the landers that are responsible for landing the loading/unloading systems and cargo. Previous studies have addressed a variety of payloads and offloading mechanisms for one given lander[1] or the offloading of a specific set of payloads for a given outpost acrchitecture[2], but this study aimed to start narrowing down the breadth of possibilities to inform future cargo studies in an open Artemis architecture where neither lander options nor payload manifests were given.

Delivery of lunar payloads will be provided by various kinds of landers, some crewed and some robotic. Early robotic missions may be similar to those initially procured by NASAs Commercial Lunar Payload Services (CLPS)[3] contract with a payload capacity approximately 1 metric ton (mt). However, as of 2022, CLPS has approved providers with advertised, projected capabilities from double digits of kilograms to tens of metric tons according to user's guides provided by those providers. Capabilities similar to those provided by the Human Landing Systems providers would likely be the next capabilities to come into service with an increased payload capacity approximately 12-15 metric tons. This mass capability expected for Human Landing System (HLS) class landers from NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) Appendix P is the expected mass requirement for a cargo only version of a lander for a human-class payload such as a surface habitat[4,5]. That crewed ascent module may simply be replaced with cargo accommodations for a surface logistics mission by providers of lunar cargo delivery services.

In April 2021, NASA selected SpaceX for the Option A portion of NextSTEP Appendix H to perform an uncrewed demonstration mission and then one crewed mission to mark the return of the next Americans to safely land on the lunar surface. After a protest to the Government Accounting Office (GAO) and a subsequent appeal to the Court of Federal Claims, the award was upheld and work began in late 2021. However, it should be noted that this work is for a single crewed landing using the Space X Starship vehicle and does not necessarily drive the characteristics or requirements for the rest of the crewed or cargo elements to be delivered to the lunar surface.

There should be an evolution of additional capabilities for lunar applications as the Artemis exploration campaign[4] matures. Those capabilities may be matured via NASA procurement mechanisms such as CLPS, the Gateway program, the Human Landing Systems program which released a Request for Information towards sustainable landers called Lunar Exploration Transportation Services (LETS) in August 2021, or other sources. Again, NASA may be the early anchor tenant for cargo to the lunar surface to establish the market much like what has happened with ISS and the Gateway with the cargo services established for each of those programs.

II. Standards and Interfaces

A. Standards Definitions for Cargo

Developing an affordable and sustainable human space exploration program, without compromising safety, continues to drive changes in the way space systems are developed and operated. Sustained human presence on the surface of the Moon requires increased independence from the crew and ground control mission support to operate efficiently, safely, and reliably. The number of astronauts and the availability of the crew to perform tasks will be limited. An operational shift toward increased automation and autonomy and less reliance on humans is needed.

Strategically infusing automation and autonomy practices early in a system's lifecycle is essential to achieve mission objectives for sustained human presence, to improve performance and mission effectiveness, to reduce operations costs, and to accommodate for ground communication delays. Standardization of interfaces, components, simulation and modeling tools, processes and procedures, and tools and repair kits can reduce costs while providing common frameworks for implementing autonomy across an entire exploration mission.

The international community has collaborated on the International Space Exploration Coordination Group (ISECG). The ISECG has developed several versions of a Global Exploration Roadmap and GER 3.0 from 2018 specifically emphasizes the use of international partnerships to define standards and interfaces. International agreements on standards and interfaces will enable an open architecture that will provide on-ramp opportunities for new and broadened commercial and international engagement. This enterprise approach also provides the flexibility to incorporate new systems and capabilities as they develop, thereby taking advantage of new technological and economic capabilities of all exploration partners. This will enable the evolution of orbital and lunar surface capabilities to conduct Artemis missions. In August 2020, the ISECG released a supplement including more international partner agencies, 24 in number, and updates in notional lunar activities in preparation for later Mars missions.

In a partnership between International Space Station Agencies, a set of International Deep Space Interoperability Standards were drafted in 2018 and released in 2019. https://www.internationaldeepspacestandards.com

- Communications
- Avionics
- Environmental Control and Life Support Systems
- Power
- Thermal
- Robotics
- Software
- Rendezvous

These documents reflect on agreement on standards that should be utilized and tailored for deep space applications rather than a prescription on the details to implement them. This does reduce the scope of possibilities and provides an onramp to document the addition of new standards and interfaces in the future.

1. Mechanical/Electrical Interfaces

For cargo applications, key relevant features of these standards include power standards for conditioned cargo, robotics interfaces for, and external mounting interfaces for "Orbital" Replacement Units (ORUs) such as Large ORU Robotic Interfaces (LORI) and Small ORU Robotic Interface (SORI). The LORI and SORI interfaces are referenced in the Rendezvous document of the International Deep Space Standards. New interfaces and standards may be driven by the optimization of cargo loading positions depending on the orientation of the landers. The landers may have low-slung payloads easily accessible from the surface or be mounted on an elevated flat deck of a descent module, or be at significant elevation from relatively tall single stage lander/ascent vehicles. Thus the mechanical attachments for the payloads may need to be either tailored to their orientation or require adapters to use a common interface.

2. *Packaging*

Additionally, much like the definition of cargo containers on Earth that allow the ease of transport of quantities of commodities from planes to boats to trucks to destinations, further definition of convenient sizes of cargo containers is required for cargo supplies to be utilized for launch from their point of origin, in-space transportation, landing, and transport to the surface sire for their intended use. Additionally, defining the boundary conditions for commencing cargo operations should also be standardized. Those conditions include environmental conditions including lighting and dust from local disturbances to be able to discern visual cues and perform observations and resource availability such as power and communication windows with Earth.

B. Shared Services to Surface Systems Infrastructure

Looking forward to sustainable operations on the lunar surface, there are interfaces to infrastructure on the lunar surface that are interdependent for the cargo offloading function as described below in Table 1. These services will be inherent to the overall lunar outpost architecture elements as well as the cargo offloading function.

Table 1 – Surface Systems Infrastructure Interfaces

Interface	Description
Surface power	Includes function to deploy power systems and to be able to connect/disconnect to power the offloader itself if not integral to the lander.
Surface Mobility	Includes function to translate a payload to various areas across the lunar surface
Surface Communication/Navigation	Includes ability to receive and transmit comments and telemetry to Earth and to other surface infrastructure
Support Crew	Includes ability to support or be facilitated by EVA activities
Support Dust Mitigation	Includes ability to mitigate and adapt to dusty conditions created by surface operations
Support Safety	Includes ability to mitigate risks to crew and equipment
Plan and Schedule Ops	Includes ability to schedule and align tasks with other infrastructure plan sequences of mission operations
Provide Fault Management	Includes ability to maintain and monitor systems, detect, repair, and recover from anomalies and failures
Provide Logistics Management	Includes ability to repurpose, replace, or dispose of supplies and equipment
Protect Environmental Control and Contaminants	Includes ability to minimize environmental impact on operations through disturbance or contamination by controlling operations
Provide Excavation Support	Includes ability to support excavation by offloading equipment and having the ability to utilize excavated accommodations

III. Cargo Options

A. Cargo Packing/Integration

Cargo may be delivered in various sizes and shapes, both pressurized and unpressurized for utilization on the lunar surface. Pressurized cargo may be packed in a logistics module or a habitation element, but small, time-sensitive items may be packed in a pressurized crew cabin of a lander element or other crewed vehicle. Unpressurized cargo will be exposed to the vacuum of space and may be passive or active. Active payloads require power for temperature control, monitoring, and/or operations. The physical integration of the cargo payloads is dependent on the aforementioned standards and interfaces and the available volume and/or area on the lander for which cargo is manifested. On Earth, there may be handling limits or additional fixtures required for cargo loading based on accommodating a one-g environment for that integration. Thus, the offloading on the lunar surface may be easier than the initial cargo on Earth. But that loading, and practice unloading as required, may provide valuable insight that feeds into the mission operations procedures due to potential interferences or orientations required.

B. Cargo Categories

These payloads could be manifested on commercial launch vehicles, international partner launch vehicles, or government launch systems, and they may rendezvous with a lunar orbiting Gateway for staging and cargo transfers before descending to the lunar surface. It is useful to categorize the payloads into categories both drive and capitalize on similarities for mass, sizing, and handling interfaces to grow towards being able to handle them with common methods and equipment. Additionally, the intended value and purpose of that equipment may affect the acceptable risk for the offloading method employed. For example, a logistics container of food and clothing may be treated differently than a more valuable pressurized crew habitat or storage tanks for propellants or life support commodities. Table 2 contains a summary of cargo categories assessed for this cargo offloading analysis.

Table 2 – Cargo Categories

Payload Category	Description	Examples
Infrastructure	Dedicated equipment to prepare a location for a surface outpost or settlement	Additive manufacturing plant, landing launch pad construction devices,
Mobility	Equipment that facilitates the transport of crew and equipment to various locations on the surface	Navigation beacons, offloading devices, robotic rovers, mobile habitats, crewed rovers
Power	Equipment for power generation, conversion, storage, and distribution.	Batteries, solar panels, solar array systems, fuel cells, cable reels, fission power systems
Habitation	Equipment and materials dedicated to pressurized system to support crew living and working environment on the surface	Life support systems, consumables, logistics modules, pressurized access tunnels, food production plant, crew habitat/science modules, airlocks
Communication	Equipment to facilitate communication among assets on the surface as well as those in orbit and assets from the Earth	Antennas, relays, cameras, portable communication terminals
Science	Dedicated science equipment to characterize the space environment as well as to identify areas for ISRU activities	Lab equipment, science instruments, experiments
Surface Support Equipment	General support equipment for multiple purposes on the surface	fluid servicing umbilical panels, commodity storage vessels, unpressurized logistics storage, lifting hardware
EVA	Equipment dedicated to the support of extra	Spacesuits, EVA tools, EVA consumables

Payload Category	Description	Examples
	vehicular activity	
Radiation Shielding	Equipment for the purposes of providing radiation protection for the astronaut crew	Materials for shields, shield framework
ISRU	Equipment dedicated to the purpose of in situ resource utilization	Resource extraction equipment, excavation equipment, thermal protection systems

1. *Primary Cargo Payloads*

The term, primary payload, envelops cargo that is the main purpose for the mission and consumes most of the lander vehicle's capability. Examples of such payloads may include pressurized logistics vehicles, crewed habitat or laboratory facilities, pressurized rovers, and other comparable elements. Figure 1 below lists potential payloads for the lunar surface grouped by estimates of mass range and Figure 2 further depicts several examples in a notional Artemis Base Camp[6] concept image. Notional payload concepts for lunar surface elements such as unpressurized rover, pressurized rover, and surface habitats have continued to evolve under Artemis, most recently with data released with the HLS Appendix P[4], and those elements will continue to evolve until they are procured driving this study team to make utilize rough mass estimates. The mass estimates are useful as a rule of thumb when assessing what cargo can be manifested on a lander with a specified mass capability, either alone or co-manifested with other payloads to share the ride. This list is only a snapshot in time reflecting both notional payloads and their estimated masses and was developed to give the team an impression of the quantity of potential early payloads in the mass ranges shown to be able to think about potentially co-manifesting payloads and how that impacts offloading.

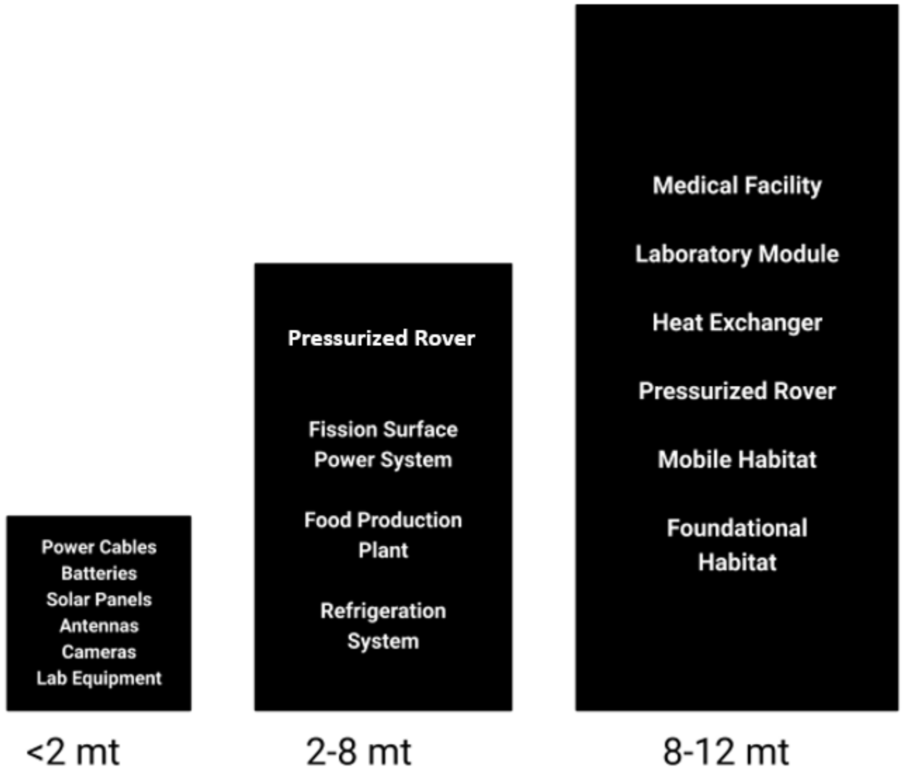


Figure 1 – Payload Mass Categorization for Possible Cargo Types

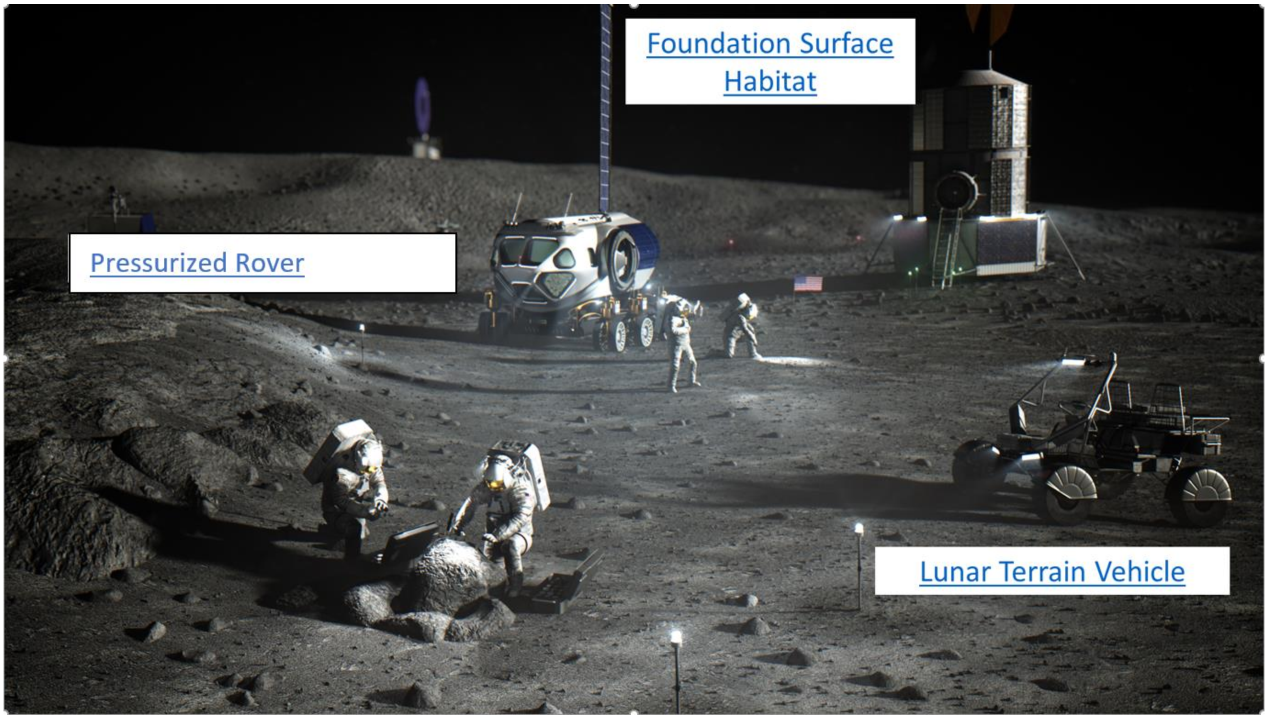


Figure 2: Notional Image of Artemis Base Camp (NASA, 2020) - Lunar terrain vehicle or LTV, transports crew. Pressurized Rover crew trips lasting up to 45 days. Lunar foundation surface habitat houses four crew members.

2. *Secondary Cargo Payloads*

These payloads are additional payloads that take advantage of additional upmass capacity not required by a mission's primary payload. These may be attached in any unused surface area and volume not consumed by the primary payload. Examples of such payloads are commonly spare parts, science packages, and commodity storage. Again, referencing Figure 1, depending on the size of the lander, the payloads could be a primary payload if they consume most of the payload mass allocation for the lander executing that mission, but if that mission is executed by a smaller lander, that same payload could be a secondary payload for another higher priority payload that consumes more mass on a larger lander.

IV. Payload Handling Capabilities

There are many techniques that can be applied to offloading payloads from landers. These capabilities include devices similar to those used on Earth and they may be part of the lander that is bringing down the payload to be offloaded. Alternately, the offloader may come down on a separate lander and be pre-positioned to support offloading of other landers. There are pros and cons to each offloader/handling approach. Table 3 below lists the different offloader (aka Handling Capability) considered in this trade study and provides a short description of each.

Table 3 – Cargo Categories

Handling Capability	Description
ATHLETE[7] and derivatives	ATHLETE is a six wheel-on-limb vehicle for heavy-duty cargo mobility, robotic construction, and dexterous tool manipulation. A high-capacity articulated crane / limb with interface fittings on both ends is capable of operating as a 7 Degree-of-freedom (DOF)

Handling Capability	**Description**
	robotic arm that can swap out a variety of tools and implement
Lunar Surface Manipulator System[8]	The LSMS is a Lightweight, long-reach manipulator architecture that can be easily scaled and customized to perform multiple functions including positioning payloads of any mass and size for surface missions (e.g. Moon, Mars).
Inflatable Ramp	The Inflatable Ramp provides an offloading path for mobility systems from the lander deck to the surface without complex mechanisms, while remaining lightweight and stowing compactly.
Metal Ramp and winch	Metallic Ramp/Winch concept provides offloading path for mobility systems from Lander deck to surface. The ramp system is a twin ramp assembly consist off series of stowed hinge panels inside two structural magazine housings. The stowed/folded ramps are deployed using independent motor drive and ramp inertia momentum to reach landing pad surface.
Metal Ramp with gear drive	With one piece ramp sections as the runway, a rack can be mounted along centerline in the ramp. As the gear meshes with rack, it brings the payload to the surface. The gear has a subassembly attached to it for a capture latch assembly, which is secured to the payload. There would be two sections of the ramp, hinged in the middle for the payload. The payload would be mounted on a skid or pallet to assist with bringing it down the ramp. A third section of (self-leveling) ramp could be utilized as a base platform for the payload on the lunar surface. A capture latch assembly can be remotely controlled to release the payload when it is on the surface.
Double boom Davit Crane	Double Boom Davit concept provides offloading of payload systems from Lander deck to surface, and is stowed with direct interface to payload system via snub attachment. Double Boom Davit structure/mechanism consists of two 4-section telescoping booms driven with two high force actuators to get the long reach to offload Rover system to one side of Lander’s far side landing legs. The two telescoping booms are connected with a gantry boom with snub interface to payload attachment for swing control offload of payload system to landing surface.
Single Boom Davit Crane	Single Boom Davit concept provides offloading of payload systems from Lander deck to surface, and is stowed with direct interface to payload system via snub attachment.
Block and Tackle	A reliable Block and Tackle tool for lowering, raising, and/or pulling cargo on Lunar or Martian surface. Can be stowed aboard various Landers with minimal intrusion. Simple operation can be autonomous, motorized, or manual. Has mechanical advantage = 4:1 (min.) and greater by adding pulleys. Is operationally versatile and can be utilized with other cargo devices. Utilizes stainless steel materials, wire rope.
Winch and Pole	Winch and Pole concept provides offloading path for mobility systems from Lander deck to surface. The pole system is a twin tube assembly with dual wheels for rolling extension to/on landing surface. The pole system is integrated into mobility payload structure, and deployed for rolling outreach to surface. Winch is needed for taller deck >1m for lowering rover after pole wheels are in contact with landing surface. Pole system is ejected off payload upon offload completion.
Propulsive Pallet	The Propulsive Pallet is a cargo pallet with thrusters and enough fuel to lift the payload off the lander deck, traverse sideways, and set the payload gently on the surface.
Lift System	A lifting payload/cargo system has many configurations and functionalities. The lifts may be controlled manually or electronically. A lifting system can lower pressurized and unpressurized cargo onto a Lunar or Martian surface and may be mounted external or internal to the lander. A lifting system that is built into the lander allows astronauts to board

Handling Capability	Description
	with heavy payloads and astronauts can make less trips to the lander to unload/load cargo.

V. Selection Criteria

These selection criteria used in the trade study were determined through an iterative refinement process to be the key characteristics that could be used to assess which handling capabilities may be best suited for a particular assumed combination of payload and lander. The selection criteria are listed in Table 4 along with a brief description of each.

Table 4 – Summary of Lunar Surface-focused Architectural Goals & Objectives

Category	Selection Criteria	Definition
Technical	Payload mass ratio	Mass of handling technique : total payload mass capacity of the handling technique
	Volumetric "intrusions"	Volumetric "intrusion" associated with handling technique; area/volume/dimensions of handling technique in both its stowed and deployed configurations
	Design simplicity	Design simplicity of the handling technique (e.g., smaller number of moving parts, fewer number of degrees of freedom)
	Design maturity	Level of maturity of handling technique based on proven space and/or terrestrial applications & performance
Operational	Operational simplicity	e.g., how many steps to operate the handling technique
	Reliability	Level of robustness; probability that the device successfully offloads the payload (including an option for the crew to provide over-ride capability)
	Operational versatility to handle multiple payloads &/or payload types	Ability to accommodate multiple payloads of same type (e.g., same size, shape, volume, etc.) and/or multiple payload types (e.g., different sizes, shapes, etc.)
	Operational versatility beyond offloading	Ability to provide additional capabilities beyond offloading (e.g., translation, rotation, other manipulations, etc.)
	Level of operational autonomy	Degree to which technique enables autonomous (i.e., independent of crew/ground-required input), semi-autonomous, and manual operations for nominal & off-nominal situations
Architecture	Adaptability to different lander deck heights	Ability to be used for a variety of lander deck heights
	Extensibility to Mars architectures	Ability of the handling technique design and operations to be extensible to Mars surface
	Design reusability	Reusability of the handling technique design over the 2023-2029 manifest (not a measure of reusability of the same physical device)

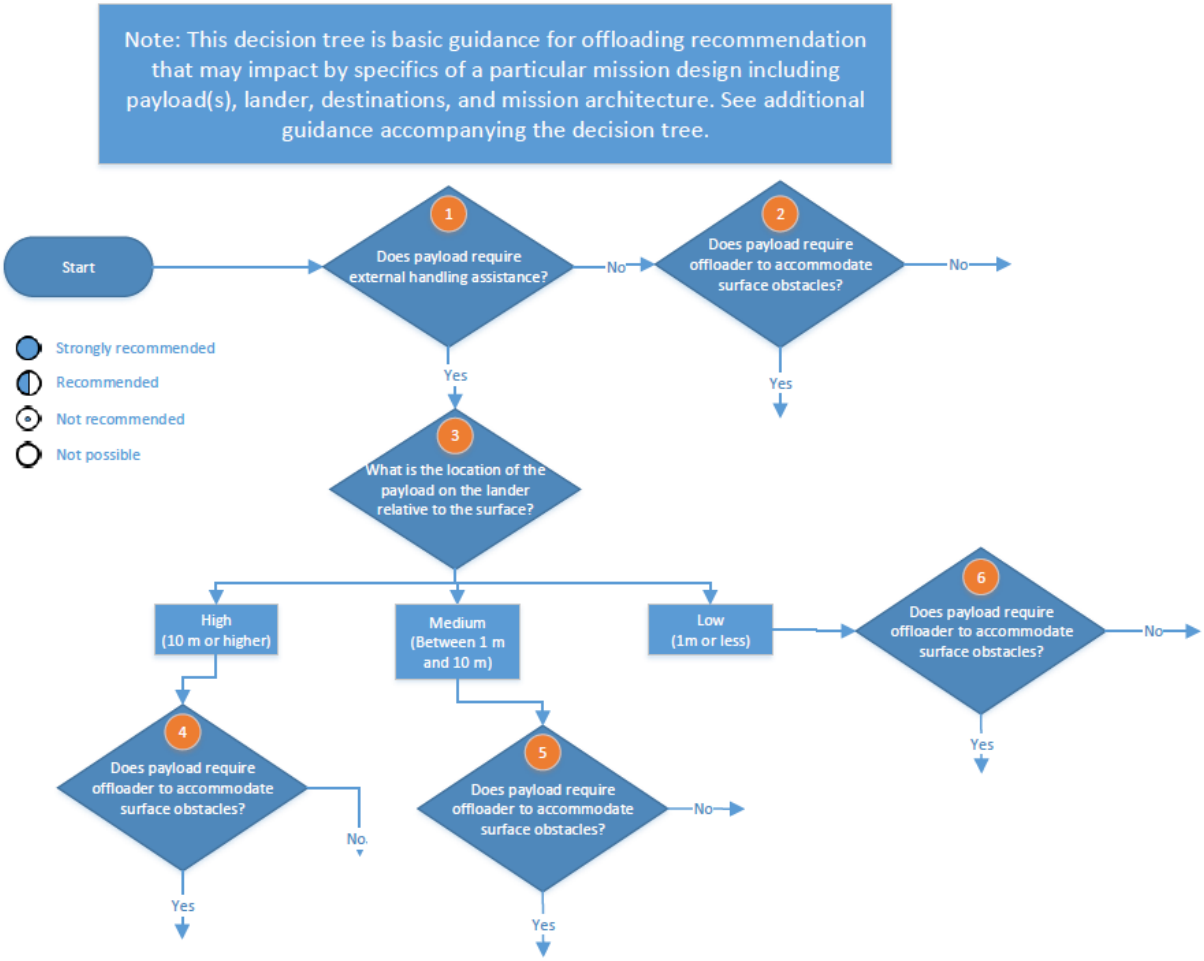
VI. Surface Cargo Offloading Trade Studies

In order to run trade studies regarding offloading techniques, it becomes necessary to prioritize and weight different criteria that are deemed important by analysts. To this end a modified Kepner-Tregoe and Analytical Hierarchy decision making analysis was performed. Three separate trade studies were executed using the selection criteria importance factors documented in section **V.** of this paper. Unweighted scores were established for how well each offloading/handling technique met the selection criteria for that payload. The unweighted scores were multiplied by the appropriate selection criteria weighting factors to produce weighted ratings for each offloading/handling technique. The reliability assessment specifically stemmed from their flexibility to offload a payload to a different location in the event that one side of the lander was blocked by an obstacle (e.g., a boulder or crater). It is possible given the nature of a particular handing technique that it may not apply to particular payloads, in which case it becomes unnecessary to evaluate that technique. An example of this could be a ramp system utilized for a payload that has no mobile capability. The modifications of a ramp to accommodate the payload would likely yield an entirely new technique. The answer to this question is that non-payload specific handling technique mass estimates caused them to be penalized by high mass and they also were expected to be less reliable due to the potential for the ramp to be blocked by a terrain obstacle; potential mitigating factors such as having more than one ramp were not considered.

During the trade study, the team identified other important factors that need to be considered for architecturally informed offloading decisions when assessing particular mission designs. Since these factors can play a large role in determining the best solutions, it is important to consider them prior to performing trades of this type. The factors to consider are single mission vs. cross-architecture use, surface transportation requirements to final staging area, cargo location on lander, handling interfaces and standards, and coordinated handling techniques. In the case of single mission offloading, the engineer will find it more important to have a technique that employs the least mass and volume to allow for more payload capability on the lander. When a cross-architecture capability is leveraged the overall downmass of the offloader may be reduced as compared to multiple landings that include individual offloaders. In this case, an offloader may be manifested on a dedicated lander. While this offers the advantage of greater capability across the architecture it does pose reliability and maintenance risks on the system that should be considered. When considering operations post offloading, it may be necessary to transport the cargo to its final location. When the payload does not possess this mobility element, either including this capability with the offloader or as a separate element would be important. It is also important to consider the cargo's access position, location, and elevation relative to the surface. This can be a primary driver for the use of a specific handling capability. In general, many more options will be applicable for cargo that are situated close to the surface and it becomes more challenging at higher elevations, both for capabilities on the lander that have to each down and for capabilities on the surface that have to reach up. Additionally, whether the cargo is under-slung, side mounted, top mounted, or has to be accessed by moving other equipment may pose additional complex operations that would not be possible with some techniques. Payload handling interfaces and standards also need to be defined to best determine offloading and transportation schemes. Standards are under development for how passive and active cargo are attached to landers, but they have not yet been baselined by space agencies or commercial partners. Defining these standards and interfaces is critical to being able to finalize designs for the offloading capabilities and for being able to maximize flexibility for being able to install cargo on a variety of commercial landers. Those same standards and interfaces may also be utilized for other surface functions like charging, mobility, communications, etc. discussed earlier in Section **II. B.** of this paper for Shared Services. Finally, it is important to recognize that some handling capabilities may be most optimized by operating in tandem with each other to be best suited for a particular lander or cargo configuration. They could also be modified or relocated to the surface or to another assets to allow for future reuse.

VII. Surface Cargo Offloading Decision Path Guidance

To establish basic guidance for future trade studies a decision tree was developed (Figure 3) to understand implications for particular payloads and landers. This generalized guidance also helps to understand each offloading techniques performance against different configurations. This is general guidance and does not replace the value of running a structured trade study tailored for a specific design reference mission using a particular payload, lander, and mission architecture. This is simply a communication tool that can be used as a guide to narrow down the suite of possibilities in offloading capabilities to a few options that are likely to be the most applicable. In the following decision tree, an example output is presented for a mobile payload and large static payload (represents things like large habitat elements). To assess applicability of each technique relative to the configurations and offloader, the analysis team should use engineering judgment based on design, operations, and architecture analysis. This decision tree does not account for tailoring the design of any capability to optimize it for a mission application, such as customizing a ramp for a lander configuration or combining two capabilities like a block and tackle with an inflatable ramp. Including these sample payloads is intended to help a reader see examples that may be relevant to their payload of interest. It also does not account for infrastructure or equipment that may already be in place such as an offloader that is already on the surface but is not the most optimized piece of equipment for the job. That is a game changing variable where an offloading capability available from a previous mission enables mass savings on a future mission that does not need to account for the mass of a co-manifested offloading capability on that mission.



Handling Technique	Mobile Payload	Large Static Payload
Inflatable Ramp	◐	○
Ramp w/ Gear Drive	●	○
Metallic Ramp/Winch	●	○
Winch and Pole	◐	○
Single Boom Davit	⊙	●
Double Boom Davit	◐	●
Block and Tackle	◐	○

Figure 3 – Decision Path Guidance

After the start condition, the first diamond decision block ① asks the reader "does the payload require external handling assistance?" ① defines if the payload needs manipulation prior to being offloaded onto the surface. The selection criteria utilized in this decision are design simplicity, operational simplicity, and level of operational autonomy. If the reader answers "No" then the selection criteria level of operational autonomy is dismissed from the study due to the purpose of simplicity. In contrast, if the reader answers "Yes" then the simplicity selection criteria's are dismissed from the study.

The next diamond decision block ② in the "Yes" condition asks the reader "What is the location of the payload on the lander relative to the surface?" ② defines how high the payload is elevated from the surface. The decision block is divided into three different categories ranging from Low (1 meter or less), Medium (Between 1 meter and 10 meters), and High (10 meters or higher). This also pulls in the selection criteria "adaptability to different deck heights" into the analysis.

Finally the remaining diamond decision blocks ③④⑤⑥ asks the reader "Does the payload require offloader to accommodate surface obstacles?" The selection criteria utilized is reliability, which was used in this case for the purpose of mission success. That essentially is a measure of confidence that the offloader will be reliable when bringing the payload safely to the lunar surface. This decision will determine the complexity of which handling technique should be utilized to offload the specific payload.

The decision tree utilized four categories in defining ratings for handling techniques. These categories included not possible, not recommended, recommended, and strongly recommended. All ratings determined for the handling techniques in Figure 3 relative to the three payloads are not to be taken as a final assumption. The ratings were based on information provided in early development and are to be used as a reference for possible outcomes for specific payloads. These ratings were all based on engineering judgement as annotated above and to be used as a reference while utilizing the decision tree.

VIII. Relationships to Other Operations

A. Mobility Systems

To be able to utilize payloads brought to the lunar surface, the payloads will often not only need to be removed from the lander vehicle but transported to another location for its intended use with a mobility system. This requires both the offloading system and the payload to be able to interface with the mobility systems to be successfully loaded onto a mobility system to be delivered to its work site. For example, a communications relay may be delivered on a lander, but it may need to be repositioned at a more advantageous position via a mobility system. Mobility systems may include pressurized or unpressurized rovers and may be robotic or crew-tended. And in the a cases of some offloading capabilities considered in this study such as the ATHLETE and LSMS, the mobility function may be an inherent function of the offloader. While that may be advantageous to have that dual function for mobility and offloading, that decision would need to be studied in a trade to assess whether it is more cost effective over a period of time to have those functions together and to implement them separately.

B. Repurposing and Disposal

Because of the costs associated with delivering payloads to the surface of the moon, getting the most out of that investment encompassed integrating ideas that allow any materials left over from the landers, offloading systems, support equipment, and packaging to be repurposed into another function on the surface. Clearly, remaining commodities on a lander vehicle may be the first resource that comes to mind, and provisions need to be supplied to allow those commodities to be scavenged and transferred to a reserve where they can be put into use. Next, commodity tanks on the landers, metal struts and platers, multilayer insulation and more can be put into use in a lunar outpost assuming there is a capability for crew or for robotic assets to be able to disassemble the remaining hardware to allow it to be repurposed. If there is not a direct application for those systems, harvesting the equipment to be repurposed back into raw materials for additive manufacturing or other purposes is an attractive option for the long term but requires some pre-planning into the materials choices to optimize repurposing rather than just optimal mission performance.

C. Cargo Loading for Surface Departure

By design, techniques and equipment designed for offloading cargo from landers should also work well for loading cargo back onto vehicles that will ascend from the surface to return cargo to the Gateway, to Earth, and/or eventually to Mars. This capability should rely on the same standards and interfaces used for cargo loading for lunar missions. This cargo may include supplies such as water harvested from lunar resources, science samples being delivered for analysis, or space parts that may need to be repaired or relocated as examples.

D. Mars Exploration Architectures

As discussed in the introduction, the activities on the surface of the moon are a steppingstone to similar activities on the ultimate destination of Mars. While this has focused on the offloading operations on the surface of the moon, Space Policy Directive #1 directs NASA to go to Mars learning the lessons required through lunar exploration activities. The challenges of operating in the environment of Mars have many parallels to the challenges of operating in the lunar environment with reduced gravity, regolith covered surface, dust generated from the regolith, rocky terrain, and uneven surfaces. Landers may be similar to lunar landers but are likely to be large due to the commitment required to send mass that distance and to the challenge of slowing down for landing through the thin atmosphere. Initial estimates for landers to support crewed missions are in the neighborhood of 20-30 metric tons of cargo. Because of those challenges due to the expected large landers, offloading techniques for tall landers and for payloads located at a distance of several meters from the surface are expected to be applicable. The insight from the lunar activities and accommodating offloading for a variety of landers should be able to validate capabilities and operations that will be able to be applied to the later Mars missions.

IX. Risks and Potential Issues

A. Dust

Regolith on the Moon, as well as Mars, is known to pose challenges to operating in those environments. Dust stirred up from operations on the surface can cover solar arrays, radiators, optical surfaces, seals, mechanisms, etc. That dust needs to be removed or remediated to prevent loss of functionality. Any offloading capability has to be designed to overcome the challenges of the dust through a variety of strategies such as the use of operational limitations including speed of movement and delays and technologies including dust shields, blankets, etc.

B. Terrain

There are obvious risks for offloading conditions near landers due to the terrain that are pervasive across the surface of the moon. The surface is uneven including hills, slopes, and craters. While most of those risks should be minimized in landing zones, there will still be inclines that will pose operational challenges. An additional terrain challenge will be rocks and boulders spread across the surface. That affects both mobility paths and where payloads can be placed on the surface. In some cases, it may be possible to use robotic capabilities to clear rocks and boulders as a mitigation strategy.

C. Operational Environment

Dust and terrain are prominent among the challenges of the operational environment. But many other aspects of the environment are significant factors as well. There are zones in the area of each landing that will be subject to the sandblasting-like effects of plume dispersion. Distance, positioning, and even the creation of berms around designated landing sites can reduce those risks. Additionally, lighting conditions for cargo offloading operations will need to allow remote camera visibility to observe operations without astronaut crew in place. Near the South Pole of the Moon, lighting should exist nearly all year long, but lighting conditions in other areas closer to the equator will have longer outages that will need to be avoided in operations planning. And, as mentioned in the dust section earlier, visibility may be affected by not only lighting but dust that gets disturbed during operations. Next, communication windows for teleoperations also have to be considered. If there are not direct communications sight lines to Earth assets, those windows will be defined by lunar orbiting or Earth-orbiting satellites that serve as relay stations. Finally, temperature variances across the surface and on hardware systems between areas in shadow and areas illuminated by sunlight can vary by hundreds of degrees and that may impact operational limits and design tolerances on both offloading equipment and the cargo.

For reference, additional detail on the lunar environment can be found in the NASA document Cross-Program Design Specification for Natural Environments (DSNE), which is available to the public on the NASA Technical Reports Server (NTRS).

D. Safety and Security

Any equipment that operates on another planetary surface will have to account for safety precautions both for high value assets that have been delivered and are operating at those locations and to the astronaut crews that will be active at those sites. This includes both the handling of the payloads themselves and potential damage that could occur to other assets due to the offloading operations. Security precautions for communications systems will be required to prevent unauthorized interference or intrusion that would preclude the successful operation of cargo offloading systems.

X. Conclusion

The goal for this study team was to start narrowing down the breadth of possibilities to inform future cargo studies in an open Artemis architecture where neither lander options nor payload manifests were fixed. In review of the findings of this exploratory study for lunar cargo offloading, this study team concludes that the two most important determining factors in offloading a particular cargo is the height above the surface on which the cargo is mounted and the ability of the cargo itself to be mobile instead of fixed or static. This is mostly a result of the scaling of most offloading systems and the additional ancillary system down mass required to minimize the overall architectural mass and by extension campaign cost. Additionally, optimizing whether cargo offloading accommodations should be provided on each mission or whether a general purpose asset is deployed for offloading over a series of missions requires an analysis of the manifest over a given time period.

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