"Commercialization and Human Settlement of the Moon and Cislunar Space using ISRU, Fission Surface Power, and Advanced In-Space Propulsion Systems"

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Introduction and Presentation Overview

- Over 50 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 aboard a commercial space plane. He then embarks on a commuter flight to the Moon arriving there ~25 hr later.

- Today, on the 50th anniversary 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 & Clarke's film.

- This presentation looks at key technologies, systems, and supporting infrastructure

  - In-situ resource utilization (ISRU) – using polar icy regolith and volcanic glass as feedstock;
  - Fission power systems (FPS) – to supply abundant "24/7" power on the lunar surface and in orbit;
  - Advanced in-space propulsion systems – allowing bipropellant LO_2/LH_2 operation; and
  - Space transportation nodes (STNs) – provide 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".

- A reusable, space-based lunar transportation system (LTS) that uses lunar-derived propellants (LDPs) and operates between STNs/depots located in LEO, LPO and LLO is examined.

- Included in the analysis are the LDP production, mining, and power requirements that also include the needs of the LLVs supporting a particular mission type (e.g., crew cargo transport or commuter shuttle).

- A comparison of the requirements using icy regolith and volcanic glass as feedstock materials is included and the synergy with an evolving helium-3 mining industry is also discussed.

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.

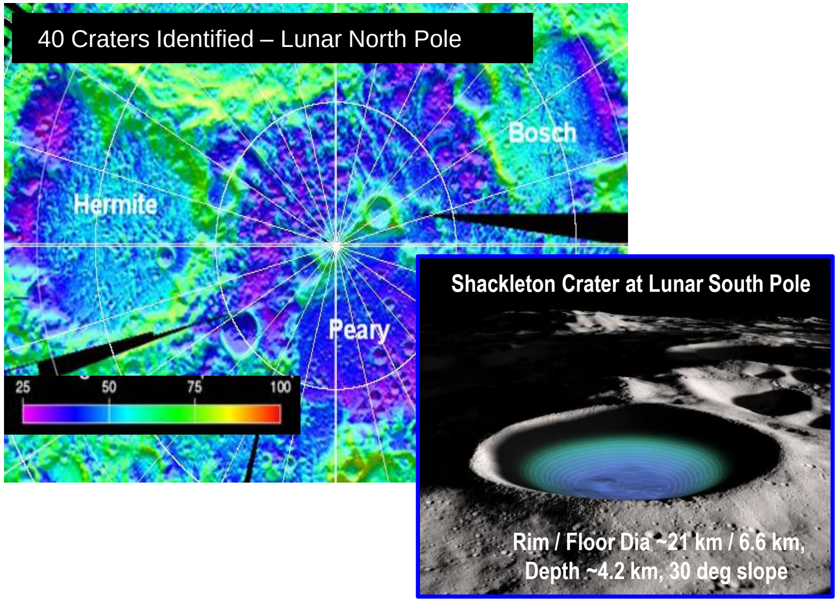
- The world's 10 coldest mines are located in Russia's extreme northeastern territory. At the coldest of these mines, Sarylakh, the temperatures can drop to nearly -50 C (~223 K).

- By contrast, the temperatures inside the polar craters, where the LPI is thought to exist, are ~30 – 50 K – 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

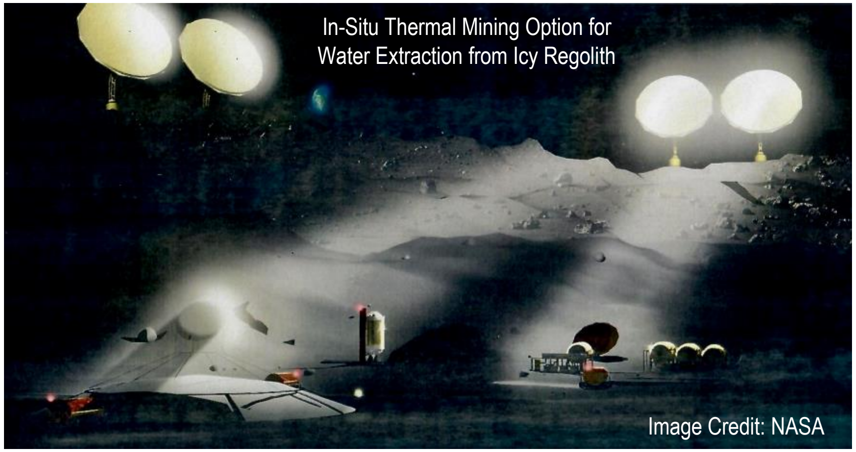
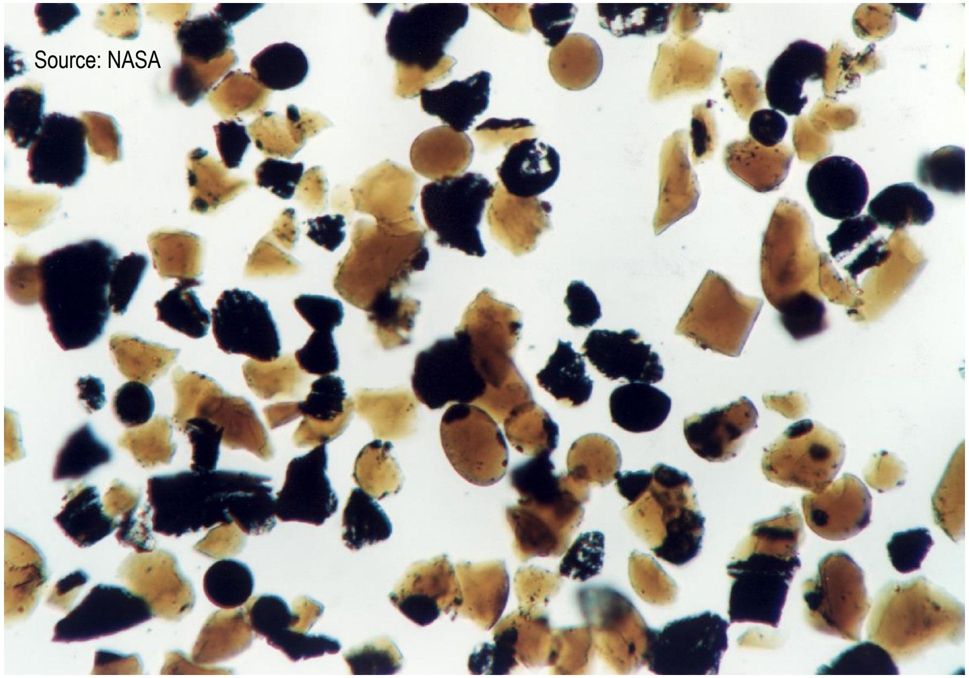

In-Situ Thermal Mining Option for Water Extraction from Icy Regolith

Image Credit: NASA

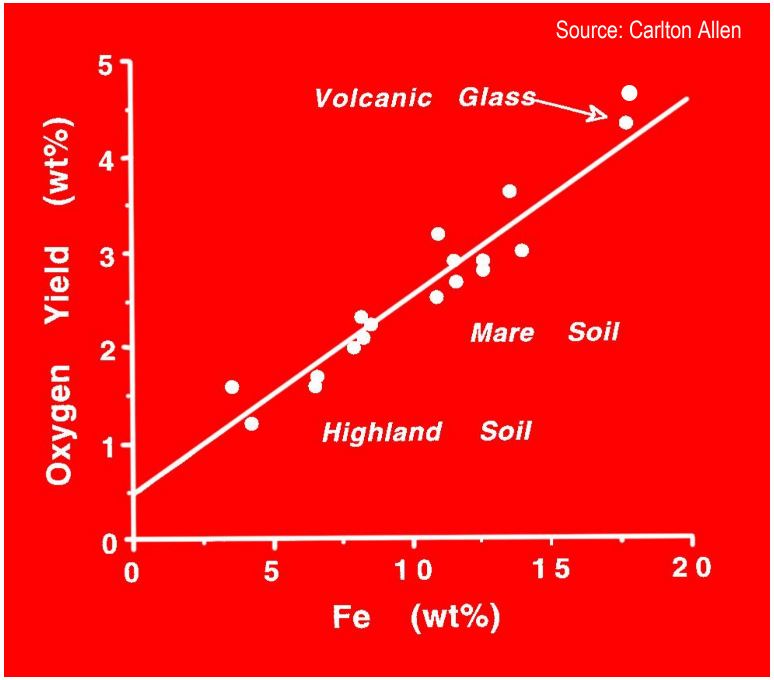
*D. Kornuta, et al., Commercial Lunar Propellant Architecture – A Collaborative Study of Lunar Propellant Production (2018)

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)

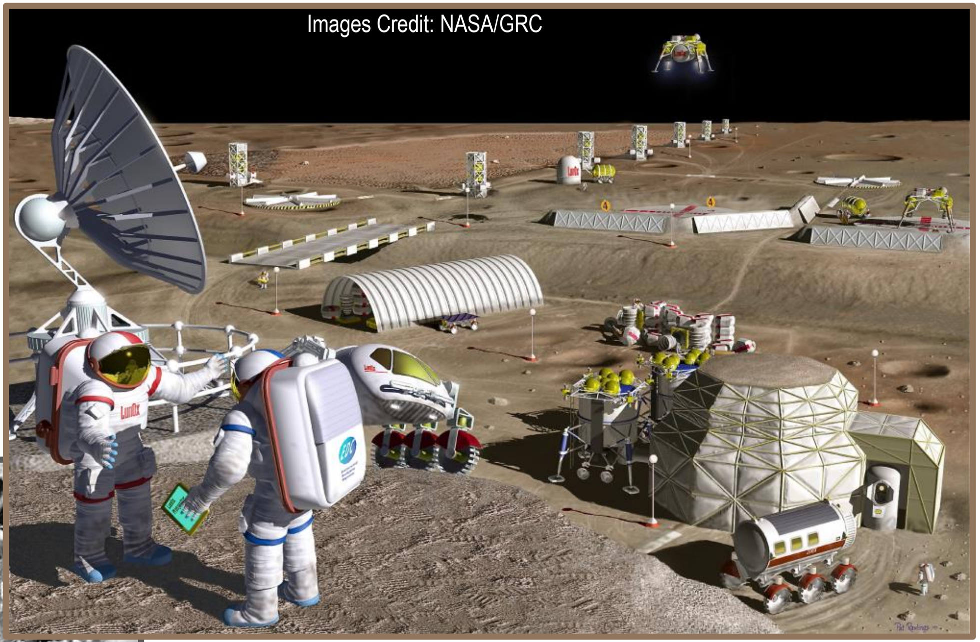
$2 H_2O$ -------> $2H_2 + O_2$ (*LUNOX*)
(Water Electrolysis & Hydrogen Recycling)

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

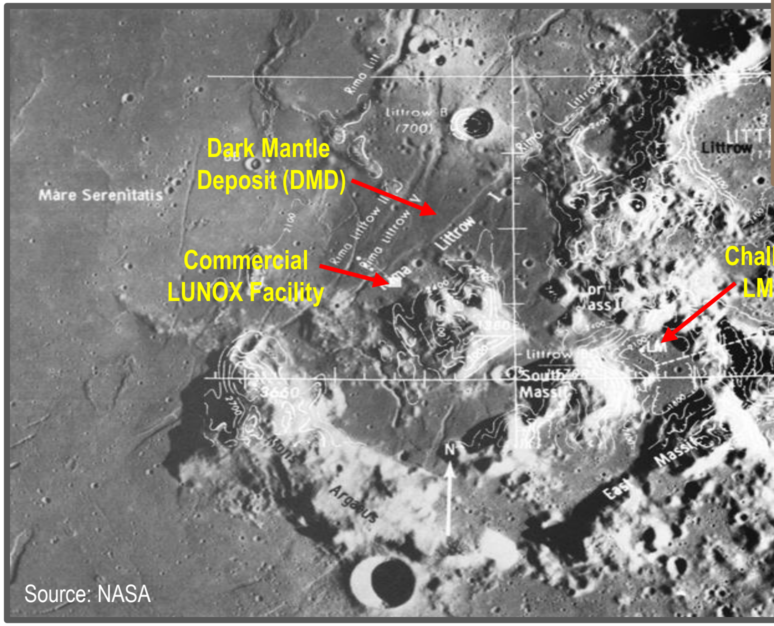
Commercial LUNOX Production Facility

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.


Images 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

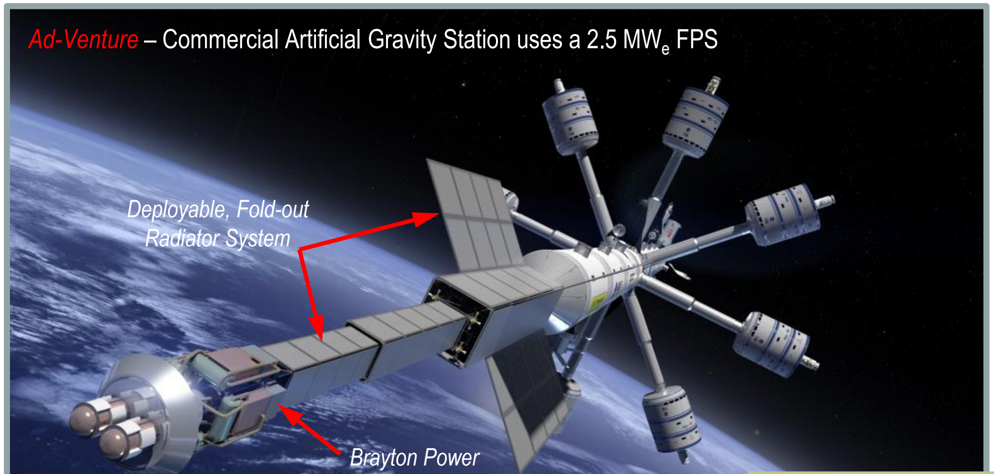
Index Map Showing the Apollo 17 Landing Site and Major Geographic Features of Taurus-Littrow Region

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

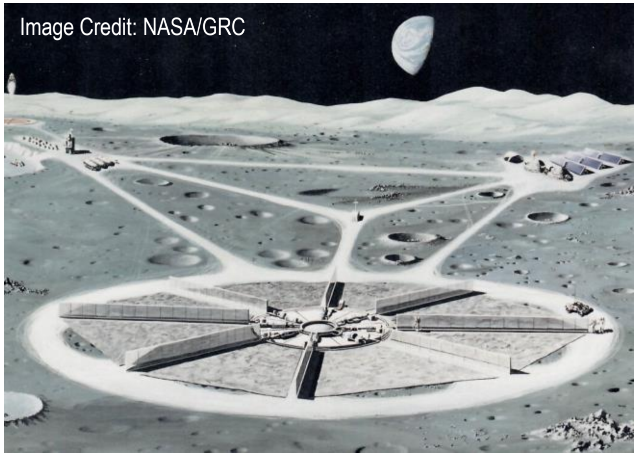


Image Credit: NASA/GRC

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

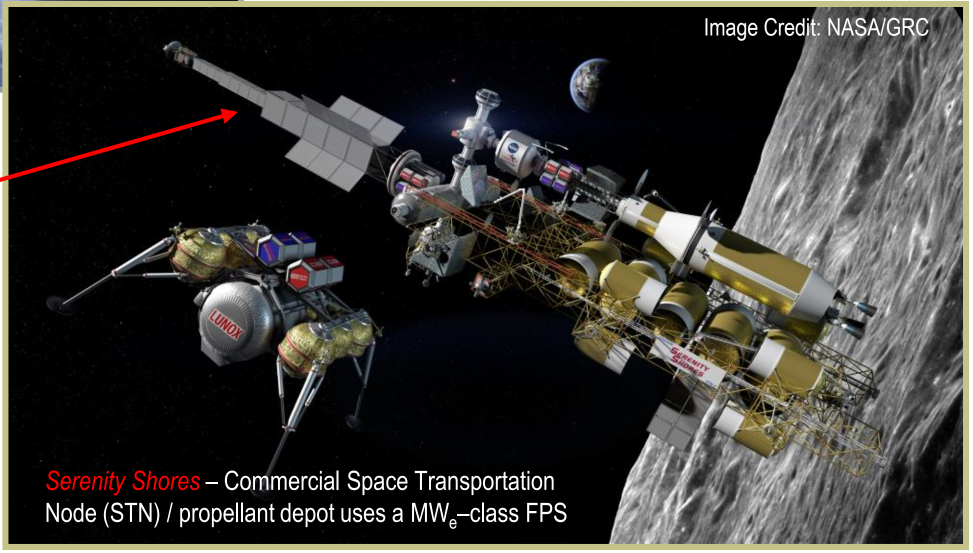


Image Credit: NASA/GRC

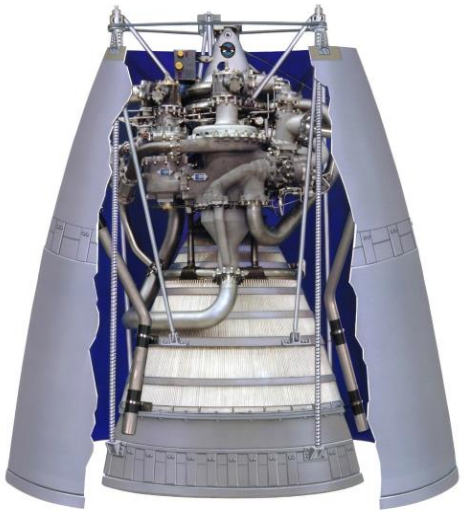
Serenity Shores – Commercial Space Transportation Node (STN) / propellant depot uses a MW_e–class FPS

MW_e-class fission power system (FPS) has 3 major elements:

1) Twin liquid metal-cooled, fast-spectrum reactors using highly 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

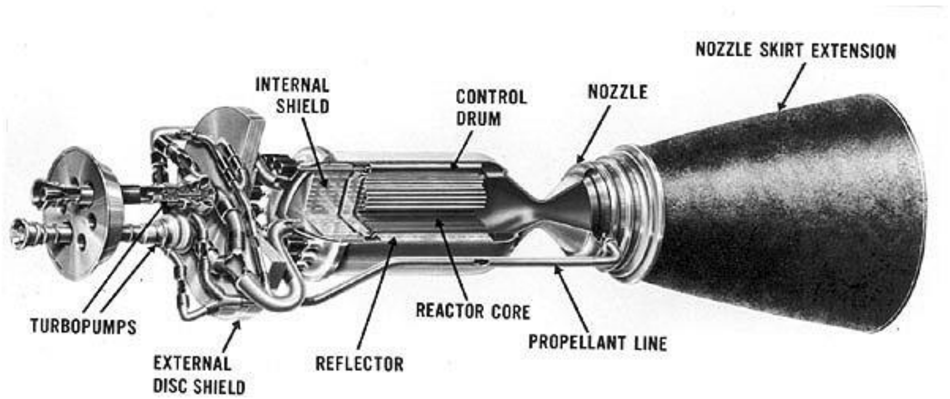
Propulsion Options: RL10B-2 LO_2/LH_2 Chemical Rocket and Nuclear Thermal Rocket (NTR) Engine



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: **~3000 K**
- Chamber Pressure: **640 psia**
- Nozzle Area Ratio: **280:1**
- Specific Impulse (I_{sp}): **~465.5 s**
- Engine Power Level: **~251 MWt**
- F/W_{eng}: **~37.3**

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



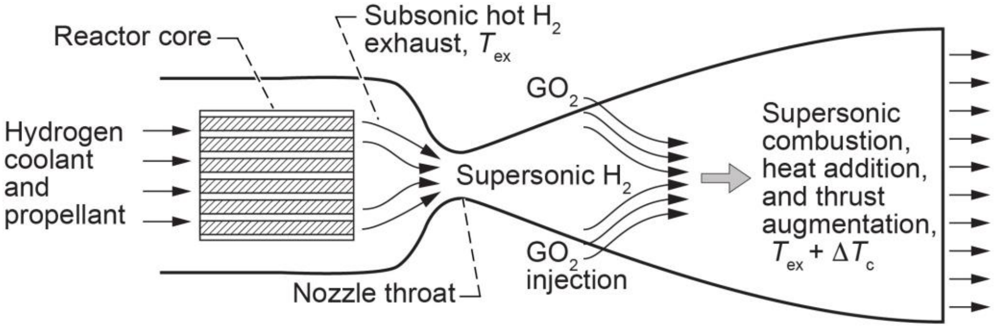
Small Nuclear Rocket Engine (SNRE) Performance Parameters:

- Propellant: LH_2
- Engine Cycle: **Expander**
- Thrust Level: **16.5 klb_f**
- Reactor Exit Temperature: **2734 K**
- Chamber Pressure: **1000 psia**
- Nozzle Area Ratio: **300:1**
- Specific Impulse (I_{sp}): **~900 s**
- Reactor Power Level: **~365 MWt**
- F/W_{eng}: **~3.03**

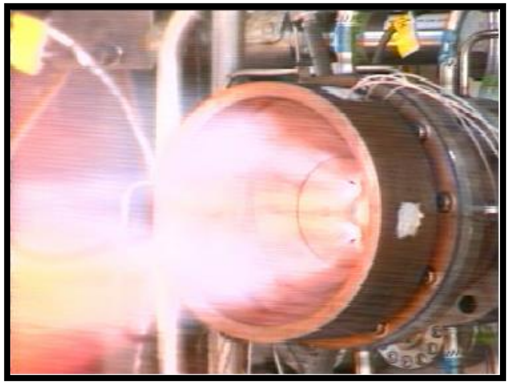
Ref: S. K. Borowski, et al., "Affordable Development and Demonstration of a Small NTR Engine: How Small is Big Enough?", AIAA-2015-4524; alnd NASA/TM—2016-219402

“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 Isp (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 psia and NAR = 300 to 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, 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.

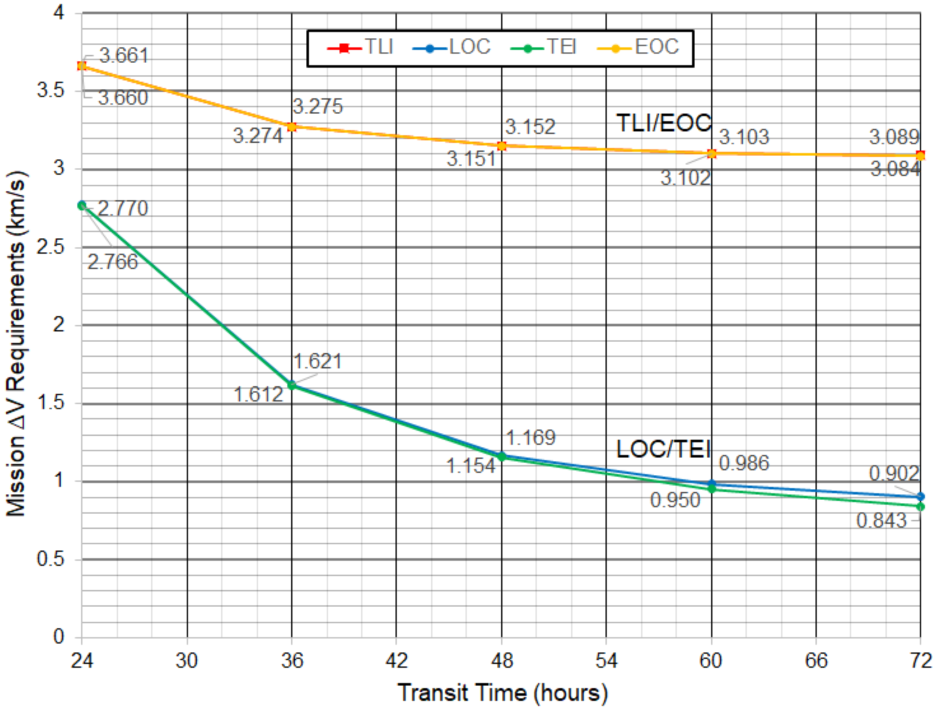

Image Credit: NASA/GRC

***Oasis* – LEO STN / Propellant Depot**


Image Credit: NASA/GRC

***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.



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 LANTR Engines, a Common NTPS 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

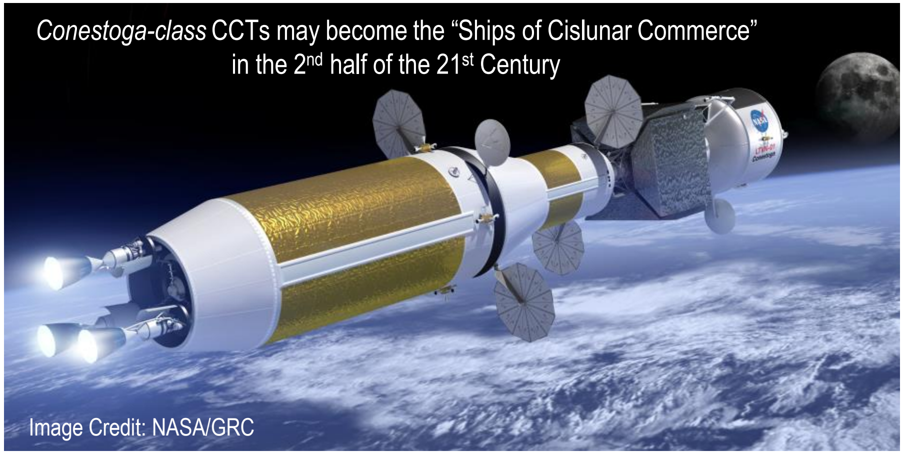
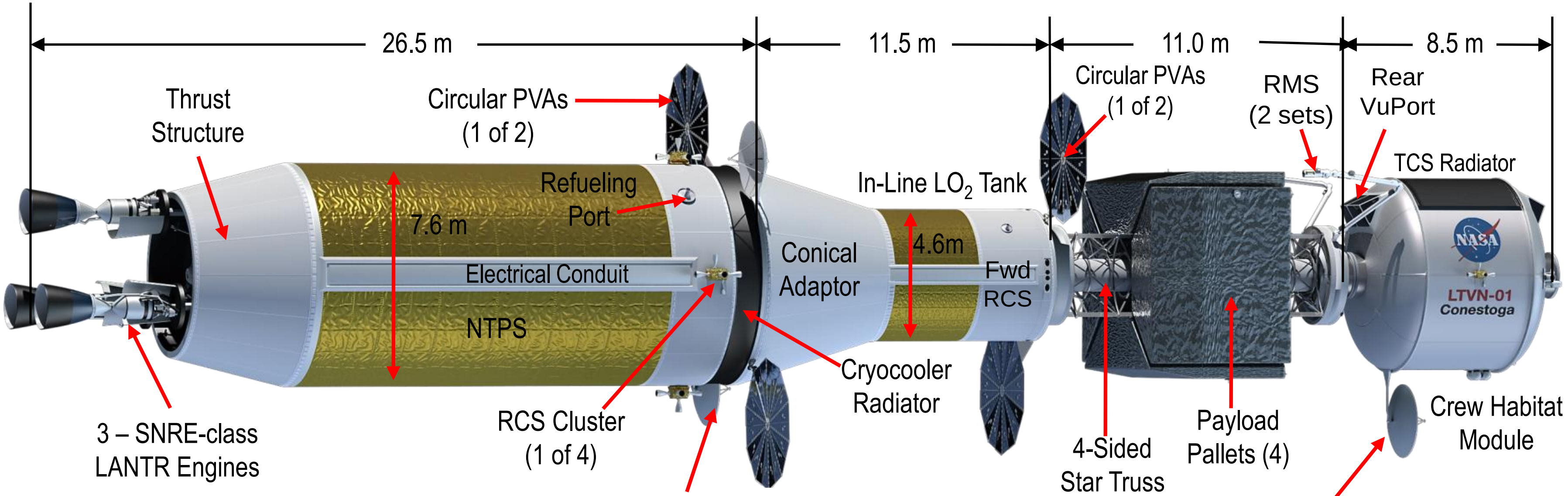

Conestoga-class CCTs may become the “Ships of Cislunar Commerce” in the 2nd half of the 21st Century

Image Credit: NASA/GRC


26.5 m

11.5 m

11.0 m

8.5 m

Thrust Structure

Circular PVAs (1 of 2)

Refueling Port

7.6 m

Electrical Conduit

NTPS

In-Line LO_2 Tank

4.6m

Conical Adaptor

Fwd RCS

Circular PVAs (1 of 2)

RMS (2 sets)

Rear VuPort

TCS Radiator

Cryocooler Radiator

3 – SNRE-class LANTR Engines

RCS Cluster (1 of 4)

Communication Dishes (1 of 2)

4-Sided Star Truss (11 – 16 m)

Payload Pallets (4)

Communication Dish

Crew Habitat Module

Image Credit: NASA/GRC

Conestoga – LANTR-propelled Crewed Cargo Transport uses a "Common" NTPS and In-Line LO_2 Tank Assembly

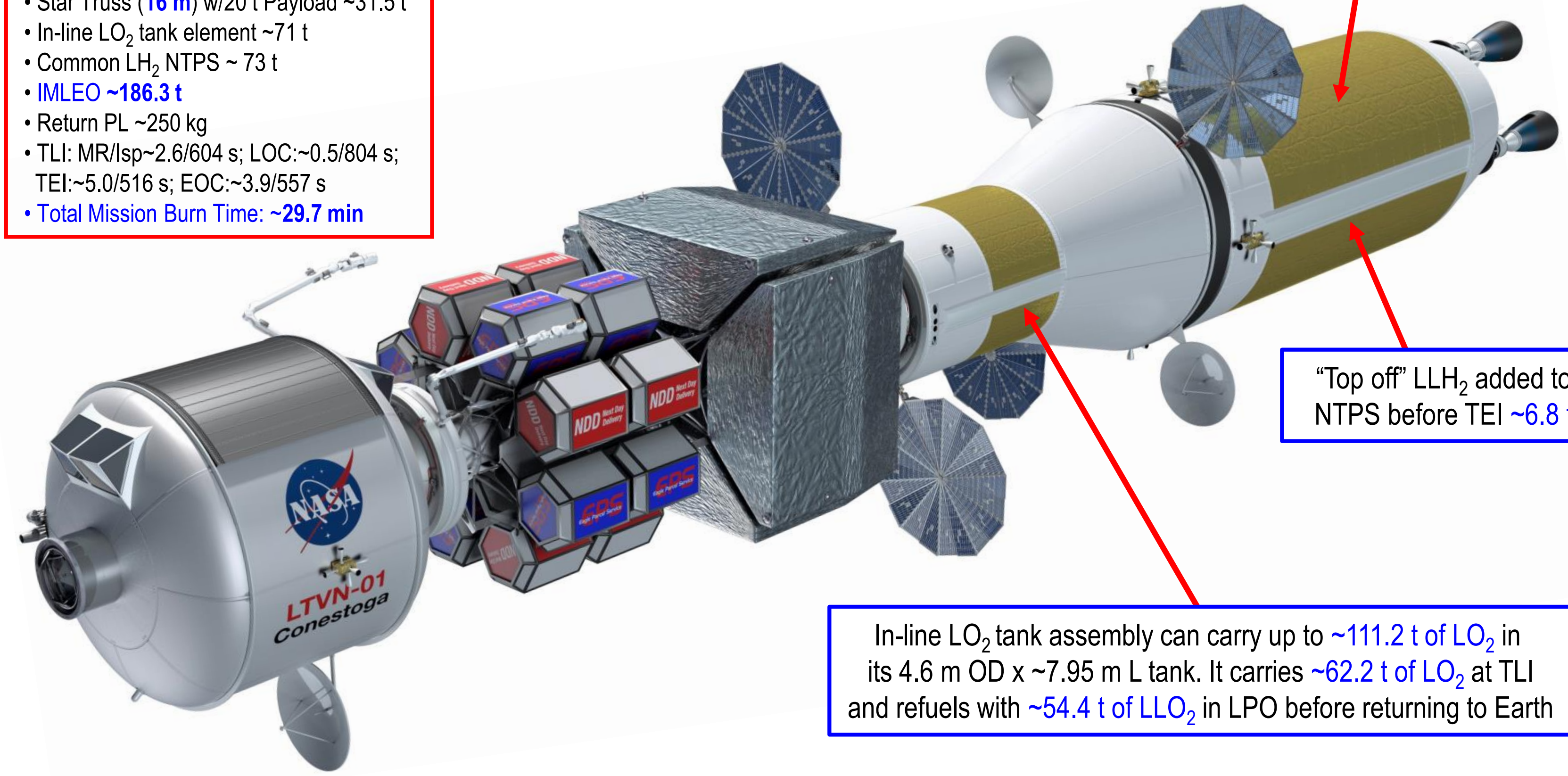
*CCT delivers **20 t** of cargo; refuels with LDPs*

(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
- Common LH_2 NTPS ~ 73 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**

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

NTPS carries ~39.8 t LH_2 in its 7.6 m OD x ~15.7 m L tank at TLI



"Top off" LLH_2 added to NTPS before TEI ~6.8 t

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. It carries ~62.2 t of LO_2 at TLI and refuels with ~54.4 t of LLO_2 in LPO before returning to Earth

Image Credit: NASA/GRC

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

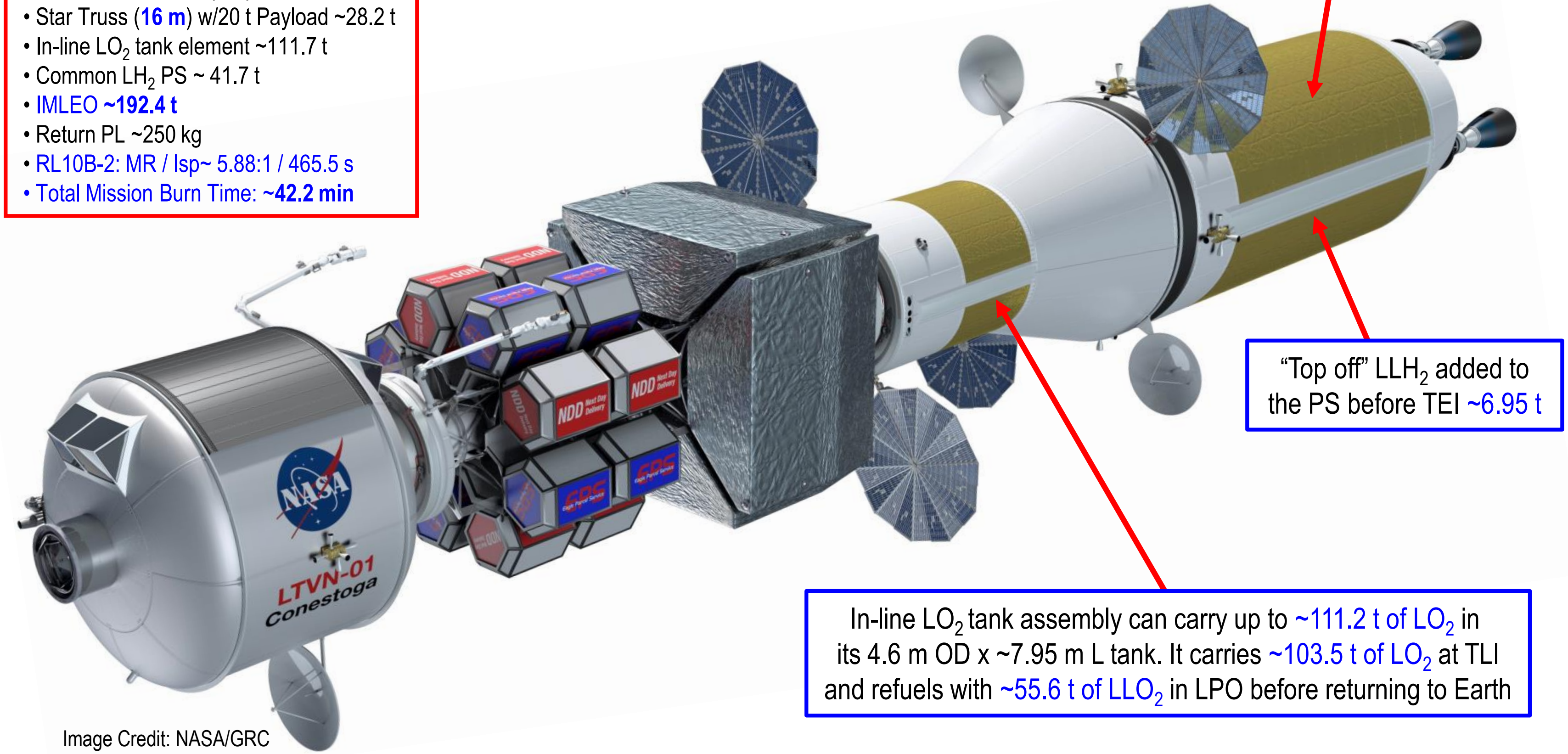
An Alternative Propulsion Option for *Conestoga* uses 3 – 24.75 klb$_f$ RL10B-2 LO_2 / LH_2 engines*

NOTE: CCT refuels with LLO_2 and “tops off” its NTPS with excess LLH_2 from water electrolysis at 8:1 ratio

*CCT delivers **20 t** of cargo; refuels with LDPs*

(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
- Common LH_2 PS ~ 41.7 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**



PS can carry up to ~39.8 t LH_2 in its 7.6 m OD x ~15.7 m L tank. It carries ~20.5 t of LH_2 at TLI

“Top off” LLH_2 added to the PS before TEI ~6.95 t

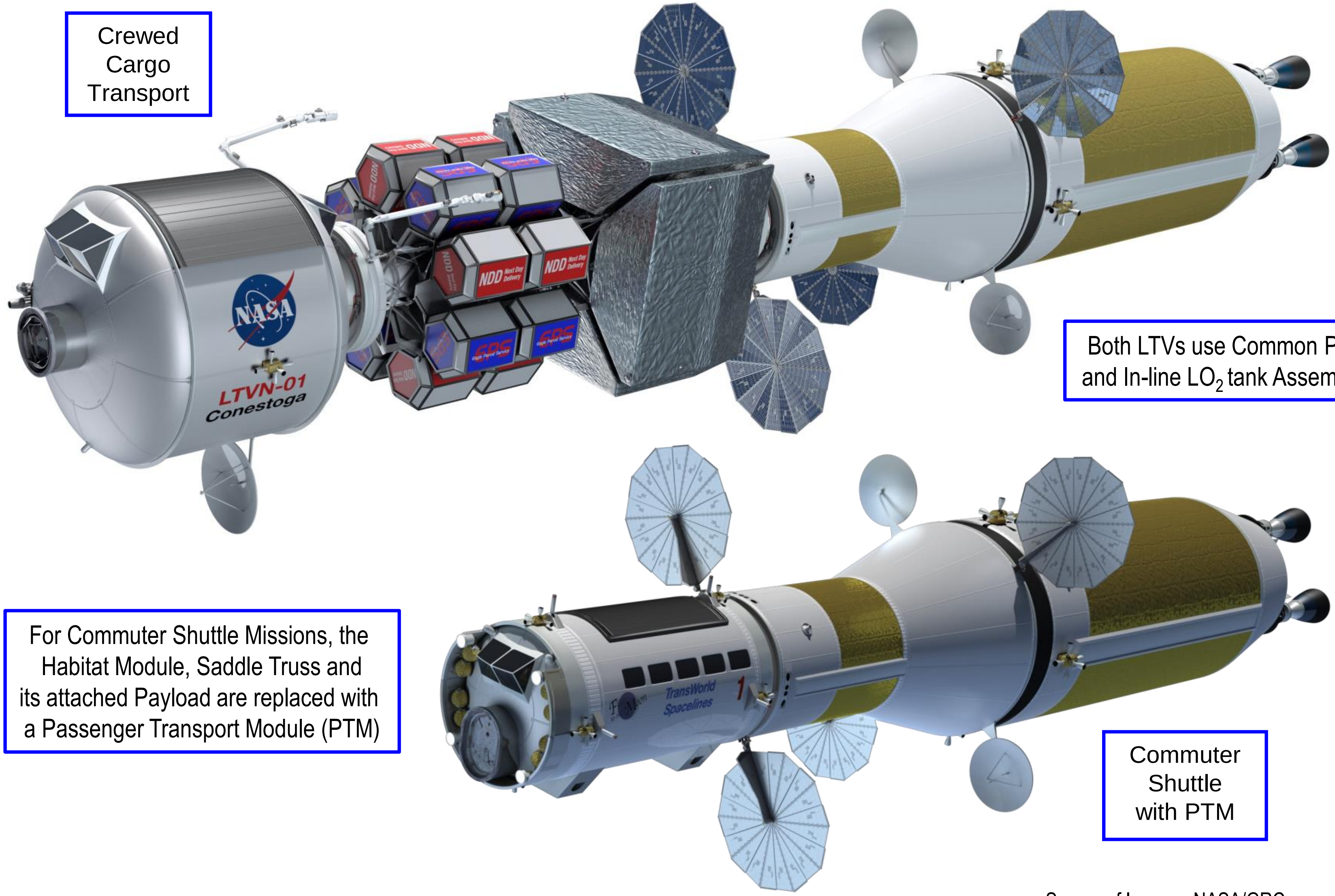
In-line LO_2 tank assembly can carry up to ~111.2 t of LO_2 in its 4.6 m OD x ~7.95 m L tank. It carries ~103.5 t of LO_2 at TLI and refuels with ~55.6 t of LLO_2 in LPO before returning to Earth

Image Credit: NASA/GRC

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

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

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

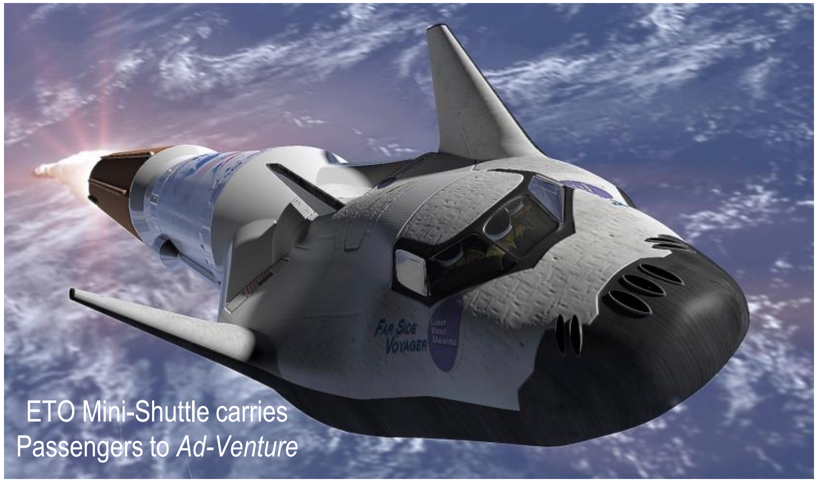
For Commuter Shuttle Missions, the Habitat Module, Saddle Truss and its attached Payload are replaced with a Passenger Transport Module (PTM)

Commuter Shuttle with PTM

Source of Images: NASA/GRC

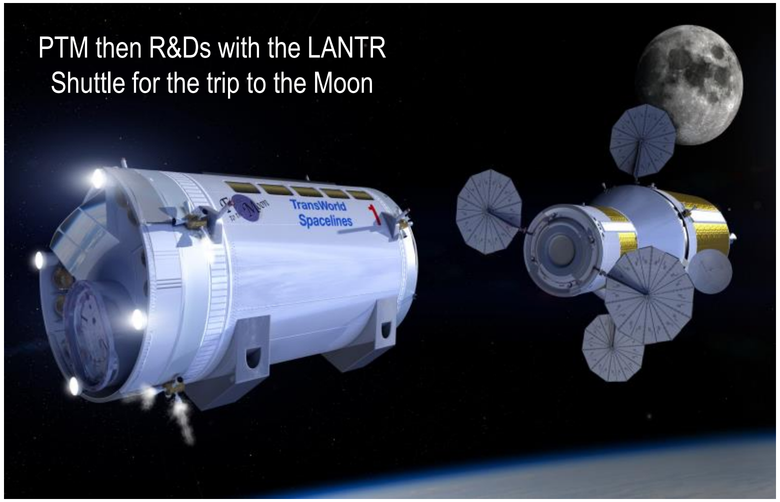
How Might a Typical Commuter Flight to the Moon Proceed?

A possible scenario might start with passengers boarding a future “Earth-to-Orbit” shuttle for a flight to a future commercial artificial gravity station (AGS) located in LEO. There travelers would enter a Passenger Transport Module (PTM) containing its own life support, power, instrumentation and control, and RCS. The PTM provides the “brains” for the LANTR-powered shuttle and is home to the 18 passengers and 2 crewmembers operating it while on route to the Moon. After departing the AGS, the PTM docks with the fully fueled LANTR shuttle awaiting it a safe distance away. At the appropriate time, the shuttle fires its LANTR engines to begin the trip to the Moon.

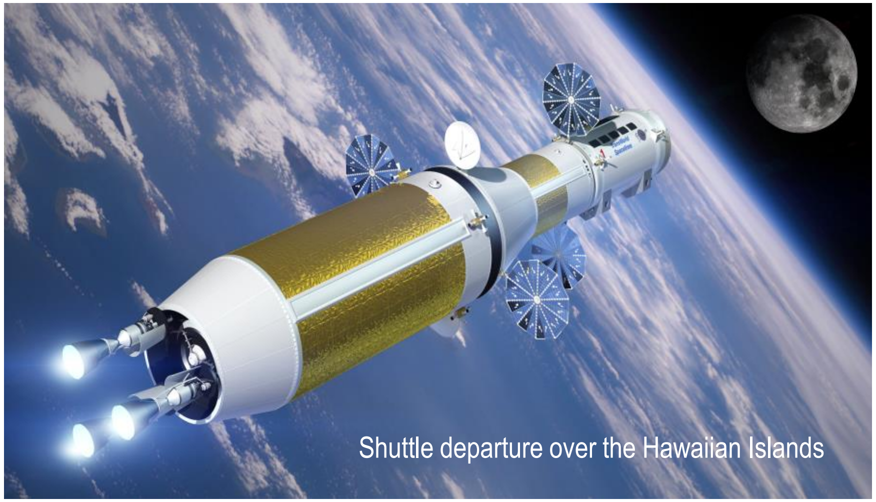


ETO Mini-Shuttle carries Passengers to *Ad-Venture*

Travelers transfer to PTM awaiting them at *Ad-Venture*



PTM then R&Ds with the LANTR Shuttle for the trip to the Moon

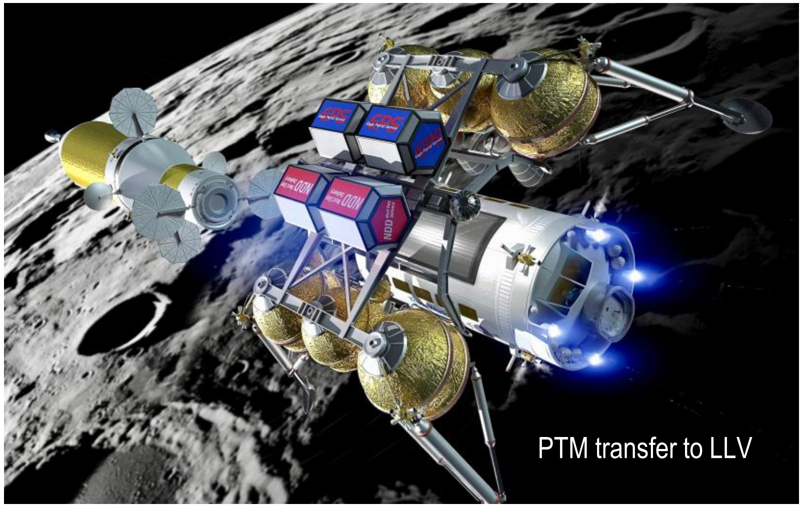


Shuttle departure over the Hawaiian Islands

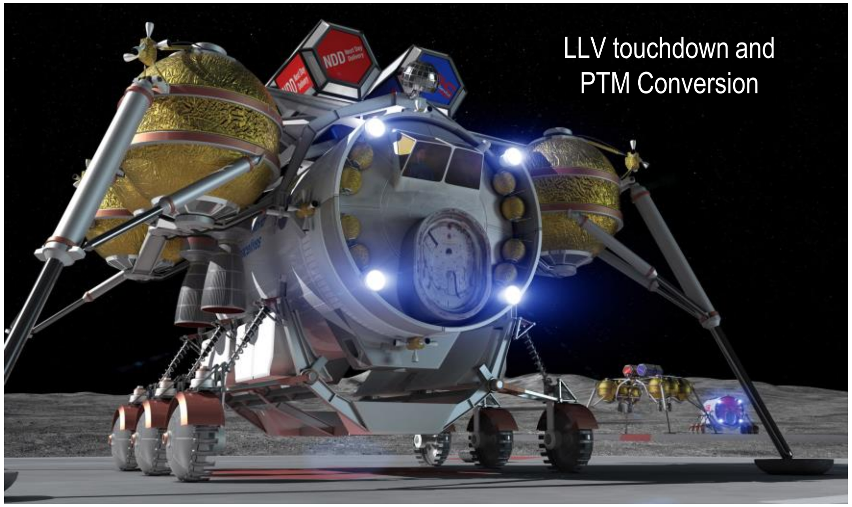
Source of Images: NASA/GRC

How Might a Typical Commuter Flight to the Moon Proceed?

After a 1-1.5-day transfer, the LANTR shuttle arrives in LLO where the PTM detaches and docks with a “Sikorsky-style” LLV awaiting it in LLO. After its delivery to the lunar surface, the PTM is lowered to a “flat-bed” surface vehicle and electronically engaged providing the PTM with surface mobility. The PTM then drives itself to the lunar base airlock for docking and passenger unloading. This scenario is reversed on the return trip back to Earth.

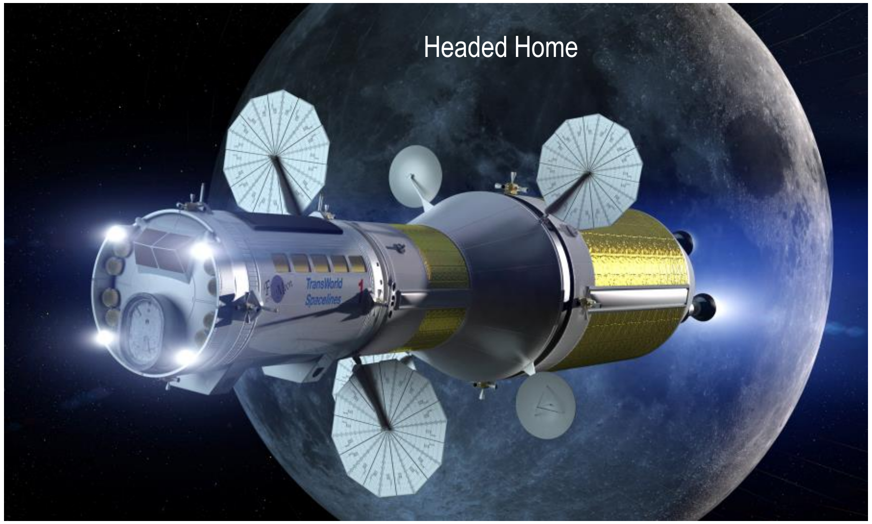


PTM transfer to LLV



LLV touchdown and PTM Conversion

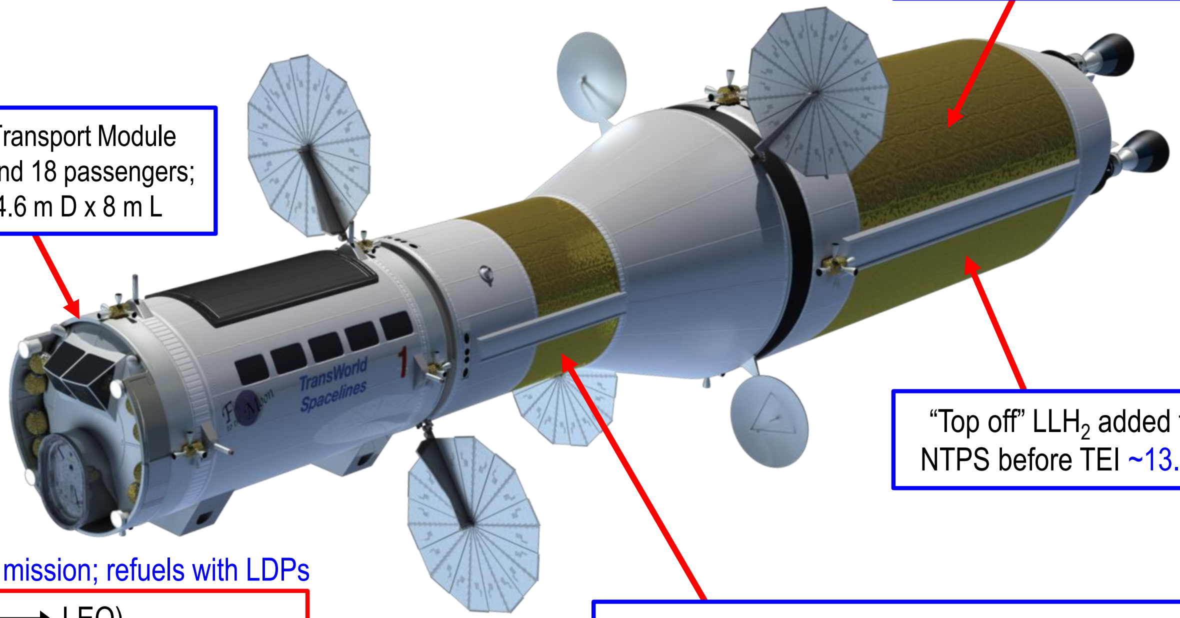
On the Final Leg



Headed Home

Source of Images: NASA/GRC

LANTR Commuter Shuttle Mission to LPO



NTPS carries ~39.8 t LH_2 in its 7.6 m OD x ~15.7 m L tank at TLI

Shuttle's Passenger Transport Module (PTM) carries 2 pilots and 18 passengers; OML Dimensions: ~4.6 m D x 8 m L

"Top off" LLH_2 added to NTPS before TEI ~13.6 t

Shortest transit time mission; refuels with LDPs

(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
- Common LH_2 NTPS ~72.8 t
- IMLEO **~207.5 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**

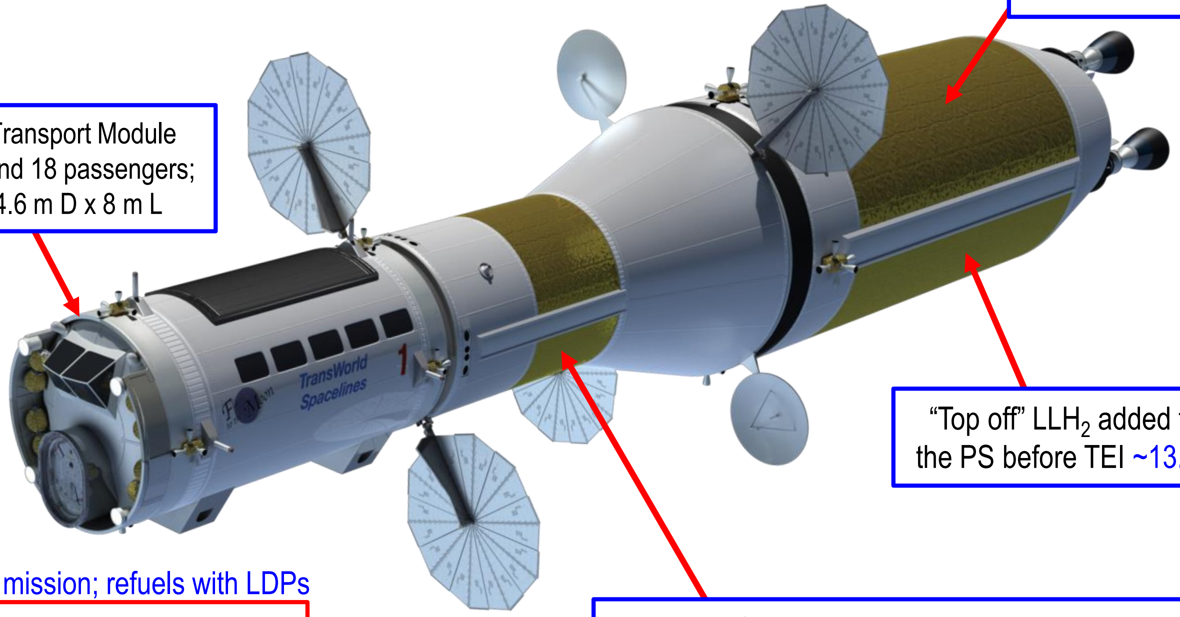
In-line LO_2 tank assembly can carry up to ~111.2 t of LO_2 in its 4.6 m OD x ~7.95 m L tank. It carries ~111.2 t of LO_2 at TLI and refuels with ~109 t of LLO_2 in LPO before returning to Earth

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

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

Image Credit: NASA/GRC

RL10B-2 Commuter Shuttle Mission to LPO



PS can carry up to ~39.8 t LH_2 in its 7.6 m OD x ~15.7 m L tank. It carries ~19.4 t of LH_2 at TLI

Shuttle's Passenger Transport Module (PTM) carries 2 pilots and 18 passengers; OML Dimensions: ~4.6 m D x 8 m L

"Top off" LLH_2 added to the PS before TEI ~13.6 t

Shortest transit time mission; refuels with LDPs

(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
- Common LH_2 PS ~36.6 t
- IMLEO **~141.4 t**
- RL10B-2: MR / Isp~ 5.88:1 / 465.5 s
- Total Mission Burn Time: **~51.1 min**

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. It carries ~82.8 t of LO_2 at TLI and refuels with ~109 t of LLO_2 in LPO before returning to Earth

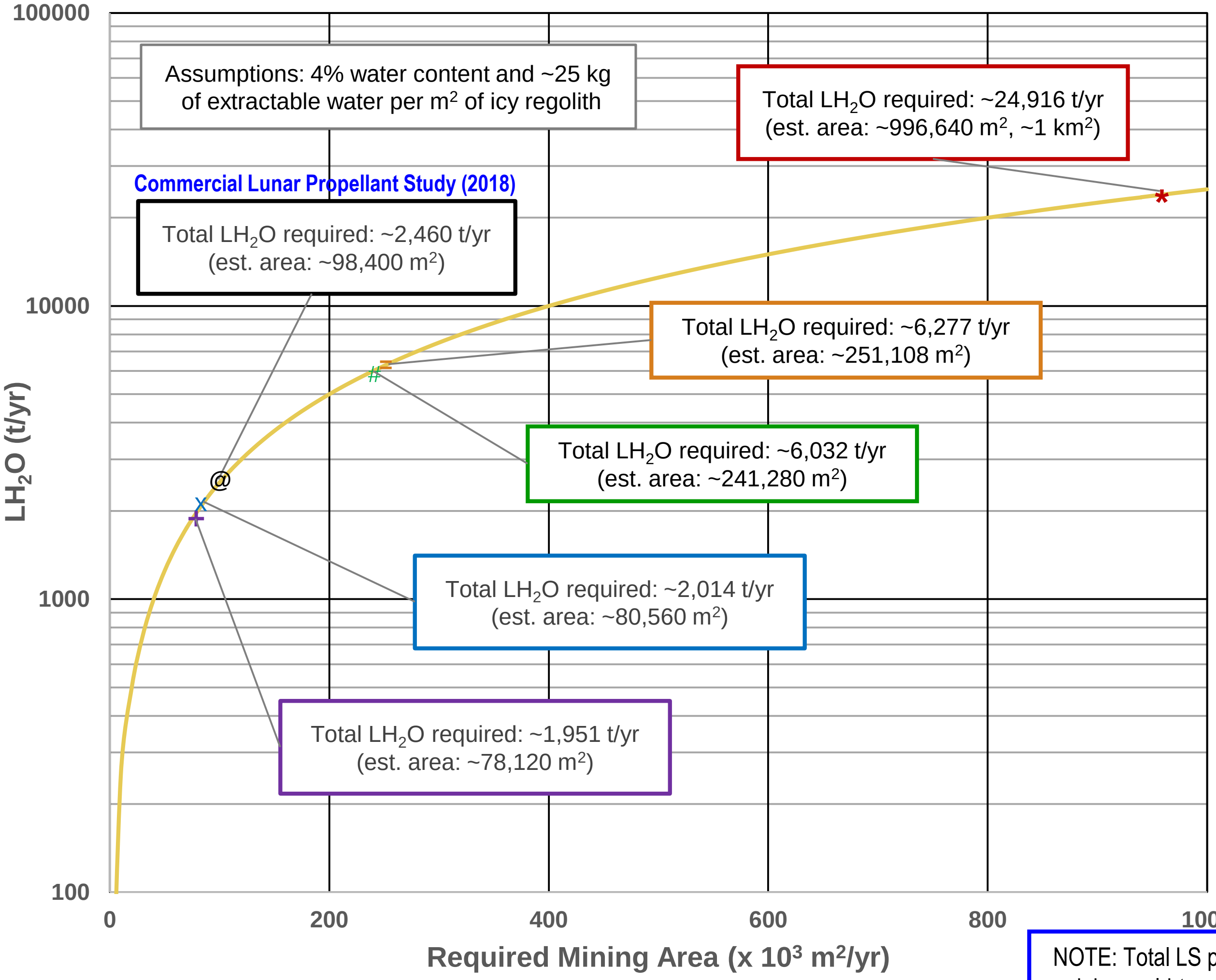
RL10B-2 Shuttle refuels with LLO_2 and "tops off" its PS with excess LLH_2 from water electrolysis at 8:1 ratio

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

Commercial Lunar Propellant Study (2018)

Total LH_2O required: ~2,460 t/yr (est. area: ~98,400 m^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 33.5 / 36.5hr, 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

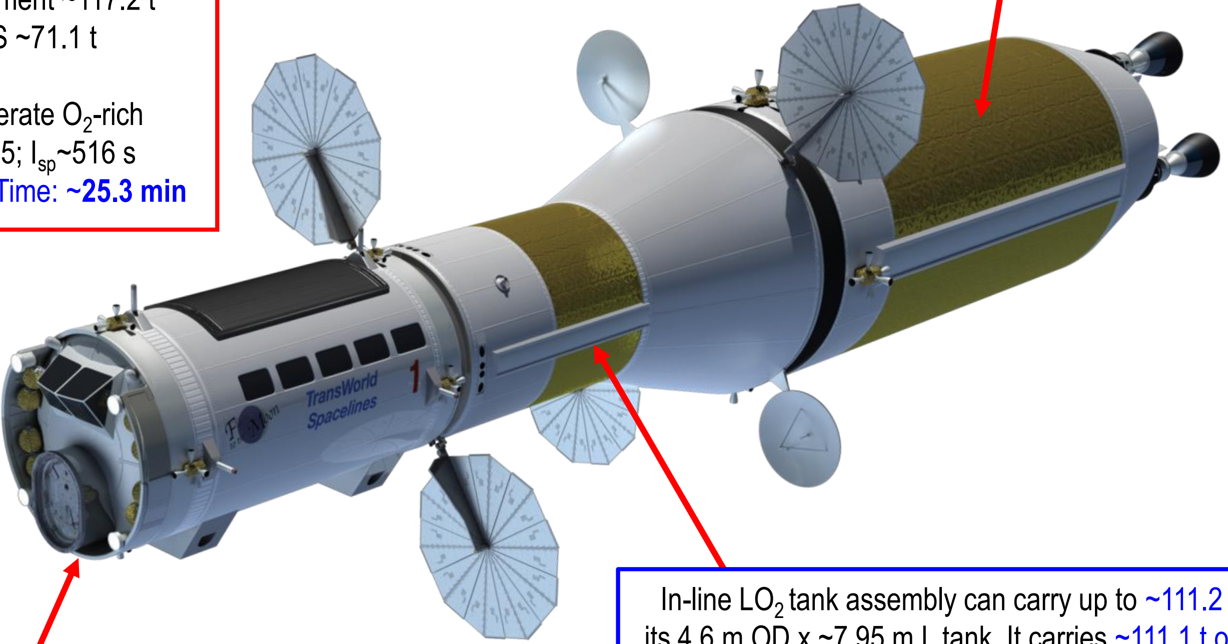
*P_e (MW_e) ~0.2042 x H_2O Electrolysis Rate (t/day)

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

LANTR Commuter Shuttle Mission to Equatorial LLO uses only LUNOX Refueling for Earth Return

Shortest transit time mission using LUNOX only

(LEO ⟶ LLO ⟶ LEO)
- **32.8-hr** "1-way" transit times
- Total Mission ΔV ~10.481 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~117.2 t
- Common LH_2 NTPS ~71.1 t
- IMLEO **~203.3 t**
- LANTR engines operate O_2-rich Out and Back: MR~5; I_{sp}~516 s
- Total Mission Burn Time: **~25.3 min**



NTPS carries ~39.8 t of Earth-supplied LH_2 – sufficient for the round trip mission – 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. It carries ~111.1 t of LO_2 at TLI and refuels with **~80.4 t of LUNOX** before returning to Earth

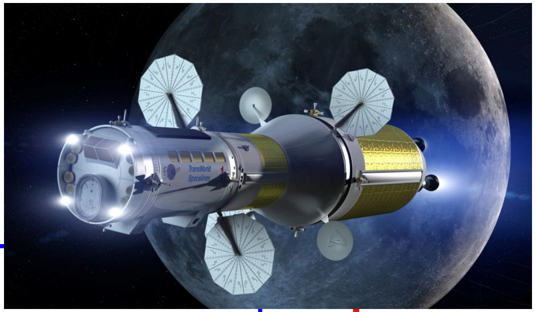
Shuttle's Passenger Transport Module (PTM) carries 2 pilots and 18 passengers; OML Dimensions: ~4.6 m D x 8 m L

Image Credit: NASA/GRC

Total LUNOX Required for "Weekly" Commuter Flights

LANTR Shuttle
Departing LEO
for the Moon

LANTR Shuttle
Headed Home



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

LANTR Shuttle: (80.4 t LUNOX /mission/week)
x 52 weeks/year = 4,181 t/yr

LLV*+ : (33.8 t LUNOX / flight)
x (1 flight/LLV/week) x 4 LLVs x 52 weeks/year = 7,030 t/yr

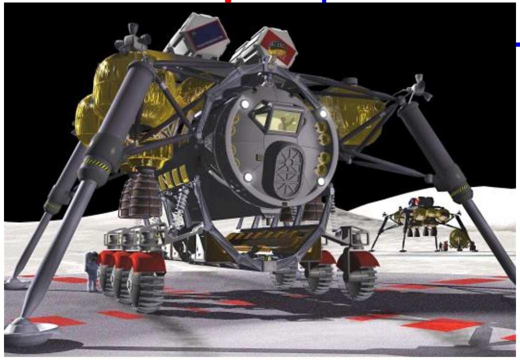
LLV*# : (49.1 t LUNOX# / round trip flight / week)
x (1 flight/LLV/week) x 52 weeks/year = 2,553 t/yr

Total LUNOX Production = 13,764 t/yr

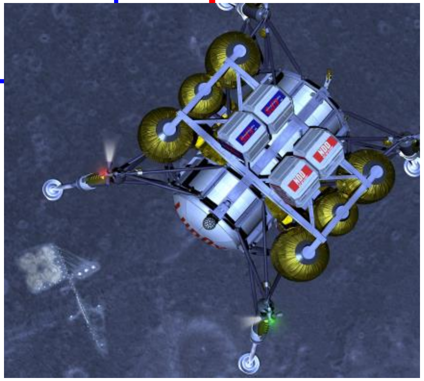
*O/H MR = 5.5:1, I_{sp} = 450 s, ΔV_{desc} = 2.115 km/s & ΔV_{asc} = 1.985 km/s assumed

+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

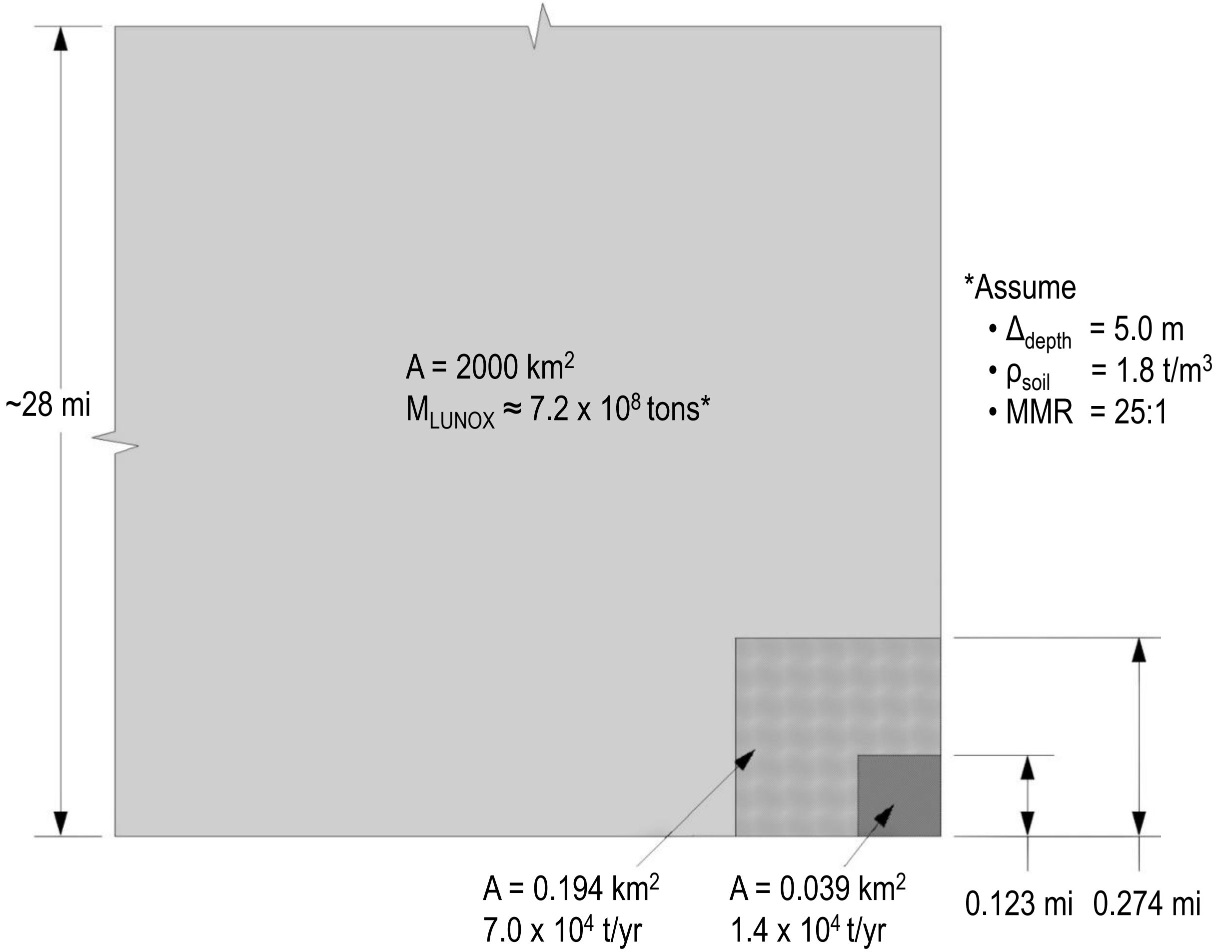


Tanker LLV Delivering
LUNOX to LLO Depot

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

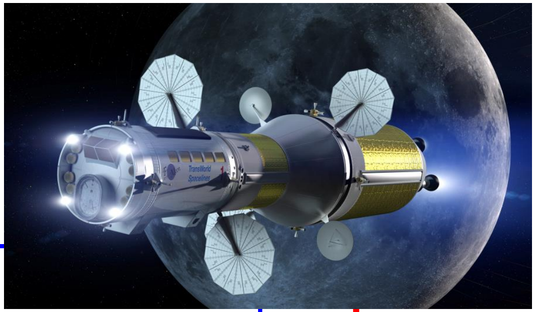
Plant Mining Rate:

- To produce 14,000 t of LUNOX annually requires glass throughput of ~3.50×10^5 t/yr at MMR = 25:1
- Assuming 14 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 front-end loaders and 4 haulers
- The mining rate at each plant is just over 4 t per hour per 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 2057 yrs!

Total LUNOX Required for “Weekly” Commuter Flights

LANTR Shuttle
Departing LEO
for the Moon



LANTR Shuttle
Headed Home

32.8 Hour “1-Way” Transits (15 t / 20 Person PTM):

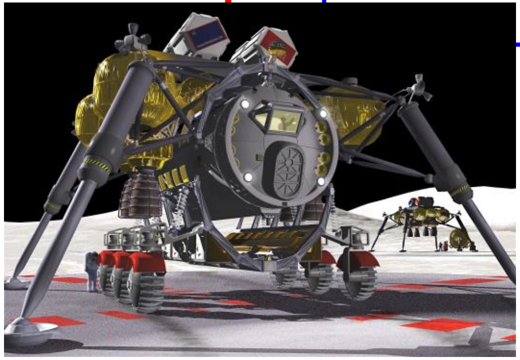
LANTR Shuttle: (80.4 t LUNOX /mission/week)
x 52 weeks/year = 4,181 t/yr

LLV^{*+} : (33.8 t LUNOX + 6.14 t ELH_2 / flight)
x (1 flight/LLV/week) x 4 LLVs x 52 weeks/year = 7,030 t/yr
+ 1,277 t/yr (ELH_2)

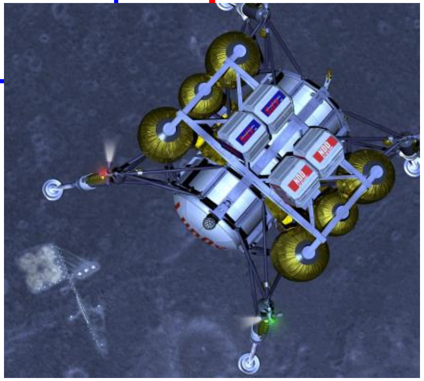
LLV$^{*\#}$: (49.1 t LUNOX$^{\#}$ + 8.92 t ELH_2 / round trip flight)
x (1 flight/LLV/week) x 52 weeks/year = 2,553 t/yr
+ 464 t/yr (ELH_2)

Total LUNOX Production = 13,764 t/yr
Total ELH_2 Required 1,741 t/yr

*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

Synergy with an Emerging He-3 Mining Industry

- For ambitious LUNOX architectures, the increasing amounts of ELH_2 required 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 lunar volatiles are produced as “by-products”. Eight automated Mark II miners (each producing ~33 kg of He-3 per yr) can supply over 1700 t of LH_2 while also producing ~262 kg of He-3 annually (This is ~95 x smaller than the 25 t/yr discussed previously by Kulcinski & Schmidt).

- The mass, power requirement, annual regolith throughput, excavation rate and area, of each He-3 miner is ~18 t, 200 kW_e, ~5 million tons, 1630 t per hr, and ~1 km^2, respectively.

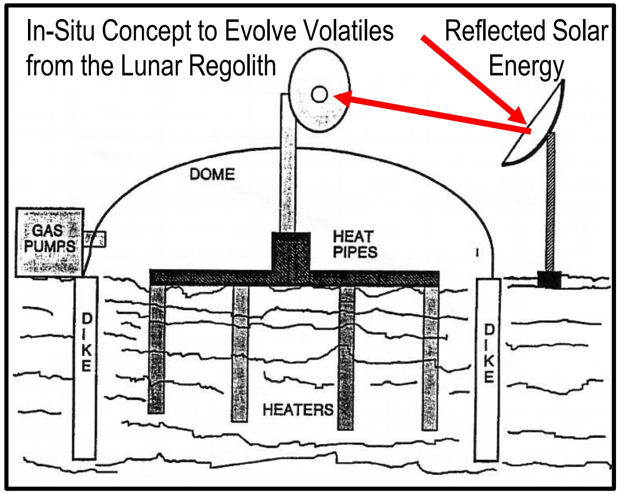
- Mare Tranquillitatus has titanium-rich regolith, large surface area (~190,000 km^2) and could contain ~7100 t of He-3. To the northwest is Mare Serenitatis, another location for He-3 mining and LUNOX production.

- An alternative to the conventional mining approach is in-situ extraction of lunar soil volatiles. Proposed by Wittenberg in 1994, it has many of the same features as today’s thermal mining approach for water extraction.

(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


In-Situ Concept to Evolve Volatiles from the Lunar Regolith

(Ref: L.J. Wittenberg, Space 94, 4th Int. Conf. on Engineering, Construction & Operations in Space, Feb. 26 – Mar 3, 1994, Albuquerque, NM)

Summary and Conclusions

• Commercialization and human settlement of the Moon and cislunar space will be greatly aided by the development and utilization of ISRU, FPS, reusable, ISRU-compatible propulsion systems and the strategic positioning of STNs in LEO, lunar polar and equatorial orbits.

• Lunar-derived propellants (LDPs) can be extracted from abundant reserves of icy polar regolith, vast volcanic glass deposits on the lunar nearside, and, longer term, from volatile byproducts extracted during He-3 mining.

• The combination of LDP with chemical and LANTR propulsion can lead to a robust LTS with unique mission capabilities that include short transit time, crewed cargo transports and commuter flights to the Moon.

• Chemical propulsion exists now but LANTR propulsion offers some unique features. It provides a variable thrust and I_{sp} capability, has shorter total mission burn times and potentially longer engine life, and allows bipropellant operation. The use of high density LO_2 also leads to smaller LTVs.

• Scalable, megawatt-class FPS can satisfy the requirements for abundant “24/7” electrical power, at low mass, needed for the continued growth of commercial activities in LEO, lunar orbit, and on the lunar surface.

• Besides providing a propellant depot and cargo transfer function, orbiting STNs offer convenient staging locations where propellant, cargo and passengers can be dropped off and/or picked up.

• The biggest challenge to making this vision a reality will be the production of increasing amounts of LDP and the development of STNs in LEO, LLO and LPO. Industry-operated, privately financed ventures, with NASA as its initial customer, might provide a possible blueprint for future development and operation.

• With industry interested in developing cislunar space and commerce, and competitive forces at work, the timeline for developing this capability could well be accelerated beyond anything currently being imagined. Only time will tell, and it may be sooner than any of us can imagine.