"Key Technologies, Systems, and Infrastructure Enabling the Commercialization and Human Settlement of the Moon and Cislunar Space"

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Introduction and Presentation Overview

• Over 50 years have passed since the *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.

• Today, in this the 50th anniversary year of the Apollo 11 lunar landing, the images in *2001* remain well beyond our capabilities and *2100: A Space Odyssey* seems a more appropriate title for Kubrick and Clarke's film.

• This presentation looks at 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 propulsion systems – utilizing Earth- and lunar-supplied LO_2/LH_2 propellant; and
- Space transportation nodes – providing convenient staging locations in LEO, LPO, and LLO

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

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.

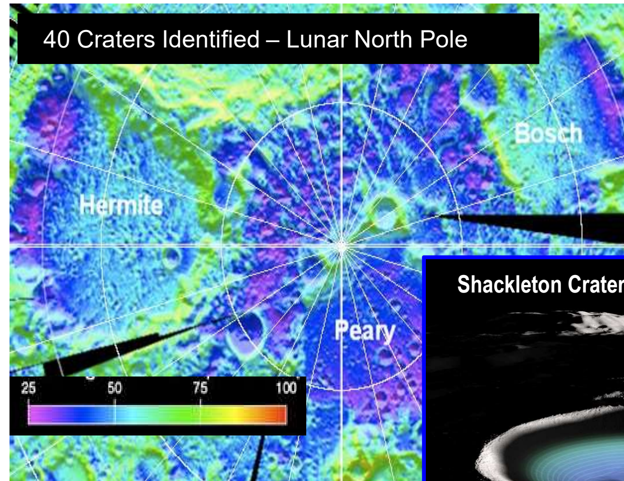
• The world's 10 coldest mines are located in Russia's extreme northeastern territory. At the coldest of these mines, Sarylakh, the temperatures can drop to nearly -50 C (~223 K).

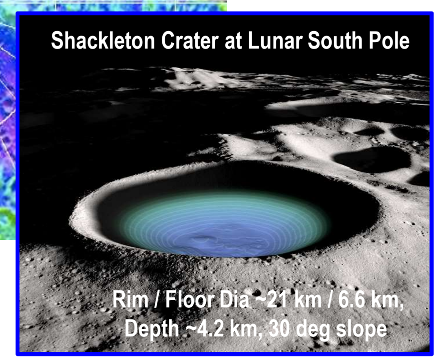
• By contrast, the temperatures inside the polar craters, where the LPI is thought to exist, are ~30 – 50 K – significantly colder than the coldest mines on Earth! At these temperatures, metals can become brittle.

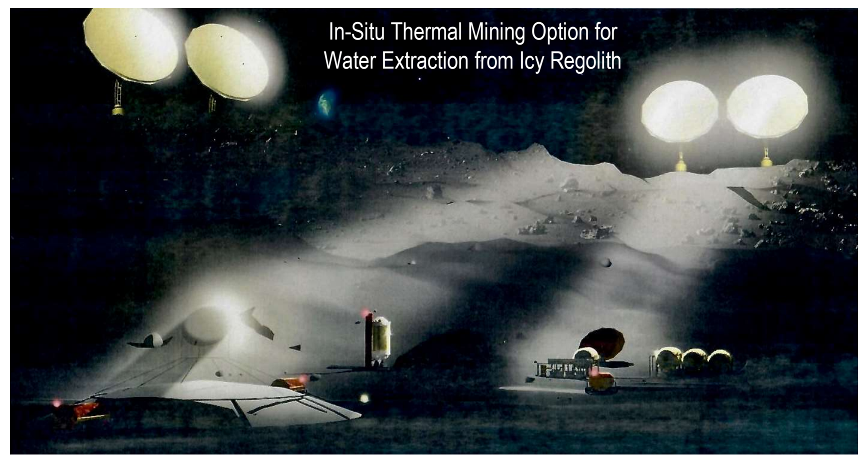
• Conventional mining requires break up, excavation and transport of the ice-bearing regolith to the water extraction plant. It must also operate in a hard vacuum and be able to tolerate the abrasive nature of the lunar dust.

• 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.



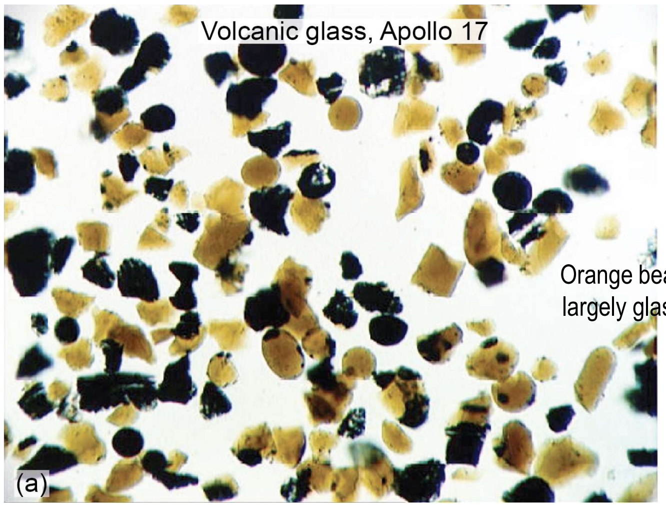




*C. B. Dryer, et al., "Ice Mining in Lunar Permanently Shadowed Regions," SRR / PTMSS 9th Joint Mtg, Golden, CO, June 12 -15, 2018. .

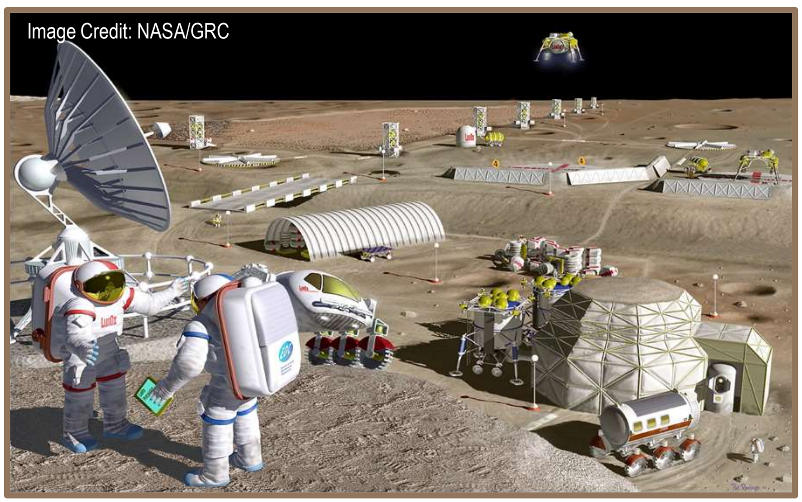
Volcanic Glass from the Apollo 17 Mission to Taurus Littrow is Attractive for LUNOX Production

Black beads largely crystalline



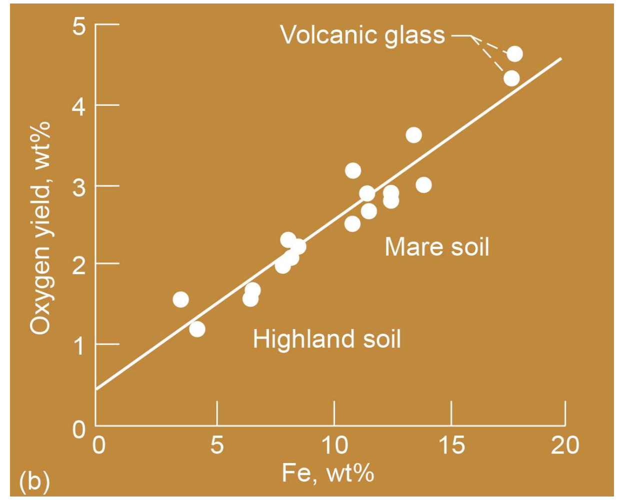
Orange beads largely glass

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



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.



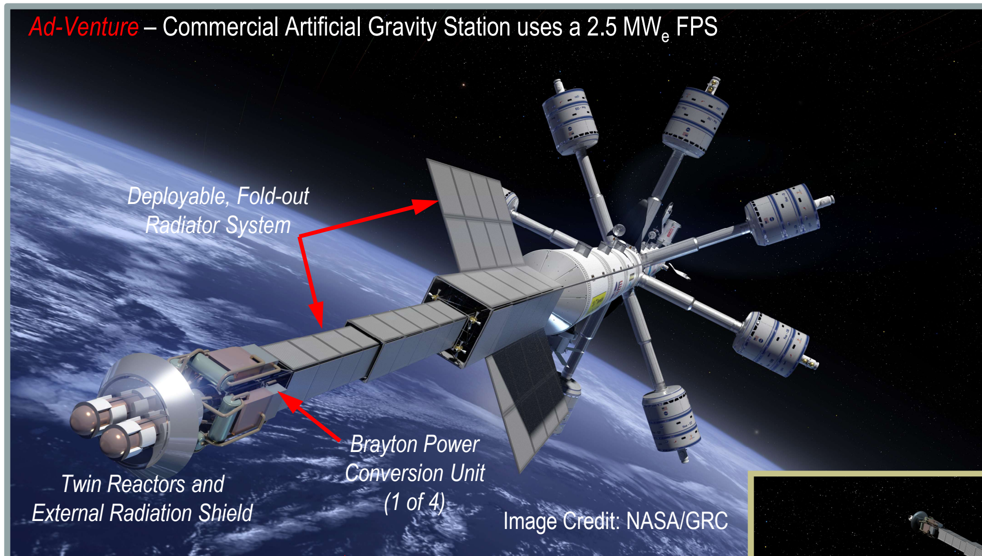
Ref: Carlton Allen, et al., "Oxygen extraction from lunar soils and pyroclastic glass", *J. Geophysical Research*, Nov. 25, 1996

Large regional pyroclastic deposits include:

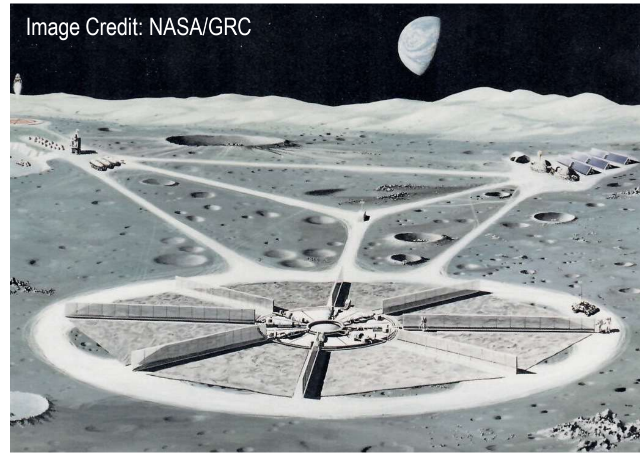
(1) Aristarchus Plateau (~49,015 km^2)
(2) Southern Sinus Aestuum (10,360 km^2)
(3) Rima Bode (~6,620 km^2)
(4) Sulpicius Gallus (4,320 km^2)
(5) Southern Mare Vaporum (~4,130 km^2)
(6) Taurus Littrow (~2,940 km^2) ✓

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

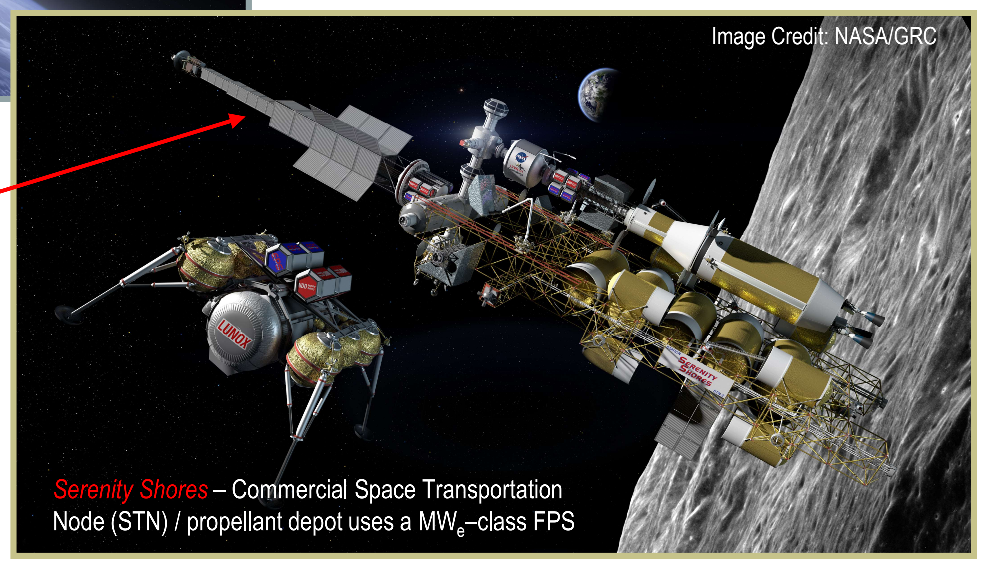


Megawatt-class Lunar FPS with Surface Radiator Panel
– Number of units will depend on mining production rates

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.

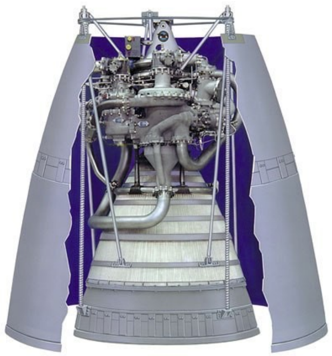
Ref: Human Exploration of Mars Design Reference Architecture 5.0, NASA-SP-2009-566-ADD2, pp.136-138, March 2014



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

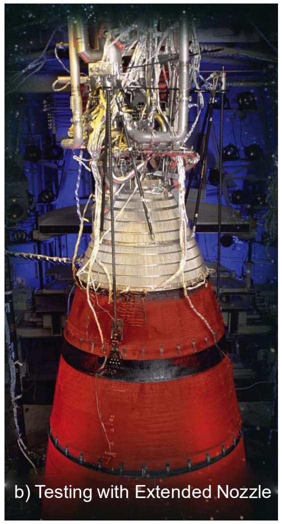
Propulsion Options: RL10B-2 LO_2/LH_2 Chemical Rocket and Nuclear Thermal Rocket (NTR) Engine

RL10B-2 Engine

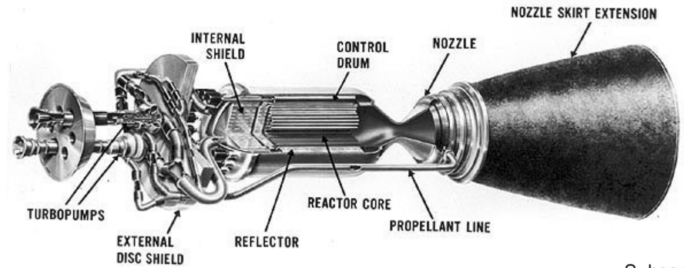


a) Retracted Nozzle Configuration

(Source of Images: Aerojet-Rocketdyne)

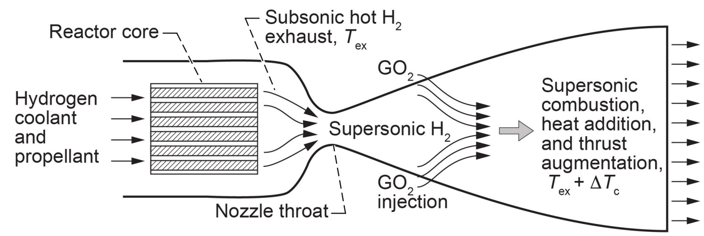


b) Testing with Extended Nozzle



NTR Engine Components

"LO_2 Augmented" NTR (LANTR) Schematic



RL10B-2 Chemical Rocket Engine Performance Parameters:

- Propellants / MR: LO_2 & LH_2 at 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**
- T/W_{eng}: **~37.3**

Small Nuclear Rocket Engine (SNRE) Performance Parameters:

- Propellant: LH_2
- Engine Cycle: **Expander**
- Thrust Level: **16.5 klb_f**
- Reactor Exit Temperature: **~2734 K**
- Chamber Pressure: **1000 psi**
- Nozzle Area Ratio: **300:1**
- Specific Impulse (I_{sp}): **~900 s**
- T/W_{eng}: **~3.02**

SNRE with "O_2 Afterburner Nozzle" Performance Parameters:

- Propellant: **LH_2 & LO_2; MR = 0 to 5**
- Engine Cycle: **Expander / O_2-rich GG**
- Thrust Level: **16.5 – 56.8 klb_f**
- Reactor Exit Temperature: ~2734 K
- Chamber Pressure: 1000 psi
- Nozzle Area Ratio: 300:1
- Specific Impulse (I_{sp}): **~900 – 516 s**
- T/W_{eng}: **~3.02 – 9.02**

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

Ref: S. K. Borowski, et al., "Commercial and Human Settlement of the Moon and Cislunar Space – A Look Ahead at the Possibilities Over the Next 50 Years", AIAA-2019-3917.

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, equatorially 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.

• 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

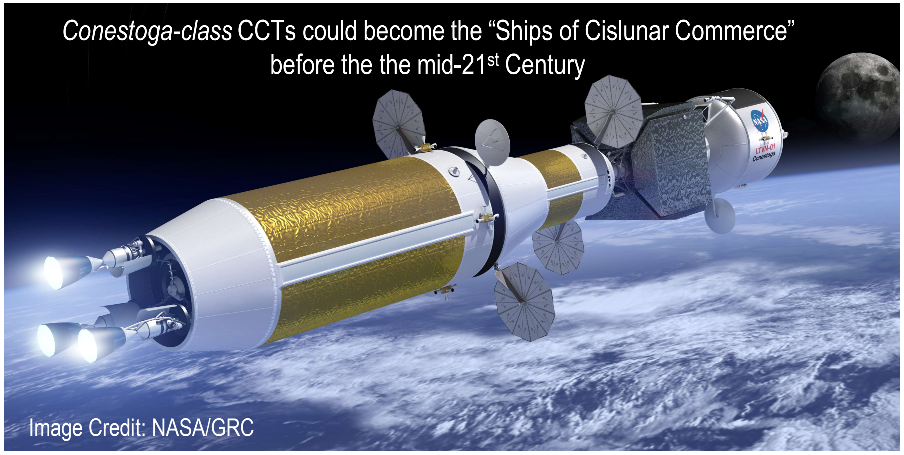
• Cutting the Earth-Moon transit times in half to ~36 hours increases the mission's total ΔV budget by ~25% – from ~8 to 10 km/s. For 24 hour LEO to LLO transit times the increase is ~62.5% – from ~8 to 13 km/s.

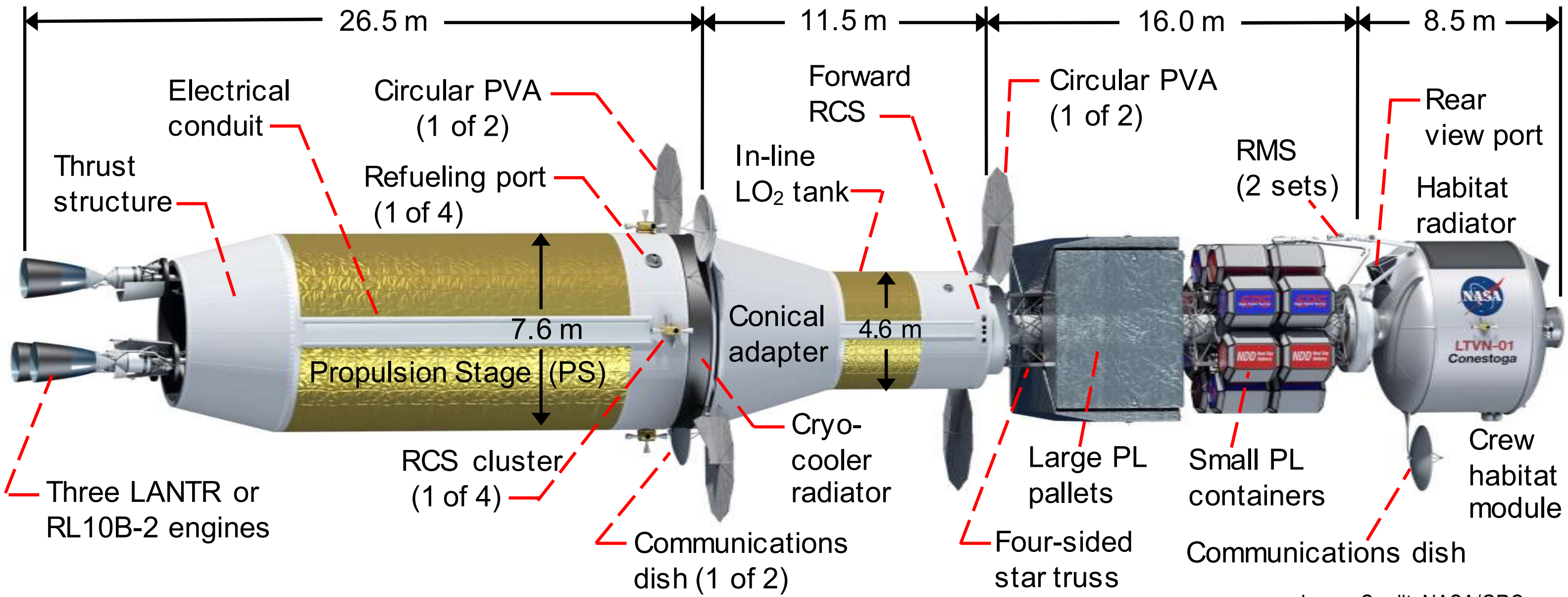
• For round trip LEO to LPO missions, a "3-burn" LOC and TEI maneuver is baselined which requires additional ΔV and time (~2.5 hr) to complete.

Conestoga – A Reusable Space-based Crew Cargo Transport

Uses a Common LH_2 PS and In-line LO_2 Tank Assembly

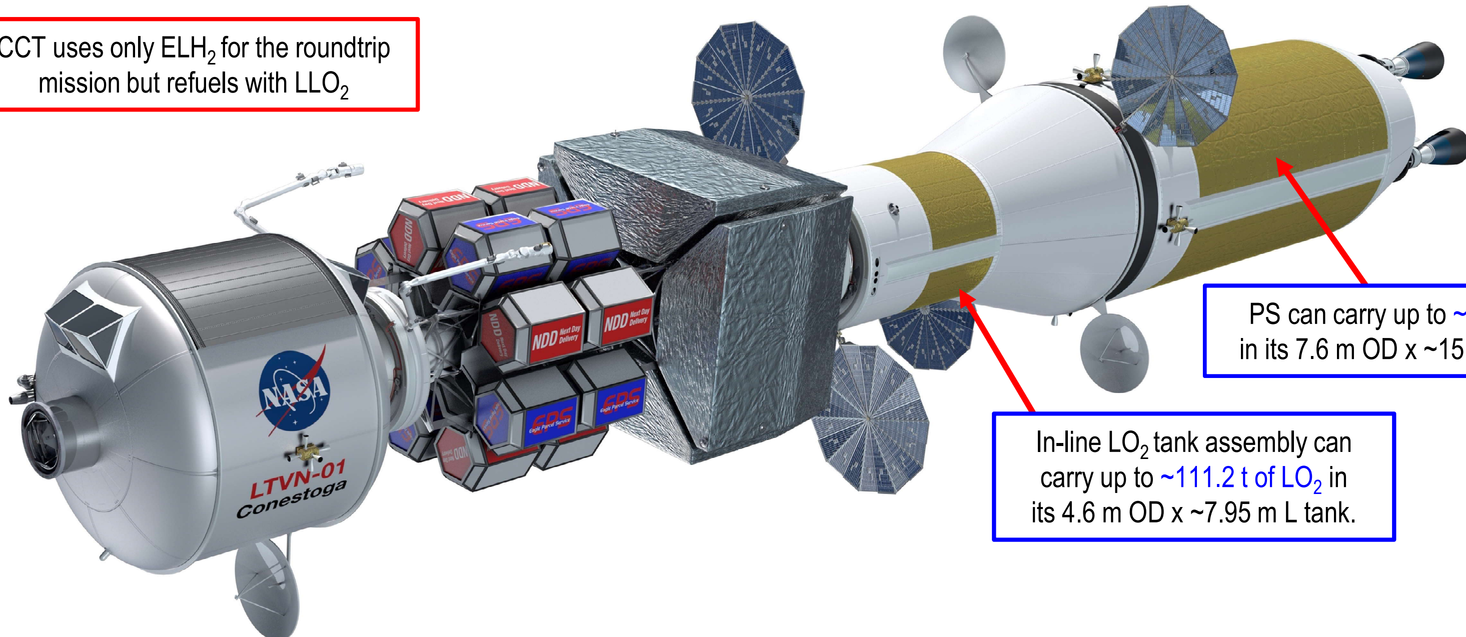
Conestoga Wagons, the "Ships of Inland Commerce," Transported Settlers, Farm Produce, and Freight across Pennsylvania and Neighboring States for over 150 years





Conestoga Crewed Cargo Transport (CCT) Mission to LLO

CCT uses only ELH_2 for the roundtrip mission but refuels with LLO_2



PS can carry up to ~39.8 t LH_2 in its 7.6 m OD x ~15.7 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.

***LANTR** CCT delivers **20 t** of cargo*

(LEO ⟶ LLO ⟶ LEO)

- **72-hr** "1-way" transit times
- Total Mission ΔV ~8.049 km/s
- Habitat Module w/4 people ~10.8 t
- Star Truss (16 m) w/20 t Payload ~31.5 t
- In-line LO_2 tank element ~81.7 t (~74.7 t LO_2)
- Common LH_2 PS ~ **71.3 t** (~39.8 t LH_2)
- Refuel LLO_2 **~54.9 t**
- IMLEO **~195.3 t**
- Return PL ~250 kg
- TLI: MR/Isp~3.3/577 s; LOC:~1.5/672 s; TEI:~4.3/541 s; EOC:~4.2/544 s
- Total Mission Burn Time: **~25.3 min**

***RL10B-2** CCT delivers **20 t** of cargo*

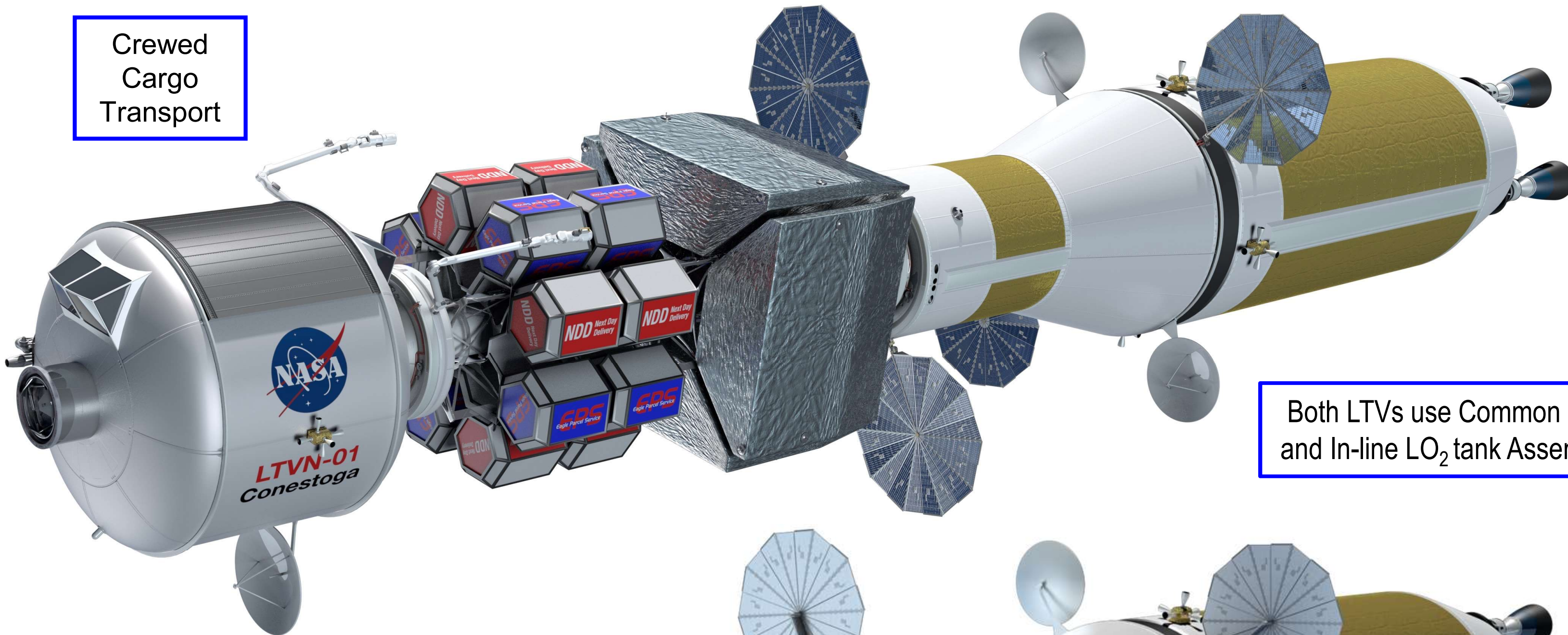
(LEO ⟶ LLO ⟶ LEO)

- **72-hr** "1-way" transit times
- Total Mission ΔV ~8.145 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 element ~106.3 t (~99.6 t LO_2)
- Common LH_2 PS ~ **43.6 t** (~26.6 t LH_2)
- Refuel LLO_2 **~54.6 t**
- IMLEO **~191.5 t**
- Return PL ~250 kg
- RL10B-2: MR / Isp~ 5.88:1 / 465.5 s
- Total Mission Burn Time: **~40.9 min**

Image Credit: NASA/GRC

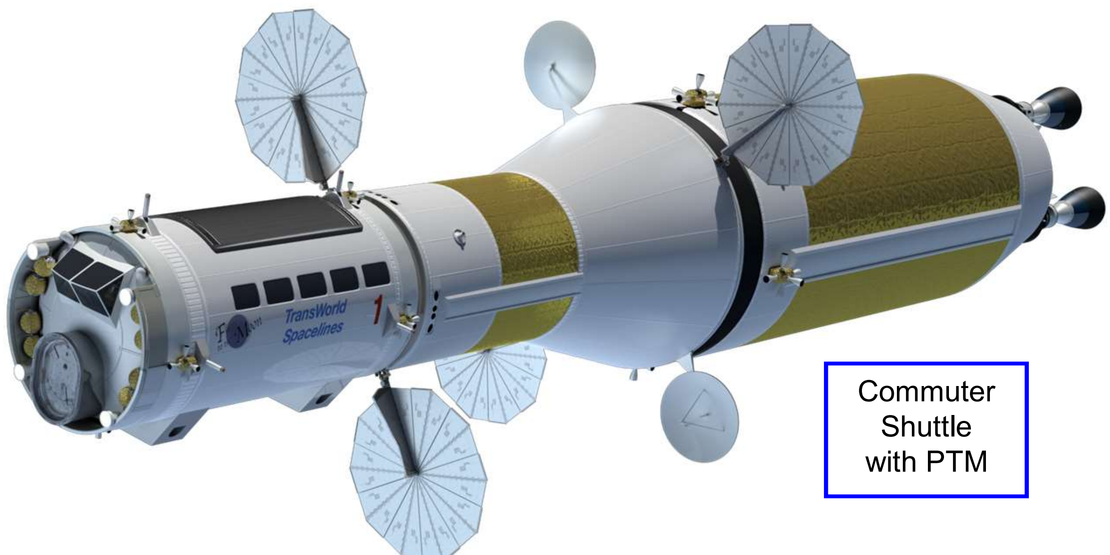
Relative Size of the *Conestoga* Crewed Cargo Transport and Passenger Commuter Shuttle

Crewed Cargo Transport



Both LTVs use Common PS and In-line LO_2 tank Assembly

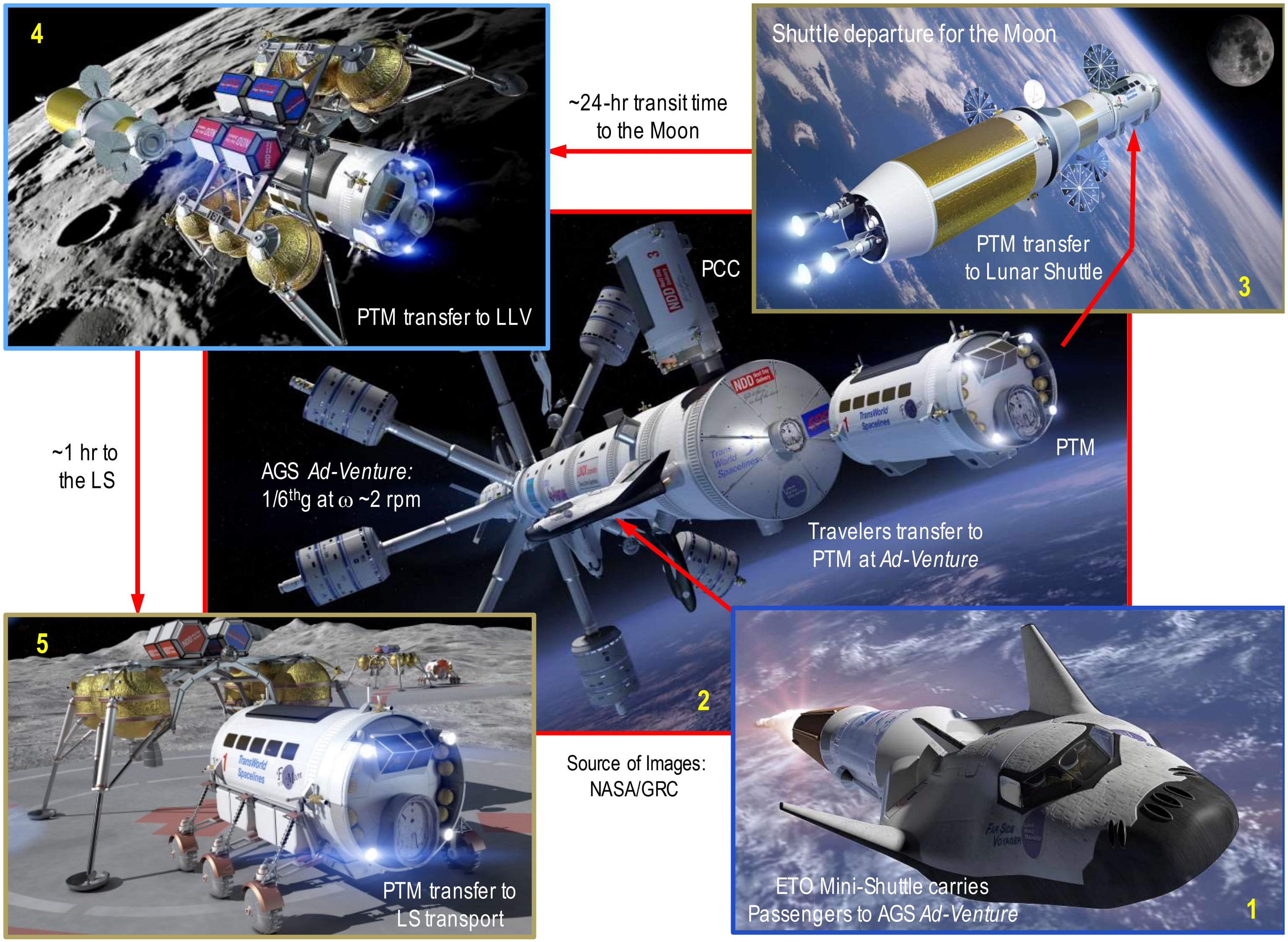
For Commuter Shuttle Missions, the Habitat Module, Saddle Truss and its attached Payload are replaced with a Passenger Transport Module (PTM)



Commuter Shuttle with PTM

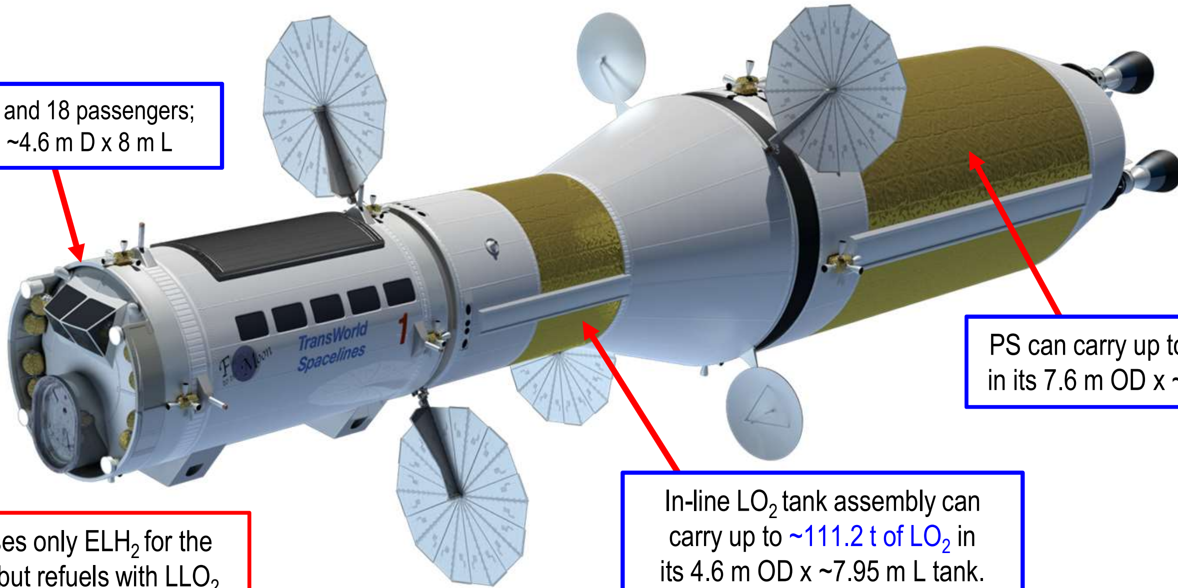
Source of Images: NASA/GRC

How Might a Typical Commuter Flight to the Moon Proceed?



Commuter Shuttle Mission to LLO using only LUNOX Refueling

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



PS can carry up to ~39.8 t ELH_2 in its 7.6 m OD x ~15.7 m L tank

NOTE: Shuttle uses only ELH_2 for the roundtrip mission but refuels with LLO_2

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.

LANTR shortest transit time mission

(LEO ⟶ LLO ⟶ LEO)

- **33.1-hr** "1-way" transit times
- Total Mission ΔV ~10.416 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~117.9 t (~111.2 t LO_2)
- Common LH_2 PS ~ **71.1 t** (~39.8 t ELH_2)
- IMLEO **~204 t**
- Refuel LUNOX **~80.3 t**
- LANTR engines operate O_2-rich Out and Back: MR~5; I_{sp}~516 s
- Total Mission Burn Time: **~25.3 min**

RL10B-2 shortest transit time mission

(LEO ⟶ LLO ⟶ LEO)

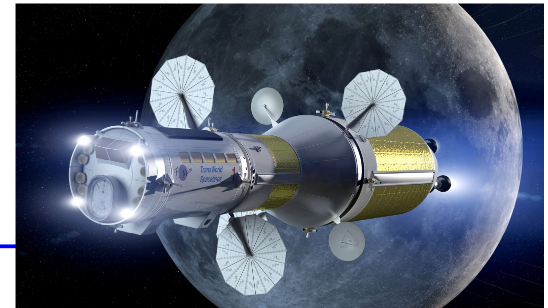
- **31.1-hr** "1-way" transit times
- Total Mission ΔV ~10.966 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~117.7 t (~111.2 t LO_2)
- Common LH_2 PS ~ **49.2 t** (~32.2 t ELH_2)
- IMLEO **~181.9 t**
- Refuel LUNOX **~76.5 t**
- RL10B-2: MR / Isp~ 5.88:1 / 465.5 s
- Total Mission Burn Time: **~50 min**

Image Credit: NASA/GRC

Total LUNOX Required for "Weekly" Commuter Flights

RL10B-2 Shuttle
Departing LEO
for the Moon

RL10B-2 Shuttle
Headed Home



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

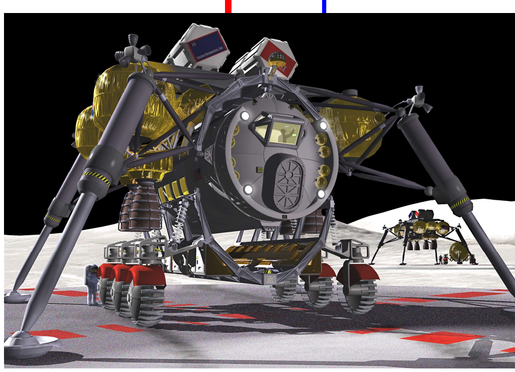
RL10B-2 Shuttle**: (76.5 t LUNOX /mission/week)
x 52 weeks/year = 3,978 t/yr

LLV*+: (33.8 t LUNOX + 6.14 t LH_2 / flight)
x (3.06 LLV flights/week) x (52 weeks/year) = 5,378 t/yr
+ 977 t/yr (LH_2)

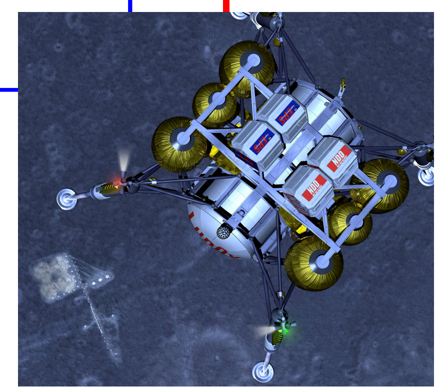
LLV*#: (49.1 t LUNOX# + 8.92 t LH_2 / round trip flight)
x (1 flight/LLV/week) x 52 weeks/year = 2,553 t/yr
+ 463 t/yr (LH_2)

Total LUNOX Production = 11,909 t/yr
Total LH_2 Required = 1,440 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

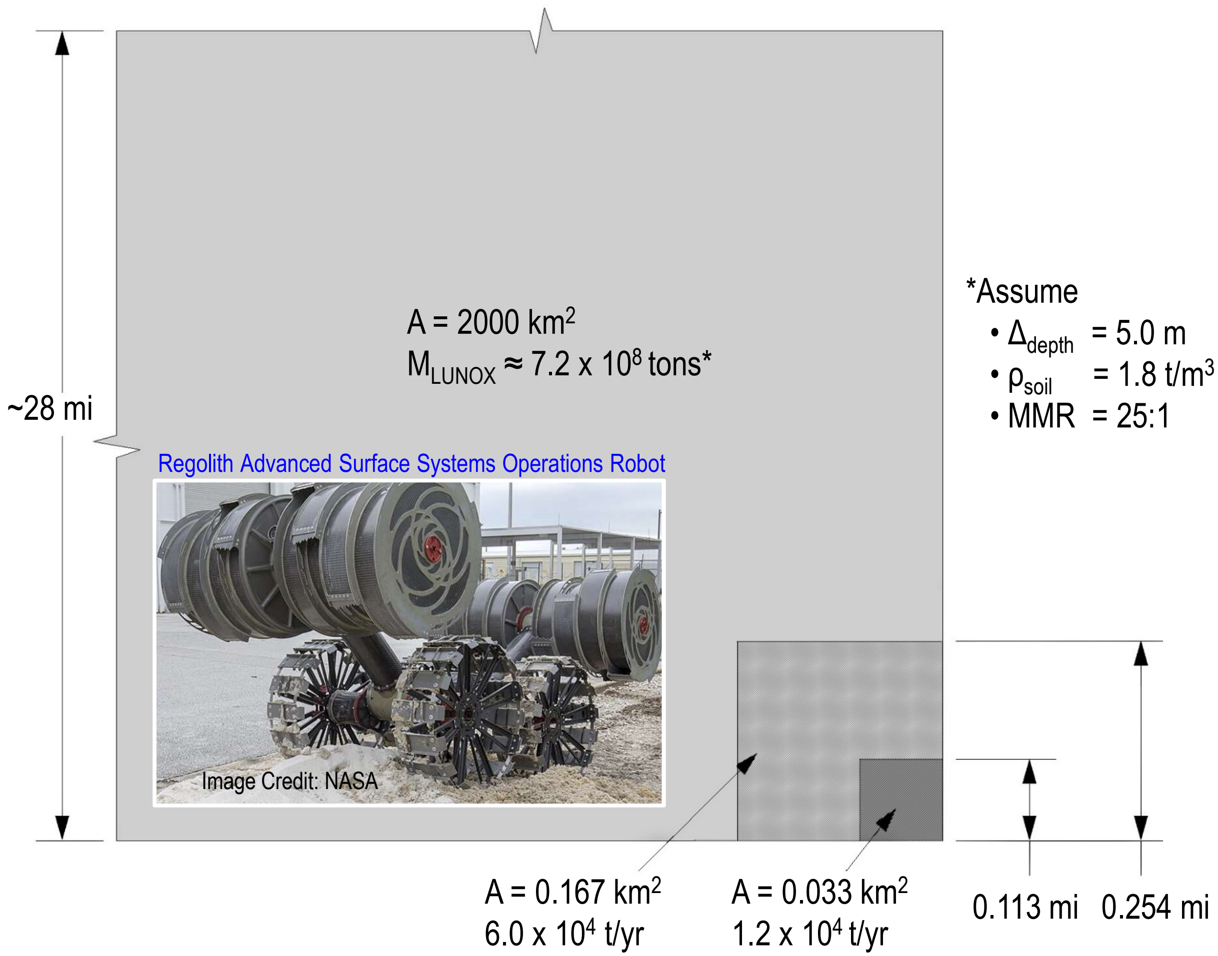


Tanker LLV Delivering
LUNOX to LLO Depot

Source of Images: NASA/GRC

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.



*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 x 10^5 t/yr at MMR = 25:1
- Assuming 12 LUNOX production plants – each producing 1000 t/yr – each plant processes ~2.5 x 10^4 t/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 ~46 x 10^6 t of SWI H_2. To the northwest is Mare Serenitatis, another attractive location for He-3 mining and LUNOX production.

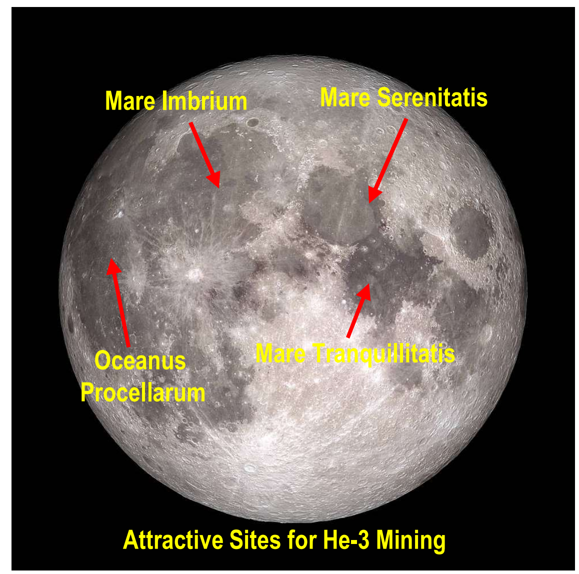
• By right-sizing the PS LH_2 tank for the RL10B-2 shuttle, 24-hr transits to and from LLO appear possible if LLH_2 is supplied to both the LLVs and shuttles. For 5 shuttle flights/week, the LUNOX production rate and mining area increase to 85,000 t/yr and ~0.236 km^2. The required amount of LLH_2 is ~15,000 t/yr and the annual He-3 production rate would be just under 2.5 t/yr.

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)

Summary and Conclusions

• Commercialization and human settlement of the Moon and cislunar space will be greatly aided by the development and utilization of lunar derived propellants, fission power systems, STNs, and reusable propulsion systems with long operating lifetimes – 10s of hours not 10s of minutes.

• Lunar derived propellants from polar ice deposits, are 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 the lunar regolith during He-3 mining.

• Combining LDP with chemical and LANTR propulsion can lead to a robust LTS with unique mission capabilities. It is also worth noting that missions using the lower mass RL10B-2 engine have overall performance comparable to or better than those using the heavier LANTR engine and have a simpler concept-of-operations as well.

• In this, the 50th anniversary year of the Apollo 11 lunar landing, it is comforting to know that work is underway on many of the key technologies and systems discussed in this paper.

• With industry interested in developing cislunar commerce and competitive forces at work, the timeline to develop and implement the capabilities discussed here could well be accelerated beyond anything currently being envisioned so that future Dr. Floyds may have the opportunity to experience "for real" – a routine flight to the Moon.