AIAA-2019-3971

“Commercialization and Human Settlement of the Moon and Cislunar Space – A Look Ahead at the Possibilities Over the Next 50 Years”

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Presentation Overview

• 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 private sector over the next several 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 ∆Vs 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.

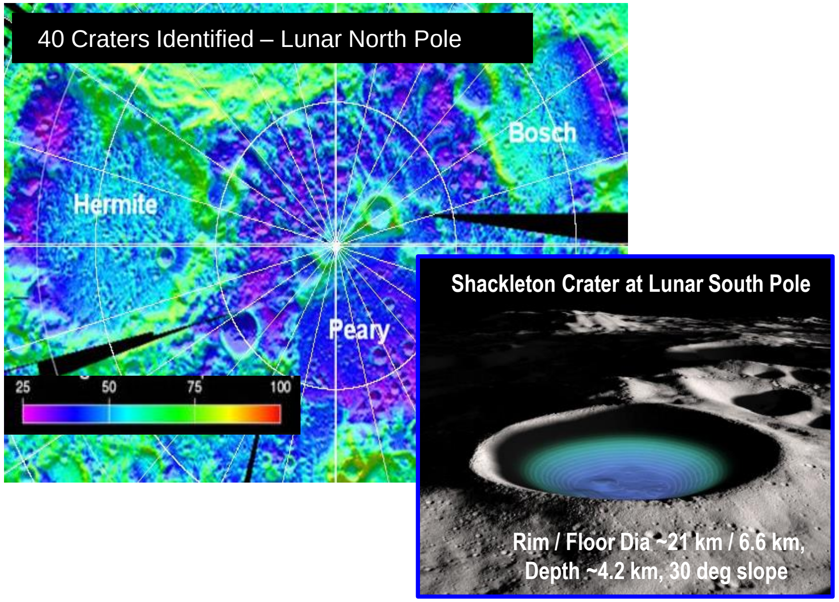
- The world's 10 coldest mines are located in Russia's extreme northeastern territory. At the coldest of these mines, Sarylakh, the temperatures can drop to nearly -50 C (~223 K).

- By contrast, the temperatures inside the polar craters, where the LPI is thought to exist, are ~30 – 50 K – more than 5x 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*, heat is applied to the regolith surface using directed sunlight, or subsurface, via heating elements, 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

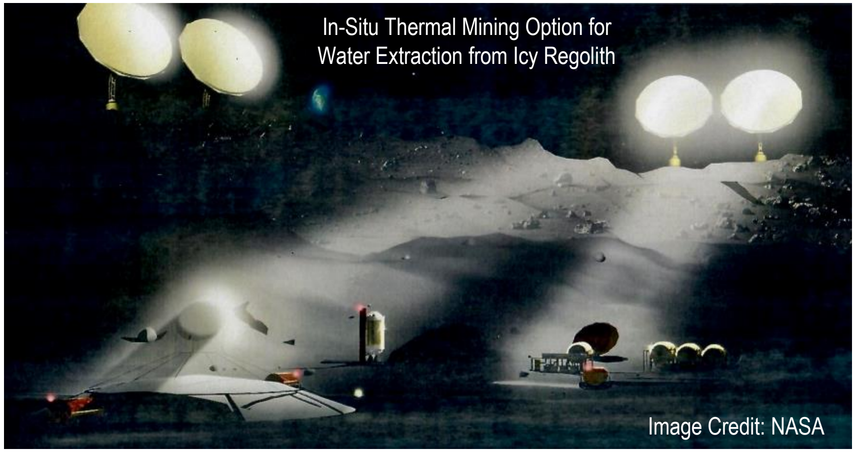
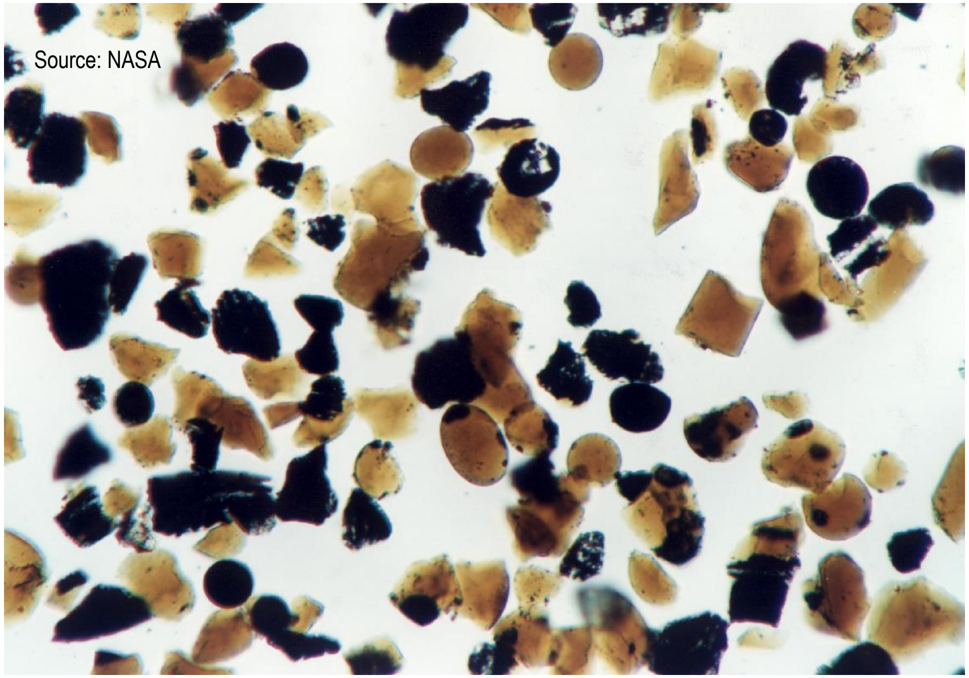

In-Situ Thermal Mining Option for Water Extraction from Icy Regolith

Image Credit: NASA

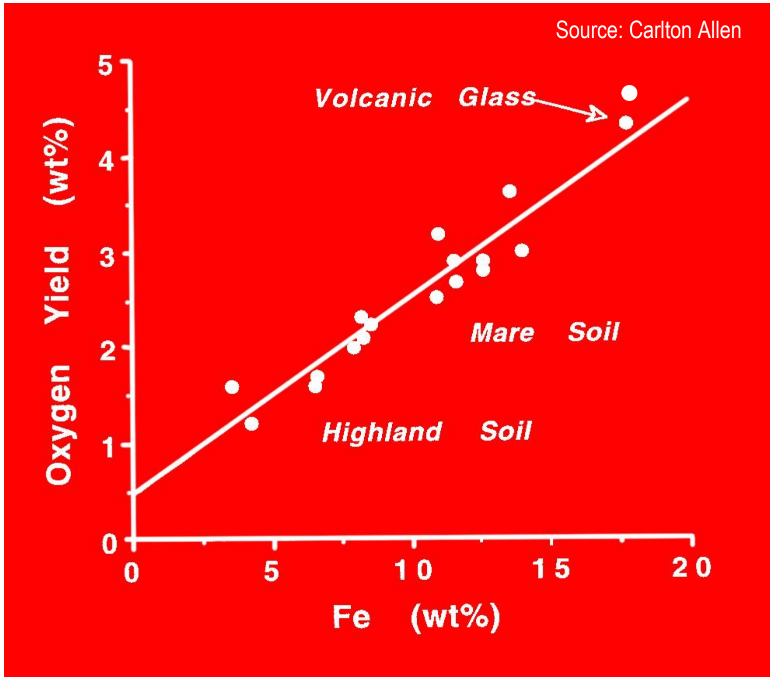
*D. Kornuta, et al., Commercial Lunar Propellant Architecture – A Collaborative Study of Lunar Propellant Production (2018)

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



Source: NASA

The best lunar oxygen ore found during the Apollo Program is the volcanic glass, found at Taurus Littrow. The glass beads are fine grained and ~40 mm in diameter. The orange beads are clear glass, while the black beads cooled at bit more slowly and had a chance to crystallize.



Source: Carlton Allen

Oxygen yield is directly related to iron abundance for the full range of soil compositions. Highest yields are from " FeO-rich" volcanic glass.

Oxygen production from "FeO-rich" volcanic glass is a 2 step process:

$FeO + H_2$ -------> $Fe + H_2O$
(Hydrogen Reduction & Water Formation)

$2\ H_2O$ -------> $2H_2 + O_2$ (*LUNOX*)
(Water Electrolysis & Hydrogen Recycling)

Ref: Carlton Allen, et al., "Oxygen extraction from lunar soils and pyroclastic glass", *J. Geophysical Research*, Vol. 101, No. E11, pgs. 26,085 – 26,095, Nov. 25, 1996

Commercial LUNOX Production Facility

Location: "Taurus-Littrow DMD" (~21°N, ~29.5°E)

Vast deposits of "FeO-rich" volcanic glass beads have been identified at numerous sites on the lunar near side. The smallest of these sites, the Taurus-Littrow DMD, is close to the Apollo 17 site, has an areal extent of ~3000 km^2, and is rich in black crystalline and orange glass beads.

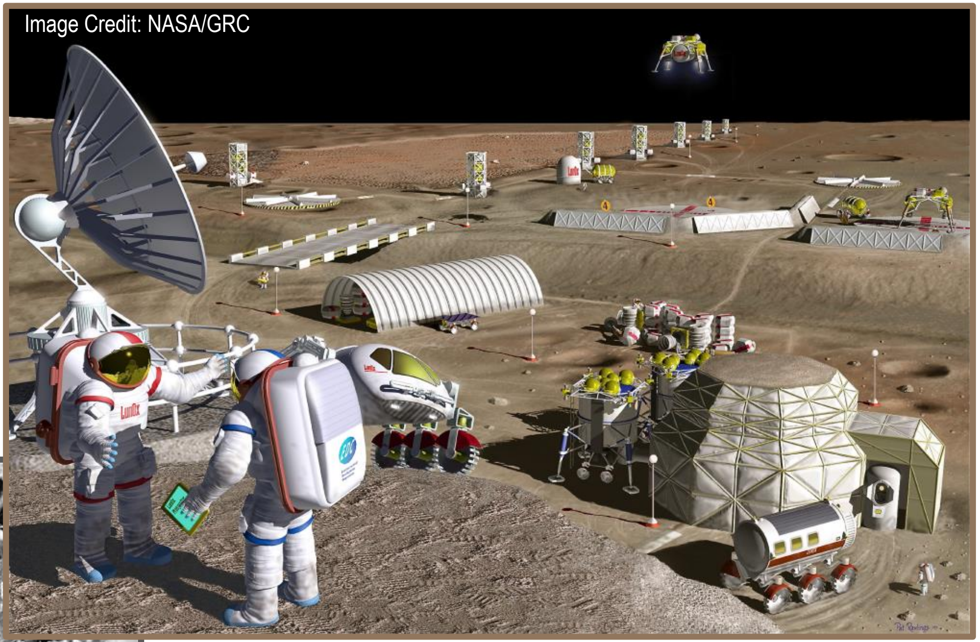
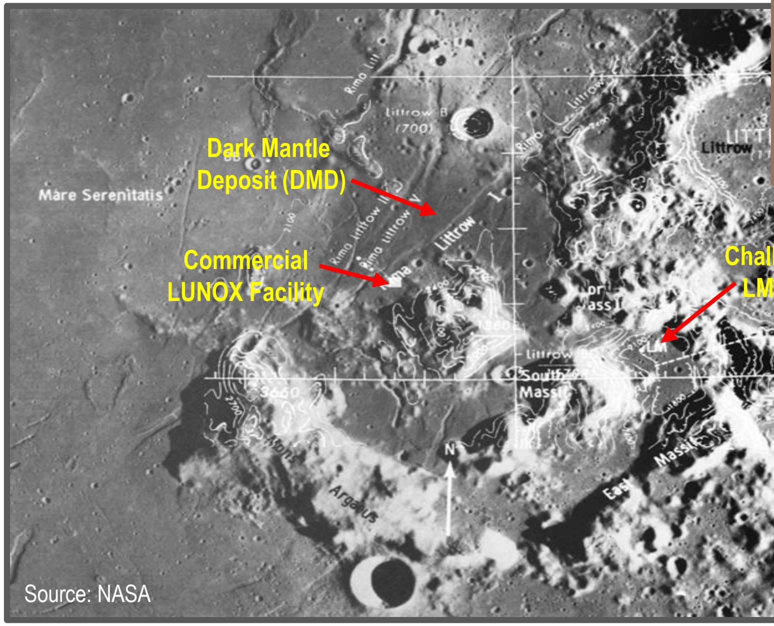


Image Credit: NASA/GRC

Ref: Borowski, et al., "*2001: A Space Odyssey*" Revisited – The Feasibility of 24 Hour Commuter Flights to the Moon Using NTR Propulsion with LUNOX Afterburners", AIAA-1997-2956; also as NASA/TM—1998-208830 / Rev2



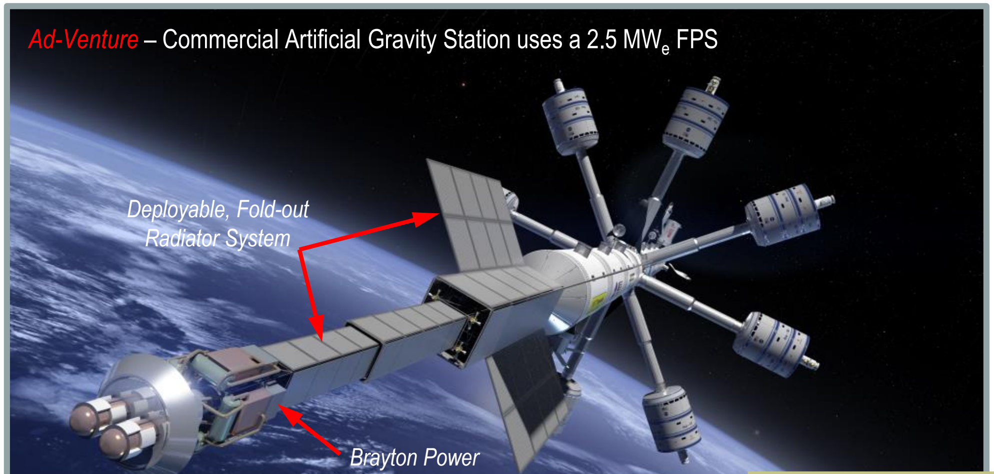
Source: NASA

Index Map Showing the Apollo 17 Landing Site and Major Geographic Features of Taurus-Littrow Region

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

Image Credit: NASA/GRC

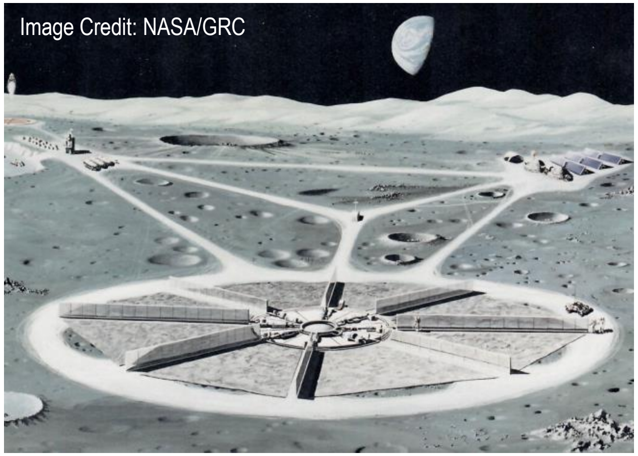


Image Credit: NASA/GRC

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

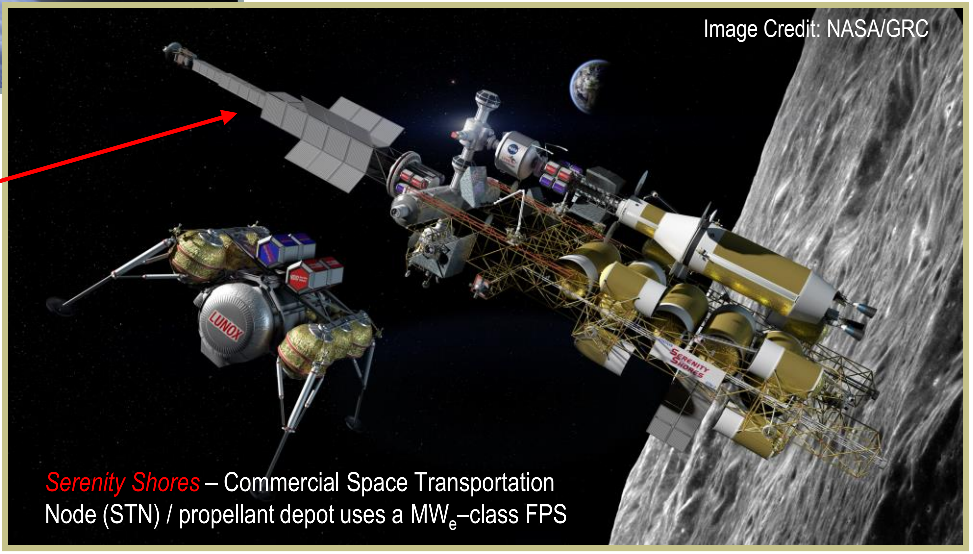
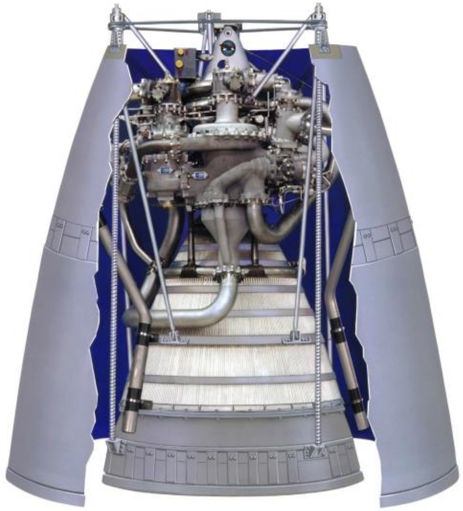
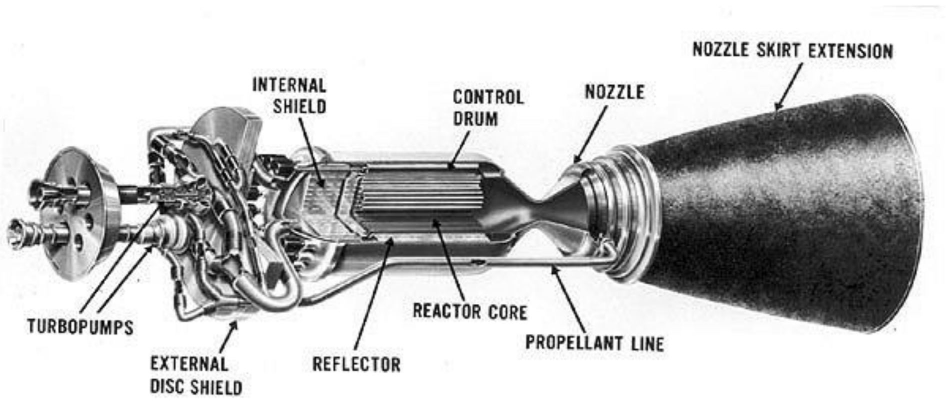


Image Credit: NASA/GRC

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 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**

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

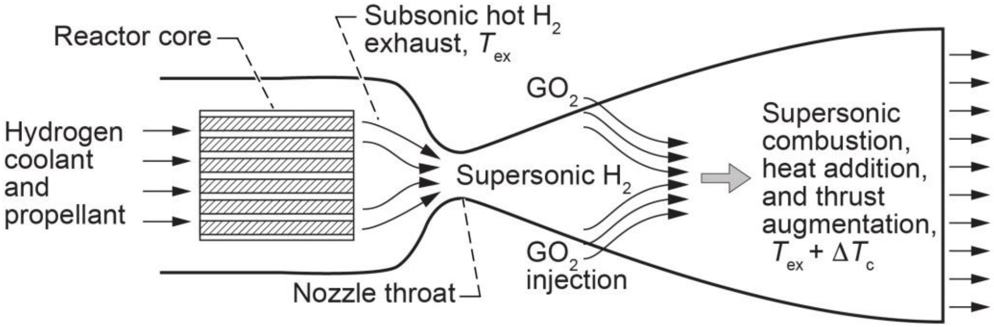
Small Nuclear Rocket Engine (SNRE) Performance Parameters:

- 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**

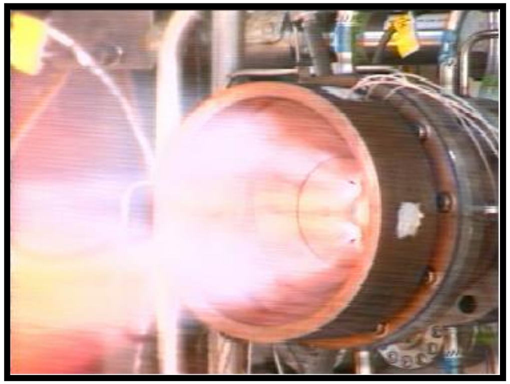
Ref: S. K. Borowski, et al., "Affordable Development and Demonstration of a Small NTR Engine: How Small is Big Enough?", AIAA-2015-4524; alnd NASA/TM—2016-219402

"LO_2-Augmented" NTR (LANTR) Concept:
Operational Features and Performance Characteristics

LANTR adds an O_2 "afterburner" nozzle and O_2-rich GG feed system to a conventional NTR engine that provides a variable thrust and Isp capability, shortens burn times, extends engine life, and allows bipropellant operation



LANTR Schematic



Aerojet / GRC Non-Nuclear O_2 "Afterburner" Nozzle Test*

O/H Mixture Ratio	0	1	2	3	4	5
Delivered I_{sp} (s)	900**	725	637	588	552	516
Thrust Augmentation Factor	1.0	1.611	2.123	2.616	3.066	3.441
Thrust (lb_f)	16,500	26,587	35,026	43,165	50,587	56,779
Engine Mass (lb_m)	5,462	5,677	5,834	5,987	6,139	6,295
Engine T/W	3.02	4.68	6.00	7.21	8.24	9.02

** Fuel Exit Temperature (T_{ex}) = 2734 °K , Chamber Pressure = 1000 psi, and NAR = 300:1

*Ref: M. J. Bulman and T. M. Neill, "Simulated LANTR Testing", AIAA 2000–3897

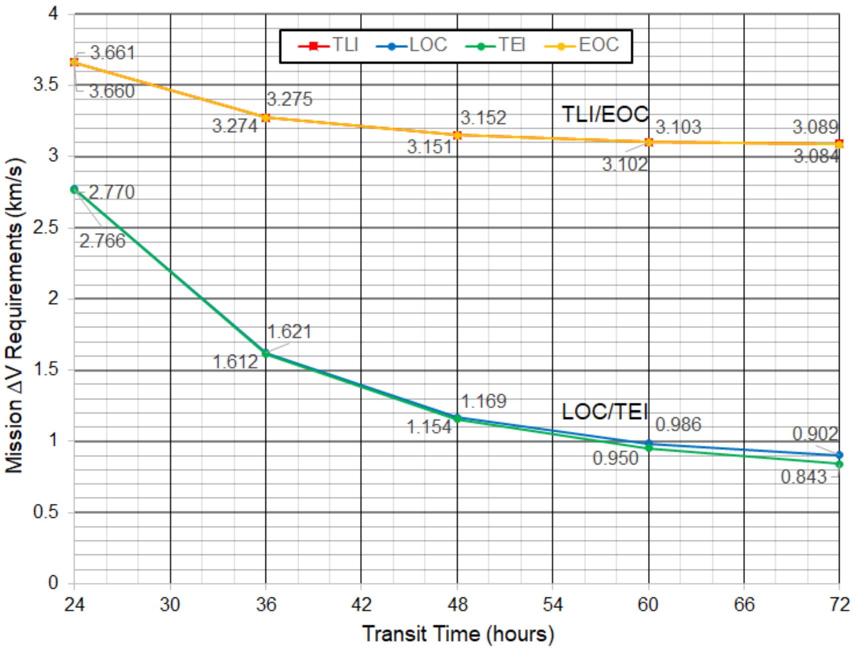
Growth Missions and Faster Trip Times are Possible using Space Transportation Nodes (STNs) with Refueling Capability

Over time we envision the development of a totally space-based LTS with different types of LTVs operating between STNs located in LEO, equaorially LLO and LPO. The STN provides a propellant depot andcargo transfer function and offers a convenient staging location wherepropellant, 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 personnelrepresenting both government and private ventures, more frequent flights of shorter duration could become commonplace.

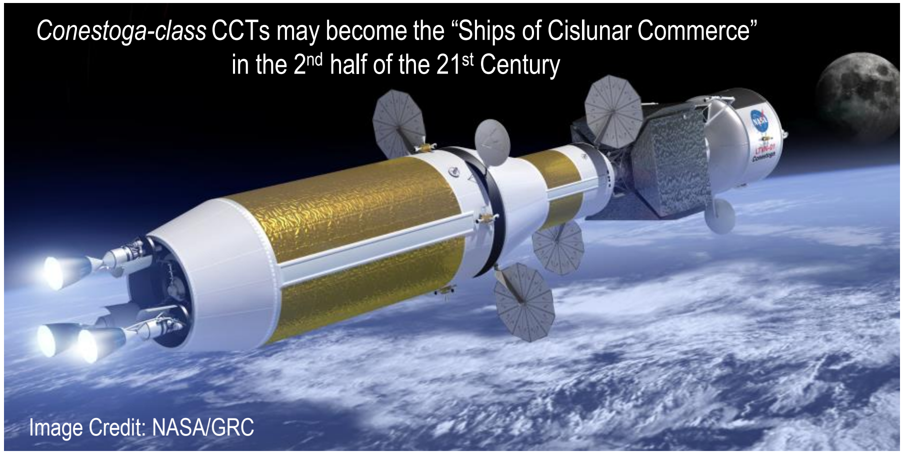


Cutting the Earth-Moon transit times in half to ~36 hours will require the mission's total ΔV budget to increase by ~25% – from ~8 to 10 km/s. For 24 hour LEO to LLO transit times the total mission ΔV increases by ~62.5% – from ~8 to 13 km/s.

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 may become the "Ships of Cislunar Commerce" in the 2nd half of the 21st Century

Image Credit: NASA/GRC

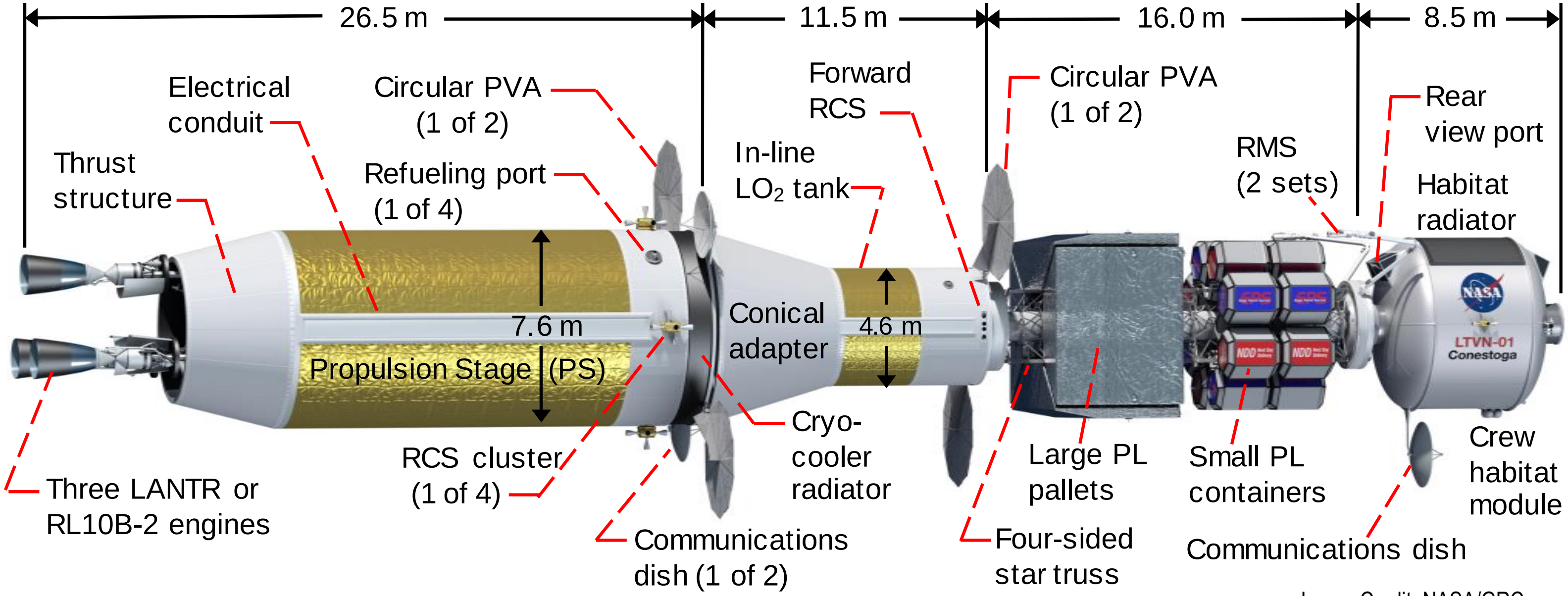
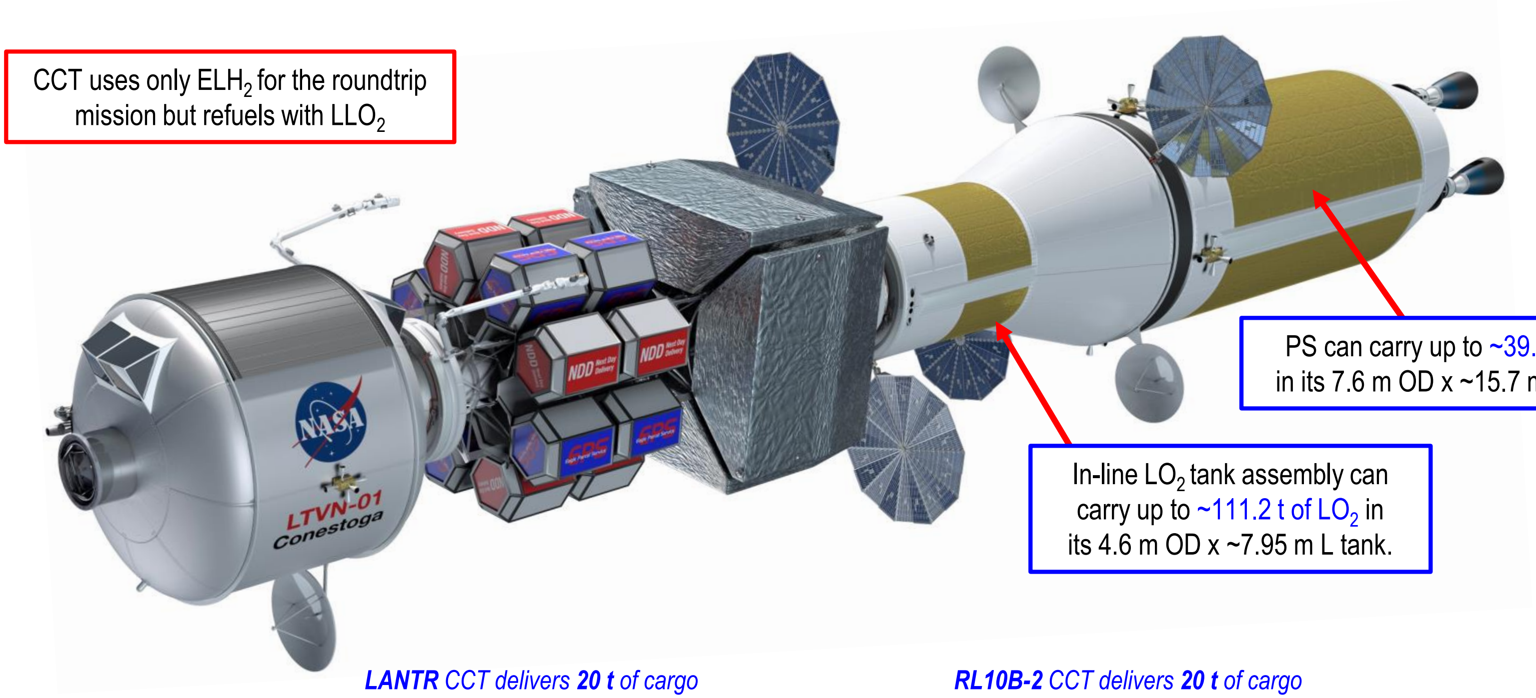


Image Credit: NASA/GRC

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 ∆V ~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**

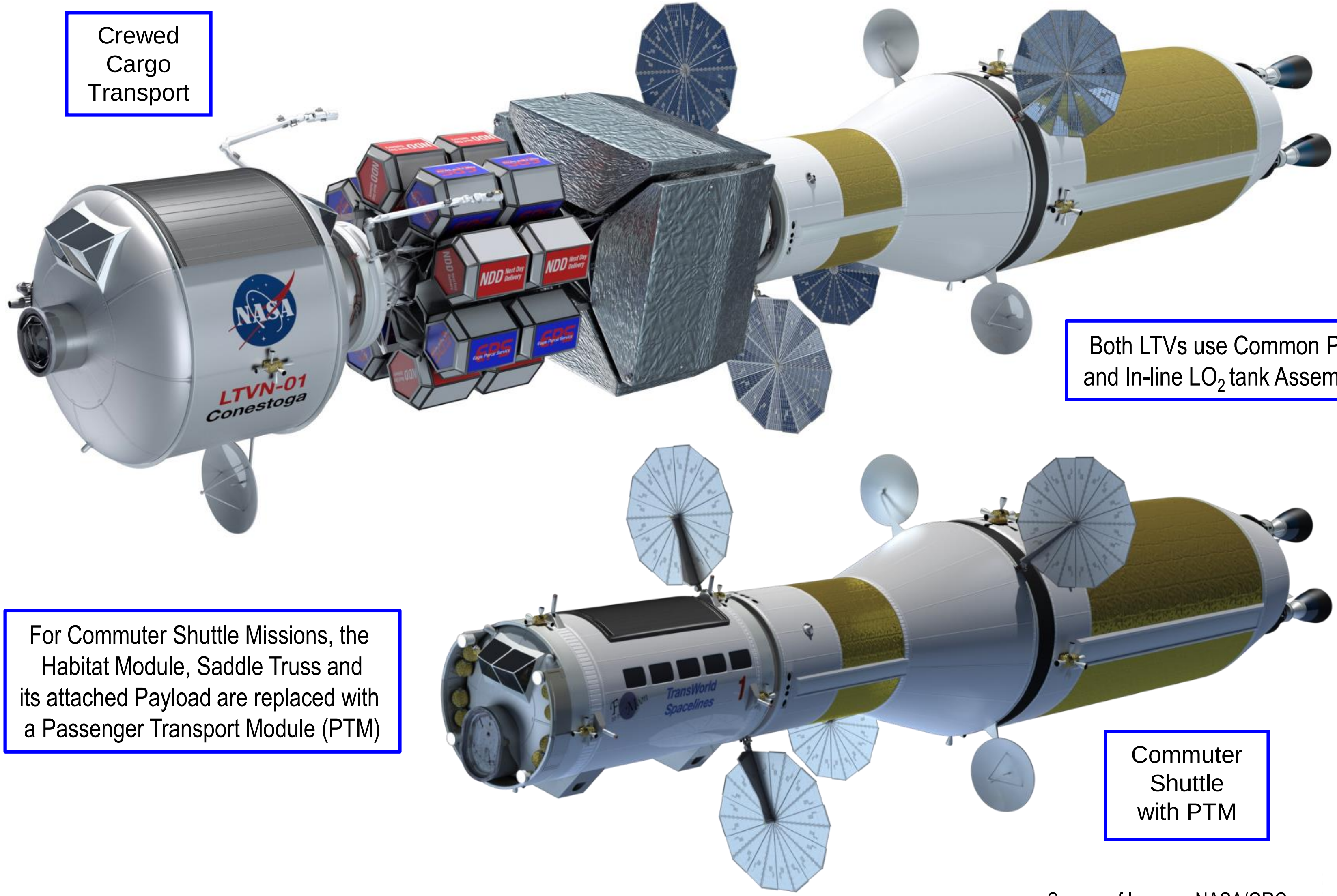
***RL10B-2** CCT delivers **20 t** of cargo*

(LEO ⟶ LLO ⟶ LEO)

- **72-hr** "1-way" transit times
- Total Mission ∆V ~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

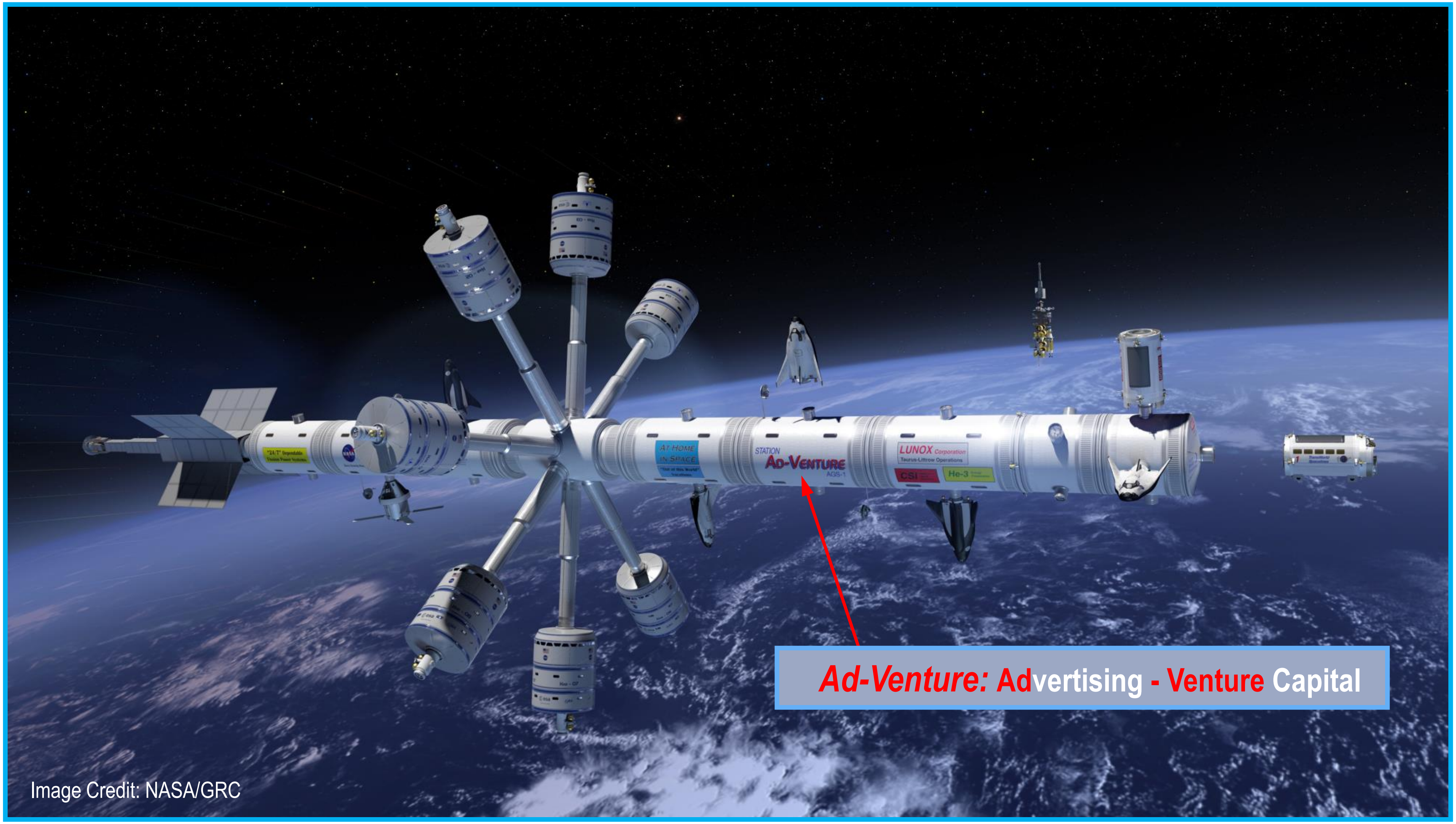
Both LTVs use Common PS and In-line LO_2 tank Assembly

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

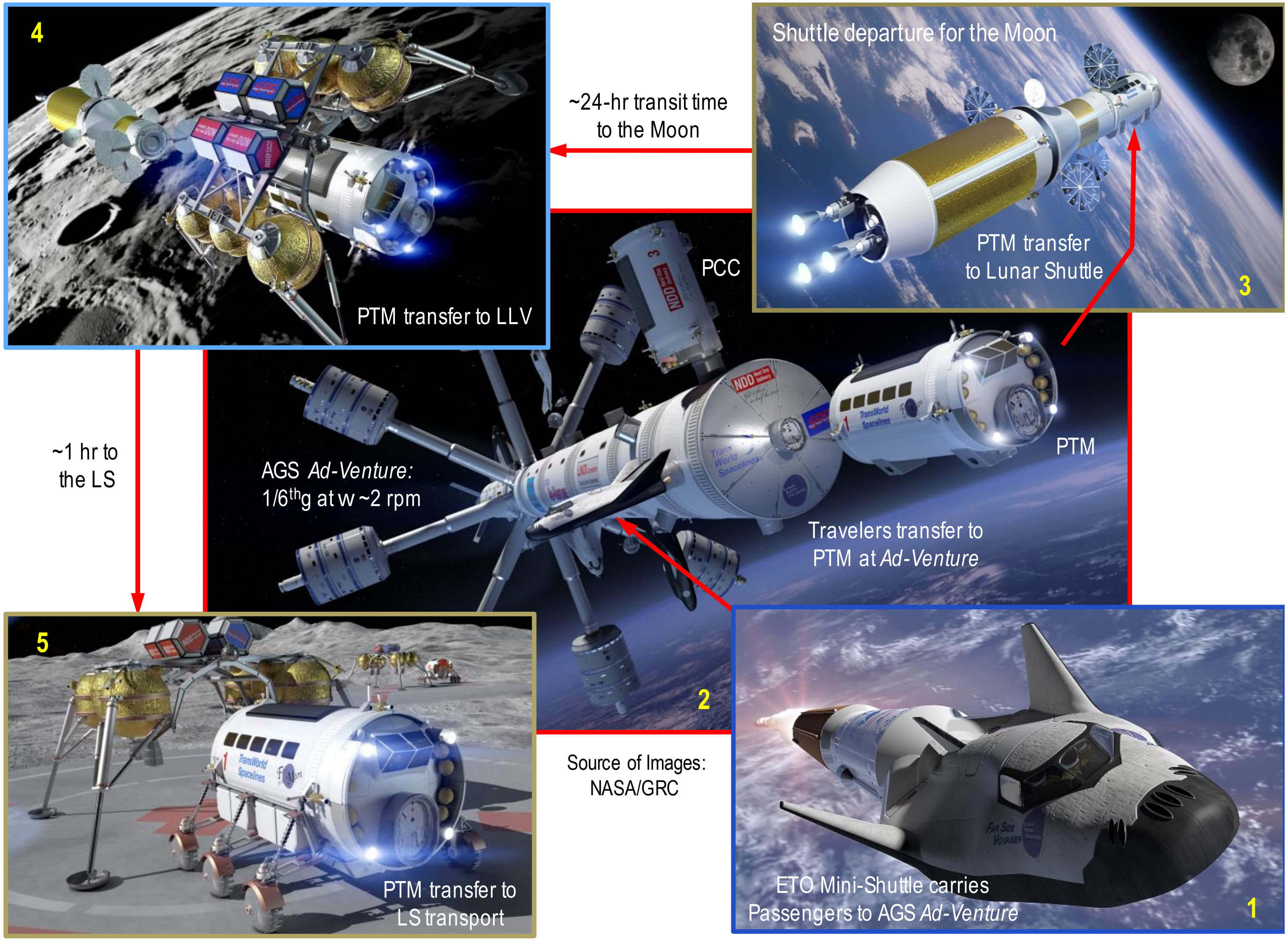
Ad-Venture – Commercial Artificial Gravity Station (AGS) with Facilities Supporting Power Generation, R&D, Tourism, Cislunar Industry & Space Transportation



Ad-Venture: **Ad**vertising - **Venture** Capital

Image Credit: NASA/GRC

How Might a Typical Commuter Flight to the Moon Proceed?



1

ETO Mini-Shuttle carries Passengers to AGS *Ad-Venture*

2

AGS *Ad-Venture:*
1/6thg at w ~2 rpm

PCC

PTM

Travelers transfer to PTM at *Ad-Venture*

3

Shuttle departure for the Moon

PTM transfer to Lunar Shuttle

~24-hr transit time to the Moon

4

PTM transfer to LLV

~1 hr to the LS

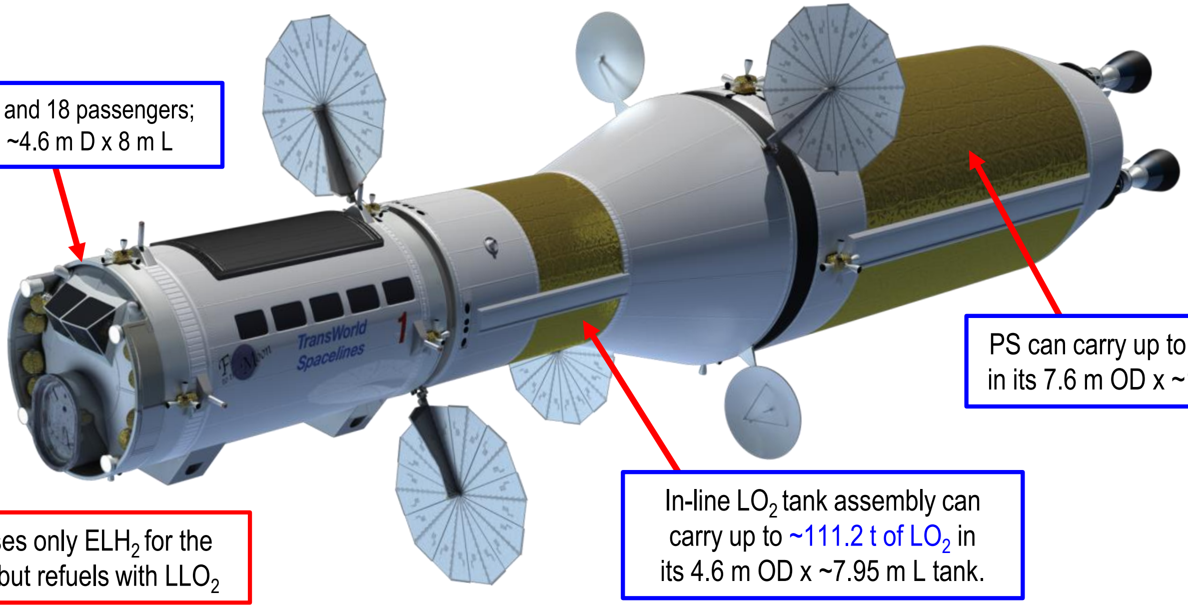
5

PTM transfer to LS transport

Source of Images: NASA/GRC

Source of Images: NASA/GRC

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

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.

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

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

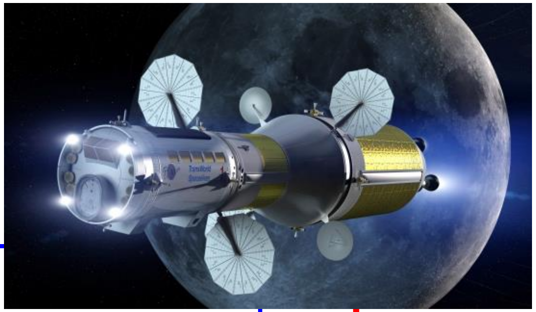
✓

(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):

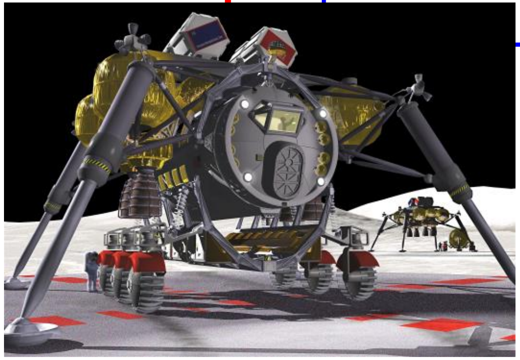
RL10B-2 Shuttle**: (76.5 t LUNOX/mission/week)
x 52 weeks/year = 3,978 t/yr

LLV^{*+}: (33.8 t LUNOX / flight)
x (3.06 LLV flights/week) x (52 weeks/year) = 5,378 t/yr

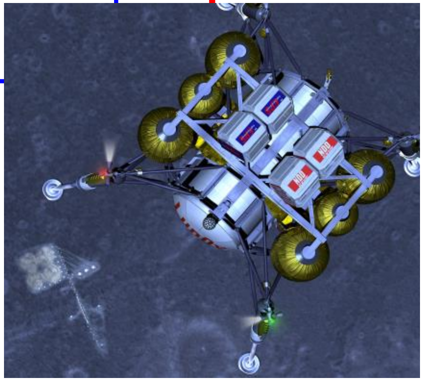
LLV$^{*\#}$: (49.1 t LUNOX$^{\#}$ / round trip flight)
x (1 flight/LLV/week) x 52 weeks/year = 2,553 t/yr

Total LUNOX Production = 11,909 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

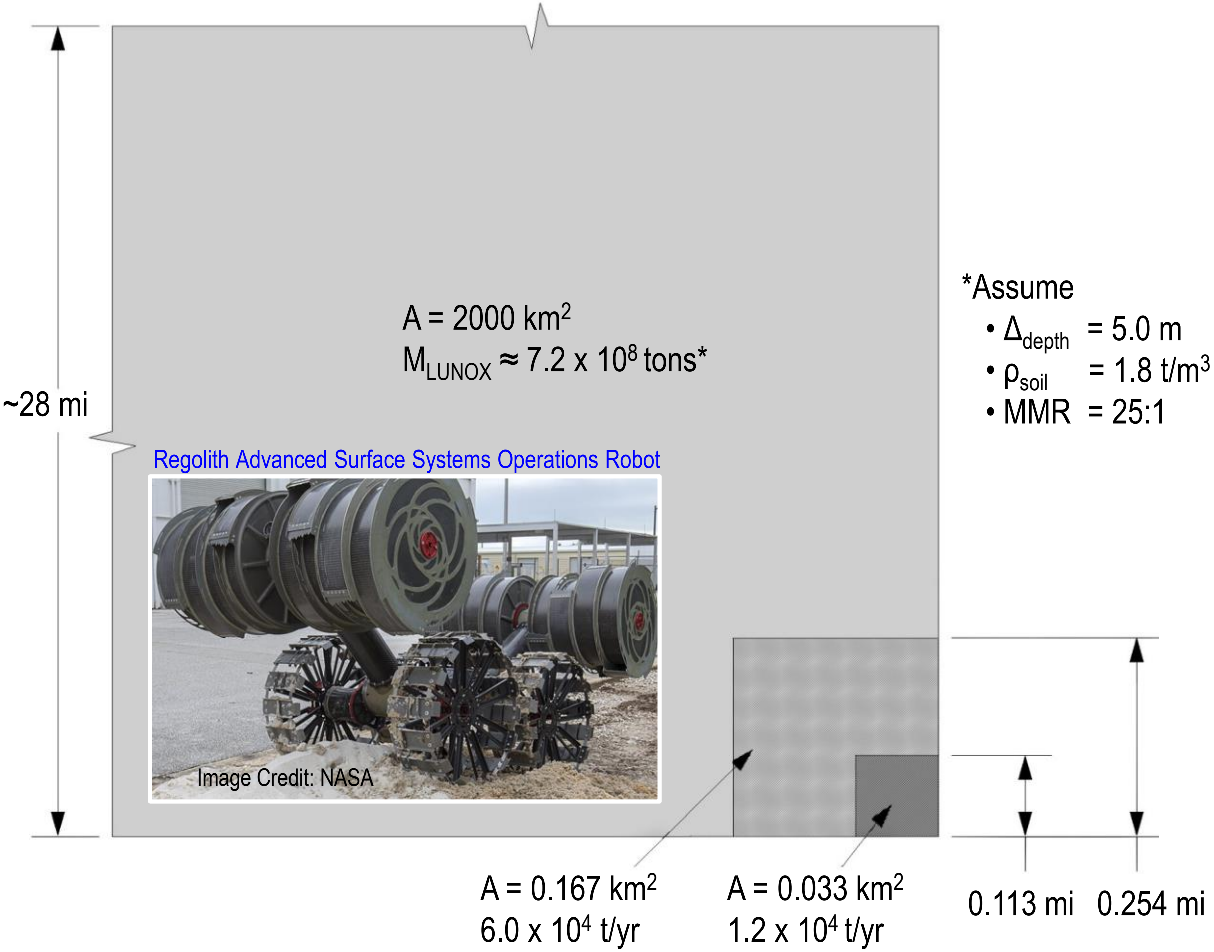


Tanker LLV Delivering
LUNOX to LLO Depot

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.



~28 mi

A = 2000 km^2
$M_{LUNOX} \approx 7.2 \times 10^8$ tons*

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

Regolith Advanced Surface Systems Operations Robot

Image Credit: NASA

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

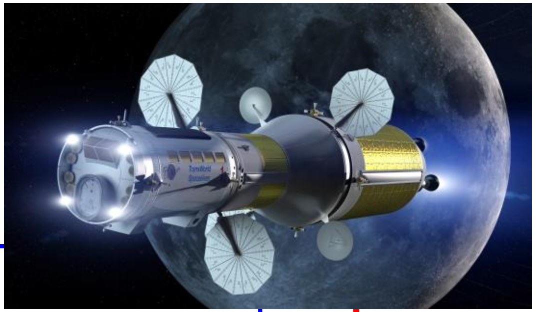
Plant Mining Rate:
- To produce 12,000 t of LUNOX annually requires glass throughput of ~3.0×10^5 t/yr at MMR = 25:1
- Assuming 12 LUNOX production plants – each producing 1000 t/yr – each plant processes ~2.5×10^4 t/yr
- The mining equipment at each plant includes 2 automated RASSOR-type excavator/ 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$_e$

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

Total LUNOX Required for "Weekly" Commuter Flights

RL10B-2 Shuttle
Departing LEO
for the Moon

RL10B-2 Shuttle
Headed Home



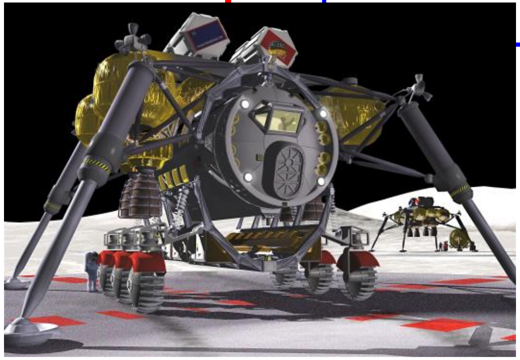
31.1 Hour "1-Way" Transits (15 t / 20 Person PTM):

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$_2$)

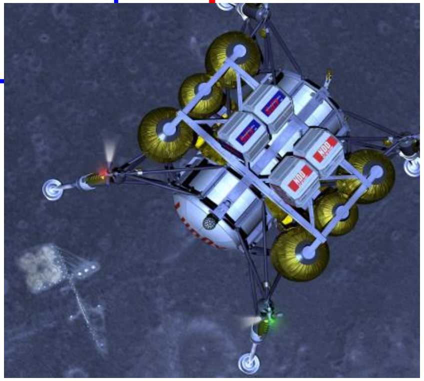
Total LUNOX Production = 11,909 t/yr
Total LH$_2$ Required = 1,440 t/yr



LLV Unloading PTM onto
a Mobile Surface Vehicle

**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

Tanker LLV Delivering
LUNOX to LLO Depot



Source of Images: NASA/GRC

Synergy with an Emerging He-3 Mining Industry

- The large amounts of LH_2 required for the tanker and PTM transport LLVs and methods for delivering it to LLO are concerns. A solution to the LH_2 resupply issue is solar-wind-implanted (SWI) volatiles extraction.

- During He-3 mining, significant quantities of gaseous volatiles are produced as “by-products”. An automated volatile miner design developed by the UW’s FTI was sized to produce ~33 kg of He-3/yr so seven miners can supply ~1494 t of LLH_2 while also producing 231 kg of He-3 annually.

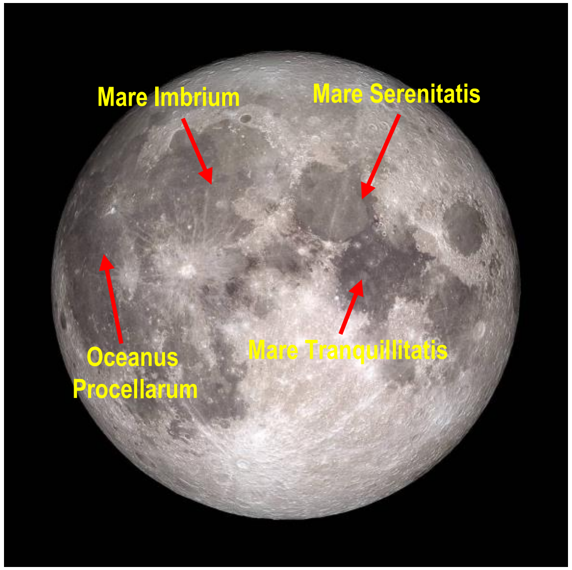
- This value is ~108x smaller then the He-3 mining estimate of 25 t/yr made by Kulcinski and Schmidt in 1990 to support a clean DHe-3 fusion-based power industry supplying the electrical power needs for the entire U.S.*

- 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. Other He-3 mining sites are Mare Imbrium and Oceanus Procellarum.

(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



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*U.S. electrical energy usage: ~240,000 MW_e-yr (1990); ~480,000 MW_e-yr (2018); ~630,000 MW_e-yr (2050)

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

Total LUNOX and LLH$_2$ Needed for Weekly RL10B-2 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, DV_{desc} = 2.115 km/s and DV_{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.

- For acquisition of the needed LLH$_2$, ~14 to 71 automated volatile miners would be required to support a flight rate of 1 to 5 flights/week. The corresponding amounts of He-3 produced annually would be ~462 to 2,343 kg.

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, reusable propulsion systems, and the strategic positioning of STNs in LEO, lunar polar and equatorial orbits. Reusable propulsion systems implies long service life: 10s of hr not 10s of min.

- Lunar derived propellants, specifically LLO_2 and LLH_2 derived 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.

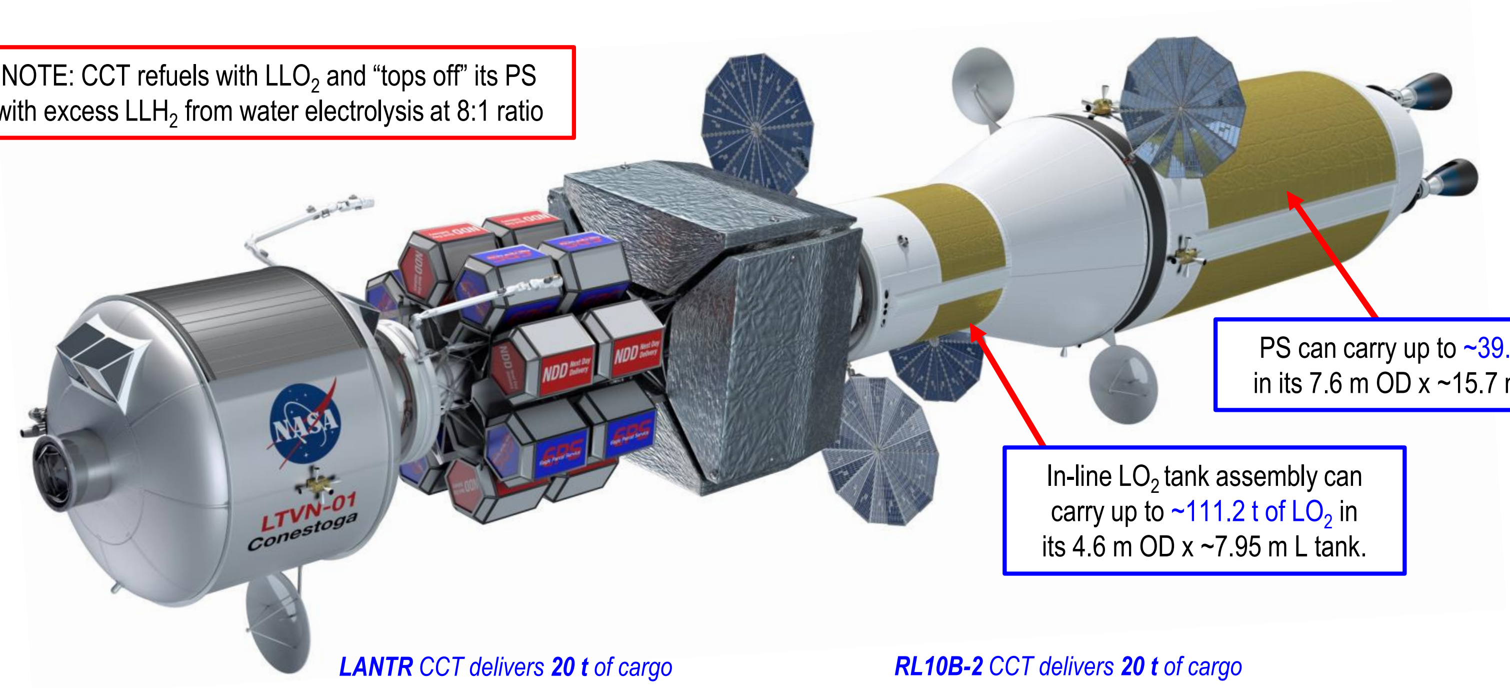
- In this, the 50th anniversary year of the Apollo 11 lunar landing, it is comforting to know that work is underway on many of the key technologies and systems discussed in this paper.

- 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 tomorrow's traveling public may have the opportunity to experience "for real" – a routine flight to the Moon.

Backup

Conestoga Crewed Cargo Transport (CCT) Mission to LPO

NOTE: CCT refuels with LLO_2 and "tops off" its PS with excess LLH_2 from water electrolysis at 8:1 ratio



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 → LPO → LEO)

- **72-hr** "1-way" transit times*
- Total Mission ΔV ~8.378 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 ~71 t (~62.2 t LO_2)
- Common LH_2 PS ~ **73 t** (~39.8 t LH_2)
- Refuel LLO_2 / LLH_2 ~54.4 t / 6.8 t
- IMLEO **~186.3 t**
- Return PL ~250 kg
- TLI: MR/Isp~2.6/604 s; LOC:~0.5/804 s; TEI:~5.0/516 s; EOC:~3.9/557 s
- Total Mission Burn Time: **~29.7 min**

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

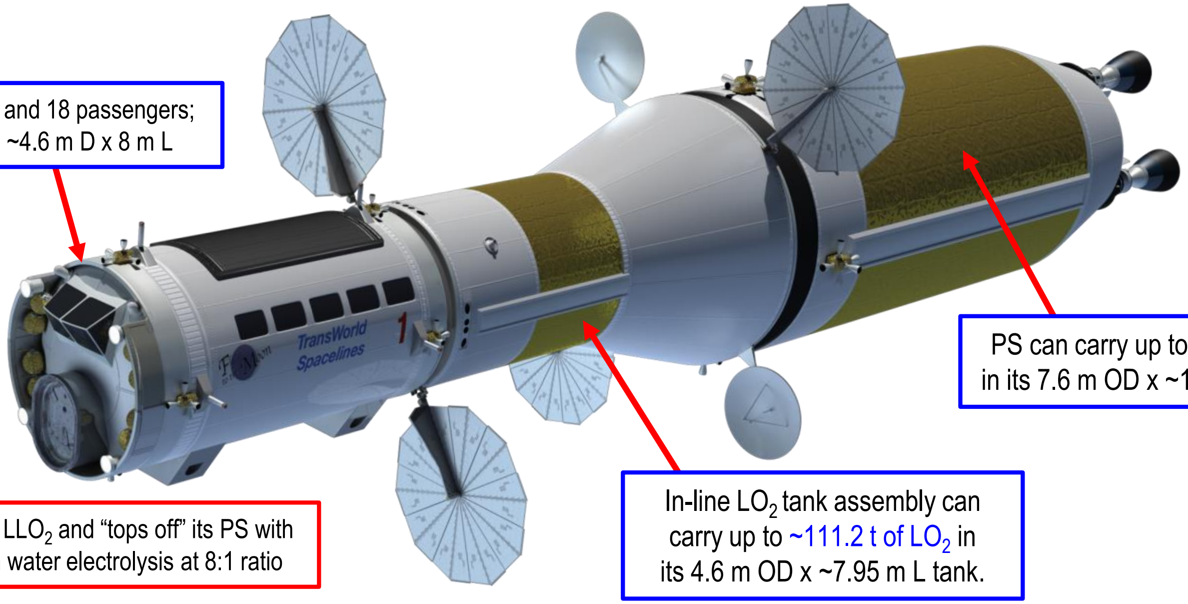
(LEO → LPO → LEO)

- **72-hr** "1-way" transit times*
- Total Mission ΔV ~8.490 km/s
- Habitat Module w/4 people ~10.8 t
- Star Truss (**16 m**) w/20 t Payload ~28.2 t
- In-line LO_2 tank element ~111.7 t (~103.5 t LO_2)
- Common LH_2 PS ~ **41.7 t** (~20.5 t LH_2)
- Refuel LLO_2 / LLH_2 ~55.6 t / 6.95 t
- IMLEO **~192.4 t**
- Return PL ~250 kg
- RL10B-2: MR / Isp~ 5.88:1 / 465.5 s
- Total Mission Burn Time: **~42.2 min**

Image Credit: NASA/GRC

*NOTE: 1-way transit times shown do not include the 2.5-hr long, 3-burn LOC maneuver into LPO

Commuter Shuttle Mission to LPO



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 LH_2
in its 7.6 m OD x ~15.7 m L tank

Shuttle refuels with LLO_2 and "tops off" its PS with
excess LLH_2 from water electrolysis at 8:1 ratio

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 ⟶ LPO ⟶ LEO)

- **31-hr** "1-way" transit times*
- Total Mission ΔV ~12.326 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~119.7 t (~111.2 t LO_2)
- Common LH_2 PS ~ **72.8 t** (~39.8 t LH_2)
- IMLEO **~207.5 t**
- Refuel LLO_2 / LLH_2 ~109 t / 13.6 t
- TLI: MR/Isp~5/516 s; LOC: MR~4.0 / Isp ~552 s, TEI3: MR~4.9, 4.8, 4.0 / I_{sp} ~519, 524, 552 s, EOC: MR/Isp~3.0/588 s
- Total Mission Burn Time: **~34.1 min**

RL10B-2 shortest transit time mission

(LEO ⟶ LPO ⟶ LEO)

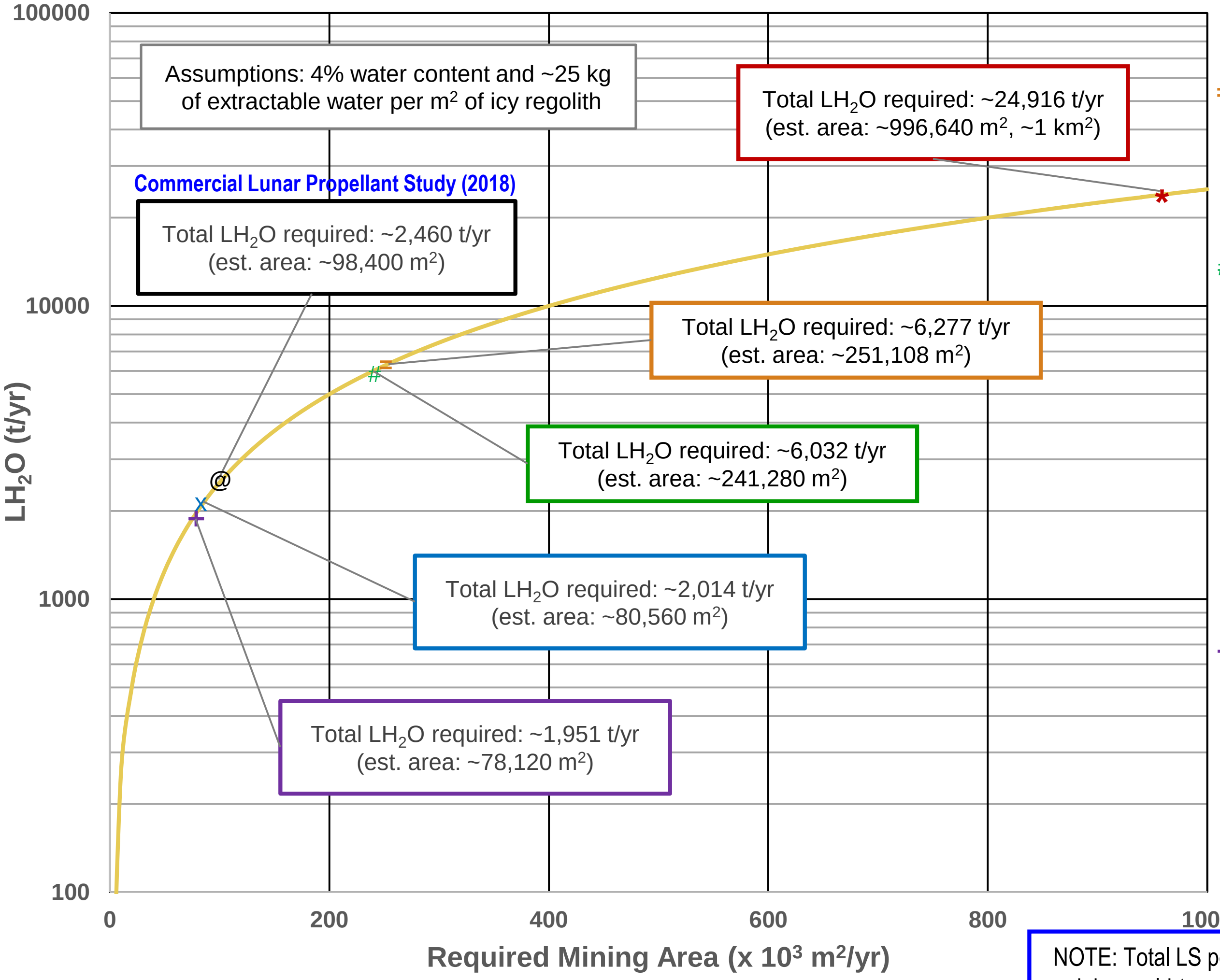
- **34-hr** "1-way" transit times*
- Total Mission ΔV ~11.688 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~89.8 t (~82.8 t LO_2)
- Common LH_2 PS ~**36.6 t** (~19.4 t LH_2)
- IMLEO **~141.4 t**
- Refuel LLO_2 / LLH_2 ~109 t / 13.6 t
- RL10B-2: MR / Isp~ 5.88:1 / 465.5 s
- Total Mission Burn Time: **~51.1 min**

*NOTE: 1-way transit times shown do not include
the 2.5-hr long, 3-burn LOC maneuver into LPO

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

Commercial Lunar Propellant Study (2018)

Total LH_2O required: ~2,460 t/yr
(est. area: ~98,400 m^2)

Total LH_2O required: ~24,916 t/yr
(est. area: ~996,640 m^2, ~1 km^2)

Total LH_2O required: ~6,277 t/yr
(est. area: ~251,108 m^2)

Total LH_2O required: ~6,032 t/yr
(est. area: ~241,280 m^2)

Total LH_2O required: ~2,014 t/yr
(est. area: ~80,560 m^2)

Total LH_2O required: ~1,951 t/yr
(est. area: ~78,120 m^2)

*	Weekly LANTR / RL10B-2 Shuttle flights to LPO, 1-way transits of 31 / 34 hr, 8:1 refuel ratio, LH_2O electrolyzed for Shuttle: 6,376 t; for LLV use: 18,540 t. P_e (MW_e)* ~3.57 at STN; ~10.4 on LS
=	Fast LANTR CCT mission delivers 20 t to LPO in 39.2 hr, 8:1 refuel ratio, 12 missions/yr. LH_2O electrolyzed for CCT use: 1,471 t; for LLV use: 4,806 t. P_e (MW_e)* ~0.823 at STN; ~2.69 on LS
#	Fast RL10B-2 CCT mission delivers 20 t to LPO in 41.7 hr, 8:1 refuel ratio, 12 missions/yr. LH_2O electrolyzed for CCT use: 1,415 t; for LLV use: 4,617 t. P_e (MW_e)* ~0.790 at STN; ~2.58 on LS
x	RL10B-2 CCT mission delivers 20 t to LPO in 72 hr, refuels at 8:1 ratio, then returns to LEO. 6 missions/yr assumed. LH_2O electrolyzed for CCT use: 376 t; for LLV use: 1,638 t. P_e (MW_e)* ~0.210 at STN; ~0.92 on LS
+	LANTR CCT mission delivers 20 t to LPO in 72 hr, refuels at 8:1 ratio, then returns to LEO. 6 missions/yr assumed. LH_2O electrolyzed for CCT use: 367 t; for LLV use: 1,584 t. P_e (MW_e)* ~0.205 at STN; ~0.89 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