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

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NFF-04: Nuclear Thermal Propulsion II

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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., SpaceX, 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\textsubscript{2} (LLO\textsubscript{2}) or "LUNOX" in a lunar space transportation system (LTS)

• With a LTS using LO\textsubscript{2}/LH\textsubscript{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 6/7\textsuperscript{th} 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\textsubscript{2} and hydrogen (LLH\textsubscript{2}) from lunar polar ice (LPI) deposits can provide significant mission leverage

• Providing LUNOX for use in fuel cells, life support systems and LO\textsubscript{2}/LH\textsubscript{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\textsubscript{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\textsubscript{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:

\[
\text{FeO} + \text{H}_2 \rightarrow \text{Fe} + \text{H}_2\text{O} \\
(\text{Hydrogen Reduction & Water Formation})
\]

\[
2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \text{(LUNOX)} \\
(\text{Water Electrolysis & Hydrogen Recycling})
\]

Key Activities and Systems at a LUNOX Production Plant
Processing Ilmenite-bearing Feedstock Materials (circa 1983)
“Commercial” LUNOX Production Facility
Location: “Taurus-Littrow DMD” (~21ºN, ~29.5ºE)

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.

Large regional pyroclastic deposits include:
1. Aristarchus Plateau (~49,015 km²)
2. Southern Sinus Aestuum (10,360 km²)
3. Rima Bode (~6,620 km²)
4. Sulpicius Gallus (4,320 km²)
5. Southern Mare Vaporum (~4,130 km²)
6. Taurus-Littrow (~2,940 km²)

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

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

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

Reusable Lunar Cargo Transport uses 3 – 16.5 klbf “SNRE-class” Engines – (2013-16)


Reusable Crewed Landing Mission uses 3 – 16.5 klbf “SNRE-class” Engines – (2013-16)
### Baseline Small Nuclear Rocket Engine (SNRE) Performance Parameters:

- **Engine Cycle:** Expander
- **Thrust Level:** 16.5 kbf
- **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. FE / TT:** 564 / 241
- **FE-to-TT Ratio:** ~2:1
- **Reactors Power Level:** ~365 MWt
- **Fuel Matrix Power Density:** ~3.44 MWt / liter
- **U-235 Enrichment:** 93%
- **Fuel Loading:** ~0.6 grams / cm³
- **U-235 Inventory:** ~60 kg

"LO₂-Augmented" NTR (LANTR) Concept: Operational Features and Performance Characteristics

LANTR adds an O₂ “afterburner” nozzle and O₂-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 O₂ “Afterburner” Nozzle Test*

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

** Fuel Exit Temperature (Tₑₓ) = 2734 °K, Chamber Pressure = 1000 psia and NAR = 300 to 1
The Potential of LANTR Propulsion using Lunar-Derived Oxygen (LUNOX) was Analyzed at GRC more than 20 years ago!

- 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 LO₂ Tank Assembly.

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

Conestoga Wagons, the “Ships of Inland Commerce,” transported settlers, farm produce, and freight across Pennsylvania and neighboring states for over 150 years.

Glenn Research Center at Lewis Field

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**Conestoga – LANTR-propelled Crewed Cargo Transport**

uses a “Common” NTPS and In-Line LO₂ Tank Assembly

**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 LO₂ tank element ~117.2 t
- Common LH₂ NTPS ~71 t
- IMLEO ~214.3 t
- Refueled LLO₂ ~75 t
- Return PL ~250 kg
- O₂-rich operation: MR~5; Iₚₑₛ ~516 s
- Total Mission Burn Time: ~25.3 min

**Cargo Transport and LH₂ 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 LO₂ tank element ~96.9 t
- Common LH₂ NTPS ~71 t
- IMLEO ~194.0 t
- ELH₂ transfer to LLO depot ~9.62 t
- Refueled LLO₂ ~54 t
- Return PL ~250 kg
- O₂-rich operation: MR~5; Iₚₑₚ ~516 s
- Total Mission Burn Time: ~19 min

NTPS carries ~39.8 t of Earth-supplied LH₂ in its 7.6 m OD x ~15.7 m L tank

In-line LO₂ tank assembly carries up to ~111.2 t of LO₂ in its 4.6 m OD x ~7.95 m L tank and refuels with LUNOX in LLO before returning to Earth

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Conestoga-II – LANTR-propelled Heavy Crewed Cargo Transport uses a “Common” NTPS, In-Line LO₂ Tank Assembly and 2ⁿᵈ Star Truss

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 LO₂ tank element ~77.1 t
- Common LH₂ NTPS ~ 71.1 t
- IMLEO ~189.6 t
- Refueled LLO₂ ~52.1 t
- Return PL ~250 kg
- MRs Used: TLI (MR~3.4, Iₚ~573 s); LOC (MR~0.9, Iₚ~737 s); TEI (MR~4.7, Iₚ~527 s); EOC (MR~3.8, Iₚ~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 LO₂ tank element ~117.4 t
- Common LH₂ NTPS ~ 71.2 t
- IMLEO ~230 t
- Refueled LLO₂ ~70.9 t
- Return PL ~250 kg
- MRs Used: TLI (MR~4.9, Iₚ~519 s); LOC (MR~3.5, Iₚ~568 s); TEI (MR~5.0, Iₚ~516 s); EOC (MR~5.0, Iₚ~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 LO₂ tank element ~116 t
- Common LH₂ NTPS ~ 71.2 t
- IMLEO ~250.7 t
- Refueled LLO₂ ~60.3 t
- Return PL ~250 kg
- MRs Used: TLI (MR~4.4, Iₚ~536 s); LOC (MR~3.3, Iₚ~578 s); TEI (MR~5.0, Iₚ~527 s); EOC (MR~4.8, Iₚ~522 s)
- Total Mission Burn Time: ~25.2 min

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

Both LTVs use Common NTPS with LANTR Engines and same In-line LO₂ tank Assembly

For Commuter Shuttle Missions, the Habitat Module, Saddle Truss and its attached Payload are replaced with a Passenger Transport Module (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. 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 $\Delta V$ Budgets, and LUNOX Refueling Requirements

Minimize LUNOX refueling

- (LEO $\rightarrow$ LLO $\rightarrow$ LEO)
- 36-hr “1-way” transit times
- Total Mission $\Delta V \sim 9.924$ km/s
- PTM mass $\sim 15$ t
- In-line LO$_2$ tank element $\sim 117.3$ t (includes 111.2 t of LEO LO$_2$)
- Common LH$_2$ NTPS $\sim 71.2$ t
- IMLEO $\sim 203.5$ t
- Refueled LLO$_2$ $\sim 55.7$ t
- OB: MR $\sim 5$, $I_{sp} \sim 516$ s; TEI: MR $\sim 4.2$, $I_{sp} \sim 546$ s; EOC: MR $\sim 3.1$, $I_{sp} \sim 584$ s
- Total Mission Burn Time: $\sim 25.3$ min

Minimize LEO LO$_2$ refueling

- (LEO $\rightarrow$ LLO $\rightarrow$ LEO)
- 36-hr “1-way” transit times
- Total Mission $\Delta V \sim 9.914$ km/s
- PTM mass $\sim 15$ t
- In-line LO$_2$ tank element $\sim 82.1$ t (includes $\sim 76$ t of LEO LO$_2$)
- Common LH$_2$ NTPS $\sim 71.1$ t
- IMLEO $\sim 168.2$ t
- Refueled LLO$_2$ $\sim 72.8$ t
- TLI: MR $\sim 3.9$, $I_{sp} \sim 556$ s; LOC: MR $\sim 1.7$, $I_{sp} \sim 655$ s; IB: MR $\sim 5$, $I_{sp} \sim 516$ s
- Total Mission Burn Time: $\sim 25.3$ min

Shortest transit time possible

- (LEO $\rightarrow$ LLO $\rightarrow$ LEO)
- 32.8-hr “1-way” transit times
- Total Mission $\Delta V \sim 10.481$ km/s
- PTM mass $\sim 15$ t
- In-line LO$_2$ tank element $\sim 117.2$ t (includes 111.1 t of LEO LO$_2$)
- Common LH$_2$ NTPS $\sim 71.1$ t
- IMLEO $\sim 203.3$ t
- Refueled LLO$_2$ $\sim 80.4$ t
- LANTR engines operate O$_2$-rich
Out and Back: MR $\sim 5$, $I_{sp} \sim 516$ s
- Total Mission Burn Time: $\sim 25.3$ min

Commuter Shuttle’s Forward PTM carries 2 pilots and 18 passengers; OML Dimensions: $\sim 4.6$ m D x 8 m L

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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.
Total LUNOX Required for “Weekly” Commuter Flights

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\text{sp} = 465 s, DV\text{desc} = 2000 m/s and DV\text{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
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 km²) and tens of meters thick.

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

**Plant Mining Rate:**
- To produce 13,000 t of LUNOX annually requires glass throughput of ~3.25 x 10⁸ t/yr at MMR = 25:1
- Assuming 13 LUNOX production plants – each producing 1000 t/yr – each plant processes ~2.5 x 10⁴ 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)
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 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.