https://ntrs.nasa.gov/search.jsp?R=20180000364 2018-07-24T01:05:25+00:00Z

"Propelling Us to New Worlds"

"Robust Exploration and Commercial Missions to the Moon Using LANTR Propulsion and In-Situ Propellants Derived From Lunar Polar Ice (LPI) Deposits"

AIAA-2017-5272
EXPL-04: Advance Propulsion and Power Systems

Stanley K. Borowski, Stephen W. Ryan, Laura M. Burke (NASA/GRC)
David R. McCurdy, James E. Fittje (Vantage Partners, LLC at GRC)
Claude R. Joyner (Aerojet Rocketdyne)
216-977-7091, Stanley.K.Borowski@nasa.gov

presented at the

2017 AIAA Space Forum and Exposition – Space 2017
Hyatt Regency Orlando
Orlando, Florida

Wednesday, September 13, 2017

Background Information and Presentation Overview

• NASA's current focus is on the *"Journey to Mars"* sometime around the mid-to-late 2030's. However, it is also supporting the development of commercial cargo and crew delivery to the ISS (e.g., Space*X*, Orbital ATK, SNC, Boeing) where inflatable habitation technology (e.g., Bigelow Aerospace's BEAM) is currently being tested

• Significant private sector interest in commercial lunar activities has also been expressed by Bigelow Aerospace, Blue Origin, Golden Spike Company, Shackleton Energy Company (SEC), and most recently by United Launch Alliance (ULA) in their "Cislunar-1000" plan

• Lunar-derived propellant (LDP) production offers significant mission leverage and are central themes of both SEC's and ULA's plans for commercial lunar development

• An efficient, proven propulsion technology with reuse capability – like NTP – offers the potential for affordable "*access through space*" essential to realizing commercial lunar missions

• ***Question***: *How can high performance NTP and the leverage potential of LDP best be exploited?*
Answer: *"LO_2-Augmented" NTR (LANTR) – LH_2-cooled NTR with "O_2-afterburner" nozzle combines NTR and supersonic combustion ramjet engine technologies allowing "bipropellant" engine operation*

• This presentation examines the performance potential of an "evolutionary" lunar transportation system (LTS) architecture using NTR initially, then transitioning to LANTR as LDP (e.g., specifically LLO_2 and LLH_2 derived from LPI) become available at propellant depots in lunar equatorial and polar orbits

• Cargo delivery, crewed landing, space-based crewed cargo transports, and routine commuter flights to and from transportation nodes/depots located in LEO, LLO and LPO are examined and discussed

Benefits and Options for Using Lunar-Derived Propellants

- Studies conducted by NASA and its contractors (early 1980's – early 1990's) indicated a substantial benefit from using lunar-derived propellants – specifically lunar-derived LO_2 (LLO_2) or "*LUNOX*" in a lunar space transportation system (LTS)

- With a LTS using LO_2/LH_2 chemical rockets, ~6 kilograms (kg) of mass in low Earth orbit (LEO) is required to place 1 kg of payload on the lunar surface (LS). Of this 6 kg, ~70% (4.2 kg) is propellant and 6/7th of this mass (3.6 kg) is oxygen assuming an O/H MR = 6:1

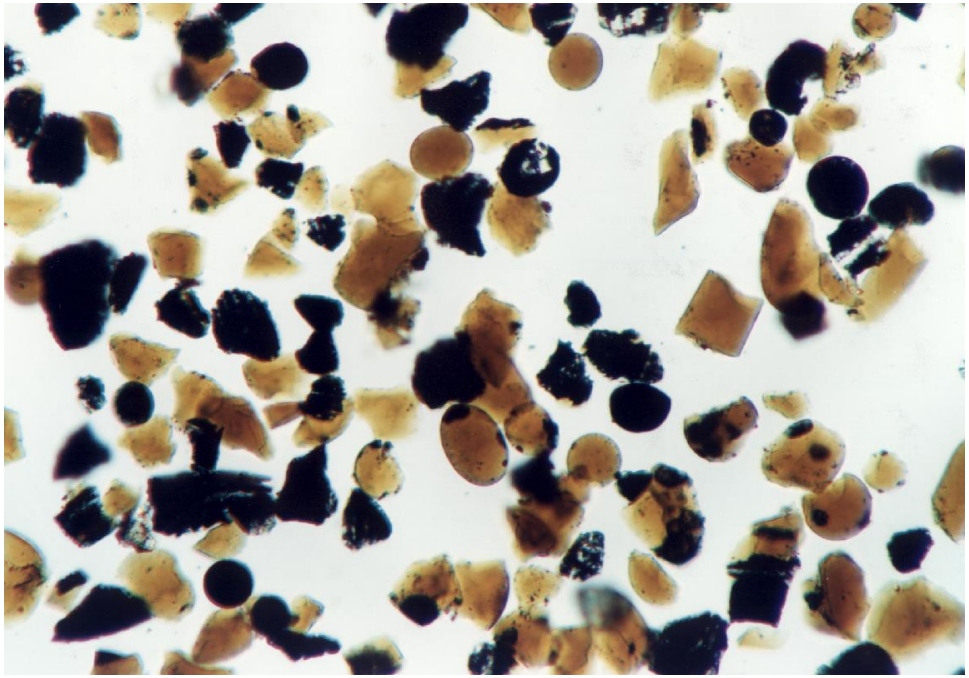
- Since the cost of placing a kilogram of mass on the LS is ~6X the cost of delivering it to LEO, the ability to produce and utilize LUNOX or lunar-derived LO_2 and hydrogen (LLH_2) from lunar polar ice (LPI) deposits can provide significant mission leverage

- Providing LUNOX for use in fuel cells, life support systems and LO_2/LH_2 chemical rockets used on lunar landing vehicles (LLVs), can allow "high value" cargo (people, manufacturing and scientific equipment, etc.) to be transported to LEO, then to the Moon instead of bulk LO_2 propellant

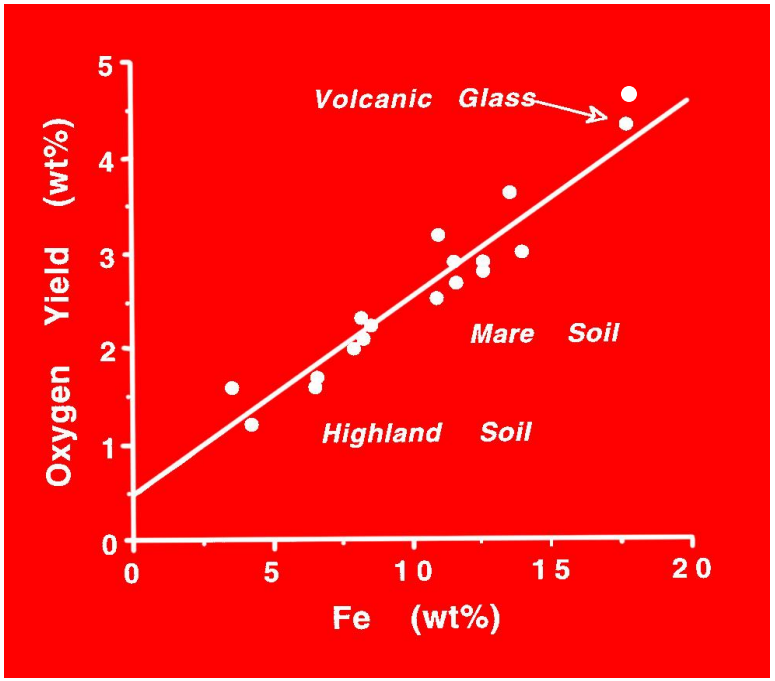
- Oxygen is abundant in the lunar regolith (~43% by mass) and can be extracted using a variety of techniques, such as hydrogen reduction of "ilmenite ($FeOTiO_2$)" or "FeO-rich" volcanic glass ("orange soil") discovered during the Apollo 17 mission to Taurus-Littrow

- While considerable interest has been expressed about mining and processing LPI for rocket propellant, *"ground truth"* must first be established to quantify the physical state of the ice (e.g., its vertical thickness and areal extent, levels of soil contamination, etc.) & the deep, extremely cold (~26 –100 K) permanently shadowed craters where the ice resides

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



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.



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

Scientific Evidence for Water Ice in Permanently Shadowed Craters (Cold Traps) Found in the Moon's Polar Regions

- Since the 1960's, scientists have conjectured that water ice could survive in the cold, permanently shadowed craters located at the Moon's poles

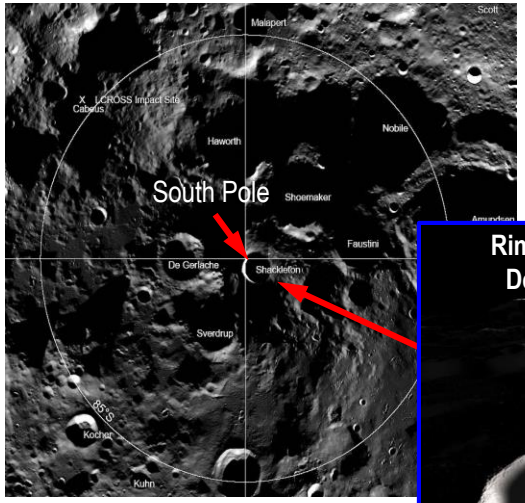
- *Clementine* (1994), *Lunar Prospector* (1998), *Chandrayaan-1* (2008), and *Lunar Reconnaissance Orbiter* (*LRO*) and *Lunar CRater Observation and Sensing Satellite* (*LCROSS*) (2009) lunar probes have provided data indicating the existence of large quantities of water ice at the lunar poles

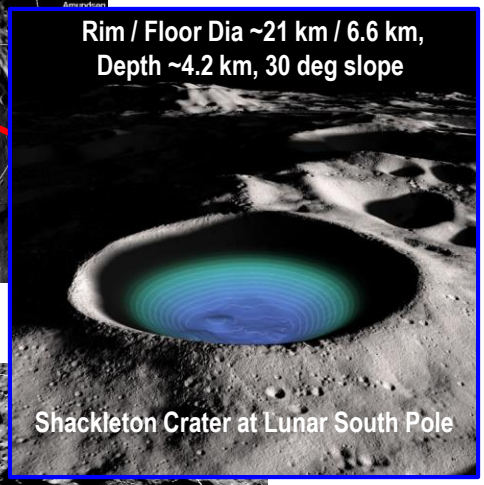
- The Mini-SAR onboard *Chandrayaan-1* discovered more than 40 permanently shadowed craters near the lunar north pole that are thought to contain ~600 million metric tons of water ice

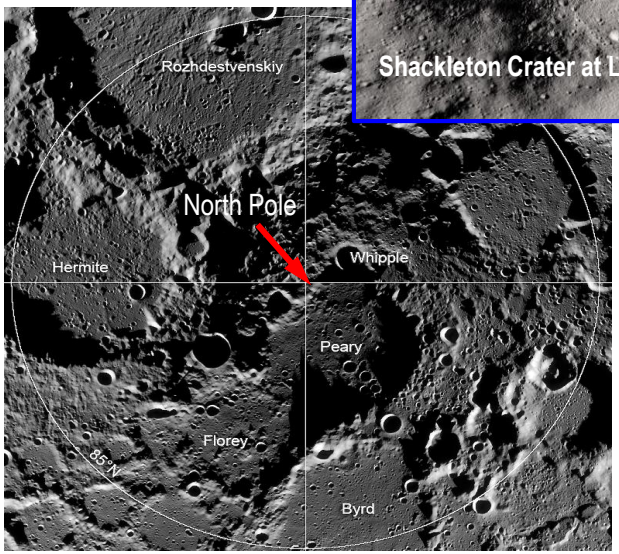
- Using neutron spectrometer data, the *Lunar Prospector* science team estimated a water ice content (~1.5 +/-0.8 wt% in the regolith) found in the Moon's polar "cold traps" and estimated the total amount of water at both poles at ~2 billion metric tons

- Using Mini-RF and spectrometry data, the *LRO / LCROSS* science team estimated the water ice content in the regolith in the south polar region to be ~5.6 +/- 2.9 wt%

- On the basis of the above scientific data, it appears that the water ice content can vary from ~1-10 wt% and the total quantity of LPI at both poles can range from ~600 million to ~2 billion metric tons







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

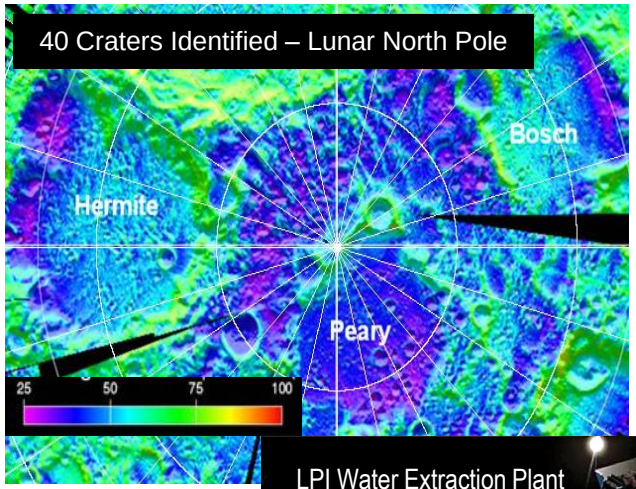
- The world's 10 coldest mines are located in Russia's extreme northeastern territory. At the coldest of these mines, Sarylakh, the temperatures can drop to nearly -50 C (~223 K)

- 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

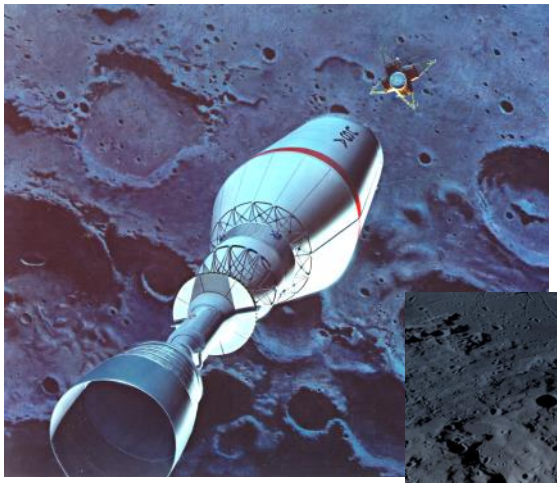
- Mining equipment must be able to break up, excavate and transport the ice-bearing regolith to the water extraction plant. It must also operate in a hard vacuum and be able to tolerate the abrasive nature of the lunar dust

- Experiments conducted by Gertsch et al. using LN_2-cooled ice / regolith mixtures with ~10 wt% water content indicate the mixture behaves like high strength concrete requiring heavy excavation equipment

- Once produced, the LPI-derived water would then be electrolyzed on the Moon and in space (at an orbiting propellant depot)

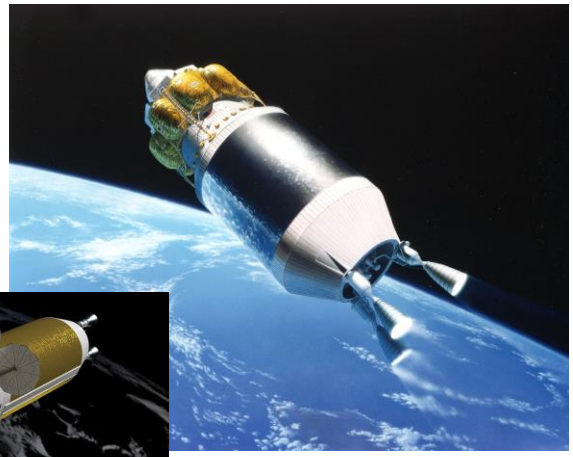


Sampling of Crewed, Cargo & Commercial Lunar Transfer Vehicle Concepts Developed by GRC During the Past 25 Years

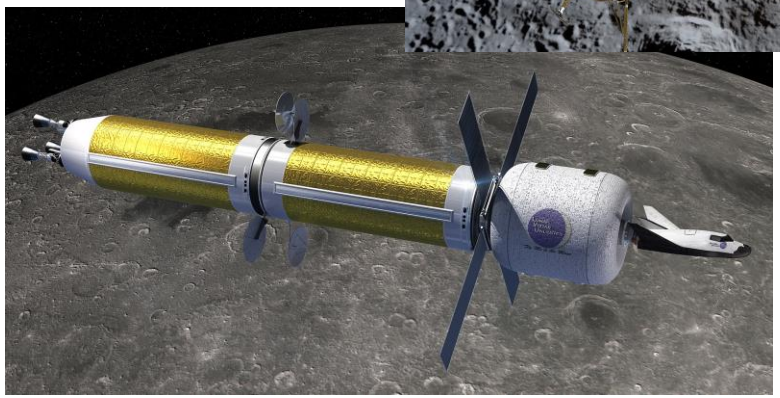


Reusable Lunar Transfer Vehicle uses Single 75 klb_f NTR Engine – SEI (1990 - 91)

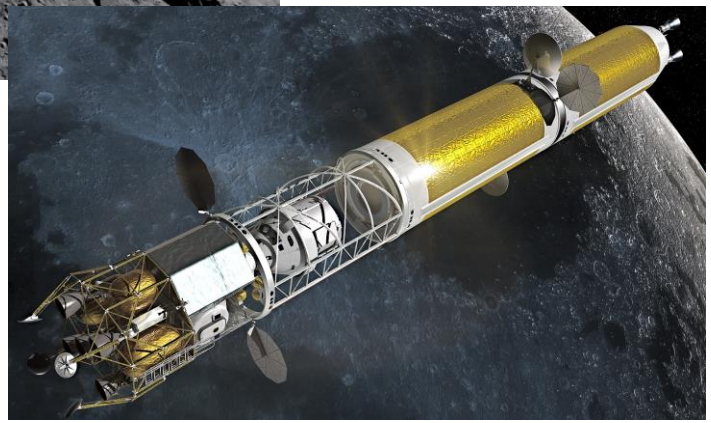
Expendable TLI Stage for "First Lunar Outpost" Mission uses 3 - 25 klb_f NTR Engines – Fast Track Study (1992)



Reusable Lunar Cargo Transport uses 3 – 16.5 klb_f "SNRE-class" Engines – (2013-16)

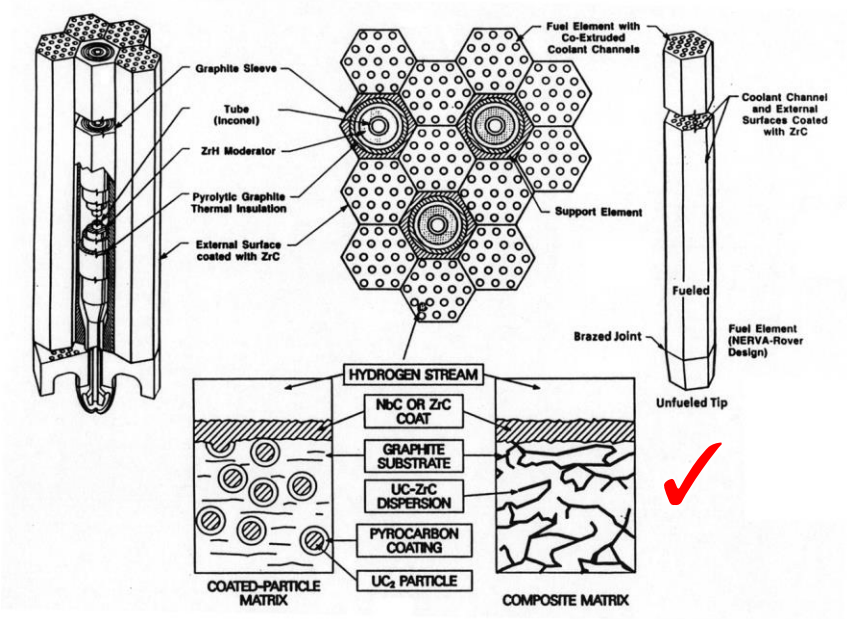


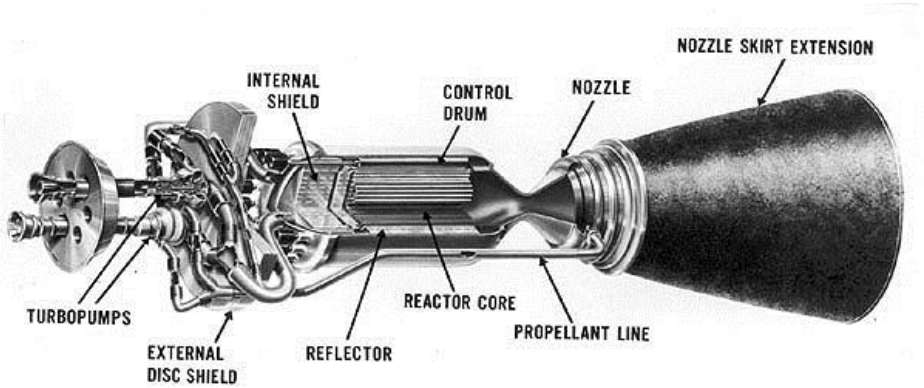
Commercial Tourism Polar Orbit Mission uses 3 – 16.5 klb_f "SNRE-class" Engines – (2013-16)



Reusable Crewed Landing Mission uses 3 – 16.5 klb_f "SNRE-class" Engines – (2013-16)

"Heritage" Fuel Element (FE) / Tie Tube (TT) Arrangement / Performance Parameters for Small Nuclear Rocket Engine





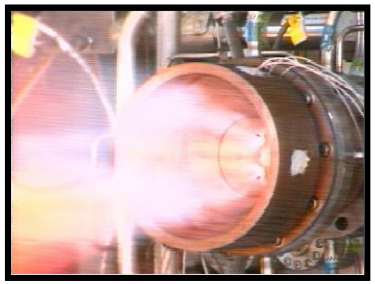
Baseline Small Nuclear Rocket Engine (SNRE) Performance Parameters:

- 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**
- Hydrogen Flow Rate: ~8.3 kg/s
- F / W_{eng} Ratio: **~3.03**
- Engine Length: ~5.8 m
- Nozzle Exit Diameter: ~1.53 m
- FE Length ~0.89 m (~35 inches)
- No. FEs / TTs: 564 / 241
- FE-to-TT Ratio: ~2:1
- Reactor Power Level: **~365 MWt**
- Fuel Matrix Power Density: ~3.44 MWt / liter
- U-235 Enrichment: **93%**
- Fuel Loading: ~0.6 grams / cm^3
- U-235 Inventory: ~60 kg

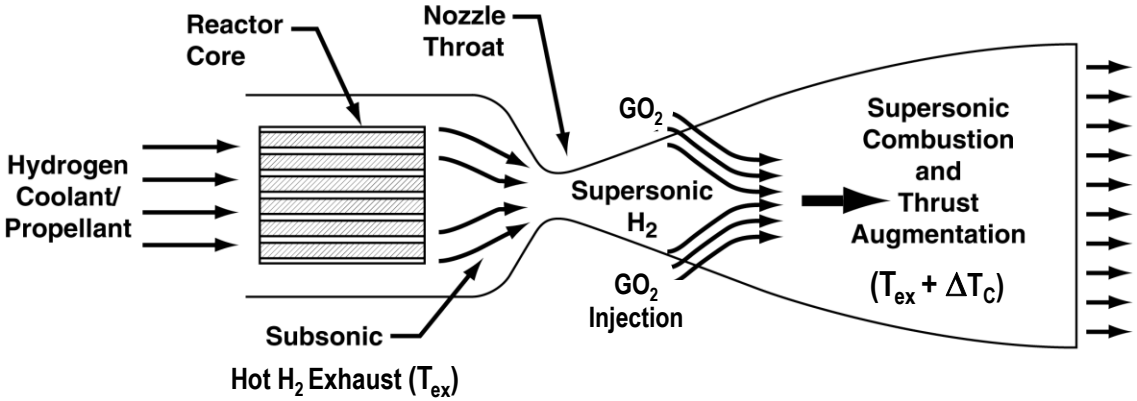
Ref: S. K. Borowski, et al., "Affordable Development and Demonstration of a Small NTR Engine: How Small is Big Enough?", AIAA-2015-4524; also as NASA/TM—2016-219402

"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



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



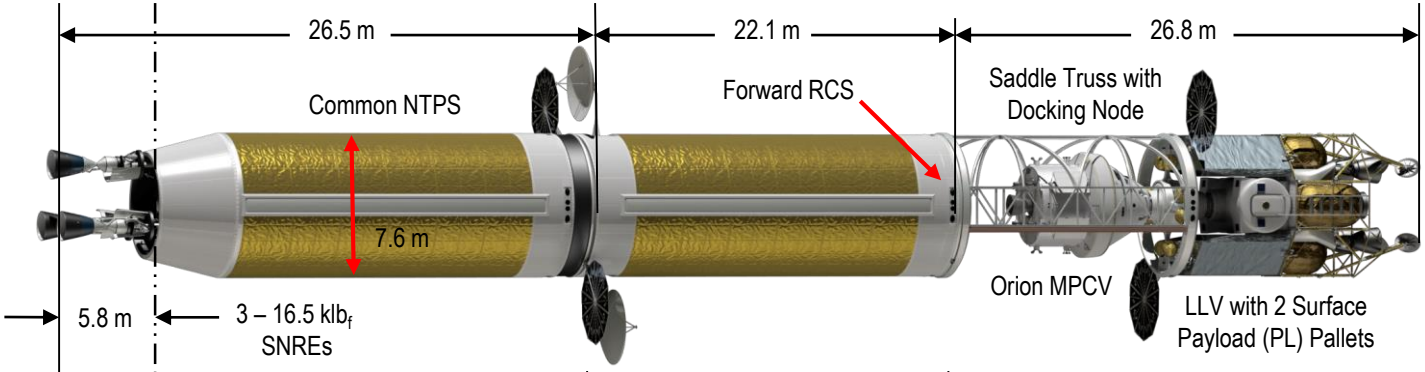
O/H Mixture Ratio	0	1	2	3	4	5
Delivered Isp (s)	900**	725	637	588	552	516
Thrust Augmentation Factor	1.0	1.611	2.123	2.616	3.066	3.441
Thrust (lb_f)	16,500	26,587	35,026	43,165	50,587	56,779
Engine Mass (lb_m)	5,462	5,677	5,834	5,987	6,139	6,295
Engine T/W	3.02	4.68	6.00	7.21	8.24	9.02

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

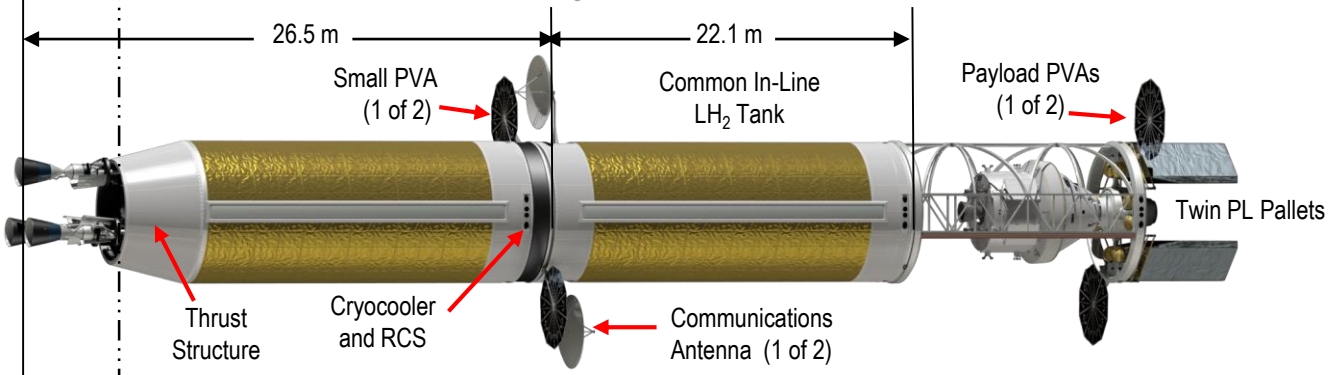
*Ref: M. J. Bulman and T. M. Neill, "Simulated LANTR Testing", AIAA 2000–3897

Variation in NLTV Size, IMLEO, Mission Capability and Burn Time Resulting from Use of LLO_2 and Transition to LANTR Engines

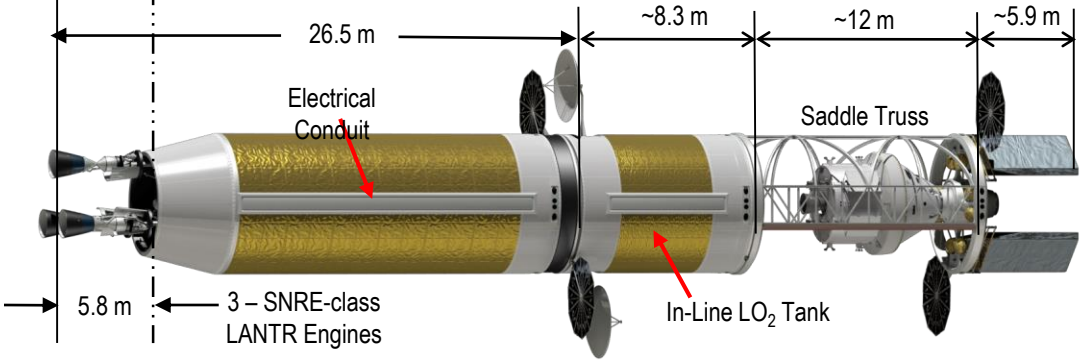
"Propelling Us to New Worlds"



a) Crewed Lunar Landing:
(LEO – LPO – 24-hr EEO)
- 4 crew
- MPCV + LLV ~48 t
- IMLEO ~182.4 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: ~53.2 min



b) Crewed Lunar Landing:
(LEO – LPO – 2.86-hr EEO)
- MPCV + 4 crew + 5 t PL
- Lunar Surface-based LLV
- IMLEO ~152.2 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: ~53.2 min

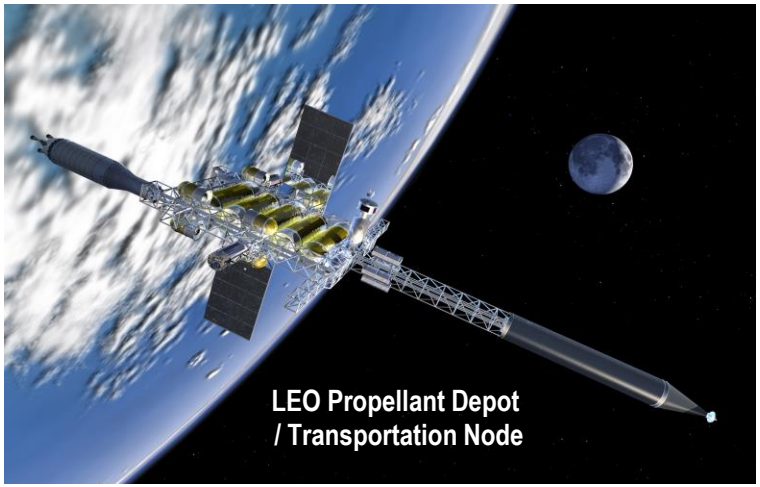


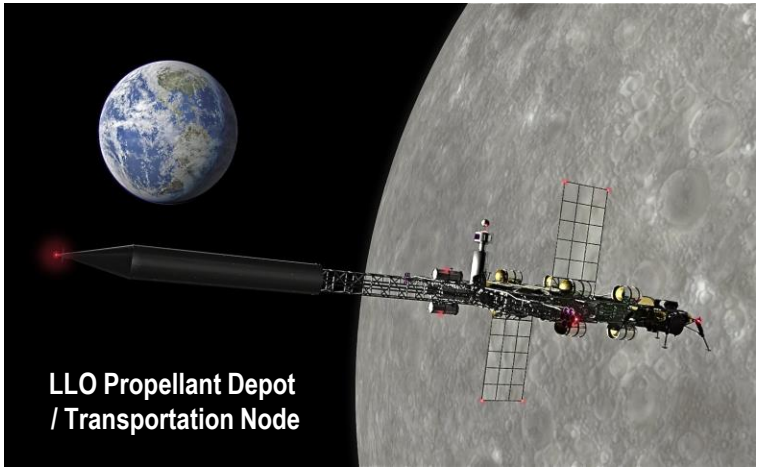
c) Crewed Lunar Landing:
(LEO – LPO – LEO)
- MPCV + 4 crew + 5 t PL
- Lunar Surface-based LLV
- IMLEO ~133 t
- Supplied LLO_2 ~51.4 t
- Supplied LLH_2 ~6.42 t
- Total Mission Burn Time: ~29.5 min

Excess LLH_2 from H_2O electrolysis used to "top off" NTPS

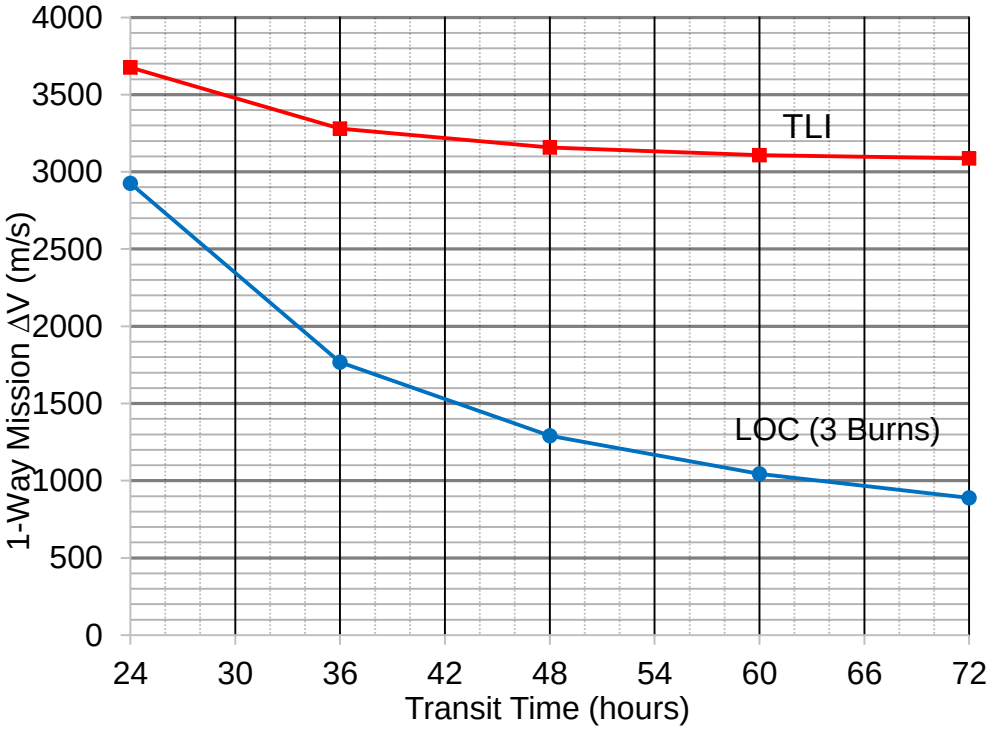
Growth Mission Possibilities and Faster Trip Times using Depots and LUNOX Refueling

Over time we envision the development of a totally space-based LTS with different types of NLTVs operating between transportation nodes / propellant depots located in LEO, equatorially LLO and LPO.





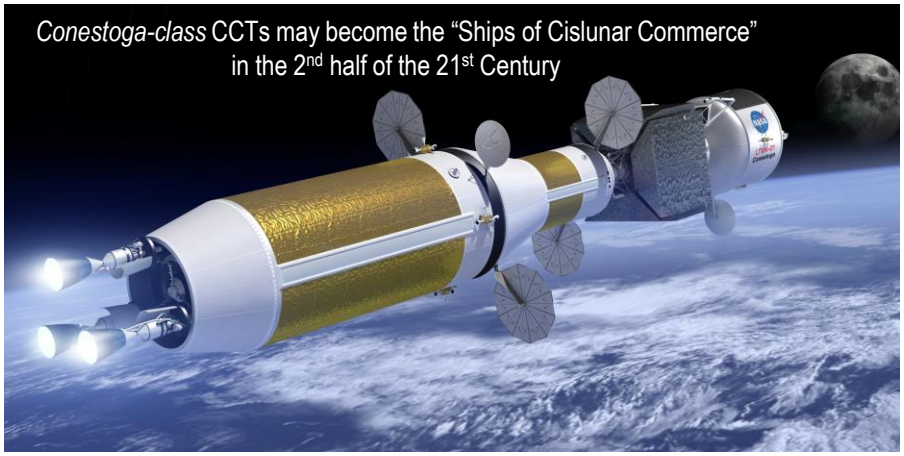
One-way transit times to and from the Moon on the order of 72 hours would be the norm initially. As lunar outposts grow into settlements staffed by visiting scientists, engineers and administrative personnel representing both government and private ventures, more frequent flights of shorter duration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

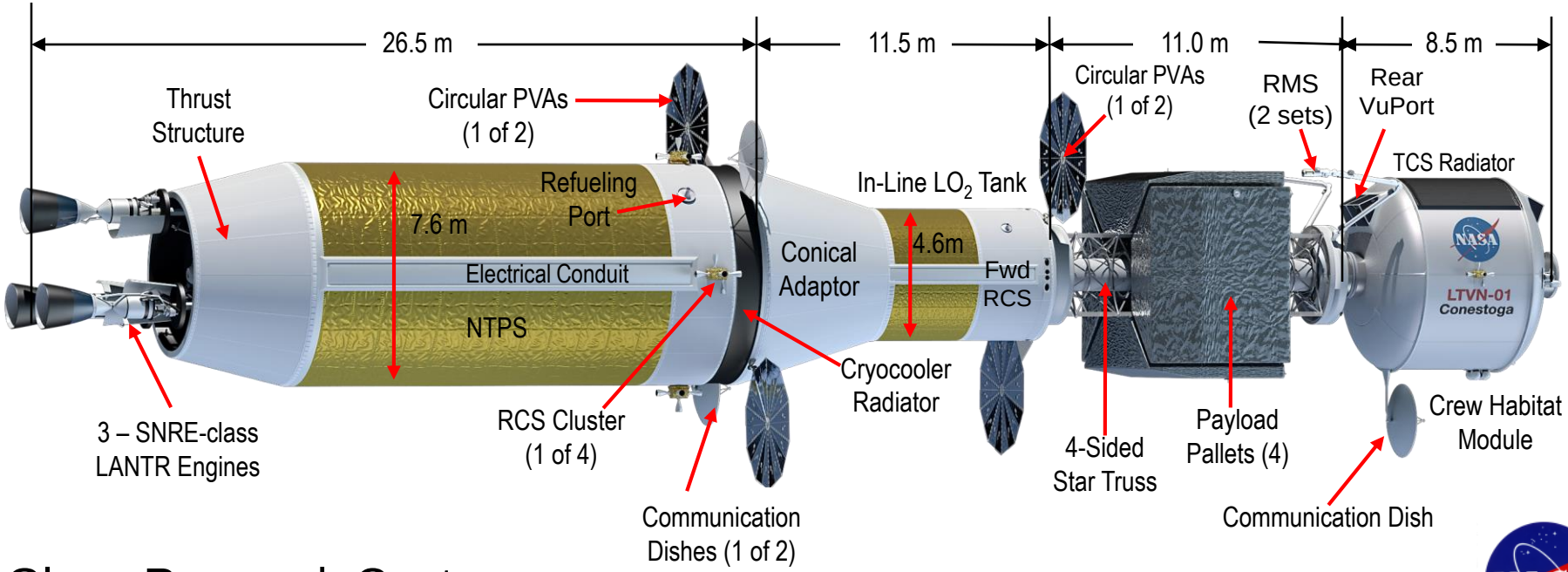


Cutting the Earth-Moon transit times in half to ~36 hours will require the mission's total ΔV budget to increase by ~25% – from ~8 to 10 km/s. For 24 hour LEO to LPO transit times the total mission ΔV increases by ~63% – from ~8 to 13 km/s.

Conestoga – A Reusable Space-based Crew Cargo Transport uses LANTR Engines, a Common NTPS and In-line LO_2 Tank Assembly

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





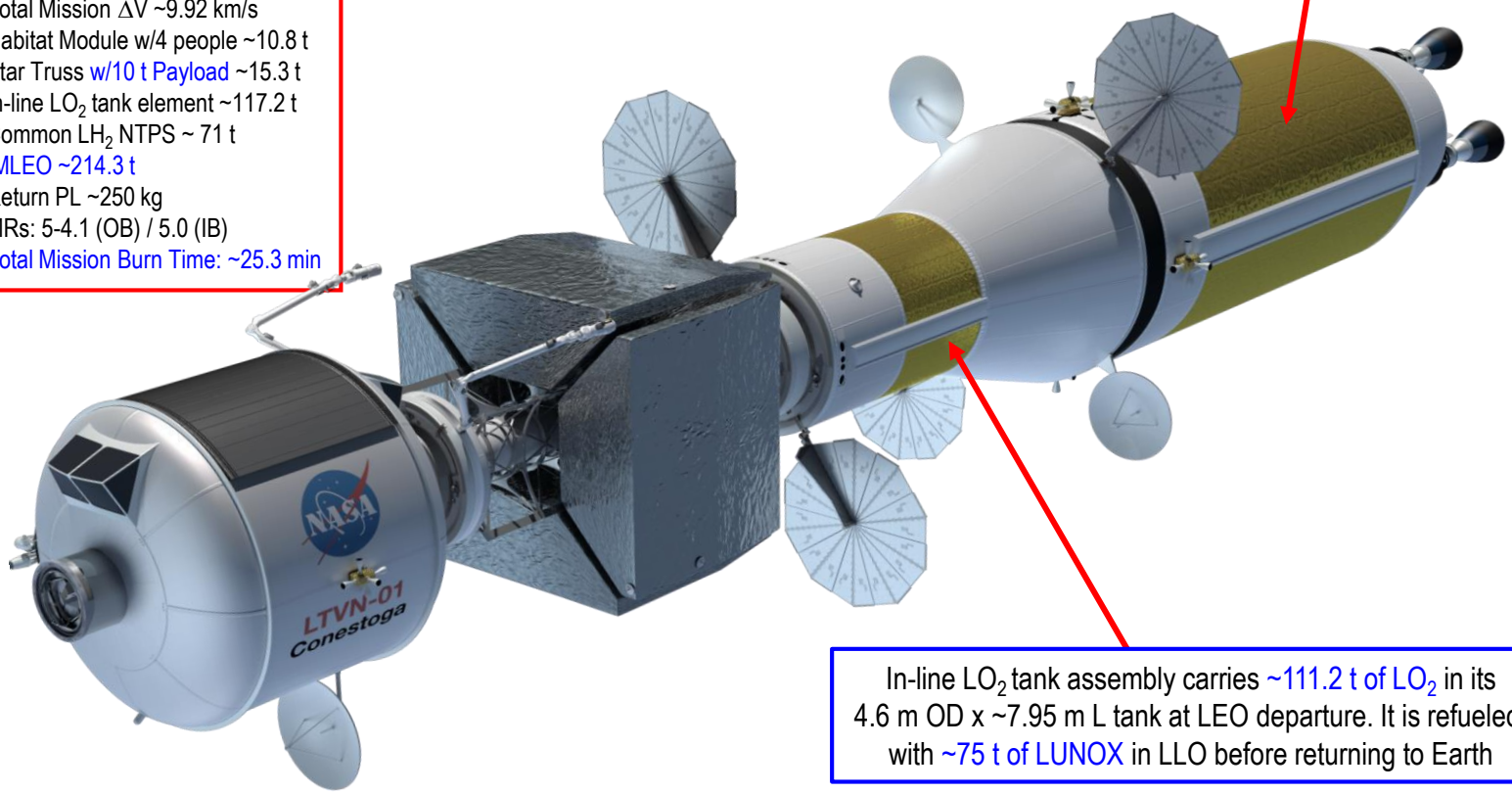
Conestoga – LANTR-propelled Crewed Cargo Transport uses a "Common" NTPS and In-Line LO_2 Tank Assembly

Twice the Cargo in Half the Time / uses LUNOX only

(LEO ⟶ LLO ⟶ LEO)

- 36-hr "1-way" transit times
- Total Mission ΔV ~9.92 km/s
- Habitat Module w/4 people ~10.8 t
- Star Truss w/10 t Payload ~15.3 t
- In-line LO_2 tank element ~117.2 t
- Common LH_2 NTPS ~ 71 t
- IMLEO ~214.3 t
- Return PL ~250 kg
- MRs: 5-4.1 (OB) / 5.0 (IB)
- Total Mission Burn Time: ~25.3 min

NTPS carries ~39.8 t of Earth-supplied LH_2 in its 7.6 m OD x ~15.7 m L tank



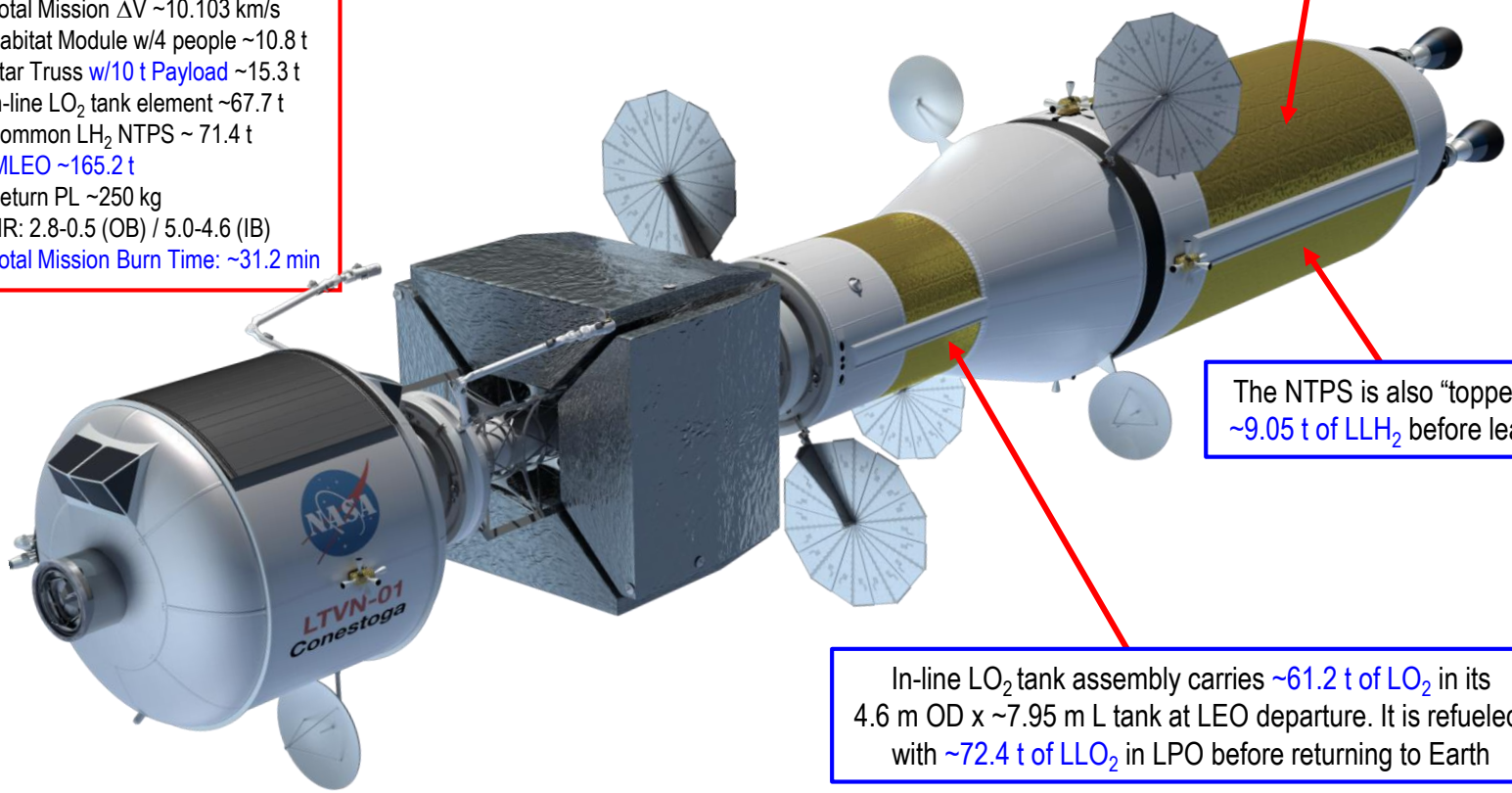
In-line LO_2 tank assembly carries ~111.2 t of LO_2 in its 4.6 m OD x ~7.95 m L tank at LEO departure. It is refueled with ~75 t of LUNOX in LLO before returning to Earth

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

Twice the Cargo in Half the Time / uses LLO_2 & LLH_2

(LEO ⟶ LPO ⟶ LEO)

- 36-hr "1-way" transit times
- Total Mission ΔV ~10.103 km/s
- Habitat Module w/4 people ~10.8 t
- Star Truss w/10 t Payload ~15.3 t
- In-line LO_2 tank element ~67.7 t
- Common LH_2 NTPS ~ 71.4 t
- IMLEO ~165.2 t
- Return PL ~250 kg
- MR: 2.8-0.5 (OB) / 5.0-4.6 (IB)
- Total Mission Burn Time: ~31.2 min

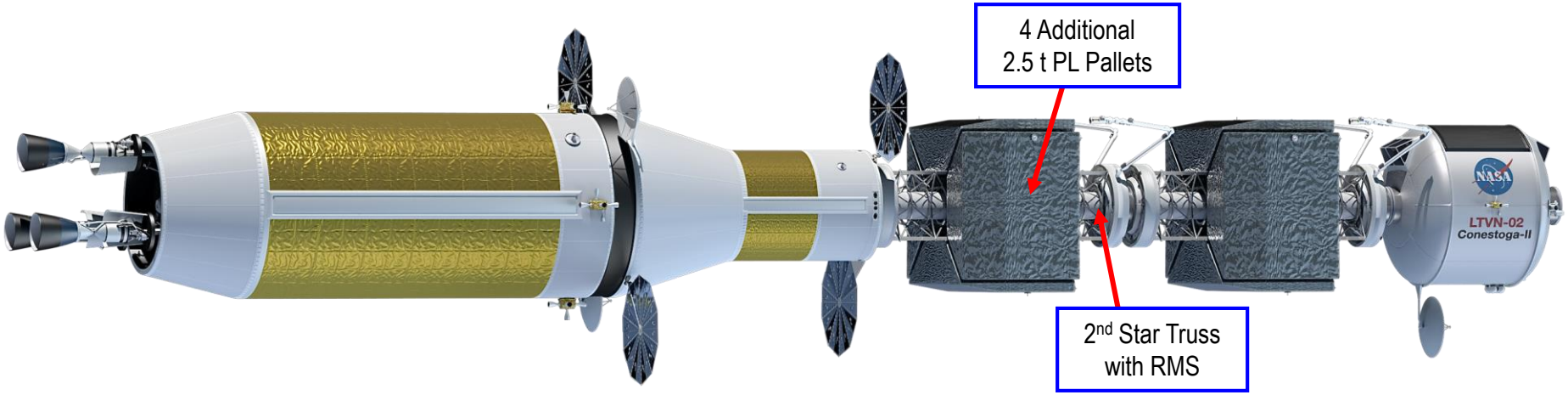


NTPS carries ~39.8 t of Earth-supplied LH_2 in its 7.6 m OD x ~15.7 m L tank

The NTPS is also "topped off" with ~9.05 t of LLH_2 before leaving LPO

In-line LO_2 tank assembly carries ~61.2 t of LO_2 in its 4.6 m OD x ~7.95 m L tank at LEO departure. It is refueled with ~72.4 t of LLO_2 in LPO before returning to Earth

Conestoga-II – LANTR-propelled Heavy Crewed Cargo Transport uses a "Common" NTPS, In-Line LO_2 Tank Assembly and 2nd Star Truss



Double the PL: 10 to 20 t / LUNOX only

(LEO ⟶ LLO ⟶ LEO)
- 72-hr "1-way" transit times
- Total Mission ΔV ~8.057 km/s
- Habitat Module w/4 people ~10.8 t
- 2 Star Trusses w/20 t PL ~30.6 t
- In-line LO_2 tank element ~77.1 t (initial LEO-supplied LO_2 ~71 t)
- Common LH_2 NTPS ~ 71.1 t
- IMLEO ~189.6 t
- Refueled LLO_2 ~52.1 t
- Return PL ~250 kg
- MRs Used: TLI (MR~3.4, I_{sp}~573 s); LOC (MR~0.9, I_{sp}~737 s); TEI (MR~4.7, I_{sp} ~527 s); EOC (MR~3.8, I_{sp}~558 s)
- Total Mission Burn Time: ~25.3 min

Deliver 20 t PL w/LLO_2 / LLH_2 refueling

(LEO ⟶ LPO ⟶ LEO)
- 72-hr "1-way" transit times
- Total Mission ΔV ~8.081 km/s
- Habitat Module w/4 people ~10.8 t
- 2 Star Trusses w/20 t PL ~30.6 t
- In-line LO_2 tank element ~59.9 t (initial LEO-supplied LO_2 ~52.7 t)
- Common LH_2 NTPS ~ 72.1 t
- IMLEO ~173.4 t
- Refueled LLO_2 ~47.5 t
- Refueled LLH_2 ~5.93 t
- Return PL ~250 kg
- MRs Used: TLI (MR~2.5, I_{sp}~612 s); LOC (MR~0, I_{sp}~900 s); TEI (MR~4.4, I_{sp} ~537 s); EOC (MR~3.1, I_{sp}~585 s)
- Total Mission Burn Time: ~29.1 min

Double the PL: 20 to 40 t / LUNOX only

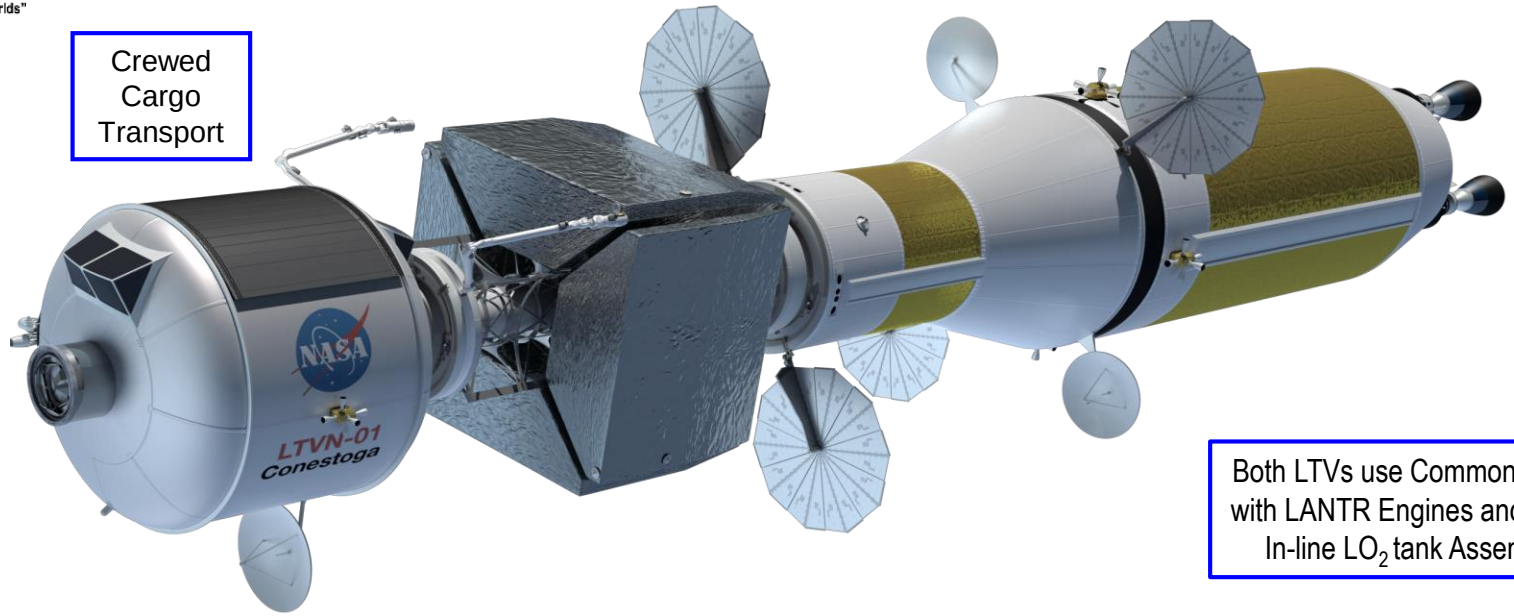
(LEO ⟶ LLO ⟶ LEO)
- 72-hr "1-way" transit times
- Total Mission ΔV ~8.064 km/s
- Habitat Module w/4 people ~10.8 t
- 2 Star Trusses w/40 t PL ~52.7 t
- In-line LO_2 tank element ~116 t (initial LEO-supplied LO_2 ~109.8 t)
- Common LH_2 NTPS ~ 71.2 t
- IMLEO ~250.7 t
- Refueled LLO_2 ~60.3 t
- Return PL ~250 kg
- MRs Used: TLI (MR~4.4, I_{sp}~536 s); LOC (MR~3.3, I_{sp}~578 s); TEI (MR~5.0, I_{sp}~516 s); EOC (MR~4.8, I_{sp}~522 s)
- Total Mission Burn Time: ~25.2 min

Deliver 40 t PL w/LLO_2 / LLH_2 refueling

(LEO ⟶ LPO ⟶ LEO)
- 72-hr "1-way" transit times
- Total Mission ΔV ~8.092 km/s
- Habitat Module w/4 people ~10.8 t
- 2 Star Trusses w/40 t PL ~52.7 t
- In-line LO_2 tank element ~81.7 t (initial LEO-supplied LO_2 ~74.3 t)
- Common LH_2 NTPS ~ 72.4 t
- IMLEO ~217.6 t
- Refueled LLO_2 ~57.2 t
- Refueled LLH_2 ~7.15 t
- Return PL ~250 kg
- MRs Used: TLI (MR~2.9, I_{sp}~594 s); LOC (MR~0.5, I_{sp}~795 s); TEI (MR~5, I_{sp} ~516 s); EOC (MR~4.3, I_{sp}~543 s)
- Total Mission Burn Time: ~29.9 min

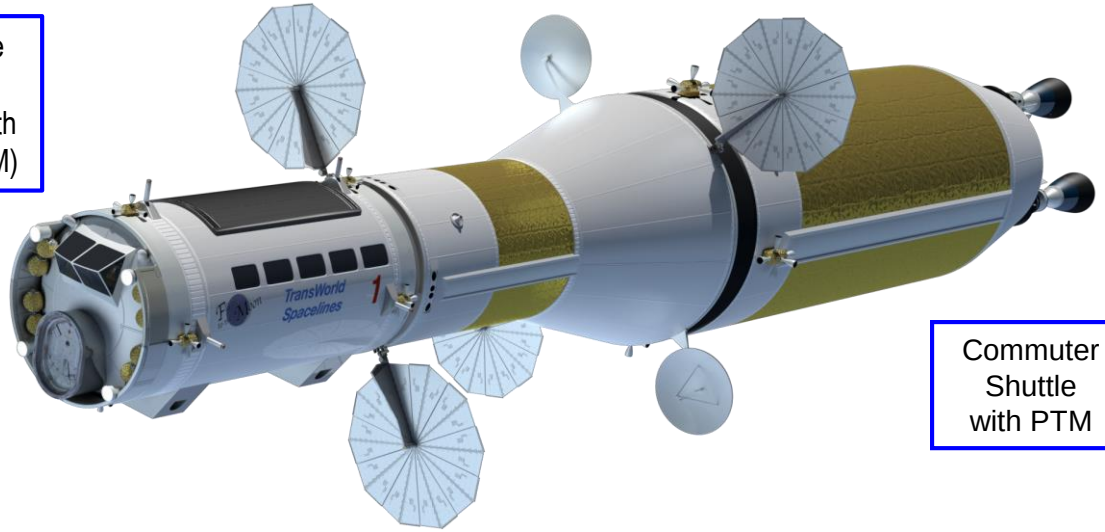
Relative Size of the *Conestoga* Crewed Cargo Transport and Passenger Commuter Shuttle

Crewed Cargo Transport



Both LTVs use Common NTPS with LANTR Engines and same In-line LO_2 tank Assembly

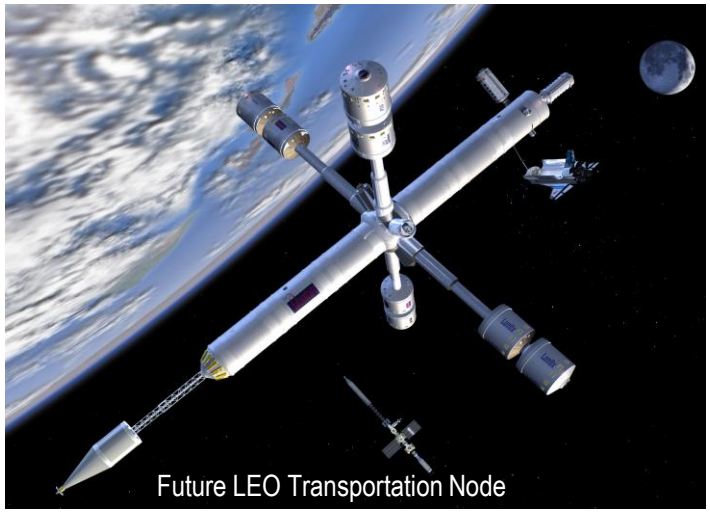
For Commuter Shuttle Missions, the Habitat Module, Saddle Truss and its attached Payload are replaced with a Passenger Transport Module (PTM)

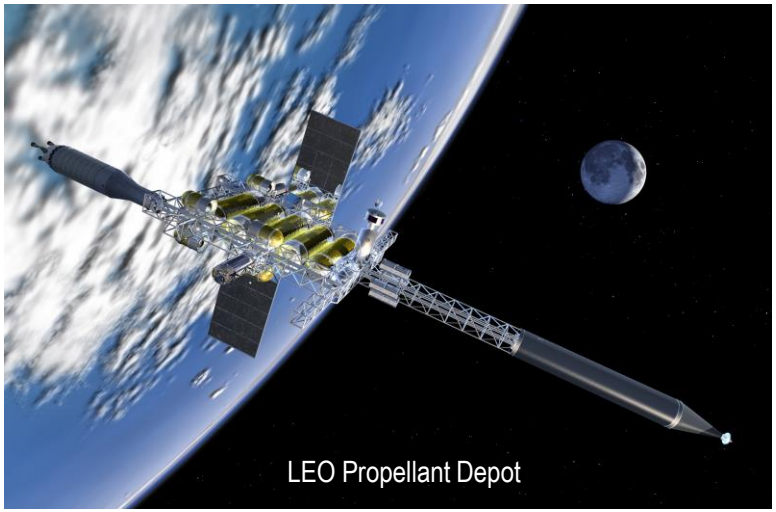


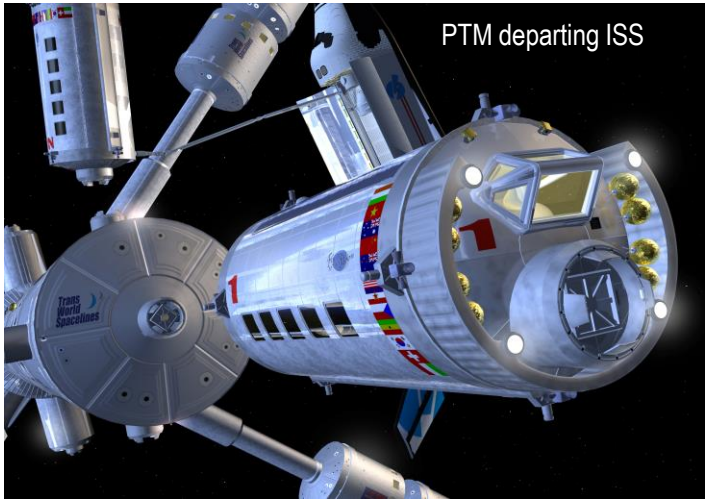
Commuter Shuttle with PTM

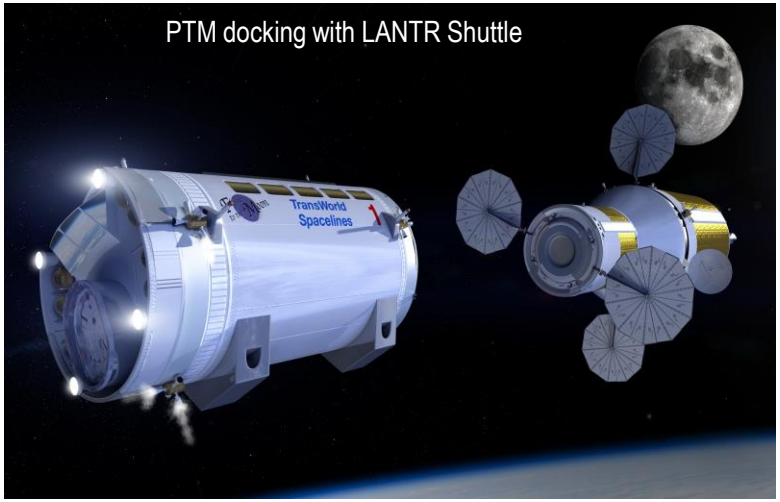
How Might a Typical Commuter Flight to the Moon Proceed?

A possible scenario might start with passengers boarding a future “Earth-to-Orbit” shuttle for a flight to a future International Space Station (ISS) with artificial gravity capability. There they 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 ISS, the PTM docks with the fully fueled LANTR shuttle awaiting it a safe distance away.



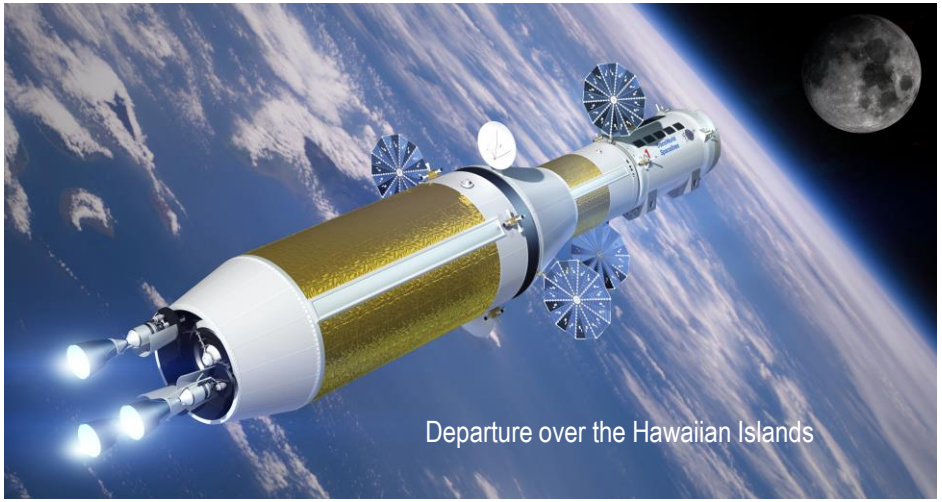


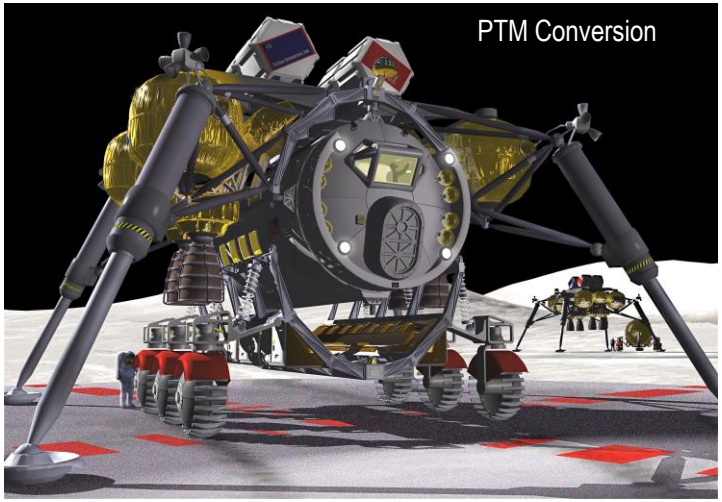


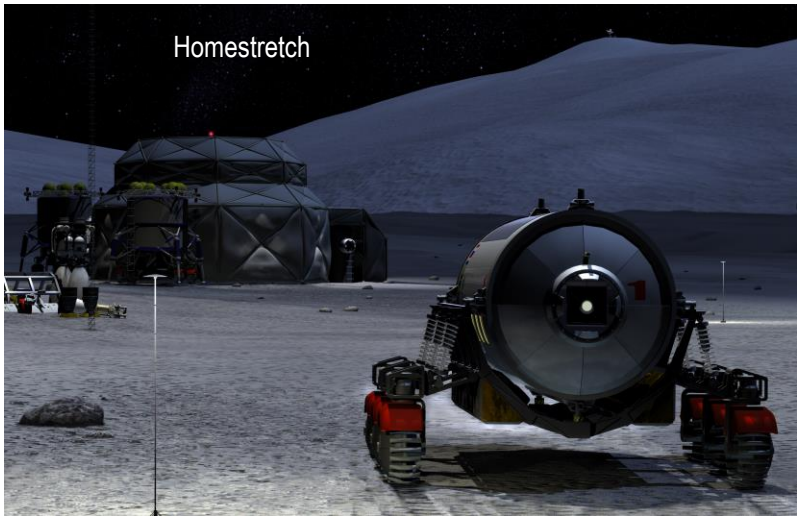


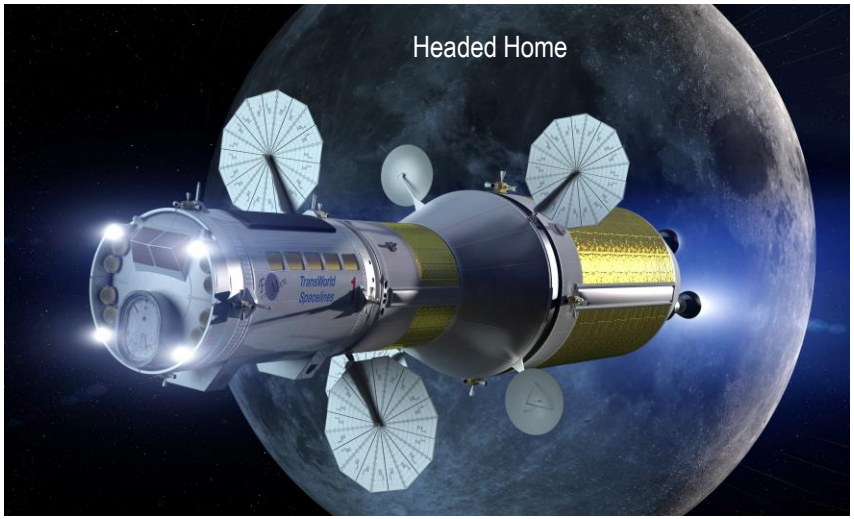
How Might a Typical Commuter Flight to the Moon Proceed?

At the appropriate moment, the LANTR engines are powered up and the shuttle climbs rapidly away from Earth. 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.

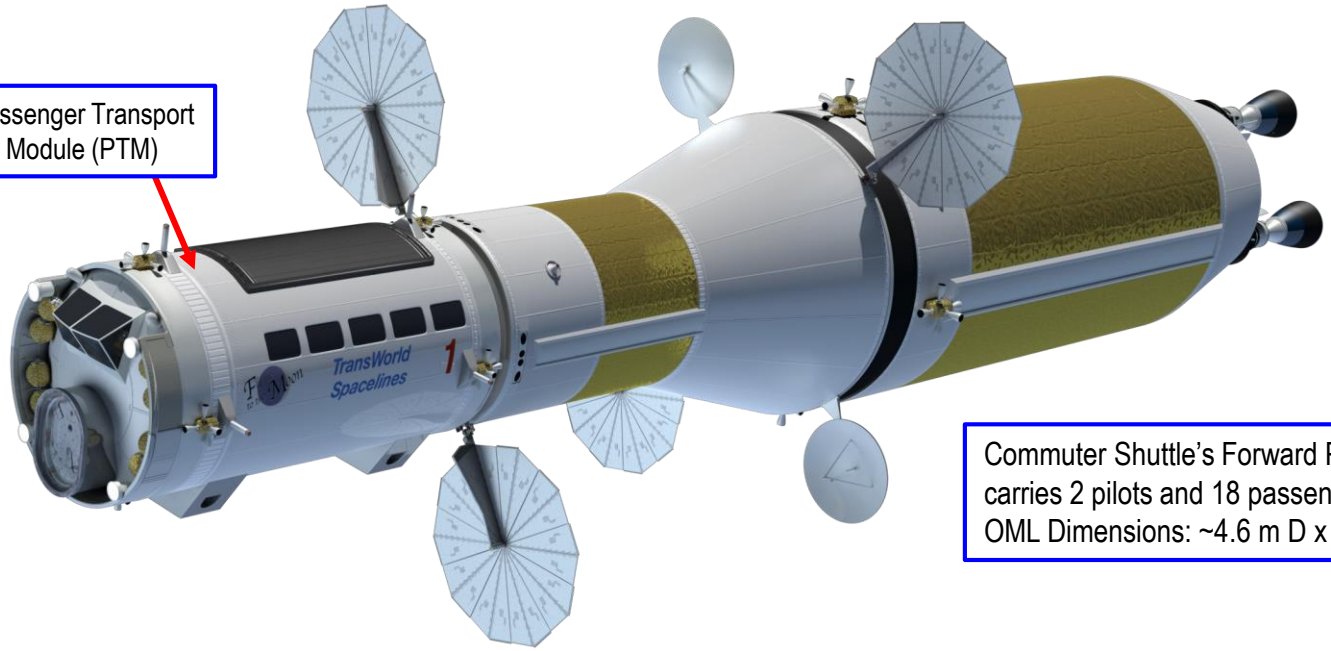








LANTR Commuter Shuttle Mission Options, Trip Time and ΔV Budgets, and LDP Refueling Requirements



Commuter Shuttle's Forward PTM carries 2 pilots and 18 passengers; OML Dimensions: ~4.6 m D x 8 m L

Shortest transit time / using LUNOX only

(LEO ⟶ LLO ⟶ LEO)

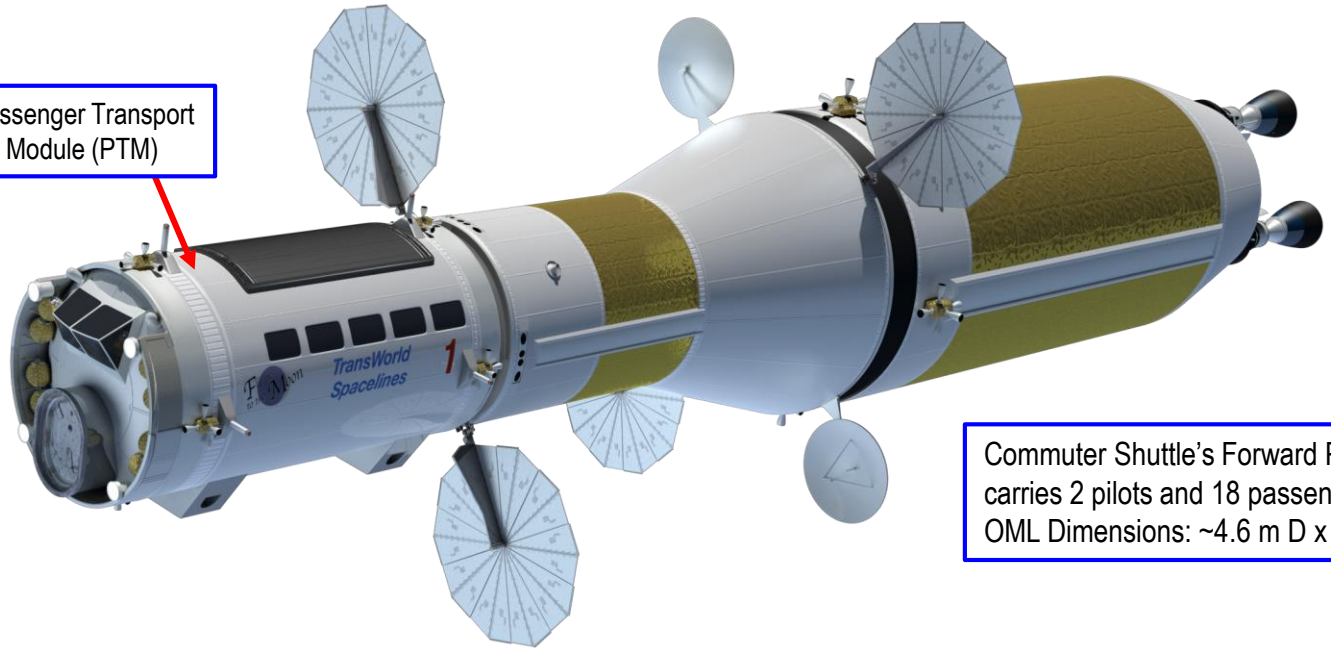
- 32.8-hr "1-way" transit times
- Total Mission ΔV ~10.481 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~117.2 t (includes 111.1 t of LEO LO_2)
- Common LH_2 NTPS ~71.1 t
- IMLEO ~203.3 t
- Refueled LLO_2 ~80.4 t
- LANTR engines operate O_2-rich Out and Back: MR~5; I_{sp}~516 s
- Total Mission Burn Time: ~25.3 min

Shortest transit time w/LLO_2 / LLH_2 refueling

(LEO ⟶ LPO ⟶ LEO)

- 25.6-hr "1-way" transit times
- Total Mission ΔV ~12.519 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~118 t (includes 111.2 t of LEO LO_2)
- Common LH_2 NTPS ~71.8 t
- IMLEO ~204.8 t
- Refueled LLO_2 ~106.4.7 t
- Refueled LLH_2 ~13.3 t
- TLI: MR/Isp~5/516; LOC: MR~3-1.1 /I_{sp}~586-715, IB: MR~5, I_{sp}~516 s
- Total Mission Burn Time: ~33.9 min

LANTR Commuter Shuttle Mission Options, Trip Time and ΔV Budgets, and LDP Refueling Requirements



Commuter Shuttle's Forward PTM carries 2 pilots and 18 passengers; OML Dimensions: ~4.6 m D x 8 m L

Shortest transit time / 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 (includes 111.1 t of LEO LO_2)
- Common LH_2 NTPS ~71.1 t
- IMLEO ~203.3 t
- Refueled LLO_2 ~80.4 t ✓
- LANTR engines operate O_2-rich Out and Back: MR~5; I_{sp}~516 s
- Total Mission Burn Time: ~25.3 min

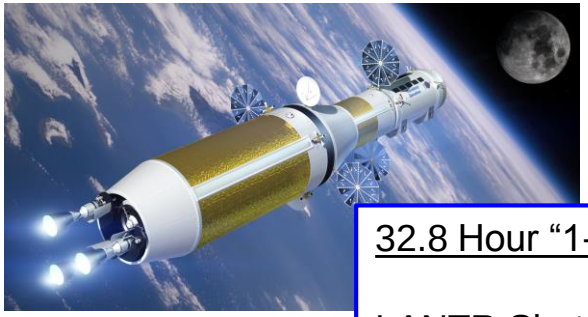
Shortest transit time w/LLO_2 / LLH_2 refueling

(LEO ⟶ LPO ⟶ LEO)

- 25.6-hr "1-way" transit times
- Total Mission ΔV ~12.519 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~118 t (includes 111.2 t of LEO LO_2)
- Common LH_2 NTPS ~71.8 t
- IMLEO ~204.8 t
- Refueled LLO_2 ~106.4.7 t
- Refueled LLH_2 ~13.3 t
- TLI: MR/Isp~5/516; LOC: MR~3-1.1 /I_{sp}~586-715, IB: MR~5, I_{sp}~516 s
- Total Mission Burn Time: ~33.9 min

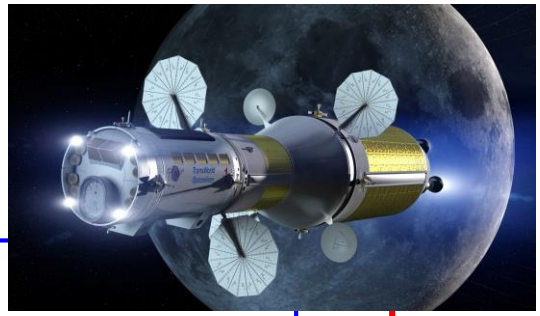
Plus additional time – ranging from several hours to a day – to transfer from an initial elliptical capture orbit to a 300 km circular LPO

Total LUNOX Required for "Weekly" Commuter Flights



LANTR Shuttle
Departing LEO
for the Moon

LANTR Shuttle
Headed Home



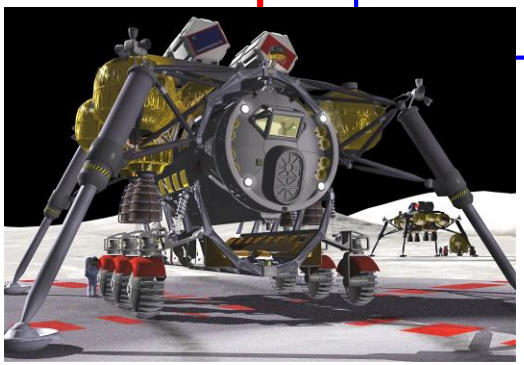
32.8 Hour "1-Way" Transits (15 t / 20 Person PTM):

LANTR Shuttle: (80.5 t LUNOX /mission/week)
x 52 weeks/year = 4,186 t/yr

LLV*+ : (29.5 t LUNOX / flight+) x (1 flight/LLV/week)
x 4 LLVs x 52 weeks/year = 6,136 t/yr

LLV*# : (42.7 t LUNOX# / round trip flights / week)
x 52 weeks /year = 2,220 t/yr

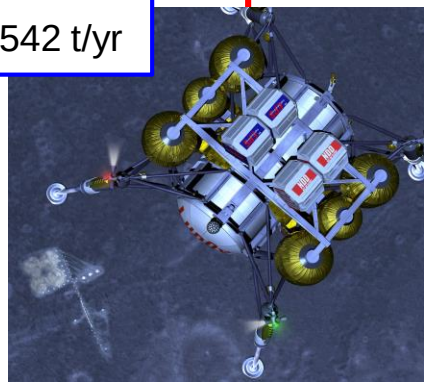
Total LUNOX Rate = 12,542 t/yr



* O/H MR = 6, I_{sp} = 465 s, ΔV_{desc} = 2000 m/s and ΔV_{asc}= 1900 m/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

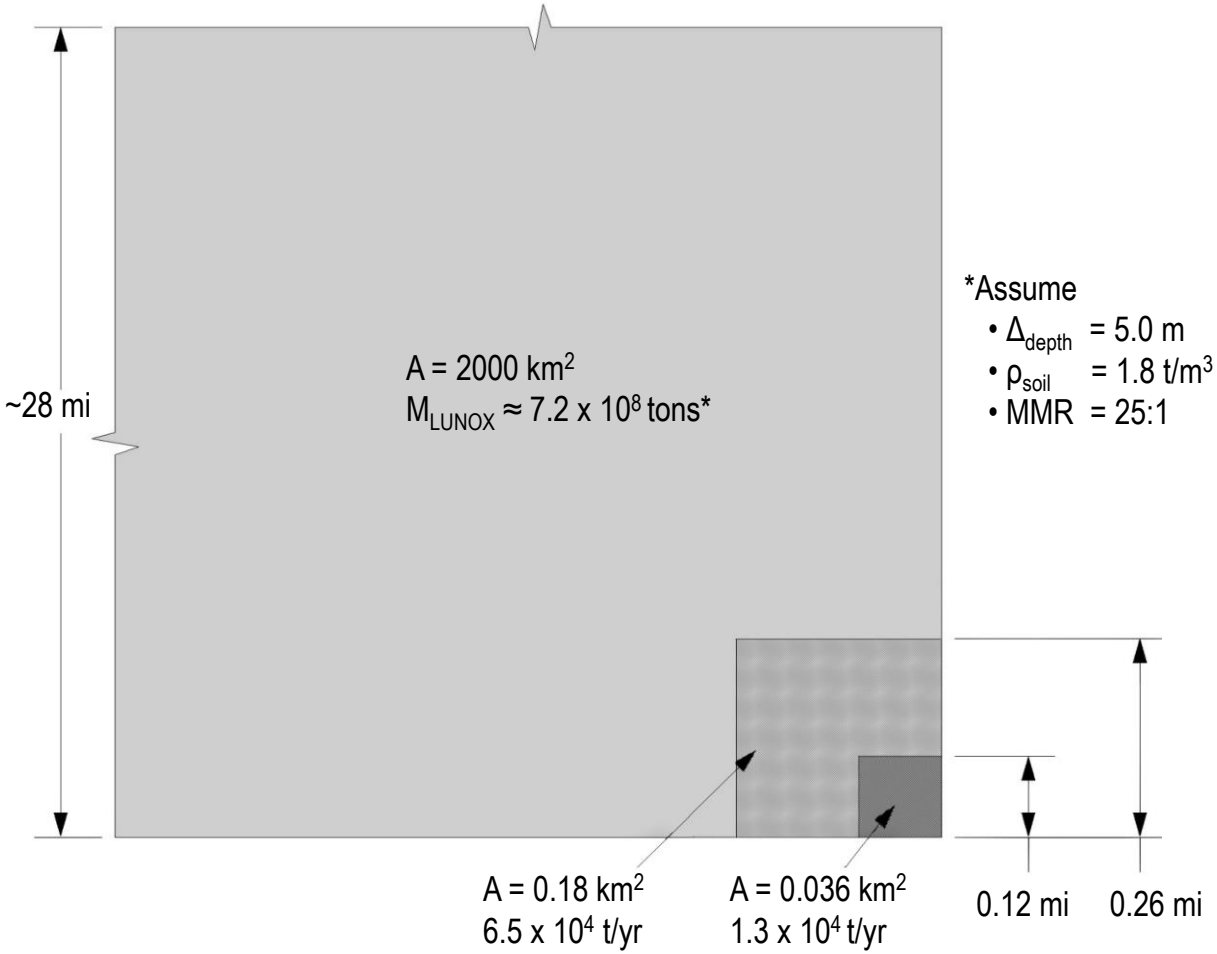
LLV Unloading PTM onto
a Mobile Surface Vehicle

Tanker LLV Delivering
LUNOX to LLO Depot



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

At the SE edge of the "Sea of Serenity" lies the Taurus-Littrow DMD of FeO-rich black crystalline and orange glass beads. The deposit is vast (~3000 km^2) and 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 13,000 t of LUNOX annually requires glass throughput of ~3.25 x 10^5 t/yr at MMR = 25:1
- Assuming 13 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 front-end loaders and 4 haulers
- The mining rate at each plant is just under 6 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)

Could supply LUNOX for 25 commuter flights carrying 450 passengers each week for next 2215 yrs!

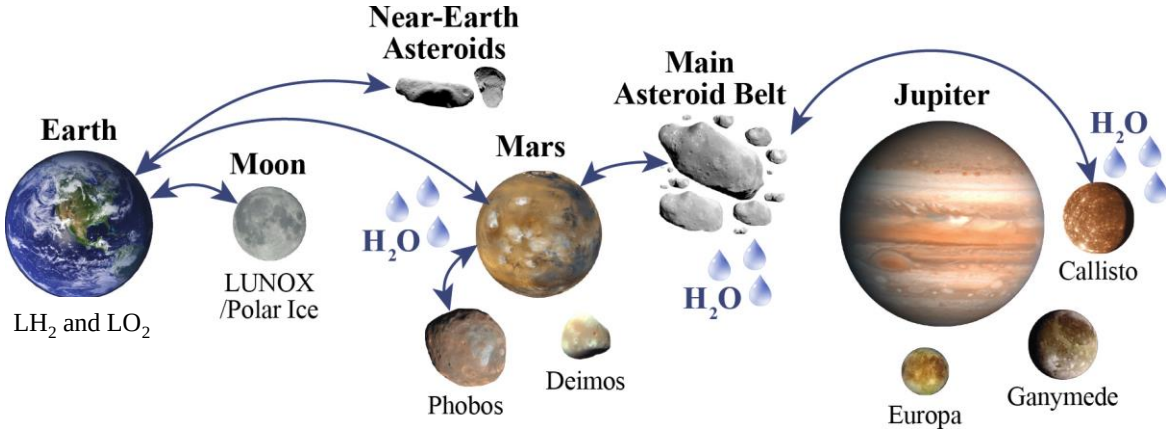
Summary, Concluding Remarks, and a Look Ahead

• NTP offers significant benefits for lunar missions and can take advantage of the leverage provided from using LDPs – *"when they become available"* – by transitioning to LANTR propulsion. LANTR provides a variable thrust and I_{sp} capability, shortens burn times and extends engine life, and allows bipropellant operation

• The combination of LANTR and LDP has performance capability equivalent to that of a hypothetical "gaseous fuel core" NTR (effective I_{sp} ~1575 s) and can lead to a robust LTS with unique mission capabilities that include short transit time crewed cargo transports and routine commuter flights to the Moon

• The biggest challenge to making this vision a reality will be the production of increasing amounts of LDP and the development of propellant depots in LEO, LLO and LPO. An industry-operated, privately financed venture, 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, quicker than any of us can imagine, and just the beginning of things to come….



Human Expansion Possibilities using LANTR Propulsion and Extraterrestrial Propellant Resources