CIS-LUNAR BASE CAMP

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Historically, when mounting expeditions into uncharted territories, explorers have established strategically positioned base camps to pre-position required equipment and consumables. These base camps are secure, safe positions from which expeditions can depart when conditions are favorable, at which technology and operations can be tested and validated, and facilitate timely access to more robust facilities in the event of an emergency. For human exploration missions into deep space, cis-lunar space is well suited to serve as such a base camp. The outer regions of cis-lunar space, such as the Earth-Moon Lagrange points, lie near the edge of Earth's gravity well, allowing equipment and consumables to be aggregated with easy access to deep space and to the lunar surface, as well as more distant destinations, such as near-Earth Asteroids (NEAs) and Mars and its moons.

Several approaches to utilizing a cis-lunar base camp for sustainable human exploration, as well as some possible future applications are identified. The primary objective of the analysis presented in this paper is to identify options, show the macro trends, and provide information that can be used as a basis for more detailed mission development. Compared within are the high-level performance and cost of 15 preliminary cis-lunar exploration campaigns that establish the capability to conduct crewed missions of up to one year in duration, and then aggregate mass in cis-lunar space to facilitate an expedition from Cis-Lunar Base Camp. Launch vehicles, chemical propulsion stages, and electric propulsion stages are discussed and parametric sizing values are used to create architectures of in-space transportation elements that extend the existing in-space supply chain to cis-lunar space.

The transportation options to cis-lunar space assessed vary in efficiency by almost 50%; from 0.16 to 0.68 kg of cargo in cis-lunar space for every kilogram of mass in Low Earth Orbit (LEO). For the 15 cases, 5-year campaign costs vary by only 15% from 0.36 to 0.51 on a normalized scale across all campaigns. Thus the development and first flight costs of assessed transportation options are similar. However, the cost of those options per flight beyond the initial operational capability varies by 70% – from 0.3 to 1.0 on a normalized scale. The 10-year campaigns assessed begin to show the effect of this large range of cost beyond initial operational capability as they vary approximately 25% with values from 0.75 to 1.0 on the normalized campaign scale. Therefore, it is important to understand both the cost of implementation and first use as well as long term utilization. Finally, minimizing long term recurring costs is critical to the affordability of future human space exploration missions. Finally minimizing long term recurring costs is critical to the affordability of future human space exploration missions.

INTRODUCTION

Extending existing in-space supply chains from Low Earth Orbit (LEO) to cis-lunar space and establishing a Cis-Lunar Base Camp (CLBP) enables increased experience and confidence outside of the Earth's Van Allen radiation belts while still allowing crew members to return home within a few days in the event of an emergency. The operational environment is similar to deep space, allowing technology and operational approaches to be tested and validated, and facilitates the scheduled initiation of more ambitious expeditions. Additionally, a cis-lunar base camp allows for the establishment of a human-tended scientific laboratory and sample return and quarantine facility, as well as a location for aggregating in-situ resources from NEAs or the lunar surface. This paper explores the evolved exploration capabilities that can be realized with a cis-lunar base camp approach. An in-space architecture enabled by combined launch vehicle (LV) flight rates similar to the cadence afforded by existing ground infrastructure and ongoing investments must be formulated that enables a compelling set of missions that are valuable enough to garner continued support and funding. The current NASA capability driven framework [1,2] strategy provides a set of in-space elements and missions that are proposed to enable human exploration beyond LEO. These elements and missions, along with international partner capabilities, are sequenced in the International Space Exploration Coordination Group (ISECG) Global Exploration

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Roadmap (GER) [3], which identifies several high-level campaign case studies.

An in-space architecture enabled by combined launch vehicle (LV) flight rates similar to the cadence afforded by existing ground infrastructure and ongoing investments must be formulated that enables a compelling set of missions that are valuable enough to garner continued support and funding. The current NASA capability driven framework [1,2] strategy provides a set of in-space elements and missions that are proposed to enable human exploration beyond LEO. These elements and missions, along with international partner capabilities, are sequenced in the International Space Exploration Coordination Group (ISECG) Global Exploration Roadmap (GER) [3], which identifies several high-level campaign case studies.

As NASA and its International Partners continue to develop plans for human exploration beyond LEO, it is important to assess available options for cis-lunar transportation. These approaches help to build an understanding of the impacts of continued successful in-space enterprises and associated technologies on the feasibility and efficiency of concepts for vehicle and logistics aggregation. This paper compares integrated campaign performance and high level relative costs for several transportation architecture options. These campaigns leverage abstracted technology classes for launch vehicles and in-space propulsion stages that include technology options for implementation available now (Medium Technology) and over the next decade (High Technology).

The benefit of utilizing a CLBC and possible future applications are discussed in the next section to provide motivation for the analysis that follows. In order to understand various campaign options, the architectural approaches (locations, vehicles, and maneuvers) for transit from LEO to cis-lunar space are described in the section *Cis-Lunar Transportation*. The base camp facility, logistics resupply and associated assets are discussed in the section titled *Base Camp Facility Deployment Resupply and Use* along with several example campaigns. The relative cost of those campaigns is presented in the section *Transportation Architecture Cost Comparison* followed by *Summary Findings and Future Work*.

CLBC UTILIZATION AND POSSIBLE FUTURE APPLICATIONS

The CLBC approach can help enable human missions to a variety of deep-space destinations, as well as facilitate human lunar missions and tele-operations of robotic assets in cis-lunar space and on the lunar surface. Foremost, the CLBC provides a facility that can support the aggregation and assembly of vehicle stacks at the edge of the Earth's gravitational influence, beyond the orbital debris field and thermal environment of LEO, and outside the radiation effects of the Earth's Van Allen radiation belts. The CLBC can provide a platform that allows berthing/capture or monitored autonomous rendezvous and docking for the various vehicles that will be used to perform crewed missions into deep-space, and provides resources that maximize the probability that these missions will be successful. The system mass and propulsion requirements of human missions will almost certainly require multiple launches to provide sufficient capability, with smaller capacity launch vehicles requiring more launches than heavy lift vehicles, such as NASA's Space Launch System (SLS) [4]. Each of the payloads on these launches can be sent directly to the CLBC and utilize its available resources (e.g., power, attitude control, communications, etc.) to the greatest extent possible, rather than have these capabilities built into one or more of the mission elements in order for them to be able to function autonomously until further infrastructure is delivered. This build-up and assembly support should also translate into less architecture mass required for the deep-space mission, thus making it easier to complete the mission by reducing the in-space propulsion requirements of the transportation system. The CLBC also allows facilitating the extensive, integrated check-out and testing of the deep-space vehicles prior to crew departure. This deep-space check-out and testing of the integrated vehicle stack prior to the critical departure maneuver will aid in maximizing the probability of mission success and reducing the potential loss of crew. Since the CLBC is only a few days journey from Earth (between 4 and 28 days depending on crew transport performance and cis-lunar location), it offers the ability for return to the Earth during a mission in the event of an emergency.

The CLBC, or a portion of the facility, could be used to provide habitation capability and other vital functions, such as EVA support, berthing/capture, logistics storage, etc., for deep-space exploration missions. For example use of an 80-100 kW-class Solar Electric Propulsion system enables multiple crewed missions of this nature to NEAs via re-capture of habitation in cis-lunar space [5]. The initial CLBC facility is expected to have a useful lifetime on the order of 10 years. Having a spacecraft that has been operational for a certain amount of time can increase the probability of mission success in deep-space and avoid the "infant mortality" problems associated with new spacecraft systems. New elements and systems could be launched to cis-lunar space to replace or upgrade those that are used for the deep-space mission. On the other hand, care must be taken to ensure that elements and systems used for the deep-space mission still possess sufficient reliability and useful lifetime to allow for completion of the deep-space mission. Taking a

CLBC that is too far "past its prime" on a mission beyond the Earth-Moon (E-M) system could jeopardize the mission and the crew members. If this approach is taken, determining the optimal time will be an important systems analysis and probabilistic risk assessment problem and will likely impact the design of the elements and associated systems.

Additionally, the CLBC allows for the establishment of a human-tended scientific laboratory and sample return and quarantine facility. Samples could be returned from destinations such as the lunar surface, NEAs and Mars to be high-graded and analyzed before being returned to the Earth's surface. Since the Orion Multi-Purpose Crew Vehicle (MPCV) [6] is currently only required to return 100 kg of samples to the Earth's surface (including containers and support equipment), many of the samples that could be collected by the crew would have to be discarded. The CLBC could alleviate this constraint and also provide a facility to allow the quarantine of samples that could possibly pose a risk, no matter how small, if returned directly to the Earth's surface. For example, a 10-20 kW-class Solar Electric Propulsion (SEP) system could be utilized to return to cis-lunar space up to several tons of geologic samples that could be collected during a human NEA mission. The CLBC would facilitate valuable on-going research on these samples with the return of selected samples to Earth as needed. This research would also provide an improved knowledge base for future planetary defense efforts.

Finally, the CLBC could function as a location for facilitating the aggregation and extraction of in-situ resources from NEAs or the lunar surface, such as water, oxygen, metals, and material for radiation shielding. For example, a 40-50 kW-class SEP system could return a small NEA (~7-10 meters in diameter) to a stable high-lunar orbit where the extraction and processing of asteroidal resources could be conducted, potentially paving the path for future commercial mining and resource extraction industries to become economically viable [7]. Resources extracted from the lunar surface could also be transported to the CLBC for storage and utilization. These asteroidal and lunar resources could benefit future human space exploration and potentially be returned to Earth for sale in terrestrial markets. Eventually, these resources along with more powerful SEP systems, could allow the emplacement of deep-space cycler spacecraft that use the resources and radiation protection extracted in-situ to allow astronauts and future settlers to make the long journey through interplanetary space to reach the surface of Mars, or even more distant locations like Saturn's moon Titan. Finally, aggregation of sufficient mass at an E-M Lagrange point could also enable the development of a lunar space elevator providing more affordable access to and from the lunar surface. Just like the forward base camps that helped settle the American West, in the not too distant future the Cis-Lunar Base Camp could be instrumental in opening up the vast frontier of space for all of humanity.

CIS-LUNAR TRANSPORTATION

Transportation to and within cis-lunar space requires identification of locations for possible CLBC locations. Trajectories from Earth to those locations for cargo and crew transit are identified in this section, as well as trajectories between those locations to enable both assessment of multi-segment transits to maximize cargo and transfer of the CLBC facility within cis-lunar space. These trajectories allow for assessment of options for transportation vehicles that can be utilized in campaigns to deliver infrastructure, logistics, and crew to the CLBC. Although the crew was assumed to be launched on a SLS for this study, it is still necessary to discuss crew trajectories as an in-space stage is required to transfer the crew to the CLBC.

Locations

For the purposes of comparison and identification of trends, locations in cis-lunar space have been generalized for analysis purposes to individual Earth, Moon, and halo-orbits about the Earth-Moon (E-M) Lagrange points 1 or 2 (E-M L1 or E-M L2). Locations

Location	Description	Use
Low Perigee High Earth Orbit [LP – HEO]	LEO x Lunar Distance 400 km x 400,000 km	Earth Departure to Heliocentric Space
High Perigee High Earth Orbit [HP-HEO]	Outside Van Allen belts x Lunar Distance 50,000 km x 400,000 km	Aggregation as an alternative to E-M L1 halos, E-M L2 halos, or LP-HLO.
Earth Moon Lagrange Point 1 Halo [L1 Halo]	Medium Sized Halo 14-15 day 35k X-magnitude	Aggregation
Low Perigee High Lunar Orbit [LP-HLO]	Highly stable elliptical retrograde 100km x 49500 km	Aggregation/Operations with objects that require extremely stable orbits
Low Lunar Orbit [LLO]	100 km near equatorial circular Lunar Orbit	Lunar Surface Access and study of the Moon.
Earth Moon Lagrange Point 2 Halo [L2 Halo]	Medium Sized Halo 14-15 day 35k X-magnitude	Aggregation

Table 1 Cis-Lunar Locations

utilized for CLBC deployment and utilization in order of distance from Earth are shown in Table 1.

There are many options for specific orbits. The choice of exact parameters will be epoch, mission, and vehicle specific.

Trajectories

Following the Apollo program, which marked the first human venture into cis-lunar space more than 40 years ago, several robotic spacecraft have operated in cis-lunar space [8,9,10]. These missions have proven that complex trajectories leveraging 4-body dynamics with multiple powered gravity assists are feasible and can facilitate significant reductions in the velocity change (ΔV) required to achieve orbits in cis-lunar and heliocentric space. However, these trajectories trade complexity and duration for energy, and are therefore only practical for robotic or cargo delivery missions. This limitation dictates that one class of trajectories is leveraged for crew transit to cis-lunar space that has one-way mission durations of less than 10 days, and a second class of trajectories for cargo deployment that have approximately 100-450 day transfer times. The short-duration crew transits require high-thrust propulsion stages for in-space transportation, while the long-duration cargo missions can leverage high-thrust, low-thrust or a combination of the two propulsive approaches.

Crew Trajectories

The trajectories for crewed missions in these analyses are evolved from patched conics and Hohmann transfers, and are similar to those leveraged by the Apollo program. They include both a high-thrust departure propulsive maneuver (trans-lunar injection), commonly referred to as a “burn”, and a high-thrust arrival burn (cis-lunar orbit insertion). For trajectories from LEO to cis-lunar space – a Lunar Gravity Assist (LGA) is leveraged where possible (e.g., LEO to E-M L2 Halo). However, using an LGA in the transfer from LEO to E-M L1 requires more than ten days of mission duration and therefore is not used for a crew mission. Crew transfers to and between cis-lunar locations are depicted in Table 2. These trajectories are short duration transfers compared to high-thrust or low-thrust cargo trajectories shown in subsequent tables, and illustrate the differences in required ΔV and Time of Flight (ToF). It should be noted that ToF can be traded for ΔV in many of these trajectories, and additional detail is required to determine optimal transfers given mission specific constraints.

Cargo Trajectories

All cargo trajectories are limited to 450 days for this set of analyses and can be divided into two main classes based on the vehicles executing the required high-thrust or low-thrust maneuvers.

High-thrust cis-lunar cargo trajectories leverage Weak Stability Boundary (WSB) physics and are often called Ballistic Lunar Transfers (BLTs) [11,12,13]. For these trajectories, the Earth departure burns target an invariant manifold and course corrections are used for targeting and arrival at halo-orbits around either E-M L1 or E-M L2, or a small arrival burn is performed for lunar orbits. These trajectories take 90-180 days and require less ΔV than quicker trajectories. They also require nearly all of the ΔV be provided on the Trans Lunar Injection (TLI) burn so that the efficiency of the launch vehicle upper stage or in-space chemical cryogenic propulsion system (e.g., liquid oxygen-liquid hydrogen) can be leveraged without implementing significant boil-off mitigation measures. Cargo transfers between cis-lunar locations shown in Table 3 can be used by both cargo vehicles and crew vehicles that are capable of supporting the crew for long durations. These transfers increase the ToF from 10 days or less to greater than 90 days while decreasing the ΔV in most cases by an order of magnitude.

One major difference between high-thrust and low-thrust trajectories is that low-thrust trajectory durations vary significantly with the thrust-to-weight of the integrated vehicle. The thrust-to-weight of the integrated vehicle dictates the incremental velocity change that can be applied during a given time interval.

Crew: From		To: ES	LPHEO	HPHEO	HLO	LLO	L1 Halo	L2 Halo
LEO	ΔV (km/s)		3.13	3.46	3.36	4.00	3.55	3.35
	ToF (d)		5	6	4	4	10	10
LPHEO	ΔV (km/s)	0.01		0.34	0.22	0.86	0.41	0.21
	ToF (d)	5		6	4	4	10	10
HPHEO	ΔV (km/s)	0.35	0.34		0.15	0.79	0.31	0.15
	ToF (d)	6	6		5	5	5	10
HLO	ΔV (km/s)	0.22	0.22	0.15		0.64	0.03	0.06
	ToF (d)	4	4	5		0	5	5
LLO	ΔV (km/s)	0.86	0.86	0.79	0.64		0.67	0.70
	ToF (d)	4	4	5	0		5	5
L1 Halo	ΔV (km/s)	0.41	0.41	0.31	0.03	0.67		0.00
	ToF (d)	10	10	5	5	5		14
L2 Halo	ΔV (km/s)	0.21	0.21	0.15	0.06	0.70	0.00	
	ToF (d)	10	10	10	5	5	14	

Table 2 Crew Transfers

HighThrust Cargo: From		To: ES	LPHEO	HPHEO	HLO	LLO	L1 Halo	L2 Halo
LEO	ΔV (km/s)		3.13	3.46	3.23	3.77	3.20	3.20
	ToF (d)		5	6	90	90	120	90
LPHEO	ΔV (km/s)	0.01		0.01	0.08	0.72	0.06	0.06
	ToF (d)	5		30	90	90	120	90
HPHEO	ΔV (km/s)	0.01	0.01		0.08	0.72	0.06	0.06
	ToF (d)	30	30		90	90	120	90
HLO	ΔV (km/s)	0.03	0.08	0.08		0.64	0.01	0.01
	ToF (d)	90	90	90		0	10	10
LLO	ΔV (km/s)	0.67	0.72	0.72	0.64		0.65	0.65
	ToF (d)	90	90	90	0		10	10
L1 Halo	ΔV (km/s)	0	0.06	0.06	0.01	0.65		0.00
	ToF (d)	90	120	120	10	10		14
L2 Halo	ΔV (km/s)	0	0.06	0.06	0.01	0.65	0.00	
	ToF (d)	90	90	90	10	10	14	

Table 3 High-Thrust Cargo Transfers

The amount of thrust available is determined by power level and specific impulse (I_{sp}), which is the thrust divided by the amount of propellant used per unit time. The ToF for each transfer vehicle and payload must be calculated independently and is not included. Table 4 contains top-level values for two classes of low-thrust trajectories to cis-lunar space. The first departs from LEO and "spirals" out to cis-lunar space. The second departs from an elliptical orbit, GTO in this case for simplicity, and targets a LGA used to insert into an appropriate invariant manifold that delivers the vehicle to the desired cis-lunar location [14].

The first class, low-thrust transfers initiated deep within Earth's gravity well, has a substantially higher ΔV requirement. However, low-thrust propulsion systems allow an order of magnitude improvement in I_{sp}. The increased efficiency overcomes the two-fold increase in ΔV and still increases cargo delivered. This makes them more efficient for cargo transit to cis-lunar space when time is not a critical factor. However, anticipated system reliability and the desire for reusability drive the limits of these trajectories to have a ToF less than or equal to 450 days, as assumed for this study. This time limit drives the required integrated vehicle thrust-to-weight much higher for a trajectory with a LEO departure compared to a GTO departure with a similar ToF.

Low Thrust Transfers		To: ES Cargo	LPHEO Cargo	HPHEO Cargo	HLO Cargo	LLO Cargo	L1 Halo Cargo	L2 Halo Cargo
From: LEO	ΔV (km/s)		6.80	6.80	6.84	8.06	6.83	6.83
GTO	ΔV (km/s)	0.04	3.22	3.22	2.88	4.10	2.87	2.87
LPHEO	ΔV (km/s)	0.01		0.00	0.33	1.55	0.32	0.32
HPHEO	ΔV (km/s)	0.01	0.00		0.33	1.55	0.32	0.32
HLO	ΔV (km/s)	0.33	0.33	0.33		1.54	0.01	0.01
LLO	ΔV (km/s)	1.55	1.55	1.55	1.54		1.23	1.23
L1 Halo	ΔV (km/s)	0.32	0.32	0.32	0.01	1.23		0.00
L2 Halo	ΔV (km/s)	0.32	0.32	0.32	0.01	1.23	0.00	

Table 4 Low-Thrust Cargo Transfers

Low-thrust trajectories between cis-lunar locations in this table are strictly for one point to another and do not leverage WSB physics. For intra-cis-lunar transfers the WSB physics ΔV (Table 3) can be leveraged if enough time is available.

From the trajectory information presented it is clear that a significant amount of energy is required to complete transfers to cis-lunar space, but once in cis-lunar space a transfer can require extremely low ΔVs if sufficient time is available. Performance analysis of high-thrust vehicles to cis-lunar space (that follows) assumes a transfer from 185 km circular LEO to the E-M L2 halo-orbit. From there, a transfer to an E-M L1 halo-orbit or HLO is 10 m/s or less. Low-thrust performance analysis (discussed in the next section) targets the E-M L1 halo-orbit. From there, transfer to an E-M L2 halo-orbit or HLO is also 10 m/s or less.

Transportation Vehicles

In order to assess transportation options to cis-lunar space a set of vehicles has been defined. These vehicles have been abstracted to classes, and the range of class performance is compared to existing and planned capabilities where applicable for both a minimal technology investment option and a high technology investment option. These classes bound the upper and lower performance limits of optimally sized stages. The efficiency of each vehicle is measured in terms of cargo mass (carrier + payload) delivered to cis-lunar space per mass in LEO to show a normalized effectiveness for each option regardless of the total mass delivered.

Launch Vehicles

Launch vehicles (LV) have been grouped into categories of Small, Medium, Large, and SLS classes and are comparable to existing and planned vehicles. For this study, it is assumed that launch vehicles deliver payloads into 185 km (100 nmi) circular LEO departure orbit, a highly elliptical GTO (185 km x 35,700 km), or directly to TLI.

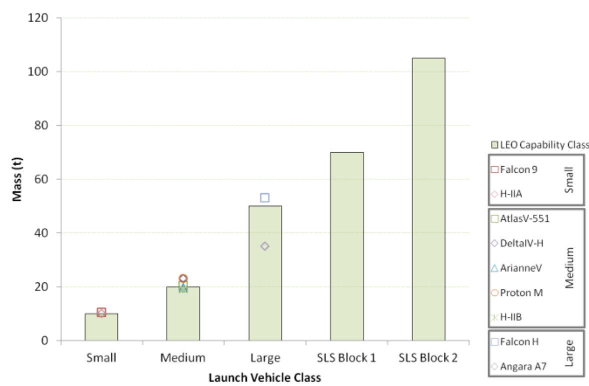

Figure 1 Launch Vehicle Class Capabilities to LEO

Estimates for the LEO and GTO delivery capabilities used in this study are shown in Figures 1 and 2, respectively. Each bar shows the assumed capability for the launch vehicle classes, and data points for existing capabilities are plotted to show variation from the assumed capability.

The SLS Block 1 (SLS1, 70t capability) and SLS Block 2 (SLS2, 105t capability) vehicles do not include an upper stage. Therefore, estimates for SLS capabilities to GTO include a Delta Cryogenic Second Stage (DCSS). For SLS capabilities to TLI an upgraded DCSS upper stage is assumed.

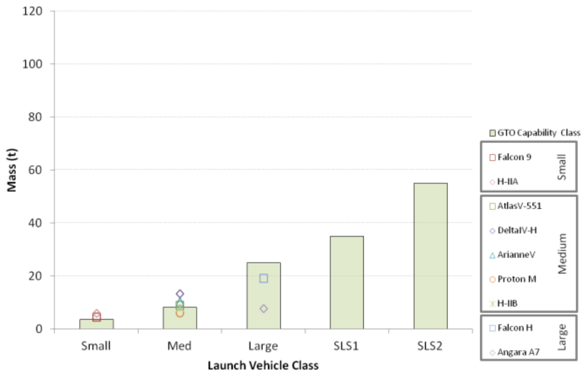

Figure 2 Launch Vehicle Class Capabilities to GTO

One method of cargo delivery to cis-lunar space is to leverage the launch vehicle TLI capability to target a LGA and then use a spacecraft bus that provides approximately 200 m/s for LGA and BLT targeting and course correction. Figure 3 represents the identified LV class payload mass capability to TLI.

Figure 3 Launch Vehicle Class Capabilities to TLI

Since the point of this type of cargo delivery is to remove the additional chemical propulsion stage, SLS1 and SLS2 will not be included in the launch vehicle TLI delivery options. For clarity, Figure 4 repeats the capabilities for the Small, Medium, and Large LV classes. These values assume a spacecraft bus with a 0.65 Propellant Mass Fraction (PMF), which is the ratio between the propellant mass and the initial mass of the vehicle, and storable propellants with an I_{sp} of 326 s. The efficiency of this transfer with respect to launch vehicle LEO capability is captured in Table 5 (discussed in detail in the next section).

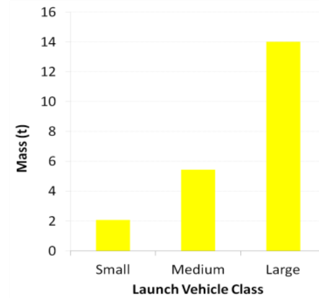

Figure 4 Launch Vehicle TLI Performance to Cis-Lunar Space

Chemical Propulsion Stages

High-thrust trajectories are enabled by chemical propulsion stages that apply the entire injection and insertion ΔVs in a relatively short duration (minutes). Parametric values used to measure the mass and engine efficiency and parametrically size these stages are the PMF and I_{sp}. Table 6 includes the upper and lower ranges of I_{sp} and PMF used to calculate the classes of high-thrust stage performance. The lower I_{sp} and PMF represent a minimal technology option while the upper values assume a high technology option. Table 5 includes the performance efficiency of these stages. Efficiency values are the same for each launch vehicle class because the stages are optimally sized for each vehicle to maximize payload to cis-lunar space. Specific vehicles will be less efficient if not sized for this specific mission. One possible issue to note is launch vehicle shroud volume, packaging of an in-space stage with payload in existing vehicles can be challenging. In particular Cryogenic Chemical (CC) liquid oxygen-liquid hydrogen (LOX-LH2) stages are an issue because of the propellant's low bulk density.

ID	Lower ISP	Upper ISP	Lower PMF	Upper PMF
Cryogenic Chemical Fuel (CC)	462	465	0.8	0.9
Long Duration Cryogenic Chemical Fuel (LDCC)	462	465	0.6	0.8
Liquid Oxygen and Methane Hydrocarbon Fuel (LOXCH4)	360	380	0.8	0.9
Liquid Oxygen and RP-1 Hydrocarbon Fuel (LOXRP1)	338	353	0.8	0.9
Hypergolic NTOMMH Fuel (Hyper)	312	326	0.8	0.9

Table 6 Chemical Stage Parameters

Figure 5 illustrates the performance (mass delivered to cis-lunar space) of chemical propulsion stages optimally sized for each launch vehicle class with the stage performance criteria from Table 6. The bar values in Figure 5 show the performance at lower PMF and I_{sp} and the error bars represent the increase in performance from lower values to upper values.

Launch Vehicle Class	LV TLI	CC		LDCC		LOXCH4		LOXRP1		Hyper		LEO SEP		GTO SEP		LEO RSEP Initial		LEO RSEP Subsequent		GTO RSEP Initial		GTO RSEP Subsequent	
		Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	2000	3000	2000	3000	2000	3000	2000	3000	2000	3000	2000	3000
Small	0.21	**0.37**	**0.44**	0.16	**0.37**	0.25	**0.36**	0.23	0.33	0.19	0.30	**0.48**	**0.49**	0.18	0.19	**0.41**	**0.40**	**0.55**	**0.62**	0.16	0.27	0.18	0.29
Medium	0.27	**0.37**	**0.44**	0.16	**0.37**	0.25	**0.36**	0.23	0.33	0.19	0.30	**0.53**	**0.61**	0.27	0.29	**0.49**	**0.55**	**0.58**	**0.68**	0.26	0.33	0.28	**0.35**
Large	0.28	**0.37**	**0.44**	0.16	**0.37**	0.25	**0.36**	0.23	0.33	0.19	0.30			**0.39**	**0.39**					**0.38**	**0.41**	**0.39**	**0.44**
SLS1		**0.37**	**0.44**	0.16	**0.37**	0.25	**0.36**	0.23	0.33	0.19	0.30			**0.38**	**0.41**					**0.38**	**0.41**	**0.40**	**0.44**
SLS2		**0.44**	**0.44**	0.16	**0.37**	0.25	**0.36**	0.23	0.33	0.19	0.30			**0.42**						**0.41**		**0.44**	

Table 5 Transportation Option Cis-Lunar Performance Efficiency

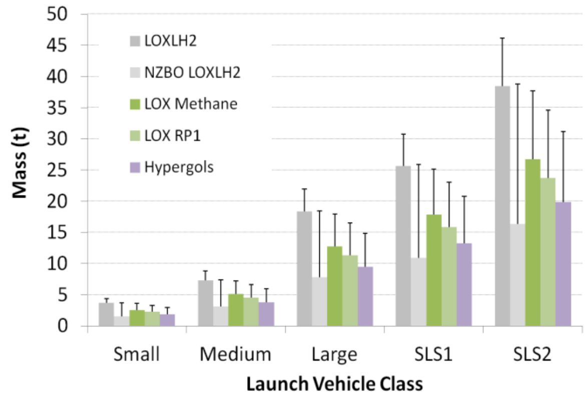

Figure 5 Chemical Propulsion Stage Cis-Lunar Delivery Capabilities

Solar Electric Propulsion Stages

While chemical propulsion stages use various fuel combinations, Solar Electric Propulsion (SEP) stages in this analysis use Hall Effect thrusters fed by xenon (Xe) propellant at various power levels. In the near-term, power levels up to 40 kW (i.e., 10, 20, and 40 kW) are considered minimal technology investment options and power levels up to 100 kW (i.e., 80 and 100 kW) are considered the high technology investments.

Low-thrust cargo trajectories to cis-lunar space, and therefore SEP stages, are divided into two classes based on their departure location. The Electric Propulsion (EP) system is identical for the same power level with the difference between these classes being the required xenon propellant capacity. Low-thrust trajectories from LEO that meet the total mission duration constraint require much higher power levels (300-600+ kW) for larger launch vehicles. In order to leverage the Large, SLS1, and SLS2 classes within the study constraints, trajectories that start in an elliptical orbit higher than LEO (i.e., GTO) are used.

A SEP vehicle's efficiency and parametric sizing is based on a fixed bus mass with parametric EP system based on the power input and xenon load. The EP system's efficiency at converting power into thrust varies with I_{sp} [15]. For these stages two modes are assumed possible with the same hardware; the lower range of I_{sp} is 2000 s and a power conversion efficiency of 0.6 and the upper range is 3000 s and an efficiency of 0.65. These performance figures in conjunction with the parametric equation [1] for the SEP vehicle mass allow the delivered mass to be calculated for both identified cis-lunar transfer trajectories.

$$M_{SEP}(kg) = 0.0213 * EP_{Power}(W) + 0.121 * Xe_{Required}(kg) + 1075\ (kg) \quad [1]$$

Single-use SEP vehicles carry enough xenon propellant to transport the integrated vehicle with cargo to cis-lunar space. The performance of the single-use SEP is shown in Figure 6; the efficiency of the stages is listed in Table 5.

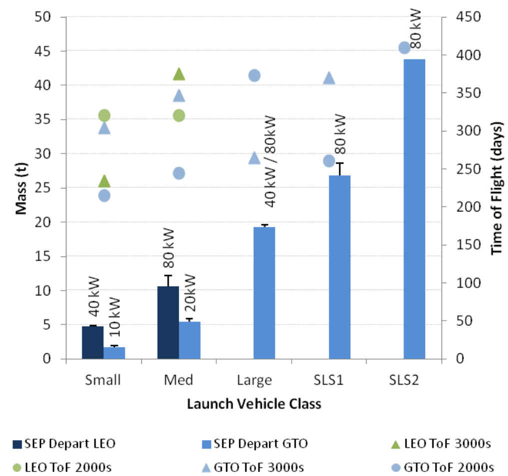

Figure 6 Single Use SEP Cis-Lunar Delivery Capabilities

Instead of only using the SEP vehicle for one transit, re-use has been discussed in past studies [16] and is included in this study. The Reusable SEP vehicle is sized with enough xenon capacity for transit from cis-lunar space to the cargo rendezvous point. The payload is launched with an integrated bus and xenon tanks sized based on the xenon portion of the SEP parametric equation [1]. The xenon in the tanker is used by the SEP to enable cargo delivery to cis-lunar space. The hardware for refuelling the SEP is based on the Orbital Express mission [17], but modified for transfer of supercritical xenon. The first flight of a re-usable SEP delivers less cargo than subsequent flights because the SEP must be launched with the cargo and xenon tanker bus. For subsequent flights, cargo and xenon tanker bus are launched into LEO or GTO and the re-usable SEP then transfers down to rendezvous. This mode of operations requires that the payload and xenon tanker bus combination maintain itself and the payload for some duration less than 30 days at the rendezvous location. This enables minimization of SEP vehicle radiation exposure within the Earth's Van Allen belts, as well as exposure to micro meteoroid and orbital debris (MMOD).

Each mission pays a penalty by bringing extra xenon for the reusable SEP's transit back to LEO or GTO. However, subsequent missions do not require the launch of a SEP saving both mass and the cost difference between the SEP and the bus and xenon tanks. For the given classes of launch vehicles, the re-usable SEP stage efficiencies are shown in Table 5. Mass delivery by launch vehicle class and flight (initial and subsequent) are plotted in Figure 7. The subsequent time of flight is for the first re-use. Array degradation based on the age of the SEP and environment experienced will slowly increase the round-trip transit times but the payload delivered can remain constant. Alternately if an increased duration is not acceptable the duration for the 3000s I_{sp} cases can be maintained by operating at 2000s I_{sp} for part or all of the transfer, but

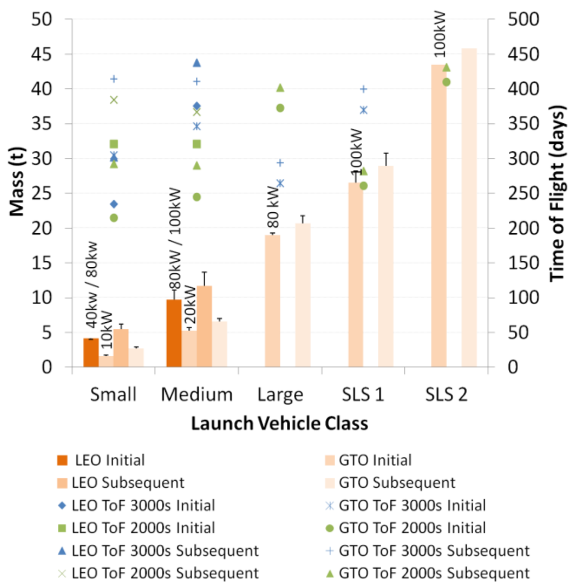

Figure 7 Reusable SEP Performance to Cis-Lunar Space

the cargo delivery capability is decremented. Note that for the SLS 2 launch vehicle there are no 3000s I_{sp} cases, this is due to those cases exceeding the ToF limitation.

Propulsion Stage Summary

Four top-level options for cargo delivery to cis-lunar space have been identified: 1.) launch vehicle TLI; 2.) chemical propulsion via BLT; 3.) single-use SEP; and 4.) reusable SEP. Each of these options and associated performance permutations are plotted in Figure 8. The ratio of cargo mass delivered to cis-lunar space with respect to launch vehicle mass in LEO (efficiency) is listed in Table 5 with the top ten performance values highlighted. This efficiency allows for comparison of option performance across launch vehicle classes. Both the mass delivered and efficiency of that delivery helps facilitate comparison of transportation performance to cis-lunar space.

It should be noted that the SEP missions that originate in LEO perform the best from a mass standpoint, but are available only for Small and Medium launch vehicles due to the limitation placed on EP power level and time of flight. For this study cryogenic chemical BLT and GTO SEP performance share the second best performance range and are applicable for all launch vehicle classes.

BASE CAMP FACILITY DEPLOYMENT, RESUPPLY, AND USE

For a cis-lunar base camp, a variety of capabilities including habitation, power, thermal control, life support, attitude control, guidance and navigation, and potentially extra-vehicular activities (EVA) are required to support crew missions. The CLBC can range from a minimal capability, providing habitable volume and EVA capability to augment the MPCV to support short (~30 day) missions, all the way to a habitation capability to support crew missions greater than one year in duration. For the purpose of this study, the

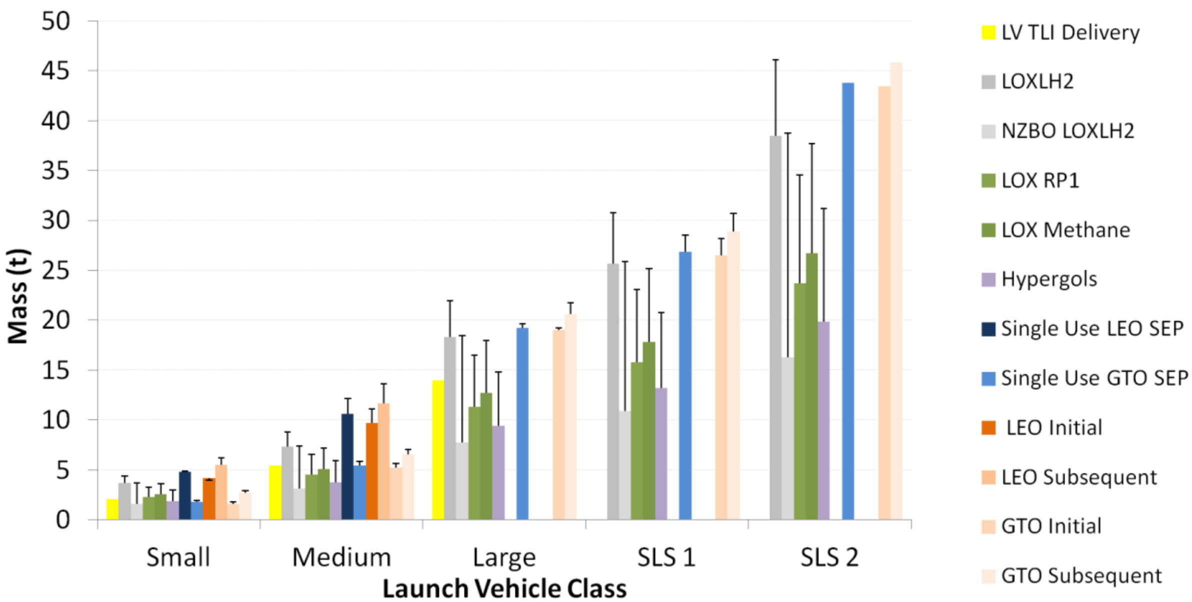

Figure 8 Transportation Architecture Option Performance to Cis-Lunar Space

Human Spaceflight Architecture Team (HAT) Cycle-C Deep Space Habitat (DSH) from “Design and Parametric Sizing of Deep Space Habitats Supporting NASA’s Human Space Flight Architecture Team” [18] is the reference for required systems to enable a yearlong crewed stay in cis-lunar space. The habitat is approximately 28 t and supports a crew of four for one year. Note this concept includes Solar Particle Event (SPE) protection, but not Galactic Cosmic Ray (GCR) protection for the crew. Since all the launch vehicles considered in the transportation architecture options are not able to deliver a 28 t payload to cis-lunar space, this habitat concept must be divided into smaller parts. Options considered in this architecture are segmented into two, three, or four modules. To investigate the potential mass penalty of increased modularity, preliminary parametric analysis was performed that split the HAT Cycle-C DSH into multiple modules.

For every split, additional hardware is added to the two resulting modules to maintain a sealed environment and allow for connection to the module which has been segmented. The additional hardware required includes pressure shell endcaps, ring frames, docking mechanisms, hatches and a docking tunnel. One major caveat with this approach is that the equipment necessary to independently operate each habitat segment may not fit into the mass or volume allocated to each individual module.

A subset of the possible transportation architecture options explored is provided in this initial evaluation of delivery options for logistics resupply requirements. Logistics include crew consumables, water, oxygen, nitrogen, and spares & maintenance. These values are based on the “Advanced Life Support Baseline Values and Assumptions Document” [19] with projected advancements in technology where appropriate. For instance, to enable long-duration missions that cannot leverage support of an Earth-based supply chain, an advanced Environmental Control and Life Support System (ELCSS) is required. Test and demonstration of such an ELCSS must be conducted prior to departure of crew missions beyond the cis-lunar realm, including the establishment of realistic maintenance and repair requirements.

To enable comparison of the selected transportation architecture options, an initial facility deployment and example use over five crew flights over a five-year period with a duration cadence of 30, 60, 90, 180, and 365 days was assessed. In addition, a second five-year period was assessed in which approximately 90 t of cargo is delivered to the CLBC in cis-lunar space by the same cargo flight type at a required cadence. This second five-year period simulates support of additional crew missions and a follow-on destination mission. It allows for a consistent comparison across options since the same amount of logistics and mass delivery over a fixed duration is required for all cases. This initial analysis did not consider volumetric constraints, only mass limitations.

Table 7 displays the details for the transportation architecture case options evaluated. These options were selected to capture parts of the campaign trade space focused on minimizing development while still including options for launch vehicles, propulsion stages, and technology assumptions. As mentioned earlier, the SLS is assumed for transportation of the crew to the CLBC. The mass to cis-lunar space for each campaign is also provided in Table 7. The initial campaigns selected (campaigns 1 through 12) only leverage one type of launch vehicle and one type of in-space propulsion for cargo. They were chosen for their simplicity and minimization of development of new elements while covering the breadth of the launch vehicle and in-space transportation element options. In addition, two mixed-fleet cases that also minimize developments were included (campaigns 13 and 14). They leverage the SLS1 launch vehicle for habitation delivery, since it is developed and used for crew transits, and a much smaller launch vehicle to provide logistics re-supply. A final case was added after additional performance analysis of the LV TLI capabilities that allows removal of an additional in-space transportation element.

Campaign Number	Launch Vehicle	LV Delivery To	Propulsion Stage(s)	Technology Assumption	Mass to Cis-lunar (t)	Reuse Mass (t)
1	Large	LEO	CBS (LOXLH2)	High	22.0	--
2	SLS1	LEO	CBS (LOXLH2)	High	30.8	--
3	Large	LEO	CBS (LOXCH4)	Med	12.7	--
4	SLS1	LEO	CBS (LOXCH4)	Med	17.8	--
5	Med	LEO	SBS (Xe-2000s)	Med	10.7	--
6	Large	GTO	SBS (Xe-2000s)	Med	19.6	--
7	SLS1	GTO	CBS (LOXLH2) SBS (Xe-2000s)	Med	28.6	--
8	Large	GTO	RSBS (Xe-2000s)	High	19.0	20.7
9	SLS1	GTO	CBS (LOXLH2) RSBS (Xe-2000s)	High	26.5	28.9
10	Med	LEO	RSBS (Xe-3000s)	High	11.1	13.6
11	Large	GTO	RSBS (Xe-3000s)	High	19.3	21.8
12	SLS1	GTO	CBS (LOXLH2) RSBS (Xe-3000s)	High	28.2	30.7
13	SLS1	LEO	CBS (LOXLH2)	High	30.8	--
	Small	LEO	RSBS (Xe-2000s)	Med	4.2	5.5
14	SLS1	LEO	CBS (LOXLH2)	High	30.8	--
	Med	GTO	RSBS (Xe-3000s)	Med	5.7	7.0
15	Large	TLI	Bus (NTOMMH)	Med	14.0	--

Table 7 Campaign Transportation Architecture Options

Figure 9 shows the cumulative mass delivery as a function of time over the first five-year period where the CLBC is established and crew experience with systems in deep-space is gained, building up to a one-year crew mission duration. The cumulative mass for each campaign is given divided into mass delivered to cis-lunar space by year for each campaign. The number of launch vehicles and associated boost stages are shown as an annual rate and as a total for the five-year period. The mass variation between the campaigns results from the modular habitation approach along with the mass capability of the launch vehicle. Although more mass capable launch vehicles might deliver more payload in fewer launches, other limitations, such as volume, might constrain the ability to utilize the full capability of those launch vehicles.

Figure 10 shows the cumulative mass delivered as a function of time over the entire ten-year period. In addition to supporting an assumed cadence of crew missions over the first five years, the launch vehicles must also place enough mass in cis-lunar space to support one crewed mission per year for the next five years along with the mass to facilitate either a crewed mission to a destination beyond cis-lunar space, lunar surface return, or in-situ resource utilization (ISRU) operations associated with a small NEA returned to lunar orbit. This comparison also provides the annual and total number of launches required.

Again, as a mass-based analysis, this does not account for volume limitations when sending pressurized goods to orbit or the inefficiencies of breaking up critical hardware or functionality into smaller packages for transportation. Therefore, this data is only representative of the trends expected given the launch and boost stage capabilities and should be considered with those limitations in mind. For a true understanding of the behaviour of the campaign options, both a more detailed set of requirements for missions staged from the CLBC and a broader set of transportation architecture options should be assessed and compared to gain an understanding of the cost versus benefit. In particular a campaign that includes multiple dissimilar cargo and crew delivery options similar to those planned by NASA and its International partners should be assessed in this manner.

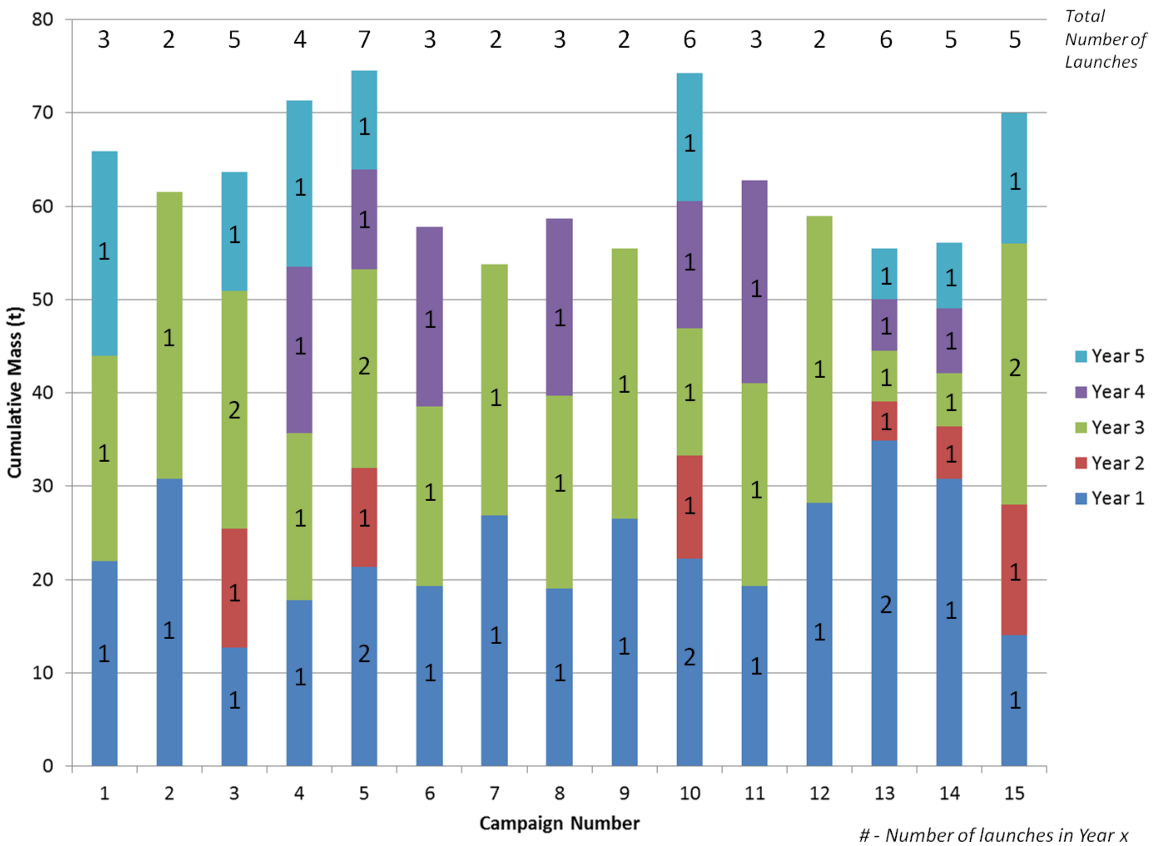

Figure 9 Mass and Launches by Delivery for 5-Year Campaigns

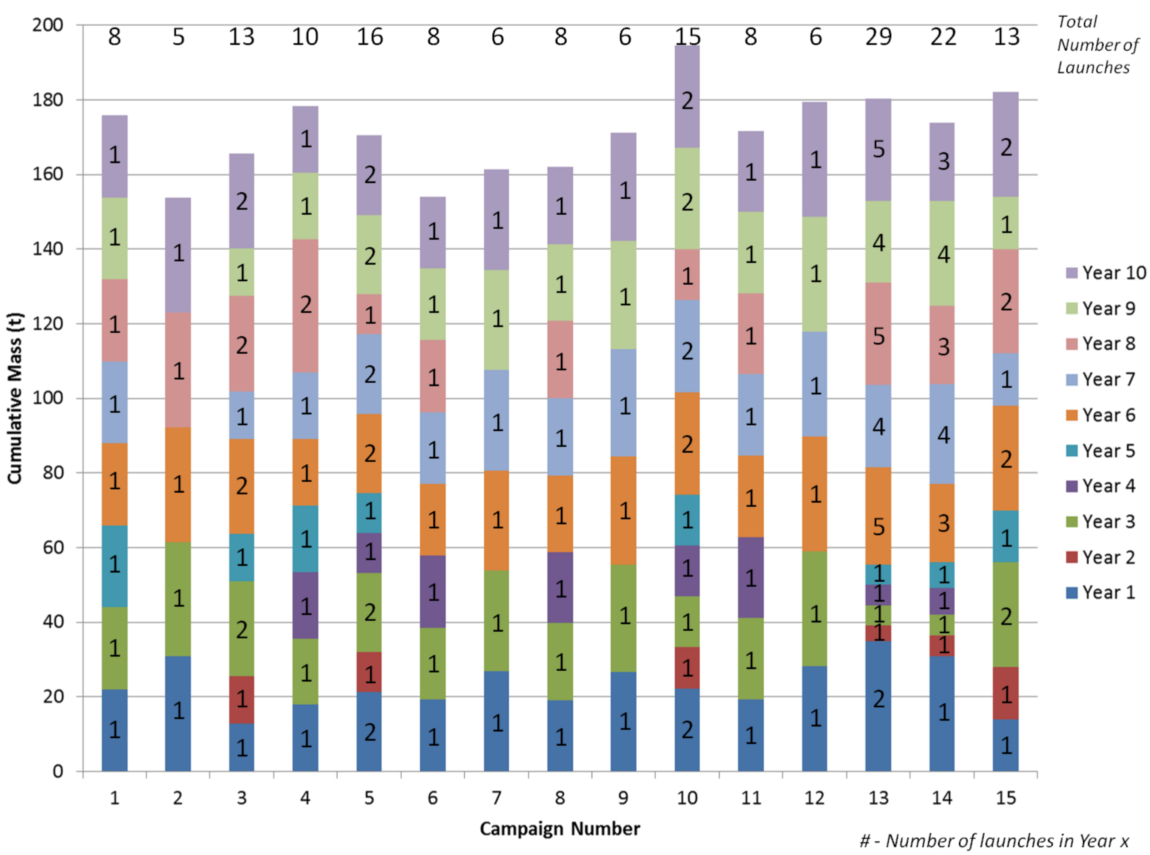

Figure 10 Mass and Launches by Delivery for 10-Year Campaigns

TRANSPORTATION ARCHITECTURE COST COMPARISON

To better understand the ramifications of the various campaign options, a high-level cost comparison of the transportation systems was performed for both the 5-year operation campaigns and the 10-year operation campaigns. The 5-year horizon provides insight into the initial investment costs required, as well as initial production costs for establishing an initial CLBC facility and logistics transportation system capability. The 10-year horizon provides insight into the impacts of quasi-steady-state production ramifications.

Due to the sensitivity and fluidity of official cost expectations of various exploration systems it is difficult to assess the various campaign options at a detailed level. Instead, analysis was performed using rough cost estimates (order of magnitude) for the following system costs:

- Launch vehicle per unit costs
- Boost stage development and production costs
- Transfer bus and tanker bus production costs

Since focus was not on crew delivery to LEO systems, neither launch vehicle development costs nor crew launch/re-entry capsule costs were considered. Also, supporting costs such as ground operations, mission operations, program integration and oversight, and reserves were not included in the cost estimates. There was no difference between chemical propulsion stages of different sizes or buses/tanker buses based on cargo mass. SEP costs were identical for power levels between 10 and 40-kW and between 80 and 100-kW. There was also no difference between expendable and reusable SEP systems since the fidelity of estimates used did not support a clear differentiation. Since the intent was to demonstrate potential trends amongst the comparison of options, all results were normalized at the architecture level.

To support the high-level campaign cost analysis, the various system cost estimates were determined using a subjective voting process. Analytical Hierarchy Process (AHP) was used to poll the paper's authors and additional conceptual design engineers to gauge their thoughts as to how each system compared to each other in terms of production and development costs (with launch vehicles only inclusive of production costs). For each system the average of the AHP voting results was translated into a cost estimate rounded to the nearest $50M. These costs were then time-phased in accordance with the 15 aforementioned campaigns using standard rule-of-thumb phasing assumptions (e.g., Beta spread over six years for development, three years for each production unit). The results of this analysis can be seen in Table 8.

To provide additional insight into the cost of transportation of cargo to CLBC over a longer period of time, the normalized cost for transportation system production per flight beyond initial operational capability (IOC) was divided by the mass delivered to cis-lunar space. This provides a cost efficiency figure that shows the marginal cost per kg to deliver cargo to the CLBC once the transportation route is established.

The normalized 5-year and 10-year campaign costs are plotted against the normalized flight cost beyond IOC per kg to cis-lunar space in Figure 11 to aid in overall comparison of the relative costs. Initial 5 year campaign costs are within 15% of each other, but over 10 years differences start to emerge based on the incremental flight costs and the costs are spread out to 25% of each other. Even at 10 years the fleets of re-usable SEP vehicles have only been operating at a constant rate for ~3 years in some cases since the flight rate increased at the 5 year mark.

Campaign	5 Year Campaign Normalized Cost	10 Year Campaign Normalized Cost	Incremental Flight Cost beyond IOC per kg
1	**0.36**	**0.76**	**0.69**
2	**0.38**	**0.79**	0.78
3	**0.40**	**0.83**	**0.63**
4	0.48	1.00	0.93
5	0.51	0.95	**0.75**
6	**0.43**	**0.81**	**0.49**
7	0.48	0.97	1.00
8	**0.43**	**0.76**	**0.32**
9	0.47	0.93	0.83
10	**0.46**	**0.84**	**0.37**
11	**0.42**	**0.76**	**0.30**
12	0.47	0.94	0.78
13	**0.39**	**0.79**	**0.40**
14	**0.41**	**0.91**	**0.72**
15	**0.36**	**0.75**	**0.47**

Table 8 Normalized Campaign and Flight Data

SUMMARY FINDINGS AND FUTURE WORK

Space exploration beyond Low Earth Orbit is currently complex and expensive. Reducing the transportation system cost is necessary to have adequate funding to develop and deploy elements to perform operations at exploration destinations. Making decisions based on 5-year or even 10-year campaigns can result in approaches that are more expensive over longer periods of time if a Cis-Lunar Base Camp is envisioned to provide support for a sustained deep-space exploration program. This paper has provided some initial insights into the options for implementing a CLBC, but a careful programmatic assessment of the long-term objectives and commitments needs to be performed. The incremental flight cost beyond IOC provides a useful metric for sustained out-year costs, but needs to be compared to performing deep-space missions without the use a CLBC. The projected additional benefits (economic, scientific, etc.) of establishing a CLBC also

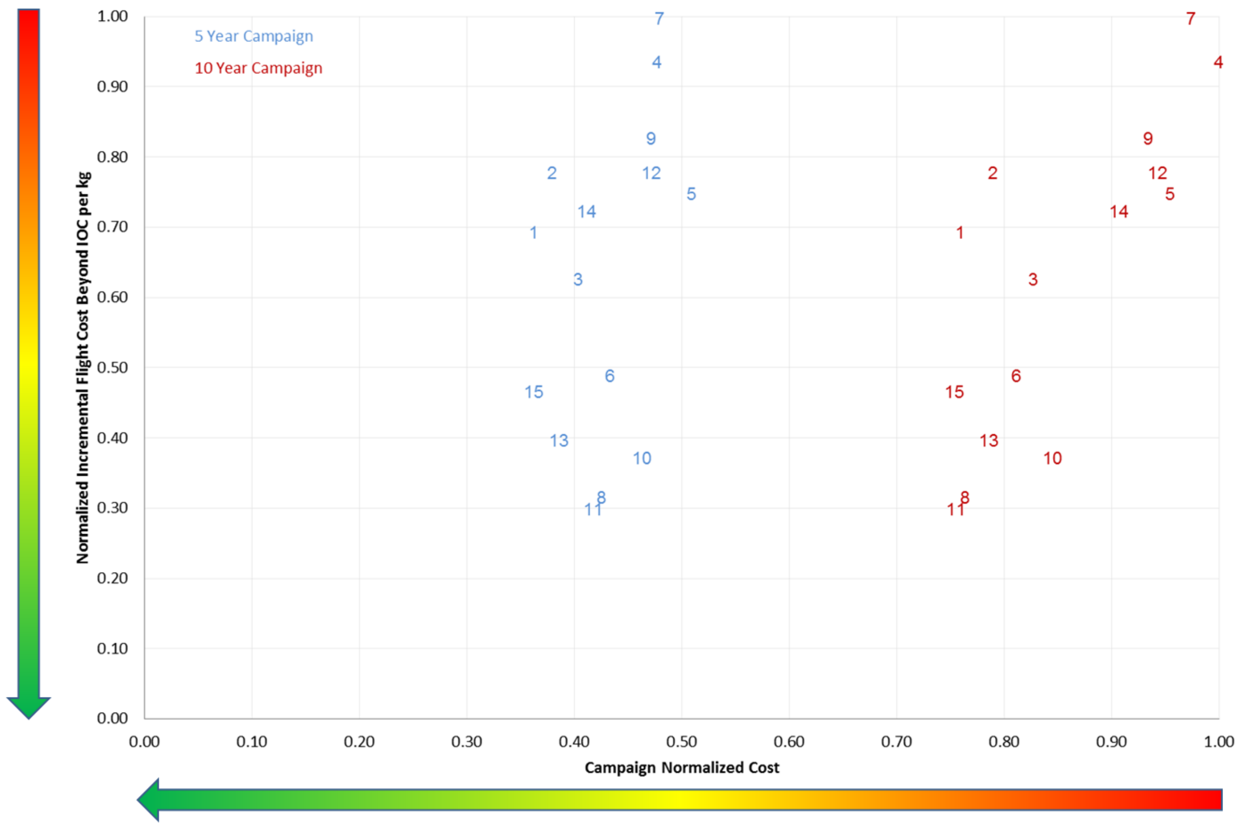

Figure 11 Relative Cost Comparisons for 5-Year and 10-Year Campaigns

need to be carefully evaluated. A permanent CLBC would be expected to be upgraded and augmented over time, but it is critical that it remain functionally focused to properly support the deep-space missions and/or other endeavours in cis-lunar space to control sustained facility costs. Alternatively, the CLBC, or a portion of the facility, could directly support deep-space exploration missions, and the remaining or replaced CLBC could transform over time to meet the evolving needs of human space exploration, both within cis-lunar space and beyond.

Using a cargo capability to cis-lunar space that delivers large infrastructure elements and then using a smaller cargo capability for logistics and re-supply is one of the better performing options based on the assumptions made in these analyses. This architecture approach is also extensible to future missions as there is the capability to send larger increments such as landers or Earth departure stages, which eliminates some of the inefficiency with smaller cargo.

A reusable SEP stage provides the lowest incremental flight costs past IOC and a GTO rendezvous approach allows use of lower power SEP systems in the 40-80 kW range, thus reducing or delaying development costs for higher power SEP systems.

For a more comprehensive understanding of the behaviour of the campaign options, both a more detailed set of requirements for missions staged from CLBC and a broader set of transportation architecture options including those likely to be developed by the International community should be assessed and compared to gain an understanding of the cost versus benefit between all of the options. Volumetric analysis for the element delivery within various launch vehicle shrouds and logistics resupply constraints also should be assessed in the future.

Time phased transportation architectures that include incremental technology development should be included in campaign assessments to show the cost and benefit of planned technology investment paths. In particular re-fuelable/re-usable chemical propulsive stages and hybrid SEP-chemical re-fueling approaches like those proposed in the Oasis study [16] should be assessed in the future to complete the trade space and investigate possible additional cost savings.

Using a subjective voting approach to quantify the magnitudes of cost differences is acceptable for an initial parametric trade study, but detailed cost estimates based on system and programmatic drivers should be utilized when making investment decisions. Additional cost and affordability analyses should be performed to validate the initial trends presented within this paper.

Probabilistic risk analyses should also be included with cost and performance to provide additional insights and understanding into how architecture design decisions will impact seemingly reasonable campaign options. Not only the planned development and explorations of cis-lunar space should be considered, but also the expected performance given vehicle and element reliability.

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