# Lunar Surface Access from Earth-Moon L1/L2

## A novel lander design and study of alternative solutions

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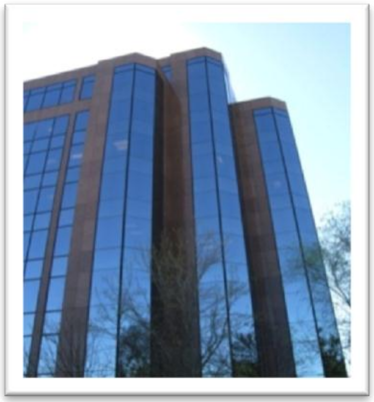
# SpaceWorks Enterprises, Inc. (SEI)



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- **Aerospace engineering services** and **space systems analysis** firm founded in 2000
  - A responsive and nimble **multidisciplinary engineering team** focused on independent concept analysis and design, technology assessment, and life cycle analysis at fidelity levels suitable for concept initiation through PDR
  - **Over a decade of experience** supporting advanced design and long range planning activities for customers in private industry, NASA, DoD, DARPA, and entrepreneurial space organizations
- Three primary operating divisions: Engineering, Commercial, and Software.
- Two partner companies: Generation Orbit Launch Services, Inc. and Terminal Velocity Aerospace, LLC.

# Introduction

The United States is considering a number of architecture solutions for conducting human space exploration beyond LEO. Among these options are crewed missions to the lunar surface.

SpaceWorks has performed a study of lunar lander designs assuming a starting point of the Earth-Moon Lagrange points L1/L2 to better understand the trade space and answer these key questions:

1. How can we use **NASA's human exploration elements** to develop the capability to access the surface from Earth-Moon L1/L2?

2. What are the **driving design constraints** in designing a lunar lander within NASA's current exploration roadmap, and how can we work within these constraints to develop a **feasible design**?

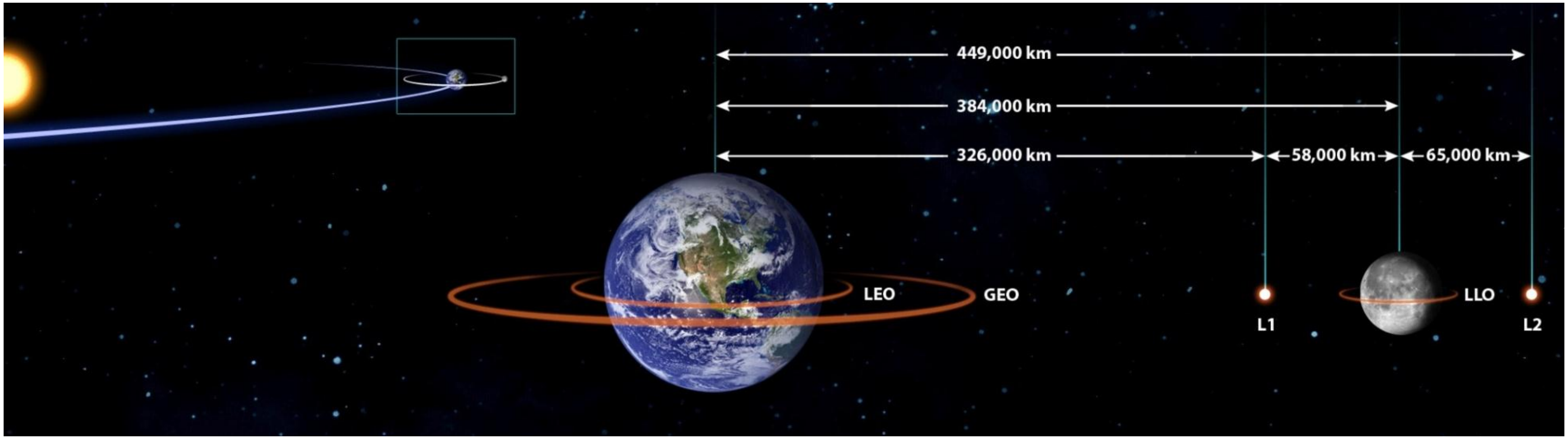
3. What are different **lunar lander options** within this trade space and how do they compare?

# Study Motivation

# Rationale for Cislunar Space

SpaceWorks believes that cislunar space, i.e. the region of space surrounding the Earth and the Moon, is the **next logical step** for NASA's human space exploration program, with **benefits** in three areas:

- **Commerce** – Development of a cislunar infrastructure will ensure continued U.S. leadership in the international community, allow the U.S. to extend its economic influence beyond LEO, and enable the utilization of the Moon's material and energy resources.
- **Exploration** – Cislunar space and the lunar surface provide a nearby proving grounds for new exploration technologies and hardware; cislunar space is also a natural basing point for deep space missions.
- **Science** – The study of the Moon's surface and interior will be useful to the fields of planetary science and solar system formation, and the lunar far side is of great interest to the astronomy community.




*Average distances based on mean Earth-Moon positions

# NASA Exploration Elements

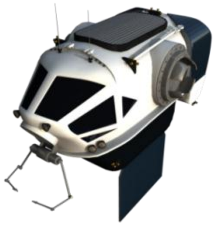
The Earth-Moon L1/L2 Lagrange points have received recent interest as a potential near-term **destination for cislunar crewed exploration missions** using the SLS, MPCV, and CPS.

A **lunar lander should be included** in any deep space exploration architectures that include L1/L2 outposts to enable crewed exploration of the lunar surface.

## IN DEVELOPMENT


**Space Launch System (SLS)**

**Multi-Purpose Crew Vehicle (MPCV)**



**Space Exploration Vehicle (SEV)**

**Cryogenic Propulsion Stage (CPS)**

## DEFINED


**Deep Space Habitat (DSH)**

**Solar Electric Propulsion (SEP)**

## UNDEFINED

**Lunar Lander**

# Design Considerations

# General Constraints on a Future Lunar Lander

To be feasible within NASA's existing exploration roadmap, any proposed lunar lander design must satisfy **ALL** of the following technical and programmatic constraints:

## Performance

**Gross Mass less than 50t**
**Diameter less than 10.0m**

SLS Block II + CPS can provide 50t to E-M L1/L2, and SLS Block II carries a 10.0m diameter fairing.

**DIFFICULTY = LOW**

## Reliability

**Loss of Crew less than 1% to 2% per mission**

As a crewed element, the lunar lander must satisfy the most stringent reliability requirements. This is particularly important for the propulsion system.

**DIFFICULTY = MEDIUM**

## Cost

**DDT&E less than $8B to $10B beginning around 2023**

With the current NASA exploration budget, special consideration must be given to the cost of any proposed lander design.

**DIFFICULTY = HIGH**

Design decisions made by mission architects must take the performance, cost, and reliability constraints into consideration. Violating any one of these constraints can **jeopardize the likelihood that the lander design will be politically and programmatically viable.**

# SpaceWorks' Design Approach

SpaceWorks believes that an L1/L2 lunar lander **can be designed to satisfy all of these constraints**. To examine this possibility, SpaceWorks has developed a notional lander concept based on the following set of design decisions:

1. Use the crew habitation element from the **Space Exploration Vehicle (SEV)**
2. Build upon the design and development of Pratt and Whitney Rocketdyne's **Common Extensible Cryogenic Engine (CECE)**, which has already been prototyped and test-fired
3. Ensure commonality with the hardware and technologies from NASA's **Cryogenic Propulsive Stage (CPS)**

# Benefits of Design Approach

SEV

CECE

CPS

| Reduce Mass | Reduce Cost | Improve Reliability |
|---|---|---|
| Reduce lunar sortie crew size from 4 to 2 to reduce mass and volume requirements | Leverage development on SEV, an already-proposed element | |
| | CECE has been demonstrated in ground testing; requires only limited development | CECE is evolved from the highly-reliable RL-10 |
| Cryogens reduce mass compared to hydrocarbons or storables | Leverage hardware and subsystems from CPS, an existing architecture element | Leverage hardware and subsystems from CPS, an existing architecture element |

# Application to a Vehicle Concept

## Space Exploration Vehicle

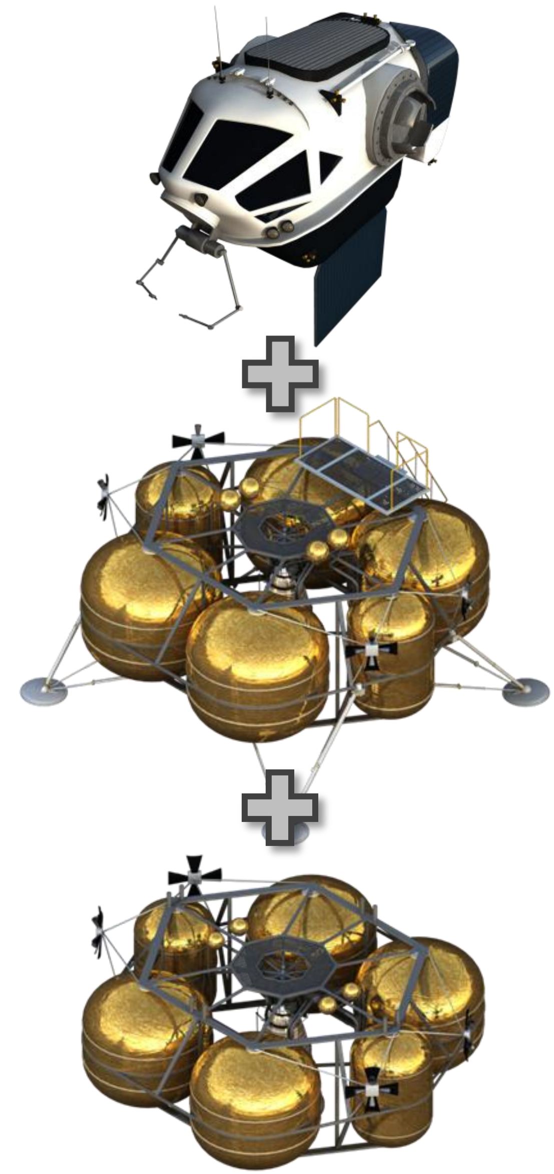
- Habitat portion of SEV modified for compatibility with lunar lander
- Provides habitat that supports 2 crew for 28 days
- Includes 2 suitlocks for lunar surface EVA capability

## Lander Stage

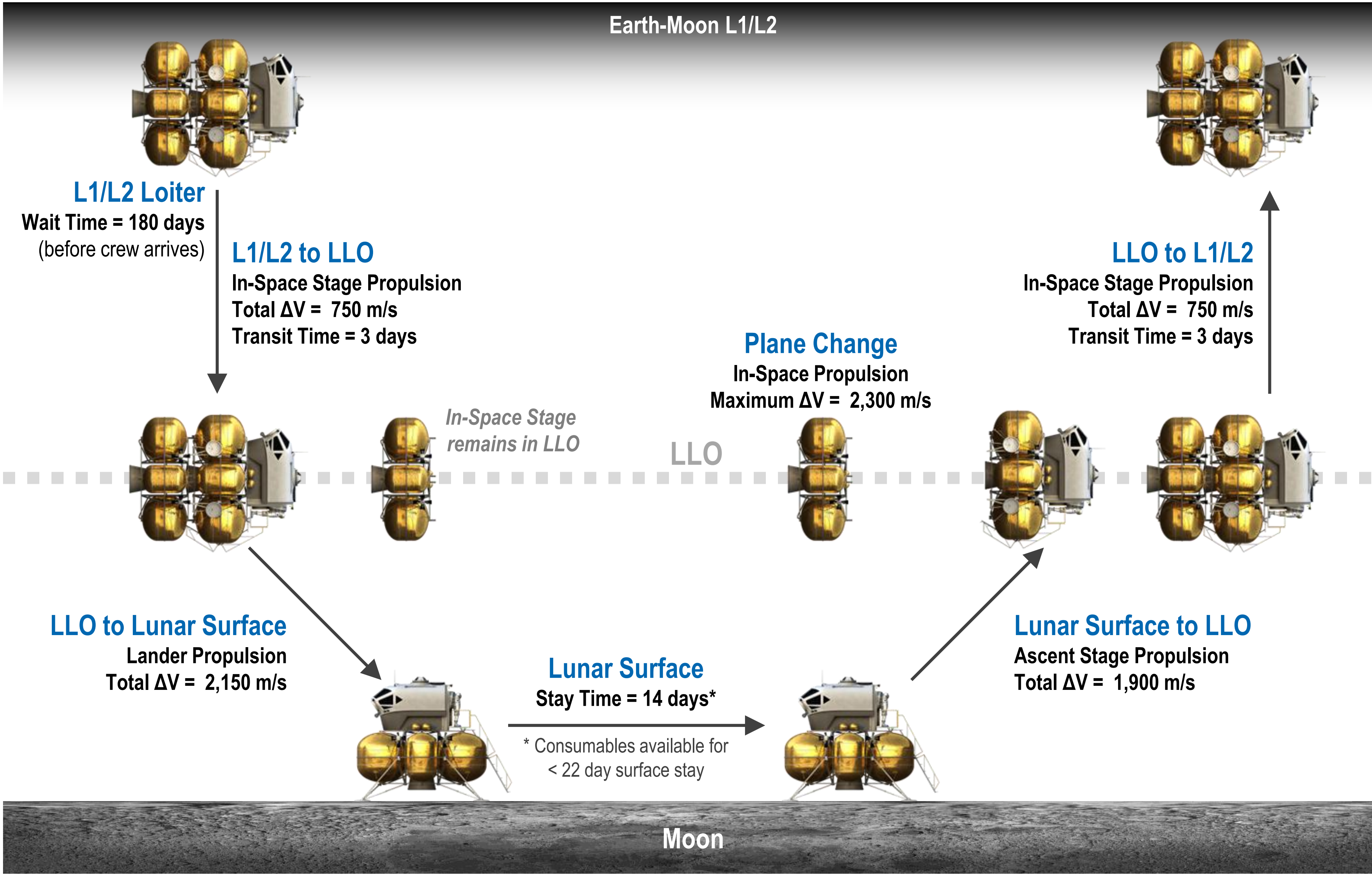
- Replaces SEV wheeled chassis (for surface ops) or in-space chassis (for asteroid ops) with landing gear and ladder for surface access
- Uses deeply throttle-able Common Extensible Cryogenic Engine (CECE) and LOX/LH2 propellants
- Provides propulsion for descent from and ascent to LLO

## In-Space Stage

- Also uses CECE and LOX/LH2 propellants; similar tank and structure design to lander stage
- Provides propulsion between L1/L2 and LLO; remains in LLO during surface mission
- Carries propellant required to adjust orbit to be above landing site at any point during the mission for contingency planning



# Concept of Operations



# Engineering Analysis

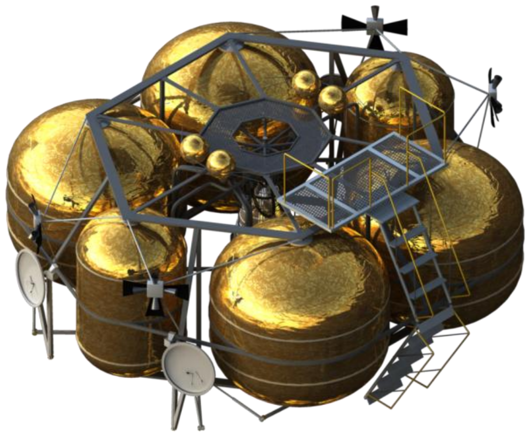
# Vehicle Design

# Design Results

| Habitat | |
|---|---|
| Dry Mass | 3.0 t |
| Payload Mass | 1.0 t |
| Wet Mass | 4.0 t |
| Crew Size | 2 |
| Duration | 28 days |

**Total Dry Mass: 9.3 t**

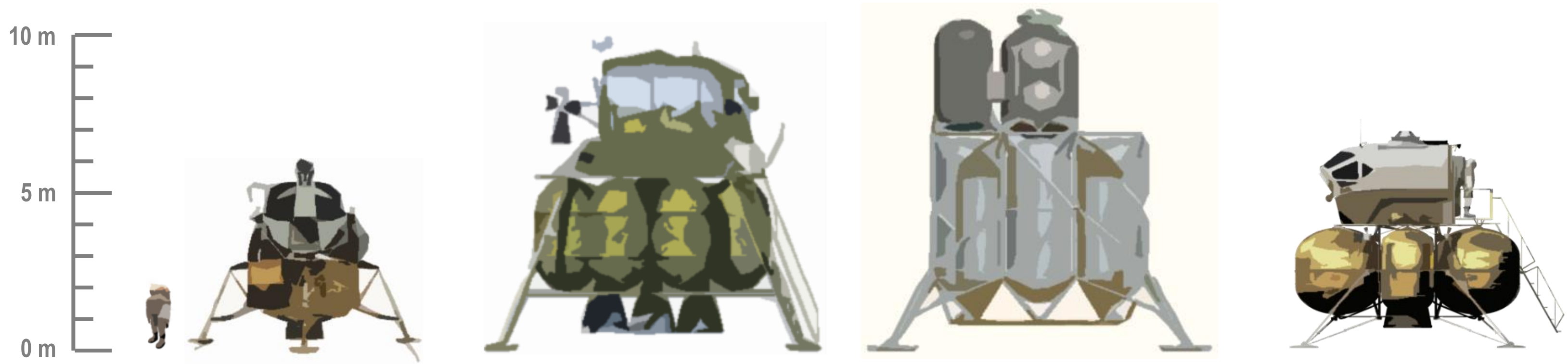
**Total Gross Mass: 34.6 t**



| Lander Stage | |
|---|---|
| Dry Mass | 4.0 t |
| Propellant Mass | 13.4 t |
| Wet Mass | 17.4 t |
| Diameter | 7.8 m |
| Height | 4.0 m |
| Thrust | 15 klbf |
| Vacuum Isp | 460 sec |
| Min Throttle | ~10% |

| In-Space Stage | |
|---|---|
| Dry Mass | 2.3 t |
| Propellant Mass | 10.9 t |
| Wet Mass | 13.2 t |
| Diameter | 7.3 m |
| Height | 3.3 m |
| Thrust | 15 klbf |
| Vacuum Isp | 460 sec |
| Min Throttle | ~10% |

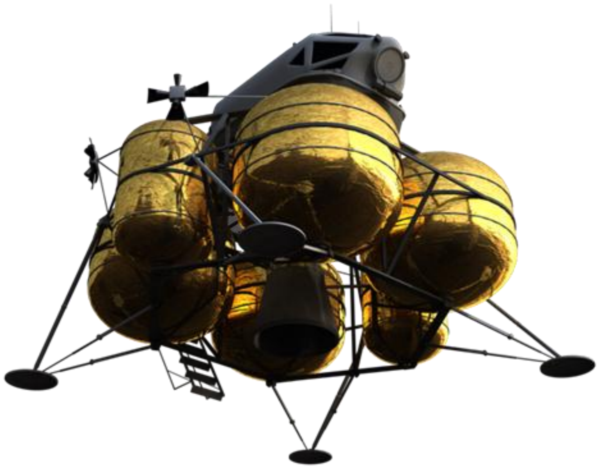
# Comparison of Lander Designs




| | Apollo | ESAS | Altair | SEV Lander |
|---|---|---|---|---|
| Number of Crew | 2 | 4 | 4 | 2 |
| Surface Time | 3 days | 7 days | 7 days | 14 days |
| Number of Stages | 2 | 2 | 2 | 1 |
| Propellants | NTO / UDMH | LOX / LH2 | LOX / LH2 | LOX / LH2 |
| Lander Mass | 14.7 t | 27.9 t | 45.6 t | 21.4 t |
| Vehicle Height | 5.5 m | 9.5 m | 10.5 m | 6.5 m |
| Airlock Height | 3.0 m | 5.5 m | 7.0 m | 4.0 m |
| Diameter | 4.3 m | 7.5 m | 7.5 m | 7.8 m |
| Maneuvers | (1) Descent from LLO<br>(2) Ascent to LLO | (1) Descent from LLO<br>(2) Ascent to LLO | (1) LOI<br>(2) Descent from LLO<br>(3) Ascent to LLO | (1) Descent from LLO<br>(2) Ascent to LLO |

# Design Observations

- Combining an in-space stage with a single stage lander provides a **fully reusable solution** for lunar surface access from L1/L2 when combined with in-space propellant loading
- By taking advantage of the large fairing diameter available on SLS, the **overall height of a lunar lander can be reduced significantly** compared to other designs
- Though the SEV is well-suited for this application, the placement of the docking ports on the SEV would need to be adjusted to allow this lander to dock with other in-space elements



# Trade Studies

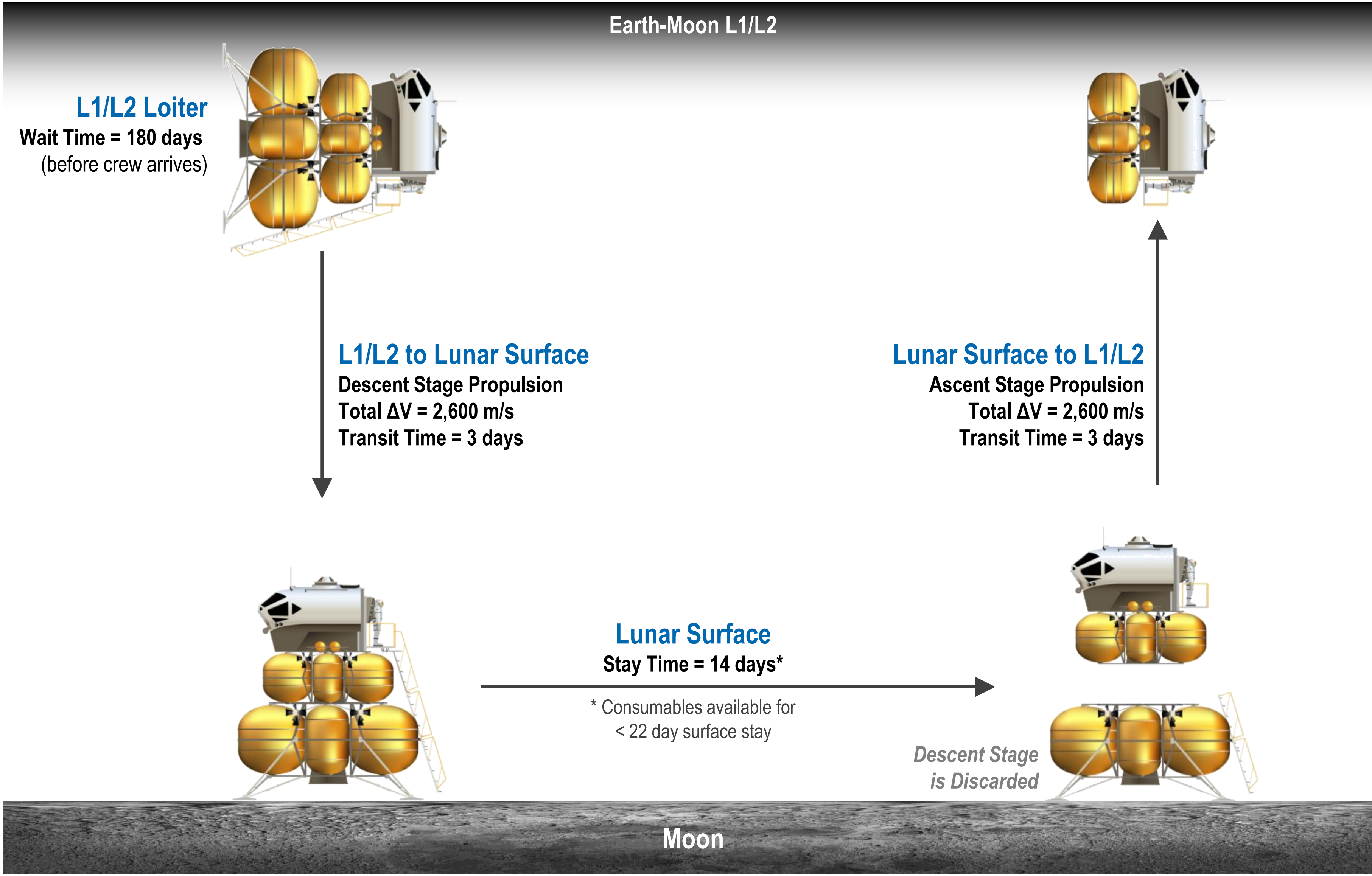
# Trade Studies

| Propellants | Advantages | Disadvantages |
|---|---|---|
| LOX/LH2 (baseline) | High performance, commonality with CPS, heritage engines | Hydrogen boil-off, low fuel density |
| LOX/CH4 | Low boil-off fuel and oxidizer, good fuel density | No heritage engines, low performance (compared to LOX/LH2) |
| LOX/RP | Storable fuel, low boil-off oxidizer, heritage engines, great fuel density | Low performance (compared to LOX/LH2 or LOX/CH4) |
| Non-toxic Storable* | Storable propellants, monopropellant or bipropellant options, great densities | Low performance (compared to LOX/LH2 or LOX/CH4) |

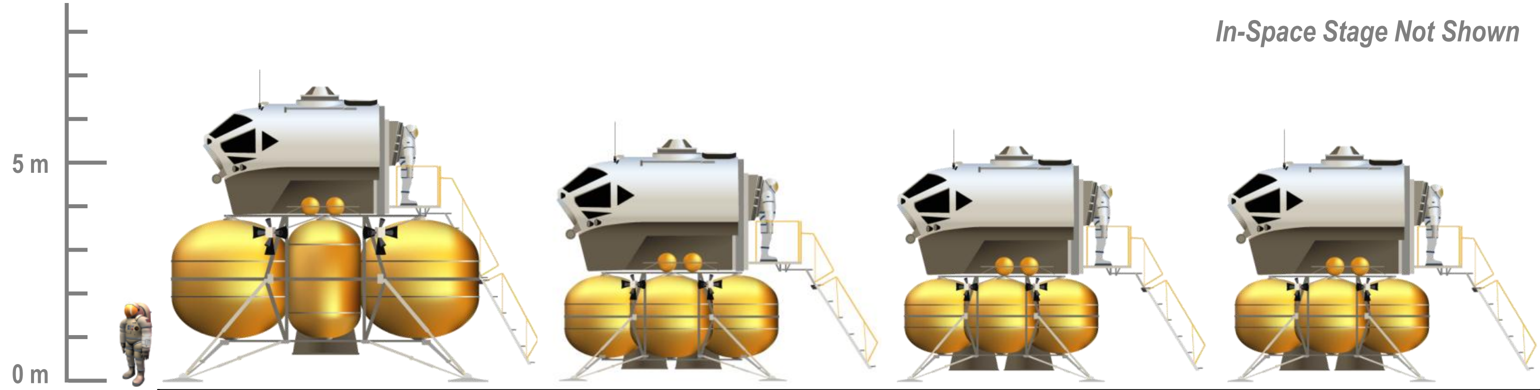
* NOFBX or equivalent non-toxic, fully storable monopropellant or bipropellant combination

| Configurations | Advantages | Disadvantages |
|---|---|---|
| In-Space Stage with Lander (baseline) | Fully reusable, small lander | LLO rendezvous and orbit plane change maneuver required |
| Apollo-style Two Stage Lander | No LLO rendezvous maneuver, simple design, lower gross mass | Expendable descent stage, large lander |
| Apollo-style Two Stage Lander with Shared Propulsion | Single propulsion system, reduced dry and gross mass | Complex vehicle design to share propulsion systems between stages |

# Concept of Operations for Alternate, Apollo-style Lander

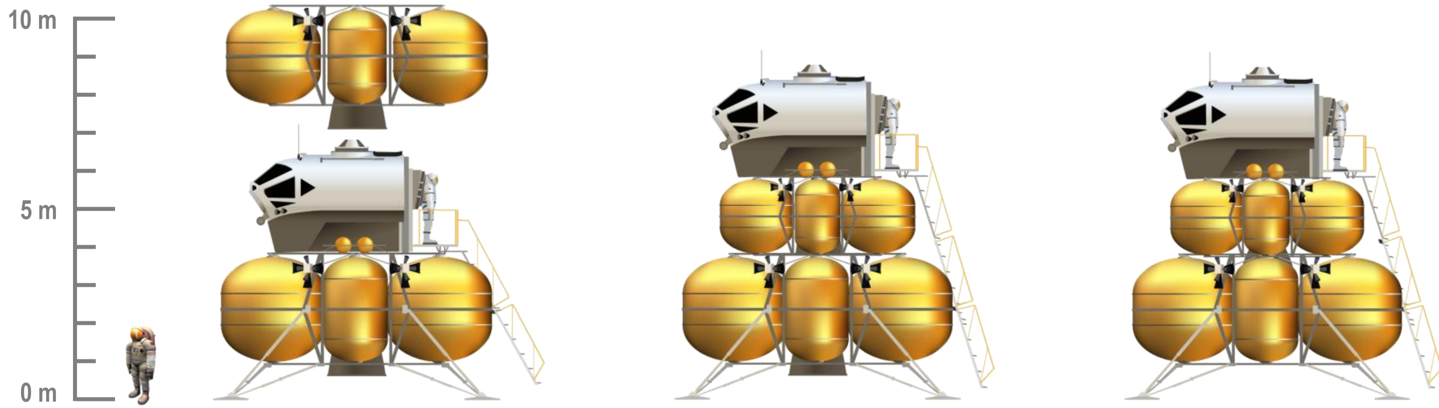


# Propellant Trade Study




| | LOX/LH2 | LOX/CH4 | LOX/RP | Non-toxic Storable |
|---|---|---|---|---|
| **In-Space Stage** | | | | |
| Dry Mass | 2.3 t | 1.9 t | 1.7 t | 1.7 t |
| Propellant Mass | 10.9 t | 14.5 t | 15.5 t | 16.4 t |
| **Lander** | | | | |
| Dry Mass (with SEV) | 7.0 t | 6.2 t | 5.9 t | 5.8 t |
| Propellant Mass | 13.4 t | 16.5 t | 17.5 t | 18.4 t |
| **Total** | | | | |
| Gross Mass | **34.6 t** | **40.2 t** | **41.6 t** | **43.4 t** |
| Δ Gross Mass | 0% | +16% | +20% | +25% |
| Height | 9.2 m | 7.2 m | 7.1 m | 7.1 m |
| Diameter | 7.8 m | 5.3 m | 4.9 m | 4.9 m |

# Configuration Trade Study




| | In-Space Stage + Lander | Apollo-style Lander | w/ Shared Prop |
|---|---|---|---|
| **Ascent/Lander Stage** | | | |
| Dry Mass (with SEV) | 7.0 t | 6.2 t | 5.9 t |
| Propellant Mass | 13.4 t | 5.6 t | 5.8 t |
| **Descent/In-Space Stage** | | | |
| Dry Mass | 2.3 t | 3.3 t | 2.7 t |
| Propellant Mass | 10.9 t | 13.6 t | 13.1 t |
| **Total** | | | |
| Gross Mass | **34.6 t** | **28.8 t** | **28.5 t** |
| Δ Gross Mass | 0% | -17% | -17% |
| Height (on surface) | 6.5 m | 8.5 m | 8.5 m |
| Diameter | 7.8 m | 7.8 m | 7.8 m |

# Trade Study Observations

- Compared to hydrogen, **hydrocarbon or fully storable propellants can reduce vehicle size significantly** at the expense of increased mass
  - Allows the crew easier access to the surface from the habitat
  - Reduces or avoids boil-off losses associated with cryogenic propellants
  - Potentially allowed for fixed landing gear (rather than deployable)

- Using an Apollo-style two stage lander, rather than a lander and an in-space stage, shows only modest improvement in total mission mass required, but significantly increases the physical size of the lander vehicle

- The use of a common propulsion system on the ascent and descent stages shows marginal performance increase, weighed against the added design complexity

# Conclusions

# Study Conclusions

- Any potential deep space human exploration architecture that involves element basing at Earth-Moon L1/L2 **should include a lunar lander** to take advantage of the easy access L1/L2 provides to the lunar surface

- **Feasible lunar lander designs may exist** within the mass, dimensions, cost, and reliability constraints of the current human exploration architecture

- A fully reusable configuration, where all elements are returned to L1/L2 for refueling, **can reduce campaign costs** compared to designs with expendable elements

- Hydrocarbon fuels provide **significant propellant volume advantages** over hydrogen with only a modest increase in system mass, reducing overall vehicle size

# Future Study

**Potential paths for future study of the proposed lunar lander design include:**

- Investigate use of **common propulsive element** for lander and in-space stages
- Evaluation of **alternate orbital basing locations** including Low Lunar Orbit, GEO, and other high Earth orbits
  - Compare those alternate basing options with the E-M L1/L2 option explored here
- Continued evaluation of **alternate mission configurations** and rendezvous options, including:
  - A single stage option between L1/L2 and the lunar surface
  - Expendable in-space stage delivers lander to LLO or surface descent trajectory; lander returns to L1/L2
  - Use of MPCV, CPS, or existing upper stage as additional propulsive element
- **Detailed investigation of mission reliability** including a similar trade study of configuration options, with particular focus on rendezvous maneuvers and engine restarts
- **Detailed development cost estimate** of a future lunar lander including required ground and flight testing, engine development for the CECE, and stage design and integration
- **Full life cycle campaign analysis** with multiple sorties from an orbital base, including launch manifesting of lander elements, crew, and propellant refuel

# Going Forward

SpaceWorks is interested in **partnering with NASA and private industry** to further develop human exploration architectures for cis-lunar space and beyond. SpaceWorks can support architecture studies and analysis teams in a variety of roles:

- **Independent assessment** of exploration architectures and element design
- Direct integration with analysis teams as **technical specialists**
- Indirect integration with analysis teams in a **support role** for a technical lead

Further analysis of the lunar lander trade space can help guide near-term study planning and inform the program level decision-making process.

# SPACE IS GO

SpaceWorks Enterprises, Inc.

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# Appendix

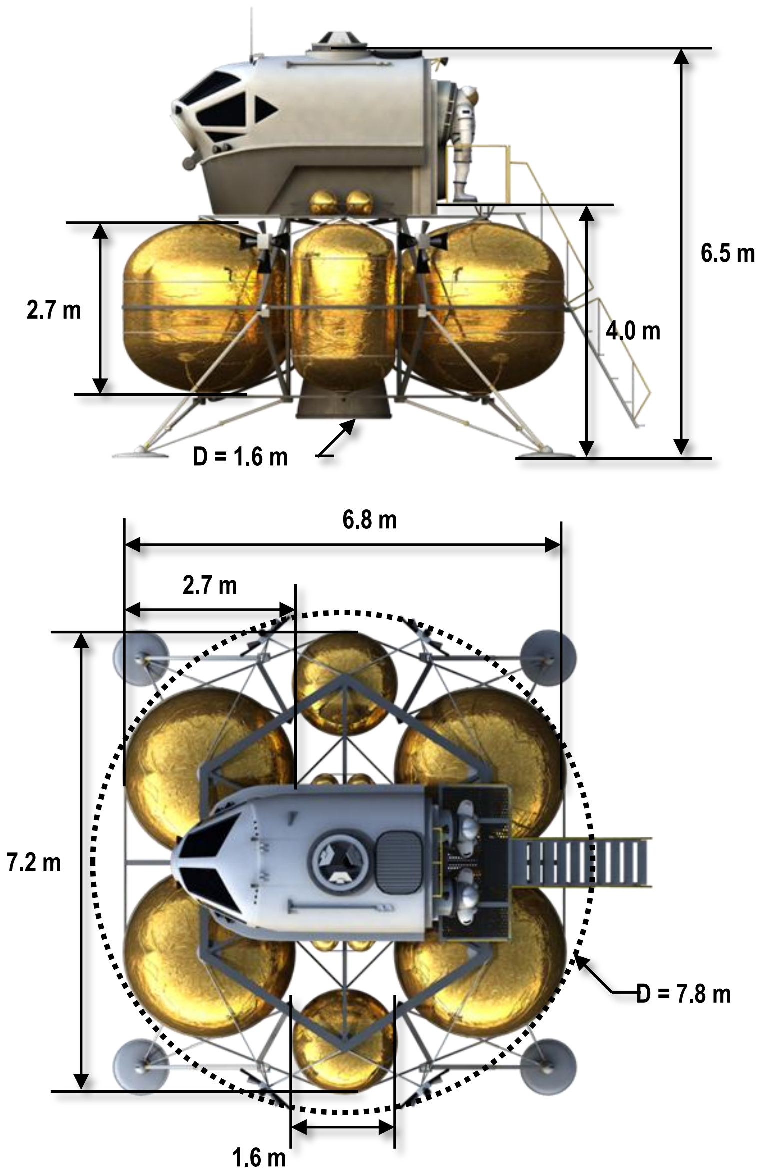
# Assumptions and Methodology

- Lander and in-space stage sized using an **integrated mass model**, based on combination of historical mass estimating relationships, physics-based equations, and empirical data
  - Existing engine design (CECE) with assumptions for T/W, Isp, and throttle-ability based on literature
  - Passive thermal management of cryogenic propellants (no active systems)

- Assume **fixed mass** for **SEV habitat** of 4,000 kg
  - 3,000 kg habitat dry mass; 1,000 kg for 2 crew, suits, and consumables for 28-day mission
  - Mass selected from literature based on current publically available data
  - SEV habitat design will require a dorsal/topside docking hatch for crew access from MPCV or other station in L1/L2

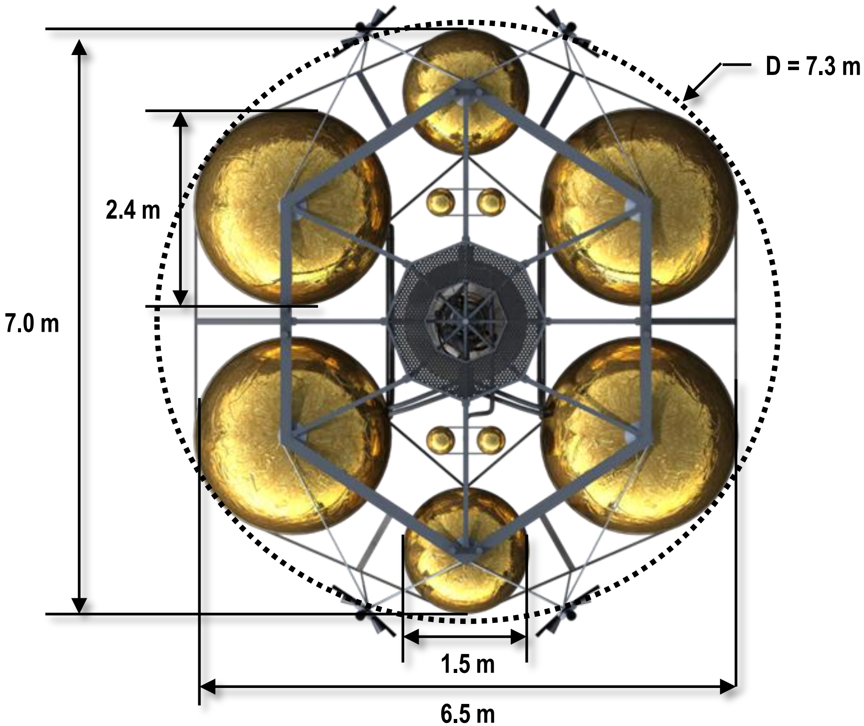
- Performance model assumes trajectory with instantaneous $\Delta V$ based on required Videal for each maneuver. Videal values are drawn from literatures and in-house trajectory models.

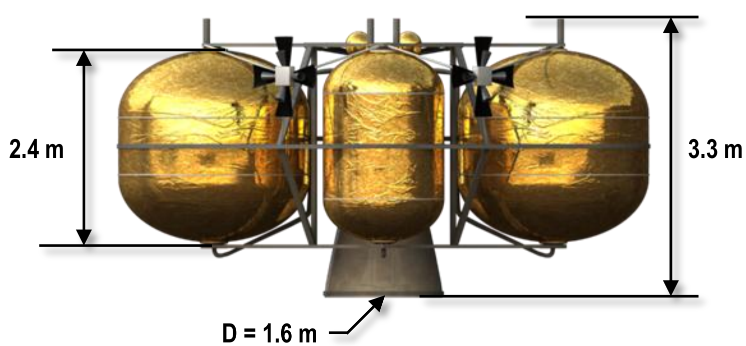
# Lander Details




| Item | Lander (kg) |
|---|---|
| Structures | 1,445 |
| Propulsion | 320 |
| Attitude Control | 160 |
| Pressurization | 95 |
| Avionics | 185 |
| Thermal Control | 440 |
| Power | 135 |
| Mass Growth (30%) | 1,190 |
| **Dry Mass** | **3,970** |
| Consumables | 15 |
| Residuals and Reserves | 200 |
| **Inert Mass** | **4,185** |
| Main Propellant | 13,155 |
| Start-up Losses | 65 |
| **Wet Mass** | **17,405** |
| Payload (SEV) | 4,000 |
| **Gross Mass** | **21,405** |

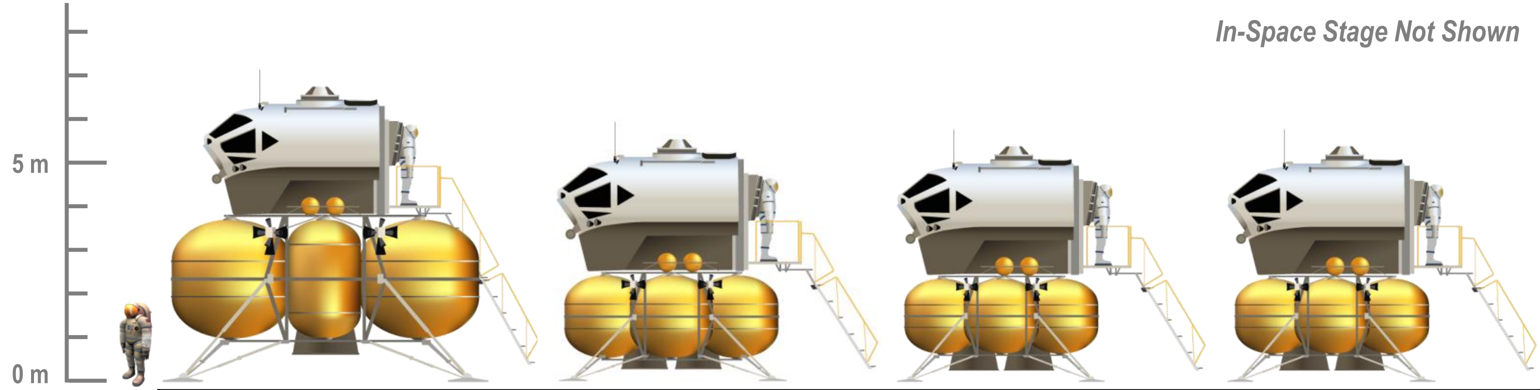
# In-Space Stage Details



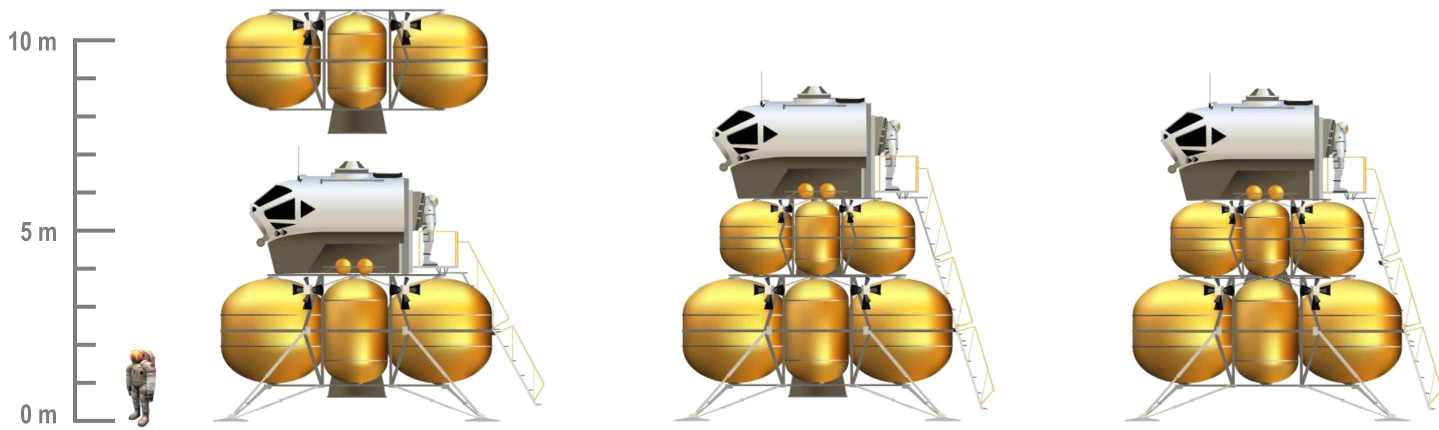

| Item | In-Space Stage (kg) |
|---|---|
| Structures | 540 |
| Propulsion | 310 |
| Attitude Control | 80 |
| Pressurization | 85 |
| Avionics | 145 |
| Thermal Control | 345 |
| Power | 105 |
| Mass Growth (30%) | 690 |
| **Dry Mass** | **2,295** |
| Consumables | 15 |
| Residuals and Reserves | 165 |
| **Inert Mass** | **2,475** |
| Main Propellant | 10,695 |
| Start-up Losses | 55 |
| **Wet Mass** | **13,225** |
| Payload | - |
| **Gross Mass** | **13,225** |

# Propellant Trade Study



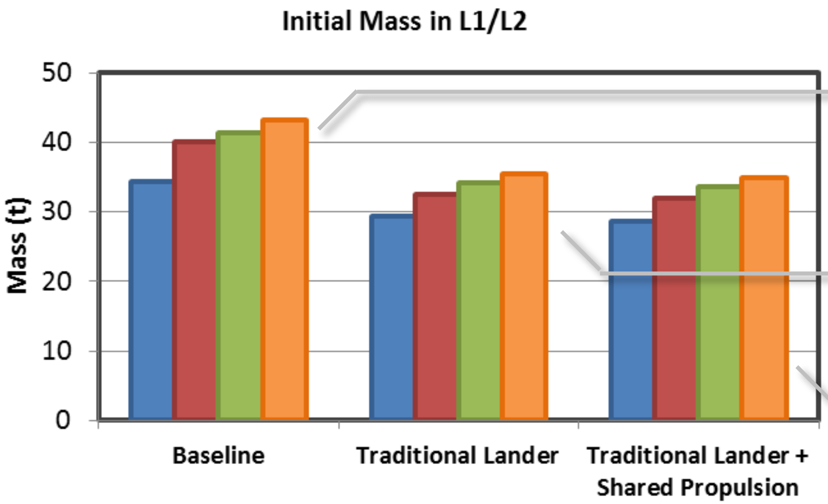

| | LOX/LH2 | LOX/CH4 | LOX/RP | Non-toxic Storable |
|---|---|---|---|---|
| **In-Space Stage** | | | | |
| Dry Mass | 2.3 t | 1.9 t | 1.7 t | 1.7 t |
| Propellant Mass | 10.9 t | 14.5 t | 15.5 t | 16.4 t |
| Propellant Mass Fraction | 83% | 88% | 90% | 91% |
| Stage Height | 2.8 m | 2.2 m | 2.0 m | 2.0 m |
| Stage Diameter | 7.3 m | 5.8 m | 5.1 m | 5.1 m |
| **Lander** | | | | |
| Dry Mass (with SEV) | 7.0 t | 6.2 t | 5.9 t | 5.8 t |
| Propellant Mass | 13.4 t | 16.5 t | 17.5 t | 18.4 t |
| Propellant Mass Fraction | 66% | 73% | 75% | 76% |
| Stage Height (on surface) | 6.3 m | 5.5 m | 5.2 m | 5.2 m |
| Stage Diameter | 7.8 m | 5.8 m | 5.1 m | 5.1 m |
| **Total** | | | | |
| Gross Mass | **34.6 t** | **40.2 t** | **41.6 t** | **43.4 t** |
| Vehicle Height | 9.2 m | 7.2 m | 7.1 m | 7.1 m |
| Vehicle Diameter | 7.8 m | 5.3 m | 4.9 m | 4.9 m |

# Configuration Trade Study




| | In-Space Stage + Lander | Apollo-style Lander | Apollo-style Lander w/ Shared Prop |
|---|---|---|---|
| **In-Space Stage** | | | |
| Dry Mass | 2.3 t | - | - |
| Propellant Mass | 10.9 t | - | - |
| Propellant Mass Fraction | 83% | - | - |
| **Ascent Stage / Lander** | | | |
| Dry Mass (with SEV) | 7.0 t | 6.2 t | 5.9 t |
| Propellant Mass | 13.4 t | 5.6 t | 5.8 t |
| Propellant Mass Fraction | 66% | 47% | 47% |
| **Descent Stage** | | | |
| Dry Mass | | 3.3 t | 2.7 t |
| Propellant Mass | | 13.6 t | 13.1 t |
| Propellant Mass Fraction | | 80% | 83% |
| **Total** | | | |
| Gross Mass | **34.6 t** | **28.8 t** | **28.5 t** |
| Vehicle Height (on surface) | 6.5 m | 8.5 m | 8.5 m |
| Vehicle Diameter | 7.8 m | 7.8 m | 7.8 m |

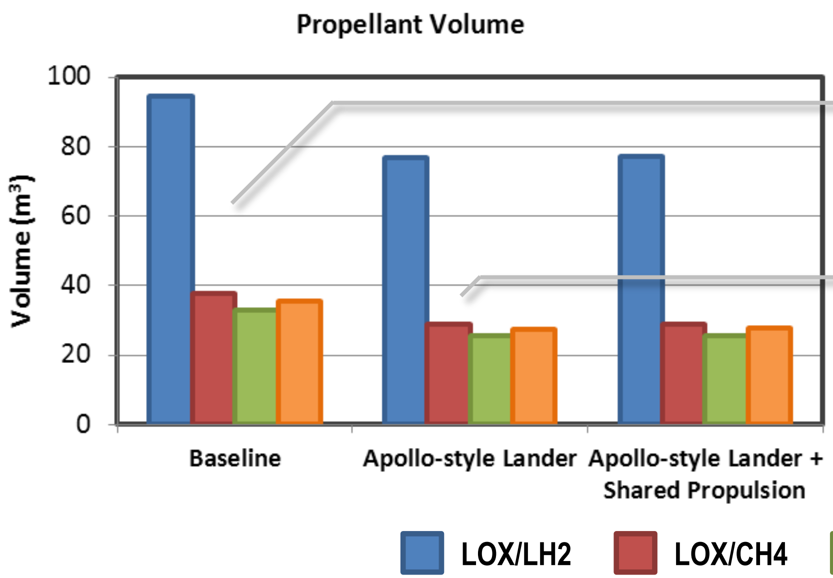
# Trade Study Results




15%-25% increase in gross mass changing from hydrogen to hydrocarbon or non-toxic storables

17% decrease in gross mass changing from baseline configuration to Apollo-style lander

Marginal change in gross mass using a shared ascent + descent stage propulsion system



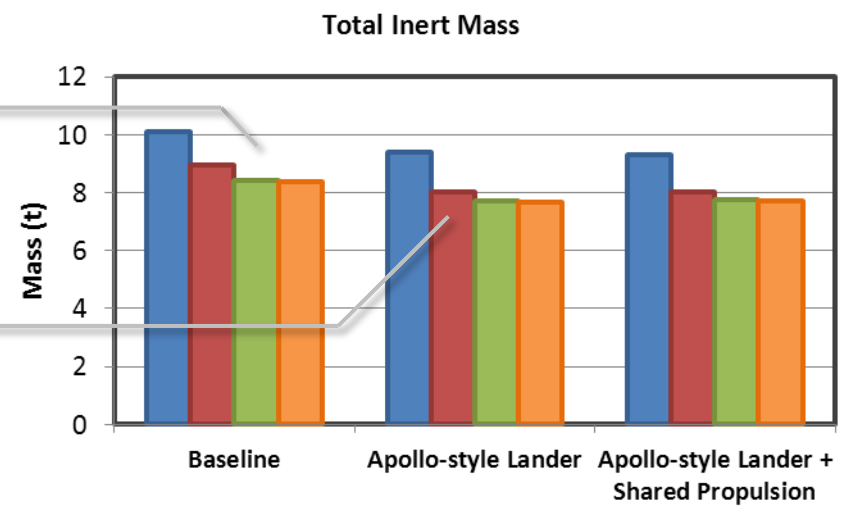

60% reduction in total propellant volume changing from hydrogen to hydrocarbon or non-toxic storables

Small differences in total propellant volume between methane, kerosene, and non-toxic storables

# Trade Study Results

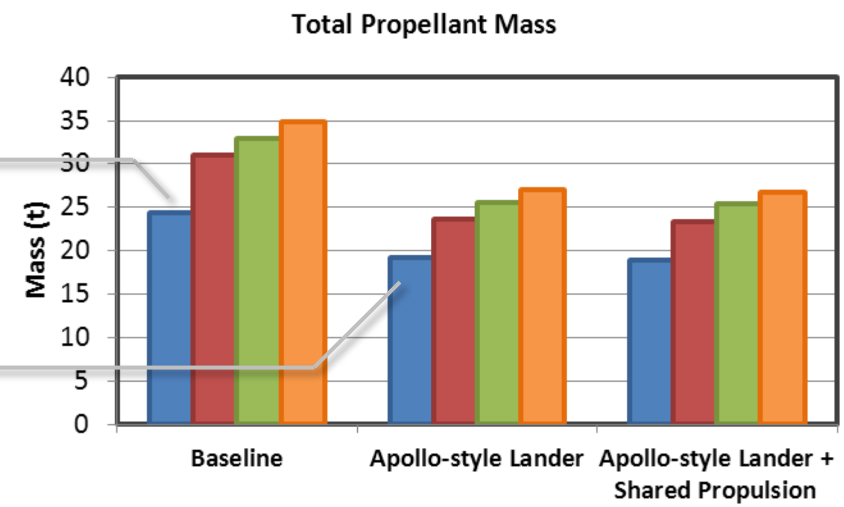
Total inert mass is 10t or less for all configurations

Apollo-style lander shows 7%-9% reduction in inert mass compared to baseline configuration




Total propellant mass is under 25t for hydrogen

Apollo-style lander shows 22%-25% reduction in propellant mass compared to baseline configuration




LOX/LH2 LOX/CH4 LOX/RP Non-toxic Storable