In-Situ Lunar Resource Utilization:
A Lunar Exploration Program Architecture to Establish Propellant Manufacturing Capability at the Lunar South Pole

ENAE 791 Final Project

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Contents

Background

- In recent years, NASA and the international space community have expressed great interest in returning human crews to the lunar surface as part of a larger goal of expanded human exploration throughout the solar system.
- Rather than another one-off visit for ‘flags and footprints’, there is increasing impetus to establish a permanent human presence in cislunar space. This will require greater infrastructure development to foster a nascent cislunar economy to fund and sustain such activity. A focal point of such an economy is the extraction of resources from the lunar crust, such as minerals and water ice that could be used to produce hydrogen and oxygen for rocket propulsion.
- This project proposes a large-scale exploration program to create a propellant depot at the lunar south pole in order to demonstrate the ability to perform meaningful in-situ resource utilization (ISRU) beyond Earth. Such a program will aim to lay the groundwork for the infrastructure necessary for humans to work and inhabit cislunar space, and eventually travel beyond.

Program Overview

Phase I: Exploration and Site Selection

- The initial missions to the lunar surface will be robotic exploration vehicles to seek out deposits of water ice at the lunar south pole. These are similar in concept to NASA's cancelled Resource Prospector mission and the proposed VIPER mission.
- Assuming a suitable site for extraction and processing of water ice is found at the lunar south pole, supply delivery missions will follow to deliver mining and processing equipment as well as prefabricated modules for the propellant production plant, to be powered by the constant solar power available at the lunar poles.

Phase II: Cislunar Transportation Network Setup

- Following the selection of a lunar surface site for operations and delivery of initial supplies to that site, the next phase in the program will establish the network to transport crew and supplies to the lunar surface. This network has two primary components:
    - SpaceBus vehicle: crew transport with propulsion module to provide Δv needed to travel between a low Earth parking orbit (LEO) and a low lunar polar parking orbit (LLO). This vehicle is completely reusable for the duration of the program.
    - Lunar Landing Vehicle (LLV): crew transport and propellant tanker to deliver liquid hydrogen and liquid oxygen propellants produced at lunar surface propellant plant to LLO for refueling of SpaceBus for another round trip to Earth and back to the moon. This vehicle is also completely reusable for the duration of the program.
- These vehicles will be launched empty or nearly empty of propellants to LEO using the Earth Launch Vehicle (ELV) which is notionally a single-stage-to-orbit (SSTO) completely expendable launch vehicle.
- For initial staging of these vehicles in LLO, they must be fueled in LEO using propellants launched from Earth. Modified SpaceBus tanker modules will be launched to LEO using the ELV where they will rendezvous and dock with the crew transport vehicles and transfer enough propellants to enable each vehicle to make the one-way trip to LLO.

Phase III: Propellant Production Operations

- Assuming that limitations of current robotic technology preclude the lunar propellant plant from being constructed and brought online in a reasonable timeframe in the near future, human crews will be ferried to the lunar surface to perform this function. The notional quantity of these missions to establish the propellant production operations is five.
- Crews of four will launch to LEO in the Crew Launch and Entry Vehicle (CLEV) using the ELV. In LEO the CLEV will rendezvous and dock with the SpaceBus and the crew will transfer from the former to the latter vehicle for the trip to the moon. The CLEV will remain in LEO for the duration of the crew's mission to the lunar surface. After reaching LLO, the SpaceBus with rendezvous and dock with the LLV and the crew will again transfer to the new vehicle before descending to the lunar surface for a two-week stay to perform ISRU duties.
- After completing the lunar surface mission, the crew will ascend to LLO in the LLV which will be completely refueled at this point. The LLV will rendezvous and dock with the SpaceBus in LLO and transfer both the crew and propellant to it to fill its tanks for the trip back to Earth. Upon return from the moon in the SpaceBus vehicle, the crew will transfer back to the CLEV in LEO for Earth atmospheric entry, descent, and landing (EDL).

Mission Profiles

Phase I

- Scout rover
  - Initial scouting missions performed by robotic lander and rover tandems that will seek out and identify optimal locations for mining and processing of lunar water ice
- ISRU equipment staging
  - Uncrewed missions to send water ice mining and processing plant equipment to sites identified by scouting rovers ahead of crew arrival

Phase II

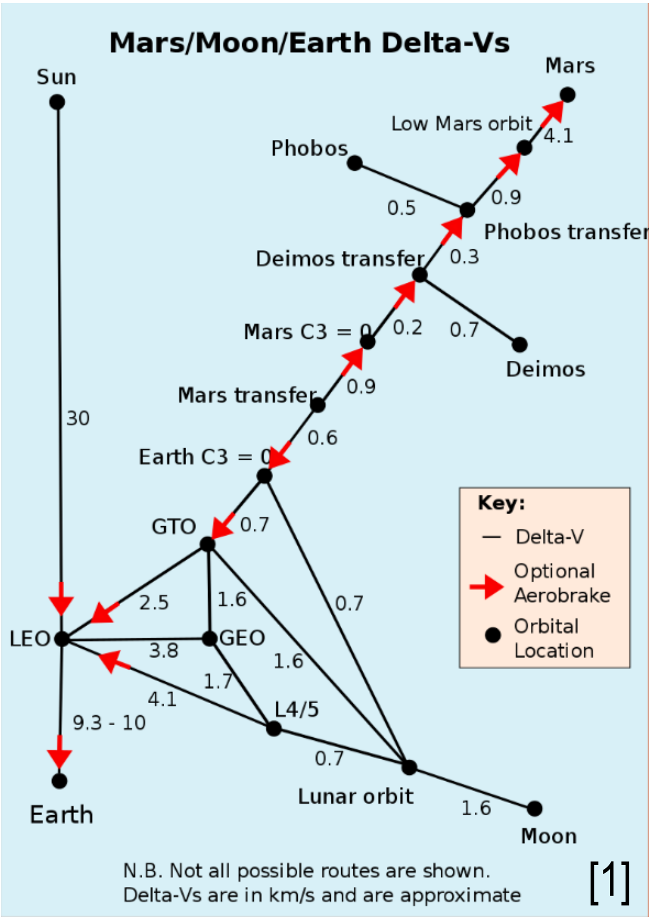
- SpaceBus crew transport
  - One-time launch of reusable crew transport vehicle to LEO
  - Awaits first crewed mission in LEO prior to one-way trip to LLO
- Lunar landing vehicle
  - One-time launch of reusable lunar landing vehicle to LEO
  - One-way trip to LLO to await first crewed landing on moon
- SpaceBus tanker
  - Expendable tanker module launches to refuel SpaceBus crew transport or lunar landing vehicle in LEO

Phase III

- Crew launch/return
  - Operational crew missions to establish ISRU water ice processing plant and demonstrate LH_2 and LO_2 production capabilities

Δv Budget - Overview

Mission Maneuver	Δv Required (km/s)	Notes/Source
Launch	9.0	crude "Hohmann Transfer" method
	9.2 – 9.5	Rule of thumb per Dr. Akin
	9.3 – 10	[2]
Trans-Lunar Injection (TLI)	5.02	Sum of separate maneuvers Apogee raise: Δv = 2.47 km/s Plane change: Δv = 2.56 km/s
	3.90	Combined maneuver
	4.04	[2]
Lunar Orbit Injection (LOI)	3.16	Sum of separate maneuvers Apogee raise: Δv = 0.85 km/s Plane change: Δv = 2.31 km/s
	1.66	Combined maneuver
Lunar descent/ascent	1.63	[1]
Trans-Earth Injection (TEI)	0.90	[2], assumes use of aerobraking

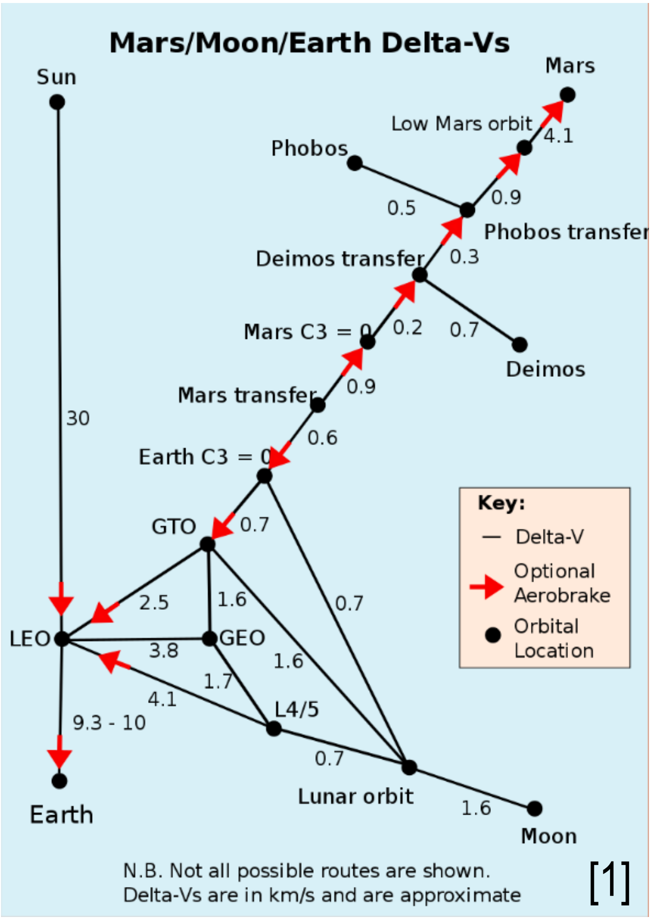


[1]

[1]: https://en.wikipedia.org/wiki/Delta-v#cite_note-marsdeltavs-5
[2]: https://web.archive.org/web/20070701211813/http://www.pma.caltech.edu/~chirata/deltav.html

Δv Budget - Design

Mission Maneuver	Δv Required (km/s)	Notes/Source
SpaceBus Earth-Moon Round Trip	10.52	**Used to size SpaceBus propellant tankage** TLI: Δv = 4.04 km/s [2] LOI (plane change only): Δv = 2.31 km/s LOI (reverse plane change): Δv = 2.31 km/s TEI: Δv = 0.90 km/s [2] +10% factor of safety
Trans-Lunar Injection (TLI)	6.985	**Used to quantify one-way propellant loading for LEO – LLO trip (SpaceBus and LLV)** Equatorial TLI: Δv = 4.04 km/s Plane change: Δv = 2.31 km/s +10% factor of safety
Lunar Descent/Ascent	1.797	**Used to size LLV propellant tankage** Descent/ascent from/to LLO: Δv = 1.63 km/s +10% factor of safety



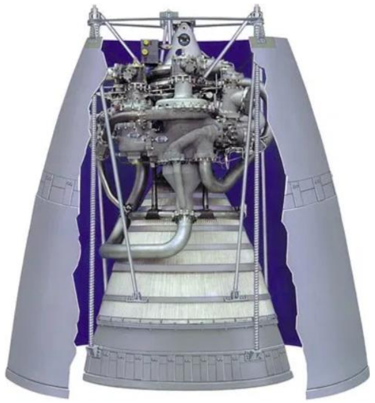
[1]: https://en.wikipedia.org/wiki/Delta-v#cite_note-marsdeltavs-5
[2]: https://web.archive.org/web/20070701211813/http://www.pma.caltech.edu/~chirata/deltav.html

SpaceBus Overview

Crew Transport
- Crew Module
  - Initial concept: ISS Destiny module
    - 14.5 MT in total [1]
    - SpaceBus required dry mass (first iteration): 19.9 MT
  - Revised concept: NASA JSC-26098 guidelines
    - Crew size: 4
    - 7 days of life support
      - Enough for round-trip from Earth to Moon and back in case of abort mode that prevents lunar landing
    - SpaceBus dry mass (final iteration): 13.5 MT
- Propulsion Module
  - 1x RL-10B-2 engine + plumbing
    - Propellants: Liquid hydrogen and liquid oxygen
  - Oxygen tank pressurization system
    - 4x He COPV (26” diameter) @ 4000 psia
    - Based on Centaur pressurization system [2]
  - Structural elements
    - Propellant tanks + insulation
    - Thrust structure
    - Fairings
  - Electrical elements
    - Avionics
    - Wiring

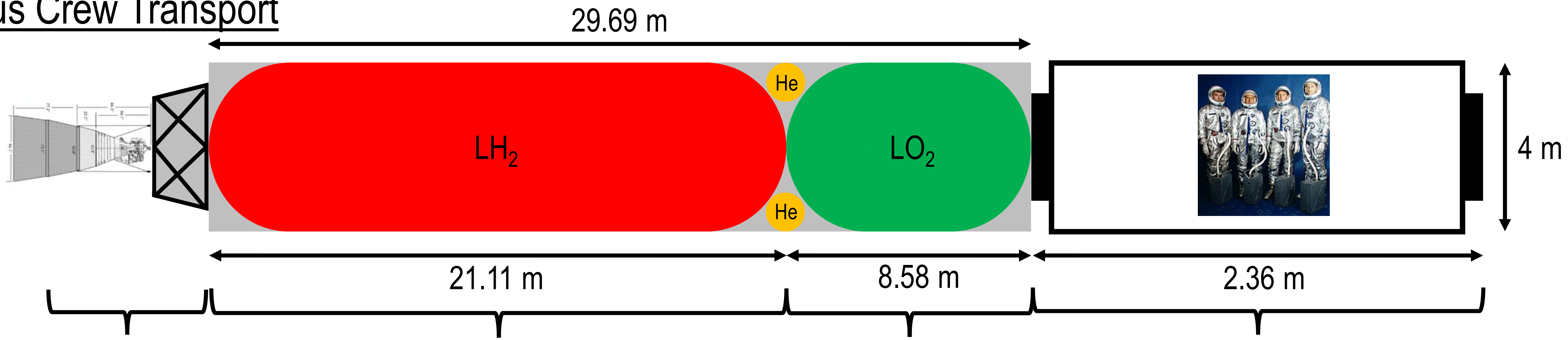
Tanker
- Same as Crew Transport configuration except:
  - No Crew Module
  - No rocket engine or associated hardware
- Propellant tanks and supporting structure, systems only

RL-10B-2 [3]
- Most efficient production rocket engine in use
- Thrust: 110100 N
- Dry mass: 301.2 kg
- Specific impulse: 465.5 s
- Exit velocity: 4.565 km/s
- Mixture ratio: 5.88



[1]: https://en.wikipedia.org/wiki/Destiny_(ISS_module)
[2]: https://www.ulalaunch.com/docs/default-source/upper-stages/the-centaur-upper-stage-vehicle.pdf
[3]: https://en.wikipedia.org/wiki/RL10

SpaceBus Crew Transport



1x RL-10B-2
Engine Mass = 301.2 kg
Plumbing Mass = 150.6 kg

Fuel
Mass = 17649 kg
Volume = 248.6 m^3
Tank Mass = 2259.6 kg

Oxidizer
Mass = 103780 kg
Volume = 91.0 m^3
Tank Mass = 1106.9 kg

Crew Module
Mass = 6043 kg
Volume = 29.63 m^3

Miscellaneous Mass
Fairings = 993.7 kg
Avionics = 711.1 kg
Wiring = 907.1 kg
Thrust structure = 28.1 kg
Helium COPV = 101.5 kg

Propulsion Module
Dry Mass = 7445 kg
Propellant Mass = 121429 kg

Overall
Dry Mass = 13488 kg
Wet Mass = 134910 kg
Launch Mass = 62265 kg

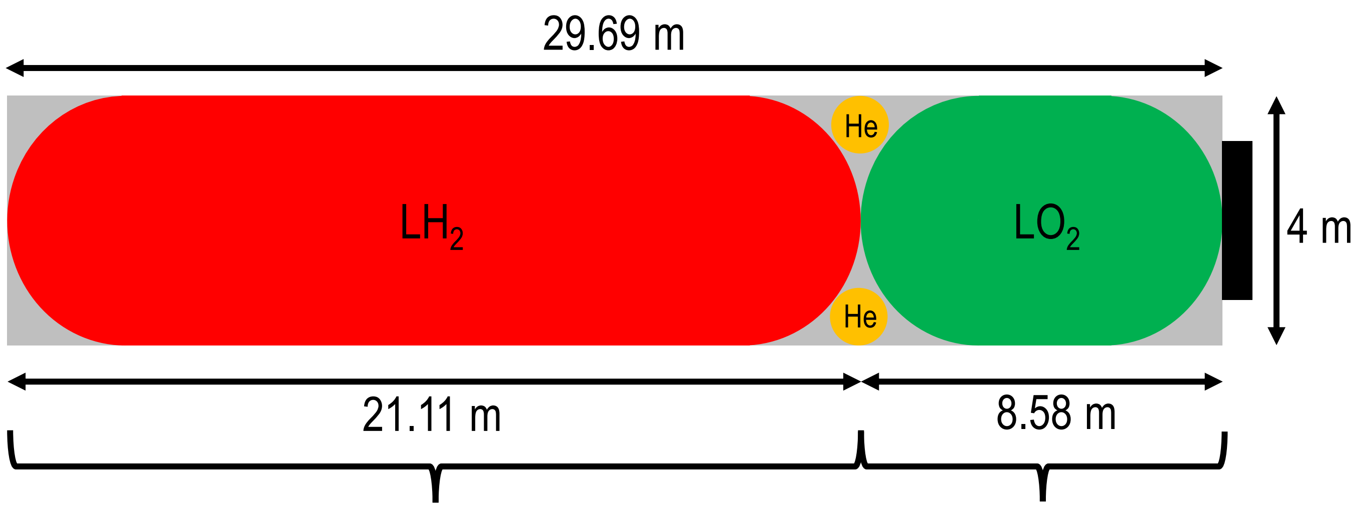
Note: figures not to scale

SpaceBus Sizing

	SpaceBus diameter (m)	4	5	6
Fuel: LH_2	Mass (kg)	17649	18593	20080
	Volume (m^3)	248.6	261.9	282.8
	Tank mass* (kg)	2259.6	2380.4	2570.8
	Tank length (m)	21.11	15.00	12.00
Oxidizer: LO_2	Mass (kg)	103780	109330	118070
	Volume (m^3)	91.0	95.9	103.6
	Tank mass* (kg)	1106.9	1166.2	1259.4
	Tank length (m)	8.58	6.55	5.66
Misc.	Fairing mass (kg)	993.7	1660.1	2525.0
	Avionics mass (kg)	711.1	724.6	745.0
	Wiring mass (kg)	907.1	859.4	849.8
Overall	Dry mass (kg)	13488	14209	15346
	Wet mass (kg)	134910	142130	153500
	Length (m)	32.05	23.06	18.71

*does not include tank insulation

SpaceBus Tanker



Fuel
Mass = 1894.6 kg
Volume = 248.6 m^3
Tank Mass = 2259.6 kg

Oxidizer
Mass = 11140 kg
Volume = 91.0 m^3
Tank Mass = 1106.9 kg

Miscellaneous Mass
Fairings = 993.7 kg
Avionics = 711.1 kg
Wiring = 907.1 kg
Helium COPV = 101.5 kg

Overall
Dry Mass = 6965.2 kg
Propellant Mass = 13034.8 kg
Wet Mass = 20000 kg

Note: figures not to scale

SpaceBus Propellant Transfer in LEO

- Due to the Earth launch vehicle (ELV) being optimally sized for the crew launch and entry vehicle (CLEV), the SpaceBus crew transport must be launched nearly empty of propellants.
  - ELV payload to LEO: 20000 kg
  - SpaceBus crew transport dry mass: 13488 kg
  - Residual propellant mass: 6512 kg
- Expendable SpaceBus tanker modules will be launched to fuel the SpaceBus crew transport vehicle in LEO.

Round-trip

- Total Δv required: 10.516 km/s
- Total propellant required: 121430 kg
- Net propellant required: 114918 kg
- Tanker flights required to fuel SpaceBus crew transport: 9

One-way

- Total Δv required: 6.985 km/s
- Total propellant required: 48777 kg
- Net propellant required: 42265 kg
- Tanker flights required to fuel SpaceBus crew transport: 4

Lunar Landing Vehicle Overview

Crew Transport

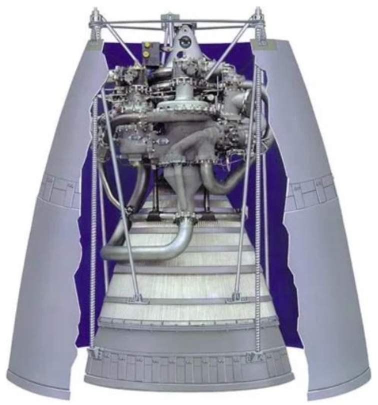
- Crew Module
    - Based on NASA JSC-26098 guidelines
    - Crew size: 4
    - 14 days of life support
        - Enough for 2-week stay on lunar surface
- Propulsion Module
    - 4x RL-10B-2 engines + plumbing
        - Propellants: Liquid hydrogen and liquid oxygen
    - Oxygen tank pressurization system
        - 4x He COPV (26” diameter) @ 4000 psia
        - Based on Centaur pressurization system [1]
    - Structural elements
        - Propellant tanks + insulation to store:
            - Ascent propellant
            - Descent propellant
            - Transfer propellant
        - Thrust structure
        - Fairings
        - Landing legs
    - Electrical elements
        - Avionics
        - Wiring

Lunar Liftoff Analysis

- LLV wet mass: 229 MT
- Lunar g = 1.6 m/s^2
- LLV weight on moon: 372 kN
- Number of engines required for liftoff: 4

RL-10B-2 [2]

- Most efficient production rocket engine in use
- Thrust: 110100 N
- Dry mass: 301.2 kg
- Specific impulse: 465.5 s
- Exit velocity: 4.565 km/s
- Mixture ratio: 5.88



[1]: https://www.ulalaunch.com/docs/default-source/upper-stages/the-centaur-upper-stage-vehicle.pdf
[2]: https://en.wikipedia.org/wiki/RL10

Lunar Landing Vehicle

Overall

Dry Mass = 22348 kg
Propellant Mass = 206716 kg
Wet Mass = 229064 kg

Crew Module

Mass = 8944.5 kg
Volume = 49.63 m^3

Miscellaneous Mass

Fairings = 993.7 kg
Avionics = 860.9 kg
Wiring = 1337.5 kg
Thrust structure = 112.3 kg
Helium COPV = 101.5 kg
Landing legs = 1000 kg

Propulsion Module

Dry Mass = 7445 kg
Propellant Mass = 121429 kg

Oxidizer

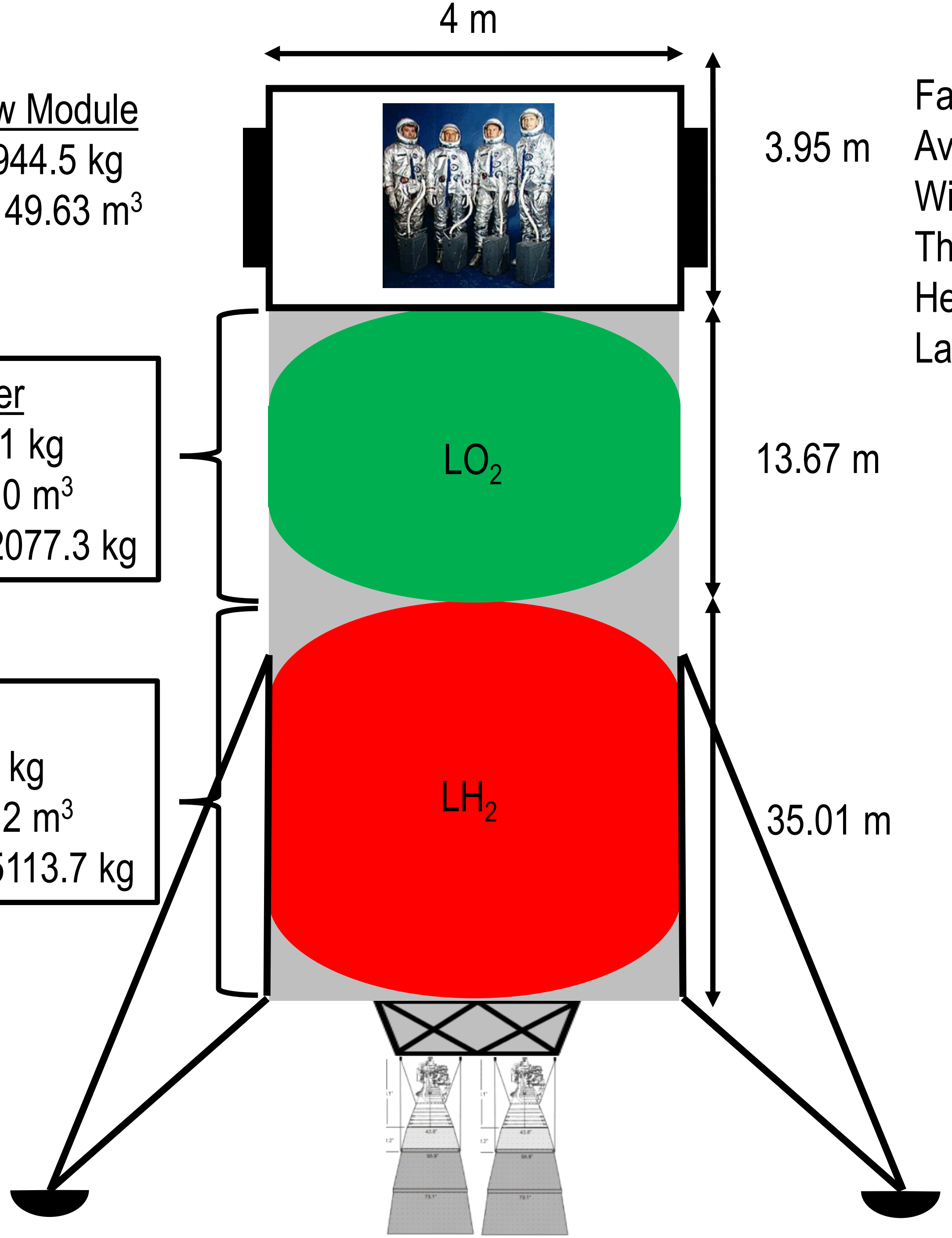
Mass = 176671 kg
Volume = 155.0 m^3
Tank Mass = 2077.3 kg

Fuel

Mass = 30045 kg
Volume = 423.2 m^3
Tank Mass = 5113.7 kg

4x RL-10B-2

Engine Mass = 1204.8 kg
Plumbing Mass = 602.4 kg



Note: figures not to scale

LLV Sizing

	LLV diameter (m)	4	5	6
Fuel: LH_2	Mass (kg)	30045	30100.2	30217.3
	Volume (m^3)	423.2	423.9	425.6
	Tank mass* (kg)	5113.7	4905.9	4794.4
	Tank length (m)	35.01	23.26	17.05
Oxidizer: LO_2	Mass (kg)	176671	176994	177681
	Volume (m^3)	155.0	155.3	155.9
	Tank mass* (kg)	2077.3	2056.8	2054.2
	Tank length (m)	13.67	9.57	7.51
Misc.	Fairing mass (kg)	993.7	1660.1	2525.0
	Avionics mass (kg)	860.9	861.8	863.8
	Wiring mass (kg)	1337.5	1213.9	1132.6
Overall	Dry mass (kg)	22348	22664	23336
	Wet mass (kg)	229064	229750	231230
	Length (m)	52.63	35.35	26.32

*does not include tank insulation

LLV Propellant Transfer in LEO

- Due to the Earth launch vehicle being optimally sized for the crew launch and entry vehicle (CLEV), the lunar landing vehicle must be launched empty of propellants.
  - Launch vehicle payload to LEO: 20000 kg
  - LLV dry mass: 22348 kg
- Expendable SpaceBus tanker modules will be launched to fuel the LLV in LEO.

Round-trip

- Total Δv required: 10.516 km/s
- Total propellant required: 206716 kg
- Tanker flights required to fuel SpaceBus crew transport: 16

One-way

- Total Δv required: 6.985 km/s
- Total propellant required: 136331 kg
- Tanker flights required to fuel SpaceBus crew transport: 11

Earth Launch Vehicle

- ‘Big Dumb Booster’ concept

- Broad Design Goals:
  - Use high flight and production rates to lower marginal flight cost
  - Take advantage of semi-modular design to increase flight and production rates
  - Use single-use SSTO to lower marginal flight cost

Earth Launch Vehicle: MER

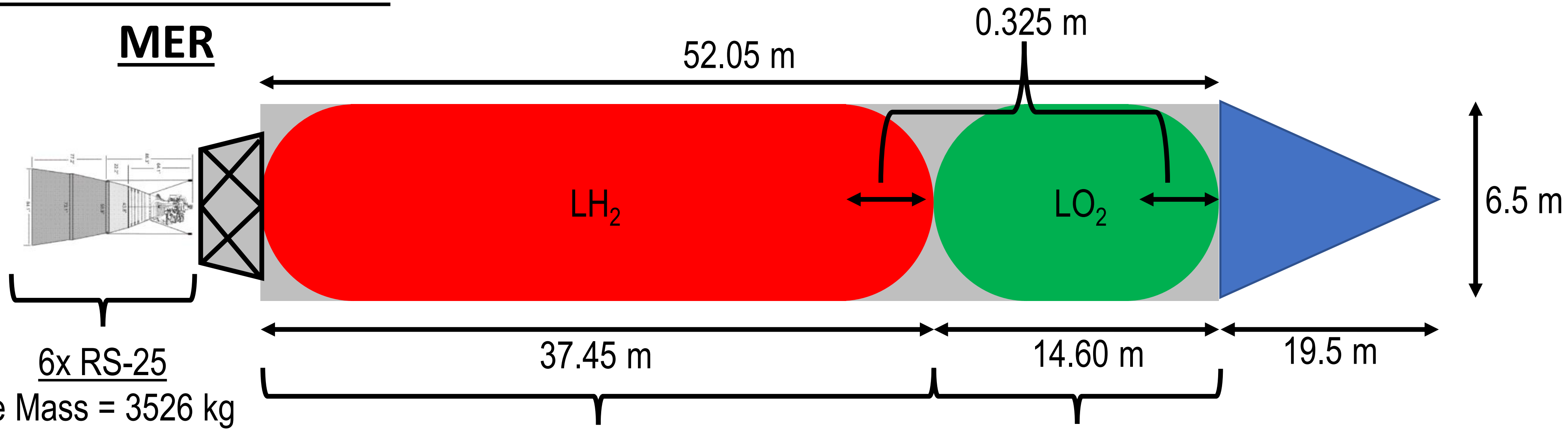
- MER optimized to minimize tank and insulation mass as a function of vehicle diameter
  - L/D ratio of approximately 9
- Tank shape was modified to reduce required insulation
  - Cylindrical tanks with flat ends allow for less insulation, but are structurally less stable
  - Cylindrical tanks with semi-spherical ends are structurally sound, but require more insulation
  - Cylindrical tanks with rounded ends ("spherical cap" [1]) were chosen to allow for reduced insulation, and tank structural integrity
- Stage uses 6 RS-25 engines

[1]: https://mathworld.wolfram.com/SphericalCap.html

ELV SSTO MER (6.5 m diameter)

	Fuel Tank Shape	Flat Tank Edges	Spherical Edges	Rounded Edges
Fuel: LH_2	Mass (kg)	85790.09	87727.67	85936.88
	Volume (m^3)	1208.31	1235.60	1210.38
	Tank mass (kg)	10983.55	11231.61	11002.34
	Tank insulation mass	2332.63	3209.25	3209.25
	Tank length (m)	35.41	48.07	37.45
Oxidizer: LO_2	Mass (kg)	514640.56	526366.00	515621.26
	Volume (m^3)	451.53	461.72	452.30
	Tank mass (kg)	5490.57	5614.57	5500.00
	Tank insulation mass	386.57	716.58	410.18
	Tank length (m)	13.607	24.75	14.60
Misc.	Fairing mass (kg)	3966.80	3966.79	3966.80
	Avionics mass (kg)	1272.99	1283.29	1273.77
	Wiring mass (kg)	2386.74	2626.91	2409.99
Overall	Initial Dry Mass (kg)	60,887.53	60.89	60887.53
	Dry mass (kg)	50,821.64 (+16.5%)	52,650.80 (+13.5%)	60,960.32 (+16.3%)
	Wet mass (kg)	651,352.29	653,181.45	662,518.46
	Length (m) (w/o engine, payload fairing)	50.02	72.82	52.05

Earth Launch Vehicle: MER



6x RS-25
Engine Mass = 3526 kg [1]

Fuel
Mass = 85,936.9 kg
Volume = 1210.4 m^3
Tank Mass = 11002.3 kg

Oxidizer
Mass = 515,621.3 kg
Volume = 452.3 m^3
Tank Mass = 5500.0 kg

Miscellaneous Mass
Fairings = 3966.8 kg
Avionics = 1273.8 kg
Wiring = 2410.0 kg

Overall
Dry Mass = 50,960 kg
Propellant Mass = 601,558 kg
Wet Mass = 652,518 kg

[1]: https://en.wikipedia.org/wiki/RS-25

Note: figures not to scale

Earth Launch Vehicle

- Three launch configurations were included in the final analysis:
  1. SSTO
     - Carries 25 tonne payload to ~9200 m/s

  2. SSTO with two additional boosters
     - Parallel staging, boosters identical to core
     - Chi value of 0 (three cores thrust simultaneously)
     - Carries 73.7 tonne payload to ~9200 m/s

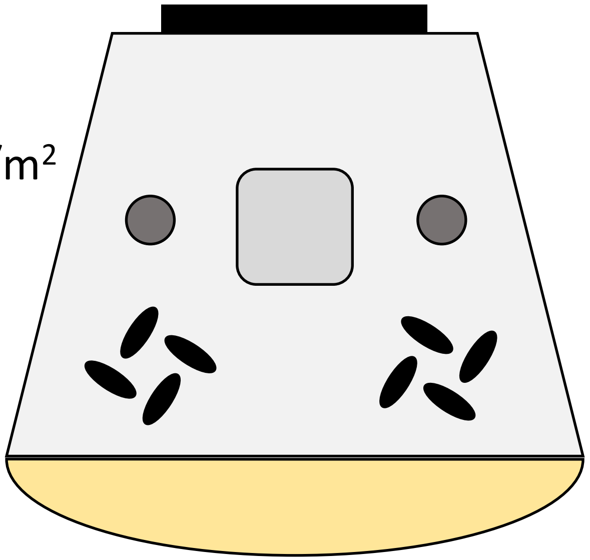
  3. Two identical serial stages
     - Carries 66.7 tonne payload to ~9200 m/s

Crew Launch and Entry Vehicle

The Crew Launch and Entry Vehicle (CLEV) is used to ferry the crew from Earth to LEO and back and is not intended for travel beyond. It provides life support functions for the crew during launch and entry, and remains in LEO in a low power mode while the crew is beyond LEO.

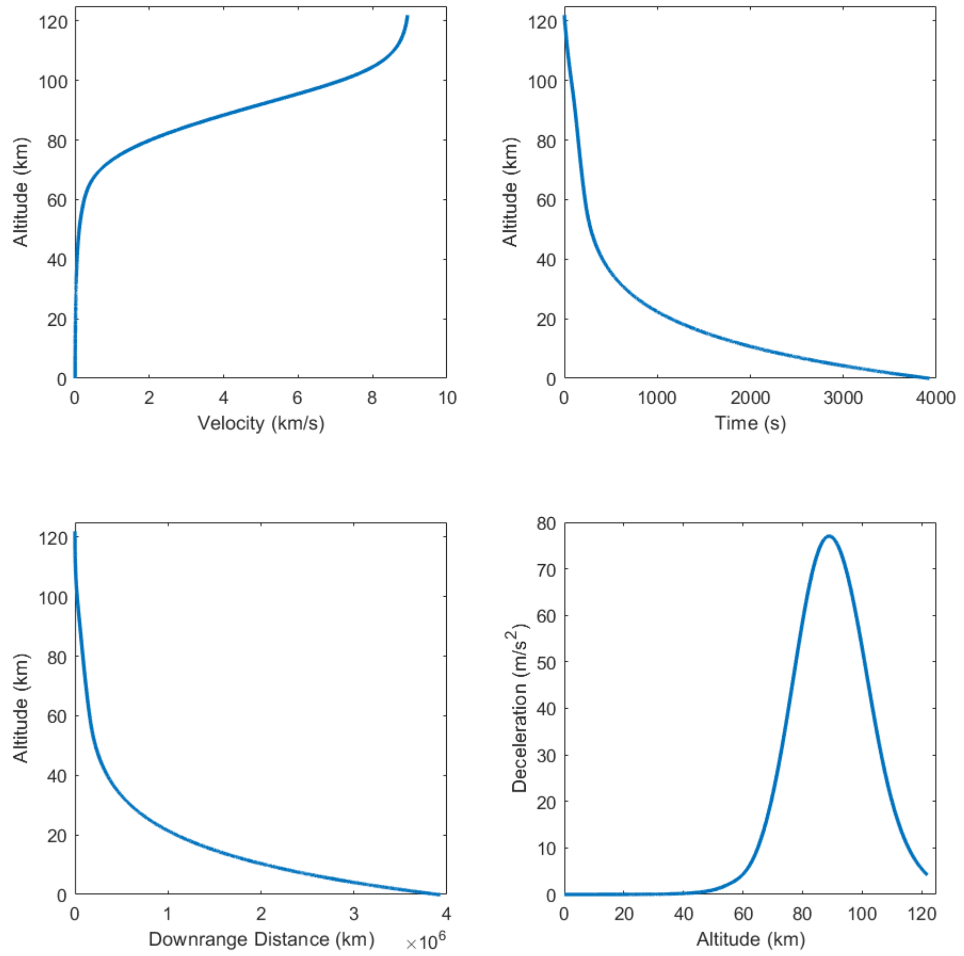
Attributes

- Mass = 15000 kg
- Heat shield diameter = 4 m
- Ballistic coefficient = 994.7 kg/m^2
- L/D ratio = 0.25
- C_D = 1.2
- Peak deceleration = 7 g's
- Terminal velocity = 3.99 m/s



CLEV depiction

CLEV Ballistic Entry



Program Outline: One-way

Launch #	Mission Profile	Notes
1 – 2	Scout Rover	• Notionally similar to NASA VIPER mission concept or CNSA Chang'e 4 mission
3 – 5	ISRU equipment staging	
6	Lunar Landing Vehicle	• LLV must safely reach LLO before first crew will depart LEO in SpaceBus
7 – 17	SpaceBus Tanker	• 11 tanker loads of propellant needed for round-trip LLV trip to LLO
18	SpaceBus Crew Transport	• Enough propellant loaded for round-trip to Moon
19 – 22	SpaceBus Tanker	• 4 tanker loads of propellant needed for round-trip SpaceBus trip to LLO
23 – 27	Crew Launch/Return	• CLEV transportation to LEO and back

<u>Staging Crew Vehicles in LLO</u>

- One-way trip provided via partial propellant load
- Abort modes possible only at selected points along the TLI, LOI, lunar descent/ascent, TEI trajectory sequence
- 27 total launches planned
- 30 launch vehicles planned for fabrication to provide development and test units
    - Marginal cost: $85M
- 15 total SpaceBus tanker modules required
    - Marginal cost: $29M

Program Outline: Round-trip

Launch #	Mission Profile	Notes
1 – 2	Scout Rover	• Notionally similar to NASA VIPER mission concept or CNSA Chang'e 4 mission
3 – 5	ISRU equipment staging	
6	Lunar Landing Vehicle	• LLV must safely reach LLO before first crew will depart LEO in SpaceBus
7 – 22	SpaceBus Tanker	• 16 tanker loads of propellant needed for round-trip LLV trip to LLO
23	SpaceBus Crew Transport	• Enough propellant loaded for round-trip to Moon
24 – 32	SpaceBus Tanker	• 9 tanker loads of propellant needed for round-trip SpaceBus trip to LLO
33 – 37	Crew Launch/Return	• CLEV transportation to LEO and back

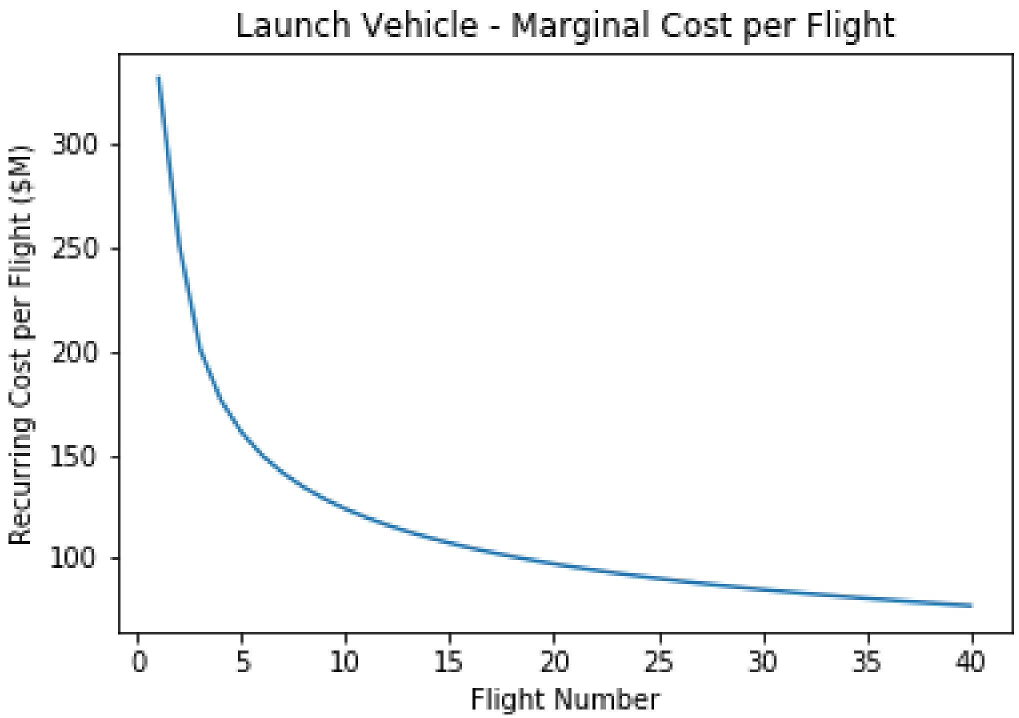
<u>Staging Crew Vehicles in LLO</u>

- Round-trip provided via full propellant load
- Abort modes possible at any point along the TLI, LOI, lunar descent/ascent, TEI trajectory sequence
- 37 total launches planned
- 40 launch vehicles planned for fabrication to provide development and test units
  - Marginal cost: $77M
- 25 total SpaceBus tanker modules required
  - Marginal cost: $24M

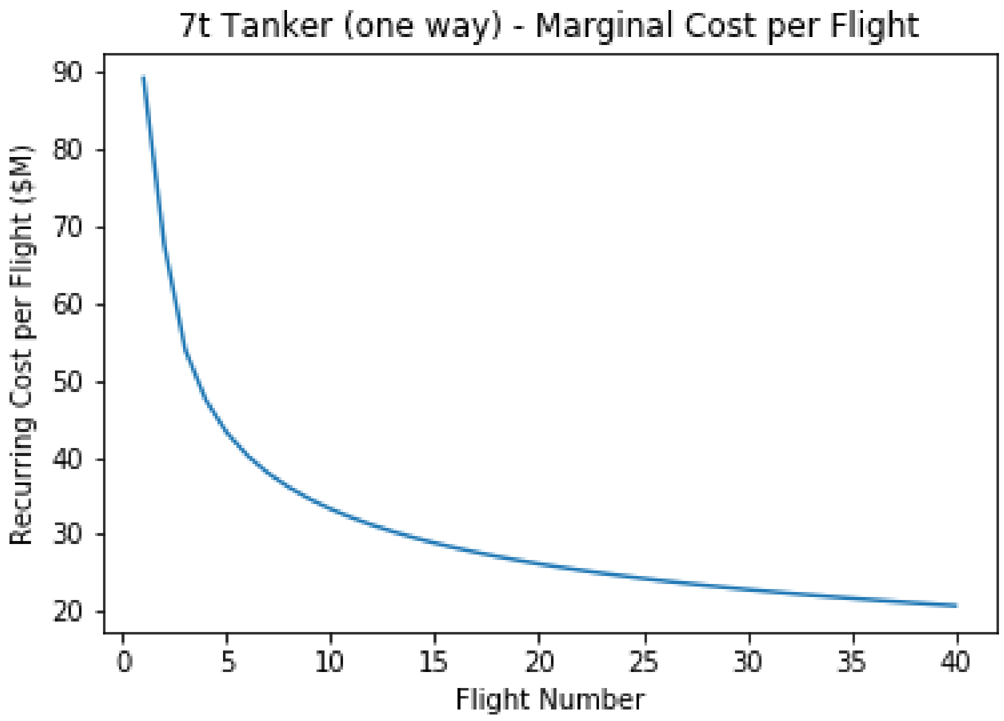
Program Cost Estimate

- Non-recurring costs:
  - SSTO ELV: $4.153 Billion
  - Tanker for one-way TLI: $1.394 Billion
  - Tanker for TLI and return: 2.120 Billion
  - 20t CLEV: $2.483 Billion

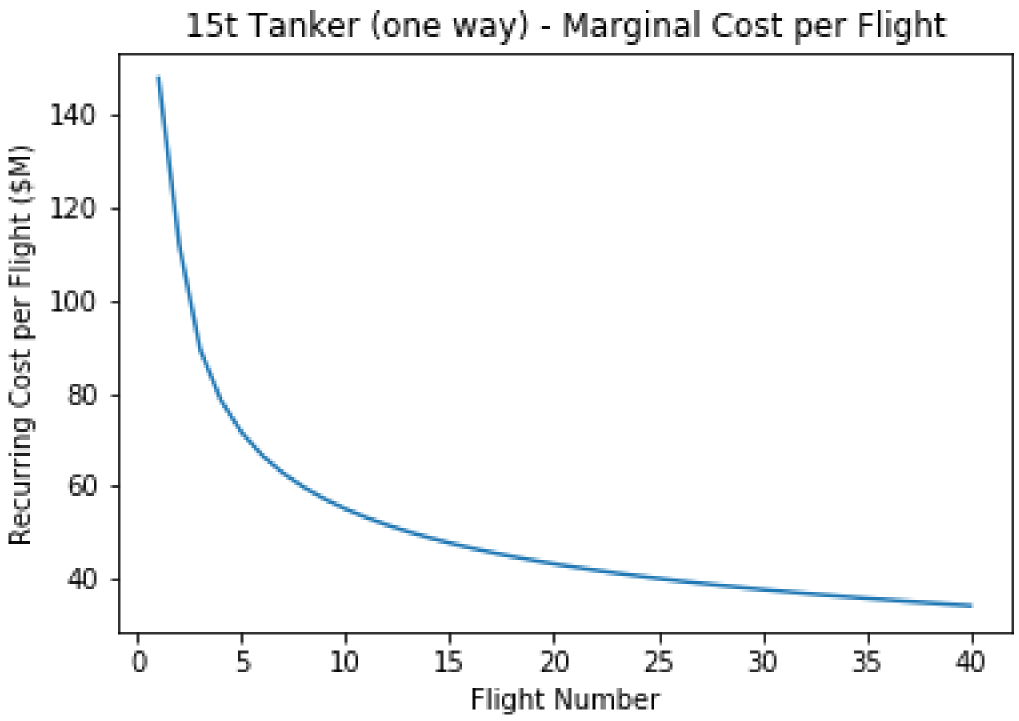
Average Marginal Cost per Flight: SSTO ELV



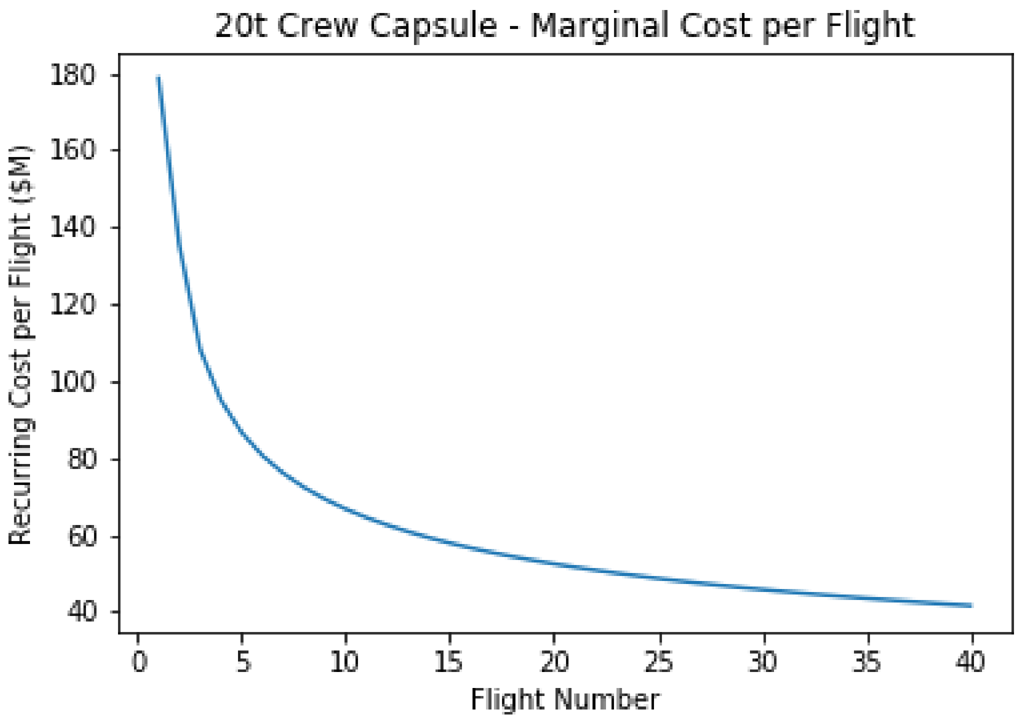
Average Marginal Cost per Flight: 7t Tanker



Average Marginal Cost per Flight: 15t Tanker



Average Marginal Cost per Flight: 20t Crew Vehicle



Conclusions

- Single-stage to anywhere architecture is a good analytical starting point but quickly proves its limitations.
- Lower marginal cost for SSTO offset by high non-recurring cost (due to high inert mass)
- Round-trip mission architecture for lunar vehicle initial staging has lower marginal cost but higher total cost, including higher NRE costs, but the additional crew abort modes provided justify the higher cost.

Future Studies

- Design Mini-SpaceBus to transport smaller payloads to lunar surface for Phase I uncrewed missions
- Optimize Earth-Moon trajectory to minimize Δv, propellant mass requirements
- Explore multi-stage LLV concept for optimization of propellant mass requirements
- Add additional redundancies and abort modes into mission architecture to reduce risk of loss of mission and/or loss of crew

Back-up

For reference only

Mission Architecture (One-way)

Launch #	Mission Profile	Launch #	Mission Profile
1	Scout Rover	15	SpaceBus Tanker
2	Scout Rover	16	SpaceBus Tanker
3	ISRU Plant Supplies	17	SpaceBus Tanker
4	ISRU Plant Supplies	18	SpaceBus Tanker
5	ISRU Plant Supplies	19	SpaceBus Tanker
6	Lunar Landing Vehicle	20	SpaceBus Tanker
7	SpaceBus Tanker	21	SpaceBus Tanker
8	SpaceBus Tanker	22	SpaceBus Tanker
9	SpaceBus Tanker	23	Crew Launch/Entry
10	SpaceBus Tanker	24	Crew Launch/Entry
11	SpaceBus Crew Transport	25	Crew Launch/Entry
12	SpaceBus Tanker	26	Crew Launch/Entry
13	SpaceBus Tanker	27	Crew Launch/Entry
14	SpaceBus Tanker		

Mission Architecture (Round-trip)

Launch #	Mission Profile	Launch #	Mission Profile	Launch #	Mission Profile
1	Scout Rover	15	SpaceBus Tanker	29	SpaceBus Tanker
2	Scout Rover	16	SpaceBus Tanker	30	SpaceBus Tanker
3	ISRU Plant Supplies	17	SpaceBus Tanker	31	SpaceBus Tanker
4	ISRU Plant Supplies	18	SpaceBus Tanker	32	SpaceBus Tanker
5	ISRU Plant Supplies	19	SpaceBus Tanker	33	Crew Launch/Entry
6	Lunar Landing Vehicle	20	SpaceBus Tanker	34	Crew Launch/Entry
7	SpaceBus Tanker	21	SpaceBus Tanker	35	Crew Launch/Entry
8	SpaceBus Tanker	22	SpaceBus Tanker	36	Crew Launch/Entry
9	SpaceBus Tanker	23	SpaceBus Crew Transport	37	Crew Launch/Entry
10	SpaceBus Tanker	24	SpaceBus Tanker		
11	SpaceBus Tanker	25	SpaceBus Tanker		
12	SpaceBus Tanker	26	SpaceBus Tanker		
13	SpaceBus Tanker	27	SpaceBus Tanker		
14	SpaceBus Tanker	28	SpaceBus Tanker		

Lunar Landing Vehicle

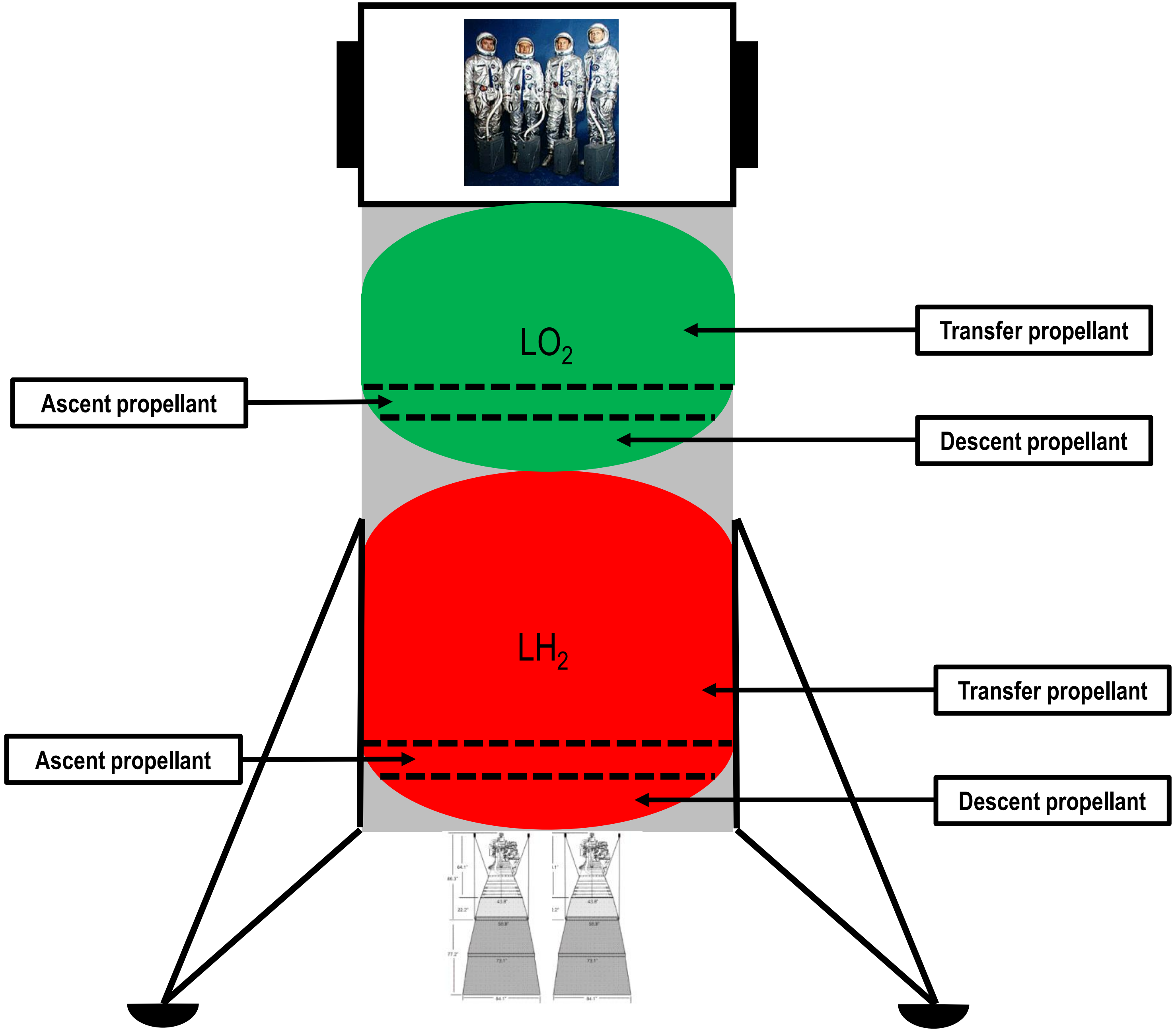
Ascent

Liftoff Mass

- Crew module
- 2x Engine+plumbing
- Landing legs
- Tank volume
    - Descent propellant
    - Ascent propellant
    - Transfer propellant
- Tank insulation
- Tank pressurization system
- Avionics
- Wiring
- **Ascent propellant**
- **Transfer propellant**
- **Descent propellant**

Final Mass

- Crew module
- 2x Engine+plumbing
- Landing legs
- Tank volume
    - Descent propellant
    - Ascent propellant
    - Transfer propellant
- Tank insulation
- Tank pressurization system
- Avionics
- Wiring
- **Transfer propellant**
- **Descent propellant**



Descent

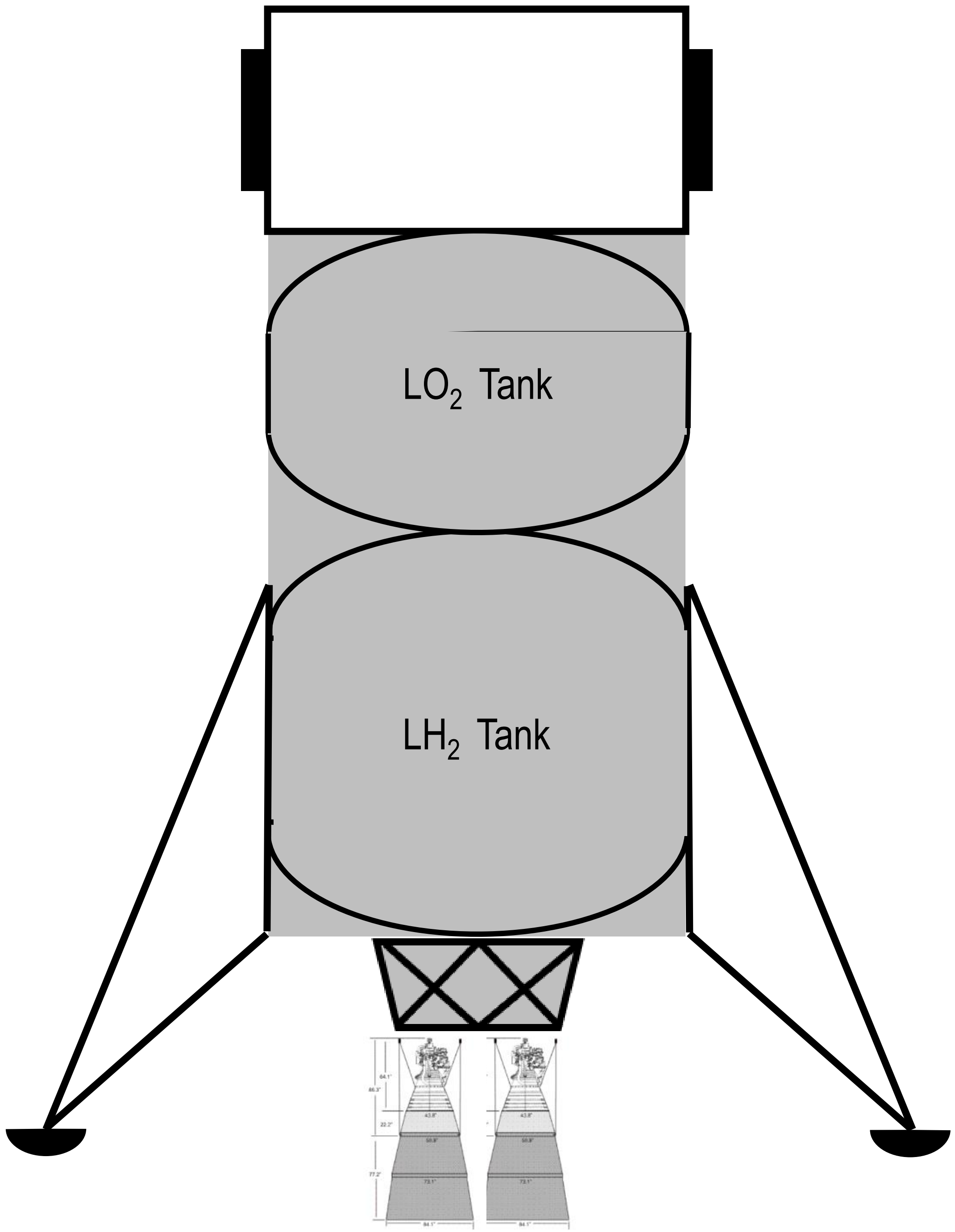
Initial Mass

- Crew module
- 2x Engine+plumbing
- Landing legs
- Tank volume
    - Descent propellant
    - Ascent propellant
    - Transfer propellant
- Tank insulation
- Tank pressurization system
- Avionics
- Wiring
- **Descent propellant**

Landing Mass

- Crew module
- 2x Engine+plumbing
- Landing legs
- Tank volume
    - Descent propellant
    - Ascent propellant
    - Transfer propellant
- Tank insulation
- Tank pressurization system
- Avionics
- Wiring

Note: figures not to scale



LO_2 Tank
LH_2 Tank

Delta-v Budget		
Mission Segment	Delta-v (km/s)	Notes
Launch	5.9059	Crude method #1 - Velocity difference • Launch site: CCAFS, Florida ○ v = 0.4076 km/s • Parking orbit: 10000 km, circular, 28.5 deg inclination ○ v = 6.3135 km/s
	9.0138	Crude method #2 - Hohmann Transfer
	9.2 - 9.5	• Rule of thumb, per Dr. Akin
TLI		
Separate maneuvers	5.0243	• Plane change from 28.5 deg inclination to 5.145 deg ○ dv = 2.5557 km/s • Apogee raise from parking orbit to lunar sphere of influence ○ dv = 2.4686 km/s
Combined maneuver	3.8961	
Literature values	4.04	• Apollo-like TLI maneuver ○ https://en.wikipedia.org/wiki/Delta-v_budget#Earth%E2%80%93Moon_space%E2%80%94high_thrust
LOI		
Separate maneuvers	3.1642	• Breaking maneuver to lower altitude from 66183 km to 100 km ○ dv = 0.85412 • Plane change from 0 deg inclination to 90 deg polar orbit ○ dv = 2.3101 km/s
Combined maneuver	1.66	
Lunar descent	1.6335	• Staging orbit: 100 km, circular, 90 deg inclination ○ v = 1.6335 km/s • Landing site: Lunar south pole ○ v = 0 km/s
Lunar ascent	1.6335	• Launch site: Lunar south pole ○ v = 0 km/s • Parking orbit: 100 km, circular, 90 deg inclination ○ v = 1.6335 km/s
TEI		
Literature values	0.90	• Apollo-like TEI maneuver ○ https://en.wikipedia.org/wiki/Delta-v_budget#Earth%E2%80%93Moon_space%E2%80%94high_thrust
Total		
Literature values (total dv to be supplied by Space Bus)	9.5602	• TLI ○ dv = 4.04 km/s • LLO plane change ○ dv = 2.3101 km/s • LLO plane change ○ dv = 2.3101 km/s • TEI ○ dv = 0.90 km/s