"Key Technologies, Systems, and Infrastructure Enabling Routine Travel from the Earth to the Moon – A Look Ahead"

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Introduction and Presentation Overview

- Over 52 years have passed since the movie *2001: A Space Odyssey* debuted in April, 1968. In the film, Dr. Heywood Floyd flies to a large artificial gravity space station orbiting Earth on a commercial space plane. He then embarks on a commuter flight to the Moon arriving there ~25 hours later.

- Are the images portrayed in *2001* merely science fiction fantasy or are they attainable possibilities, and if so, what will be required to make the vision portrayed in the film a reality?

- This presentation, and those of the subject matter experts that follow, will look at the key technologies, systems, and supporting infrastructure

- Lunar-derived propellants – using polar icy regolith and volcanic glass as feedstock;
- Fission power systems – to supply abundant "24/7" power on the lunar surface and in orbit;
- Advanced chemical propulsion systems – utilizing Earth- and lunar-supplied LO_2/LH_2 propellant;
- Space transportation nodes – providing convenient staging locations in LEO, LPO, and LLO; and
- Synergy between lunar-derived oxygen (LUNOX) production and future Helium-3 mining

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that could be developed by NASA and the private sector over the next three decades that could allow the operational capabilities presented in *2001* to be achieved, albeit on a more "spartan" scale.

Where are We Now and Where are We Headed?

- On May 30, 2020, a SpaceX Falcon 9 rocket carrying the company's Crew Dragon spacecraft launched NASA astronauts Doug Hurley and Bob Behnken to the ISS beginning a new era in human spaceflight.

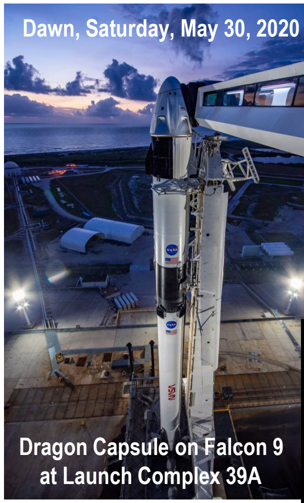
- On January 27, 2020, NASA selected Houston-based Axiom Space to develop a commercial module for installation on ISS in the second half of 2024. Additional modules for research, habitation and other activities would follow according to Axiom's development plans.

- In February 2020, Space Adventures, Inc. entered into an agreement with SpaceX to fly 4 private citizens on the first Crew Dragon free-flyer space tourism mission that will orbit Earth at ~2-3x the altitude of ISS.

- In March 2020, Axiom Space signed a deal with SpaceX to fly 3 space tourists on a 10-day mission to the ISS scheduled to launch in second half of 2021. The estimated cost per person is ~$55 million. Will need a 3 to 4 order of magnitude reduction in cost to make space tourism available to the broader public.

- Bigelow Aerospace, which has had a prototype inflatable habitat called BEAM (Bigelow Expandable Activity Module) flying on ISS since 2016, had plans to develop orbital space facilities in both LEO in 2021 and in LLO shortly thereafter using its BA-330 inflatable modules.

- SpaceX also plans on flying Japanese billionaire, Yusaku Maezawa, around the Moon in 2023 and later landing on the lunar surface using its Starship spacecraft and reusable Super Heavy booster.

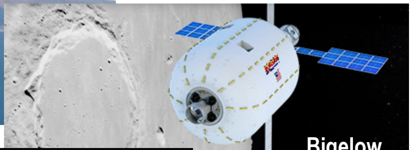

Dawn, Saturday, May 30, 2020

Dragon Capsule on Falcon 9 at Launch Complex 39A


NASA astronauts Hurley & Behnken wearing Space*X* spacesuits


Axiom Space commercial modules on ISS


BA-330 Modules in LEO


Bigelow BA-330 in LLO


Starship and its reusable Super Heavy booster

Image Credits: SpaceX, Bigelow Aerospace and Axiom Space

Extracting Water Ice from Permanently Shadowed Craters in the Moon's Polar Regions will be Extremely Challenging

- LPI deposits are important because they could supply both oxygen and hydrogen provided they can be economically accessed, mined, processed and stored for their desired use.

- Higher ΔVs are required to access LPO sites and the candidate craters are deep, extremely cold, and exist in a state of perpetual darkness posing major challenges for the mining and processing of this cold, ice-cemented regolith material.

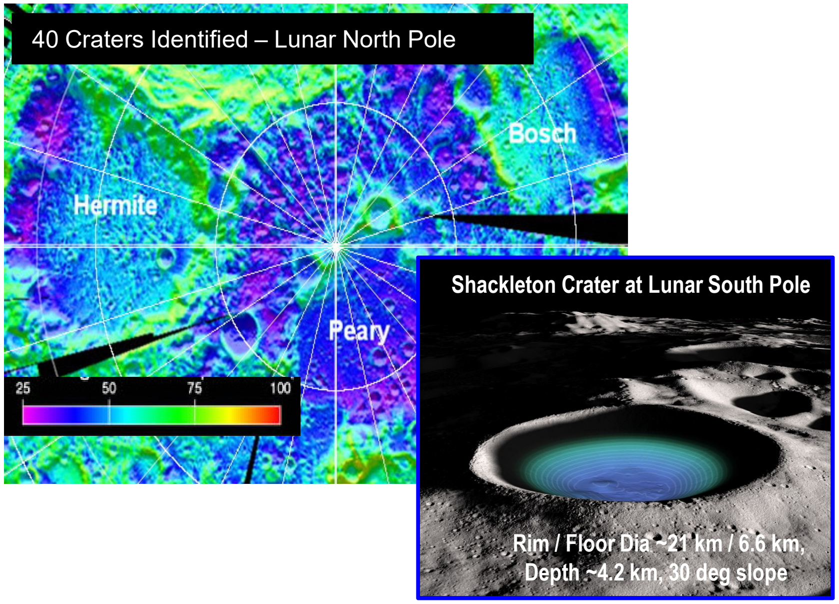
- The world's 10 coldest mines are located in Russia's extreme northeastern territory. At the coldest of these mines, Sarylakh, the temperatures can drop to nearly -50 C (~223 K).

- By contrast, the temperatures inside the polar craters, where the LPI is thought to exist, are ~30 – 50 K – significantly colder than the coldest mines on Earth! At these temperatures, metals can become brittle.

- Conventional mining requires break up, excavation and transport of the ice-bearing regolith to the water extraction plant. It must also operate in a hard vacuum and be able to tolerate the abrasive nature of the lunar dust.

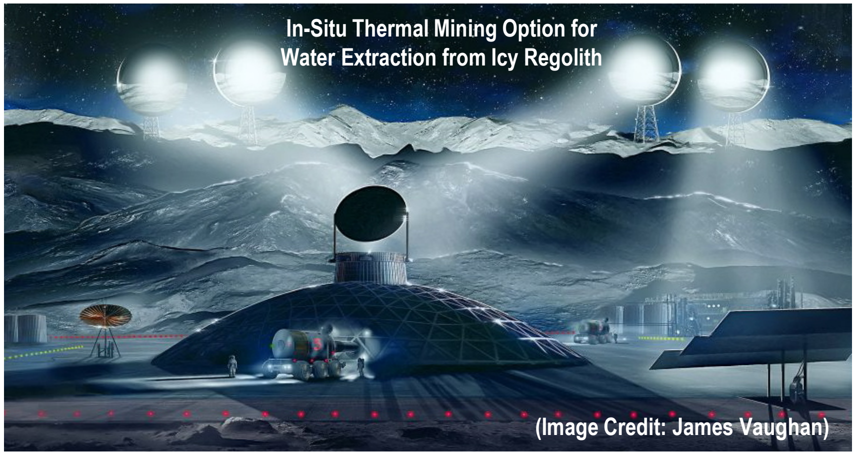
- With in-situ thermal mining*, directed sunlight from the crater rim is used to heat the surface of the icy regolith, producing sublimated water vapor within a tent enclosure. The vapor is then vented into "cold trap" ice haulers for transport to a central processing plant.

- The water is then purified and electrolyzed for propellants used by LLVs, or shipped to an orbiting propellant depot for electrolysis there.


40 Craters Identified – Lunar North Pole

Shackleton Crater at Lunar South Pole

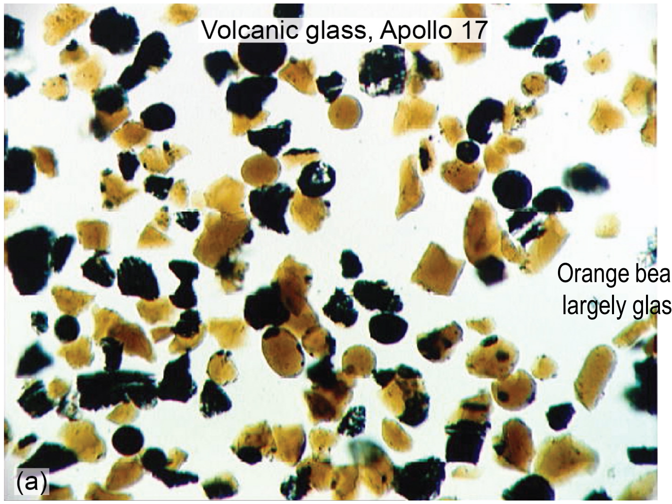
Rim / Floor Dia ~21 km / 6.6 km, Depth ~4.2 km, 30 deg slope


In-Situ Thermal Mining Option for Water Extraction from Icy Regolith

(Image Credit: James Vaughan)

*C. B. Dryer, et al., "Ice Mining in Lunar Permanently Shadowed Regions," SRR / PTMSS 9th Joint Meeting, Golden, CO, June 12 -15, 2018.

Volcanic Glass from the Apollo 17 Mission to Taurus Littrow is Attractive for LUNOX Production



Black beads largely crystalline

Orange beads largely glass

The best lunar oxygen ore found during the Apollo Program is the volcanic glass beads found at Taurus Littrow on Apollo 17.

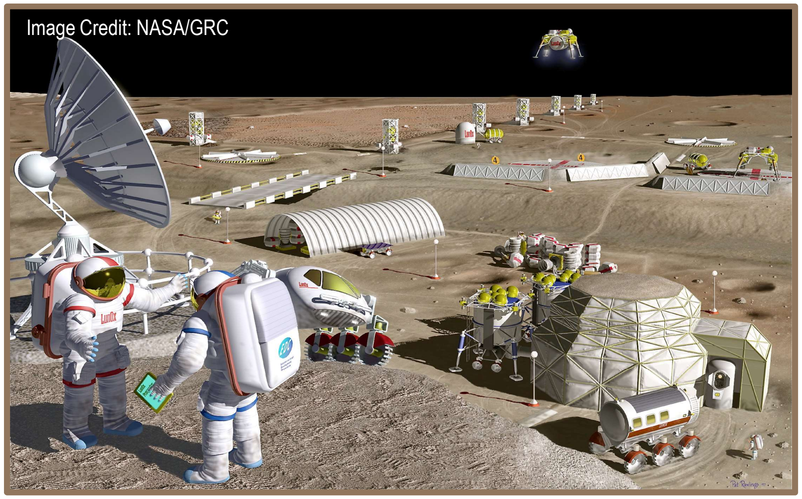
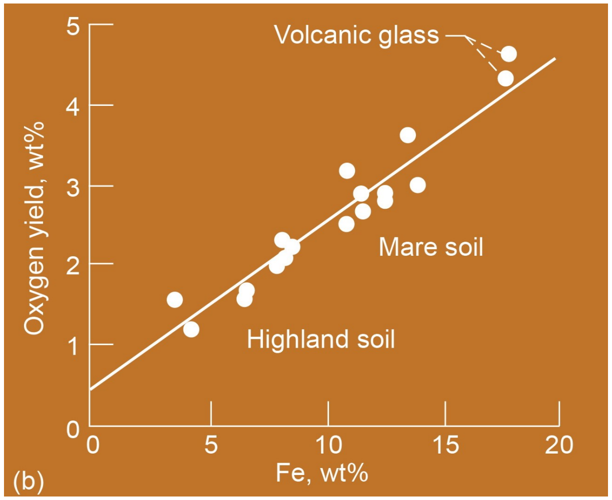


Image Credit: NASA/GRC

Ref: Borowski, et al., AIAA-1997-2956; also as NASA/TM—1998-208830 / Rev2

Using the “H_2-reduction process”, O_2 yield is directly related to iron abundance over the full range of soil compositions. Highest yields are from “FeO-rich” volcanic glass beads.



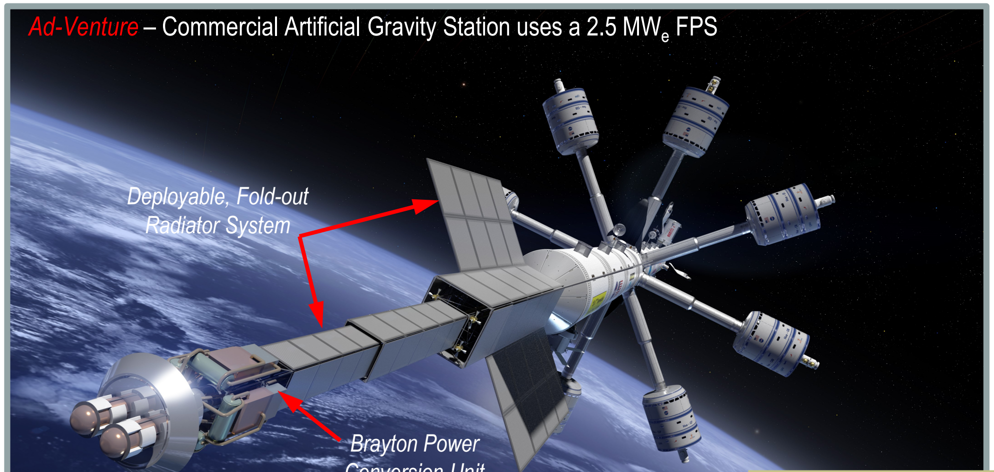
Ref: Carlton Allen, et al., “Oxygen extraction from lunar soils and pyroclastic glass”, *J. Geophysical Research*, Nov. 25, 1996

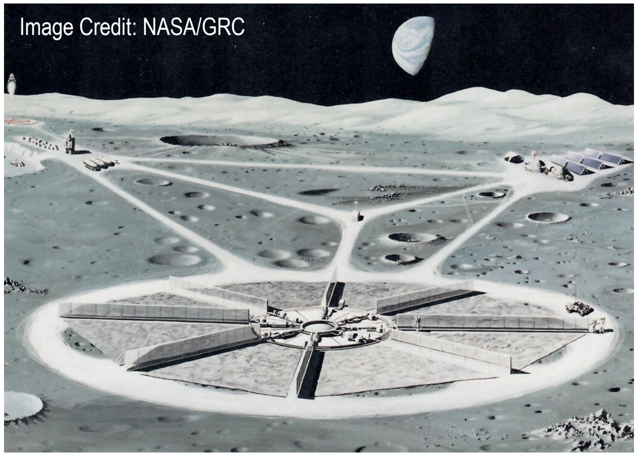
Large regional pyroclastic deposits include:
(1) Aristarchus Plateau (~49,015 km^2)
(2) Southern Sinus Aestuum (10,360 km^2)
(3) Rima Bode (~6,620 km^2)
(4) Sulpicius Gallus (4,320 km^2)
(5) Southern Mare Vaporum (~4,130 km^2)
(6) Taurus Littrow (~2,940 km^2) ✓

Ref: Gaddis, L., et al., “Compositional Analyses of Lunar Pyroclastic Deposits,” Icarus, vol.161, pp.262-280 (2003)

Megawatt Electric-class Fission Power Systems are a Key Technology for the Development of Activities in Cislunar Space and on the Moon

Ad-Venture – Commercial Artificial Gravity Station uses a 2.5 MW_e FPS

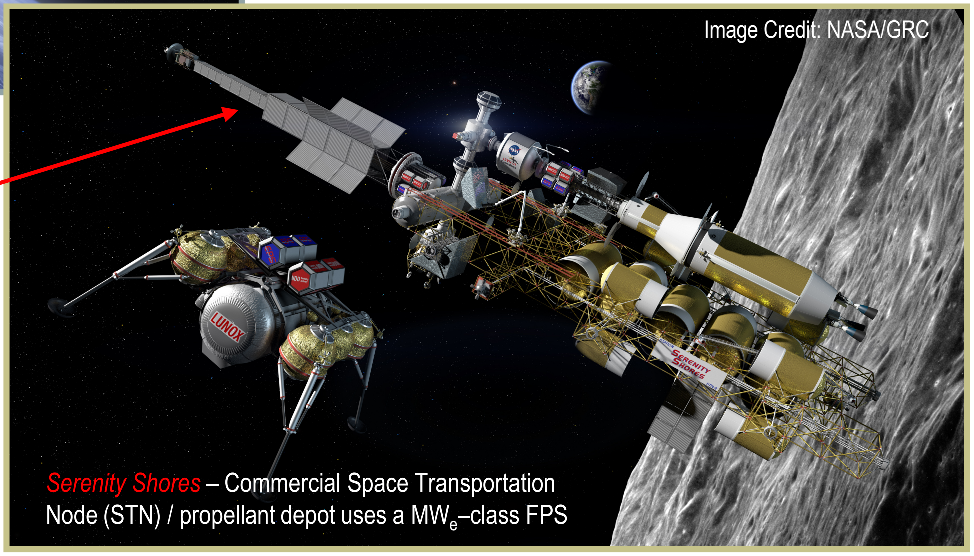




Megawatt-class Lunar FPS with Surface Radiator Panel – Number of units will depend on mining production rates

MW_e-class fission power system (FPS) has 3 major elements:
1) Twin liquid metal-cooled, fast-spectrum reactors using enriched U-235 in a uranium nitride fuel form;
2) Dynamic conversion with 4 Brayton TAC units and He-Xe working gas, combined with an AC PMAD system and;
3) Deployable, fold-out radiator system for heat rejection. It uses a liquid NaK pumped loop fluid system combined with lightweight sodium heat pipe radiator panels.

Ref: Human Exploration of Mars Design Reference Architecture 5.0, NASA-SP-2009-566-ADD2, pp.136-138, March 2014

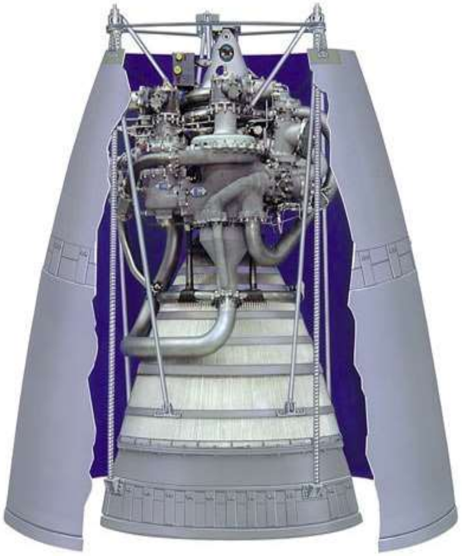


Serenity Shores – Commercial Space Transportation Node (STN) / propellant depot uses a MW_e–class FPS

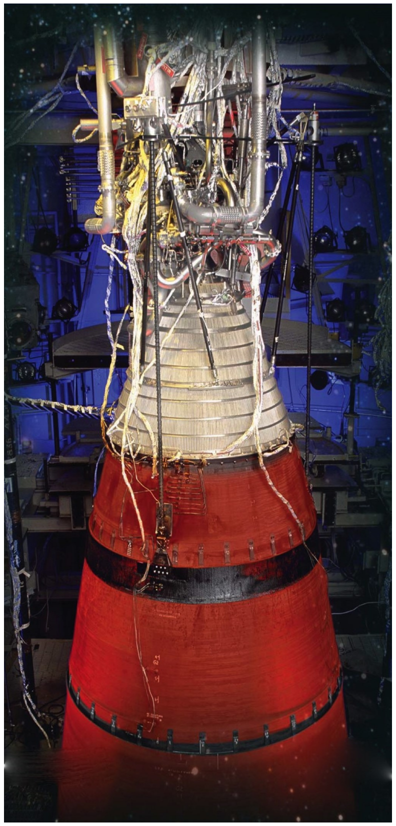
Ref: Borowski, S., et al., AIAA-2019-3971 for details on *Ad-Venture* & *Serenity Shores*

Aerojet Rocketdyne's RL10B-2 Chemical Rocket: Engine Featured in this Study

RL10B-2 Engine



a) Retracted Nozzle Configuration



b) Testing with Extended Nozzle

(Source of Images: Aerojet Rocketdyne)

RL10B-2 Chemical Rocket Engine Performance Parameters:

- Propellants: **LO_2& LH_2**
- O/H MR: **5.88:1**
- Engine Cycle: **Expander**
- Thrust Level: **24.75 klb_f**
- Exhaust Temperature: **~3165 K**
- Chamber Pressure: **640 psi**
- Nozzle Area Ratio: **280:1**
- Specific Impulse (I_{sp}): **~465.5 s**
- Engine T/W_{eng} ratio: **~37.3**
- Engine Length: **4.15 m**
- Nozzle Exit Diamter: **2.15 m**
- Est. Engine Service Life: **3500 s (?)**
- Est. # Engine Starts: **15 (?)**

Ref: Aerojet Rocketdyne RL10 Engine Specifications
@ www.rocket.com (March 2019)

Growth Missions and Faster Trip Times are Possible using Space Transportation Nodes (STNs) with Refueling Capability

- Over time we envision the development of a totally space-based LTS with different types of LTVs operating between STNs located in LEO, equatorial LLO and LPO. The STN provides a propellant depot and cargo transfer function and offers a convenient staging location where propellant, cargo and passengers can be dropped off and/or picked up.

Oasis – LEO STN / Propellant Depot

Serenity Shores – LLO STN / Propellant Depot

- One-way transit times to and from the Moon on the order of 72 hours would be the norm initially. As lunar outposts grow into settlements staffed by visiting scientists, engineers and administrative personnel representing both government and private ventures, more frequent flights of shorter duration could become commonplace.

Variation of ΔV Values with 1-Way Transit Time (from LEO to LLO to LEO)*

Transit Time (hr)	TLI (km/s)	LOC (km/s)	TEI (km/s)	EOC (km/s)	Total ΔV (km/s)
24	3.661	2.770	2.766	3.660	12.857
36	3.275	1.621	1.612	3.274	9.782
48	3.152	1.169	1.154	3.151	8.626
60	3.101	0.986	0.950	3.102	8.139
72	3.089	0.902	0.843	3.084	7.918

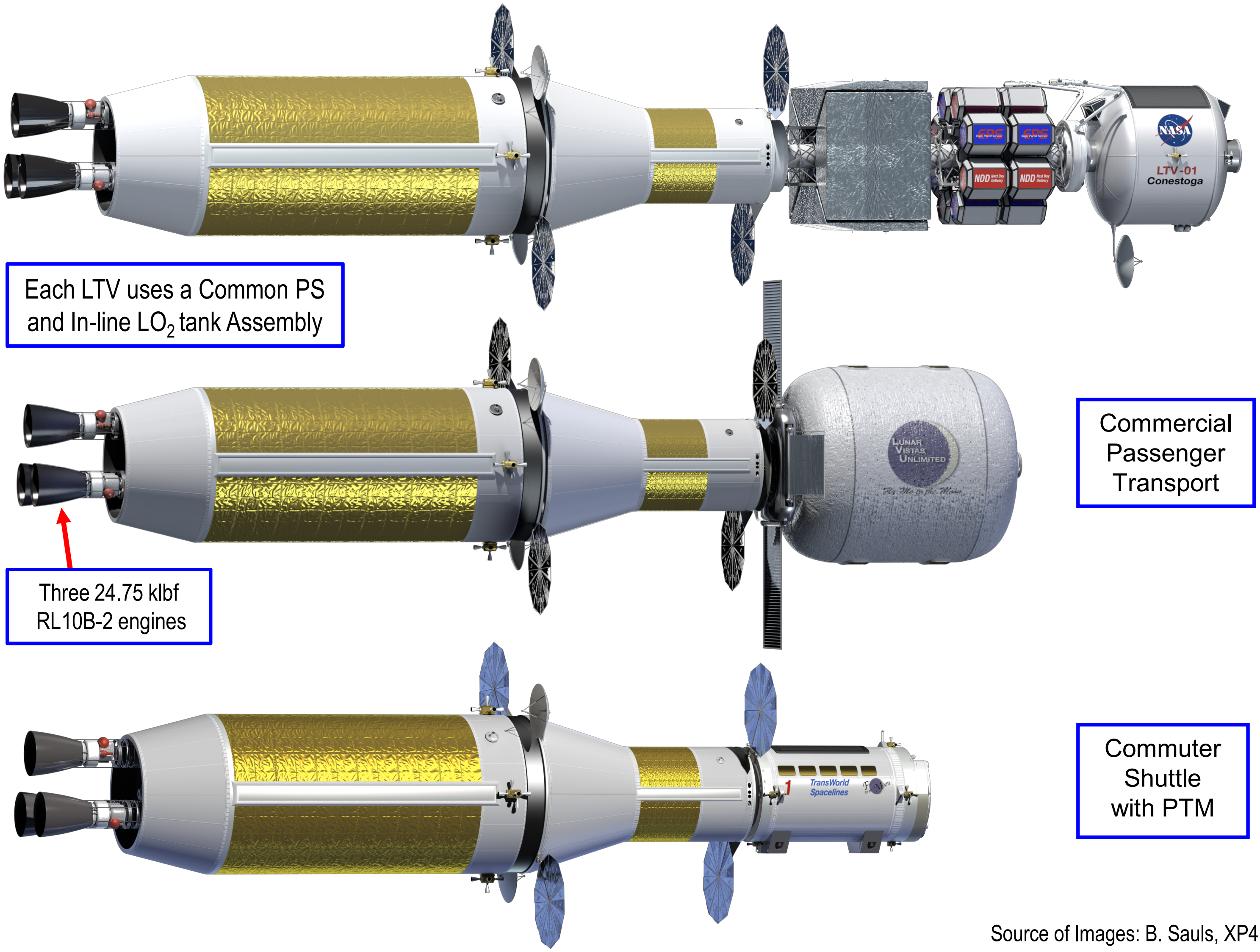
*LEO – 407 km circular, equatorial LLO – 300 km circular

- Cutting the Earth-Moon transit times in half to ~36 hours increases the mission's total ΔV budget by ~25% – from ~8 to 10 km/s. For 24 hour LEO to LLO transit times the increase is ~62.5% – from ~8 to 13 km/s.

- For round trip LEO to LPO missions, the ΔV requirements are larger ranging from 8.245 km/s (for 72-hr transit times) to 15.015 km/s (for 24-hr transit times)

Ref: Borowski, S., et al., AIAA-2019-3971 for details on *Oasis* & *Serenity Shores*

Relative Sizes of the Crewed Cargo Transport (CCT), the Commercial Passenger Transport (CPT) and the Commuter Shuttle



Crewed Cargo Transport

Each LTV uses a Common PS and In-line LO_2 tank Assembly

Commercial Passenger Transport

Three 24.75 klbf RL10B-2 engines

Commuter Shuttle with PTM

Source of Images: B. Sauls, XP4D, LLC

Free Return Lunar Flyby Missions Could Occur Sooner Than You Think


Mini-Shuttle carries 5 Passengers to LEO on Commercial Launch Vehicle


Commercial Passenger Transport (CPT) picks up 5 tourists at Commercial LEO Station….

….or directly from the Mini-Shuttle in LEO


Total Time of Flight for Commercial Flyby Mission is ~5.6 days

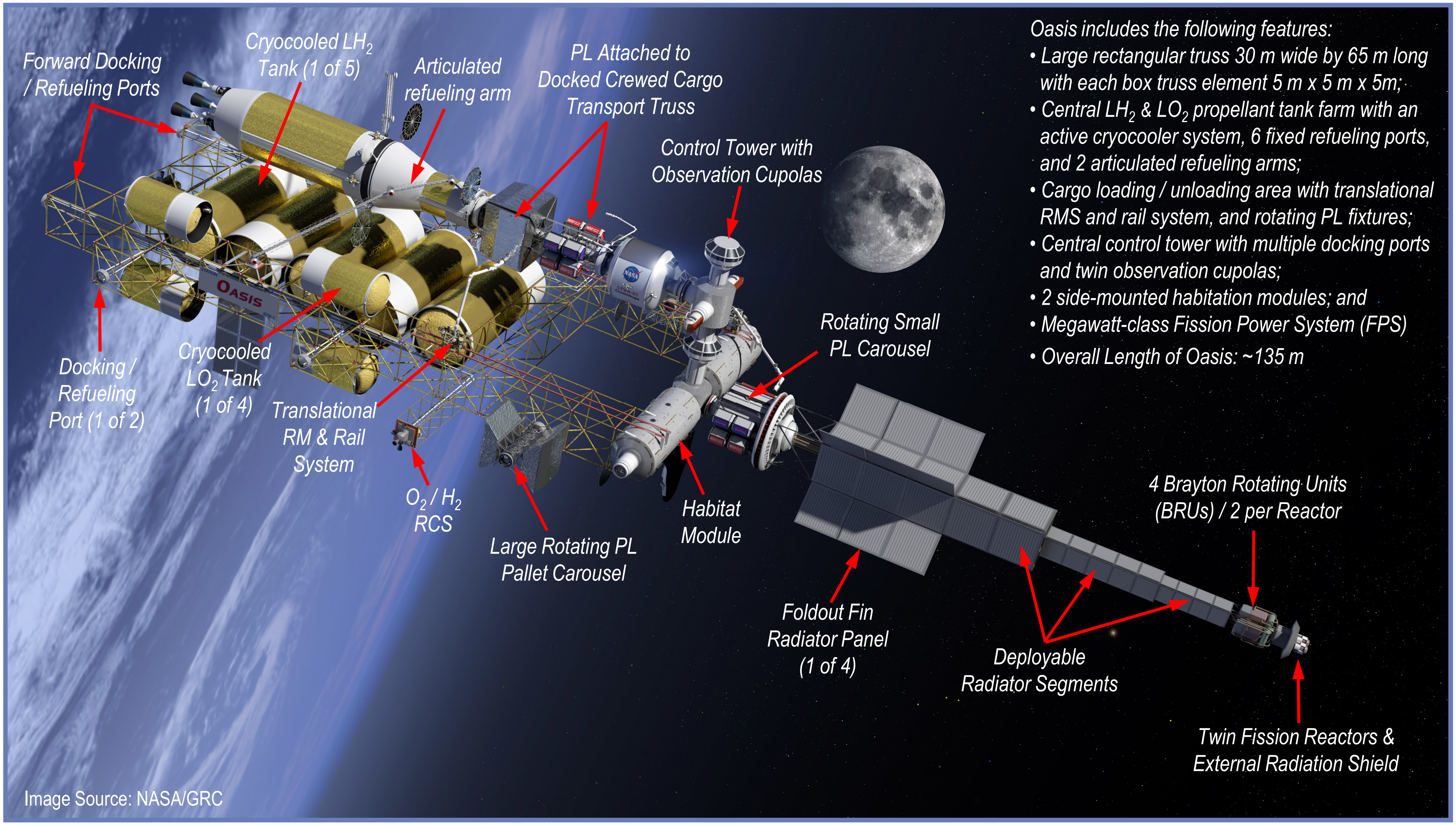

Passengers re-board Mini-Shuttle at mission's end and return to Commercial Spaceport

Image Credits: B. Sauls, XP4D, LLC

Case Description *	Objectives	Transit Times/Orbits**/ Mission ΔV***and Burn Times	LH_2 Propulsion Tank and In-line LO_2 Tank	Start Mass and Propellant Needs
1. RL10B-2 lunar flyby tourist mission carrying an ~25 t Habitat Module with 7 individuals and consumables	Determine the LO_2 and LH_2 required in LEO for an ~5.6 day long lunar flyby mission capturing into an ~1.9-hr elliptical Earth orbit (EEO)	~67.2-hr 1-way transit times LEO → 300 km → 1.9-hr EEO ΔV ~5.889 km/s Engine Burn Time ~29.4 min	7.6 m OD x ~12.29 m L (~30.0 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~176.9 t; ~111.2 t LO_2 and ~19.14 t LH_2 supplied at LEO STN
2. RL10B-2 lunar orbit tourist mission carrying an ~25 t Habitat Module with 7 individuals and consumables	Determine the LO_2 and LH_2 required in LEO for an ~5.6 day long lunar flyby mission capturing back into low Earth orbit (LEO)	~67.2-hr 1-way transit times LEO → 300 km → LEO ΔV ~6.410 km/s Engine Burn Time ~35 min	7.6 m OD x ~12.29 m L (~30.0 t LH_2) 4.6 m OD x ~9.22 m L (~132.4 t LO_2)	IMLEO ~202.3 t; ~132.4 t LO_2 and ~22.7 t LH_2 supplied at LEO STN

*Cases 1 and 2 use a common LH_2 PS; Propellant depot assumed in LEO; RL10B-2 engines operate at fixed MR = 5.88:1 and Isp = 465.5 s;
**LEO – 407 km, Flyby altitude – 300 km, 1.9-hr EEO (407 km x 2378 km); ***Total ΔV values include g-losses

Oasis – Commercial LEO Space Transportation Node (STN) provides cargo and propellant transfer capability, habitation, and incorporates a FPS



Oasis includes the following features:

- *Large rectangular truss 30 m wide by 65 m long with each box truss element 5 m x 5 m x 5m;*
- *Central LH_2 & LO_2 propellant tank farm with an active cryocooler system, 6 fixed refueling ports, and 2 articulated refueling arms;*
- *Cargo loading / unloading area with translational RMS and rail system, and rotating PL fixtures;*
- *Central control tower with multiple docking ports and twin observation cupolas;*
- *2 side-mounted habitation modules; and*
- *Megawatt-class Fission Power System (FPS)*
- *Overall Length of Oasis: ~135 m*

Image Source: NASA/GRC

Ref: Borowski, S., et al., AIAA-2019-3971

Conestoga – A Reusable Space-based Crew Cargo Transport
Uses a Common LH_2 PS and In-line LO_2 Tank Assembly


Image Credit: Landis Valley Village & Farm Museum, PA

Conestoga Wagons, the “Ships of Inland Commerce,” Transported Settlers, Farm Produce, and Freight across Pennsylvania and Neighboring States for over 150 years

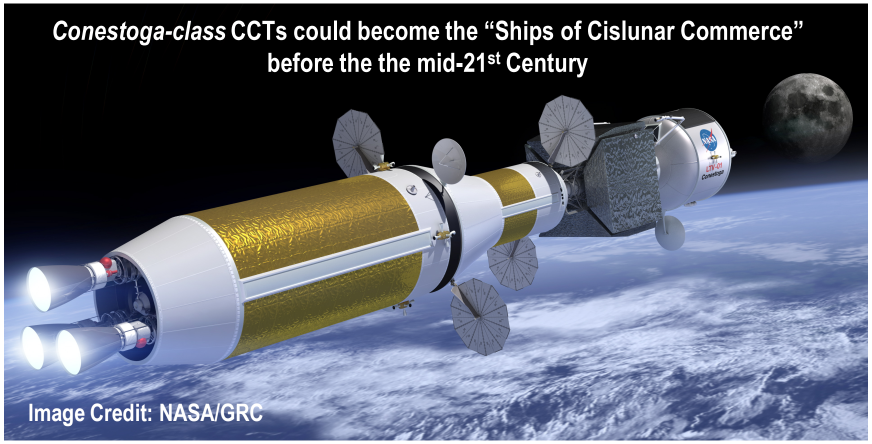

***Conestoga-class* CCTs could become the “Ships of Cislunar Commerce” before the the mid-21st Century**

Image Credit: NASA/GRC

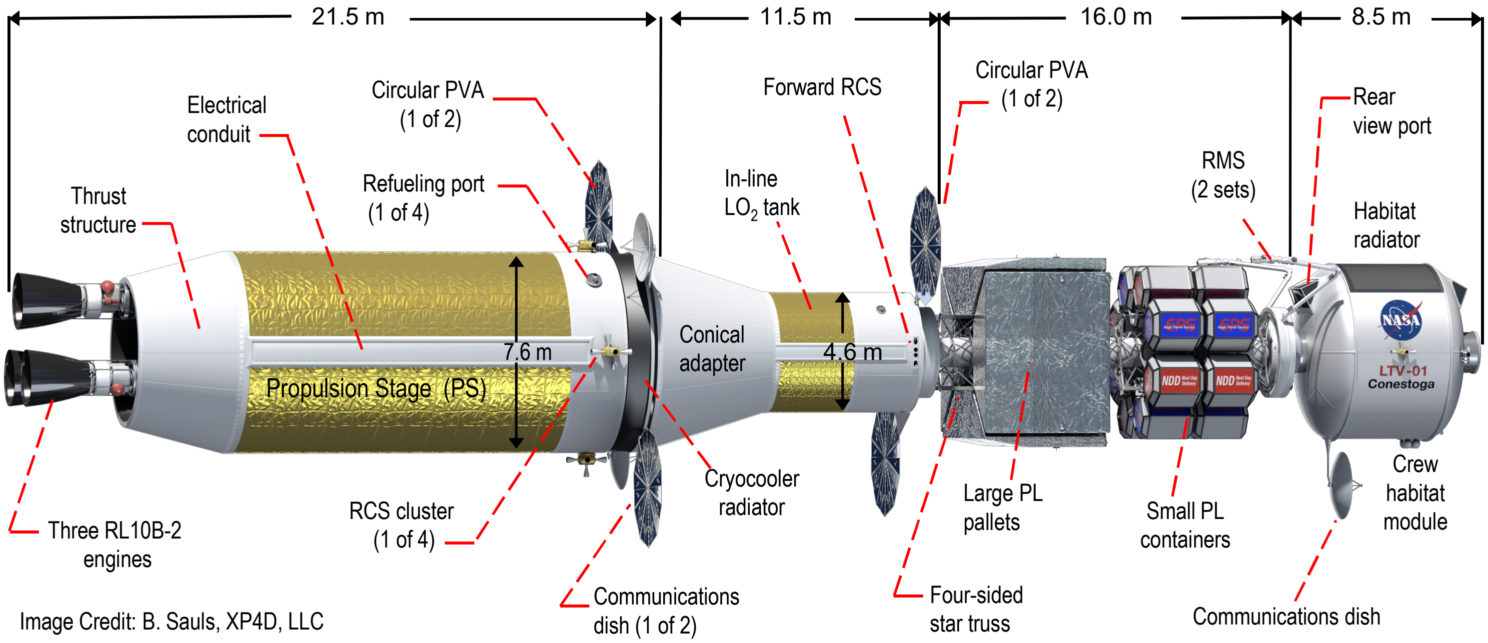
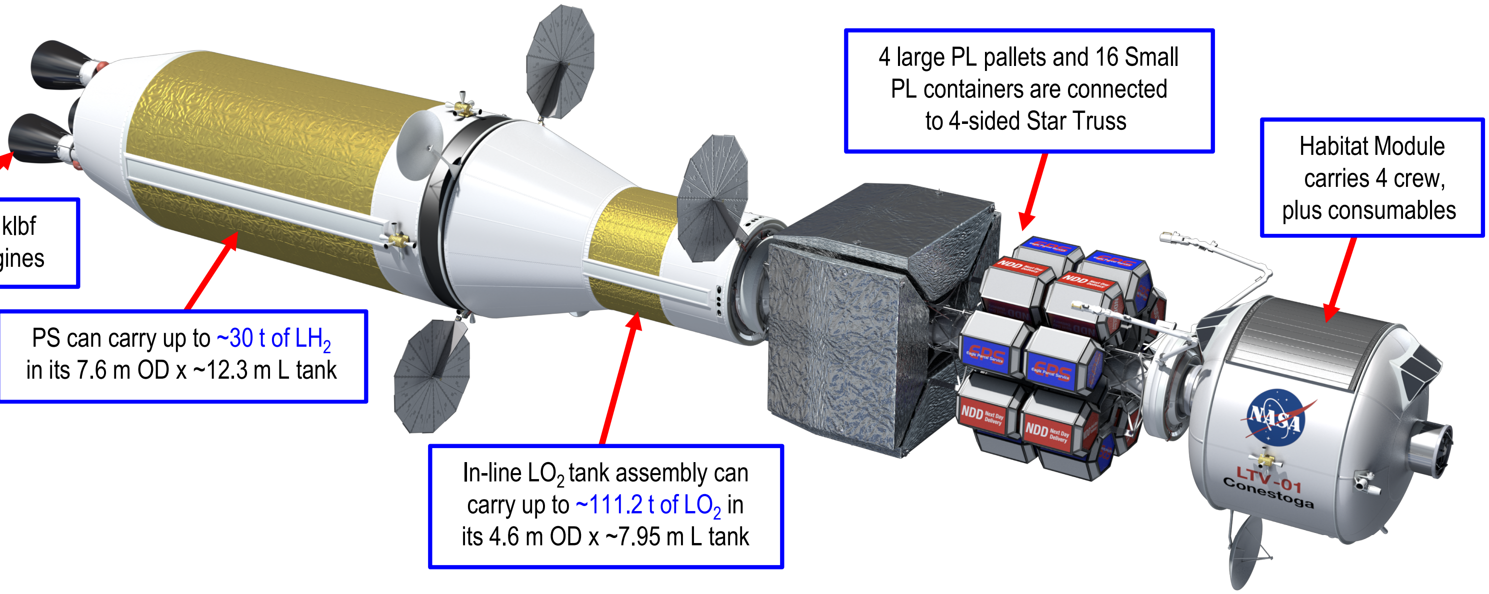


Image Credit: B. Sauls, XP4D, LLC

Conestoga Crewed Cargo Transport (CCT) Missions to Polar (LPO) and Equatorial Low Lunar Orbits (LLO)



Three 24.75 klbf RL10B-2 engines

PS can carry up to ~30 t of LH$_2$ in its 7.6 m OD x ~12.3 m L tank

In-line LO$_2$ tank assembly can carry up to ~111.2 t of LO$_2$ in its 4.6 m OD x ~7.95 m L tank

4 large PL pallets and 16 Small PL containers are connected to 4-sided Star Truss

Habitat Module carries 4 crew, plus consumables

20 t of cargo to LPO / 2 t of cargo to LEO

(LEO ⟶ LPO ⟶ LEO)
- **72-hr** "1-way" transit times
- Total Mission ΔV ~8.319 km/s
- Habitat Module w/4 people ~**10.8 t**
- Star Truss (16 m) w/20 t Payload ~**30.8 t**
- In-line Assembly ~**94.5 t** (~88 t LO$_2$)
- Common PS ~**33.2 t** (~17.8 t LH$_2$)
- Refuel LLO$_2$ / LLH$_2$ **~59.15 t / 7.39 t**
- IMLEO **~169.3 t**
- Return PL ~2000 kg
- RL10B-2: MR / Isp~ 5.88:1 / 465.5 s
- Total Mission Burn Time: **~39 min**

For roundtrip LPO missions, the CCT R&D with LPO STN and refuels with LLO$_2$ and LLH$_2$ at a ratio of 8:1; implies ~66.5 t LH$_2$O must be electrolyzed per mission

20 t of cargo to LLO / 2 t of cargo to LEO

(LEO ⟶ LLO ⟶ LEO)
- **72-hr** "1-way" transit times
- Total Mission ΔV ~8.139 km/s
- Habitat Module w/4 people ~**10.8 t**
- Star Truss (16 m) w/20 t Payload ~**30.8 t**
- In-line LO$_2$ tank ~**103.5 t** (~97 t LO$_2$)
- Common PS ~**41.5 t** (~26 t LH$_2$)
- Refuel LLO$_2$ **~54.8 t**
- IMLEO **~186.6 t**
- Return PL ~2000 kg
- RL10B-2: MR / Isp~ 5.88:1 / 465.5 s
- Total Mission Burn Time: **~40.3 min**

For roundtrip LLO missions, the CCT uses only Earth-supplied LH$_2$. It R&D with LLO STN and refuels with only LLO$_2$

Image Credit: B. Sauls, XP4D, LLC

Serenity Shores – Commercial LLO STN and *Oasis* clone provides cargo and propellant transfer capability and habitation for CCT and CPT missions

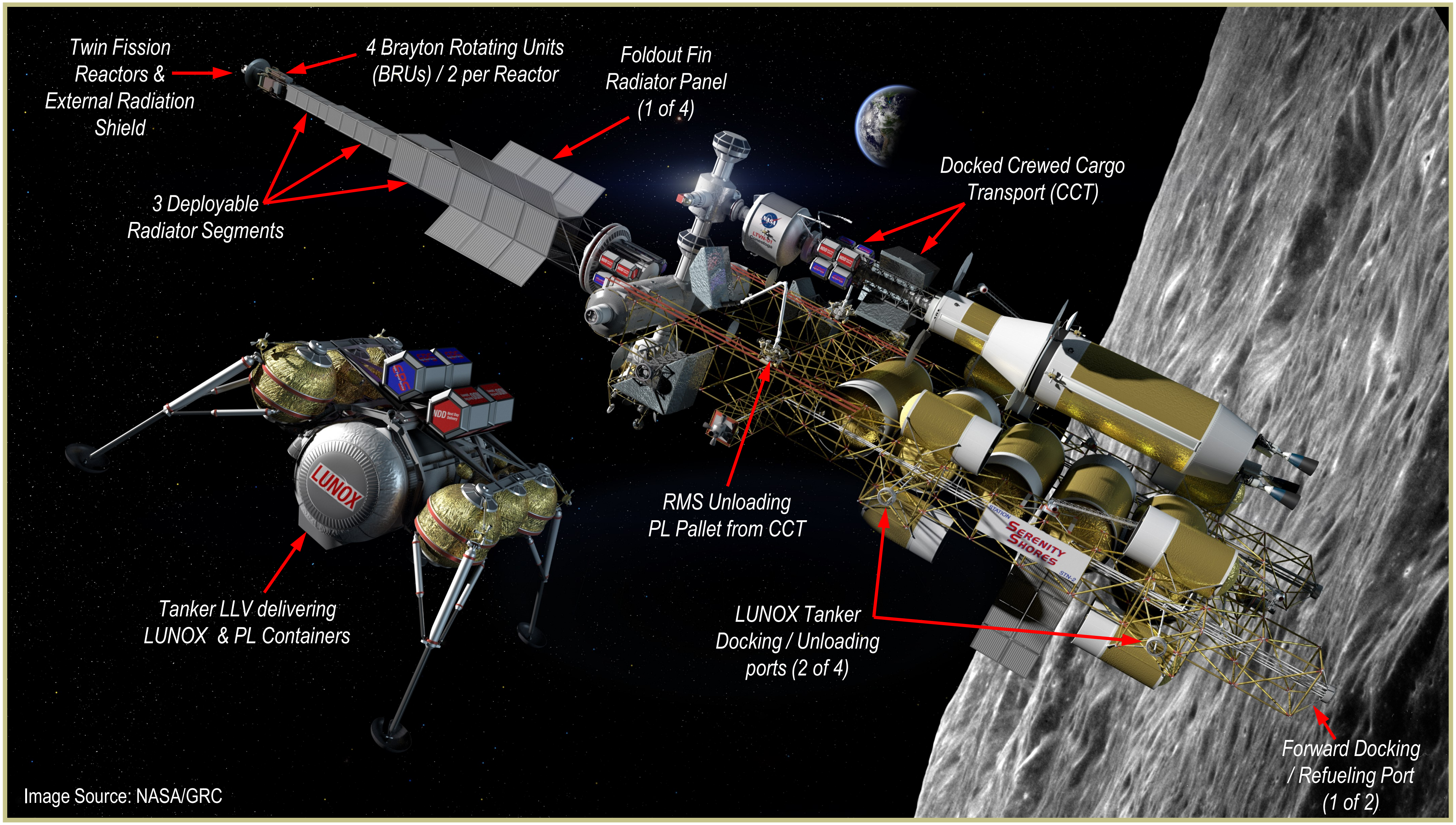
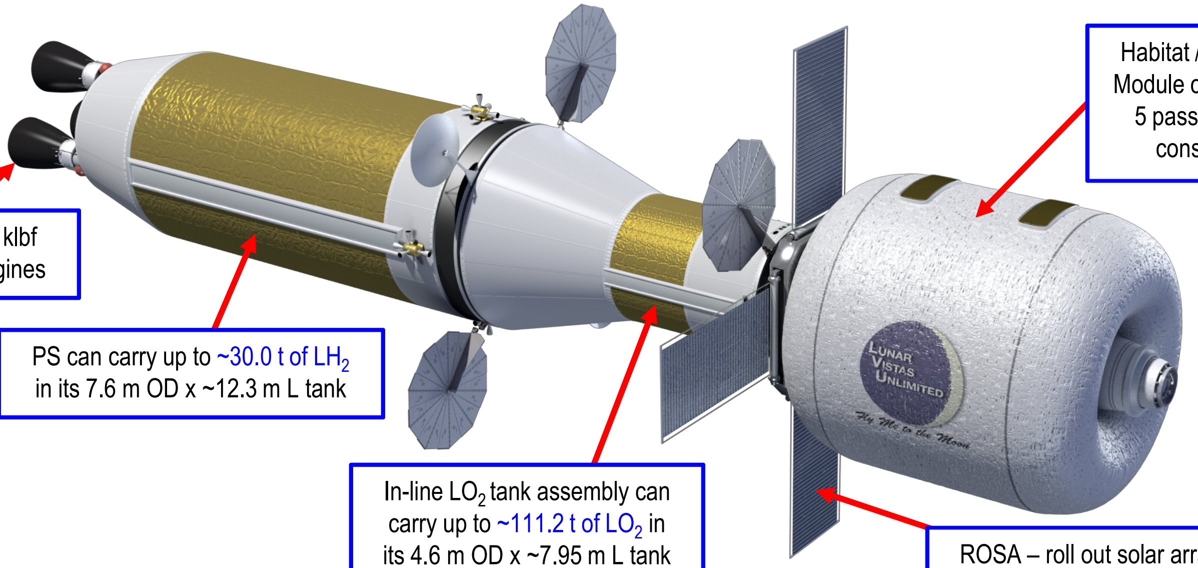


Image Source: NASA/GRC

Ref: Borowski, S., et al., AIAA-2019-3971

Commercial Passenger Transport (CPT) Missions to Polar (LPO) and Equatorial Low Lunar Orbits (LLO)



Three 24.75 klbf RL10B-2 engines

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In-line LO$_2$ tank assembly can carry up to ~111.2 t of LO$_2$ in its 4.6 m OD x ~7.95 m L tank

Habitat / Observation Module carries 2 crew, 5 passengers plus consumables

ROSA – roll out solar arrays (1 of 4 panels)

Mission Duration: 1 week with 1 day in LPO

(LEO → LPO → LEO)

- **66-hr** "1-way" transit times
- Total Mission ΔV ~8.638 km/s
- Habitat/ Observation Module with 2 crew, 5 passengers plus consumables **~26,5 t**
- In-line Assembly **~79.4** (~72.9 t LO$_2$)
- Common PS **~30.1 t** (~15.6 t LH$_2$)
- Refuel LLO$_2$ / LLH$_2$ **~64.9 t / 8.11 t**
- IMLEO **~136 t**
- RL10B-2: MR / Isp~ 5.88:1 / 465.5 s
- Total Mission Burn Time: **~36.5 min**

For roundtrip LPO missions, the CPT R&D with LPO STN and refuels with LLO$_2$ and LLH$_2$ at a ratio of 8:1; implies ~73 t LH$_2$O must be electrolyzed per mission

Mission Duration: 1 week with 1 day in LLO

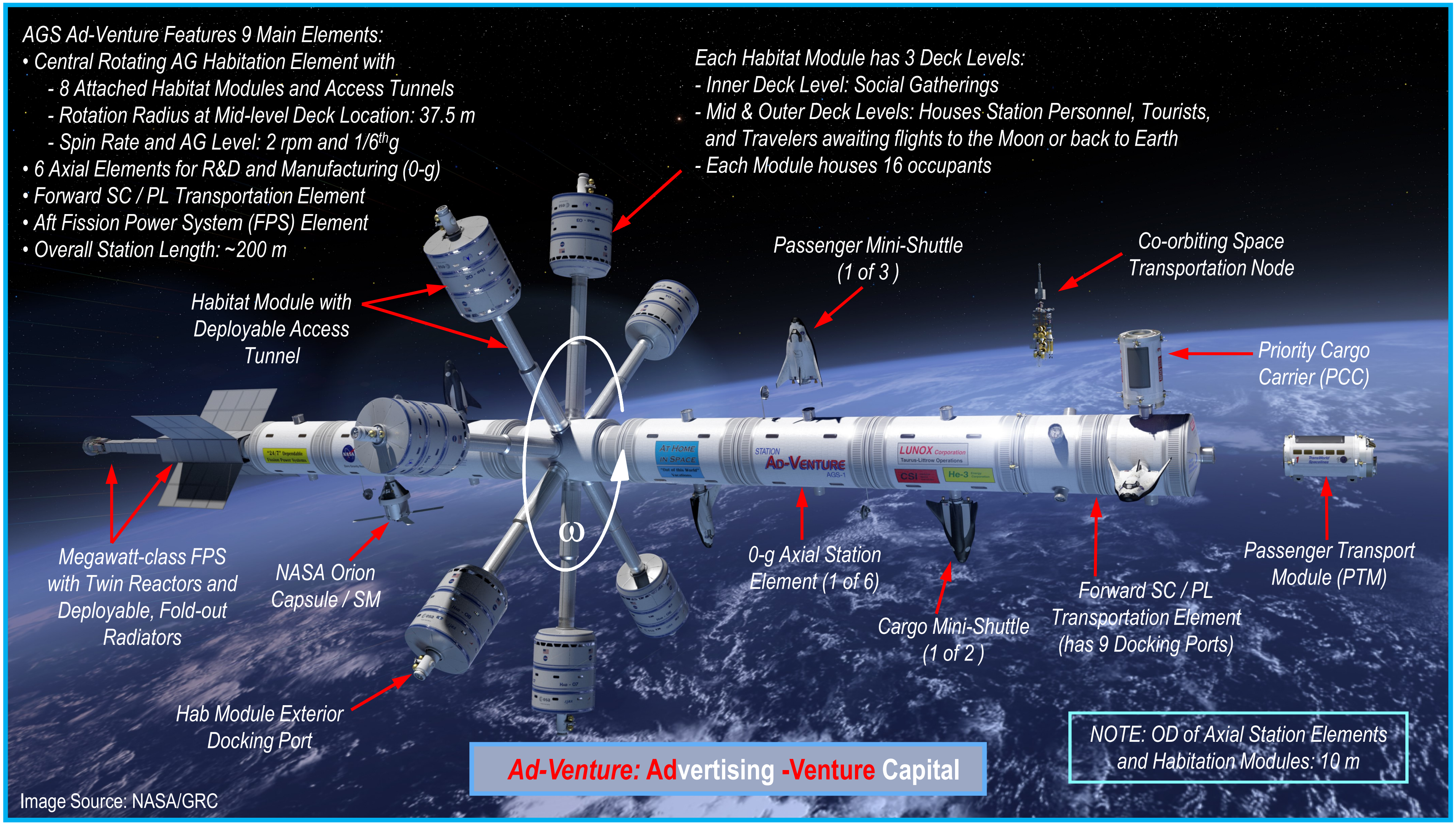
(LEO → LLO → LEO)

- **66-hr** "1-way" transit times
- Total Mission ΔV ~8.166 km/s
- Habitat / Observation Module with 5 crew, 5 passengers plus consumables **~26.5 t**
- In-line Assembly **~84 t** (~77.4 t LO$_2$)
- Common PS **~37.8 t** (~23.3 t LH$_2$)
- Refuel LLO$_2$ **~58.1 t**
- IMLEO **~148.3 t**
- RL10B-2: MR / Isp~ 5.88:1 / 465.5 s
- Total Mission Burn Time: **~35.9 min**

For roundtrip LLO missions, the CPT uses only Earth-supplied LH$_2$. It R&D with LLO STN and refuels with only LLO$_2$

Image Credit: B. Sauls, XP4D, LLC

Ad-Venture – Commercial Artificial Gravity Station (AGS) with Facilities Supporting Power Generation, R&D, Tourism, Cislunar Industry & Space Transportation



AGS Ad-Venture Features 9 Main Elements:

- *Central Rotating AG Habitation Element with*
  - *8 Attached Habitat Modules and Access Tunnels*
  - *Rotation Radius at Mid-level Deck Location: 37.5 m*
  - *Spin Rate and AG Level: 2 rpm and 1/6thg*
- *6 Axial Elements for R&D and Manufacturing (0-g)*
- *Forward SC / PL Transportation Element*
- *Aft Fission Power System (FPS) Element*
- *Overall Station Length: ~200 m*

Each Habitat Module has 3 Deck Levels:

- *Inner Deck Level: Social Gatherings*
- *Mid & Outer Deck Levels: Houses Station Personnel, Tourists, and Travelers awaiting flights to the Moon or back to Earth*
- *Each Module houses 16 occupants*

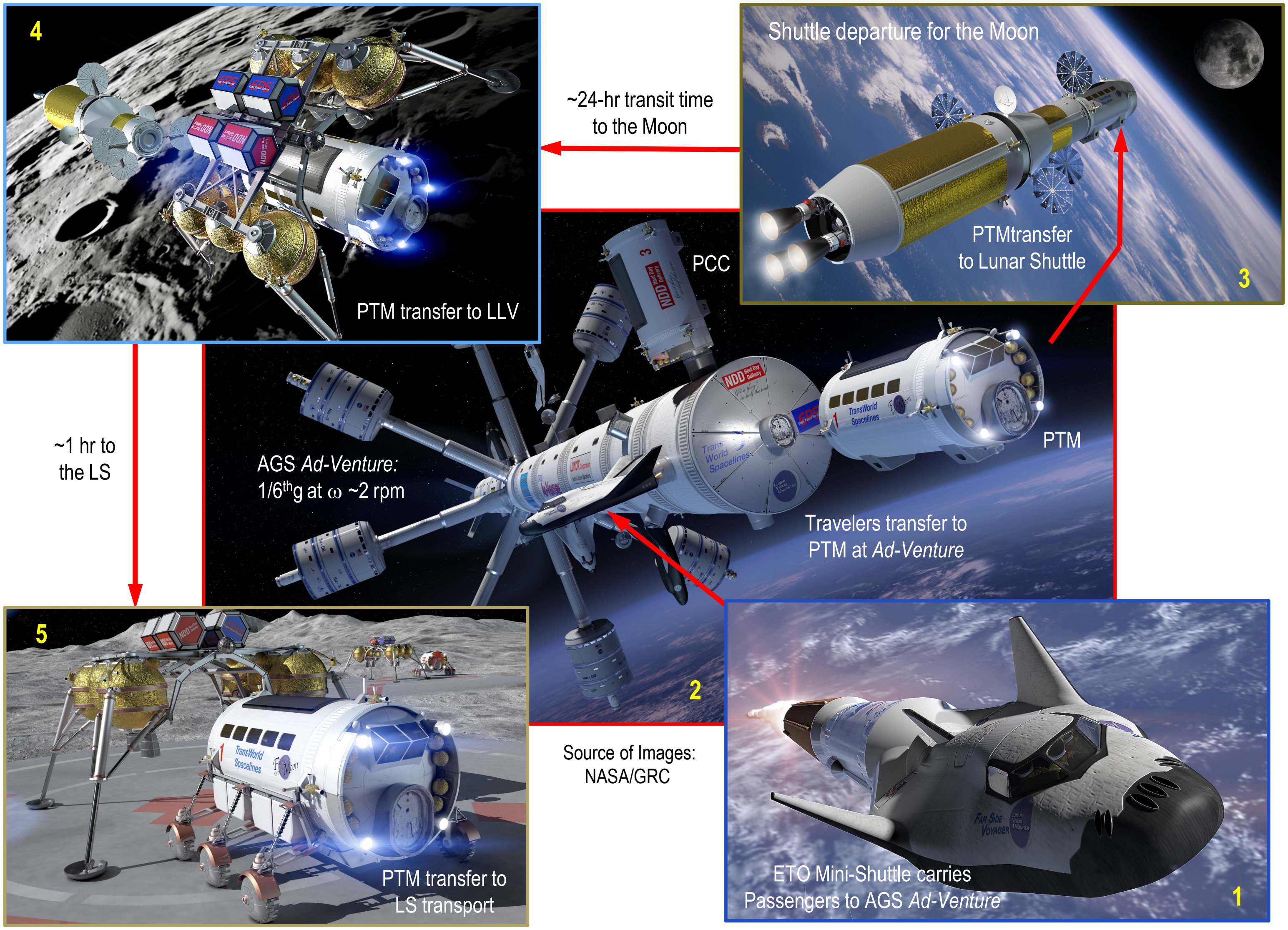
NOTE: OD of Axial Station Elements and Habitation Modules: 10 m

Ad-Venture: Advertising -Venture Capital

Image Source: NASA/GRC

Ref: Borowski, S., et al., AIAA-2019-3971

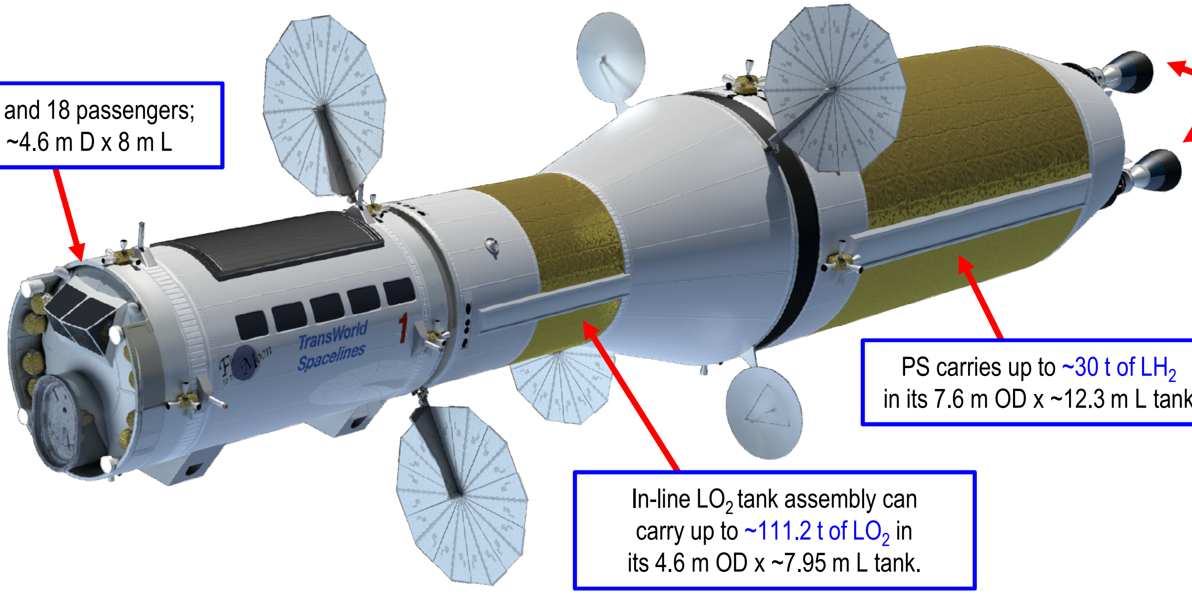
How Might a Typical Commuter Flight to the Moon Proceed?



Source of Images: NASA/GRC

Ref: Borowski, S., et al., AIAA-2019-3971

Commuter Shuttle Missions to Lunar Polar (LPO) and Equatorial Low Lunar Orbit (LLO)



PTM carries 2 pilots and 18 passengers; OML Dimensions: ~4.6 m D x 8 m L

24.75 klbf RL10B-2 Engines (2 of 3)

PS carries up to ~30 t of LH_2 in its 7.6 m OD x ~12.3 m L tank

In-line LO_2 tank assembly can carry up to ~111.2 t of LO_2 in its 4.6 m OD x ~7.95 m L tank.

Shortest transit time mission to LPO

(LEO ⟶ LPO ⟶ LEO)

- **32.4-hr** "1-way" transit times
- Total Mission ΔV ~12.402 km/s
- PTM mass ~**15 t**
- In-line Assembly ~**117.7 t** (~111.2 t LO_2)
- Common PS ~ **38.6 t** (~23.2 t LH_2)
- IMLEO **~171.3 t**
- Refuel LLO_2 / LLH_2 **~91.5 t / 11.44 t**
- RL10B-2: MR / Isp ~5.88:1 / 465.5 s
- Total Mission Burn Time: **~54 min**

For roundtrip LPO missions, the Shuttle R&D with LPO STN and refuels with LLO_2 and LLH_2 at a ratio of 8:1; implies ~103 t LH_2O must be electrolyzed per mission

Shortest transit time mission to LLO

(LEO ⟶ LLO ⟶ LEO)

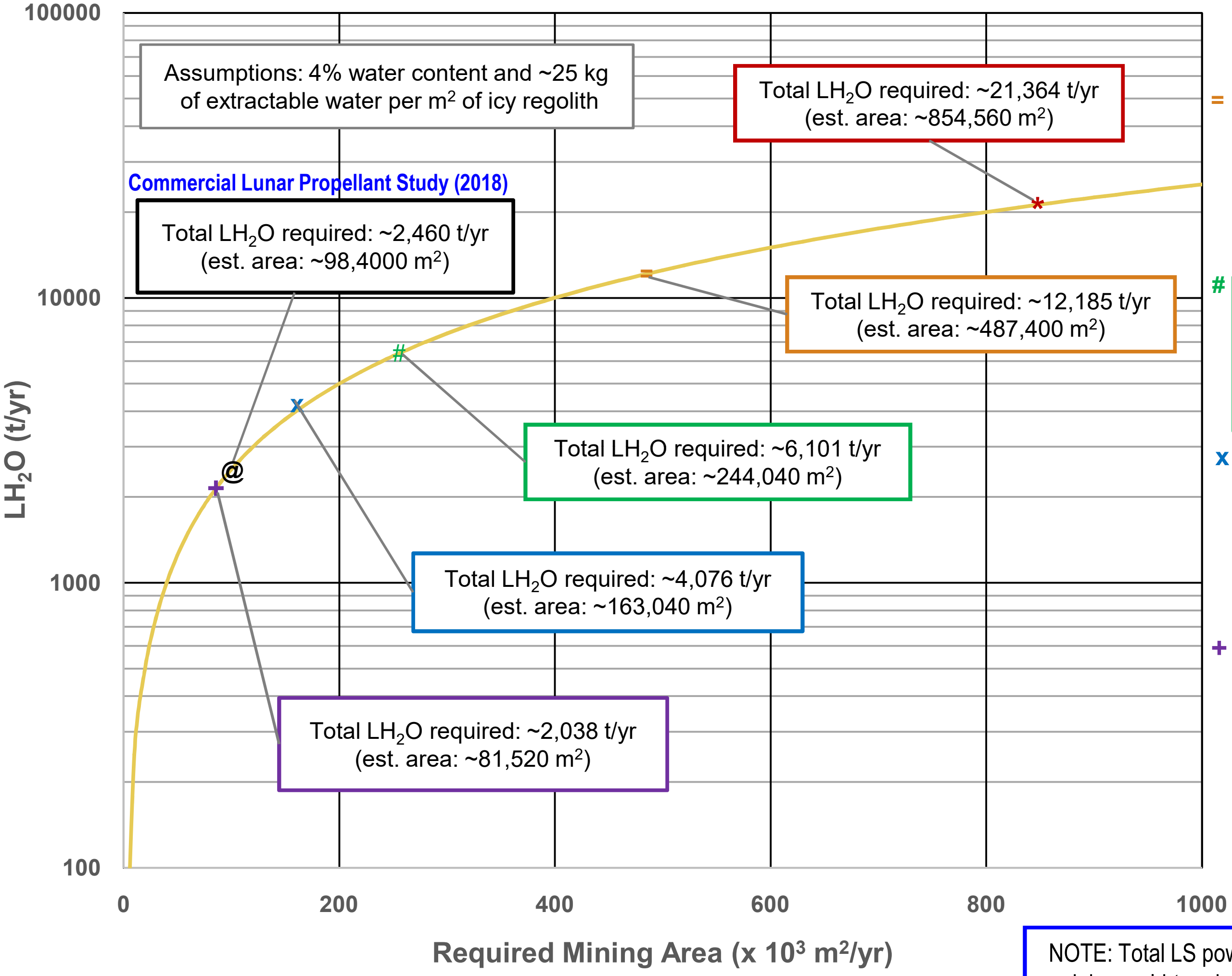
- **31.7-hr** "1-way" transit times
- Total Mission ΔV ~10.807 km/s
- PTM mass ~**15 t**
- In-line Assembly ~**110 t** (~103.5 t LO_2)
- Common PS ~ **45.4 t** (~30 t LH_2)
- IMLEO **~170.4 t**
- Refuel LLO_2 **~71.7 t**
- RL10B-2: MR / Isp ~5.88:1 / 465.5 s
- Total Mission Burn Time: **~46.6 min**

For roundtrip LLO missions, the Shuttle uses only Earth-supplied LH_2. It R&D with LLO STN and refuels with only LLO_2

Image Credit: NASA/GRC

Lunar Water Production Rate, Mining Area, and Electrolysis Power Requirements

To determine the quantities of LDP needed at both the surface mining facility, and the orbital STN, one must look at the different mission types, their transit times, and their frequency of occurrence. The needs of the different LLVs supporting each mission type must also be taken into account.



Assumptions: 4% water content and ~25 kg of extractable water per m^2 of icy regolith

Total LH_2O required: ~21,364 t/yr (est. area: ~854,560 m^2)

Commercial Lunar Propellant Study (2018)

Total LH_2O required: ~2,460 t/yr (est. area: ~98,4000 m^2)

Total LH_2O required: ~12,185 t/yr (est. area: ~487,400 m^2)

Total LH_2O required: ~6,101 t/yr (est. area: ~244,040 m^2)

Total LH_2O required: ~4,076 t/yr (est. area: ~163,040 m^2)

Total LH_2O required: ~2,038 t/yr (est. area: ~81,520 m^2)

* Weekly Commuter Shuttle flight to LPO, 1-way transits of 32.4hr, 8:1 refuel ratio, LH_2O electrolyzed for Shuttle: 5,353 t; for LLV use: 16,011 t. P_e (MW_e)*~3.0 at STN; ~8.96 on LS

= Week-long orbital CPT tourist mission to LPO with 7 passengers; 8:1 refuel ratio, 52 flights/yr. LH_2O electrolyzed for CPT use: 3,797 t; for LLV use: 8,388 t. P_e (MW_e)* ~2.13 at STN; ~4.7 on LS

Week-long orbital CPT tourist mission to LPO with 7 passengers; 8:1 refuel ratio, 26 flights/yr. LH_2O electrolyzed for CPT use: 1,898 t; for LLV use: 4,203 t. P_e (MW_e)* ~1.06 at STN; ~2.35 on LS

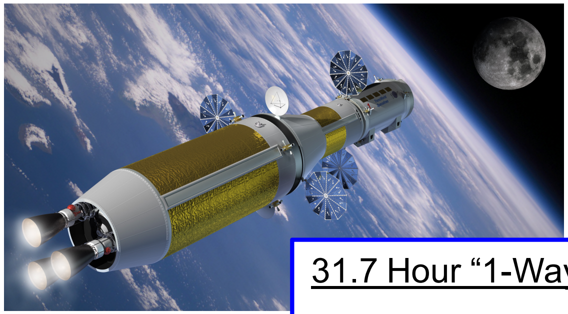
x CCT delivers 20 t to LPO / 2 t to LEO; 8:1 refuel ratio, 12 missions/yr assumed. LH_2O electrolyzed for CCT use: 800 t; for LLV use: 3,276 t. P_e (MW_e)* ~0.448 at STN; ~1.84 on LS

+ CCT delivers 20 t to LPO / 2 t to LEO; 8:1 refuel ratio; 6 missions/yr assumed. LH_2O electrolyzed for CCT use: 400 t; for LLV use: 1,638 t. P_e (MW_e)* ~0.225 at STN; ~0.917 on LS

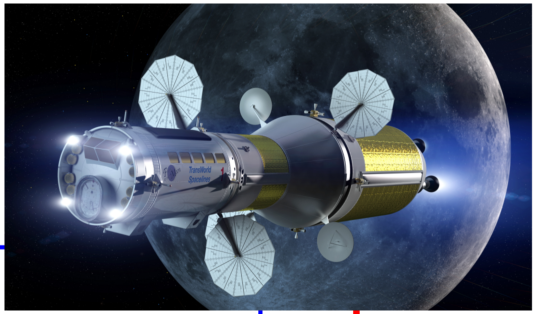
*P_e (MW_e) ~0.2042 x H_2O Electrolysis Rate (t/day)

NOTE: Total LS power required will include thermal mining, cold-trap ice hauler operation, processing and H_2O purification, electrolysis and storage

Total LUNOX Required for "Weekly" Commuter Flights



Commuter Shuttle
Departing LEO
for the Moon



Commuter Shuttle
Headed Home

31.7 Hour "1-Way" Transits (15 t / 20 Person PTM):

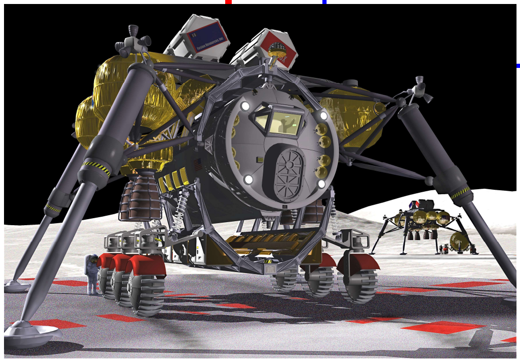
Commuter Shuttle**: (71.7 t LUNOX /mission/week)
x (52 weeks/year) = 3,729 t/yr

LLV^{*+}: (33.8 t LUNOX + 6.14 t LH$_2$ / flight)
x (3 LLV flights/week) x (52 weeks/year) = 5,273 t/yr
\+ 958 t/yr (LH$_2$)

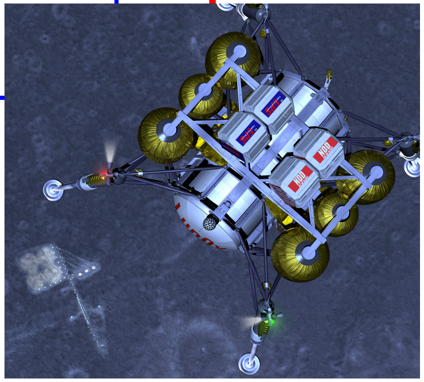
LLV$^{*\#}$: (49.1 t LUNOX$^{\#}$ + 8.92 t LH$_2$ / round trip flight)
x (1 flight/LLV/week) x (52 weeks/year) = 2,553 t/yr
\+ 463 t/yr (LH$_2$)

Total LUNOX Production = 11,555 t/yr
Total LH$_2$ Required = 1,421 t/yr

**RL10B-2: O/H MR = 5.88:1, I_{sp} = 465.5 s; Shuttle uses 3 engines.
*O/H MR = 5.5:1, I_{sp} = 450 s, ΔV_{desc} = 2.115 km/s & ΔV_{asc} = 1.985 km/s assumed
$^{+}$LLV tanker transports ~25 t of LUNOX to LLO; returns to LS with empty 5 t tank
$^{\#}$Total for LLV delivery of PTM from LLO to LS plus PTM return from the LS to LLO



LLV Unloading PTM onto
a Mobile Surface Vehicle



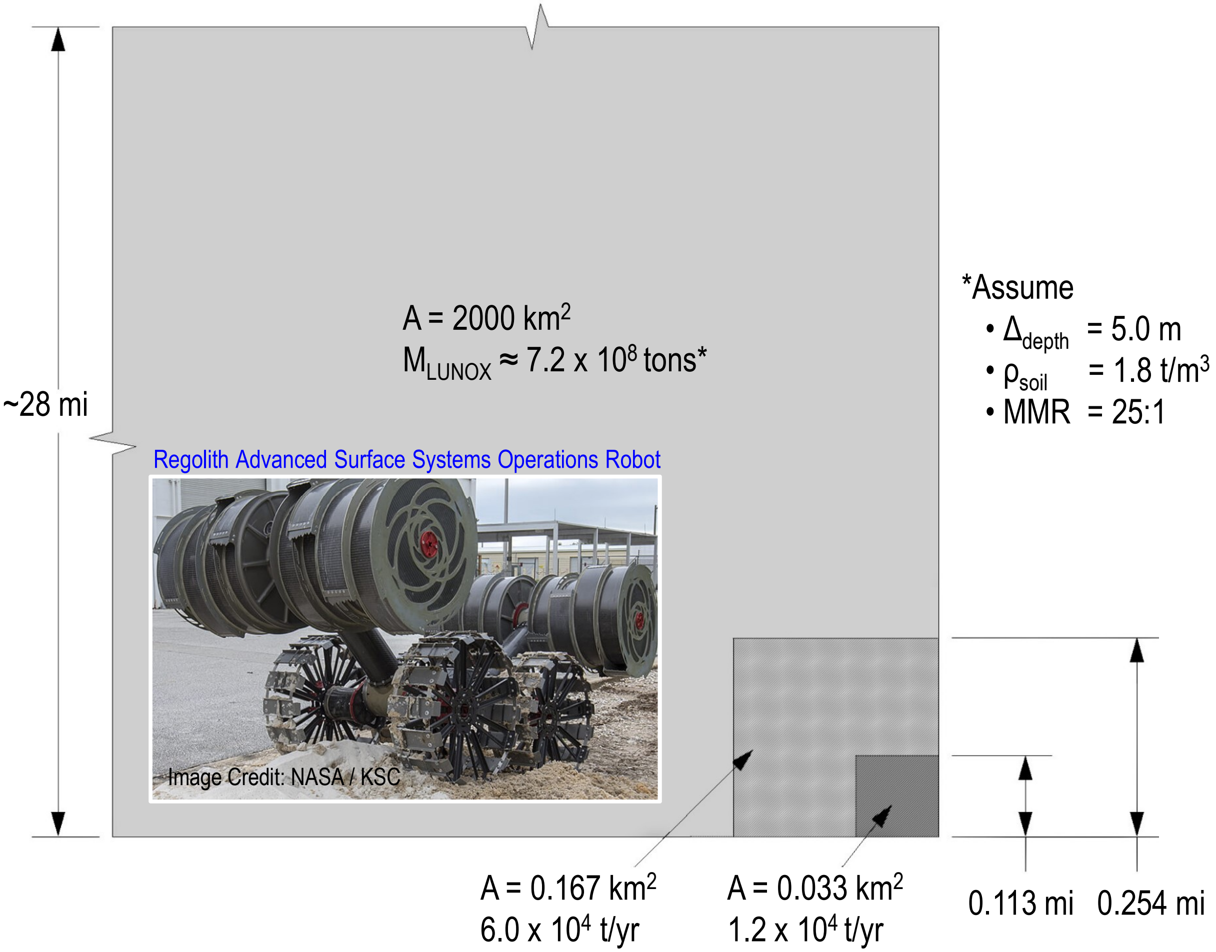
Tanker LLV Delivering
LUNOX to LLO Depot

Source of Images: NASA/GRC

NOTE: LH$_2$ can be supplied from Earth or via ballistic hopper tanker LLVs operating from LPI production plants

Mining Area and LUNOX Production Rate Required to Support Weekly Commuter Flights to the Moon

The Taurus-Littrow DMD is large (~3000 km^2) and is tens of meters thick.



A = 2000 km^2

$M_{LUNOX} \approx 7.2 \times 10^8$ tons*

~28 mi

Regolith Advanced Surface Systems Operations Robot

Image Credit: NASA / KSC

A = 0.167 km^2
6.0×10^4 t/yr

A = 0.033 km^2
1.2×10^4 t/yr

0.113 mi 0.254 mi

*Assume

- Δ_{depth} = 5.0 m
- ρ_{soil} = 1.8 t/m^3
- MMR = 25:1

Plant Mining Rate:

- To produce 12,000 t of LUNOX annually requires glass throughput of ~3.0×10^5 t/yr at MMR = 25:1
- Assuming 12 LUNOX production plants – each producing 1000 t/yr – each plant processes ~2.5×10^4t/yr
- The mining equipment at each plant includes 2 automated RASSOR-type excavator/ loaders & 4 glass haulers
- The mining rate at each plant is ~4 t per hour per excavator / loader based on a 35% mining duty cycle
- Corresponds to mining operations during 70% of the available lunar daylight hours (~3067 hours per year)
- The power needed for mining and processing per plant is ~1.5 - 2 MW$_e$

Can supply LUNOX for 25 RT commuter flights carrying 450 passengers each week for next 2400 yrs!

Synergy of LUNOX Production with an Emerging He-3 Mining Industry

- He-3 mining releases significant quantities of solar wind implanted (SWI) volatiles as “by-products” and can provide a solution to the LH_2 resupply issue while also helping to meet Earth’s future demands* for clean energy. Automated volatile miner designs developed by the University of Wisconsin’s Fusion Technology Institute have been sized to produce ~33 kg of He-3/yr so eight miners, each processing ~1 km^2 per year, can supply over ~1600 t of LLH_2 while also producing ~264 kg of He-3 annually.

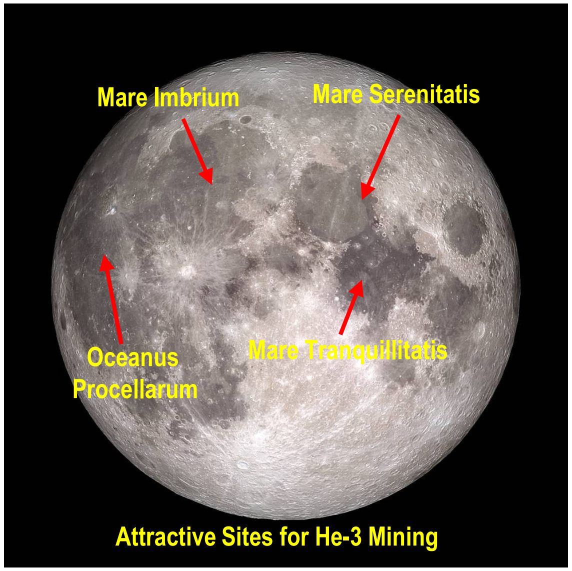
- Mare Tranquillitatis has titanium-rich regolith, large surface area (~190,000 km^2) and could contain ~7100 t of He-3, along with ~43 x 10^6 t of SWI H_2. To the northwest is Mare Serenitatis, another attractive location for He-3 mining and LUNOX production.

Mark II Automated Lunar Volatiles Miner

(Ref: Kulcinski et al., AIAA-96-0490, 1996)

Gaseous Volatiles Released During Heating of Lunar Ilmenite to 700 C

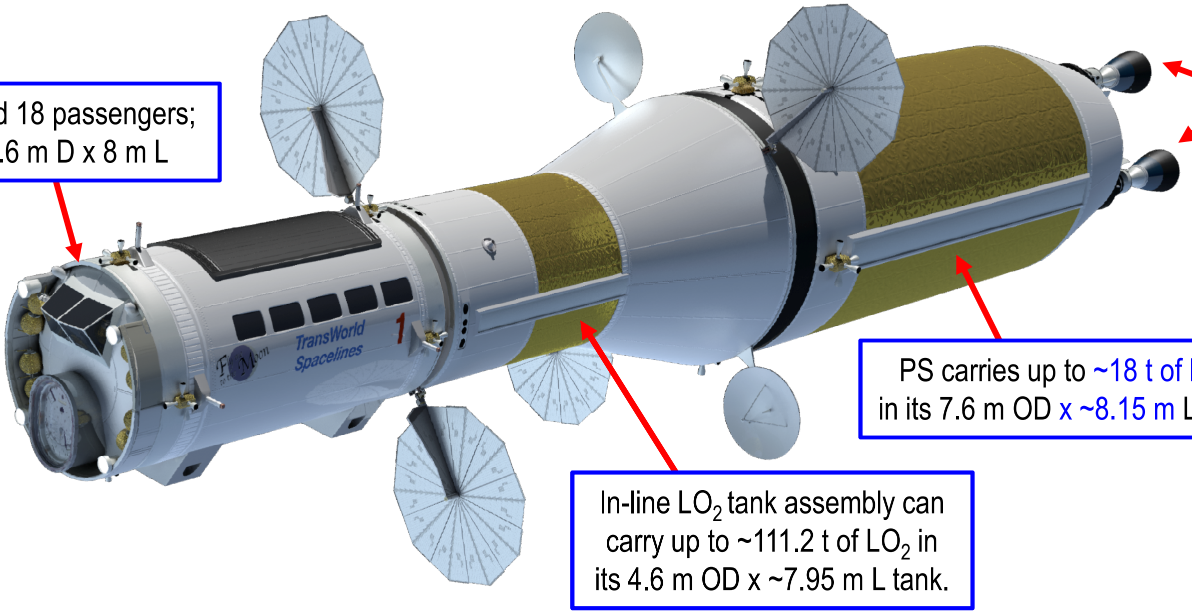
Isotope Molecule, or Compound	t of Volatile Released per kg of He-3
H_2	**6.1**
H_2O	**3.3**
He-4	3.1
CO	1.9
CO_2	1.7
CH_4	1.6
N_2	0.5
Total Volatiles =	18.2



Attractive Sites for He-3 Mining

***NOTE**: 1 t of He-3 burned with abundant deuterium from Earth’s oceans can produce ~10,000 MW_e-yr of electrical energy – implies ~50 – 65 t of He-3/yr can supply the U.S. electrical energy needs estimated to be ~480,000 MW_e-yr (2018) and ~630,000 MW_e-yr (2050)

Dr. Floyd's 25-hr Flight to the Moon – Is it Possible and What's Required?



PTM carries 2 pilots and 18 passengers; OML Dimensions: ~4.6 m D x 8 m L

24.75 klbf
RL10B-2
Engines
(2 of 3)

PS carries up to ~18 t of LH_2 in its 7.6 m OD x ~8.15 m L tank

In-line LO_2 tank assembly can carry up to ~111.2 t of LO_2 in its 4.6 m OD x ~7.95 m L tank.

24-hr transit time missions to LLO

(LEO ⟶ LLO ⟶ LEO)

- Total Mission ΔV ~13.158 km/s
- PTM mass ~**15 t**
- In-line Assembly ~**112.5 t** (~106.1 t LO_2)
- Common PS ~ **31.5 t** (~18 t LH_2)
- IMLEO **~159 t**
- Refuel LLO_2 / LLH_2 **~97.24 t / 16.54 t**
- RL10B-2: MR / Isp ~5.88:1 / 465.5 s
- Total Mission Burn Time: **~54.2 min**

For 24-hr transit time LLO missions, the Shuttle R&D with the LLO STN and refuels with both LLO_2 and LLH_2

Image Credit: NASA/GRC

LUNOX and SWI H_2 Needed for Weekly 24-hr Commuter Flights to LLO

24-hr 1-way transits carry a 15-t, 20-person PTM: (1-hr "orbit-to-LS" transfer not included)

- RL10B-2 shuttle**: (97.24 t LUNOX + 16.54 t LLH$_2$ / mission)
  x (1 mission/week) x (52 weeks/year) = 5,057 t LUNOX/yr
  \+ 860 t LLH$_2$/yr
- LLV^{*a}: (21.0 t LUNOX + 3.82 t LLH$_2$ / LLV flight)
  x (2.22 LLV flights/week) x (52 weeks/year) = 2,424 t LUNOX/yr
  \+ 441 t LLH$_2$/yr
- LLV^{*+}: (33.8 t LUNOX + 6.14 t LLH$_2$ / LLV flight)
  x (3.89 LLV flights/week) x (52 weeks/year) = 6,837 t LUNOX/yr
  \+ 1,242 t LLH$_2$/yr
- LLV$^{*\#}$: (49.1 t LUNOX + 8.92 t LLH$_2$ /round trip flight/week)
  x (52 weeks/year) = 2,553 t LUNOX/yr
  \+ 464 t LLH$_2$/yr

NOTE: Total Engine Burn Time for Shuttle Mission ~54.2 min

Total LUNOX Production = 16,871 t/yr
Total LLH$_2$ Required = 3,007 t/yr

Assumed Operating Conditions:

**RL10B-2 shuttle refuels with LUNOX and LLH$_2$ at an O/H MR = 5.88:1; LH$_2$ tank L reduced to 8.15 m

*LLV O/H MR = 5.5:1, I_{sp} = 450 s, ΔV_{desc} = 2.115 km/s and ΔV_{asc}= 1.985 km/s;

^{a}LLV LLH$_2$ tanker transports ~7.5 t of LLH$_2$ to LLO; returns to LS with empty 2-t tank;

$^{+}$LLV LUNOX tanker transports ~25 t of LUNOX to LLO; returns to LS with empty 5-t tank;

$^{\#}$Total for LLV delivery of PTM from LLO to LS plus PTM return from the LS to LPO

- Assuming a LUNOX production rate of ~17,000 t/yr, the required mining areas needed to support 24-hr commuter flights to the Moon are ~0.047 km^2 and ~0.236 km^2 for 1 to 5 flights/week, respectively.

- Even at five times the higher rate of ~85,000 t/yr, the Taurus-Littrow DMD can still supply sufficient LUNOX to support 25 commuter flights to the Moon each week for the next ~1,700 years.

- To supply the 15,035 t/yr of LLH$_2$ needed to support a flight rate of 5 flights/week, ~75 automated volatile miners would be required. The corresponding amount of He-3 produced annually would be ~2,465 kg.

Summary and Conclusions

- Routine travel between the Earth the Moon will be greatly aided by the development and utilization of of low cost, reusable launch vehicles, lunar derived propellants, fission power systems, strategically positioned STNs, and reusable LTVs using propulsion systems with long operating lifetimes – 10s of hours not 10s of minutes.

- Lunar derived propellants from polar ice deposits is currently receiving a lot of attention. There are, however, other source materials for LDPs that should not be overlooked. Vast deposits of volcanic glass on the lunar nearside can supply well in excess of 25 billion tons of LUNOX and, longer term, ~5 billion tons of SWI volatiles can be recovered for propellant and life support use from TiO_2-rich lunar regolith during He-3 mining.

- Vehicle concepts and performance requirements for flyby, orbital cargo and passenger transport, and short transit time commuter shuttle missions have been developed that use RL10B-2 chemical propulsion with long lifetimes.

- The refueling needs for these different types of LTVs, traveling between STNs in LEO, LPO, and LLO, have been quantified, including that needed by the LLVs supporting the different mission types, and preliminary mining and power requirements for producing LDPs from LPI and LUNOX from volcanic glass have been established.

- For mission scenarios involving LUNOX refueling, an alternative solution to LLV LH_2 resupply from Earth or the lunar poles could lie in the extraction of SWI H_2 and other key volatiles associated with an emerging He-3 mining industry.

- Regarding the presentation's opening question – Is routine travel between the Earth and Moon possible? – only time will tell. But with governments and industries worldwide interested in lunar exploration, developing cislunar commerce, and with competitive forces at work, the timeline to develop and implement the systems and infrastructure discussed here could well be accelerated beyond anything currently being envisioned, thereby allowing future Dr. Floyds the opportunity to experience "for real" – a routine flight to the Moon.