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A Cis-Lunar Propellant Infrastructure for Flexible Path Exploration and Space Commerce

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Abstract

This paper describes a concept for a cis-lunar propellant infrastructure that exploits lunar water for propellant production and delivers it to users in cis-lunar space. The concept supports multiple goals: to provide responsive economical space transportation beyond low Earth orbit (LEO), enable in-space commerce, and support the multiple destinations of “flexible path” exploration. This concept is “game changing” because it would fundamentally affect the architecture of future space operations, provide greater access to space beyond Earth orbit, and broaden participation in space exploration. The challenge is to create the infrastructure with minimum development costs and yet assure that operational costs do not diminish its benefits. The approach to achieving these objectives includes employing telerobotics, avoiding maintenance intensive machinery, exploiting the natural lunar environment, employing directed energy technologies for resource extraction, and processing and establishing a robust electric power infrastructure.

Since the main exported product is propellants, the infrastructure also includes the means of stockpiling, packaging, and delivering propellants to users at various rendezvous points in cis-lunar space ranging from LEO to the lunar orbit. The product delivery aspect will also include a mix of technologies including cryopropellant management, reusable lunar landers, propellant tankers, orbital transfer vehicles, aerobraking technologies, and electric propulsion. To minimize operational cost, the infrastructure is entirely telerobotic. Resource-intensive human flight operations are deferred until the infrastructure is operational and capable of supporting human missions. Ultimately, the infrastructure is intended to reduce the cost of both robotic and human space missions. This infrastructure is not strictly dependent on human missions to justify the investment and can be scalable and would serve a wide user base ranging from commercial satellite servicing to large-scale human exploration missions. A cis-lunar propellant and logistics infrastructure dramatically reduces the size and cost of launch vehicles for missions beyond Earth orbit. Since it can extend the effective reach of existing vehicles, in effect, it provides access to deep space to any user capable of reaching LEO. The cis-lunar propellant and logistics infrastructure is sustained without the need for dedicated logistics launches. This paper introduces the concept where users of the infrastructure can buy propellant services by trading logistics packages with the infrastructure. This process of exchanging logistics for propellants can be regarded as an early form of in-space commerce.

Introduction

In this paper the term “cis-lunar” means “in the vicinity of the Moon” and refers to the fact that even vehicles in Earth orbit, from a propulsive energy standpoint, are actually closer to the Moon than they are to Earth’s surface. This concept called the cis-lunar propellant infrastructure exploits lunar water as a resource for spacecraft propellant production and uses it to refuel spacecraft in space. By refueling spacecraft in low Earth orbit (LEO), the infrastructure could dramatically reduce the size and cost of launch vehicles for missions beyond Earth orbit. By extending the effective reach of existing launch vehicles, in effect, provides access to deep space to any user capable of reaching LEO. The concept exploits the fact that delivering lunar-launched propellants to LEO will be more than 5 to 6 times more efficient than delivering Earth-launched propellants to LEO. To prevent the operating costs from diminishing the benefits, the architecture adopts a propellant and logistics exchange strategy to sustain the

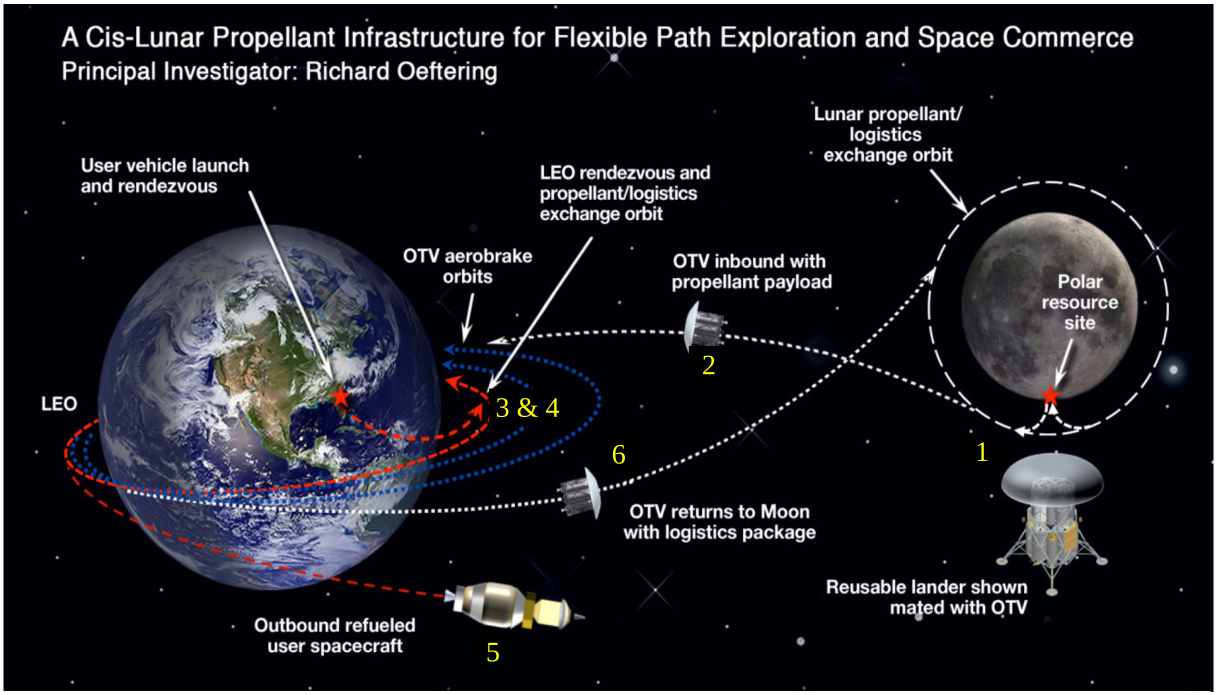


Figure 1.—Cis-lunar propellant infrastructure concept: (1) A reusable lunar lander launches a propellant payload into lunar orbit. (2) An orbital transfer vehicle (OTV) with aerobraking capability transfers to low Earth orbit (LEO). (3) A user spacecraft and OTV meet in LEO. (4) The OTV transfers propellants and picks up a logistics package (Log-Pak) (i.e., it exchanges propellants for logistics). (5) The refueled user spacecraft proceeds to its destination or is transferred to its destination by the OTV directly. (6) The OTV returns to the Moon with the Log-Pak. The exchange allows the cis-lunar propellant infrastructure to operate without dedicated logistics launches.

cis-lunar propellant infrastructure as shown in Figure 1. With this novel approach, users of the infrastructure, in effect, will "buy" propellant services or propulsion services by trading logistics packages (Log-Paks) with the infrastructure. This process of exchange can be regarded as an early form of in-space commerce.

Strategies that ensure a high level of resource independence will be used to keep deployment and operating costs from diminishing benefits. This study examines the in-space elements of the infrastructure that transport propellants, such as reusable lunar landers, orbital transfer vehicles (OTVs), or propellant tankers. This cis-lunar propellant infrastructure takes an evolutionary approach that starts producing propellants at a small scale and uses them to help bootstrap a larger operation. It delivers propellants on demand from the lunar surface and avoids the costs of maintaining a large propellant depot in space. It is expected to provide near-term value to commercial, government, and nongovernment users, and eventually expand to a scale that supports "flexible path" missions. This concept is regarded as "game changing" because it uses lunar propellants to "lower the bar" to access to space beyond Earth orbit with existing vehicles. By doing so, it broadens participation in space exploration and fundamentally alters the architecture of future space operations.

The Need for a Cis-Lunar Infrastructure

An Infrastructure for Long-Term Sustainability

The Exploration System Architecture Study indentified the major elements of the program and the funding needed to accomplish the ambitious goals (Ref. 1). Constellation was not responding to a high-priority "urgent national need" thus funding remained near pre-Constellation levels. The Constellation

Program looked to acquire funding by a process where NASA would shut down existing programs to acquire their funds. The retirement of the Space Shuttle Program was to be the first major step to be followed by the International Space Station (ISS) retirement by 2015 (Ref. 2). This is ample evidence that any future program must consider its operational support costs and relevance to future NASA goals. A program that has both high operational cost and limited relevance to future space objectives is likely to become a victim of future program termination. The alternative is to form a program that provides value to a wide array of mission objectives that provides program flexibility so that no one goal is achieved at the expense of other goals. That is, an enabling infrastructure that satisfies near- and long-term objectives and forms the foundation of in-space architectures.

Reusable Spacecraft Versus Reusable Launch Vehicles

It is important to understand the distinction between reusable spacecraft and reusable launch vehicles. A reusable spacecraft is launched once and used for multiple missions. The primary servicing between missions is refueling. In contrast, elements of a reusable launch vehicle must be recovered, repaired, refurbished, reassembled, tested, and refueled between launches. This cycle shares many of the same activities as newly manufactured vehicles. Launch is the most highly stressed event where launch vehicles and spacecraft have the narrowest margins of safety. These narrow margins impose stringent inspection, maintenance, and reverification processes that are time consuming and costly.

Unlike launch vehicles, spacecraft provide ample evidence that having survived a single launch cycle, spacecraft can have long continuous life spanning a decade or more. Therefore, expendable vehicles may be the best option for launch, but reusability is appropriate for spacecraft (Ref. 3). The main life limitation for many spacecraft has been the fuel supply. Reusable spacecraft implies an in-space refueling capability. Concepts for in-space propellant depots and reusable OTVs have been considered since the inception on the space program. A reusable spacecraft supported by an in-space refueling capability provides greater flexibility and availability. The limitation is the cost of creating and sustaining the in-space refueling and servicing infrastructure.

Case for In-Space Servicing

In recent years, the proliferation of satellite constellations such as satellite phone systems, multiple global position systems, and the continued growth of direct broadcast television satellites have dramatically increased the number of assets in orbit. This growth; however, has also seen the growth of orbital debris hazards. Collisions involving dead satellites have occurred and they give rise to more debris hazards. Even satellites in high geosynchronous orbits (GEOs) have seen disruption due to drifting dead satellites. Actual collisions have driven regulations that require new spacecraft designs to reserve propellants for de-orbit as part of their life cycle (Ref. 4). Forcing spacecraft to effectively “commit suicide” when propellants reach a minimum level, shortens the useful life of spacecraft at great cost (or loss of revenue) to the users (Ref. 5). Therefore, there is a need for a cost-effective in-space servicing capability to either refuel spacecraft to extend their useful lives or physically remove them as future debris hazards.

Case for Orbital Transportation and Tanker Services

The main barrier to exploration or commercial activity beyond LEO is the high cost of carrying the additional propellants needed for travel beyond Earth orbit. For a lunar landing mission, the added propellant mass requires that a launch vehicle loft 5 to 6 times more mass than it would to deliver the same payload to LEO. That is, at least 80 to 85 percent of the spacecraft mass starting in LEO is propellant and propulsion hardware. Closer to Earth, the payloads, such as weather or telecom satellites, are delivered to GEO. Departing LEO for GEO requires a vehicle that may be composed of propulsion and propellant mass that makes up 71 to 90 percent of the initial mass in LEO. Despite the vast difference in distance between LEO to GEO and LEO to LLO (low lunar orbit) the propulsion energy required is comparable and therefore, propellant needs are also comparable.

Providing in-space refueling or orbital transfer service can eliminate the need to launch propellants into space. Eliminating this load on the launch vehicles effectively multiplies launch vehicle capacity by 3.5 to 10 times, depending on the mission. Conversely, it means that the launch vehicle can be scaled back to a smaller much less expensive vehicle. The overall effect is to lower the bar and dramatically increase user options since there are many existing small launch vehicles available. Lowering the bar also means that space beyond LEO is accessible to more organizations and thus more participation. It cannot be overstated that the technology investment that lowers the bar is a game changing development that provides many benefits toward the human development of space.

Case for a Lunar Resource Infrastructure

Constellation was the first program to consider in situ resource utilization (ISRU) technologies to exploit lunar regolith for potential water and oxygen on the Moon and Mars for crew consumables. In the last two decades studies determined that ISRU could provide significant program cost savings. The cost savings are best realized when the overall program architecture takes lunar oxygen production into account (Ref. 6).

The Constellation Program assumed that the main objective was to return human crews to the Moon and did not intend to establish in-space infrastructures. Constellation, sought to solve transportation issues with massive launch vehicles. ISRU was regarded as experimental with no commitment to exploit the in situ resource at an architecture level. With the recent discovery of large lunar water deposits, a new strategy must be developed that exploits the resource. This can forever alter our view of the Moon as not just a destination but as a resource gateway to space. If ISRU is not embraced early in the program architecture then there is no opportunity to use it to reduce cost (Ref. 7).

Game Changing Benefits

The cis-lunar propellant infrastructure makes lunar propellants a widely available high-value commodity that would dramatically change how we carry out space operations. It affects the size of launch vehicles and the mobility and useful life of spacecraft and it expands the participation in space. Lunar propellants can be traded for other materials. In effect, the trade between the infrastructure and users can be instrumental in the establishment of in-space commerce.

- Greater access to space beyond LEO: In-space refueling and orbital transportation services enable smaller launch vehicles to reach GEOs, Lagrange points, the Moon and Mars, and near-Earth objects (NEOs). The user can exploit an array of low-cost launch vehicles. Even the heavy-lift launch vehicles for human operations could be scaled back to a more affordable, more versatile design. Low-cost access to space beyond LEO encourages broader participation in space.
- Greater spacecraft mobility and utility: Mobility is dependent on the ready availability of fuel. Just as the military in-flight refueling improves the range and mobility of aircraft, readily available propellants can improve mobility in space. Using lunar resources for in-flight refueling enables spacecraft to accomplish multiple missions and extend the life of valuable space assets.
- Enabling reusable spacecraft*:* In-space refueling is essential for enabling reusable spacecraft like the OTVs, tankers, and reusable lunar landers. Reusable spacecraft preserves the hardware value and helps amortize their cost by making them available for multiple missions. Reusable spacecraft lets users focus on the payload and eliminate the cost of developing unique departure stages and landers. Reusable landers used as suborbital “hoppers” enhance the ability to deploy science instruments, infrastructure communication, navigation aids, and equipment virtually anywhere on the lunar surface. They also enable cis-lunar infrastructure to discover and exploit new resources.

- Enable spacecraft salvaging: In-space refueling has an unexpected value in that it provides the mobility to salvage and reuse spent stages. Upper stages can be redesigned to be reconfigured for secondary roles including propellant storage tanks such as self-propelled tankers, or orbital tugs. Salvaged hardware can also be decomposed for spare subassemblies and components.
- Trading propellant for logistics: Both the user and the infrastructure can exploit any unused portion of the dramatically expanded payload capacity. The user can use the capacity for a secondary payload Log-Pak that contains logistics material and equipment for maintaining and expanding the infrastructure. The user, in turn, can use the Log-Pak as a reimbursable element to help buy down the cost of the flight. The user benefits from a reduced cost and the infrastructure benefits by eliminating costly logistics flights.
- Basis for in-space commerce: Not only does a lunar propellant support commercial space tanker, space tug, satellite servicing, or reusable lander services but it creates a new form of in-space trade. Trading propellants for logistics provides the mutual benefit of reducing costs for both user and infrastructure. Refueling of salvaged stages creates a secondary market for upper stages. Users can "trade" used stages to the infrastructure for credit toward future services. Exploiting lunar resources not only increases access to space but spawns space commerce helping to make the cis-lunar propellant infrastructure a self-sustaining operation.

Concept of an Evolving Cis-Lunar Infrastructure

Ground Rules and Assumptions

The cis-lunar propellant infrastructure described here is one of many possible alternative architectures. A supportable cis-lunar propellant infrastructure considers the following ground rules from lessons learned in supportability studies (Ref. 8). These ground rules are intended to prevent costs from diminishing the benefits while assuring continued growth. The "bootstrap approach" starts with a small capability that is used to acquire resources and, in turn, use the resources to expand capability in repeated cycle. The cis-lunar propellant infrastructure is treated like a small lunar economy that is focused on growth. This economy strives for resource independence to minimize the need for continued logistics launches. When propellants are produced they are used initially to expand capability. Exporting of resources is deferred until a resource surplus is achieved. Then resources are traded for equipment and material that once again expand capability. The following ground rules apply to this bootstrap process:

- Reusable reconfigurable vehicles: Vehicles that can be reconfigured to support multiple roles assure flexibility and minimize the number of unique vehicles.
- Minimize the need for logistics launches: Supporting the infrastructure with frequent and costly logistics launches diminishes the benefits of the infrastructure. The logistics strategy involves employing technologies that reduce the logistics needs to a minimum and exploit any available resources.
- Scavenge and reuse flight hardware: Resource scarcity drives the need to exploit every piece of hardware to the greatest possible extent. This means salvaging spent flight hardware and assimilating it into the infrastructure or scavenging hardware for key components or reusable materials.
- Employ technologies that simplify maintenance: Equipment maintenance drives logistics and impacts hardware availability. Systems must minimize complexity and dependency on scarce resources.
- Defer human operations: Humans are perishable and logistically intensive and simply not suited to a cryogenically cold environment. Humans need a complex support infrastructure, which will not exist in the early bootstrap stages of the infrastructure development.

- Support for human exploration and space commerce: The ultimate goal of the cis-lunar infrastructure is to make access to space beyond Earth orbit affordable and sustainable for science missions, robotic and human exploration, and space commerce. The investment in the infrastructure to exploit space resources pays short- and long-term dividends. The near-term benefit is lowering the cost of space beyond LEO, while the long-term benefit is the creation of a robust and flexible self-sustaining infrastructure that supports a flexible path to human exploration.

Lunar Surface Depot Concept

There have been many concepts for space propellant depots. Until recently the majority depended on Earth-launched propellants. The assumption was that low-cost expendable vehicles would ferry propellants to space to keep the depot loaded. In effect, the propellants are simply shifted onto other launch vehicles. For large human-scale missions, several launch vehicles would be required to fuel a large Earth departure stage. When faced with the complexity and risk of launching several vehicles to build an orbiting propellant depot, the program will tend to favor the development of very large launch vehicles (Ref. 9).

Providing propellants from sources already in space dramatically lowers the launch vehicle scale. From a propulsive energy standpoint, a spacecraft in LEO is actually closer to the Moon than it is to the surface of the Earth. Because of the one-sixth gravity of the Moon, the propulsive energy required to achieve orbit is at least 16 times less per kilogram. Lunar launch acceleration forces may start at 1/3 g at lift-off to approach 1 g at engine cutoff. The very low launch acceleration combined with the elimination of aerodynamic forces and the intense rocket motor vibration and acoustic stresses reduce structural mass and enables single-stage reusable landers.

Carrying a loaded OTV or a tanker, the reusable lander delivers a mass to orbit that is roughly 63 percent of the initial launch mass to LLO. In comparison to an Earth launcher that only delivers about 3 to 4 percent to LEO, this represents a 15- to 21-fold performance advantage. Upon separation, roughly 21 percent of the initial launch mass is reserved for the lander and propellant to return to the lunar launch site. This leaves 42 percent of the initial mass as OTV or tanker. After the transfer to Earth and aerobrake insertion into LEO the remaining propellant available is roughly 25 percent of the original launch mass.

Locating the depot in LEO seems obvious since that is where the users are. However, the LEO thermal environment is not favorable to cryogenic storage. Further, phasing and orbital plane inclination changes near Earth are particularly inefficient. A cryogenic depot system placed in Lagrange point 1 (L–1) is a more favorable thermal environment. The propulsion costs of supplying lunar propellants to a depot in L–1 are reasonable and access to other cis-lunar orbits is favorable. Transporting lunar propellants from L–1 to LEO is “downhill,” thus the propulsion energy from L–1 to LEO is modest. The dissipation of the kinetic energy as a vehicle approaches LEO is handled by aerodynamic braking using an aeroshell (Refs. 4 and 10).

Because the lunar surface portion of the infrastructure uses in-situ-produced propellants before it exports them, it is important to establish the primary depot capacity on the lunar surface. This minimizes duplication of equipment, which is very important to keep the cost low in the early phase. The thermal environment in permanently shadowed polar areas is often colder than 100 K (Ref. 11). Liquid hydrogen can be processed and stored with much lower energy than at L–1 or LEO. Liquid oxygen is very easily stored at 100 K with little need for further chilling. Exploiting the extreme environment allows the infrastructure to operate with a minimum initial investment. This is consistent with a bootstrap philosophy where initial and operational costs are minimized so that infrastructure can grow as the demand for propellant grows. In the early operational phase, the cis-lunar propellant infrastructure operates as an on-demand launch and delivery service from the lunar-surface-based depot. The infrastructure can operate in this manner until demand drives the need to create a separate in-space propellant depot.

Evolution of the Infrastructure

Initial Bootstrap Phase

It is assumed that some precursor science and prospecting missions have landed and have confirmed the presence of water and determined that the surface concentration is adequate for water acquisition and processing into propellants. The scale of the equipment delivered in this phase is entirely dependent on the capabilities of existing launch vehicles. Consistent with the bootstrap approach, the initial objective is to deliver equipment and generate as much electric power as possible. A robust power system will be needed to power robotic equipment that deploys the systems.

Once the power infrastructure is in place the next phase focuses on employing technologies capable of extracting water and producing propellant. In the all-electric approach, the techniques will exploit the natural high vacuum and thermal environment. Energy will be projected via short-range microwaves to sublimate water molecules and collect them directly as frost accumulations or by guiding them into a process that dissociates the water molecules directly into propellant gases by plasma chemical methods (Refs. 12 and 13). Cryogenic cooling techniques will be used to condense the gases directly into liquids. The initial propellant production rate may be quite small but the propellants will be accumulated until a modest lander can be launched.

Expanding Capability

The bootstrap strategy is focused on continuously expanding capabilities. Therefore propellant produced at this bootstrap stage will be used to transport equipment and materials for building the surface infrastructure capability. In the early production phase the cis-lunar infrastructure will only have a Light Reusable Lunar Lander (LRLL) using lunar propellant. There will not be enough propellant for an OTV or tanker at this stage. A reusable lander using lunar propellant can capture and land payloads in LLO. This capability eliminates the expendable lander and, as a result, nearly doubles the payload capability of existing launch vehicles for lunar missions. The LRLL can transfer propellants to assist in its first landing of the next-generation Medium Reusable Lunar Lander (MRLL).

As capabilities grow the landers can be replaced with more capable units. The MRLL will be capable of launching and handling 10+ metric tons (mt). A Heavy Evolved Expendable Launch Vehicle (EELV) can launch a partially loaded MRLL. The MRLL will weigh about 4.5 mt empty with a fully loaded gross weight of 30 mt. At this point, a reusable tanker or OTV is added to the infrastructure. The tanker or OTV will be capable of exporting limited amounts of propellant.

To further expand export capability and to set the stage for human operations, a Heavy Reusable Lunar Lander (HRLL) is the next step in the evolution of the infrastructure (Fig. 2). The HRLL is an Altair-class vehicle (Fig. 3) capable of a lift-off gross weight of 60 mt. The HRLL will be coupled with an appropriately scaled tanker or OTV capable of 20 to 25 mt of propellants. The capabilities of these vehicle and analysis of cis-lunar missions are described in a latter section.

Evolving to Human Operations

Human operations would employ a “human-rated” reusable lunar lander for lunar landings. The 60-mt HRLL can handle virtually any of the lunar surface payloads envisioned by Constellation. The HRLL eliminates the need to launch expendable landers and a lunar mission can be launched by a single heavy lift vehicle possibly derived from Space Shuttle elements. The HRLL is actually capable of capturing and landing a fully loaded Orion spacecraft and relaunching it to orbit. Cis-lunar OTVs can be used to return Orion vehicles home should its propulsion systems fail. The cis-lunar propellant infrastructure makes it easier and safer for humans to operate in cis-lunar space while minimizing launch vehicle cost.

In support of a large human mission to NEOs, or Mars, a large propellant depot in L–1 is needed. HRLL and tankers would ferry large amounts of cryogenic propellants to L–1. Cis-lunar OTVs could also serve as reusable boosters for the initial L–1 departure.

Cis-Lunar Infrastructure Architecture

Flight Elements of the Cis-Lunar Infrastructure

This architecture adheres to the ground rules and assumptions of supportability and sustainability. The focus of the author's study was to develop the flight portion of the infrastructure. Where possible the author uses existing vehicles and systems with well characterized capabilities. In other cases information was derived from well documented studies such as the Constellation Altair design. As an architecture study, there is no intent to design a spacecraft and the vehicle concepts illustrated are notional. The architecture evolved in the course of the study. The analysis that helped define these elements is discussed in the next section.

The cis-lunar infrastructure is composed of

- Reusable lunar landers (light, medium, and heavy)
- Tanker/OTV
- Aeroshell
- Electric propulsion (EP) unit
- Log-Pak

Reusable Lunar Lander

A key element of the cis-lunar infrastructure is the reusable lunar lander. Unlike Earth, the Moon's low gravity and lack of atmosphere allows a single-stage lander to perform both launch vehicle and lander roles. Carrying a loaded tanker or OTV, the hydrogen and oxygen propelled reusable lander delivers a mass to orbit that is roughly 63 percent of the initial launch mass to LLO. Upon separation in LLO, roughly 21 percent is reserved for the lander with sufficient propellant to return to the lunar launch site. The remaining 42 percent of the initial mass is dedicated to the tanker or OTV.

In the early build-up phase prior to propellant production, the landers will be small single mission units. Their size is due to the constraints of existing launch vehicles. When lunar propellants become available, the landers are scaled to match propellant production capacity. Scaling the lander exploits the propellants as early as possible to accelerate the infrastructure growth. Light, medium, and heavy reusable landers are envisioned.

Light Reusable Lunar Lander (LRLL)

When an initial propellant production starts up, a LRLL will be employed. Its primary role will be to capture and land inbound payloads used in the expansion of the surface infrastructure. It will rely on a modest propellant production capacity. This first reusable lander is envisioned to be capable of using lunar propellants, have an empty weight of 2.4 mt, and a gross weight of 15 mt, and able to handle incoming payloads up to 5.6 mt.

Medium Reusable Lunar Lander (MRLL)

The next step up is a more capable MRLL expected to operate with a fully loaded gross weight of 30 mt. Its empty weight is estimated to be roughly 4.5 mt. It will be capable of handling 11.3 mt of incoming logistics and early OTV stages. The OTV will be refueled and launched atop the lander much like an upper stage. The lander will need to retrieve the returning OTV and incoming logistics payloads. For large payloads, the lander would retrieve the payload and OTV in separate sorties. The reusable lunar lander may be derived from the Altair concept. The array of multiple tanks in combination with a modular tubular construction makes it easier to reconfigure and thus scalable. Scalability may allow a large lander to be constructed from medium lander components.

Heavy Reusable Lunar Lander (HRLL)

The HRLL, as shown in Figure 2, is an adaptation of the Altair Cargo Lander with a gross lift-off weight of 60 mt. The Constellation Altair, fully loaded, weighed 53.6 mt at launch (Ref. 14). The Altair was designed to handle this mass under 4+ g launch accelerations of an Aries V. In contrast, the HRLL, at lunar launch will likely see no more than a 1 g load. Thus an Altair-derived structure could easily handle a 60 mt launch mass.

Unlike the Altair Cargo Lander the HRLL will launch with a lift-off gross weight of 60 mt. As a rule of thumb, launching in 1/6 g needs thrust roughly equal to about one-third the vehicle weight in 1 g. For the heavy lift: 60 mt is equivalent to 132,277 lb in 1 g. Like the Altair, the HRLL can use the same Rocketdyne RL–10A engines rated at 22,300 lbf (99.2 kN) each (Ref. 15). Unlike Altair, The HRLL will need a dual-engine configuration that provides to meet the lift-off thrust requirement.

Lunar lift-off thrust = 1/3 × (1 g vehicle weight) = 44,092 lbf thrust
Dual RL–10 thrust = 44,600 lbf (198.4 kN)

To improve reliability for an “engine out” scenario, a third engine is added. To maintain the desired thrust level, each of the three engines are operated at nominal 14,700 lbf. In this way, an off-nominal engine out scenario is easily covered by two engines at normal rated thrust. The de-rated thrust level of the three-engine configuration can also improve engine life.

The RL–10 specific impulse is assumed to be a conservative 440 sec. Table 1 illustrates how a common engine design can be used for all three generations of reusable lunar landers.

TABLE 1.—SUMMARY OF REUSABLE LUNAR LANDER EVOLUTION USING A COMMON ENGINE

Reusable lander generation	Lift-off mass, mt	RL–10A engines	Rated thrust, percent
Light	15	1	49
Medium	30	1 or 2	99 to 49
Heavy	60	2 or 3	99 to 66

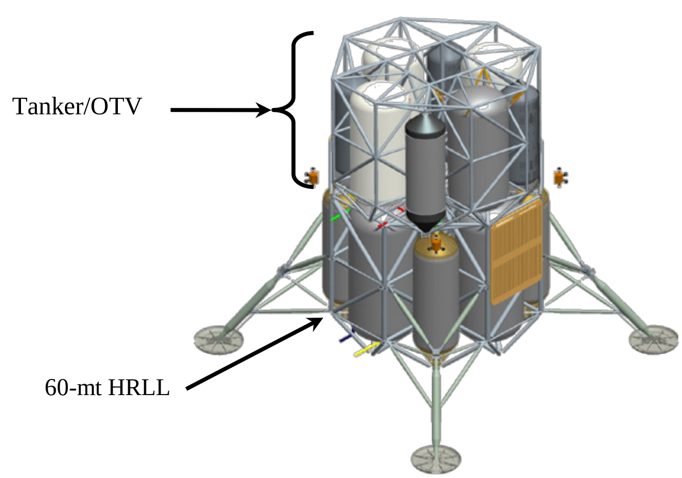


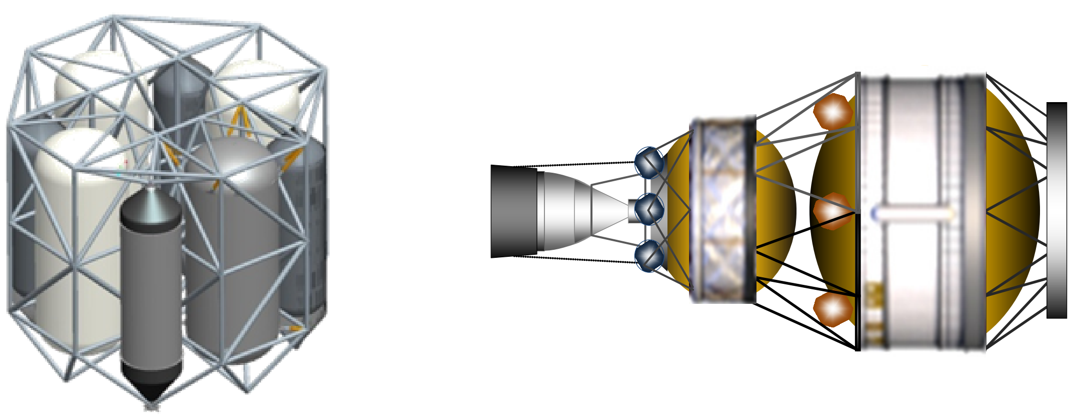
Figure 2.—Cis-lunar Heavy Reusable Lunar Lander (HRLL) and tanker/orbital transfer vehicles (OTVs). This notional HRLL concept is derived directly from the Constellation Altair and is inherently modular. The fully loaded HRLL mass is 60 mt at lift-off and delivers a tanker/OTV to low lunar orbit (LLO).

HRLL delivery can involve launch vehicles of the scale of a Heavy EELV to launch an HRLL into geosynchronous transfer orbit (GTO). The unit is delivered to GTO with a payload assist stage or it uses its own engines with a partial fuel load. A medium tanker/OTV can refuel the HRLL or transport it in LLO. If needed, a tanker can transfer additional propellant for landing. HRLL delivery in this manner is constrained by payload fairings of the current Heavy EELV, which cannot accommodate the physical dimensions of an Altair class lander. Therefore, the alternative is to use a Heavy EELV with an OTV and MRLL to deliver the HRLL as subassemblies and assembled the complete unit on the lunar surface.

Propellant Tanker/OTV

In this study the tanker and OTV are viewed as variations of the same vehicle. The tanker/OTV, illustrated in Figure 3, may be an adaptation of an existing upper stage. In this study the performance of liquid-hydrogen- and liquid-oxygen-based RL–10 engines is used. Adapting existing upper stages pose a major advantage in that they will already be part of the existing launch fleet. This also means that the infrastructure could acquire spent stages and reconfigure them as OTVs or tankers. These stages also provide a source of spare engines, which can be expected to have useful life beyond their initial use (Ref. 16).

The tanker/OTV will have features that let it capture and securely hold the payload for transport. Since most payloads conform to some standard mounting interface the OTV may be designed to exploit that common feature. To support transfer Log-Pak items, a light and dexterous robotic arm(s) will be needed. It is assumed that the user vehicle incorporates features that allow it to be either captured or refueled in orbit by teleoperated means.



(a) Tanker/OTV derived from Altair

(b) Tanker/OTV derived from a high-energy upper stage

Figure 3.—Potential core elements of a tanker/orbital transfer vehicle (OTV). (a) One approach uses a design derived from the Altair lunar lander. The modular structure, multiple tanks, and common propulsion systems are suited to scaling the vehicle for specific missions. (b) Another approach adapts existing hardware and propulsion system of high-energy upper stages. The cis-lunar infrastructure may exploit both types.

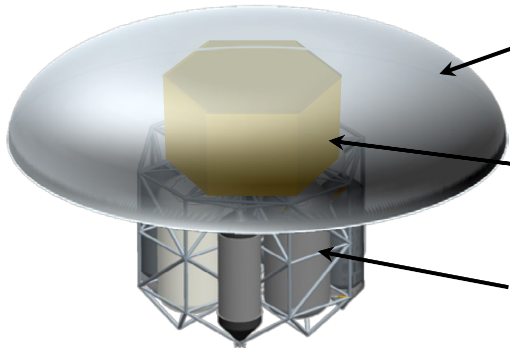


Figure 4.—Tanker/orbital transfer vehicle (OTV) with aeroshell. The aeroshell conserves propellant for low-Earth orbit (LEO) insertion; however, it carries the penalty of added propellant required for returning it to the Moon.

Aeroshell for LEO Aerocapture

The cis-lunar infrastructure cannot be based on chemical propulsion alone because entry into LEO from the Moon would effectively consume nearly all the propellant delivered. Most cis-lunar transportation concepts rely on aerobraking to minimize propellant transportation between cis-lunar space and LEO. The aeroshell performs the braking efficiently so the trip from lunar orbit or L–1 to LEO uses a modest amount of propellant. As illustrated in figure 4, reusable aeroshells represent a considerable portion of the total vehicle mass (Ref. 10). The mass may be reduced if the aerobraking energy (heating) is distributed into multiple passes. This may make the aeroshell lighter but the additional passes slow delivery and allows more time for propellant boil-off. In this study, the aeroshell was assumed to be 15 percent of the vehicle mass. There is strong motivation to eject the mass once aerobraking is done. To avoid the need to launch replacements the aeroshell must be recovered or it must be replaced by in situ fabrication from lunar resources. In this study, the aeroshell ejected in LEO is then recovered and returned to L–1 by specialized high specific impulse EP unit described below.

Electric Propulsion (EP) Units

In a mixed fleet concept, EP units are used to recover infrastructure assets. The primary application of EP is the recovery of the aeroshell and returning it to L–1. Without this recovery option, a tanker/OTV must carry the aeroshell back to L–1 as a fixed element at very high propellant cost and limited payload performance. High specific impulse EP systems allow the infrastructure to use between 0.8 and 1.3 mt (Isp = 3000 to 4500) of propellant (Ref. 17). Solar EP uses large arrays, which must be stowed during aerobraking and redeployed for the trip to L–1. Because the return to L–1 may take up to 500 days, it will be necessary to have multiple EP driven aeroshells in the cis-lunar infrastructure cycle. The EP propellant mass is delivered by the Log-Pak described below. The impact of EP on logistics can be reduced if the EP thruster technology can be adapted to use lunar volatiles as propellant.

Logistics Package (Log-Pak)

There is no specific package design for the Log-Pak since logistics will vary in type and content. Log-Paks will likely include storable hydrazine and EP propellants, as well as surface consumables, new equipment, and repair parts. The user can accommodate the Log-Paks by using a readily available adapter that does not interfere with the primary payload. This payload adapter has been used on many missions to support secondary payloads and special brackets can be used to attach Log-Pak items (Ref. 18).

Role of Salvaged Flight Hardware

Note that in the case where the user vehicle destination is L–1 or LLO, the infrastructure can capture and salvage the spent user stage. This stage can be assimilated into the architecture in multiple ways.

- Salvaged and modified to perform infrastructure roles such as tanker/OTV or serve as part of a space depot.
- Scavenged for hardware (tanks, engines, structures, and avionics) to support replacement or expansion of infrastructure elements.
- Scavenged for raw materials to serve as feedstock for fabrication and repair on the lunar surface.

Cis-Lunar Destinations

Low Earth Orbit (LEO)

LEO is where a cis-lunar OTV picks up payloads and tankers refuel user vehicles. Cryogenic propellants are not well suited for transportation within LEO. Cis-lunar vehicles are most suited for supporting large payloads bound for destinations beyond LEO involving large delta-v values.

Geosynchronous Transfer Orbit (GTO)

Most launch vehicles designed to deliver communications satellites to GEO actually deliver them to a GTO. In the last leg from GTO to GEO the upper stage is expending much of the remaining fuel transporting nearly empty tanks. At this point, it is more effective to separate the OTV and rely on a smaller propulsion segment. Typically, a satellite is equipped with a small solid propulsion system (apogee “kick motor”) that makes the final transfer to GEO. The empty weight may only be a few hundred kilograms whereas the larger cryogenic stage may weigh 2.5 mt at the end of the burn.

In this study, cis-lunar tanker/OTV delivers 9 to 13 mt of payload from LEO to GTO. Launch vehicles such as an Atlas or a Delta are available in a payload capacity ranging from 4 mt to nearly 13 mt (Ref. 19). By using tankers and OTVs to assist with payload delivery, the smallest vehicle in the family can now deliver to GTO the equivalent to the largest vehicle.

Geosynchronous Orbit (GEO)

GEOs are 24-hr orbits that are synchronized with a target longitude on Earth. In terms of delta-v, GEO is more remote than L–1 and LLO. GEO is where virtually all communications and television satellites are located and thus is very important to commerce. The payload performance for an OTV to GEO is the lowest among the cis-lunar destinations.

Lagrange Point 1 (L–1)

In this study, L–1 serves primarily as a staging area for the aeroshell/EP hardware. Consistent with the affordable on-demand approach, a cryogenic propellant depot facility is located on the lunar surface and a L–1 depot is deferred until it is justified by propellant demand. However, there may be a modest teleoperated “dry dock” that services the aeroshell and the EP unit and facilitates the mating of the aeroshell/EP assembly with the tanker/OTV. This facility could evolve into a full-scale depot to support human missions (Ref. 20).

Low Lunar Orbit (LLO)

LLO is where the OTV and reusable lunar lander rendezvous take place. When delivering a tanker/OTV to LLO the lander immediately descends to the polar surface depot for refueling. Refueling the reusable lunar lander gives it the capacity to ascend to LLO again to capture and recover the OTV and Log-Pak. To maximize performance the vehicle is loaded with only enough propellant to match the needs of the recovery operation. Because of the polar location of the lunar resources, most cis-lunar LLO activity will be polar orbits.

Lunar Surface

The bulk of the traffic to the lunar surface will be to the polar-based depots. The reusable lunar landers can provide transport and deployment services for users. This eliminates the need for users to invest in lander development. In most cases, the user payload will be first delivered to the depot site. A lander of appropriate scale and propellant load deploys the payload in a suborbital hop and then returns to the depot.

Beyond Cis-Lunar Space (Flexible Path)

Lagrange points provide efficient points of departure into interplanetary space. Cis-lunar infrastructure supports missions beyond cis-lunar space to flexible path destinations like Mars and NEOs. In those scenarios the cis-lunar infrastructure can transport spacecraft elements from LEO to L–1. At L–1, cis-lunar tankers can load large chemical departure stages in support of outbound missions. Eliminating the propellant consumed between LEO and L–1 and providing propellants for departure, the cis-lunar infrastructure can eliminate hundreds of metric tons of Earth-launched propellants. By providing transport and fueling services the cis-lunar propellant infrastructure enables an interplanetary mission to be launched from Earth with only the propellant needed to reach LEO. A mission could be assembled with existing Heavy EELVs or a shuttle-derived vehicle. As noted earlier, multiple OTVs could serve as L–1 departure stage boosters that separate after the boost and return to the Moon or L–1 for another mission.

Cis-Lunar “Mixed Fleet” Concept and Analysis

As in any modern navy, the fleets are composed of a diverse set of vessels that have dramatically varied capabilities yet complement each other when operating as a coordinated unit. In this section, various combinations of cis-lunar of elements are considered. The reference mass of each element is shown in Table 2. The analysis assumes a 60-mt HRLL is used to place a tanker/OTV into LLO. The figure of merit in this analysis is the user payload capability, which is related to propellant mass delivered and how efficiently it is used. In the following analyses, the Log-Pak mass is assumed 0 to simplify the comparison. The impact of Log-Pak as a fraction of the user payload is shown in a separate analysis.

TABLE 2.—REFERENCE MASS FRACTIONS FOR KEY ELEMENTS

Element	Percent of reference mass	Reference mass
Heavy Reusable Lunar Lander (HRLL) dry	13	60 mt lift-off mass
Tanker/orbital transfer vehicle (OTV) gross	67	Mass at reusable lunar lander and OTV separation
Tanker/OTV dry	10	Tanker/OTV gross
Aeroshell	15	Tanker/OTV at L–1
Electric propulsion (EP)	35	Aeroshell mass (for return to L–1)
EP propellant	40	Aeroshell mass (for return to L–1)
Logistics package (Log-Pak)	(0 to 100)	Payload mass

The source of the delta-v values in Table 3 are found in References 14, 20, and 21. Note that the low thrust to weight ratio of EP results in higher effective delta-v than the high thrust chemical propulsion system.

TABLE 3.—DELTA-v VALUES USED IN THE CIS-LUNAR ANALYSIS

Delta-v	
LEO_GTO_Delta V	–2500
LEO_GEO_Delta_V	–4330
LEO_L1_DeltaV	–3770
LEO_LLO_DeltaV	–4040
GTO_GEO_DeltaV	–1830
GTO_L1_DeltaV	–1270
GTO_LLO_DeltaV	–1540
GEO_L1_DeltaV	–1400
GEO_LLO_DeltaV	–2000
L1_LLO_DeltaV	–600
L1_Landing_DeltaV	–2520
LLO_Landing_DeltaV	–2000
Lunar Surface_LLO_DeltaV	–2000
Lunar Surface_L1_DeltaV	–2520
LLO_L1_DeltaV	–600
Delta-v with aerobraking	
LLO_LEO_Brake_DeltaV	–875
L1_LEO_Brake_DeltaV	–770
L1_GTO_Brake_DeltaV	–500
Delta-v Electric Propulsion (EP)	
EP_LEO_GEO_DeltaV	–6000
EP_LEO_L1_DeltaV	–7000
EP_L1_LLO_DeltaV	–800

HRLL + OTV + Fixed Aeroshell Configuration

Figure 5 shows a sequence that only includes a HRLL unit and an OTV with a fixed aeroshell. This is the simplest configuration considered but the least capable.

The OTV aeroshell combination are loaded on the lunar surface and launched. The reusable lunar lander and OTV aeroshell separate in LLO. The reusable lunar lander returns to the surface depot as the OTV aeroshell transfers to Earth. After aerobraking, the vehicle rendezvous with the user payload in LEO and transports it to its destination while acquiring any Log-Pak items. Note that in this configuration the performance is very limited. In fact, the negative value for payload to GEO indicates that this particular scenario provides no payload capability for GEO missions. The main problem is the energy required to return the OTV with the aeroshell to LLO diminishes payload performance.

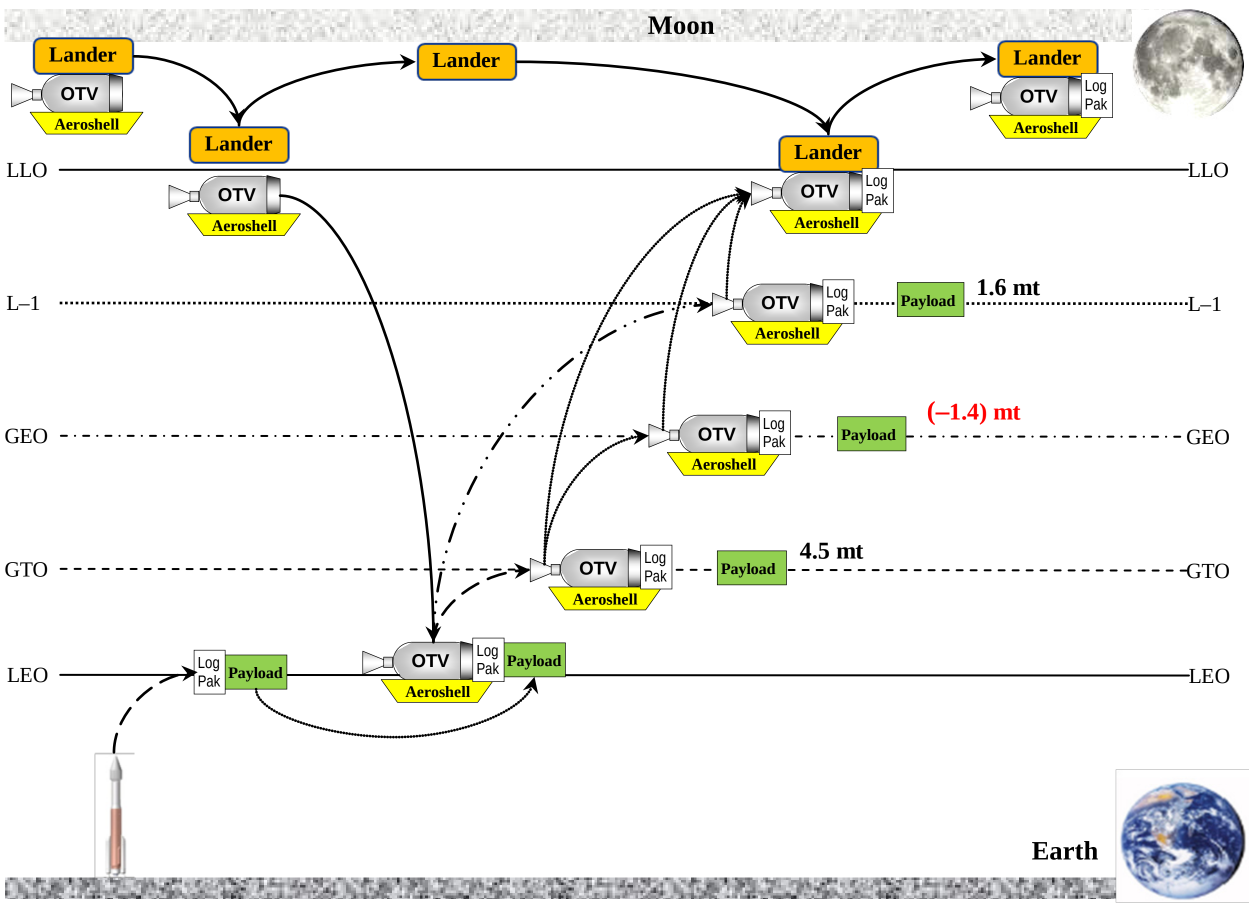


Figure 5.—Orbital transfer vehicle (OTV) with fixed aeroshell has limited capability.

HRLL + OTV + Aeroshell Ejection

Figure 6 shows the OTV using an aeroshell in the transfer to Earth where the aeroshell ejected once it provides the aerodynamic braking and capture functions.

The performance this scenario provides the user is dramatically improved over the prior scenario. The loss of the aeroshell; however, requires replacement. This scenario is only effective if some form of lunar fabrication using in situ materials can produce suitable replacement aeroshells. In this scenario, the HRLL still needs to carry the aeroshell mass from the lunar surface, which reduces the amount of propellant delivered.

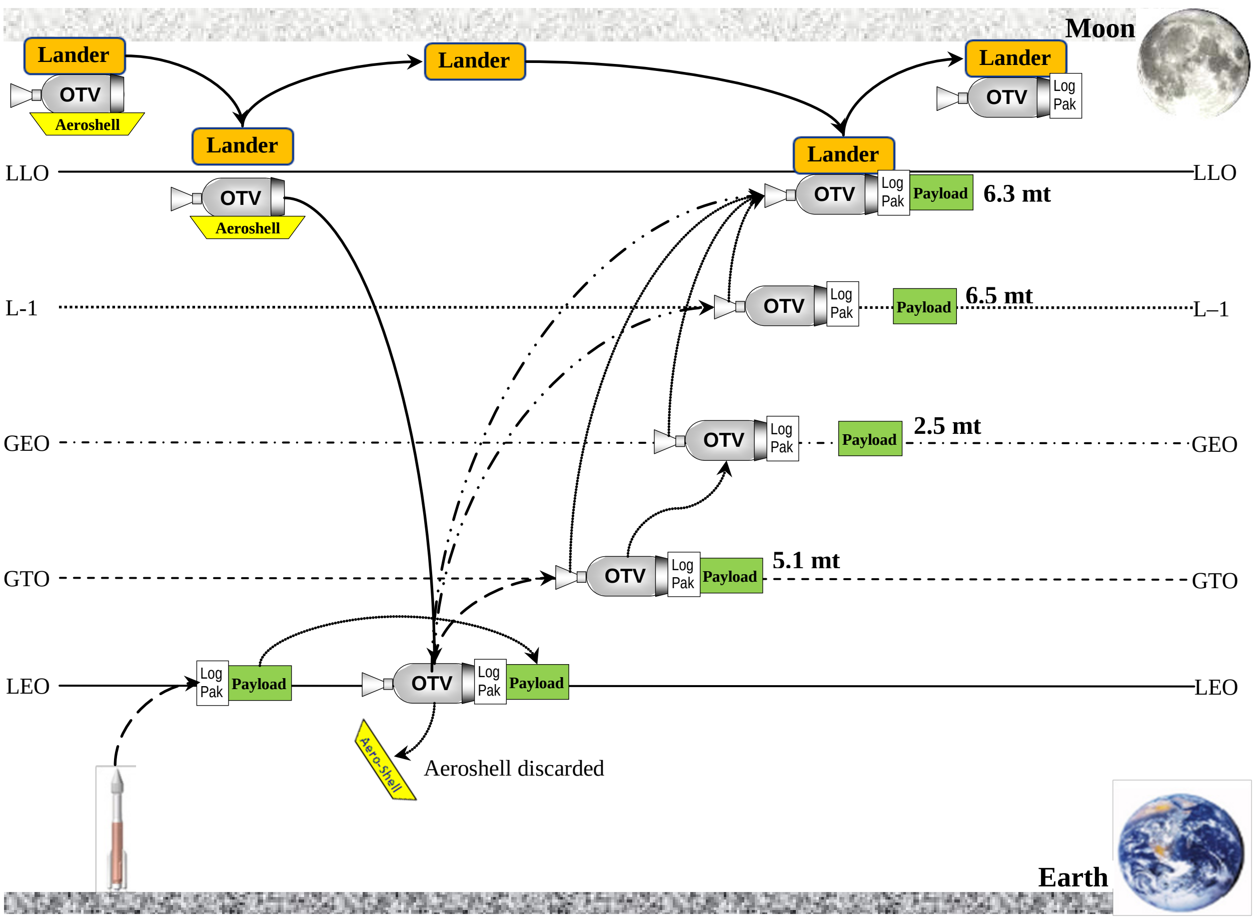


Figure 6.—Orbital transfer vehicle (OTV) with aeroshell ejected at low Earth orbit (LEO) provides a dramatic increase in capability.

HRLL + OTV + Aeroshell Ejection and EP Recovery

Figure 7 shows that the OTV picks up an aeroshell located at L–1, which is then ejected after LEO aerocapture. In this case the aeroshell is recovered by a built-in EP system. The OTV returns to LLO to be recovered by the HRLL for refueling on the lunar surface.

In this scenario, the need to lift the aeroshell from the lunar surface is eliminated. The aeroshell is returning to L–1 by the EP unit. The EP unit adds considerable mass to the aeroshell but the delta-v transfer to Earth is modest so its impact is minimized. The EP propellant mass will likely be delivered via the Log-Pak. The EP solar arrays are stowed during aerocapture and deployed after separation for the transition to L–1. Note that the aeroshell return will need as much as 500 days to return to L–1 (Ref. 17).

To further improve the performance to GEO, an alternate scenario involves a Payload Assist Motor (PAM) for the final leg between GTO and GEO (Ref. 22). In this case a PAM stage raises the payload capacity from 2.6 to 5.7 mt.

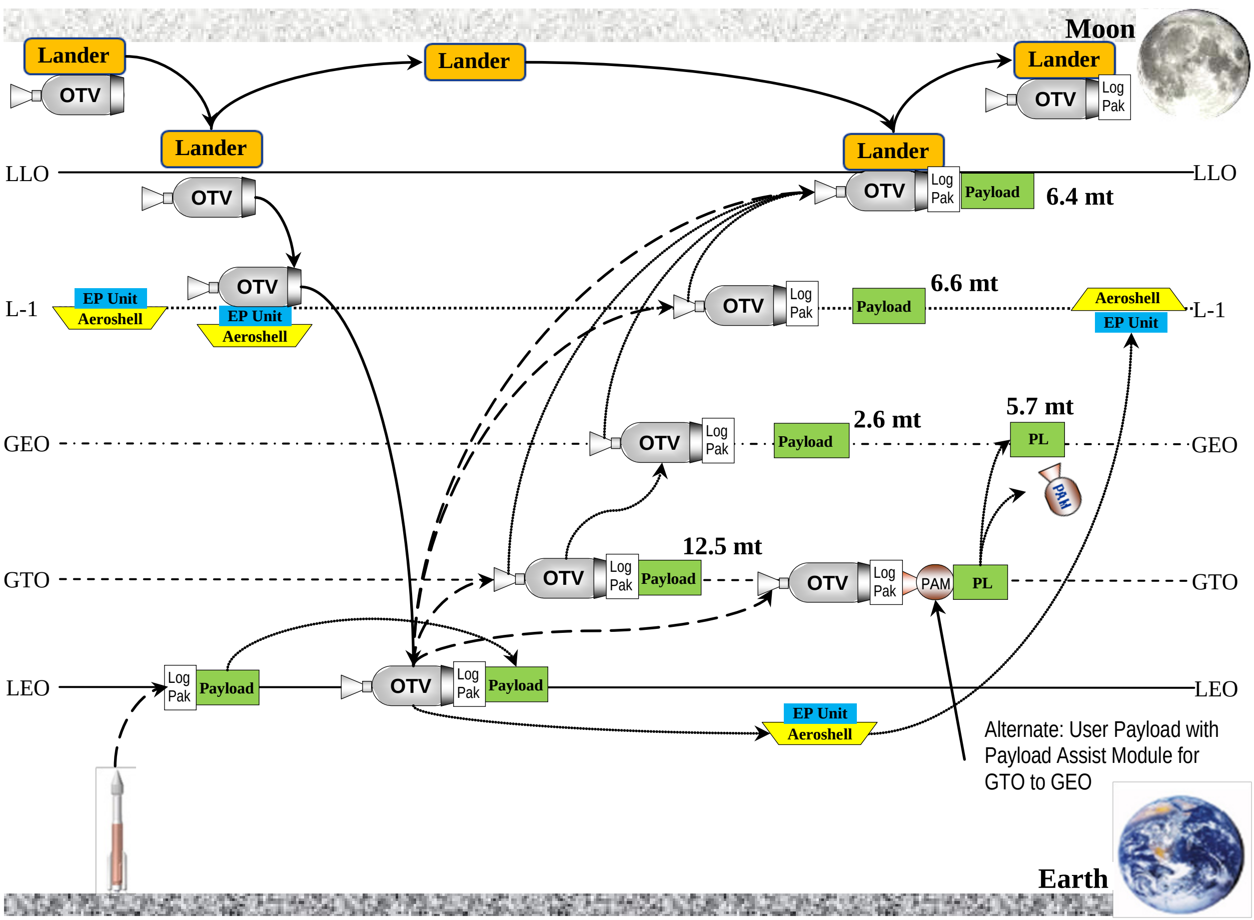


Figure 7.—Orbital transfer vehicle (OTV) + aeroshell with integrated electric propulsion (EP). The OTV acquires an aeroshell equipped with an integrated EP stage parked at Lagrange point 1 (L–1). After the transition and aerocapture in low Earth orbit (LEO), the aeroshell/EP system ejects and returns to L–1 under solar electric power.

HRLL + Tanker + Aeroshell Ejection and EP Recovery

Figure 8 shows cis-lunar propellant tanker service that refuels the user vehicle (upper stage). The sequence is the same as the OTV but the tanker proceeds directly to LLO after refueling and acquiring the Log-Pak. The tanker is less efficient than the OTV since the same amount of propellant is now used to propel two separate vehicles. Further, two vehicles will tend to double the amount of unused residuals. Once again the user can deliver a greater payload if a PAM unit is used for the final transition between GTO and GEO. The tanker offers the opportunity to salvage a spent stage. Note that the reusable lunar lander third flight is for salvaging the user stage and payload.

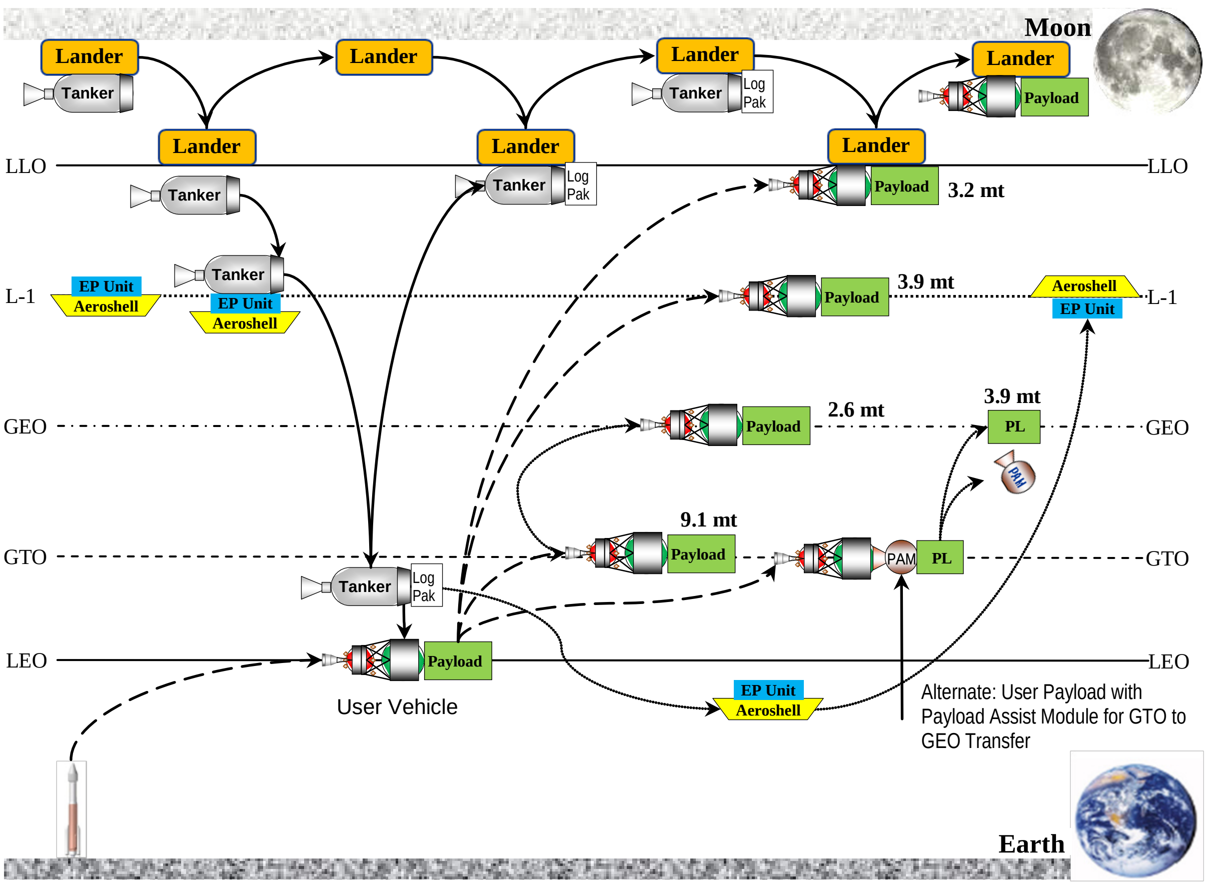


Figure 8.—Cis-lunar tanker refuels user vehicle and returns directly to low lunar orbit (LLO) with logistics package (Log-Pak).

Comparison of OTV and Tanker Performance

Figures 9 to 11 show the impact of the Log-Pak on payload delivery. The Log-Pak is part of the users launch payload. Based on the 60 mt total launch mass and mass fractions shown in Table 2, the OTV is assumed to arrive at LEO with 14.7 mt of propellant. Returning to LLO requires a large delta-v so the OTV must reserve additional 1.48 kg of propellant for every 1 kg of Log-Pak mass. In comparison, a user payload to GTO needs 1.32 kg of propellant per 1 kg of payload. Therefore, for the OTV the overall payload capacity is diminished as Log-Pak percentage of the total payload mass grows. The sensitivity to Log-Pak size is dependent on the difference in destinations. This effect depends on delta-v difference between user payload destination and Log-Pak destination at separation. For example, in Figure 11 the user destination of L–1 is very close to the LLO and thus, a payload composed of 50 percent Log-Pak mass reduces the overall capability by only 11 percent.

The Log-Pak becomes an important discriminator between OTV and tanker operations depending on the destination and portion of the payload. The tanker shows less sensitivity to Log-Pak size, in part, because the tanker goes directly to LLO by the most efficient route. As noted earlier, the tanker splits the propellant between itself and the user vehicle. There are now two vehicle masses to propel and both will have unspent residuals that tend to reduce the overall effectiveness. In Figure 9 (LEO to GTO), the OTV clearly provides higher capacity than the tanker particularly for small Log-Pak sizes. Similarly, the L–1 destination favors the OTV over the tanker in Figure 11 (LEO to L–1).

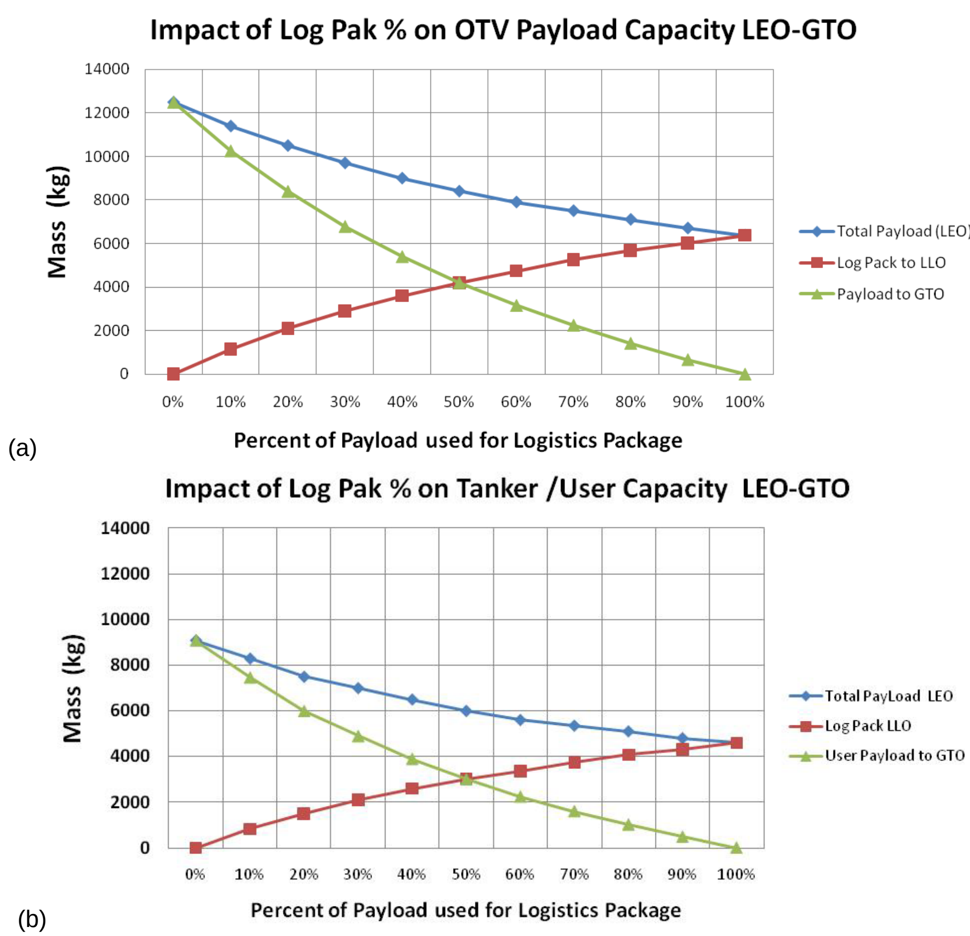
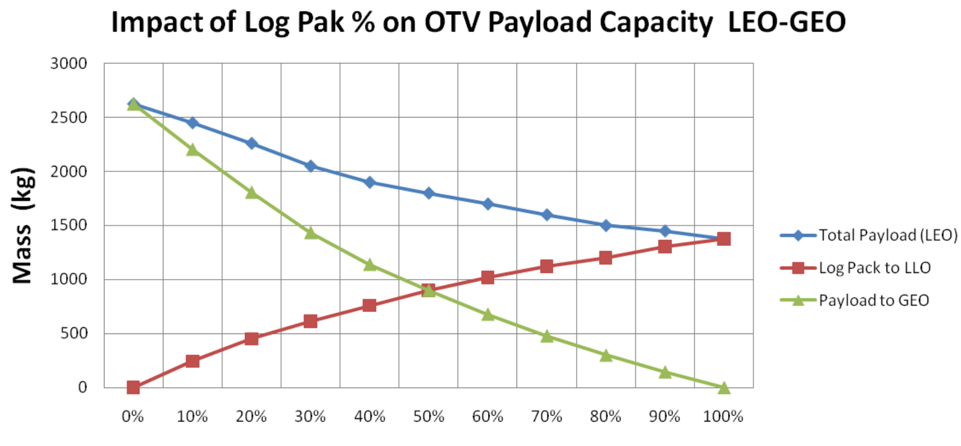
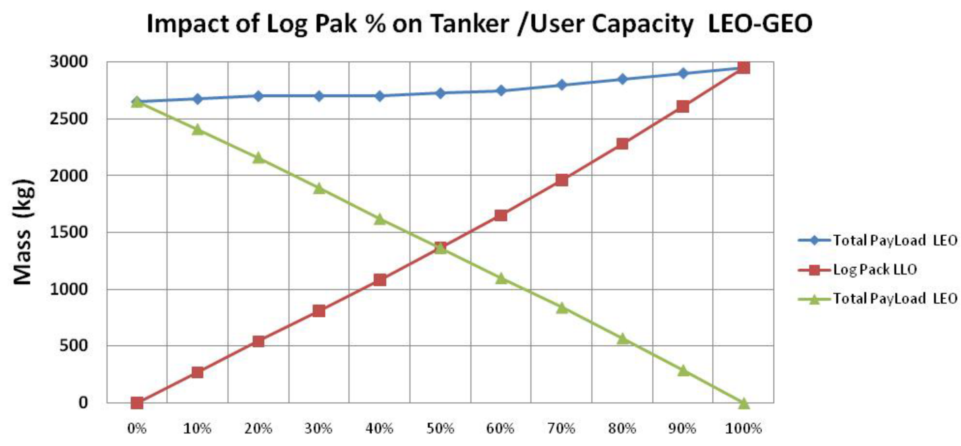


Figure 9.—Logistics packages (Log-Paks) effect on low Earth orbit (LEO) to geosynchronous transfer orbit (GTO) missions. The orbital transfer vehicle (OTV) has higher initial performance than the tanker. Log-Pak size should be less than 20 percent of the overall payload effectiveness.

In Figure 10 (LEO–GEO), the tanker and OTV start at the same value for a GEO mission but the total payload quickly favor the tanker as the Log-Pak portion grows. This is because the destinations have similar delta-v requirements thus the tanker and the user consume similar amounts of propellant per kilogram. The OTV; however, must carry everything to GEO and then transport itself and the Log-Pak to LLO. This means that the OTV must produce 6430 m/s delta-v to get to LLO as opposed to 4040 m/s for the tanker moving directly to LLO. GEO is significantly “out of the way” of a vehicle bound for LLO.



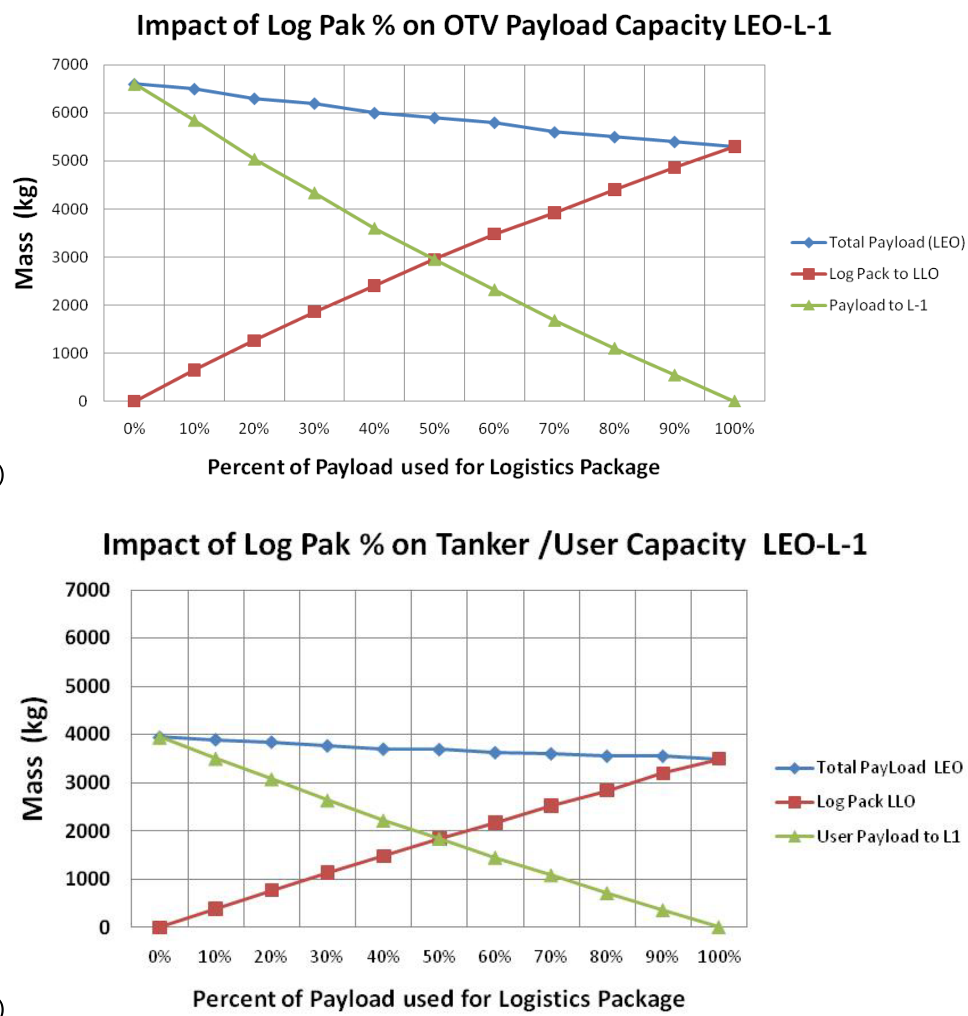
(a)



(b)

Figure 10.—Log-Pak effect on low Earth orbit (LEO) to geosynchronous orbit (GEO). For LEO to GEO missions, the orbital transfer vehicle (OTV) and tanker have similar performance initially. However, the tanker performance is favored as Log-Pak portion increases.

For the L–1 destination, shown in Figure 11 (LEO to L–1), the OTV is favored once again because the L–1 destination is effectively “on the way” to LLO. In contrast the tanker scenario involves the mass and residuals of two vehicles traveling in virtually parallel paths. The proximity of L–1 to LLO destinations also make the OTV less sensitive to increasing the Log-Pak portion of the payload.



(a)

(b)

Figure 11.—Logistics-package (Log-Pak) effect on low Earth orbit (LEO) to Lagrange point 1 (L–1). For LEO to L–1 missions, L–1 is “on the way” to low lunar orbit (LLO) the OTV clearly provides greater overall performance than the tanker and modestly affected by logistics package (Log-Pak) size.

Impact on In-Space Commerce and Human Exploration

Impact of Lunar Propellants on Access to Space

As shown in the earlier analysis lunar resources distributed in cis-lunar lowers the bar for access to space beyond LEO. Many countries have the capacity to launch spacecraft into Earth orbit. There are dozens of vehicles available to access LEO for a wide range of payload classes. In contrast, in the 40 years since Apollo, no country has been able to fund the development and deployment of a large launch vehicle that bridges the gap between Earth and Moon for human missions in a single launch. Exploiting lunar propellants allows those users to leverage existing launch vehicles. In fact, anyone that can currently reach LEO could then reach beyond to high orbits or planetary destinations. Cis-lunar propellants provide greater mobility and utility for existing spacecraft and enables reusable spacecraft.

In-Space Commerce

Lunar propellants serve as a commodity for trade. The availability of propulsion and propellant services extends the useful life of revenue generating spacecraft. Reusable, refuelable, and refurbishable spacecraft stimulates spacecraft servicing. The ability to refuel spacecraft provides continued revenue while the ability to refuel spent stages can launch a market for secondary applications for hardware that would otherwise be discarded. Some of these secondary applications include supporting the cis-lunar infrastructure as propellant storage elements for depots, and as assets like tugs and tankers. They may serve as sources of scarce replacement components or materials for in situ repair or fabrication.

Since user launch vehicles effectively multiply their payload capacity, a portion of this surplus payload capacity can be used for secondary payloads. The cis-lunar infrastructure needs logistics and equipment to build capabilities and to sustain itself. Therefore, the user trades a portion of this capacity to provide logistics for cis-lunar propulsion services or propellants. This trade reduces cost to both parties and effectively becomes in-space commerce.

Bootstrap Approach to an Affordable Infrastructure

The cis-lunar infrastructure is conceived as an architecture that exploits the lunar environment and resources as soon as possible. By taking an all-electric bootstrap approach the infrastructure minimizes its own needs by reducing consumables down to electric power alone. Focusing on building a simple but robust power infrastructure assures high capability early on. Alleviating constraints on power enables the adoption of high power processes and shortens the time required to produce propellants. Early propellant production is used to power reusable landers that ferry power and propellant production equipment to the lunar surface. The bootstrap cycle continues to grow capacity until progressively larger landers can be used. Propellant production will need storage capacity and part of that need can be met by using OTVs and reusable landers to capture spent stages. Salvaging spent hardware continues even after lunar propellant production level reaches export capacity. The mixed fleet approach that employs special EP stages to recover assets like the aeroshell is consistent with the strategy of exploiting every possible resource and eliminating expendable elements.

International Cis-Lunar Resource Consortium

No one really owns lunar resources and there are international treaties regarding the exploitation of the Moon. The scale of the effort combine with the need to share a resource makes the cis-lunar infrastructure an international effort. Multiple nations can contribute to the creation of the infrastructure. All users can contribute by trading logistics for propellants while at the same time sharing in the benefits of the resource. International partners can contribute space communications and navigation systems to support the cis-lunar propellant infrastructure. Commercial operators can serve as both part of the infrastructure and users of the infrastructure.

Impact on Human Space Development

Moving out from LEO makes access to space resources even more important. Lunar, Mars, and NEO missions have huge launch vehicle requirements. Even support by the massive Aries V, the mission to Mars requires multiple vehicles. The experience of building the ISS is evidence that large structures can be constructed successfully in space. Constructing large interplanetary vessels in L–1 may be the best overall solution for NEO and Mars missions. The cis-lunar propellant infrastructure reduces the demands on launch vehicles so that they need only achieve LEO. The infrastructure elements take over from there. Cis-lunar propellants can be used to preposition assets for human missions for Mars and NEO missions. This reduces risk while expanding the reach of human explorers.

Conclusion

Developing technology infrastructures is an appropriate role for publicly funded investment. Public infrastructure investment in ground transportation, aviation, weather forecasting, communications, information broadcasting, and global navigation has proven to stimulate worldwide economic growth. Likewise, the economic development of space will depend on investing in an infrastructure to access and exploit in situ space resources.

Human exploration on Earth has always been closely linked to the search for resources and the economic benefits they provide. Successful, sustainable, and affordable exploration depends on exploiting resources and maintaining a close relationship with commerce. Exploration must exploit resources at first opportunity and build capability incrementally. Just as the growth of world trade depends upon an affordable resource infrastructure the economic development of space will likewise need an affordable infrastructure.

With the discovery of lunar resources that are directly applicable to space transportation we have an opportunity to create an infrastructure that effectively “lowers the bar” for access to space beyond LEO and raises the participation in space. An infrastructure capable of delivering space resources not only enables more access but provides more opportunity for trade. Trading of lunar resources for Earth logistics makes the infrastructure self sustaining and affordable. Trading materials for services or propellants lets users both benefit from the infrastructure and contribute to its growth. What is needed now is the investment in the technologies that make those resources available in an affordable manner.

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14. ABSTRACT
This paper describes a space infrastructure concept that exploits lunar water for propellant production and delivers it to users in cis-lunar space. The goal is to provide responsive economical space transportation to destinations beyond “low Earth orbit” (LEO) and enable in-space commerce. This is a “game changing” concept that could fundamentally affect future space operations, provide greater access to space beyond LEO, and broaden participation in space exploration. The challenge is to minimize infrastructure development cost while achieving a low operational cost. This study discusses the evolutionary development of the infrastructure from a very modest robotic operation to one that is capable of supporting human operations. The cis-lunar infrastructure involves a mix of technologies including cryogenic propellant production, reusable lunar landers, propellant tankers, orbital transfer vehicles, aerobraking technologies, and electric propulsion. This cis-lunar propellant infrastructure replaces Earth-launched propellants for missions beyond LEO. It enables users to reach destinations with smaller launchers or effectively multiplies the user’s existing payload capacity. Users can exploit the expanded capacity to launch logistics material that can then be traded with the infrastructure for propellants. This mutually beneficial trade between the cis-lunar infrastructure and propellant users forms the basis of in-space commerce.

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Logistics; Flight operations; Space architecture; Supportability; Lunar; In situ resource

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