"Robust Exploration and Commercial Missions to the Moon Using LANTR Propulsion and Lunar Liquid Oxygen Derived from FeO-rich Pyroclastic Deposits"

"Propelling Us to New Worlds"

AIAA-2017-4938
NFF-04: Nuclear Thermal Propulsion II

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

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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 Sciences, 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, 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$_2$ from FeO-rich volcanic glass) become available at propellant depots in equatorial low lunar orbit (LLO)

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

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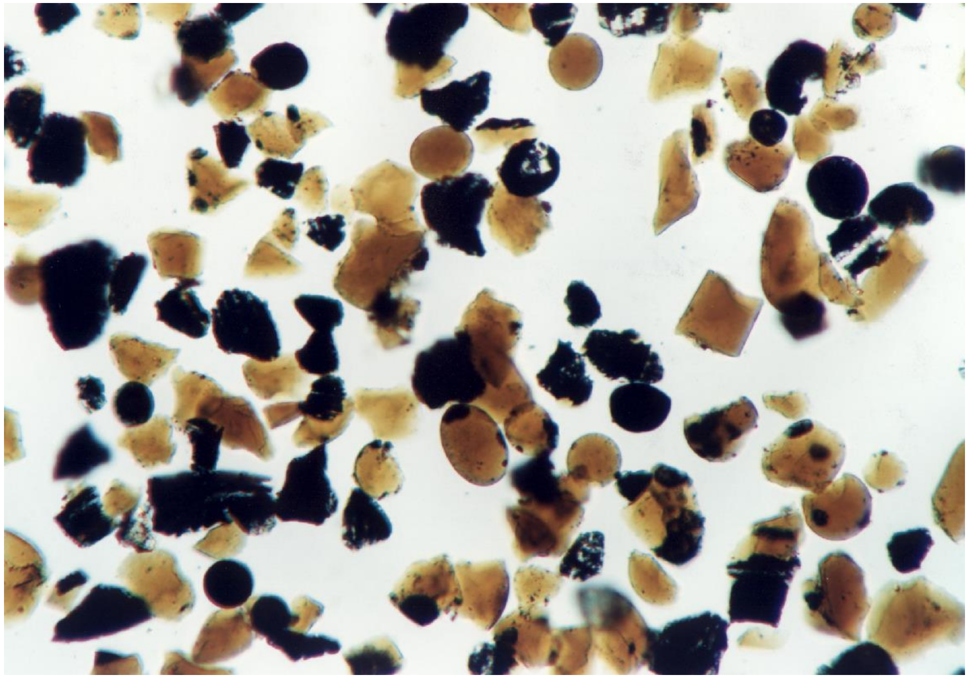
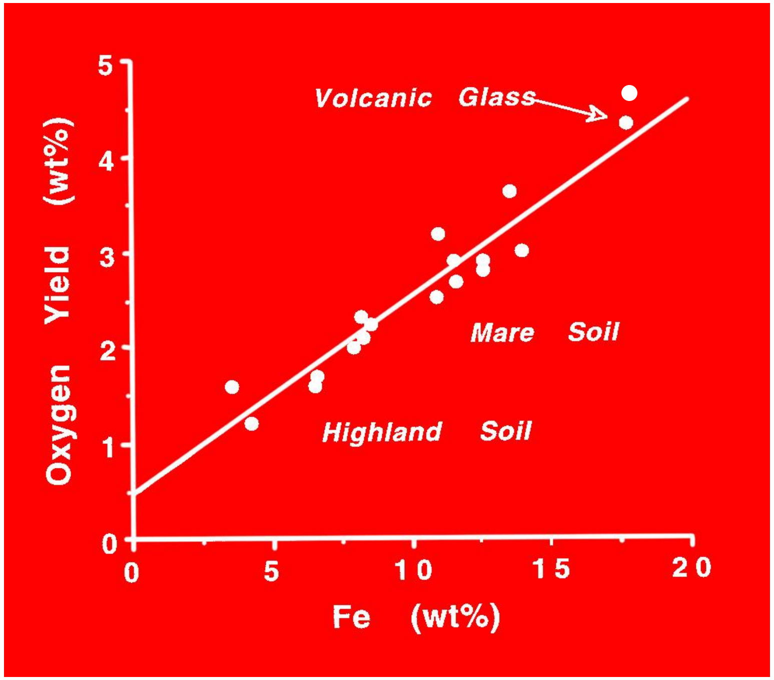


The best lunar oxygen ore found during the Apollo Program is the volcanic glass, found at Taurus-Littrow. The glass beads are fine grained and ~40 mm in diameter. The orange beads are clear glass, while the black beads cooled at bit more slowly and had a chance to crystallize.



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

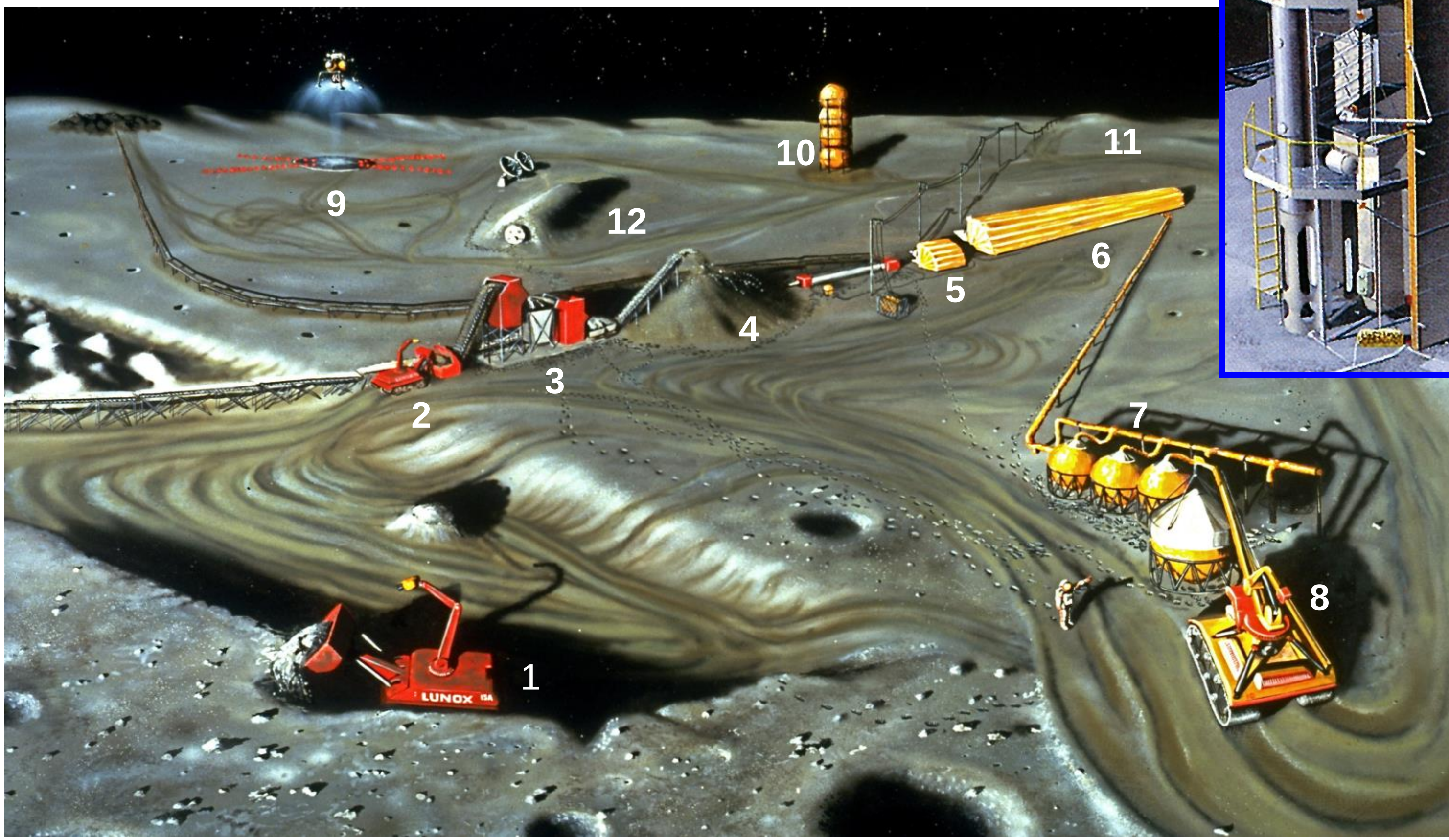
Oxygen production from "FeO-rich" volcanic glass is a 2 step process:

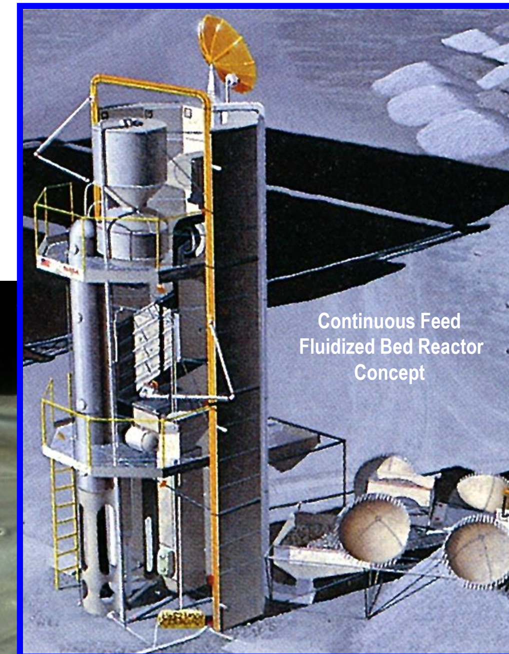
$FeO + H_2$ -------> $Fe + H_2O$
(Hydrogen Reduction & Water Formation)

$2\ H_2O$ -------> $2H_2 + O_2$ (*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

Key Activities and Systems at a LUNOX Production Plant Processing Ilmenite-bearing Feedstock Materials (circa 1983)





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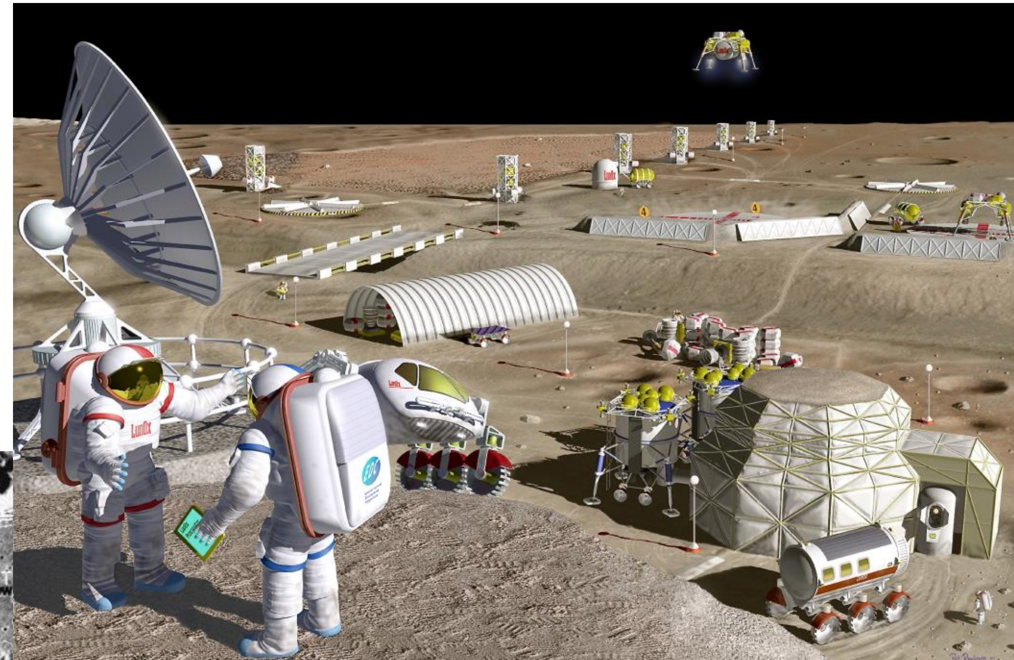
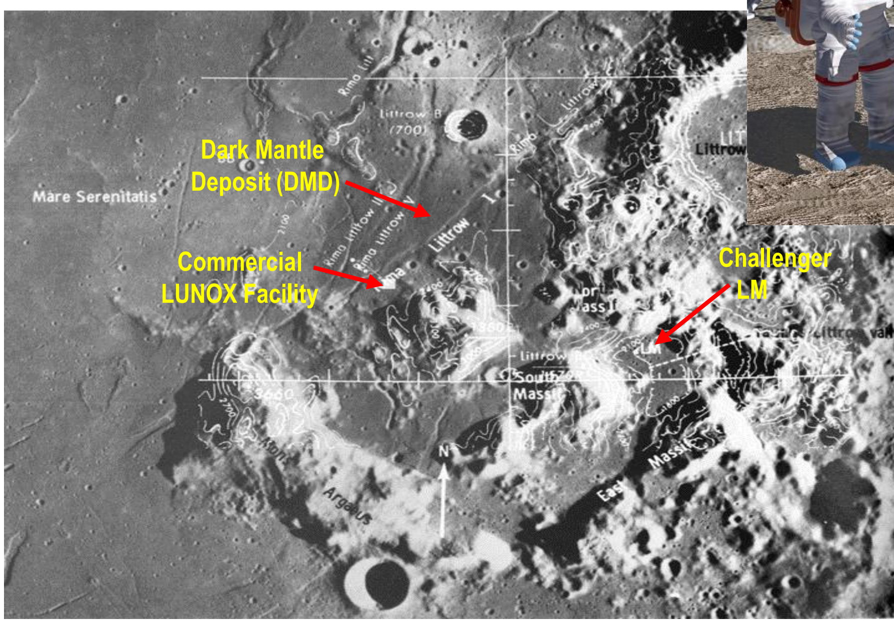
"Commercial" LUNOX Production Facility
Location: "Taurus-Littrow DMD" (~21^{o}N, ~29.5^{o}E)

Vast deposits of "iron-rich" volcanic glass beads have been identified at a number of candidate sites on lunar near side. The oxygen extraction process and efficiency using this DMD material is also well known



Ref: S. K. 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



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) ✓

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

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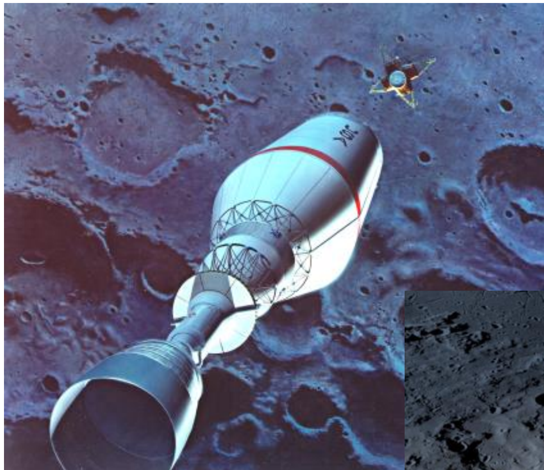
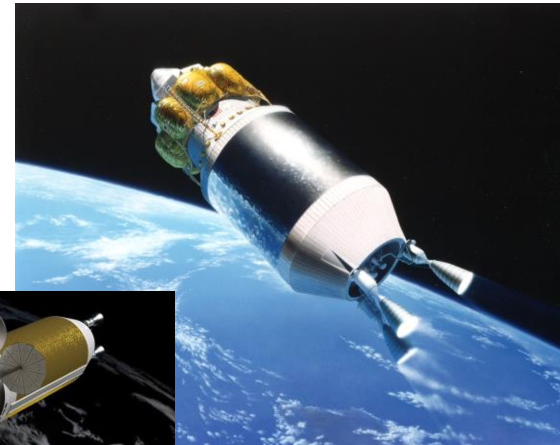
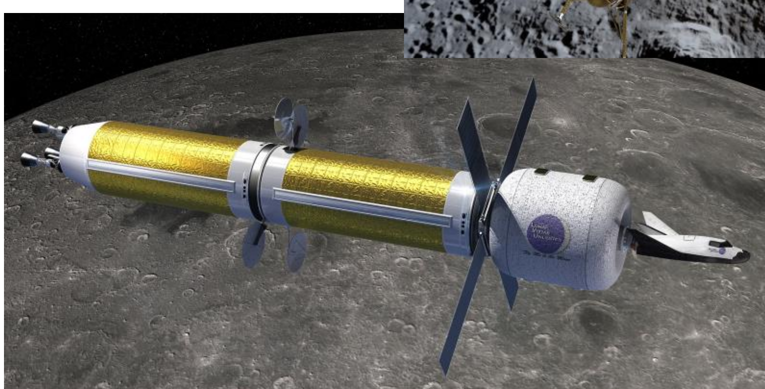


Reusable Lunar Transfer Vehicle uses Single 75 klb$_f$ NTR Engine – SEI (1990 - 91)

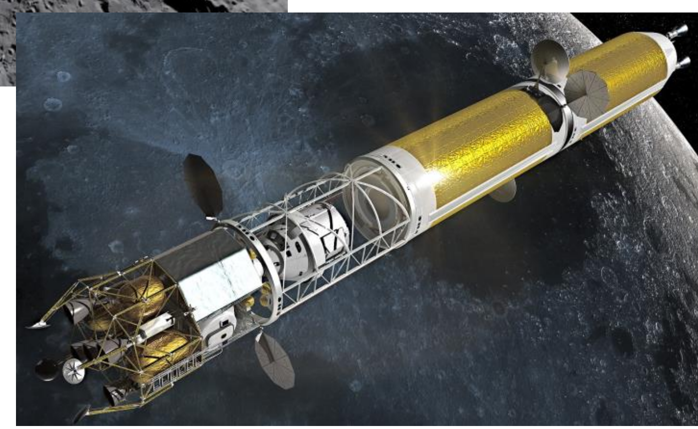
Expendable TLI Stage for "First Lunar Outpost" Mission uses 3 - 25 klb$_f$ NTR Engines – Fast Track Study (1992)



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

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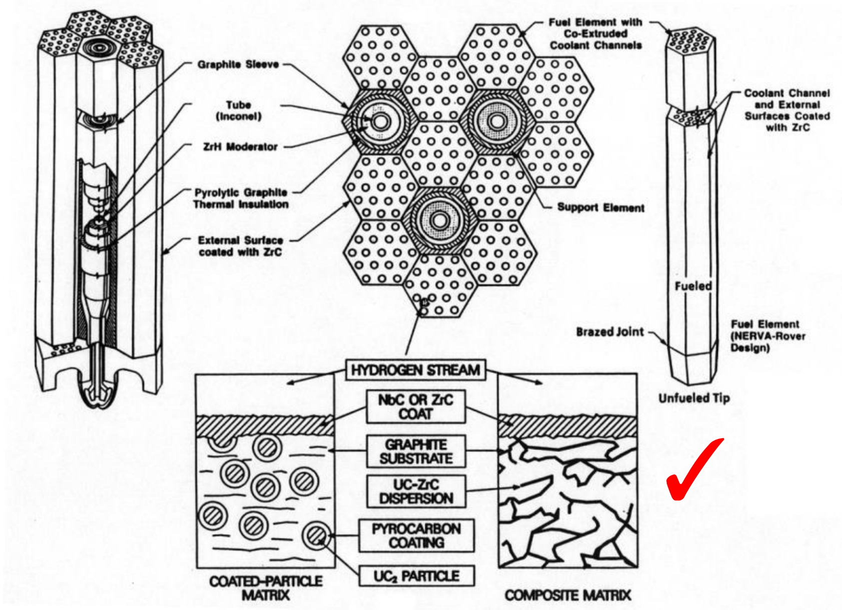

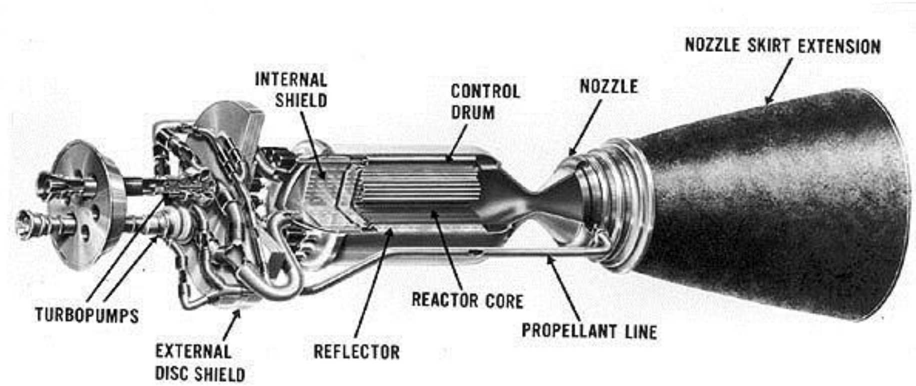

Baseline Small Nuclear Rocket Engine (SNRE) Performance Parameters:

- 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

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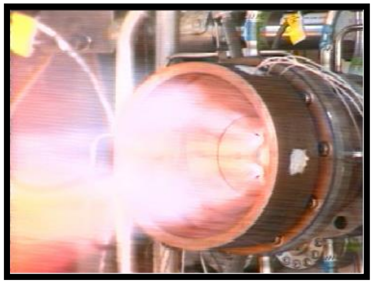
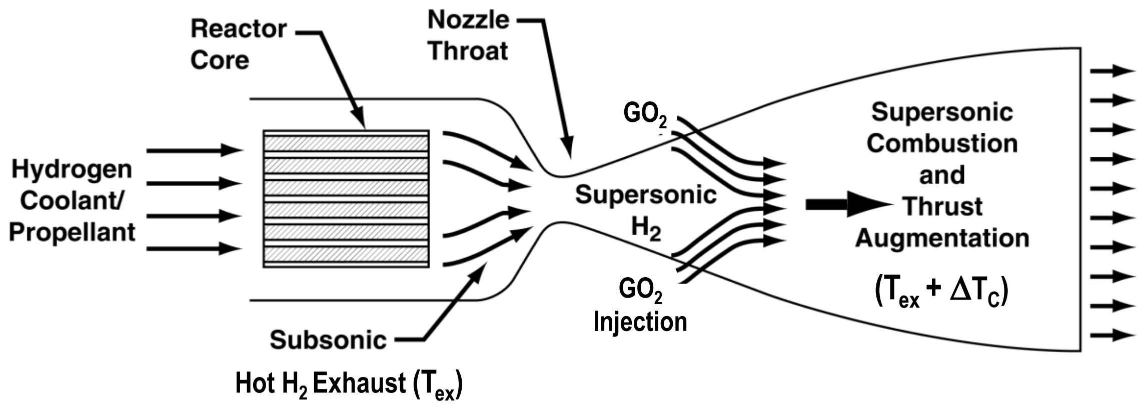
LANTR adds an O_2 "afterburner" nozzle and O_2-rich GG feed system to a conventional NTR engine that provides a variable thrust and Isp capability, shortens burn times, extends engine life, and allows bipropellant operation



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

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The Potential of LANTR Propulsion using Lunar-Derived Oxygen (LUNOX) was Analyzed at GRC more than 20 years ago!

NASA/TM—1998-208830/REV2

AIAA-1997-2956

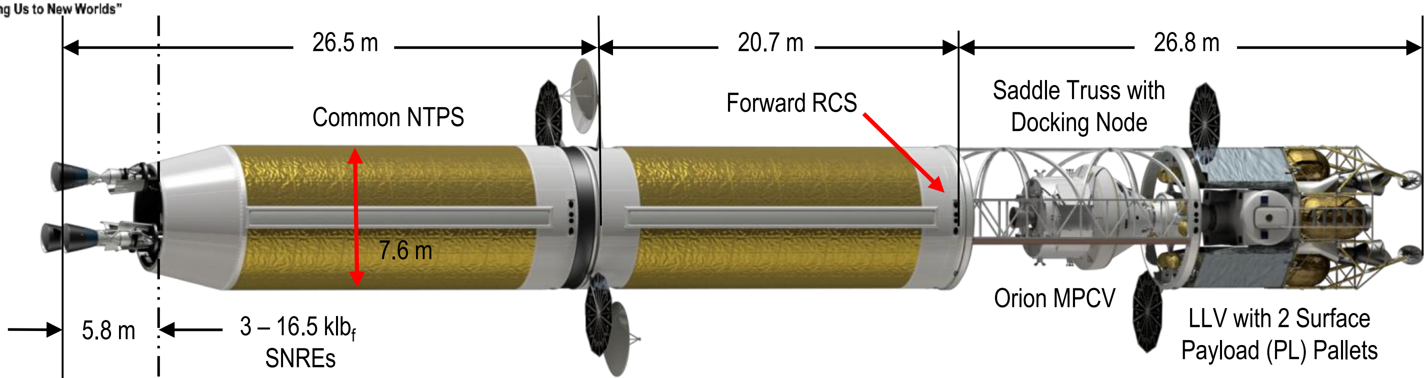
"2001: A Space Odyssey" Revisited—The Feasibility of 24 Hour Commuter Flights to the Moon Using NTR Propulsion with LUNOX Afterburners

Stanley K. Borowski and Leonard A. Dudzinski
Glenn Research Center, Cleveland, Ohio

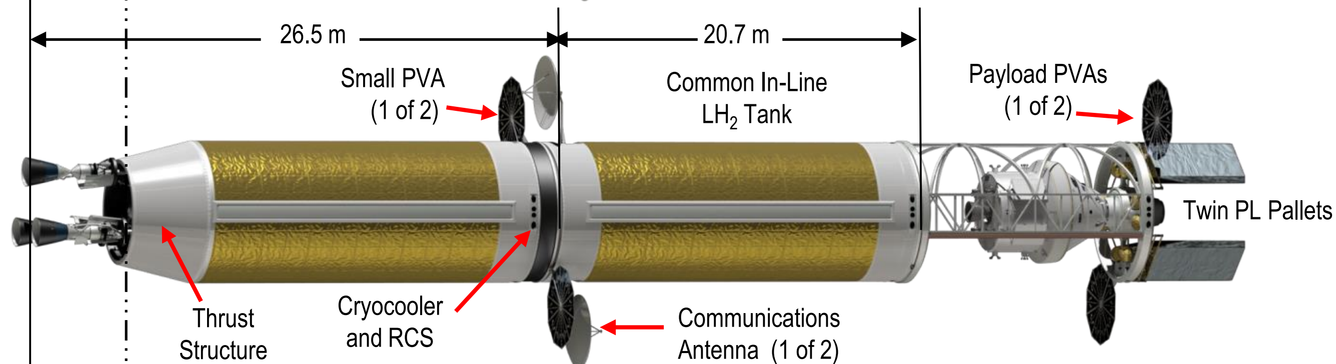
Presented at AIAA 33rd Joint Propulsion Conference
Seattle, Washington, July 6–9, 1997

- An evolutionary LTS was analyzed using conventional LH_2-cooled NTP initially then transitioning to the LANTR propulsion option
- "FeO-rich" volcanic glass beads from Taurus-Littrow dark mantle deposit (DMD) was the source material for LUNOX production
- Due to current interest being expressed in LDPs, the authors have been re-examining the impact of infusing LANTR into a nuclear-powered LTS that utilizes LDP – specifically LUNOX
- Initial LUNOX production goal focused on supporting surface-based LLV operation allowing LTVs to transport higher value cargo
- LANTR-powered LTVs use only Earth-supplied LH_2 (ELH_2) but refuel with LUNOX as it becomes available in LLO; O/H MRs out & back are optimized to meet mission objectives and constraints
- LANTR LTVs also transport ELH_2 for use by the LLVs and for use in the hydrogen reduction LUNOX production process
- Eventually, once a propellant depot is established in LLO, it will be supplied with LUNOX from tanker LLVs operating from the lunar surface and with ELH_2 from either dedicated NTR LH_2 "tankers" or from LANTR-powered crewed cargo transports

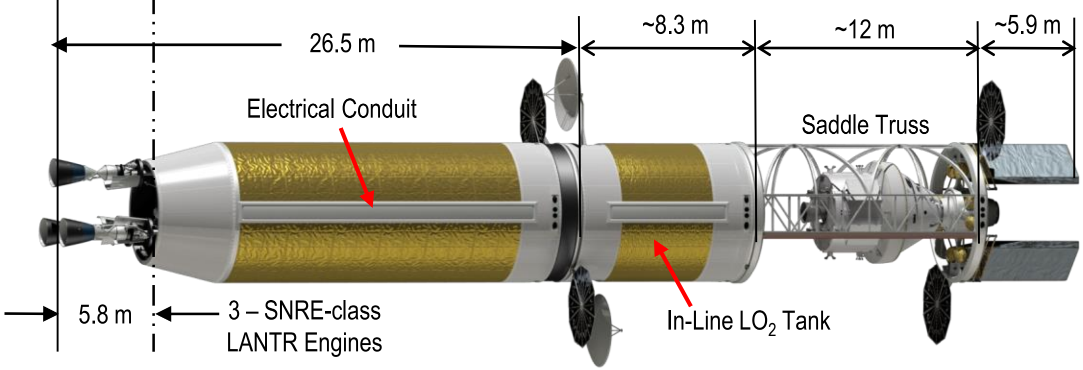
Variation in NLTV Size, IMLEO, Mission Capability and Burn Time Resulting from Use of LLO_2 and Transition to LANTR Engines



a) Crewed Lunar Landing:
(LEO – LLO – 24-hr EEO)
- 4 crew
- MPCV + LLV ~48 t
- IMLEO ~176.6 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: ~50 min



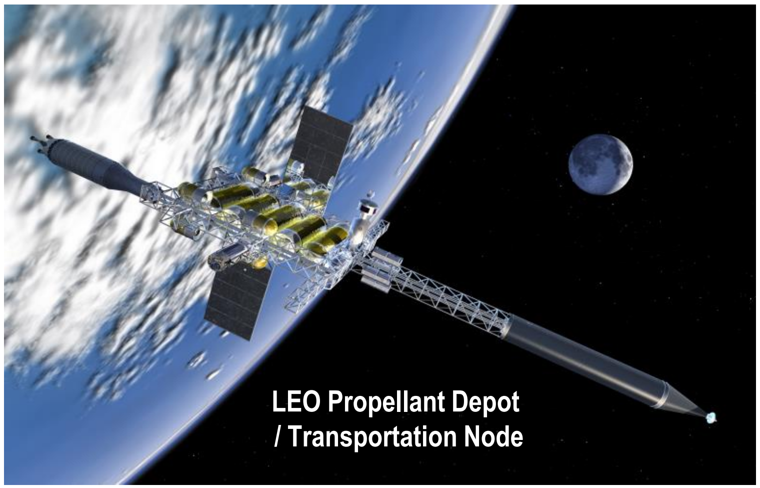
b) Crewed Lunar Landing:
(LEO – LLO – 3.25-hr EEO)
- MPCV + 4 crew + 5 t PL
- Lunar Surface-based LLV
- IMLEO ~146 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: ~50 min

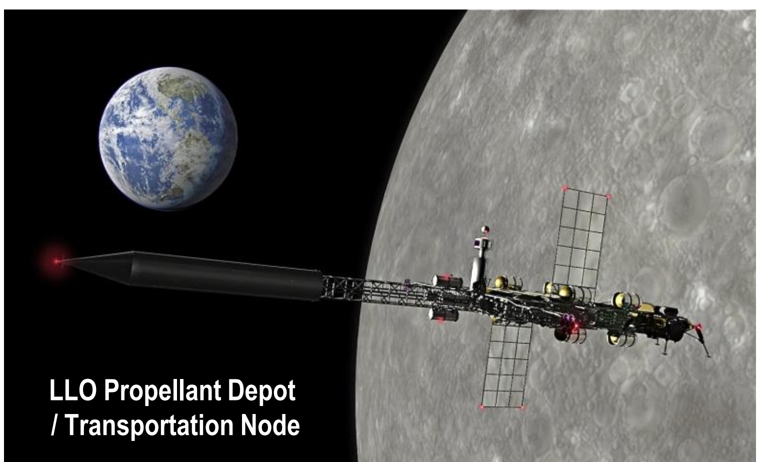


c) Crewed Lunar Landing:
(LEO – LLO – LEO)
- MPCV + 4 crew + 5 t PL
- Lunar Surface-based LLV
- IMLEO ~152.4 t
- Supplied LLO_2 ~46.9 t
- Total Mission Burn Time: ~25.3 min

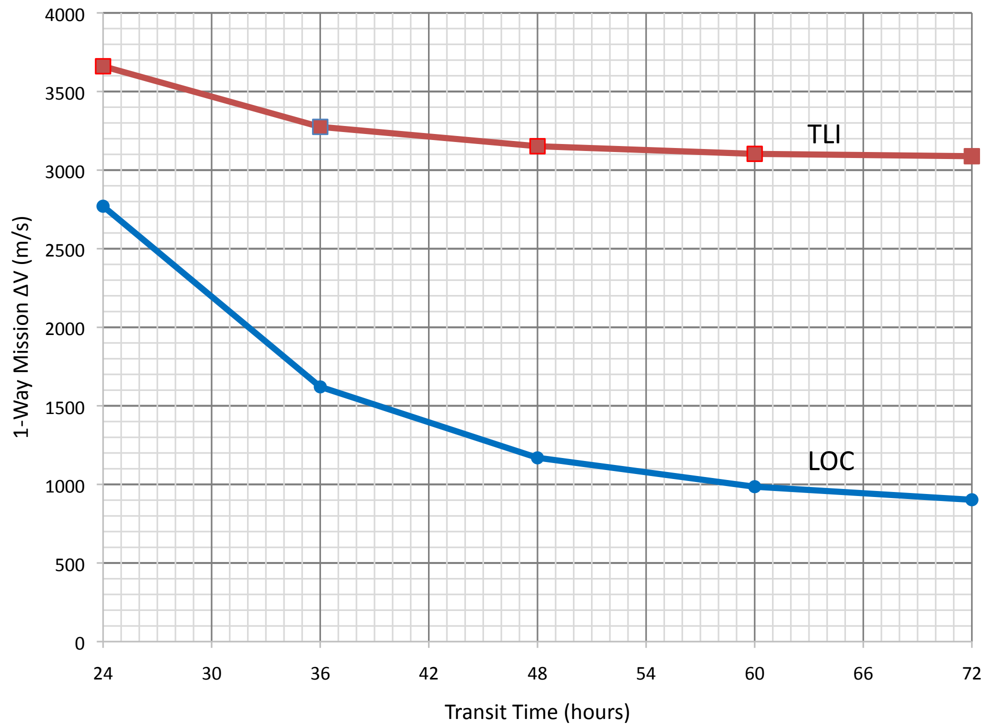
Growth Mission Possibilities and Faster Trip Times using Depots and LUNOX Refueling

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 and equatorially LLO.





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 transit times between LEO and LLO 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 ~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

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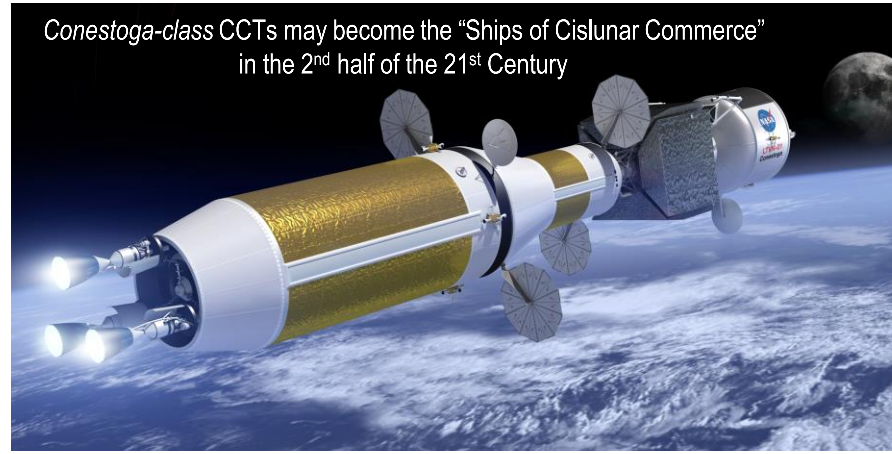
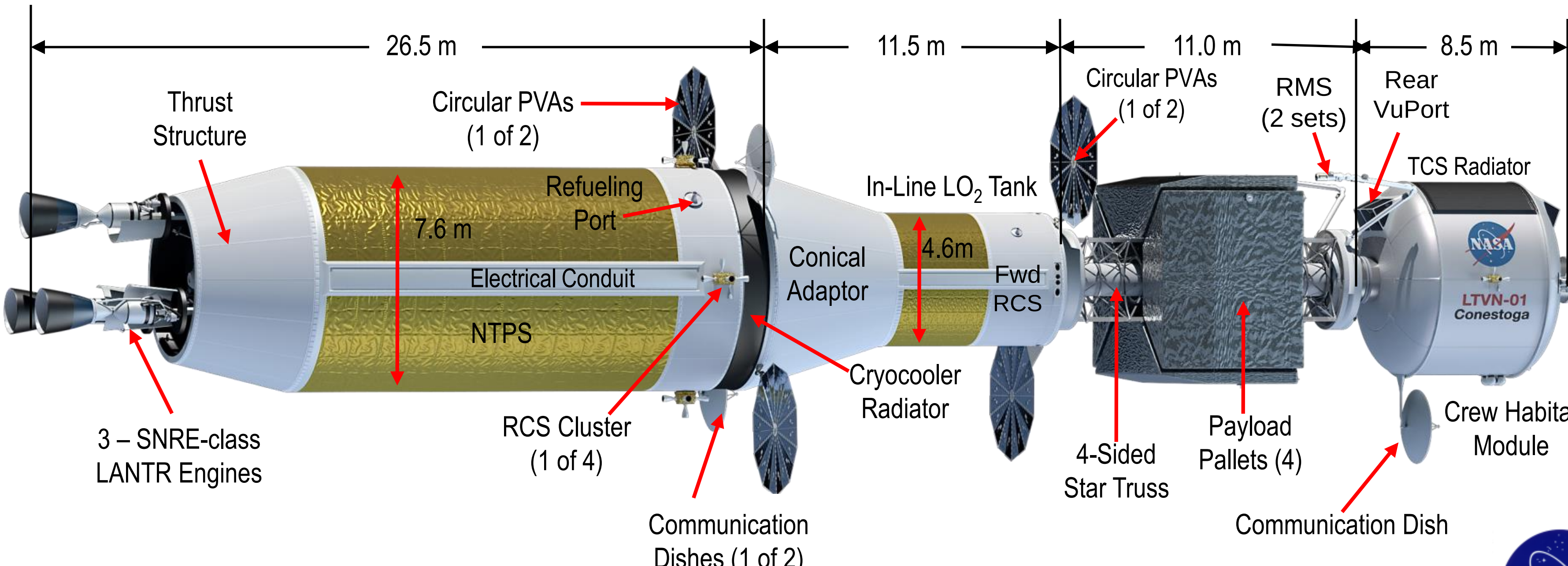
Conestoga Wagons, the "Ships of Inland Commerce," Transported Settlers, Farm Produce, and Freight across Pennsylvania and Neighboring States for over 150 years





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

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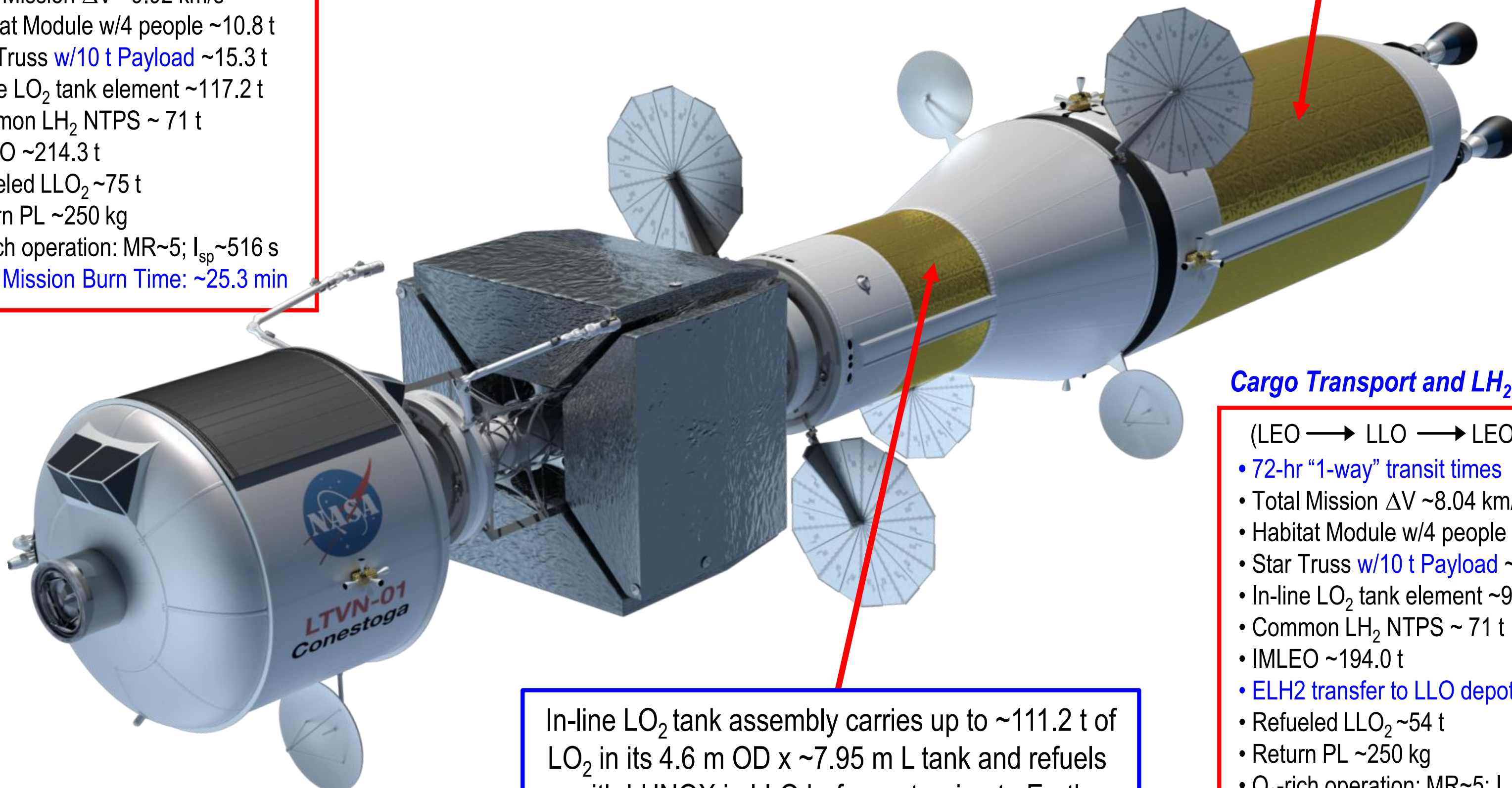
Twice the Cargo in Half the Time

(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
- Refueled LLO_2 ~75 t
- Return PL ~250 kg
- O_2-rich operation: MR~5; I_{sp}~516 s
- 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 up to ~111.2 t of LO_2 in its 4.6 m OD x ~7.95 m L tank and refuels with LUNOX in LLO before returning to Earth

Cargo Transport and LH_2 Tanker

(LEO ⟶ LLO ⟶ LEO)

- 72-hr "1-way" transit times
- Total Mission ΔV ~8.04 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 ~96.9 t
- Common LH_2 NTPS ~ 71 t
- IMLEO ~194.0 t
- ELH2 transfer to LLO depot ~9.62 t
- Refueled LLO_2 ~54 t
- Return PL ~250 kg
- O_2-rich operation: MR~5; I_{sp}~516 s
- Total Mission Burn Time: ~19 min

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

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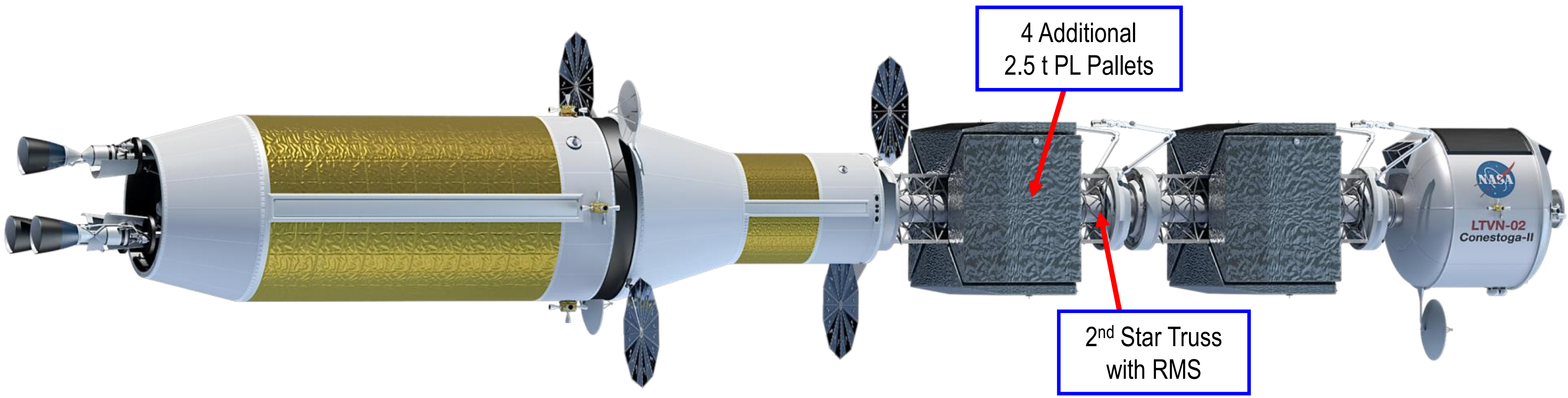


Double the Payload from 10 to 20 t

(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
- 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

20 t of Payload as Fast as Possible

(LEO ⟶ LLO ⟶ LEO)

- 44.2-hr "1-way" transit times
- Total Mission ΔV ~9.017 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 ~117.4 t
- Common LH_2 NTPS ~ 71.2 t
- IMLEO ~230 t
- Refueled LLO_2 ~70.9 t
- Return PL ~250 kg
- MRs Used: TLI (MR~4.9, I_{sp}~519 s); LOC (MR~3.5, I_{sp}~568 s); TEI (MR~5.0, I_{sp}~516 s); EOC (MR~5.0, I_{sp}~516 s)
- Total Mission Burn Time: ~25.3 min

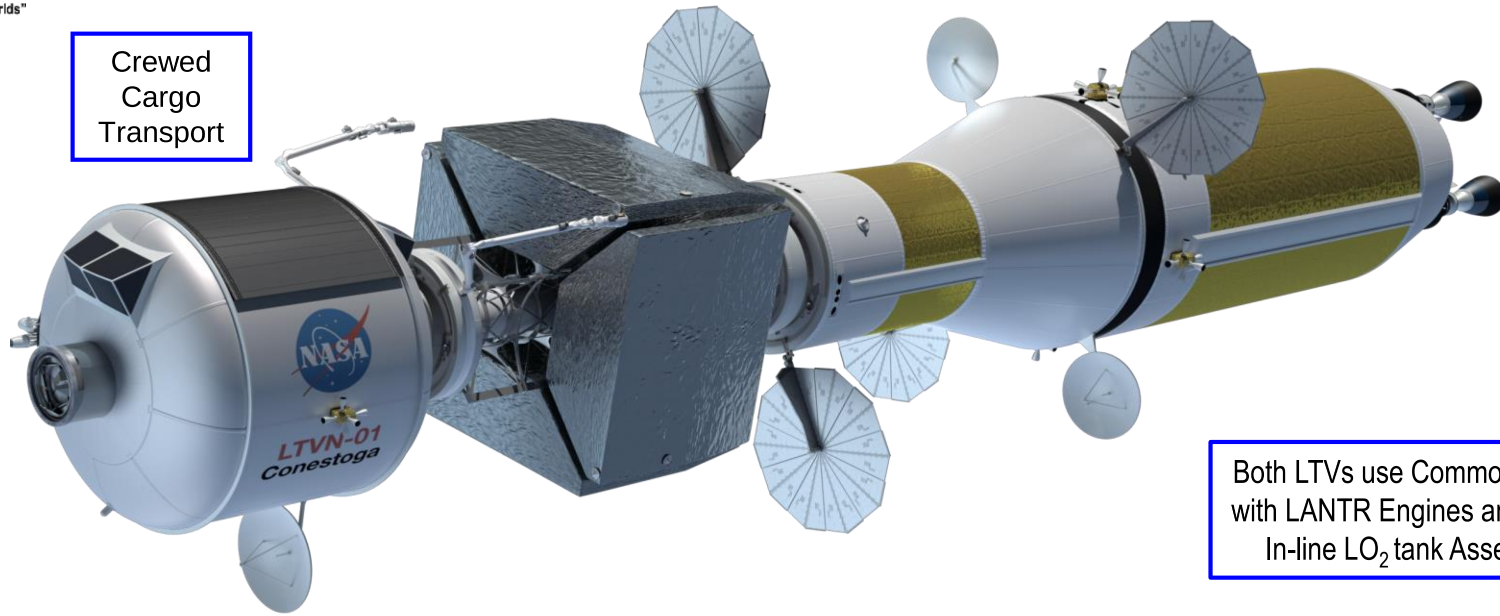
Double the Payload: 8 – 5 t PL Pallets

(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
- 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

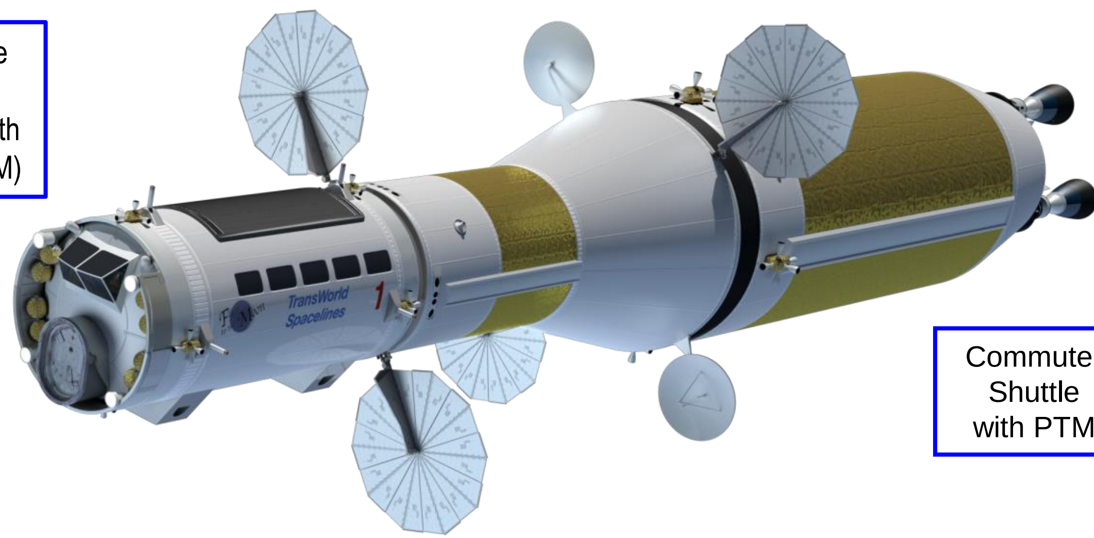
Relative Size of the Conestoga Crewed Cargo Transport and Passenger Commuter Shuttle

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

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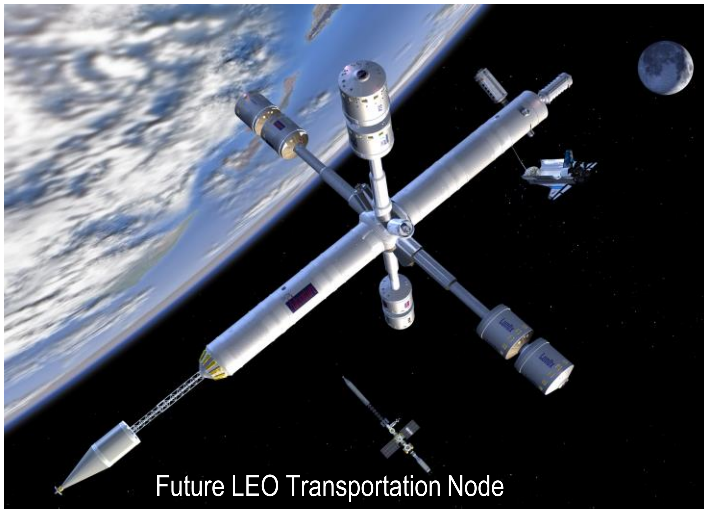
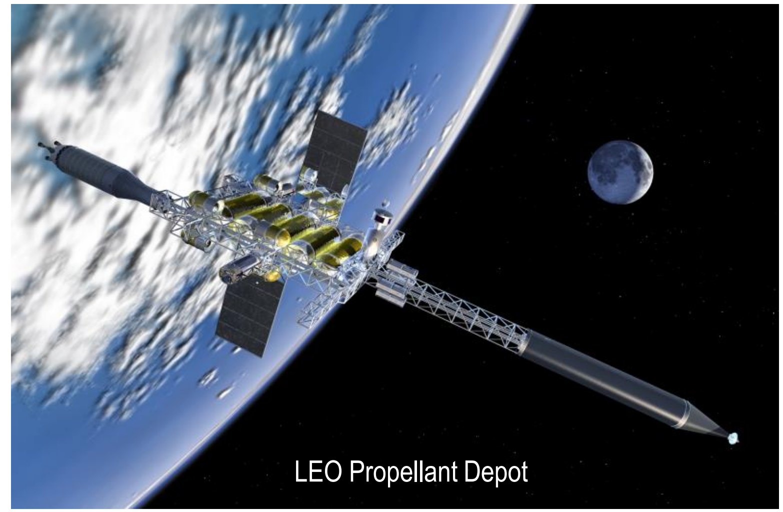
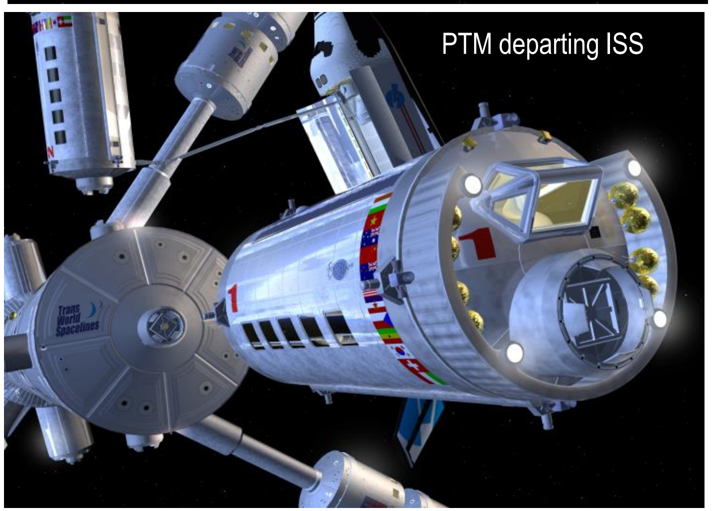
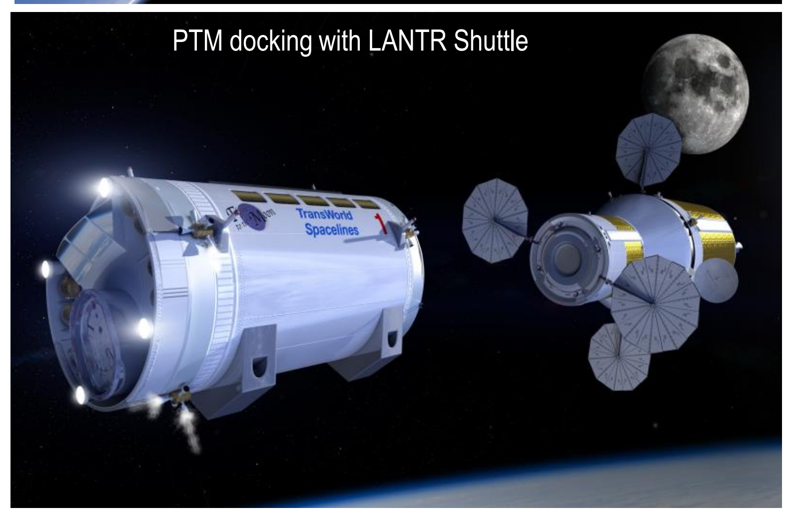
How Might a Typical Commuter Flight to the Moon Proceed?

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.


Future LEO Transportation Node

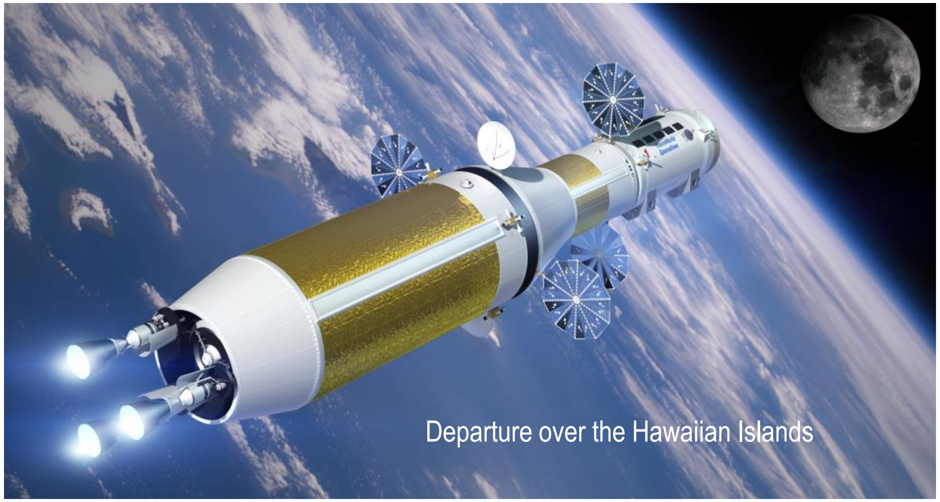

LEO Propellant Depot

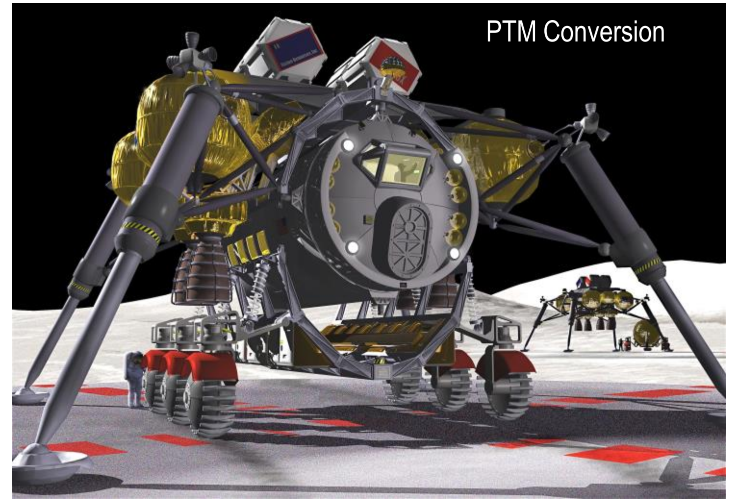

PTM departing ISS

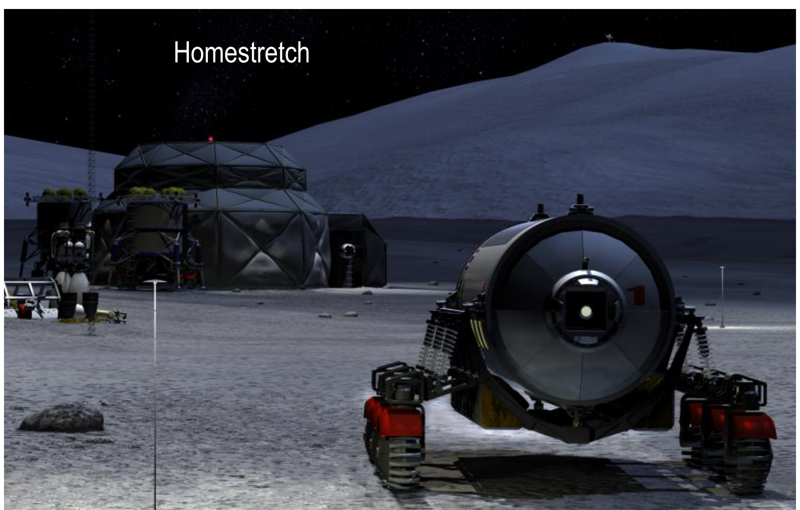

PTM docking with LANTR Shuttle

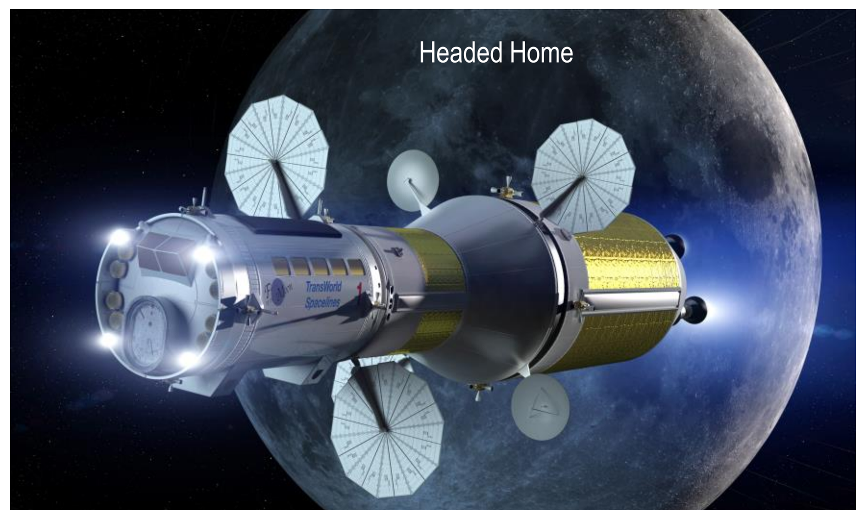
How Might a Typical Commuter Flight to the Moon Proceed?

At the appropriate moment, the LANTR engines are powered up and the shuttle climbs rapidly away from Earth. Following a 36-hour 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.





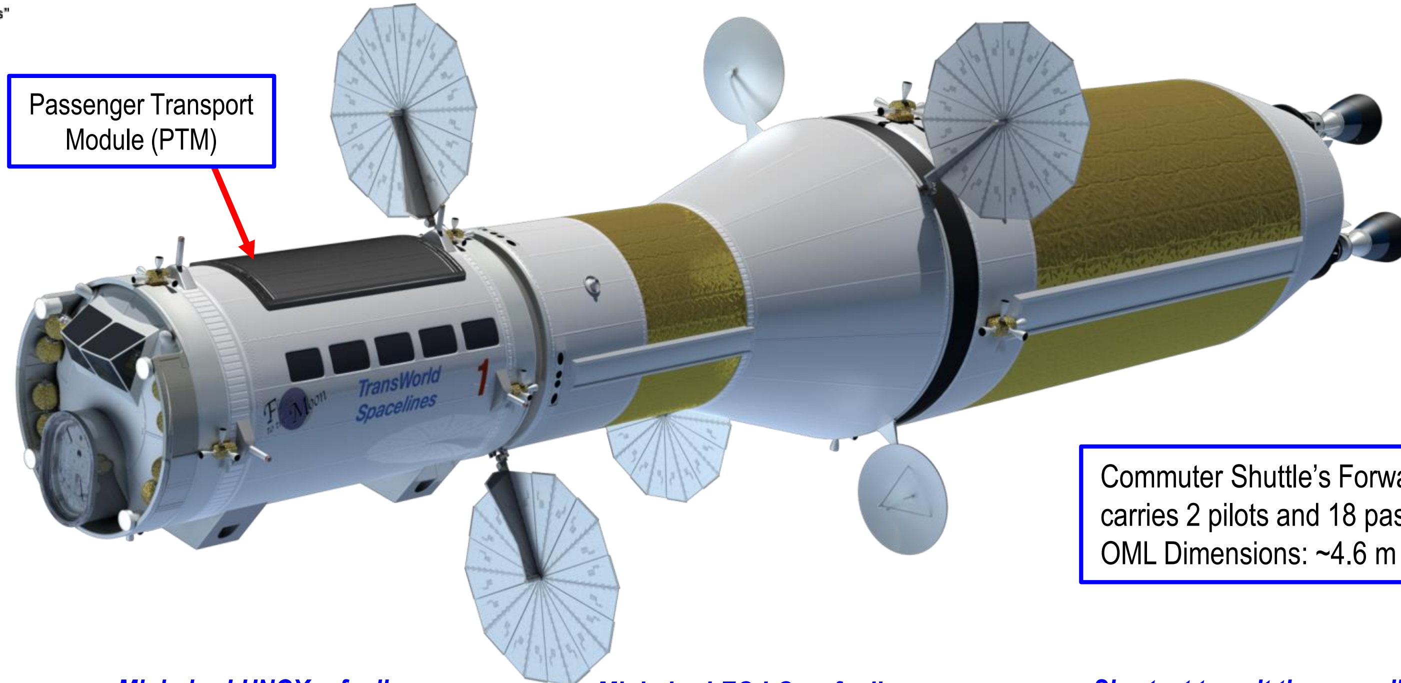




LANTR Commuter Shuttle Mission Options, Trip Time and ΔV Budgets, and LUNOX Refueling Requirements

"Propelling Us to New Worlds"

Passenger Transport Module (PTM)



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

Minimize LUNOX refueling

(LEO ⟶ LLO ⟶ LEO)

- 36-hr "1-way" transit times
- Total Mission ΔV ~9.924 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~117.3 t (includes 111.2 t of LEO LO_2)
- Common LH_2 NTPS ~71.2 t
- IMLEO ~203.5 t
- Refueled LLO_2 ~55.7 t
- OB: MR~5, I_{sp}~516 s; TEI: MR~4.2, I_{sp}~546 s; EOC: MR~3.1, I_{sp}~584 s
- Total Mission Burn Time: ~25.3 min

Minimize LEO LO_2 refueling

(LEO ⟶ LLO ⟶ LEO)

- 36-hr "1-way" transit times
- Total Mission ΔV ~9.914 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~82.1 t (includes ~76 t of LEO LO_2)
- Common LH_2 NTPS ~71.1 t
- IMLEO ~168.2 t
- Refueled LLO_2 ~72.8 t
- TLI: MR~3.9, I_{sp}~556 s; LOC: MR~1.7, I_{sp}~655 s; IB: MR~5, I_{sp}~516 s
- Total Mission Burn Time: ~25.3 min

Shortest transit time possible

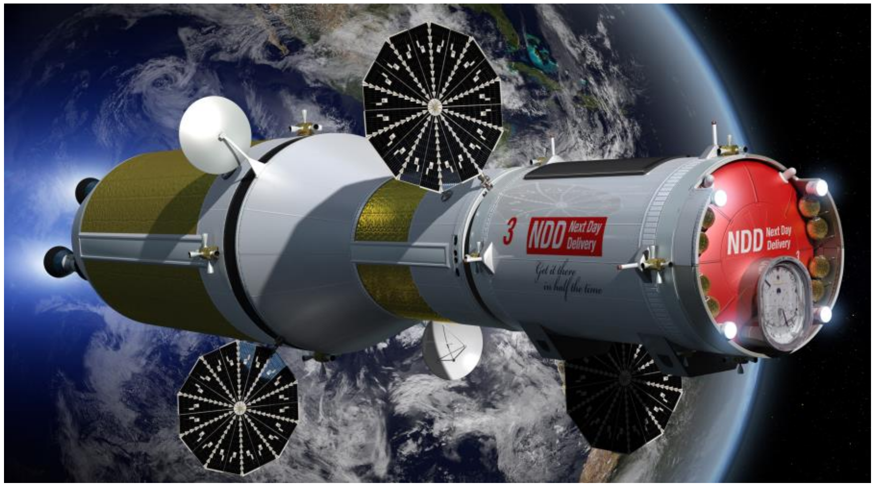
(LEO ⟶ LLO ⟶ LEO)

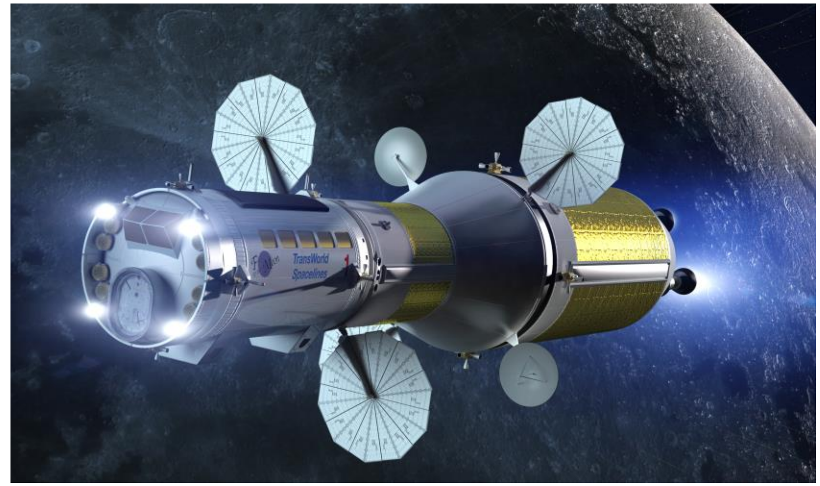
- 32.8-hr "1-way" transit times
- Total Mission ΔV ~10.481 km/s
- PTM mass ~15 t
- In-line LO_2 tank element ~117.2 t (includes 111.1 t of LEO LO_2)
- Common LH_2 NTPS ~71.1 t
- IMLEO ~203.3 t
- Refueled LLO_2 ~80.4 t
- LANTR engines operate O_2-rich Out and Back: MR~5; I_{sp}~516 s
- Total Mission Burn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

Alternating Outbound and Return PTM and Priority Cargo Payloads on the same Shuttle Flight

"Propelling Us to New Worlds"

In addition to a commercial passenger service, it is also likely that similar services will be developed for delivering high priority cargo. We envision a Priority Cargo Container (PCC) with a gross mass of ~7.5 t that carries ~5 t of cargo within its pressurized volume. The PCC is scaled from Orbital ATK's Cygnus spacecraft and draws its electrical power from the twin PVAs located at the front end of the shuttle's in-line LO_2 tank assembly





PCC (OB) – PTM (IB) Mission

(LEO ⟶ LLO ⟶ LEO)

- 36-hr "1-way" transit times
- Total Mission ΔV ~9.910 km/s
- PCC / PTM masses ~7.5 t / 15 t
- In-line LO_2 tank element ~68.1 t
- Common LH_2 NTPS ~70.9 t
- IMLEO ~146.5 t
- Refueled LLO_2 ~64.8 t
- TLI: MR~3.6, I_{sp}~567 s; LOC: MR~1.1, I_{sp}~713 s; TEI: MR~4.5, I_{sp}~535 s; EOC: MR~3.9, I_{sp}~554 s
- Total Mission Burn Time: ~25.3 min

PTM (OB) – PCC (IB) Mission

(LEO ⟶ LLO ⟶ LEO)

- 36-hr "1-way" transit times
- Total Mission ΔV ~9.910 km/s
- PTM / PCC masses ~15 t / 7.5 t
- In-line LO_2 tank element ~71.8 t
- Common LH_2 NTPS ~70.8 t
- IMLEO ~157.6 t
- Refueled LLO_2 ~55.1 t
- TLI: MR~3.6, I_{sp}~567 s; LOC: MR~0.9, I_{sp}~733 s; TEI: MR~4.8, I_{sp}~525 s; EOC: MR~3.7, I_{sp}~563 s
- Total Mission Burn Time: ~25.3 min

PTM (OB) – PCC (IB) Mission

(LEO ⟶ LLO ⟶ LEO)

- 24-hr (PTM) / 48-hr (PCC) transit times
- Total Mission ΔV ~10.959 km/s
- PTM / PCC masses ~15 t / 7.5 t
- In-line LO_2 tank element ~111 t
- NTPS w/2 LANTR engines ~65.2 t
- IMLEO ~191.2 t
- Refueled LLO_2 ~44.7 t
- TLI: MR~4.5, I_{sp}~534 s; LOC: MR~2.1, I_{sp}~630 s; TEI: MR~5.0, I_{sp}~516 s; EOC: MR~4.8, I_{sp}~524 s
- Total Mission Burn Time: ~37.8 min

PCC (OB) – PTM (IB) Mission

(LEO ⟶ LLO ⟶ LEO)

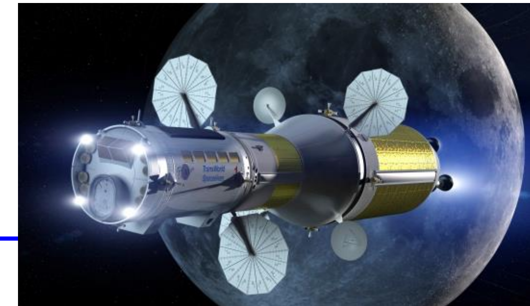
- 48-hr (PCC) / 24-hr (PTM) transit times
- Total Mission ΔV ~10.951 km/s
- PCC / PTM masses ~7.5 t / 15 t
- In-line LO_2 tank element ~71.8 t
- NTPS w/2 LANTR engines ~65.4 t
- IMLEO ~144.7 t
- Refueled LLO_2 ~93.2 t
- TLI: MR~4.2, I_{sp}~544 s; LOC: MR~3.0, I_{sp}~590 s; TEI: MR~5.0, I_{sp}~516 s; EOC: MR~3.5, I_{sp}~570 s
- Total Mission Burn Time: ~37.9 min

Total LUNOX Required for "Weekly" Commuter Flights

"Propelling Us to New Worlds"

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

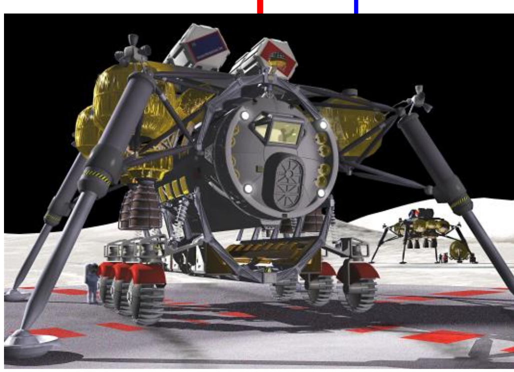
LLV*# : (42.7 t LUNOX# / round trip flights / week) x 52 weeks /year = 2,220 t/yr

Total LUNOX Rate = 12,542 t/yr

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

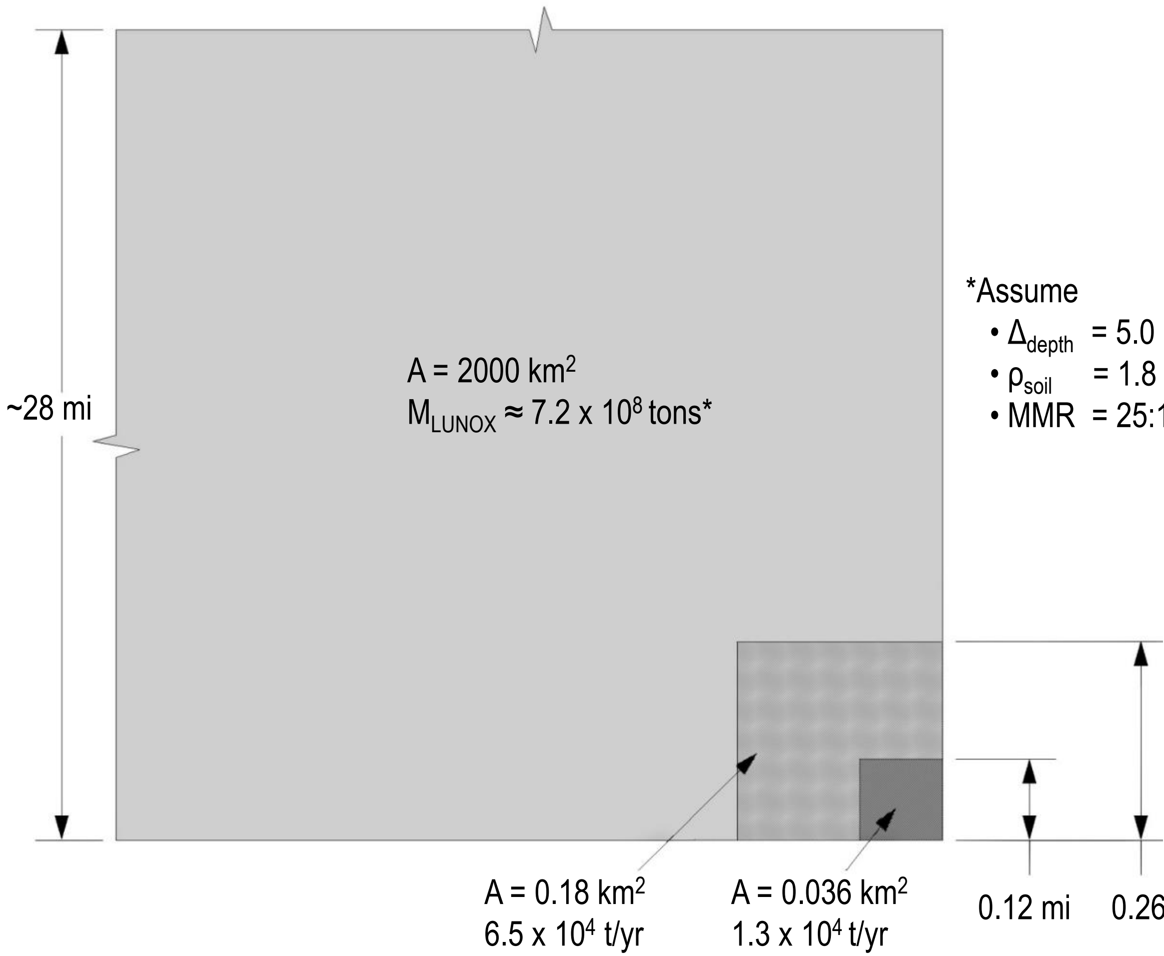


LLV Unloading PTM onto a Mobile Surface Vehicle

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 (~3066 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

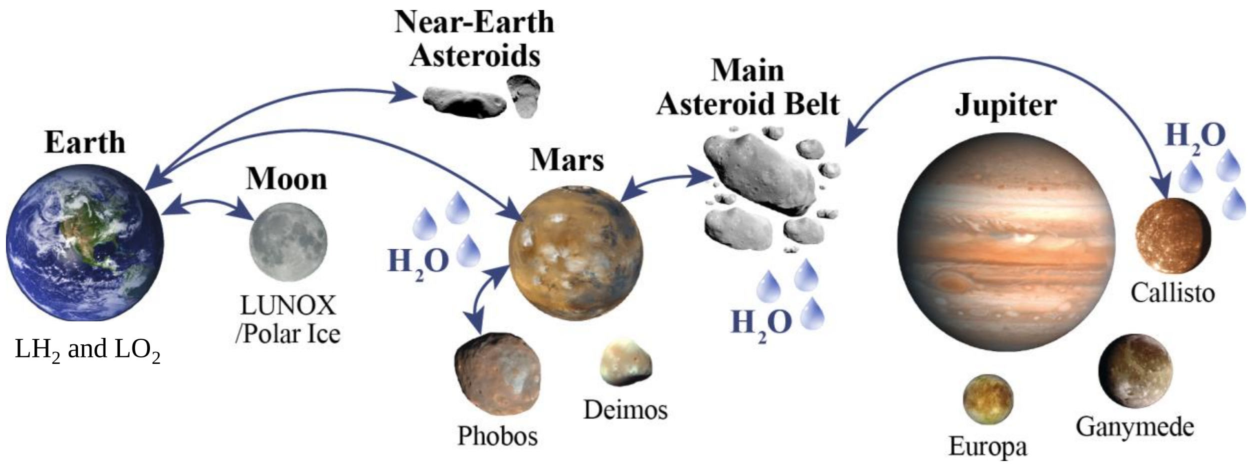
"Propelling Us to New Worlds"

• 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 Isp capability, shortens burn times and extends engine life, and allows bipropellant operation

• The combination of LANTR and LUNOX can lead to a robust LTS with unique mission capabilities that include short transit time crewed cargo transport, commuter shuttle and priority cargo delivery systems

• 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 and LLO. 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