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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   The nuclear thermal rocket (NTR) has frequently been identified as a key space asset required for the human exploration of Mars. This proven technology can also provide the affordable "access through cislunar space" necessary for commercial development and sustained human presence on the Moon. It is a demonstrated technology capable of generating both high thrust and high specific impulse (I_{sp} ~900 s) – twice that of today's best chemical rockets. Nuclear lunar transfer vehicles – consisting of a propulsion stage using three ~16.5 klb$_f$ "Small Nuclear Rocket Engines (SNREs)", an in-line propellant tank, plus the payload – can enable a variety of reusable lunar missions. These include cargo delivery and crewed lunar landing missions. Even weeklong "tourism" missions carrying passengers into lunar orbit for a day of sightseeing and picture taking are possible. The NTR can play an important role in the next phase of lunar exploration and development by providing a robust in-space lunar transportation system (LTS) that can allow initial outposts to evolve into settlements supported by a variety of commercial activities such as in-situ propellant production used to supply strategically located propellant depots and transportation nodes. The use of lunar liquid oxygen (LLO$_2$) derived from iron oxide (FeO)-rich volcanic glass beads, found in numerous pyroclastic deposits on the Moon, can significantly reduce the launch mass requirements from Earth by enabling reusable, surface-based lunar landing vehicles (LLVs) using liquid oxygen/hydrogen (LO$_2$/LH$_2$) chemical rocket engines. Afterwards, a LO$_2$/LH$_2$ propellant depot can be established in lunar equatorial orbit to supply the LTS. At this point a modified version of the conventional NTR – called the LOX-augmented NTR, or LANTR – is introduced into the LTS allowing bipropellant operation and leveraging the mission benefits of refueling with lunar-derived propellants for Earth return. The bipropellant LANTR engine utilizes the large divergent section of its nozzle as an "afterburner" into which oxygen is injected and supersonically combusted with nuclear preheated hydrogen emerging from the engine's choked sonic throat—essentially "scramjet propulsion in reverse." By varying the oxygen-to-hydrogen mixture ratio, LANTR engines can operate over a range of thrust and I_{sp} values while the reactor core power level remains relatively constant. A LANTR-based LTS offers unique mission capabilities including short transit time crewed cargo transports. Even a "commuter" shuttle service may be possible allowing "one-way" trip times to and from the Moon on the order of 36 hours or less. If only 1% of the extracted LLO$_2$ propellant from identified resource sites were available for use in lunar orbit, such a supply could support daily commuter flights to the Moon for many thousands of years! The proposed paper outlines an evolutionary architecture and examines a variety of mission types and transfer vehicle designs, along with the increasing demands on LLO$_2$ production as mission complexity and ΔV requirements increase. A comparison of vehicle features and engine operating characteristics, for both NTR and LANTR engines, is also provided along with a discussion of the propellant production and mining requirements associated with using FeO-rich volcanic glass as source material.

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Nomenclature

$°C / °K$	=	temperature (in degrees Celsius / Kelvin)
EEO	=	Elliptical Earth Orbit
ELH_2	=	Earth-supplied Liquid Hydrogen propellant
$IMLEO$	=	Initial Mass in Low Earth Orbit
klb_f	=	thrust (1000's of pounds force)
LEO	=	Low Earth Orbit (= 407 km circular / 28.5 deg inclination)
LLO	=	Low Lunar Orbit (= 300 km circular / equatorial)
LTV	=	Lunar Transfer Vehicle
$LUNOX$	=	Lunar-derived Liquid Oxygen; another name for LLO_2
$NERVA$	=	Nuclear Engine for Rocket Vehicle Applications
$NLTV$	=	Nuclear-powered Lunar Transfer Vehicle
$O/H\,MR$	=	Oxygen-to-Hydrogen Mixture Ratio
SLS / HLV	=	Space Launch System / Heavy Lift Vehicle
t	=	metric ton (1 t = 1000 kg)
ΔV	=	velocity change increment (km/s)

I. Introduction and Background

Today there is considerable discussion within NASA, the Congress and industry regarding the future direction and focus of the United States' human space program. According to NASA, the direction and focus is a "Journey to Mars" [1] sometime around the mid-to-late 2030's. However, while NASA's sights are set on Mars, there is another destination of interest to the worldwide space community – the Moon. Located just 3 days from Earth, the Moon is an entire world awaiting exploration, future settlement and potential commercialization. It has abundant resources and is an ideal location to test and demonstrate key technologies and systems (e.g., surface habitation, long-range pressurized rovers, surface power and resource extraction systems) that will allow people to explore, work, and live self-sufficiently on another planetary surface.

Despite NASA's past "been there, done that" attitude towards the Moon, a human lunar return mission has strong appeal to many others who would like to see humans again walk on its surface. With the upcoming 50th anniversaries of the Apollo 8 orbital mission of the Moon (on December 24-25, 1968) and the Apollo 11 landing mission (on July 20-21, 1969) fast approaching, lunar missions are again a topic of considerable discussion both within NASA [2] and outside. Plans for human surface missions and even settlements on the Moon in the 2025 – 2030 timeframe are being openly discussed by Europe, China, and Russia [3,4,5]. A number of private companies in the United States – SpaceX [6], Bigelow Aerospace (BA) [7], Shackleton Energy Company (SEC) [8], United Launch Alliance (ULA) [9], and Blue Origin [10] – are also discussing commercial ventures to the Moon, along with possible public-private partnerships with NASA.

This past February, Space X announced [6] that it would send two tourists on a week-long, "free return" flyby mission around the Moon in 2018 – undoubtedly to capitalize on the significance of NASA's historic Apollo 8 mission. In early March, Bigelow Aerospace discussed its plans [7] to launch a private space station into LEO by 2020 using ULA's Atlas V launch vehicle. The station would use the BA-330 habitat module – the numerical designation referring to the 330 m^3 of internal volume that the BA-330 possesses once inflated. The company went on to say that a variant of the BA-330 module could also be placed in low lunar orbit to serve as a transportation node / refueling depot for astronauts and spacecraft making their way to and from the Moon and the lunar surface.

Lunar-derived propellant (LDP) production – specifically LLO_2 and LLH_2 – has been identified as a key technology offering significant mission leverage [11] and it figures prominently in both SEC's and ULA's plans [8,9] for commercial lunar development. Samples returned from different sites on the Moon during the Apollo missions have shown that the lunar regolith has a significant oxygen content. The FeO-rich volcanic glass beads returned on the final Apollo (17) mission have turned out to be a particularly attractive source material for oxygen extraction based on hydrogen reduction experiments conducted by Allen et al. [12]. Post-Apollo lunar probe missions have also provided orbital data indicating the possible existence of large quantities of water ice trapped in deep, permanently shadowed, craters located at the Moon's poles [13]. This data has generated considerable excitement and speculation, including plans for a commercial venture by SEC [8] that proposes to mine lunar polar ice (LPI), convert it to rocket propellant, and then sell it at propellant depots located in LEO.

Besides providing an ideal location for testing surface systems and "in-situ" resource utilization (ISRU) equipment, lunar missions also provide a unique proving ground to demonstrate an important in-space technology – Nuclear Thermal Propulsion (NTP). With its high thrust and high specific impulse ($I_{sp} \sim 900$ s) – twice that of today's best chemical rockets – the NTR can play an important role in *"returning humans to the Moon to stay"* by enabling a reusable in-space LTS that provides the affordable access through cislunar space necessary for initial lunar outposts to evolve into thriving settlements engaged in a variety of commercial activities.

Over the past three decades, engineers at Glenn Research Center (GRC) have analyzed NTP's use for lunar missions, quantified its benefits and developed vehicle concept designs for a variety of exploration and commercial mission applications [14,15,16,17]. A sampling of these vehicle concepts and mission applications is shown in Fig. 1. Also shown is a transition away from vehicles using a single high thrust engine (Fig. 1a) to vehicles using clustered lower thrust engines (Figs.1b–1e) to help reduce development costs and increase mission safety and reliability by providing an "engine out" capability.

The NTR achieves its high specific impulse by using LH_2 to maintain the reactor fuel elements at their required operating temperature then exhausting the heated hydrogen gas exiting the reactor out the engine's nozzle to generate thrust. Because the NTR is a monopropellant engine, a key question emerges *"How can the high performance of the NTR and the leverage potential of LDP best be exploited?"* The answer is *the "LO₂-Augmented" NTR (or LANTR) – a LH₂-cooled NTR outfitted with an O₂ "afterburner nozzle" and feed system* [18,19,20]. Combining NTR and supersonic combustion ramjet engine technologies, LANTR is a versatile, high performance engine that can enable a robust nuclear LTS with unique capabilities and can take full advantage of the mission leverage provided by using LDPs by allowing "bipropellant" operation.
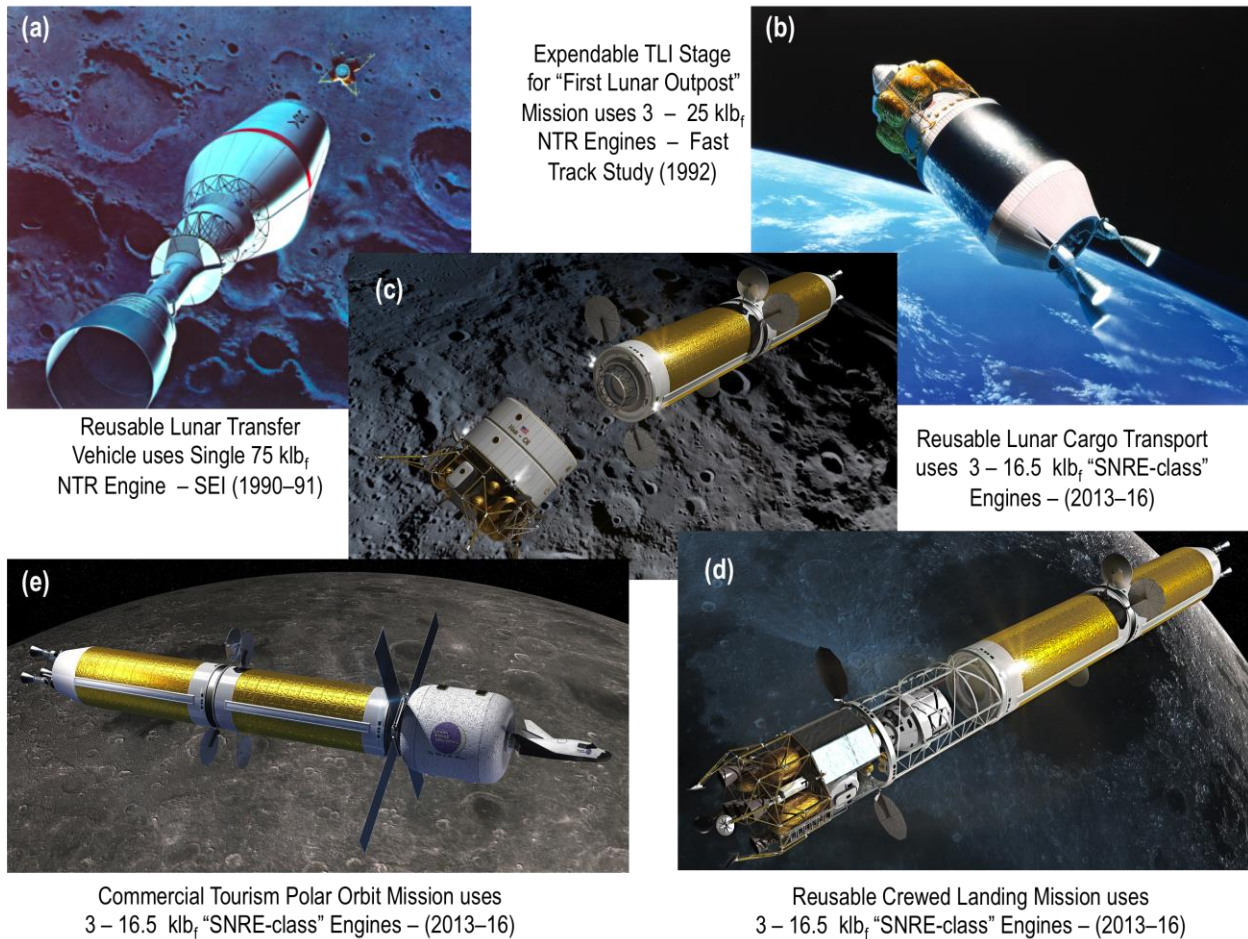

Figure 1. Sampling of Past and Recent Crewed, Cargo and Commercial Lunar Transfer Vehicles Designed by GRC Shows a Transition Away from Single Large to Multiple Smaller Engines

In light of the current interest being expressed in LDPs [8,9], GRC engineers have been re-examining the impact of infusing LANTR propulsion into a nuclear-powered LTS that utilizes LDPs. The author (Borowski) presented a paper on this topic 20 years ago at the 33rd Joint Propulsion Conference in Seattle, Washington [18]. In that work, the primary LDP and feedstock material considered was LLO_2, also referred to as LUNOX, and FeO-rich volcanic glass beads, and only ELH_2 was used in the LANTR LTS. The decision to use LUNOX back then was based on an extensive set of hydrogen reduction experiments [21,22] that established "*ground truth*" for oxygen release from samples of lunar soil and volcanic glass beads returned by the Apollo missions. The highest yields – in the range of 4-5 weight percent (wt%) – were obtained from the iron-rich volcanic glass samples [21,22] collected during the Apollo 17 mission to Taurus-Littrow (Fig 2). Another important consideration was the identification of a significant number of large pyroclastic "dark mantle deposits" (DMDs) containing this glassy material on the lunar nearside just north of the "equatorial corridor" [23,24].

Figure 2. Astronaut Harrison Schmitt Collects Samples of DM Material at Shorty Crater – Apollo 17 Mission

This same degree of certainty cannot be claimed for LPI. While considerable enthusiasm has been expressed about mining and processing LPI for rocket propellant, and using it to create a space-faring cislunar economy [25], the ground truth about LPI must first be established before this enthusiasm is warranted. Robotic surface missions will be required to quantify the physical state of the water ice, its vertical thickness and areal extent, and the levels of soil contamination. Also, the permanently shadowed craters, where LPI is thought to exist, are deep (~4.2 km for Shackleton Crater near the lunar south pole), and extremely cold (ranging from ~25 to 100 °K) posing major challenges for mining and processing any cold, ice-bearing regolith that might be uncovered [26]. These conditions may negate the apparent advantage that LPI has over volcanic glass as a feedstock material – namely, the ability to provide a source of LLH_2 as well as LLO_2.

There are many scientifically interesting sites on the Moon that are far from the lunar poles. For example, the Aristarchus Plateau (~27°N, 52°W) is located in the midst of a large expanse of DMD that can supply the feedstock material needed to produce LUNOX. Access to this nearside, near-equatorial site should also be relatively easy. If a decision were made to locate a research station or base there, producing oxygen locally would probably make more sense rather than incurring the added complexity and cost of transporting it from the poles. Finally, oxygen extraction from iron-rich mare soil or volcanic glass has an additional benefit – it also produces useful metals (iron and titanium) which using LPI feedstock does not.

In view of these facts, this paper again focuses on LUNOX and volcanic glass as the primary LDP and feedstock material. The potential mission benefits and issues associated with using LPI will be examined in a follow-on paper. This paper provides a summary of our ongoing analysis results to date and touches on the following topics. First, the oxygen extraction process and yields from candidate feedstock materials, system mass and power requirements, siting and features of a commercial LUNOX production plant are discussed. Next, a system description of the NTR and the LANTR concept are presented along with performance projections for the engine as a function of the oxygen-to-hydrogen mixture ratio used in the afterburner nozzle. The mission and transportation system ground rules and assumptions used in our analysis are then provided and used in an evolutionary mission architecture that illustrates the benefits of using LANTR and LUNOX technologies quantifying them in terms of reduced vehicle size, launch mass and required engine burn times. The potential for a robust, reusable LTS that includes short transit

time crewed cargo transports and commuter shuttles is discussed next along with the refueling needs, LUNOX production rates and mining requirements needed to support these more demanding and higher ΔV missions. The paper ends with some concluding remarks and thoughts on the possibilities for future human expansion into the Solar System using LANTR propulsion and sources of locally produced extraterrestrial propellant.

II. LUNOX: Its Benefits, Extraction Efficiency, Plant Characteristics and Siting Locations

Previous studies conducted by NASA and its contractors [27,28] have indicated a substantial benefit from using lunar-derived propellants – specifically LLO_2 in the lunar space transportation system. In a LTS using LO_2/LH_2 chemical rockets, ~6 kilograms (kg) of mass in 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 ~85.7% of this mass (3.6 kg) is oxygen assuming the engines operate with an O/H MR of 6:1. Since the cost of placing a kilogram of mass on the LS is ~6 times the cost of delivering it to LEO [11], the ability to produce LUNOX from processed lunar material can provide a significant mission benefit. By providing a local source of oxygen for use in life support systems, fuel cells and the chemical rocket engines used on LLVs, the IMLEO, launch costs and LTS size and complexity can all be reduced. Greater quantities of "higher value" cargo (e.g., people, propellant processing equipment and scientific instruments) can also be transported to LEO and on to the Moon instead of bulk propellant mass further reducing LTS costs.

LUNOX has also been mentioned as a potential commercial product because of its abundance. From the analysis of samples brought back on the Apollo missions, nearly half the mass (~43%) of the Moon's surface material is oxygen [11] and at least 20 different techniques [29,30] have been identified for its extraction. The reduction of iron oxide in the mineral "ilmenite" ($FeTiO_3$) or in volcanic glass using hydrogen gas is among the simplest and best studied. The technique involves a two-step process in which the FeO is first reduced to metal liberating oxygen and forming water as shown below:

$$FeTiO_3 + H_2 \text{ ---> } Fe + TiO_2 + H_2O \quad \text{or} \quad FeO \text{ (glass)} + H_2 \text{ ---> } Fe + H_2O$$

The water in then electrolyzed to produce oxygen and the hydrogen is recycled back to the processing plant to react with more feedstock material [29,30]. In the hydrogen reduction experiments conducted by Allen et al. [21,22], oxygen release was measured from samples of lunar soil and volcanic glass beads returned by the Apollo missions. The results indicated that oxygen can be produced from a wide range of lunar soils and is strongly correlated with the Fe^{2+} / FeO abundance in the soil as shown in Fig. 3. Iron-rich highland soils produced the smallest amount of oxygen, ~1 to 2 wt%, while iron-rich mare soil samples produced ~3.6 wt%. The highest yields – in the range of 4 to 5 wt% – were obtained from the pyroclastic (volcanic) glass collected at the Apollo 17 Taurus-Littrow landing site. The glass is extremely iron-rich with a Fe^{2+} content of ~17.8 wt%. The orange and black beads shown in Fig. 3 have identical elemental compositions, but the black beads are largely crystalline while the orange beads are largely glass.
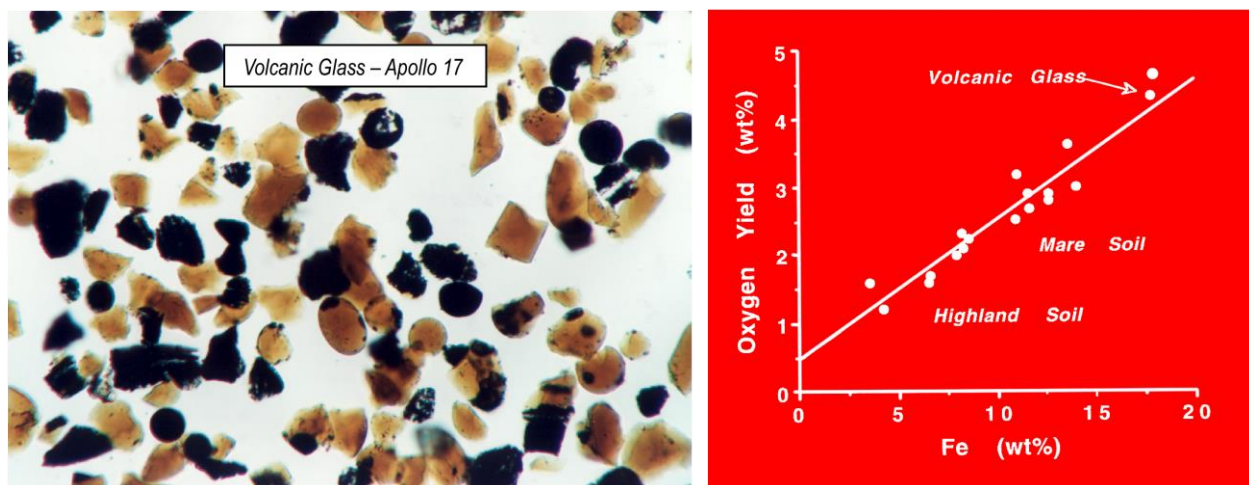

Figure 3. Volcanic Glass Beads and Oxygen Yields from Full Range of Apollo Samples [22]

Reduction of the orange glass beads produced an oxygen yield of ~4.3 wt% while the black crystalline beads produced ~4.7 wt%, the highest for any of the samples [22]. Assuming the hydrogen reduction process, volcanic glass feedstock, and a conservative oxygen yield of 4 wt%, a metric ton of LUNOX could be produced by processing ~25 t of volcanic glass – a significant improvement over previous estimates.

As mentioned above, one of the most studied concepts for oxygen extraction utilizes hydrogen reduction of the mineral ilmenite that is found in the lunar soil or mare basalts (lunar rock). LUNOX production scenarios that use ilmenite exclusively will require processing to separate out the mineral and minimize the amount of material that must be heated in order to release the oxygen. Processing of soil requires sizing and magnetic separation. If an ilmenite-rich basalt is used, an initial crushing step will also be required.

The key activities involved at a LUNOX production plant are depicted in Fig. 4. Teleoperated front-end loaders (1) and regolith haulers (2) mine and transport the feedstock material to an automated plant (3) where the ilmenite is beneficiated and chemically reduced by hydrogen gas in a fluidized bed reactor operating at ~900 to 1050 °C (~1173 to 1323 °K). Water is produced along with the process tailings (4) – iron, rutile (TiO_2) and residual solids. The water is then piped to electrolysis equipment (5) where it is separated into hydrogen and oxygen. The hydrogen is recycled back to react with more ilmenite while the oxygen is liquefied (6) and stored in "well-insulated" tanks (7). A surface vehicle (8) then transports individual tanks of LUNOX over to a tanker LLV (9) that delivers the LUNOX from the lunar surface to a propellant depot in LLO. The LLV then returns with a tank of ELH_2. A stack of these tanks (10) supply the LH_2 propellant needed by the LLV and the makeup hydrogen needed by the production plant. The power to allow "24/7" plant operation is provided by a nuclear fission reactor located a safe distance (11) away from the plant and the regolith-covered habitat module (12) occupied by the plant workers.

A detailed conceptual design study of a lunar oxygen pilot plant was performed for NASA by Christiansen et al. of Eagle Engineering in 1988 [30]. The study selected hydrogen reduction of ilmenite as the baseline concept because of process simplicity and well understood reaction chemistry. It developed computer models for the mining, beneficiation, and processing equipment that allowed estimates of the mass and power required for both a pilot plant producing 24 t of LUNOX/year and larger production plants producing up to 1000 t/year. Key trades and sensitivity analyses were also conducted including evaluations on: (1) soil or basalt feedstock; (2) solar photovoltaic arrays with regenerating fuels cell reactants or nuclear fission power sources; (3) smaller, modular production units to increase oxygen production versus constructing larger capacity plants; and (4) the sensitivity of plant mass and power to the oxygen production rate.

Figure 4. Activities at a LUNOX Production Plant Processing Ilmenite-bearing Feedstock Materials (ca. 1983)

In the Eagle Engineering study, a three-stage fluidized bed reactor concept [31] was baselined for the ilmenite reduction process (shown in Fig. 5). The plant is supplied by two teleorobotic regolith haulers. While one hauler is being filled at the mining site, the other hauler travels to and from the plant. At the plant the hauler (1) dumps its load into the process feed bin (2) and collects a load of either screened soil or tailings (unprocessed ilmenite, rutile and iron) from the plant's discharge bin (3). It then dumps these materials at the appropriate collection area (4) and returns to the mining site to begin the cycle over again.

From the feed bin a magnetic separator (5) isolates the slightly magnetic ilmenite from the rest of the bulk soil which is then discarded. The "enriched" ilmenite feedstock is then transported to the top of the processing plant (6) by a continuous-flow conveyor system. Here in the top bed of the reactor (7), the feedstock is preheated by hot, recycled hydrogen gas from the middle bed (8) and the electrolysis cell (9). Ilmenite reduction takes place primarily in the middle reaction bed. Waste heat from the spent solids is extracted and used to preheat the hydrogen stream in the bottom bed (10) before the material is discharged through a gas/solid separator (11). The water produced in the middle bed is then dissociated into oxygen and hydrogen in a solid-state electrolysis cell (12) operated at the reaction temperature. The oxygen is then cooled, liquefied, and stored (13) while the hydrogen is used to preheat more ilmenite feedstock (9). The process heat required in the reaction bed is provided by electric resistance heaters (14) that heat the hydrogen stream before it enters the bed.

The 24 t/year LUNOX pilot plant shown in Fig. 5 was sized to fit within a Shuttle payload bay pallet and has an outer diameter of ~4.3 m and a length of ~13.7 m. The pallet would serve as a strong back and mounting structure (15) for the processing unit allowing it to be delivered to the lunar surface fully integrated. Once there the unit is lifted into the vertical position (as shown in Fig. 5) and stabilized. The vertical orientation is required for proper plant operation and to take advantage of gravity during material processing. Although operations are largely autonomous, the facility is human-tended so accommodations are provided for human access to different plant levels. This includes ground level, the mid-level reaction bed location at ~4.6 m (16) and the upper ilmenite feed location at ~9.2 m (17) along with connecting ladders (18) and guard rails to allow human inspection and maintenance of the process equipment.

The Eagle Engineering study considered both an "ilmenite-rich" basalt feedstock (containing ~33 wt% ilmenite) and a soil feedstock (with ~7.5 wt% ilmenite) in assessing plant performance. With basalt feedstock, ~186 t of mined material is required per ton of LUNOX produced. Using lower ilmenite content, soil feedstock eliminated the
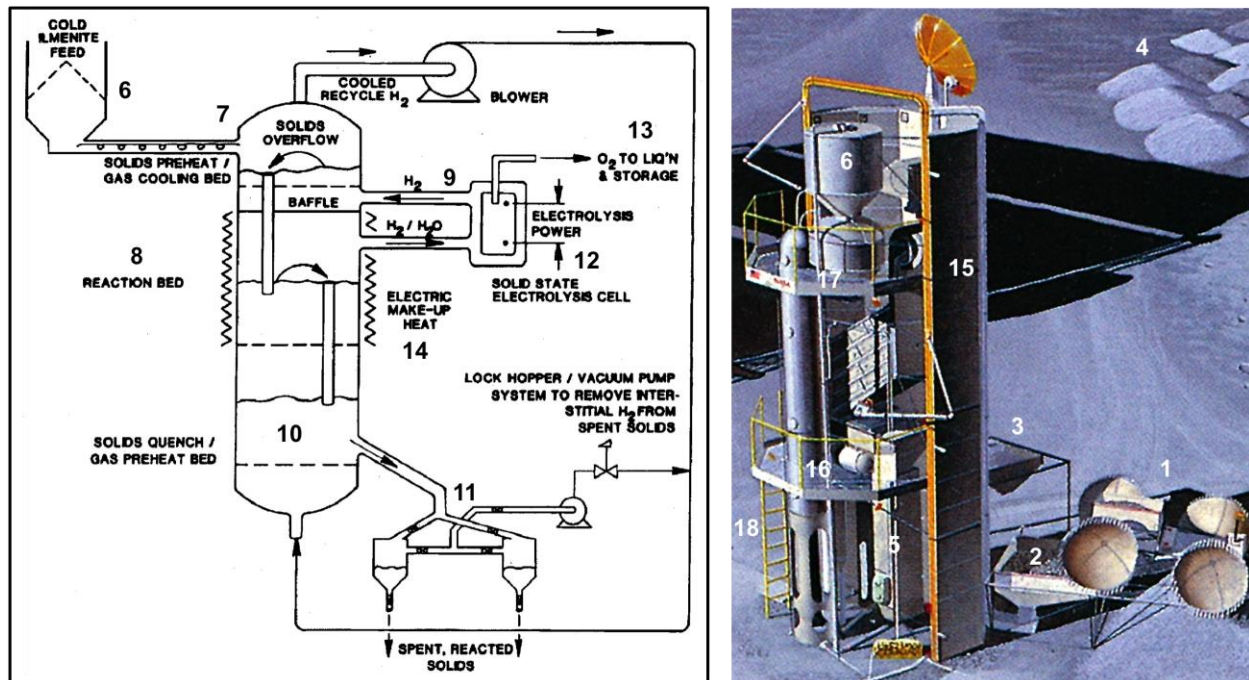

Figure 5. Schematic and Illustration of a LUNOX Pilot Plant Utilizing a
Continuous Fluidized Bed Reactor for Ilmenite Reduction with Hydrogen

need to crush and grind tons of rock for ilmenite extraction, but it increased the mining mass ratio to ~327 t of soil per ton of LUNOX. Estimates of LUNOX plant mass and power levels for a soil feedstock system obtained from the Eagle Engineering study [30] are shown in Figures 6 and 7 as a function of the annual production rate. The 35% duty cycle assumes that mining operations occur during 70% of the available lunar daylight hours (~3066 per year).
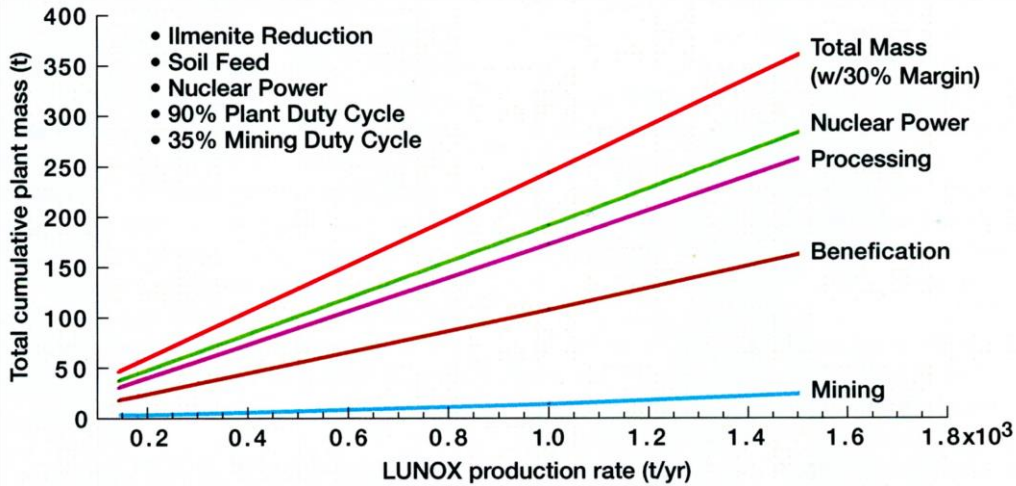

Figure 6. Variation of LUNOX Production Plant Component Mass with Annual Production Rate
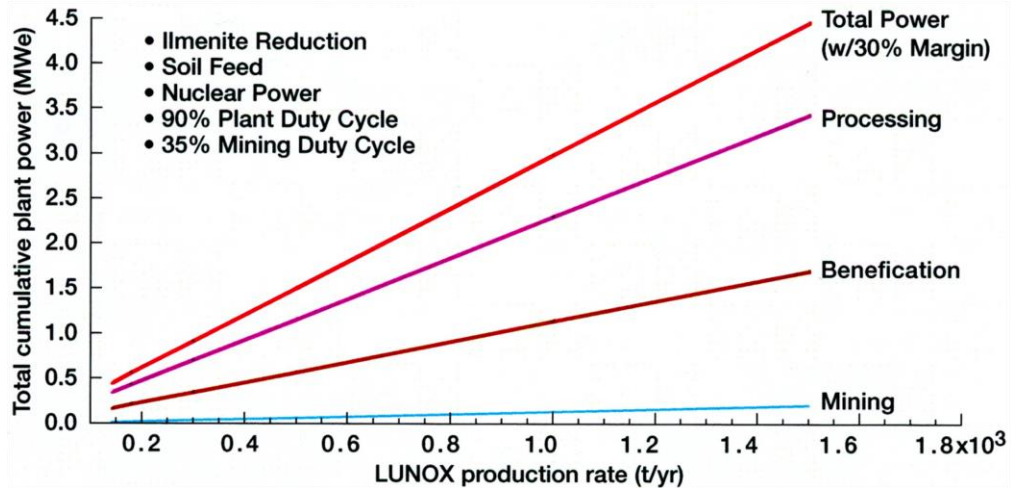
Figure 7. Variation of LUNOX Production Plant Power with Annual Production Rate

Unfortunately, the Eagle Engineering study performed in 1988 was unable to benefit from the subsequent hydrogen reduction experiments conducted by Allen et al. [22] several years later that indicated significantly higher oxygen yields (~4 to 5 wt%) are achievable using iron-rich volcanic glass. Oxygen yield was also found to correlate directly with the sample's iron abundance suggesting that the oxygen production potential of any location on the Moon can be determined from orbit [32] using demonstrated and complementary gamma ray spectrometry [33] and multispectral imaging [34] techniques.

Assuming the same hydrogen reduction processing plant, volcanic glass as feedstock, and a conservative oxygen yield of 4 wt%, a ton of LUNOX could be produced by processing ~25 t of volcanic glass – a significant improvement over the mining mass ratio required using the ilmenite-bearing soil discussed above. According to Allen et al., volcanic glass is an attractive feedstock option because it is uniformly fine grained, reacts rapidly and can be fed directly into the LUNOX production plant with little or no processing prior to reduction. There is another important reason to consider as well – it exists in large quantities.

A significant number of large pyroclastic deposits, thought to be the result of continuous, Hawaiian-style, fire-fountain eruptions from large vents, have been identified on the lunar nearside by Gaddis et al, [24]. These deposits are of regional extent and are composed largely of crystallized black beads, orange glass beads, or a mixture of the two. Noteworthy large deposits located just north of the lunar equator include: (1) the 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); and (6) Taurus Littrow (~2,940 km^2).
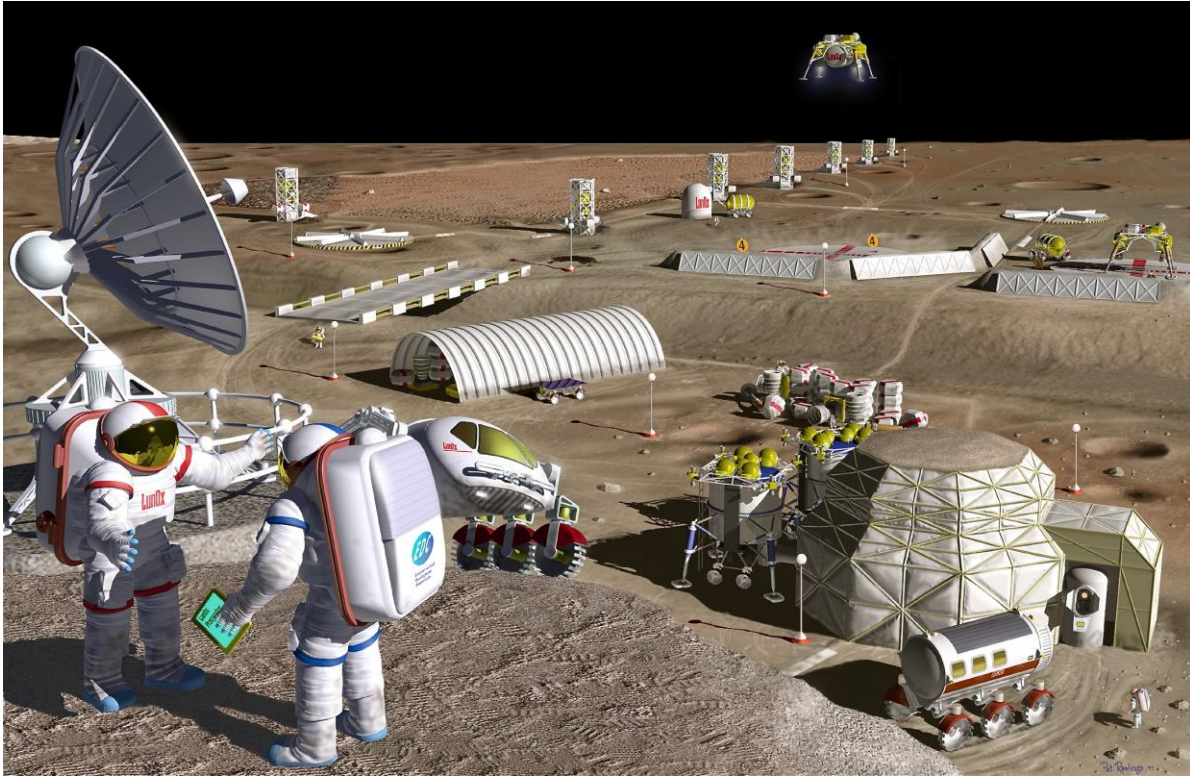

Figure 8. Commercial LUNOX Facility Bordering on the Taurus-Littrow DMD

Just like 20 years ago, our choice for siting a commercial LUNOX facility is the Taurus-Littrow DMD near the southeastern edge of Mare Serenitatis (~21°N, ~29.5°E) approximately 30 km west of the Apollo 17 landing site. This deposit of largely black crystalline beads covers ~3000 km^2, is thought to be tens of meters thick and could yield hundreds of millions of tons of LUNOX using the hydrogen reduction process. The facility image (shown in Fig. 8) was developed and first presented in the author's 1997 JPC paper [18] and has appeared in publications and magazines numerous times since then. Depicted in the lower left foreground are two lunar industrialists discussing planned expansions at the LUNOX facility, while to the northwest, modular production units, resembling oil rigs on Earth, generate copious amounts of LUNOX which are stored in well-insulated tanks adjacent to the facility. To the north, a bottom-loaded "Sikorsky-style" LLV lifts off from the surface carrying a tank of LUNOX to a propellant depot in LLO, while at the adjacent landing pad, a second LLV awaits servicing prior to its next mission. In the right foreground, increased numbers of government and industry personnel have taxed the capabilities of several previously landed habitat modules necessitating construction of an inflatable dome for added living space. The dome is covered on the outside by bagged regolith to provide shielding against solar flares and galactic cosmic radiation (GCR). Lastly, nuclear fission reactors will be critical to providing a good return to investors in the LUNOX enterprise. They provide abundant power at low mass to support continuous operation of the teleoperated surface vehicles, production units and habitat modules even during the two-week lunar night. As production capacity increases, the LUNOX enterprise can expand its commercial operations to include metals processing (e.g., iron and titanium), power generation, maintenance and operations of surface-based LLVs and LLO propellant depots and eventually even a lunar tourism industry complete with routine commuter flights to and from the Moon.

III. NTR / LANTR System Description and Performance Characteristics

The NTR uses a compact fission reactor core containing "enriched" uranium (U)-235 fuel to generate 100's of megawatts of thermal power (MW_t) required to heat the LH_2 propellant to high exhaust temperatures for rocket thrust [35]. In an "expander cycle" engine (shown in Fig. 9), high pressure LH_2 flowing from a turbopump assembly (TPA) is split into two paths with the first cooling the engine's nozzle, pressure vessel, neutron reflector, and control drums, and the second path cooling the engine's core support tie-tube assemblies. The flows are then merged and the heated H_2 gas is used to drive the TPAs. The hydrogen turbine exhaust is then routed back into the reactor pressure vessel and through the internal radiation shield and upper core support plate before entering the coolant channels in the reactor's fuel elements. Here it absorbs energy produced from the fission of U-235 atoms, is superheated to high exhaust temperatures (T_{ex} ~2700 °K or more depending on the uranium fuel loading), then expanded out a high area ratio nozzle (~300:1) for thrust generation.
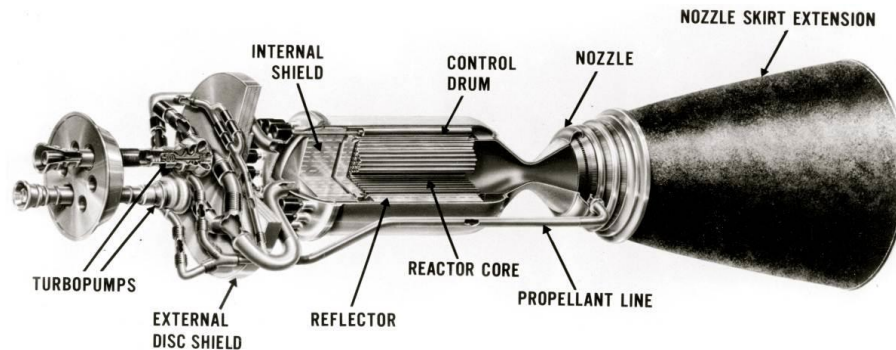

Figure 9. Schematic of "Expander Cycle" NTR Engine with Dual LH_2 Turbopumps

Controlling the NTR during its various operational phases (startup, full thrust and shutdown) is accomplished by matching the TPA-supplied LH_2 flow to the reactor power level. Multiple control drums, located in the reflector region surrounding the reactor core, regulate the neutron population and reactor power level over the NTR's operational lifetime. The internal neutron and gamma radiation shield, located within the engine's pressure vessel, contains its own interior coolant channels. It is placed between the reactor core and key engine components to prevent excessive radiation heating and material damage.

Recent studies showing the benefits of NTP for a variety of exploration and commercial lunar missions [16,17] have used a "common" Nuclear Thermal Propulsion Stage (NTPS) employing a cluster of three SNREs. The engine's reactor core is composed of hexagonal-shaped fuel elements and core support tie tubes developed and tested during the Rover/NERVA program [35]. Each fuel element (FE) was fabricated using a "graphite matrix" material that contained the U-235 fuel in the form of either coated particles of uranium carbide (UC_2) or as a dispersion of uranium and zirconium carbide (UC-ZrC) referred to as "graphite composite" (GC) fuel (see Fig 10).

This higher performance GC fuel was developed as a *"drop-in replacement"* for the coated particle fuel and was tested in the Nuclear Furnace element test reactor (NF-1) [34] near the end of the Rover program. The GC elements achieved a peak power density of ~5 MW_t per liter (~5000 MW_t/m^3) and a peak fuel temperature of ~2700 °K. The GC elements also demonstrated better corrosion resistance than the standard coated particle fuel elements used in the previous Rover/NERVA reactor tests. This improved resistance of the GC fuel was attributed to its higher coefficient of thermal expansion (CTE) that more closely matched that of the protective ZrC coating, thereby helping to reduce coating cracking. Electrical-heated composite fuel elements were also tested by Westinghouse in hot hydrogen at 2700 K for ~600 minutes – equivalent to ten 1-hour cycles.

Heritage Rover/NERVA FEs had a hexagonal cross section (~0.75 inch across the flats) and 19 axial coolant channels (shown in Fig. 10) that were coated with niobium carbide (NbC) initially, then with zirconium carbide (ZrC) using a chemical vapor deposition (CVD) process. This protective coating, applied to the FE's exterior surfaces as well, helped to reduce coating cracking, hydrogen penetration and subsequent erosion of the graphite matrix material. Individual elements were 1.32 m (52 inches) in length and produced ~1 MW_t during steady state, full power operation. Also included in the engine's reactor core were hexagonal-shaped tie tube (TT) elements that provided structural support for 6 surrounding FEs (shown in Fig. 10). A coaxial Inconel tube inside the TT carries

hydrogen coolant that is also used to supply a source of heated hydrogen for turbine drive power in the SNRE's expander cycle engine design. A sleeve of zirconium hydride (ZrH) moderator material is also incorporated into each TT (see Fig. 10) to help increase core reactivity and allow construction of smaller, lower thrust engine systems like the Small Nuclear Rocket Engine (SNRE) [35] developed by Los Alamos National Laboratory near the end of the Rover/NERVA program.

Although it was not built, the SNRE incorporated all of the lessons learned from the program's 20 previous reactor designs and test results. The FE had the same hexagonal cross section and coolant channel number, but was 35 inches long, used GC fuel, and produced ~0.65 MW_t. To help increase core reactivity, the "SNRE" FE – TT pattern increased the number of TTs so that each FE has 3 adjacent TTs and 3 adjacent FEs surrounding it (Fig. 10). With the SNRE pattern, the FE to TT ratio is ~2 to 1 with each tie tube providing redundant mechanical support for six surrounding fuel elements.
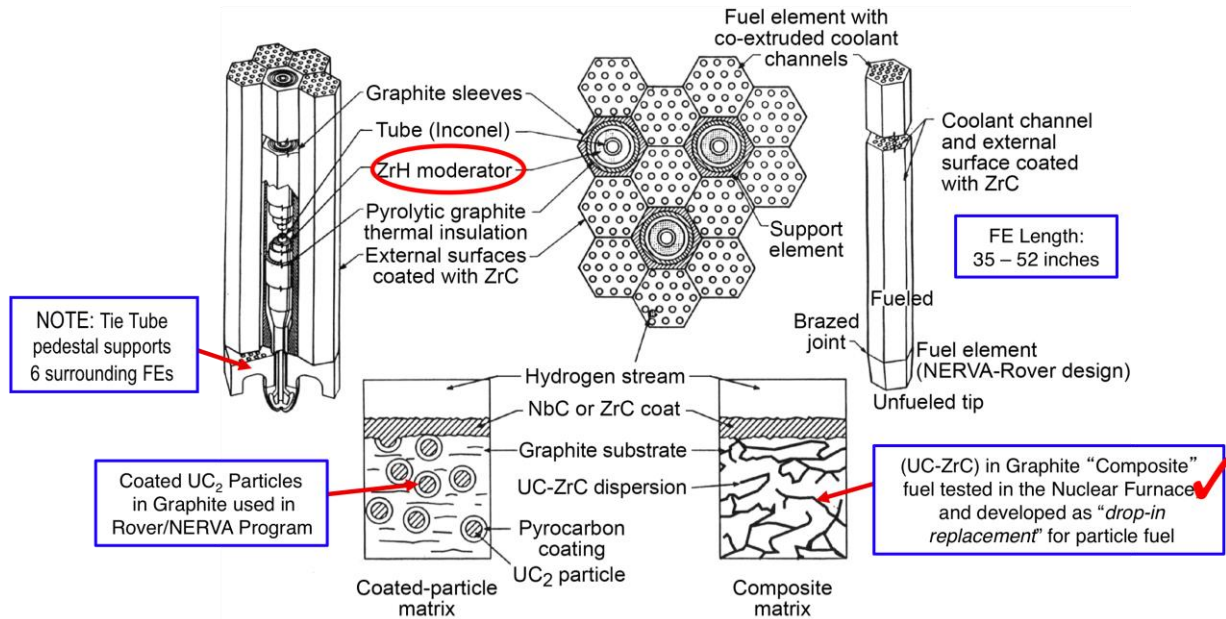

Figure 10. Coated Particle and Graphite Composite SNRE Fuel Element and Tie Tube Arrangement

The baseline SNRE used in this study has a nominal power output of ~365 MW_t, an average power density of ~3.44 MW_t/liter, and produces ~16.5 klb_f of thrust. The reactor core has 564 fuel elements and 241 tie tubes, and is surrounded by a 14.7 cm thick perimeter neutron reflector resulting in a pressure vessel diameter of ~98.5 cm. With a fuel loading of ~0.6 g/cm^3, the FEs contain ~60 kg of 93% enriched U-235. The GC fuel operates at a peak temperature of ~2860 °K and the corresponding hydrogen exhaust temperature is ~2734 °K. With a chamber pressure of 1000 psia, a hydrogen flow rate of ~8.30 kg/s and a nozzle area ratio (NAR) of ~300:1, the engine's I_{sp} is ~900 s. The total engine length is ~5.8 m with the ~1.8 m long radiation-cooled, retractable nozzle section fully extended. The nozzle exit diameter is ~1.53 m and the engine's thrust-to-weight ratio is ~3.02.

LANTR: An Enhanced NTR with "Bipropellant" Operational Capability

In order to take full advantage of LUNOX once it becomes available to the LTS, each SNRE is outfitted with an O_2 "afterburner" nozzle containing the O_2 injectors and an O_2 feed system. The oxygen is stored as a cryogenic liquid at low pressure and must be pressurized and gasified prior to its injection into the nozzle. This is accomplished by diverting a small fraction of the engine's hydrogen flow (~3%) to an oxidizer-rich gas generator that drives a LO_2 TPA used to deliver the gasified LO_2 to injectors positioned inside the afterburner nozzle downstream of the throat [18,19,20]. Here it mixes with the hot H_2 and undergoes supersonic combustion adding both mass and chemical energy to the rocket exhaust – essentially *"scramjet propulsion in reverse."*

Downstream nozzle injection in LANTR isolates the reactor core from oxygen's damaging effects provided the throat retains choked flow. This operating condition can be satisfied by using a "cascade" scramjet injector developed by Aerojet [20] – now Aerojet Rocketdyne. A 3-zone staged injection approach [20] is envisioned using multiple cascade injectors to control the oxygen addition and heat release within the nozzle while keeping the flow supersonic. This approach also increases penetration, mixing and combustion of the injected oxygen within the hydrogen flow while minimizing shock losses and the formation of high heat flux regions, thereby maximizing engine performance and life. A high reactor outlet pressure is also desirable since it allows the use of a high area ratio nozzle – important for increasing combustion efficiency – at reasonable size and mass.

A simplified schematic of LANTR engine operation is illustrated in Fig. 11. Also shown is a photograph of a non-nuclear, "proof-of-concept" demonstration test of a LANTR nozzle that used a "fuel-rich" 2100 lb_f chemical rocket engine operating at a oxygen/hydrogen MR <2 to simulate a NTR. The water-cooled, copper test nozzle had NAR of 25:1 and used 3 wedge-shaped injectors (2 of which are visible in Fig. 11) [36]. These tests and follow-on tests with a 50:1 nozzle indicated that up to 73% of the injected oxygen burned within these short nozzles resulting in an augmented thrust level of ~53% as measured on the engine thrust stand [20].
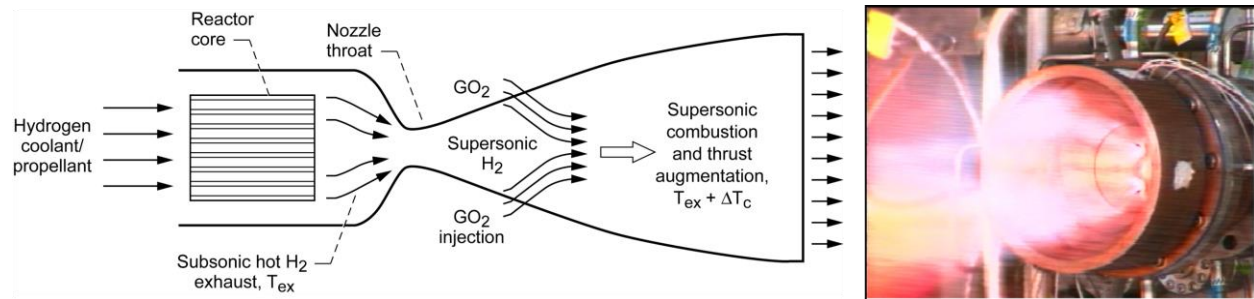

Figure 11. Simplified LANTR Schematic and Simulated "Proof-of-Concept" Test Article Photograph [36]

The LANTR concept has the potential to be an extremely versatile propulsion system. By varying the O/H MR, the LANTR engine can operate over a wide range of thrust and I_{sp} values – shown in Table 1 – while the reactor core produces a relatively constant power output. As the MR varies from 0 to 5, the engine thrust level for the SNRE increases by over 344% – from 16.5 klb_f to ~56.8 klb_f – while the I_{sp} decreases by ~57% – from 900 to 516 s which is still 54 s higher than that achieved by today's best LO_2/LH_2 chemical engine – the RL10B-2 [37]. This thrust augmentation feature means that "big engine" performance can be obtained using smaller, more affordable LH_2-cooled NTR engines that are easier to build and less costly to test on the ground. The engines can then be operated in space in the augmented high thrust mode to shorten burn times (thereby extending engine life) and reduce gravity losses (thereby eliminating the need for and concern over multiple, "perigee burn" Earth departure maneuvers). Lastly, the increased use of high-density LO_2 in place of low-density LH_2, and the ability to resupply or "reoxidize" LANTR vehicles with LUNOX prior to Earth return, are expected to significantly reduce vehicle size and mass while increasing delivered payload.

Table 1. SNRE / LANTR Performance Characteristics as a Function of O/H Mixture Ratio

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

** Fuel Exit / Hydrogen Exhaust Temperature = 2734 °K , Chamber Pressure = 1000 psia and NAR = 300 to 1

IV. Mission, Payload and Transportation System Ground Rules and Assumptions

Specific mission and payload ground rules and assumptions used in this paper are summarized in Table 2. It provides information about the different lunar mission scenarios, along with the assumed parking orbits at Earth and the Moon. Specific trajectory details and ΔV budgets for the different missions examined are provided within the appropriate sections of the paper. In addition to the large ΔV requirements for the primary propulsion maneuvers, like trans-lunar injection (TLI), smaller ΔV maneuvers are needed for propellant settling, vehicle mid-course correction (MCC) maneuvers, orbital operations in LLO, including rendezvous and docking (R&D) of the LTV with surface-based LLVs or with the lunar propellant depot, and lastly LTV-depot separation and station keeping.

A variety of different payloads are also considered. On initial "all LH$_2$" NTR crewed landing missions, a forward mounted saddle truss is used to connect the payload elements to the transfer vehicle's in-line tank. The truss is open on its underside and its forward adaptor ring provides a docking interface between the MPCV and the single stage

Table 2. Mission and Payload Ground Rules and Assumptions

• Crewed lunar landing using NTR (3 day transits to and from the Moon with 3 – 14 days on the surface) • Crewed cargo transport using LANTR (1.5 – 3 day transits to and from the Moon with 3 days in LLO) • LANTR commuter shuttle carries Passenger Transport Module (PTM) ("1-way" transit of 36 hours or less) • Rapid commuter shuttle and priority cargo delivery system using LANTR (24-hr & 48-hr transit times for passenger & priority cargo mission legs, respectively)	• Reusable LTV carries MPCV, reusable LLV and surface payload to LLO; returns MPCV and spent LLV to EEO; Orion capsule used for crew recovery at mission end • Reusable, LANTR LTV transports habitat module, crew, and varying amounts of cargo, depending on the transit times to and from LLO; LTV refuels with LUNOX at LLO depot before returning to Earth • Reusable, LANTR LTV transport a PTM to LLO for subsequent delivery to the lunar surface by LLV; LTV refuels with LUNOX at LLO depot before returning to Earth with another PTM • Reusable LANTR LTV delivers PTM to LLO then returns priority cargo back to LEO; LTV refuels with LUNOX at LLO depot before returning to Earth; PTM & cargo payloads going out & back alternate
• NTR / LANTR missions depart from LEO and capture / depart from equatorial LLO; NTR missions return to EEO while LANTR missions return to LEO	• LEO: 407 km circular • LLO: 300 km equatorial • 3.24-hr EEO: 500 km x 9,050 km • 24-hr EEO: 500 km x 71,136 km
• Primary mission ΔV maneuvers: NTR or LANTR engines used • Additional ΔV requirements: Advanced Material Bipropellant Rocket (AMBR) RCS thrusters used to perform non-primary propulsion maneuvers	• ΔV budgets for different missions discussed in appropriate sections • Propellant settling burn: ~1 m/s • Mid-course correction: ~10 m/s • Lunar orbit R&D & maintenance: ~40 m/s • Depot separation & station keeping: ~10 m/s
• Crewed landing mission payload masses: Reusable NTR LTV delivers *Orion* / MPCV and single stage LO$_2$ / LH$_2$ Lunar Descent / Ascent Vehicle (LDAV) to LLO; LDAV carries 4 crew and 5 t of payload to lunar surface; LTV with *Orion* / MPCV, LDAV and surface samples returned to a 24-hr EEO	• *Orion* / MPCV: 13.5 t • Saddle truss assembly (STA) 7.2 t • LDAV crew cab & dry mass: 8.6 t • Crew (4) & EVA suits: 0.8 t • LDAV propellant load: 20.9 – 22.4 t • LDAV surface payload: 5.0 t • Returned Samples: 0.1 t
• Crewed cargo transport payload masses: Reusable LANTR LTV delivers a habitat module, crew and cargo (10 – 20 t depending on the transit time) from LEO to LLO then returns to LEO	• Habitat Module: 9.9 t • Single Star Truss w/RMS: 5.29 t • Outbound Payload: 4-8 cargo pallets (2.5 t each) • Crew (4) & EVA suits: 0.80 t • Returned Samples: 0.25 t

• Commuter shuttle payload mass: Reusable LANTR LTV delivers a PTM from LEO to LLO then back again
 	
• PTM and priority cargo masses: Reusable LANTR LTV delivers PTM to LLO then returns to LEO with a priority cargo shipment; Payloads alternate out & back
	• PTM: 15 t
	    (includes 2 crew & 18 passengers)
	
	• PTM: 15 t
	    ("1-way" transit time for the PTM is 24 hours)
	• Cargo container: 7.5 t (includes 5.0 t of priority cargo)
	    ("1-way" transit time for cargo is 48 hours)

LO$_2$/LH$_2$ LDAV (shown in Fig. 12a). The LDAV is a "heritage" design [38] analyzed in considerable detail during NASA's earlier Space Exploration Initiative (SEI) studies. It carries a crew of 4 plus 5 t of surface payload (PL) stored in two 2.5 t PL pallets mounted on each side of the crew cab. The LDAV mass breakdown including the propellant loading and landed payload is shown in Table 2. On the lunar landing mission analyzed here, the crew also collects and returns ~100 kg of samples.

For the reusable, space-based crewed cargo transport missions using LANTR propulsion and LUNOX on the Earth return mission leg, the LTV carries a habitat module that supports a crew of 4. Two crewmembers operate the vehicle and manage the unloading of the PL. The other 2 represent rotating crewmembers on assignment at the lunar base or the LLO transportation node / propellant depot. Connecting the habitat module to the rest of the LANTR LTV is a "star truss" that has four concave sides to accommodate four PL pallets (shown in Fig. 12b). The forward circular truss ring also has a Remote Manipulator System (RMS) with twin arms attached to it. Using the habitat module's rear viewing window, the crew uses these arms to unload and attach the transport's cargo to the depot node or to a co-orbiting LLV transferring crew and awaiting cargo delivery.
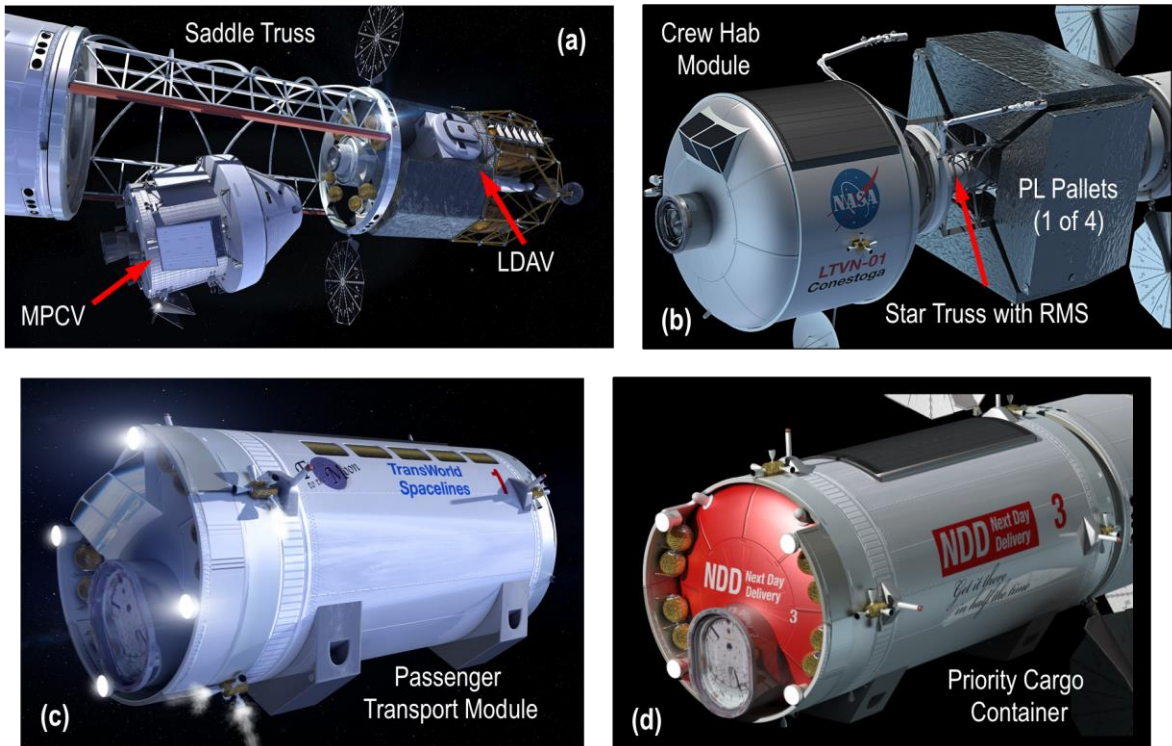

Figure 12. Payload Elements Carried by the NTR and LANTR Lunar Transfer Vehicles

Using the same LANTR LTV system elements shown in Fig. 13, routine commuter flights to and from the Moon can also be considered. For the commuter shuttle application, the cargo transport's habitat module, star truss and PL pallets are removed and replaced with a PTM (Fig. 12c) that carries 18 passengers and 2 crew members. It is also possible to deliver a 7.5 t shipping container carrying 5 t of priority cargo (Fig. 12d) on the alternating outbound and inbound legs of the same mission which will be discussed later in the paper.

Table 3 lists the key ground rules and assumptions used in the NTR / LANTR transportation system elements. The NTPS carries only ELH$_2$ and uses a three-engine cluster of SNRE-class engines initially before transitioning over to LANTR operation. The smaller diameter in-line LO$_2$ tank located forward of the NTPS carries Earth-supplied LO$_2$ on the way out to the Moon but refuels with LUNOX for the return to Earth. Details on the NTR and LANTR engine design and performance are provided in Sect. II and are summarized in Table 3. The total mission LH$_2$ and LO$_2$ propellant loadings consist of the usable propellant plus performance reserve and tank-trapped residuals. Additional LH$_2$ is also provided for engine cooldown after each major propulsive maneuver.
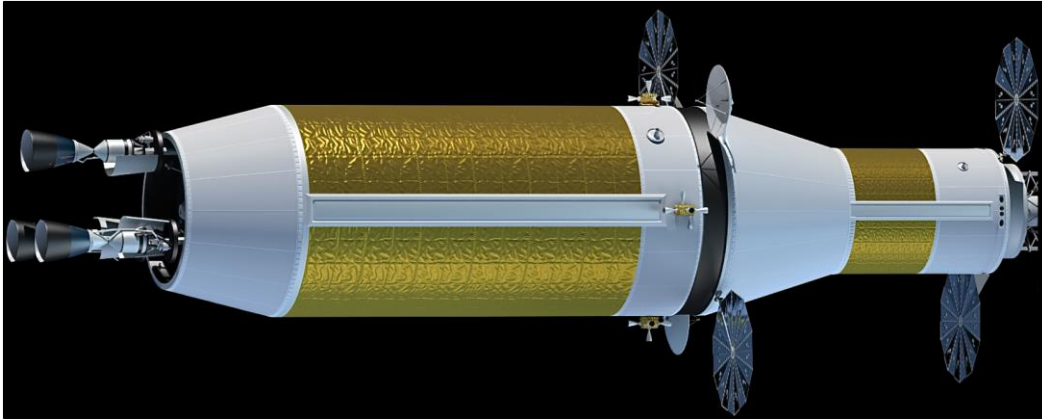
Figure 13. Key LANTR LTV System Elements – the LH$_2$ NTPS and In-Line LO$_2$ Tank

Table 3. NTR and LANTR Transportation System Ground Rules and Assumptions

NTR / LANTR Characteristics	• Engine / Fuel Type: NERVA-derived / UC-ZrC "Composite" • Propellants: LH$_2$ (NTR), LH$_2$ and LO$_2$ (LANTR) • Thrust Level: 16.5 klb$_f$ SNRE-class engine using LH$_2$ only 26.5 klb$_f$ – 56.8 klb$_f$ with LANTR (MR = 1 to 5) • Fuel Element Length: 0.89 m (SNRE baseline) • Exhaust Temp: T$_{ex}$ ~2734 °K (with 2860 °K peak temperature) • Chamber Pressure: p$_{ch}$ ~1000 psi • Nozzle Area Ratio: ε~300:1 • I$_{sp}$ Range: 900 s – 516 s with LANTR (MR = 0 to 5)
Propellant Margins	• Cooldown: 3% of usable LH$_2$ propellant • Performance reserve: 1% on ΔV • Tank trapped residuals: 2% of total tank capacity
Reaction Control System (Propellant Settling, Mid-course Correction Burns and Lunar Orbit Operations)	• Propulsion Type: AMBR 200 lb$_f$ thrusters • Propellant: NTO / N$_2$H$_2$ • Nominal I$_{sp}$: 335 seconds
LH$_2$ Cryogenic Tanks and Passive Thermal Protection System (TPS)	• Material: Aluminum-Lithium (Al/Li) • Tank OD: 7.6 m (LH$_2$); 7.6 m and 4.6 m (LO$_2$) • Tank L: 15.65 m ("core" NTPS and "in-line" LH$_2$ tanks) 5.23 m – 7.95 m ("in-line" LO$_2$ tank) • Geometry: cylindrical with root 2/2 ellipsoidal domes • Insulation: 1" SOFI (~0.78 kg/m²) + 60 layers of MLI (~0.90 kg/m²)
Active Cryo-Fluid Management / Zero Boil-Off (ZBO) LH$_2$ Propellant System	• Reverse turbo-Brayton ZBO cryocooler system powered by PVAs • ZBO system mass and power requirements driven by core stage size; ~760 kg and ~5.26 kW$_e$ (7.6 m D)
Photovoltaic Array (PVA) Primary Power System	• Circular PVA sized for ~7 kW$_e$ at 1 A.U, two arrays provide power for ZBO cryocoolers on core stage, PVA mass is ~566 kg for two ~25 m² arrays, second array set provides power to mission payloads • "Keep-alive" power supplied by lithium-ion battery system
Dry Weight Contingency Factors	• 30% on NTR system & composite structures (e.g., saddle and star trusses) • 15% on established propulsion, propellant tanks, spacecraft systems
SLS / SLS Upgrade Launch Requirements: – Usable Payload Delivered to LEO – Cylindrical Payload (PL) Envelope	• ~70 t to LEO (407 km circular) • 7.6 m OD x ~26.5 m L

For the smaller auxiliary maneuvers performed, a storable bipropellant Reaction Control System (RCS) with AMBR thrusters is used (details in Table 3). The LANTR LTV utilizes a split RCS with approximately half the AMBR thrusters and bipropellant mass located on the rear NTPS and the other half located at the front end of the in-line LO_2 tank just behind the mission-specific payload.

The LH_2 propellant carried in the NTPS is stored in the same "state-of-the-art" Al/Li LH_2 propellant tank being developed for the SLS/HLV to support future human exploration missions. Sizing of the LH_2 tank assumes a 30 psi ullage pressure, 5 g_E axial / 2.5 g_E lateral launch loads, and a safety factor of 1.5. A 3% ullage factor is also assumed. The in-line LO_2 tank with its rear conical adaptor section uses the same sizing and launch load assumptions. All tanks use a combination spray-on foam (SOFI) / multilayer insulation (MLI) system for passive thermal protection. A zero boil-off (ZBO) "reverse turbo-Brayton" cryocooler system is used on the NTPS to eliminate boil-off after the NTPS has been refueled with ELH_2 and during the course of the mission. A passive thermal protection system is used on the in-line LO_2 tank since it is drained after the lunar orbit insertion (LOI) burn and is subsequently refueled with LUNOX before the trip back to LEO. The heat load on the NTPS hydrogen tank is largest in LEO and sizes the ZBO cryocooler system. Two sets of circular solar photovoltaic arrays (PVAs) – each producing ~14 kW_e – are baselined with one set supplying the primary electrical power needed for all key LTV sub-systems and the second set providing power for the different mission payloads considered here.

Table 3 also provides the assumed "dry weight contingency" (DWC) factors, along with the requirements for delivered mass to LEO and the shroud cylindrical payload envelope for the upgraded SLS / HLV. A 30% DWC is used on the NTR and LANTR systems and advanced composite structures (e.g., stage adaptors, trusses) and 15% on heritage systems (e.g., Al/Li tanks, RCS, etc.). The NTPS mass (~70 t) and size (~7.6 m OD and ~26.5 m length) determines the required lift capability and the usable shroud PL volume for the upgraded SLS. The combined saddle truss (~13.7 m) and LDAV (~9.6 m) used on the crewed landing mission (shown below in Fig. 14b) has this same approximate length. On the crewed cargo transport mission discussed in Sect. VII, the habitat module (~6.5 m OD and ~8.5 m in length) and star truss (~11 m in length) can be launched together, or the truss can be launched together with the in-line LO_2 tank and its conical adaptor (~11.5 m in length).

V. Performance Impact of Integrating LANTR and LUNOX into the LTS Architecture

As mentioned in the Introduction, the author presented a paper on the enhanced mission capability resulting from the combined use of LANTR propulsion and LUNOX 20 years ago at the 33rd Joint Propulsion Conference in Seattle, Washington [18]. In that paper, an evolutionary LTS architecture was analyzed that began with a LTS using high performance NTP to maximize delivered surface payload on each mission. The increased PL was dedicated to installing modular LUNOX production units with the intent of using this LDP to supply surfaced-based LLVs initially, then in-space LTVs using LANTR propulsion at the earliest possible opportunity. This section re-examines this evolutionary LTS architecture to see how recent NLTV designs and missions [16,17] are impacted by the introduction of LANTR and LUNOX.
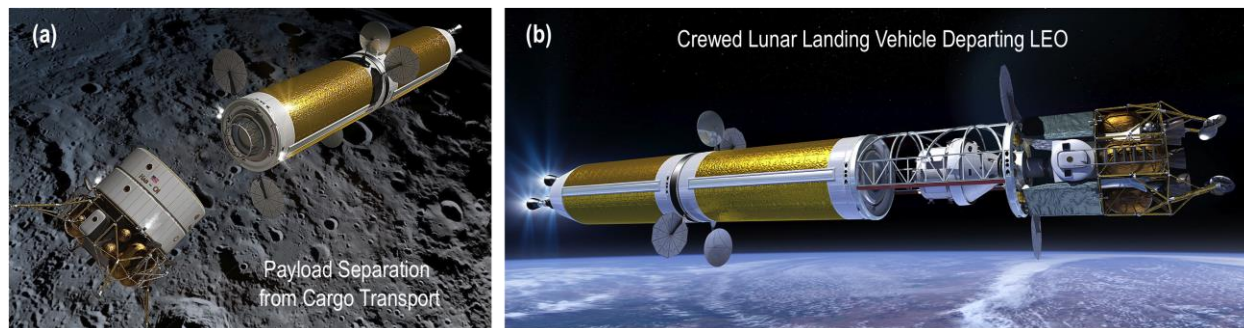

Figure 14. Reusable NTR Cargo Delivery and Crewed Lunar Landing Vehicles

The NTPS, with its three 16.5 klbf SNREs, is the "workhorse" element on the cargo and crewed NLTVs shown in Figs. 14a and 14b. It has a 7.6 m diameter by ~15.7 m long Al/Li tank that carries ~39.8 t of LH_2 propellant. Housed within and mounted on the forward cylindrical adaptor section of the NTPS are the RCS, avionics, batteries, two deployable circular PVAs, a docking system, along with a reverse turbo-Brayton cryocooler system for zero boil-off

LH$_2$ storage. The cryocooler system mass and power requirements increase with tank diameter and are sized to remove ~42 watts of heat penetrating the 60 layer MLI system while the stage is in LEO where the highest tank heat flux occurs. To remove this heat load, the 2-stage cryocooler system requires ~5.3 kW$_e$ for operation

The second major element is an "in-line" Al/Li propellant tank that connects the NTPS to the forward PL element. It has the same diameter and length LH$_2$ tank as that used in the NTPS and supplies an additional ~39.8 t of LH$_2$ propellant used during for the "2-perigee burn" TLI maneuver. The in-line tank element also includes forward and aft cylindrical adaptor sections that house quick connect/disconnect propellant feed lines, electrical connections, a RCS along with docking and payload adaptors. A ZBO cryocooler system is not used on the in-line LH$_2$ tank since it is drained during the TLI maneuver. The total length of the in-line element is ~20.7 m.

Reusable Lunar Cargo Delivery / Propellant Tanker Missions

Using the NTPS and in-line tank discussed above, the cargo transport can deliver an ~64.5 t fully integrated habitat lander with surface mobility to LLO then return to Earth for refueling and reuse. Three SLS-1B launches deliver the vehicle and payload elements to LEO where assembly occurs via autonomous R&D. The cargo transport then departs from LEO (C$_3$ ~ -1.678 km^2/s^2, ΔV_{TLI} ~3.214 km/s including a g-loss of ~117 m/s) and captures into a 300-km circular LLO (arrival C$_3$ ~1.151 km^2/s^2 and ΔV_{LOC} ~906 m/s including g-loss) approximately 72 hours later.

Once in orbit, the habitat lander separates from the cargo transport (shown in Fig. 14a) and descends to the surface, landing autonomously at a predetermined location on the Moon. The habitat lander uses LO$_2$/LH$_2$ chemical engines and is equipped with either wheels or articulated landing gear allowing movement in both the vertical and horizontal directions so the lander can either "drive or walk" short distances from the landing site. Assuming a LUNOX production plant and lander can be configured to fit within the SLS-1B PL shroud, the habitat lander can be replaced by a 36 t "wet" LLV stage capable of delivering ~28 t from LLO to the lunar surface. According to Fig. 7, a LUNOX plant mass of ~28 t corresponds to a production capacity of ~175 t/year assuming volcanic glass as feedstock. This mass includes the mining and processing equipment with a 30% margin but does not include any beneficiation hardware. The fission surface power system mass is also not included here because it is delivered and pre-deployed on an earlier mission. Without any attached PL, the cargo NLTV can also function as a propellant "tanker" delivering ~25.6 t of LH$_2$ to a LLO depot on each roundtrip mission.

After payload separation and a day in LLO, the cargo transport performs a trans-Earth injection (TEI) burn (C$_3$ ~ 0.945 km^2/s^2, ΔV_{TEI} ~857 m/s including g-loss) and returns to Earth 72 hours later. On final approach, it performs a braking burn (arrival C$_3$ ~ -1.755 km^2/s^2, ΔV_{EOC} ~366 m/s) and captures into a 24-hour EEO with a 500 km perigee x 71,136 km apogee. Post burn engine cool-down thrust is then used to assist in orbit lowering. Afterwards, an auxiliary tanker vehicle, operating from a LEO servicing node/propellant depot, rendezvouses and docks with the cargo vehicle and supplies it with the additional LH$_2$ propellant needed for final orbit lowering and rendezvous with the LEO transportation node where it is refurbished and resupplied before its next mission.

The cargo NLTV has an IMLEO of ~187.8 t consisting of the NTPS (~68.3 t), the in-line tank element (~52 t), and the habitat lander (~64.5 t) with its connecting structure (~3.0 t). The mission requires five primary burns by the SNRE engines that use ~74.8 t of LH$_2$ propellant. With ~49.5 klb$_f$ of total thrust and I$_{sp}$ ~900 s, the total engine burn time is ~50 minutes. For the propellant tanker mission, the IMLEO is ~121.2 t and the total engine burn time is ~34 minutes.

Reusable Crewed Lunar Landing Mission

On the crewed landing mission, the NLTV carries a forward mounted saddle truss that connects the payload elements to the transfer vehicle's in-line tank. The truss is open on its underside and its forward adaptor ring provides a docking interface between the *Orion* MPCV and the single stage LOX/LH$_2$ LDAV as shown in Fig. 14b. The LDAV carries a crew of 4 plus 5 t of surface payload stored in two "swing-down" pallets mounted on each side of the crew cab (shown in Fig. 15b).

Three SLS-1B launches are used to deliver the two NTR vehicle elements and the payload element to LEO for assembly via autonomous R&D. The payload element consists of the integrating saddle truss assembly (STA) plus the LDAV with its surface cargo containers. In addition to a front and rear docking capability, the STA's forward adaptor ring also carries twin PVAs and a RCS. Once assembled, the *Orion* MPCV and crew are launched and rendezvous with the NLTV positioning itself inside the STA and docking with the LDAV using the docking port and transfer tunnel mounted to the STA's forward adaptor ring (shown in Fig. 12a).

After the "2-perigee burn" TLI burn ($C_3 \sim -1.516$ km^2/s^2, $\Delta V_{TLI} \sim 3.214$ km/s including a g-loss of ~110 m/s), the crew begins its 3-day coast to the Moon. Although the crewed NLTV carries a significant amount of payload mass (the STA, MPCV, and "spent" LDAV) back from the Moon, it uses the same ~15.7 m long in-line tank to supply the required amount of LH$_2$ propellant needed for this reusable mission. After its 72-hour transit, the NLTV performs the lunar orbit capture (LOC) burn (arrival $C_3 \sim 1.217$ km^2/s^2 and $\Delta V_{LOC} \sim 913$ m/s including g-loss) inserting itself and its payload into LLO.
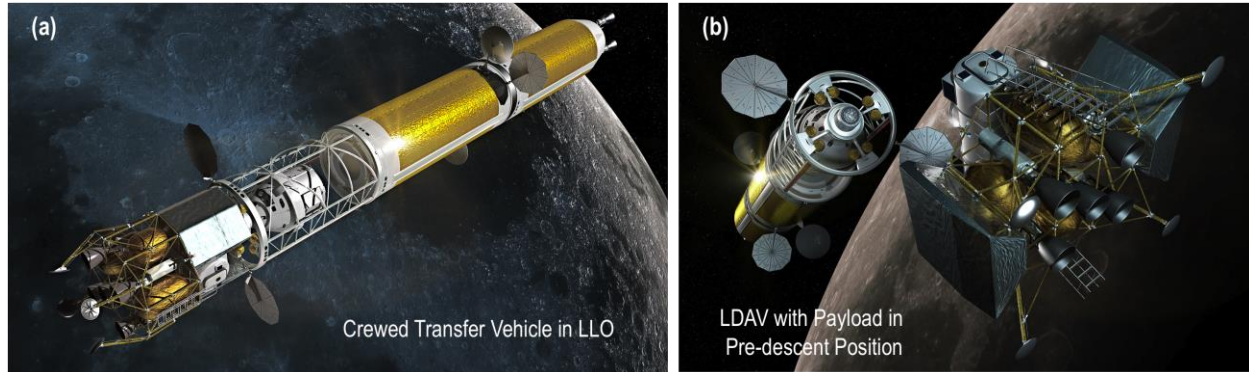

Figure 15.   Crewed Lunar Landing Mission: Transfer Vehicle Capture into LLO and LDAV Landing Preparation

Once in LLO, the crew enters the LDAV and separates from the transfer vehicle. After separation, the LDAV's two payload pallets are rotated 180 degrees and lowered into their landing position in preparation for descent to the lunar surface (Fig. 15b). The ΔV budget used in the Martin Marietta LDAV design [38] is $\Delta V_{des} \sim 2.115$ km/s and $\Delta V_{asc} \sim 1.985$ km/s. The LDAV uses five RL10A-4 engines operating with a $I_{sp} \sim 450$ s and ~13.5 t of LO$_2$/LH$_2$ propellant is expended during the descent to the surface.

After completing the surface mission, the crew returns to LLO in the LDAV carrying 100 kg of lunar samples. At liftoff, the LDAV mass is ~15.1 t and ~5.5 t of propellant is used during the ascent to LLO. The LDAV then rendezvous with the transfer vehicle and preparations for the TEI maneuver begin. After completing the departure burn ($C_3 \sim 0.949$ km^2/s^2, $\Delta V_{TEI} \sim 856$ m/s with g-loss), the crew spends the next 3 days in transit readying their vehicle for the final phase of the mission – capture into a 24-hr EEO (arrival $C_3 \sim -1.740$ km^2/s^2, $\Delta V_{EOC} \sim 367$ m/s). Afterwards, the crew re-enters and lands using the *Orion* capsule.

The crewed lunar landing mission has an IMLEO of ~176.6 t that includes the NTPS (~68.7 t), the in-line tank assembly (~51.8 t), the STA (~7.2 t), the wet LDAV (~29.5 t) with its surface payload (~5 t), the *Orion* MPCV (~13.5 t), consumables (~0.1 t), and 4 crewmembers (~0.8 t includes lunar EVA suits). At departure, the LH$_2$ propellant loading in the NTPS and the in-line tank are at their maximum capacity of ~39.8 t. The overall length of the crewed NLTV is ~74 m. Like the cargo mission, the crewed landing mission requires 5 primary burns by the NTPS using ~74.8 t of LH$_2$ propellant, and the total engine burn time is again ~50 minutes.

Impact of Using LUNOX to Refuel Surface-based LDAVs and In-Space NLTVs

Figure 16 shows the variation in NLTV size, IMLEO, increased mission capability and engine burn time resulting from the development and utilization of LLO$_2$. Figure 16a shows the reusable, crewed NLTV discussed above. It departs from LEO and captures into a 300-km equatorial LLO. At the end of the mission, the NLTV returns to Earth with the spent LLV and captures into a 24-hr EEO because it has a much lower ΔV requirement. In order to return to LEO, the NLTV would need an additional ~118 t of LH$_2$ propellant requiring the insertion of a star truss with four attached drop tanks between the vehicle's in-line tank and forward payload. The additional mass of the extra truss, propellant and tanks nearly doubles the vehicle's IMLEO to ~347.8 t!

The first significant step in LUNOX production occurs when lunar outpost assets and LLO$_2$ production levels become sufficient to support a lunar surface-based LDAV. By not having to transport a "wet" LDAV to LLO on each flight, the crewed NLTV now has a lower starting mass in LEO (~146 t) plus sufficient onboard propellant to allow a single burn departure from LEO and a return to a lower, higher energy ~3.25-hr EEO (407 km perigee x 9,050 km apogee with $\Delta V_{EOC} \sim 1793$ m/s including a g-loss of ~35 m/s) as shown in Figure 16b.

After entering orbit, a surface-based LDAV, operated autonomously from the LS during liftoff, R&Ds with the crewed NLTV to pick up the crew and cargo. The cargo, consisting of two 2.5 t PL pallets, is positioned at the front end of the saddle truss ring so that the pallets readily attach on both sides of the crew cab and can subsequently be lowered into the "saddlebag" position for descent shown in Fig. 15b. At lift off the LDAV carries up to 22.4 t of LO_2/LH_2 propellant. It uses ~13 t to achieve LLO and another 9 t returning to the LS after picking up the crew and cargo. Assuming an O/H MR of ~6, the LDAV uses ~3.2 t of LH_2 and ~19.2 t of LO_2 propellant during its roundtrip mission to LLO and back. Since a NTR tanker can deliver ~25.6 t of LH_2 propellant to a LLO depot in a single mission, it can provide sufficient LH_2 propellant for eight round trip LDAV missions provided the LUNOX facility has a production capacity of ~155 – 160 t/year.

As LUNOX production increases further and a propellant depot is established in LLO, it will be routinely supplied with LLO_2 transported from the LS by specialized tanker LLVs, and ELH_2 delivered by NTR tanker vehicles operating between LEO and LLO. At this point, the NLTV's SNREs are refitted with afterburner nozzles and LO_2 feed systems, and the large in-line LH_2 tank used in the two previous vehicles is replaced by a smaller LO_2 tank (shown in Figure 16c). The LO_2 tank, consisting of two $\sqrt{2}/2$ ellipsoidal domes, is ~5.37 m long and has a 7.6 m diameter that is compatible with the saddle truss diameter. The corresponding tank volume can hold ~163.5 t of LO_2 which is excessive for the landing mission under consideration here. By refueling with ~47 t of LLO_2 and using only ELH_2, a smaller crewed NLTV that is ~24 t lighter than the one shown in Fig. 16a and is also capable of returning to LEO is now possible – a significant advance in performance capability.

The LANTR engines used in this study are sized with the appropriate hardware mass (pumps, controls, lines, etc) for the maximum MR operation to allow the full range of O/H MRs from 0 to 5 to be accessible during the mission. Also, with the amount of LH_2 propellant in the NTPS fixed at ~39.8 t, the outbound and return MRs used by the LANTR engines are optimized to achieve the desired mission performance. Equally as important, the augmented thrust levels achieved during the mission decrease the total engine burn time – in this case cutting it in half.
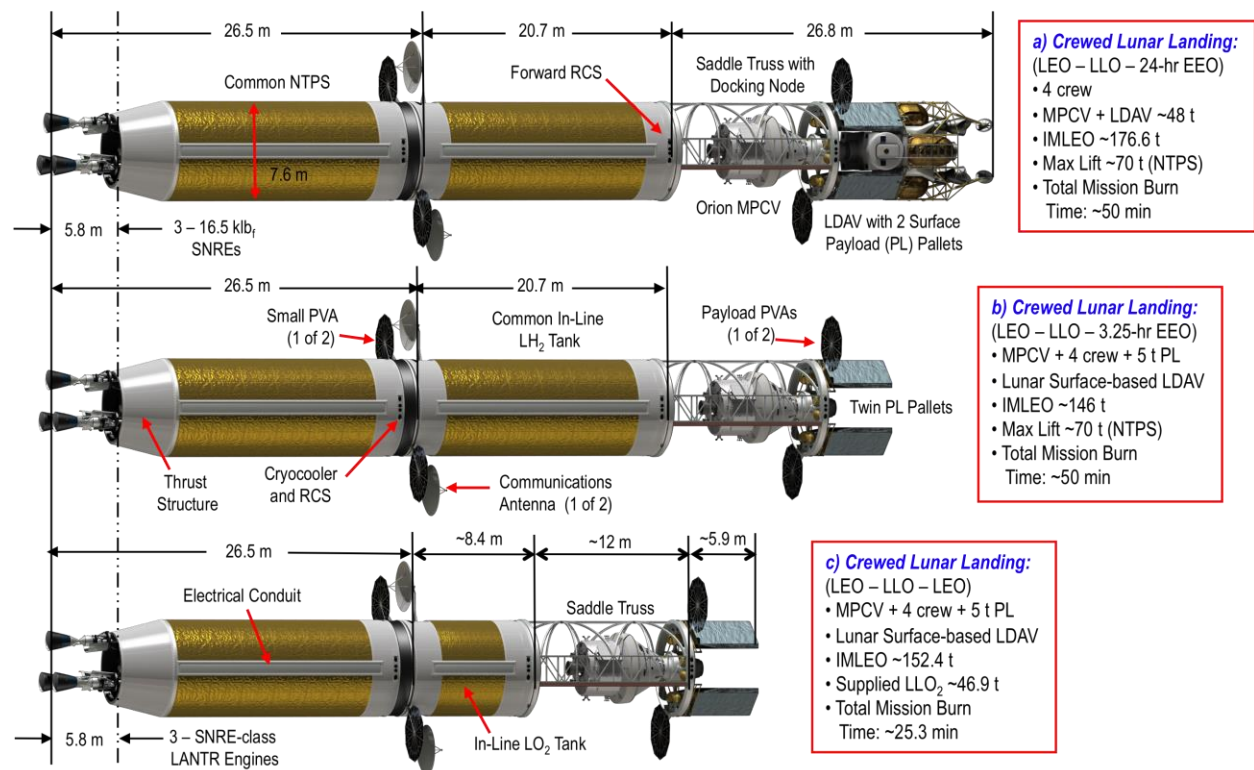

Figure 16. Variation in NLTV Size, IMLEO, Mission Capability and Engine Burn Time Resulting from the Development and Utilization of LLO_2 and the Transition to LANTR Operation

VI. Growth Mission Possibilities 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 (Fig. 17a) and LLO (Fig. 17b). Because abundant deposits of volcanic glass are located at sites just north of the lunar equator, we envision that a depot will be established in equatorial LLO initially and will be routinely supplied with LUNOX from tanker LLVs operating between LLO and the lunar surface. A transportation node/depot in LLO will also provide a convenient staging location where crewed cargo transports can drop off PL and NTR tankers can deliver ELH$_2$ that would then be picked up by LLVs for transport to the lunar surface.
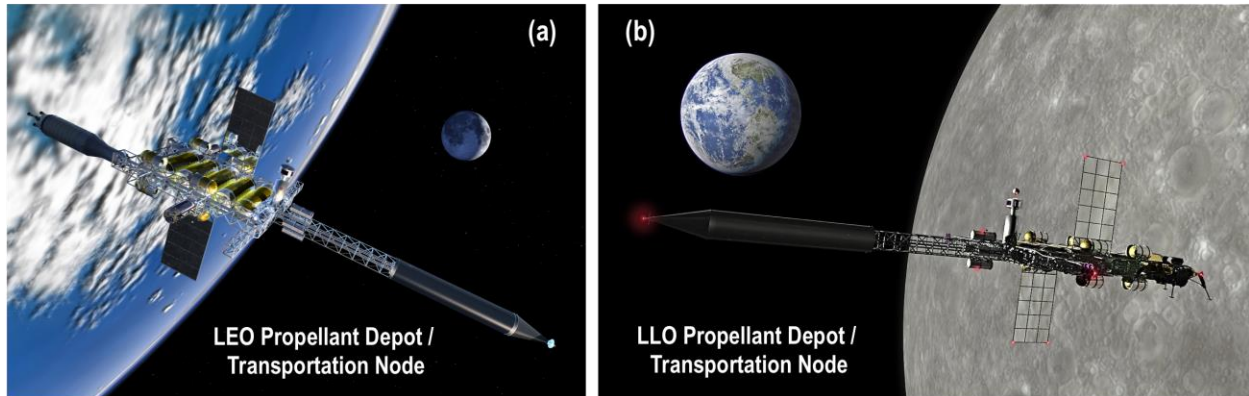

Figure 17.   Propellant Depots in LEO and LLO – Critical Elements for a Robust Lunar Transportation System

One-way transit times to and from the Moon on the order of ~72 hours would be the norm initially. Eventually, however, as lunar outposts grow into permanent settlements staffed by visiting scientists, engineers and administrative personnel representing both government and private ventures, more frequent flights of shorter duration could become commonplace. As shown in Fig. 18, 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). As a result, versatile LANTR engines with adequate supplies of LUNOX for refueling will be key to ensuring LTVs of reasonable size.
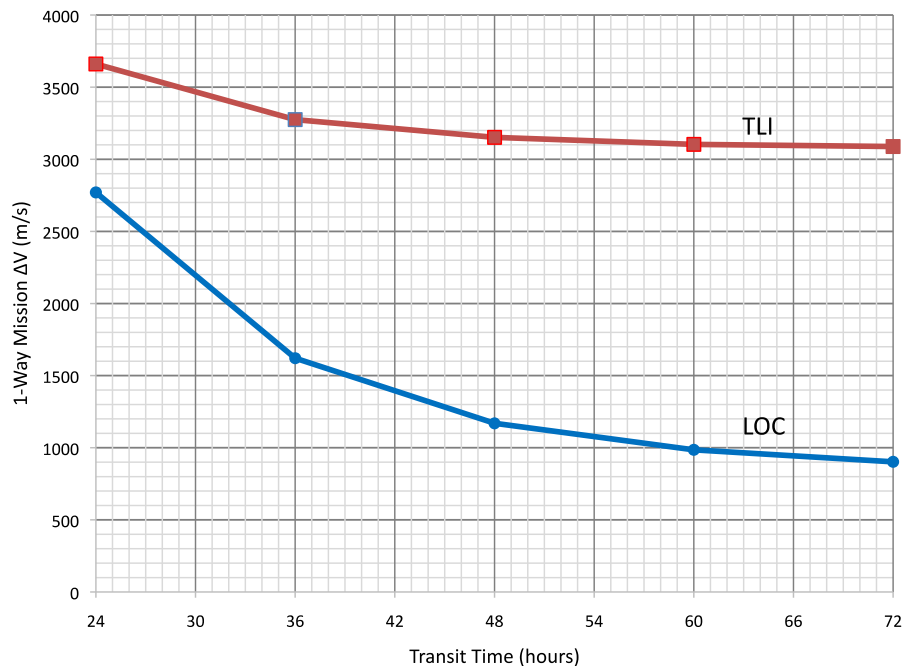

Figure 18. LEO-to-LLO ΔV Variation with Flight Time

VII. *Conestoga* - A Reusable, Space-based Crewed Cargo Transport

The original Conestoga wagon was a freight wagon developed in Lancaster County, Pennsylvania in the early 1700s [39] and used extensively in Pennsylvania and the nearby states of Maryland, Ohio and Virginia for more than 150 years. It was designed for hauling heavy loads – up to 6 tons – and had a distinctive bed that was curved upward at both ends to prevent the wagon's contents from shifting or falling out while traveling over rough roads. A white canvas cover protected the wagon's contents from inclement weather and a team of four to six strong horses pulled the wagon some 12 to 14 miles a day (shown in Fig. 19).

Figure 19. Conestoga Wagons, the "Ships of Inland Commerce," were used to Transport Settlers, Farm Produce, and Freight across Pennsylvania and Neighboring States (Image ca 1910) [40]

Named after its earlier ancestor, the *Conestoga* crewed cargo transport shown in Fig. 20 is a space-based, reusable LTV that uses LANTR propulsion and refuels with LUNOX propellant. *Conestoga* has its own dedicated habitat module that supports a crew of 4 and has a mass of ~10 t. Two crewmembers operate the vehicle and manage the unloading of the PL. The other 2 represent rotating crewmembers on assignment at the lunar base or the LLO transportation node / propellant depot. Connecting the habitat module to the rest of the LANTR LTV is a 4-sided star truss that has four PL pallets attached to it – each weighing up to ~2.5 t. To accommodate the wedge-shaped geometry of the cargo pallets, the sides of the star truss are concave – a feature similar to the upward curving ends of the Conestoga wagon's bed though not for the same design reason. Attached to the star truss' forward circular ring is a RMS with twin arms that are free to move around the ring's outer perimeter (Fig. 20). Using the habitat module's rear viewing window, the crew uses these manipulator arms to unload and attach the *Conestoga's* cargo to either the depot node or to a co-orbiting LDAV transferring crew and awaiting cargo delivery. Key features and dimensions of the *Conestoga* are shown in Fig. 21 and major mission activities are shown in Fig. 22.
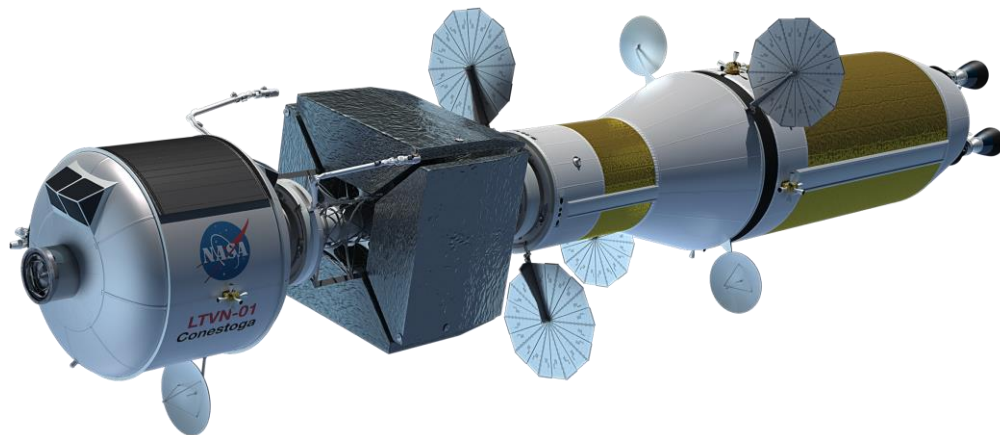

Figure 20. *Conestoga* - A Space-based Crewed Cargo Transport uses a Common NTPS and In-Line LO_2 Tank
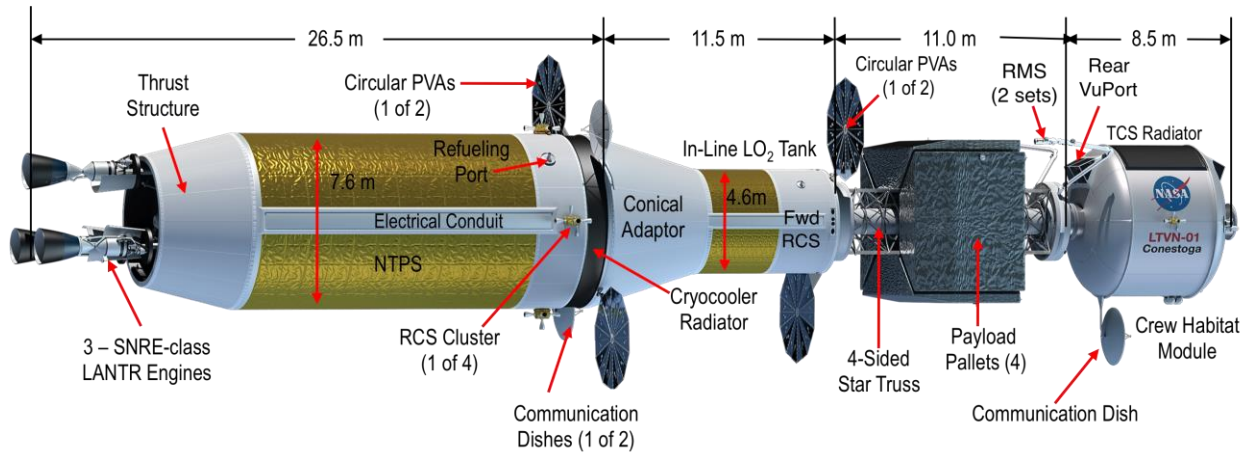
Figure 21. Key Features and Dimensions for the *Conestoga* Crewed Cargo Transport (CCT)

The *Conestoga* CCT is a versatile vehicle that can deliver varying amounts of cargo (from 10 to 40 t) to LLO depending on the transit times out and back. Once loaded with cargo at the LEO transportation node, the *Conestoga* leaves orbit for the Moon. After braking into LLO, the *Conestoga's* cargo is then unloaded and attached to the LDAV using the vehicle's RMS as shown in Fig. 22. The *Conestoga* can also be used as a tanker vehicle transferring close to 10 t of LH_2 from it NTPS to the depot. Outfitted with appropriate refueling appendages, *Conestoga* could also supply LH_2 propellant directly to the LDAV. Refueling ports and twin PVAs are located at the forward ends of the NTPS and in-line LO_2 tank assembly for refueling in LEO and LLO, and for powering the NTPS and forward PL element as shown in Fig. 21.

In this study, the *Conestoga's* NTPS is limited to a LEO launch mass of ~70 t which includes ~39.8 t of LH_2 contained in the NTPS's propellant tank. With this fixed value, the outbound and return MRs used by the LANTR engines are optimized to achieve the desired mission performance. A mission analysis and vehicle sizing code with optimization capability [41] is used to determine the customized LO_2 tank size and LUNOX refueling requirement for a particular mission application, or for a fixed LO_2 tank size to determine the maximum delivered payload and LUNOX refueling needed for a desired trip time. For a fixed LO_2 tank size and PL, the shortest trip time and LUNOX refueling needed can also be determined. A variety of other trades have also been conducted.
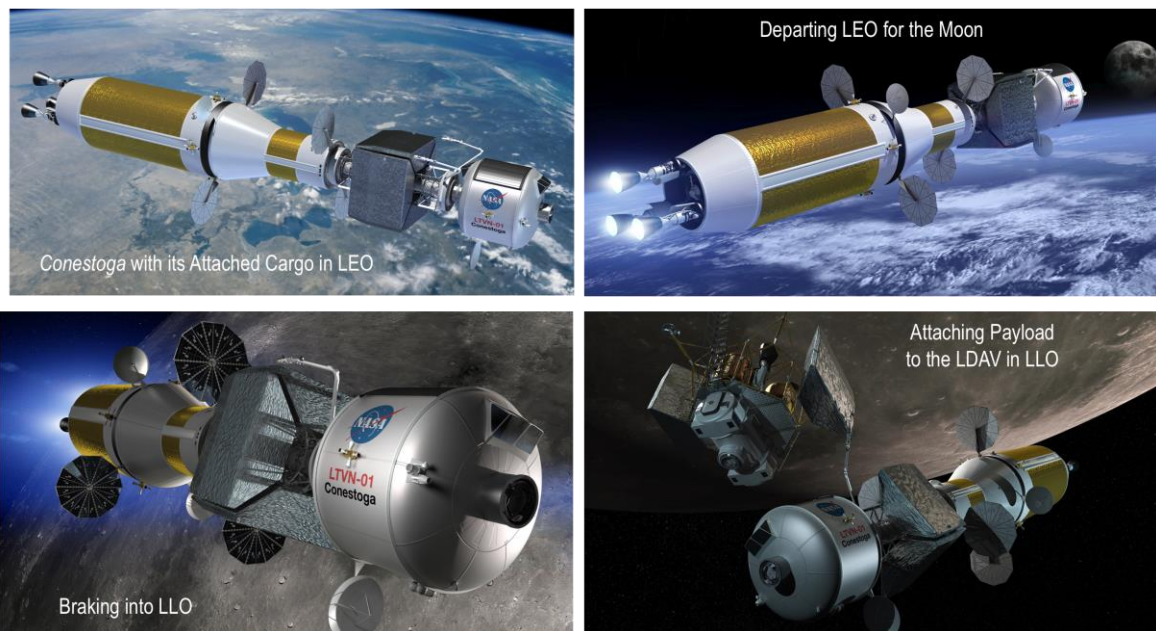

Figure 22. *Conestoga* Crewed Cargo Transport Mission - Outbound Leg and LLO Operations

Table 4. LANTR Crewed Cargo Missions, Trajectory and ΔV Budgets, and LUNOX Refueling Needs

Case Description *	Objective	Trajectory/Orbits **	In-line LO_2 Tank	Results
1. Crewed LANTR LTV with MPCV and 12 m saddle truss carrying 5 t cargo to LLO	Determine LLO_2 refueling needed to deliver 5 t cargo to LLO	72 hour 1-way transit times; LEO – LLO – LEO ΔV ~7.984 km/s	7.6 m OD x ~5.23 m L (~163.5 t LO_2)	IMLEO ~152.4 t; ~48.8 t LO_2 supplied in LEO; ~46.9 t LLO_2 refueling in LLO
2. LANTR Crewed Cargo Transport with 9.9 t hab module and 11 m star truss carrying 5 t cargo to LLO	Determine LLO_2 refueling needed to deliver 5 t cargo to LLO using alternative LTV configuration	72 hour 1-way transit times; LEO – LLO – LEO ΔV ~7.996 km/s	4.6 m OD x ~3.4 m L (~35.9 t LO_2)	IMLEO ~131.1 t; ~35.9 t LO_2 supplied in LEO; ~35.1 t LLO_2 refueling in LLO
3. LANTR Crewed Cargo Transport with 9.9 t hab module and 11 m star truss carrying 5 t cargo to LLO	Determine LLO_2 refueling needed to deliver 5 t cargo to LLO while also cutting transit times to 36 hrs	36 hour 1-way transit times; LEO – LLO – LEO ΔV ~9.838 km/s	4.6 m OD x ~6.1 m L (~81.2 t LO_2)	IMLEO ~177.4 t; ~81.2 t LO_2 supplied in LEO; ~71.6 t LLO_2 refueling in LLO
4. LANTR Crewed Cargo Transport with 9.9 t hab module and 11 m star truss carrying 10 t cargo to LLO	Determine LLO_2 refueling needed to deliver 10 t cargo to LLO while also cutting transit times to 36 hrs	36 hour 1-way transit times; LEO –- LLO – LEO ΔV ~9.920 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~214.3 t; ~111.2 t LO_2 supplied in LEO; ~74.9 t LLO_2 refueling in LLO
5. LANTR Crewed Cargo Transport with 9.9 t hab module and 11 m star truss carrying 10 t cargo to LLO	Determine LLO_2 refueling needed to deliver 10 t cargo and LH_2 propellant to LLO with transit times of 72 hrs	72 hour 1-way transit times; LEO – LLO – LEO ΔV ~8.038 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~194.1 t; ~90.8 t LO_2 supplied in LEO; ~9.62 t LH_2 to LLO depot; ~54 t LLO_2 refueling
6. LANTR Crewed Cargo Transport with 9.9 t hab module and two 11 m star trusses carrying 20 t cargo to LLO	Determine LLO_2 refueling needed to deliver 20 t of cargo to LLO with transit times of 72 hrs	72 hour 1-way transit times; LEO – LLO – LEO ΔV ~8.057 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~189.6 t; ~71.0 t LO_2 supplied in LEO; ~52.1 t LLO_2 refueling in LLO
7. LANTR Crewed Cargo Transport with 9.9 t hab module and two 11 m star trusses carrying 20 t cargo to LLO	Determine LLO_2 refueling needed to deliver 20 t of cargo to LLO in shortest transit time	~44.2 hour 1-way transit times; LEO – LLO – LEO ΔV ~9.017 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~230.0 t; ~111.2 t LO2 supplied in LEO; ~70.9 t LLO_2 refueling in LLO
8. LANTR Crewed Cargo Transport with 9.9 t hab module and two 11 m star trusses carrying 40 t cargo to LLO	Determine LLO_2 refueling needed to deliver 40 t of cargo to LLO with transit times of 72 hrs	72 hour 1-way transit times; LEO – LLO – LEO ΔV ~8.064 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~250.7 t; ~109.8 t LO2 supplied in LEO; ~60.3 t LLO_2 refueling in LLO

* Cases 1 – 8 use a "Common LH_2 NTPS" (7.6 m D x ~15.7 m L); Propellant depots assumed in LEO and LLO; LANTR engines use optimized MRs out and back
**LEO – 407 km, LLO – 300 km equatorial orbit; Total round trip mission ΔV values shown include g-losses

Table 4 provides a sampling of different crewed cargo missions, vehicle types and trip times that have been examined along with the associated LUNOX refueling requirements. All the cases shown use the same common 3-engine NTPS described previously in Sect. IV and shown in Figure 21. Case 1, the crewed lunar landing mission discussed in Sect. V and shown in Fig. 16c, carries the *Orion* MPCV and 5 t of cargo. It uses an oversized in-line LO_2 tank consisting of two 7.6 m diameter ellipsoidal domes and requires ~47 t of LUNOX for Earth return. Case 2 is a space-based crewed cargo transport (CCT) similar to *Conestoga*. It has its own dedicated habitat module weighing 9.9 t, plus a star truss that has two 2.5 t PL pallets attached to it. The LO_2 tank is smaller (~4.6 m outer diameter (OD) and ~3.4 m in length (L)) and is customized for this particular application resulting in a lower IMLEO (~131 t) and LUNOX refueling requirement (~35 t).

Case 3 shows the impact on CCT sizing of reducing the LEO-LLO transit time from 72 hours down to 36 hours. Cutting the transit time in half increases the total mission ΔV by ~23% and increases the IMLEO by ~46 t. Also, because the LH_2 propellant loading in the NTPS is fixed at ~39.8 t for these missions, the LANTR engines run at higher O/H MRs increasing the in-line LO_2 tank length to ~6.1 m and the LUNOX refueling requirement for Case 3 to ~71.6 t – more than double that needed for Case 2.

Case 4 not only cuts the "1-way" transit times to 36 hours but it also doubles the amount of cargo delivered to the LLO to 10 t. To meet these demanding mission objectives, the LANTR engines run "O_2-rich" on both the outbound mission leg (MR = 5, I_{sp} ~516 s for TLI; MR = 4.1, I_{sp} ~550 s for LOC) and return mission leg (MR = 5, I_{sp} ~516 s for both the TEI and EOC burns). *Case 4 is the defining mission used to establish the required performance and sizing for the Conestoga crewed cargo transport*. The LO_2 tank length increases to 7.95 m and it holds ~111.2 t of LO_2 just prior to mission start. This tank length is fixed for all subsequent *Conestoga-class* missions. After dropping off its cargo and picking up 250 kg of lunar samples, *Conestoga* refuels with ~74.9 t of LUNOX for the return trip home. For this mission, *Conestoga* has an IMLEO of ~214.3 t consisting of the NTPS (~71 t), the in-line LO_2 tank and conical adaptor (~117.2 t), the star truss assembly with its RMS (~5.3 t) and attached PL (10 t), the habitat module (9.9 t), consumables (~0.1 t) plus the 2 crew and 2 passengers with their EVA suits (~0.8 t). The total mission ΔV to go from LEO to LLO then back to LEO again is ~9.92 km/s including g-losses. With the augmented

thrust levels provided by the LANTR engines (~56.8 klb$_f$ per engine at MR = 5), the burn times for the individual maneuvers are ~11.5 min (TLI), ~3.8 min (LOC), ~4.4 min (TEI), and ~5.6 min (EOC) totaling to ~25.3 minutes.

This total burn time is essentially fixed by the available amount of LH$_2$ in the NTPS and the specified LH$_2$ flow rate for each engine of ~8.3 kg/s. What varies in the different cases presented in this paper is the amount of LO$_2$ supplied in LEO and LLO and the different MRs used by the LANTR engines to achieve the mission objectives.

Case 5 illustrates the mission flexibility with the *Conestoga* CCT and its LANTR engines. With its fixed size tanks able to carry ~39.8 t of LH$_2$ and up to ~111.2 t of LO$_2$, *Conestoga* can operate as both a cargo delivery and tanker vehicle. By increasing the LEO to LLO transit time back to 72 hours, and operating the LANTR engines O$_2$-rich both out and back (again at MR = 5 and I$_{sp}$ ~516 s), *Conestoga* can deliver 10 t of cargo and transfer ~9.62 t of LH$_2$ propellant from its NTPS to the LLO depot. For the return trip back to LEO, it refuels with ~54 t of LUNOX. The IMLEO required for this mission is ~194.1 t and the total mission ΔV is ~8.04 km/s. The burn times for the individual maneuvers are 9.9 min (TLI), ~1.9 min (LOC), ~2.1 min (TEI), and ~5.2 min (EOC) totaling to ~19.1 minutes. *By transferring ~9.6 t of LH$_2$ propellant from the NTPS during this mission, there is less available for the engines to use so the total mission burn time decreases and the LANTR engines operate at M = 5 to compensate.*

For the same 1-way transit time of 72 hours, Case 6 shows that a *Conestoga-class* vehicle can double the amount of cargo delivered to LLO from 10 to 20 t. Shown in Fig. 23, the *Conestoga-II* is a heavy crewed cargo transport that adds a second 11 m long star truss and RMS and four more 2.5 t PL pallets to the vehicle configuration. This addition results in an increase in the vehicle's overall length from ~57.5 to ~68.5 m. Departing from LEO, the *Conestoga-II's* LANTR engines operate for ~12.3 minutes at an O/H MR = 3.4 and I$_{sp}$ of ~573 s. During lunar orbit capture, the engines operate "fuel-rich" for ~4.4 minutes with a MR = 0.9 and the I$_{sp}$ at ~737 s. Once in orbit, the crew unloads the forward PL pallets first. This allows an unobstructed view of the rear PL section from the hab module's rear viewing port during the unloading process. After picking up samples, the *Conestoga-II's* LO$_2$ tank is refueled with ~52.1 t of LUNOX. On the return leg of the mission, the engines operate for ~2.2 minutes at MR = 4.7 and I$_{sp}$ ~527 s during the TEI maneuver. For EOC, the engines operate for ~6.4 minutes at MR = 3.8 and I$_{sp}$ ~558 s. The total mission ΔV is ~8.06 km/s, and the total burn time on the engines is ~25.3 minutes.

Even with 20 t of delivered PL, additional performance capability is still possible using the *Conestoga-II* vehicle. Since its LO$_2$ tank is only filled to ~64% of maximum capacity in Case 6, faster trip times are possible by taking advantage of the extra propellant capacity that exists within the vehicle design. By increasing the LO$_2$ loading to its maximum capacity of 111.2 t before TLI and increasing the LUNOX refueling to ~70.9 t before TEI, Case 7 shows that faster 1-way transit times – on the order ~44.2 hours – are possible even when carrying 20 t of cargo. For this mission, the LANTR engines operate at MR ~4.9, I$_{sp}$ ~519 s for TLI and MR ~3.5, I$_{sp}$ ~568 s for LOC. On the return
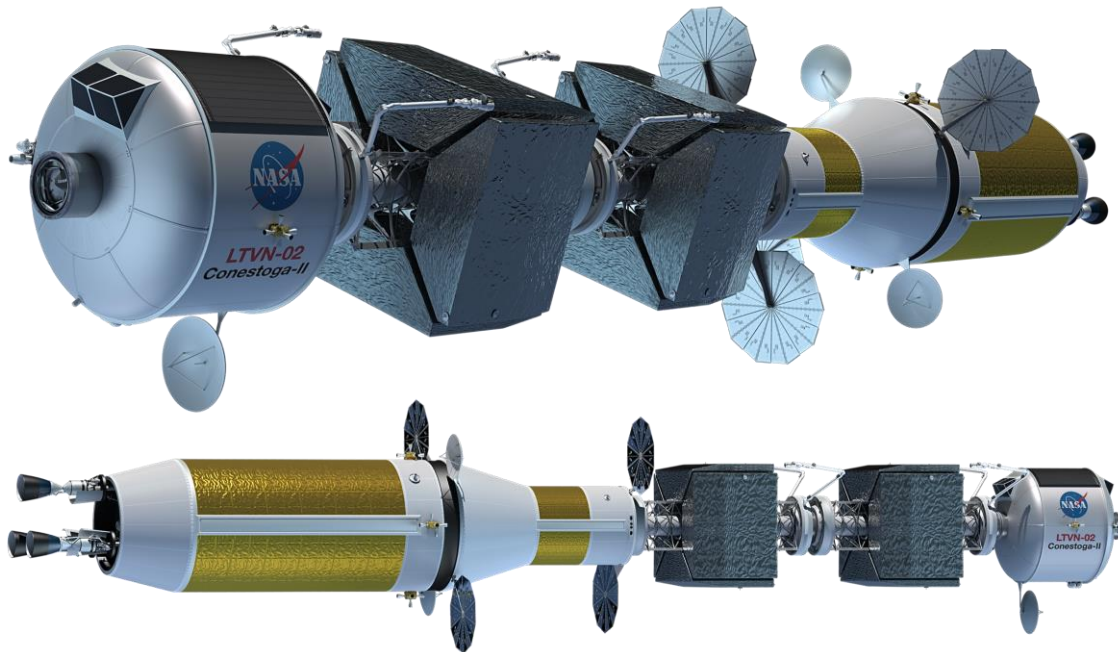

Figure 23.   *Conestoga-II* Heavy Crewed Cargo Transport Isometric and Elevation

leg, the engines operate at MR = 5, I_{sp} ~516 s for both the TEI and EOC burns. The IMLEO for the *Conestoga-II's* fast 20 t cargo delivery mission is ~230 t, the total mission ΔV is ~9.02 km/s, and the total mission burn time is again ~25.3 minutes. The burn times for the individual maneuvers are ~12.2 min (TLI), ~3.6 min (LOC), ~3.6 min (TEI), and ~5.9 min (EOC).

Case 8 pushes the *Conestoga-II's* cargo delivery capability to its limit for the amount of LH_2 and LO_2 propellant available in the NTPS and in-line LO_2 tank. Assuming 72-hour transit times, this limit is ~40 t (eight 5 t PL pallets). For this mission, the LO_2 loading at LEO departure is ~109.8 t (~98.5% of the tank's maximum capacity) and the LANTR engines are operated at MR ~4.4, I_{sp} ~536 s for TLI and MR ~3.3, I_{sp} ~578 s for LOC. On the return leg, the *Conestoga-II* is refueled with ~60.3 t of LUNOX and its engines are operated at MR = 5, I_{sp} ~536 s for TEI and MR ~4.8, I_{sp} ~522 s for LOC. These MR conditions were selected by the optimizer to deliver the specified PL while also minimizing the total LO_2 requirement for the mission. The IMLEO for Case 8 is ~250.7 t and the total mission ΔV is ~8.06 km/s. The total mission burn time of ~25.3 minutes includes the following individual burn times: ~13.8 min (TLI), ~3.2 min (LOC), ~2.3 min (TEI), and ~6 min (EOC).

The *Conestoga-class* CCTs shown departing LEO for the Moon in Fig. 24 can provide the basis for a robust and flexible LTS that offers a wide range of cargo delivery capability and transit times made possible through the use of LANTR propulsion and supplies of LUNOX provided in LLO. Today, "time is money" for the long distance freight haulers traveling our highways, oceans and skies. In the future, *Conestoga-class* vehicles could play the same important role in establishing cislunar trade and commerce as the Conestoga wagons of old did for more than a century throughout Pennsylvania and its neighboring states.

Figure 24. *Conestoga-class* Crewed Cargo Transports Departing LEO for the Moon

VIII. Commuter Shuttle and Priority Cargo Delivery

In the movie *2001: A Space Odyssey*, released by MGM in 1968 [42], Dr. Heywood Floyd departs from a huge artificial gravity space station orbiting Earth bound for the Moon. He arrives there 24 hours later [43] aboard a large spherical-shaped LTV called *Ares* which touches down on a landing pad that subsequently descends to a large sprawling lunar settlement located underground. Today, almost 50 years later, the images portrayed in Stanley Kubrick and Arthur C. Clarke's film remain well beyond our capabilities and *2100: A Space Odyssey* seems a more appropriate title for the movie. In this section, we evaluate the feasibility and requirements for commuter flights and priority cargo delivery using LANTR propulsion and LUNOX propellant to see if the operational capabilities presented in *2001* can be achieved albeit on a more "Spartan" scale.

A 24-hour commuter flight to the Moon is a daunting challenge. This is about the time it now takes to fly from Washington, D. C. to Melbourne, Australia with a 3-hour layover in San Francisco. As Fig. 18 shows, decreasing the LEO-to-LLO transit time from 72 to 24 hours increases the outbound ΔV requirement from ~4 to 6.4 km/s and the total roundtrip ΔV requirement by ~4.8 km/s! Increasing the flight time to 36 hours each way decreases this additional ΔV requirement by 37.5% – to ~1.8 km/s. Also, at these higher velocities, free return trajectories are no longer available so multiple engines will be required to improve reliability and increase passenger safety.

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) shown in Fig. 25a. 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 (Fig. 25b), the PTM docks with the fully fueled LANTR shuttle awaiting it a safe distance away (shown in Fig. 26a). At the
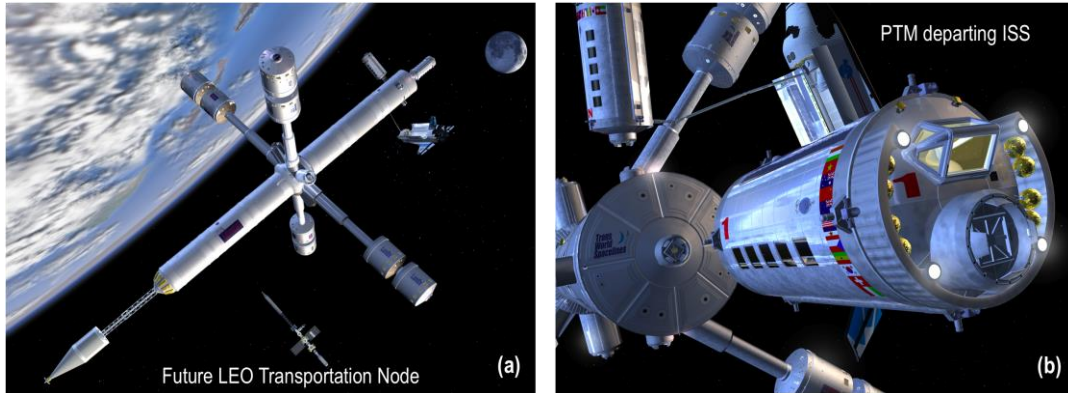

Figure 25. Future Commercial ISS Provides the Transportation Hub for PTMs Arriving and Departing from LEO

appropriate moment, the LANTR engines are powered up and the shuttle climbs rapidly away from Earth (Fig. 26b). For a 36-hour flight to the Moon, the acceleration experienced by the passengers during Earth departure will range from ~0.4 g_E to ~0.8 g_E near the end of the TLI burn.

Following the 36-hour transfer, the LANTR shuttle arrives in LLO where the PTM detaches and docks with a waiting "Sikorsky-style" LLV. A commercial propellant depot (shown in Fig. 17b) provides a convenient staging node for LLO operations supplying the LANTR shuttle with LUNOX for Earth return and the LLV with Earth-supplied LH_2 needed to deliver the PTM to the lunar surface. From here the PTM is lowered to a "flat-bed" surface vehicle (shown in Fig. 26c) and electronically engaged providing the PTM with surface mobility. The PTM then drives itself to the lunar base airlock for docking and passenger unloading (shown in the lower right corner of Fig.8).
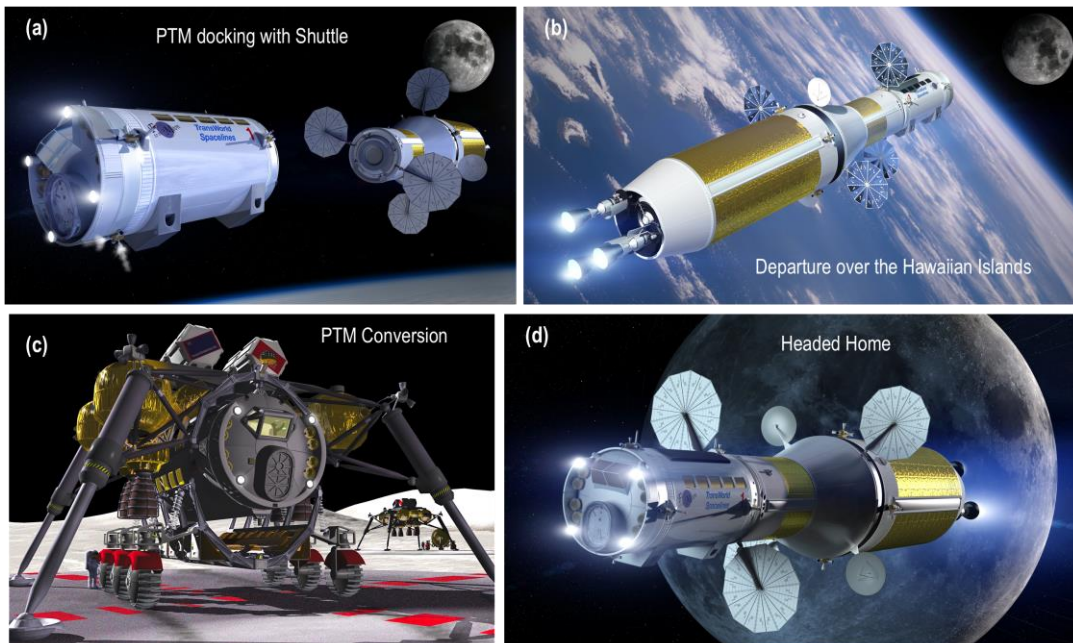

Figure 26. Various Phases of LANTR Commuter Shuttle Mission to the Moon

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This scenario is reversed on the return trip to Earth (Fig. 26d). At the end of the flight, the passengers will also experience a bit of excitement as peak acceleration levels can reach ~1.4 g_E at the end of the LEO capture burn.

The commercial commuter shuttle we envision utilizes the same NTPS, LANTR engines, and in-line LO_2 tank assembly used on the *Conestoga* CCT shown in Fig. 21. For the commuter shuttle application, the CCT's habitat module, star truss and PL pallets are removed and replaced with a 20-person PTM (shown in Fig. 27). The fully loaded PTM has an estimated mass of ~15 t and its diameter and length are ~4.6 m by ~8 m, respectively.
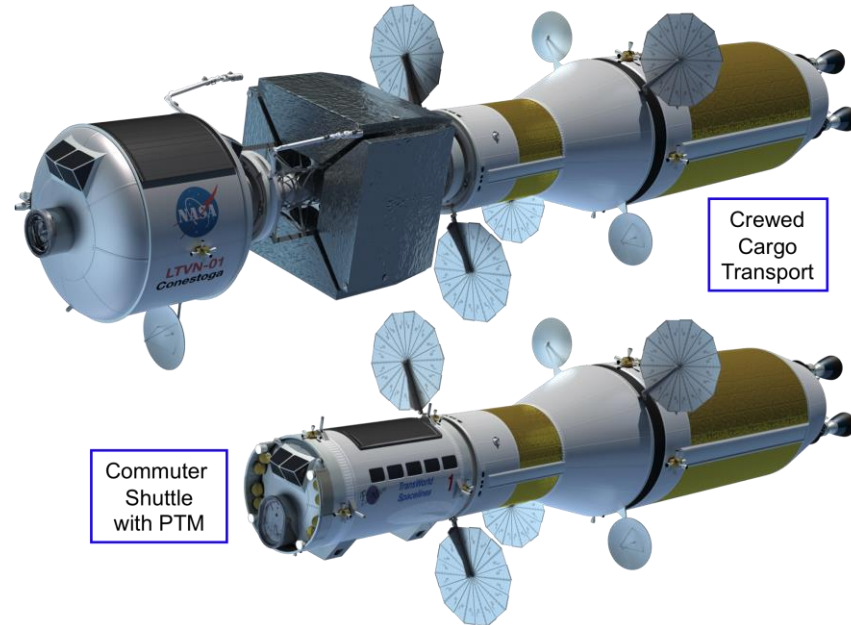

Figure 27. Relative Size of a CCT and Commuter Shuttle using a Common NTPS and In-Line LO_2 Tank Assembly

Table 5 provides a sampling of the different LANTR shuttle missions considered in this study. These missions looked at trip times ranging from 36 to 24 hours along with the associated LUNOX refueling requirements needed to achieve these transit times. Cases 1 through 5 use the same NTPS and clustered LANTR engines used on the *Conestoga-class* vehicles shown in Fig. 24. Case 1 assumes a 36-hour transit time and uses a customized LO_2 tank to determine the minimum IMLEO needed for this mission which is ~160.6 t. The amount of LO_2 supplied in LEO and LUNOX in LLO are approximately the same at ~69.3 t and 67.9 t, respectively.

Cases 2 through 4 also assume 36-hour transit times but use the fixed 7.95 m long in-line LO_2 tank baselined on *Conestoga* and shown in Fig. 27. For these cases the code optimization feature is used to minimize the requirements on the following: LUNOX refueling (Case 2); LEO LO_2 refueling (Case 3); and total mission LO_2 and LUNOX refueling (Case 4). In Case 2, the in-line LO_2 tank is filled to its maximum capacity of ~111.2 t in LEO and the LANTR engines run O_2-rich (MR = 5) on the outbound mission leg. This minimizes the LH_2 consumption so the shuttle's engines can operate at lower O/H MRs on the return leg thereby lowering the amount of LUNOX refueling required for the mission to ~55.7 t. The IMLEO for this shuttle option is the largest however at ~203.5 t and the launch costs to deliver ~40 t of LH_2 and ~112 t of LO_2 to the LEO depot will be a discriminator against this option.

Case 3 minimizes the LEO LO_2 resupply to the shuttle to just over 76 t which lowers the mission IMLEO to ~168.2 t and includes the NTPS (~71 t), the in-line LO_2 tank assembly and conical adaptor (~82.2 t), and the PTM (15 t). The engines operate at lower MRs on the outbound leg (~3.9 for TLI and ~1.7 for LOC) requiring more LH_2 to be consumed. On the return leg, the shuttle's engines operate O_2-rich (MR ~5 for TEI and ~4.9 for EOC) so the LUNOX refueling requirement is increased to ~72.8 t. The total mission ΔV is ~9.914 km/s and the total engine burn time is ~25.3 minutes which includes the following individual burn times: ~10.5 min (TLI), ~5.0 min (LOC), ~4.3 min (TEI), and ~5.5 min (EOC).

Case 4 minimizes the total amount of LEO LO_2 and LUNOX used in the mission but the savings is only ~1.1 t while the mission IMLEO actually increases by ~1.5 t. Based on these results, *Case 3 would be the preferred 36-hour commuter shuttle option using our fixed, common size tanks.*

Table 5. LANTR Commuter Shuttle Mission Options, ΔV Budgets, and LUNOX Refueling Needs

Case Description *	Objective	Trajectory/Orbits **	In-line LO$_2$ Tank	Results
1. LANTR commuter shuttle carrying 15 t Passenger Transport Module (PTM) to LLO then back to LEO	Determine LLO$_2$ refueling needed to deliver the PTM to and from LLO with transit times of 36 hrs	36 hour 1-way transit times; LEO – LLO – LEO ΔV ~9.835 km/s	4.6 m OD x ~5.4 m L (~69.3 t LO$_2$)	IMLEO ~160.6 t; ~69.3 t LO$_2$ supplied in LEO; ~67.9 t LLO$_2$ refueling in LLO
2. LANTR commuter shuttle carrying 15 t PTM to LLO then back to LEO	Minimize LLO$_2$ refueling needed to deliver the 15 t PTM to and from LLO with transit times of 36 hrs	36 hour 1-way transit times; LEO – LLO – LEO ΔV ~9.924 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO$_2$)	IMLEO ~203.5 t; ~111.2 t LO$_2$ supplied in LEO; ~55.7 t LLO$_2$ refueling in LLO
3. LANTR commuter shuttle carrying 15 t PTM to LLO then back to LEO	Minimize LEO LO$_2$ fueling needed to deliver 15 t PTM to and from LLO with transit times of 36 hrs	36 hour 1-way transit times; LEO – LLO – LEO ΔV ~9.914 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO$_2$)	IMLEO ~168.2 t; ~76.1 t LO$_2$ supplied in LEO; ~72.8 t LLO$_2$ refueling in LLO
4. LANTR commuter shuttle carrying 15 t PTM to LLO then back to LEO	Minimize total mission LO$_2$ needed to deliver 15 t PTM to and from LLO with transit times of 36 hrs	36 hour 1-way transit times; LEO --- LLO – LEO ΔV ~9.913 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO$_2$)	IMLEO ~169.7 t; ~77.6 t LO$_2$ supplied in LEO; ~70.2 t LLO$_2$ refueling in LLO
5. LANTR commuter shuttle carrying 15 t PTM to LLO then back to LEO	Determine LLO$_2$ refueling needed to deliver the PTM to and from LLO with shortest transit times possible	32.8 hour 1-way transit times; LEO – LLO – LEO ΔV ~10.481 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO$_2$)	IMLEO ~203.3 t; ~111.1 t LO$_2$ supplied in LEO; ~80.4 t LLO$_2$ refueling in LLO
6. Commuter shuttle with 2 LANTR engines and carrying 15 t PTM to LLO then back to LEO	Determine LLO$_2$ refueling needed to deliver the PTM to and from LLO with shortest transit times possible	30.3 hour 1-way transit times; LEO – LLO – LEO ΔV ~11.107 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO$_2$)	IMLEO ~197.7 t; ~111.2 t LO$_2$ supplied in LEO; ~79.0 t LLO$_2$ refueling in LLO
7. Commuter shuttle with 2 LANTR engines and carrying 15 t PTM to LLO then back to LEO	Determine LLO$_2$ and LLH$_2$ refueling needed to deliver the PTM to and from LLO with transit times of 24 hrs	24 hour 1-way transit times; LEO – LLO – LEO ΔV ~13.136 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO$_2$)	IMLEO ~198.0 t; ~111.2 t LO$_2$ supplied in LEO; ~105.7 t LLO$_2$ refueling in LLO; ~12.2 t ELH$_2$ refueling in LLO

* Cases 1 – 7 use a "Common LH$_2$ NTPS" (7.6 m D x ~15.7 m L); Propellant depots assumed in LEO and LLO; LANTR engines use optimized MRs out and back
**LEO – 407 km, LLO – 300 km equatorial orbit; Total round trip mission ΔV values shown include g-losses

Case 5 focuses on achieving the fastest transit times possible by taking full advantage of the extra propellant capacity that exists in the vehicle's in-line LO$_2$ tank. By increasing the commuter shuttle's LO$_2$ loading to its maximum capacity of ~111.2 t before TLI, refueling with ~80.4 t of LUNOX before TEI, and operating the LANTR engines O$_2$-rich (MR = 5) out and back, the shuttle can decrease its 1-way transit time from 36 to 32.8 hours. The additional LO$_2$ loading prior to TLI increases the required IMLEO to ~203.3 t which includes the NTPS (~71 t), the in-line LO$_2$ tank assembly and adaptor section (~117.3 t), and the PTM (15 t). The decreased transit time increases the total mission ΔV by ~0.567 km/s to ~10.5 km/s. The total mission burn time is ~25.3 minutes and the individual burn times are ~11 min (TLI), ~3.5 min (LOC), ~5.1 min (TEI), and ~5.7 min (EOC).

Case 6 is similar to 5 with the exception that it uses only two LANTR engines thereby decreasing the dry mass of the NTPS by ~5.5 t – the mass of the engine, its external radiation shield and thrust vector control system. By reducing the NTPS mass, the shuttle's transit times can be shortened even further – down to ~30.3 hours. For this case, the shuttle is resupplied with ~111.2 t of LO$_2$ before TLI, refuels with ~79 t of LUNOX before TEI, and its engines operate O$_2$-rich out and back. The IMLEO for this case is ~197.8 t which includes the NTPS (~65.5 t), the in-line LO$_2$ tank assembly and adaptor section (~117.3 t), and the PTM (15 t). The decreased transit time increases the total mission ΔV by an additional ~0.626 km/s to ~11.1 km/s including the increased g-losses from using only two engines. *With the available LH$_2$ and one less engine, the maximum mission burn time increases to ~37.9 minutes* with individual burn durations of ~16.5 min (TLI), ~5.6 min (LOC), ~8 min (TEI), and ~7.8 min (EOC).

Case 7 is similar to 6 except that it uses some of the ELH$_2$ delivered to the LLO depot by NTR tankers to "top off" the shuttle's LH$_2$ tank before returning to Earth. By resupplying the shuttle with ~111.2 t of LO$_2$ before TLI, refueling it with ~105.7 t of LO$_2$ and ~12.2 t of LH$_2$ before TEI, and operating O$_2$-rich on the way back to Earth, the 24-hour trip to the Moon taken by Dr. Floyd in *2001* becomes a possibility. The IMLEO for this case is ~198 t including the NTPS (~65.5 t), the in-line LO$_2$ tank assembly and adaptor section (~117.4 t), and the PTM (15 t). The total ΔV required for this rapid shuttle capability to the Moon is ~13.1 km/s including g-losses. *With additional LH$_2$ supplied to the NTPS and only two engines, the maximum mission burn time is now ~49.7 minutes* with burn times of ~18.2 min (TLI), ~10.3 min (LOC), ~12.5 min (TEI), and ~8.7 min (EOC). Although faster, Case 7 has a number of negative features when compared to Case 3: (1) it is heavier; (2) requires more LUNOX refueling; (3) has a larger total ΔV; and (4) total burn time requirement; and (5) has a less robust "engine-out" capability with only 2 engines.

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

In addition to a commercial shuttle service for passengers, it is also likely that similar services will be developed for delivering high priority cargo. Today, on their website for international shipping [44], UPS advertizes that they "...ship more packages to more places than any other carrier." They go on to say that "whether you're shipping packages or pallets, importing or exporting, our extensive transportation and logistics network can get your shipments where they need to be, when they need to be there." Similarly, with a membership in Amazon Prime [45], the company promises free two-day shipping on your purchases.

In this section, we examine the performance impact of alternating outbound and return deliveries of a PTM and priority cargo shipment on the same shuttle flight. The shipping container we envision has a gross mass of ~7.5 t and carries ~5 t of cargo within its pressurized volume. The container is scaled from the Cygnus spacecraft, developed by Orbital ATK. Cygnus is an automated cargo vehicle [46] designed to transport supplies to the International Space Station. It has a dry mass of ~5 t and can carry up to 3.5 t of cargo in its pressurized cargo module. An attached service module, provides auxiliary propulsion and up to 4 kW_e of electrical power using two PVAs [46].

The Priority Cargo Container (PCC) used in this analysis draws its electrical power from the twin PVAs located at the front end of the shuttle's in-line LO_2 tank assembly (shown in Fig. 28). We also assume it has the same outer mold line as the PTM. An example of this alternating payload delivery scenario is shown in Fig. 29 which depicts a Next Day Delivery (NDD) priority cargo flight departing LEO on its way to the Moon. After it arrives, the PCC detaches and docks with the Sikorsky-style LLV for delivery to the lunar surface in the same manner as the PTM. The shuttle's in-line LO_2 tank would then be refueled at the LLO depot in preparation for an arriving PTM from the surface and its return trip to Earth. On the next flight, a PTM would depart LEO for the Moon and the PCC would be returned.
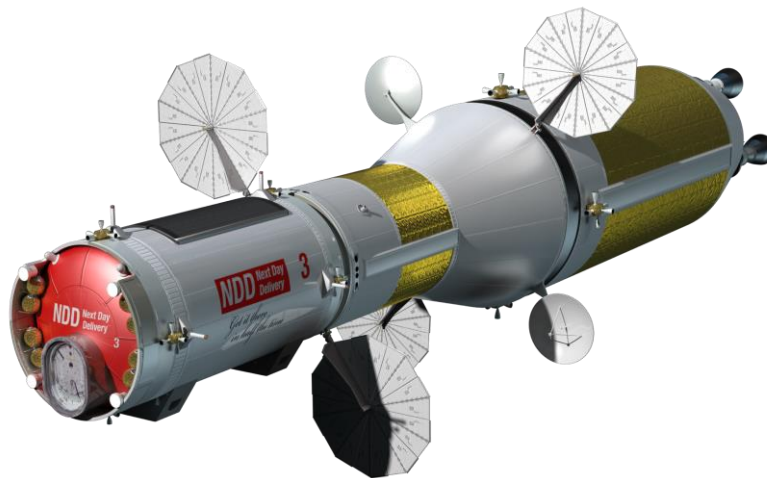

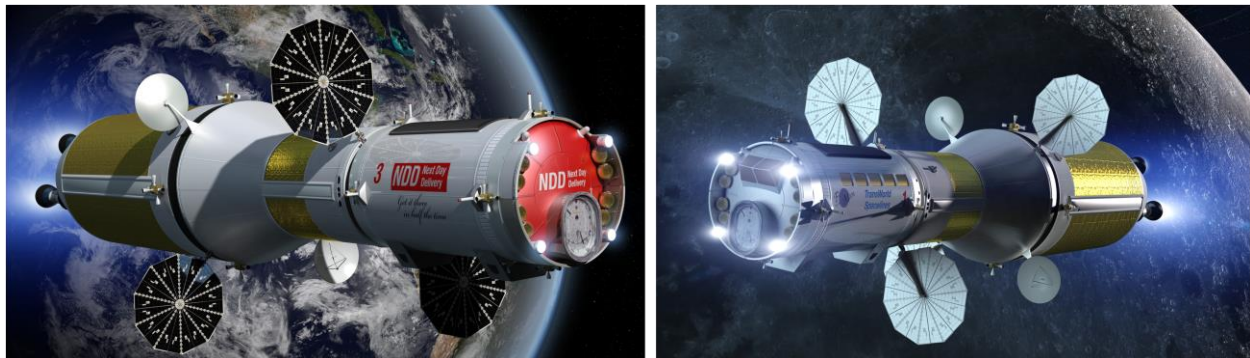Figure 28. Priority Cargo Delivery Vehicle using LANTR Shuttle System

Figure 29. Alternating PCC and PTM Payloads to the Moon and Back on the same Shuttle Flight

Table 6. Alternating PTM–PCC Mission Options, Trip Times Possibilities, and LUNOX Refueling Needs

Case Description *	Objective	Trajectory/Orbits **	In-line LO_2 Tank	Results
1. Alternating PTM out to LLO followed by priority cargo delivery back to LEO using 3 LANTR engine NTPS	Determine LLO_2 refueling needed to deliver 15 t PTM to LLO then 7.5 t priority cargo back to LEO	LEO – LLO transit time: 36 hrs LLO – LEO transit time: 36 hrs ΔV ~9.910 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~157.6 t; ~66.0 t LO_2 supplied in LEO; ~55.1 t LLO_2 refueling in LLO
2. Alternating priority cargo delivery to LLO followed by PTM back to LEO using 3 LANTR engine NTPS	Determine LLO_2 refueling needed to deliver 7.5 t priority cargo out to LLO then 15 t PTM back to LEO	LEO – LLO transit time: 36 hrs LLO – LEO transit time: 36 hrs ΔV ~9.909 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~146.5 t; ~62.2 t LO_2 supplied in LEO; ~64.8 t LLO_2 refueling in LLO
3. Alternating PTM out to LLO followed by priority cargo delivery back to LEO using 2 LANTR engine NTPS	Determine LLO_2 refueling needed to deliver 15 t PTM to LLO then 7.5 t priority cargo back to LEO	LEO – LLO transit time: 24 hrs LLO – LEO transit time: 48 hrs ΔV ~10.959 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~191.2 t; ~105.3 t LO_2 supplied in LEO; ~44.7 t LLO_2 refueling in LLO
4. Alternating priority cargo delivery to LLO followed by PTM back to LEO using 2 LANTR engine NTPS	Determine LLO_2 refueling needed to deliver 7.5 t priority cargo out to LLO then 15 t PTM back to LEO	LEO – LLO transit time: 48 hrs LLO – LEO transit time: 24 hrs ΔV ~10.951 km/s	4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~144.7 t; ~65.9 t LO_2 supplied in LEO; ~93.2 t LLO_2 refueling in LLO

* Cases 1 – 4 use a "Common LH_2 NTPS" (7.6 m D x ~15.7 m L); Propellant depots assumed in LEO and LLO; LANTR engines use optimized MRs out and back
**LEO – 407 km, LLO – 300 km equatorial orbit; Total round trip mission ΔV values shown include g-losses

Table 6 provides a sampling of two different sets of alternating PTM–PCC mission options considered in this study. In the first set of PTM–PCC delivery missions (Cases 1 and 2), the 3-engine NTPS and fixed length in-line LO_2 tank are used and the transit times out and back are 36 hours. In Case 1, the PTM is delivered on the outbound leg followed by the PCC on the return leg. Approximately 66 t of LEO LO_2 is supplied to the shuttle prior to TLI and it is refueled in LLO with ~55.1 t of LUNOX prior to TEI. The IMLEO for this mission is ~157.6 t consisting of the NTPS (~70.8 t), the in-line LO_2 assembly and adaptor section (~71.8 t) and the PTM (15 t). The total mission ΔV is ~9.910 km/s and the total engine burn time is again ~25.3 minutes for the 3-engine NTPS and its available LH_2 propellant loading.

In Case 2, the mission scenario is reversed with the PCC being delivered on the outbound leg followed by the PTM on the return leg. The shuttle is supplied with ~62.2 t of LEO LO_2 prior to TLI and is refueled with ~64.8 t of LUNOX prior to TEI. The IMLEO for this mission is ~146.5 t consisting of the NTPS (~70.9 t), the in-line LO_2 assembly and adaptor section (~68.1 t) and the PCC (7.5 t). The total mission ΔV and engine burn time are nearly identical to Case 1 at ~9.909 km/s and ~25.3 minutes. The slightly lower total ΔV for Case 2 is attributed to the PCC's smaller mass resulting in lower g-losses during the TLI burn.

In the second set of PTM–PCC delivery missions (Cases 3 and 4), we continue using the same in-line LO_2 tank but the NTPS now uses only 2 LANTR engines. We also set the transit times for PTM delivery at 24 hours and for the PCC delivery at 48 hours. Like Case 1, Case 3 delivers the PTM on the outbound leg followed by the PCC on the return leg. Because of the faster transit time used on the PTM mission leg, ~105.3 t of LO_2 must be supplied to the shuttle prior to TLI. Similarly, the LUNOX refueling requirement needed is reduced to ~44.7 t because of the PCC's smaller mass and extended transit time for the return to Earth. The IMLEO for this mission is ~191.2 t which includes the NTPS (~65.2 t), the in-line LO_2 assembly and adaptor section (~110 t) and the PTM (15 t). The total mission ΔV is ~10.959 km/s and the total engine burn time increases to ~37.8 minutes. The burn times for the individual maneuvers are ~17.9 min (TLI), ~10.8 min (LOC), ~3.2 min (TEI), and ~5.9 min (EOC).

In Case 4, the mission scenario is again reversed with the PCC being delivered on the outbound leg followed by the PTM on the return leg. The amount of LEO LO_2 now supplied to the shuttle is reduced by ~63% to ~65.9 t. Similarly, the LUNOX refueling required to return the heavier PTM back to Earth in 24 hours more than doubles to ~93.2 t. The IMLEO for this mission is ~144.7 t consisting of the NTPS (~65.4 t), the in-line LO_2 assembly and adaptor section (~71.8 t) and the PCC (7.5 t). Again, the total mission ΔV and engine burn time are nearly identical to Case 3 at ~10.951 km/s and ~37.9 minutes. However, in Case 4, the durations of the outbound and inbound burns are reversed at ~12.5 min (TLI), ~3.7 min (LOC), ~11.6 min (TEI), and ~10.2 min (EOC).

In all of the above cases, the code's optimizer routine looks for a solution that allows the mission to be executed with the minimum amount of LO_2 (i.e., the total of the initial LEO LO_2 and the refuel LUNOX supplied to the vehicle). It achieves this goal by manipulating the LO_2 amounts and the MR values until it finds the solution with the minimum total LO_2. The RCS requirements between major propulsive maneuvers are also adjusted and determined in the process.

IX. Mining and Processing Requirements and Estimated LUNOX Reserves

To get a better idea on what the mining and processing requirements are to support the kinds of missions discussed in this paper, we selected the 3-engine LANTR commuter shuttle mission (Case 5 in Table 5) that runs O_2-rich (MR = 5, Isp = 516 s) out to the Moon back, and has 1-way transit times of ~32.8 hours. The LUNOX refueling requirement for this mission is ~80.5 t and the total mission burn time on each of the LANTR engines is ~25 minutes. Assuming a 10 hour "full-power" lifetime on the engine fuel, a typical LANTR shuttle could perform ~24 missions. Assuming a 5-ship fleet and weekly trips to the Moon, each LANTR shuttle would make around 10 to 11 flights per year resulting in a service life of ~2.2 years. Near the end of life, the shuttle's NTPS would be used to inject cargo missions to various destinations before being disposed of in heliocentric space.

To support weekly commuter flights to the Moon will require annual LUNOX production levels of ~12,540 t/yr (see Table 7). Approximately 4,190 t of LUNOX is used by the LANTR shuttle, ~6,140 t by four second generation Sikorsky-style LUNOX tanker LLVs (see Fig. 30) flying one resupply mission to the LLO depot each week over the course of a year, and ~2,220 t used by the same Sikorsky-style LLVs to transport arriving and departing PTMs to and from the LS. Each LLV has a dry mass of ~10.9 t and a maximum LH_2/LO_2 propellant capacity of ~35 t.

Table 7. Total LUNOX Required for "Weekly" Commuter Flights

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

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   =   <u>2,220 t/yr</u>

                  Total LUNOX Rate = 12,542 t/yr

Figure 30. Tanker LLV Delivering LUNOX to LLO Depot

[*] O/H MR = 6, I_{sp} = 465 s, ΔV_{desc} = 2000 m/s and ΔV_{desc} = 1900 m/s assumed
[+] LLV tanker transports ~25 t of LUNOX to LLO; returns to LS with empty 5 t tank
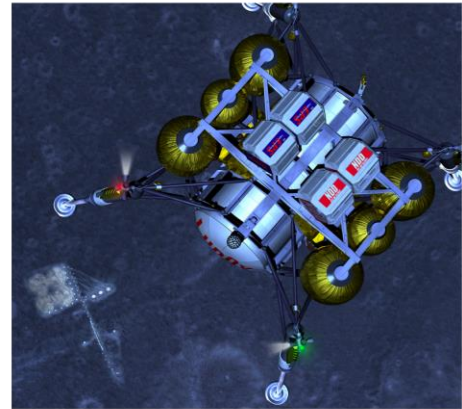[#] Total for LLV delivery of PTM from LLO to LS plus the PTM return from the LS to LLO

A preliminary assessment of plant mass, power level, feedstock throughput, and required mining area has been made assuming a LUNOX operation employing thirteen modular units each with a production capacity of 1000 t/yr. Table 8 compares the characteristics for two LUNOX plants – one based on hydrogen reduction of ilmenite [30], and the other on "iron-rich" volcanic glass feedstock. The advantages of using volcanic glass feedstock are apparent and show mass and power requirements that are 43% and 50% lower than that of an ilmenite reduction plant using a soil feedstock. Included in the volcanic glass reduction plant mass of ~105.3 t is the mining (~9.6 t) and processing equipment (84.6 t) – both of which include a 30% DWC – plus the fission reactor power source (~11.1 t). The plant power requirement of ~1.52 MW_e includes ~10.7 kW_e for the mining equipment and ~1509 kW_e for the processing equipment. Both values again include a 30% margin. The process power dominates and is a function of the LUNOX production rate and is primarily associated with the electric heaters, electrolysis cell and the oxygen liquifiers as discussed in Sect. II and pointed out in Fig. 5.

Using the "low end" 4% O_2 yield obtained from orange and black volcanic glass beads still translates into more than an order of magnitude reduction in the amount of mined material. The mining equipment used at each 1000 t/yr production plant consists of two front-end loaders and four haulers. To produce ~13,000 t of LUNOX annually will require a glass throughput of ~3.25 x 10^5 t/yr and a soil mining rate at each production plant of just under 6 t per hour per loader assuming the same 35% mining duty cycle used in the ilmenite processing plant results. This duty cycle corresponds to mining operations during ~70% of the available lunar daylight hours (~3066 hours per year).

While this number is large, it is modest compared to terrestrial coal and proposed lunar helium-3 mining activities. For example, with a single 1000 MW_e coal-fired power plant consuming about sixty 100-ton train cars of coal per day, the annual U.S. production rate for coal exceeds 500 million tons! Similarly, past proposals for mining helium-3 on the Moon [47] to support a future fusion-based power economy in the U.S. would require the processing of ~2.8 billion tons of regolith to obtain the estimated 20 t of helium-3 needed annually (see Table 8).

Table 8. Comparison of Different Lunar Mining Concepts Showing
Plant Mass, Required Operating Power, and Mining Rates

- Hydrogen Reduction of Ilmenite: (LUNOX Production @ 1000 t/year)

  - Plant Mass (Mining, Beneficiation, Processing and Power)   = 244 t

  - Power Requirements (Mining, Beneficiation and Processing)   = 3.0 MW_e

  - Regolith Throughput (assumes soil feedstock @ 7.5 wt% ilmenite
    and mining mass ratio (MMR) of 327 t of soil per ton of LUNOX)   = 3.3×10^5 t/yr

- Hydrogen Reduction of "Iron-rich" Volcanic Glass: (LUNOX Production @ 1000 t/year)

  - Plant Mass (Mining, Processing and Power)   = 105 t

  - Power Requirements (Mining and Processing)   = 1.5 MW_e

  - Regolith Throughput (direct feed and processing of "iron-rich"
    volcanic glass beads assuming a 4% O_2 yield and MMR = 25 to 1)   = 2.5×10^4 t/yr

- Lunar Helium-3 Extraction: (5000 kg (5 t) He^3/year)

  - Mobile Miners (150 miners required, each weighing 18 t,   = 2700 t
    and each miner producing 33 kg He^3 per year)

  - Power Requirements (200 kW direct solar power/miner)   = 30.0 MW

  - Regolith Throughput (processing and capture of Solar Wind
    Implanted (SWI) volatiles occurs aboard the miner)   = 7.1×10^8 t/yr

Figure 31 shows our proposed site for a commercial LUNOX facility within the Taurus-Littrow DMD at the southeastern edge of the Mare Serenitatis (~21°N, ~29.5°E) approximately 30 km west of the Apollo 17 landing site. This deposit of largely black crystalline beads covers ~3000 km^2 and is thought to be tens of meters thick. Assuming an area of ~2000 km^2 – equivalent to a square ~28 miles on a side, a mining depth of ~5 m and soil density representative of the Apollo 17 volcanic glass (~1.8 g/cm^3), and a MMR of 25 to 1 (equivalent to a 4% O_2 yield), Fig. 32 shows that the Taurus-Littrow DMD could produce ~720 million tons of LUNOX. Figure 32 also shows that the mining areas needed to support commuter flights to the Moon are not unrealistic at ~0.036 km^2 and ~0.18 km^2 for 1 to 5 flights/week, respectively. Even at five times the higher ~65,000 t/year rate, there are sufficient LUNOX resources at this one site to support ~25 commuter flights carrying 450 passengers each week for the next 2215 years and more sites containing even larger quantities of iron-rich pyroclastic glass have been identified [24].

X. Summary, Concluding Remarks and a Look Ahead

The NTR offers significant benefits for lunar missions and can take advantage of the mission leverage provided from using LDP – specifically LUNOX – by transitioning to LANTR propulsion. Using this enhanced version of NTP has many advantages. It provides a variable thrust and I_{sp} capability, shortens engine burn times, extends engine life and allows combined LH_2 and LO_2 operation. Its use together with adequate supplies of LUNOX, extracted from abundant reserves of FeO-rich volcanic glass, can lead to a robust nuclear LTS that evolves over time and has unique mission capabilities. The examples we have discussed here include short transit time crewed cargo transports, commuter shuttles and priority cargo delivery systems operating between transportation nodes /propellant
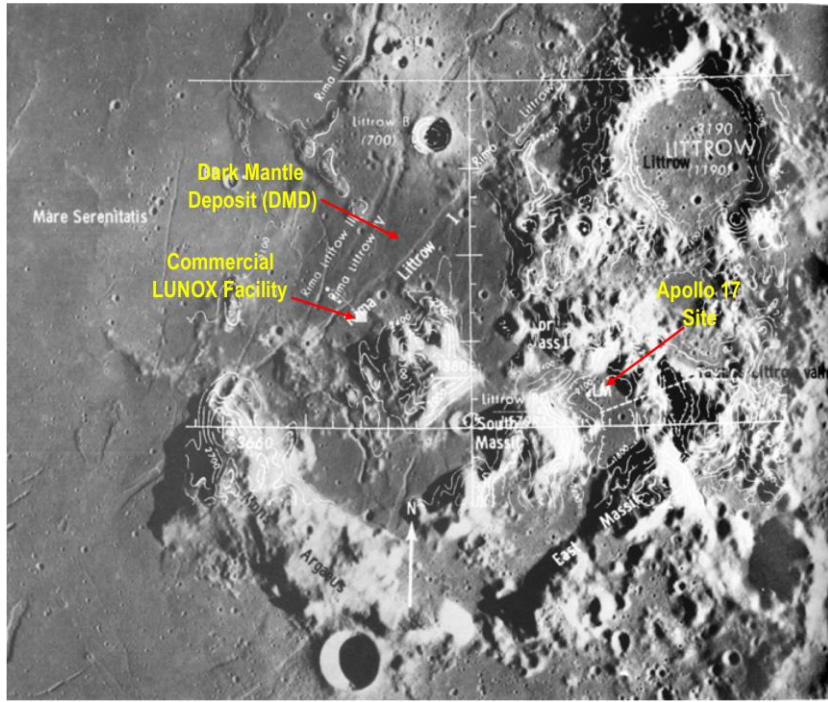
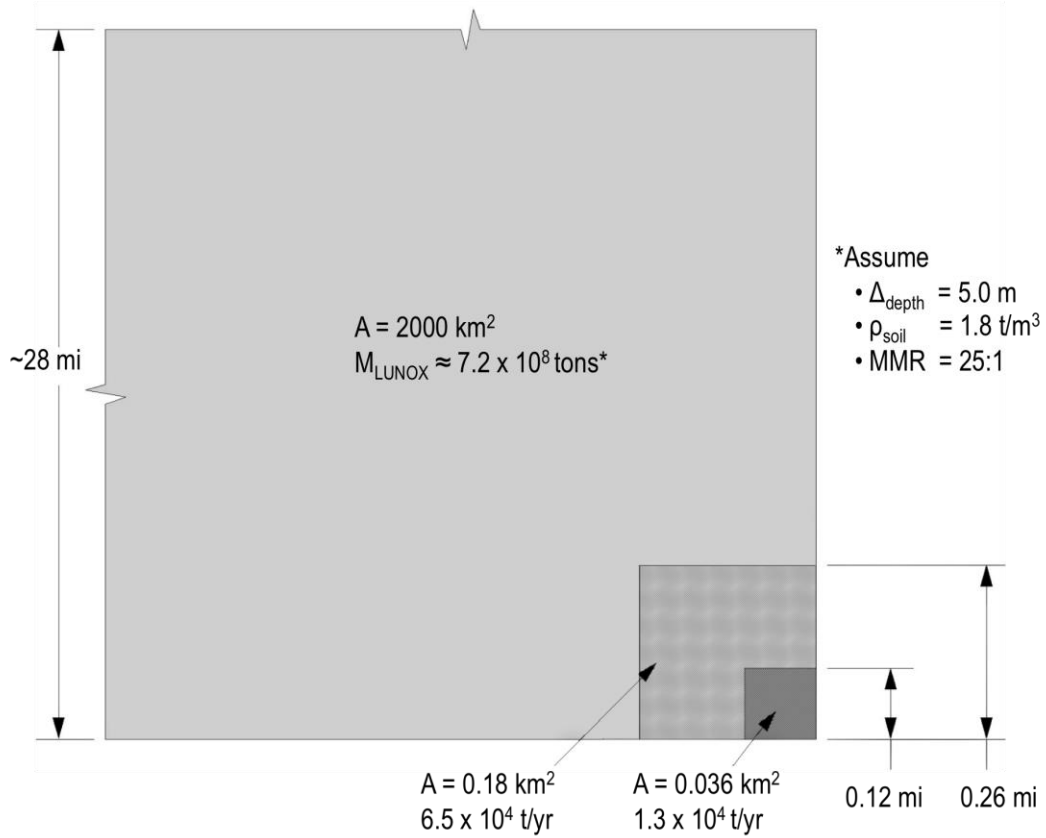Figure 31. Apollo 17 Site and Major Geographic Features of Taurus-Littrow Region

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

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

~28 mi

A = 0.18 km^2
6.5×10^4 t/yr

A = 0.036 km^2
1.3×10^4 t/yr

0.12 mi   0.26 mi

Figure 32. Required Mining Areas and LUNOX Production Rates to Support
Routine Commuter Flights to the Moon

depots located in LEO and LLO. While others have discussed more conventional space transportation systems supported by propellant depots [48], the performance capability resulting from combining these two "high leverage" technologies is quite extraordinary. For example, to perform the same 36-hour commuter shuttle mission with the same propellant tank volumes used in Case 3 of Table 5, an all LH_2 NTP system would require an "effective I_{sp}" of ~1575 s which is equivalent to that postulated for an advanced "gaseous fuel core" NTR system.

Besides enabling a robust and versatile LTS, the LANTR concept is expected to dramatically improve space transportation performance wherever extraterrestrial sources of LO_2 and LH_2 can be acquired (Fig. 33) such as the Martian system, main-belt asteroids and the Galilean satellites – Europa, Ganymede, and Callisto.
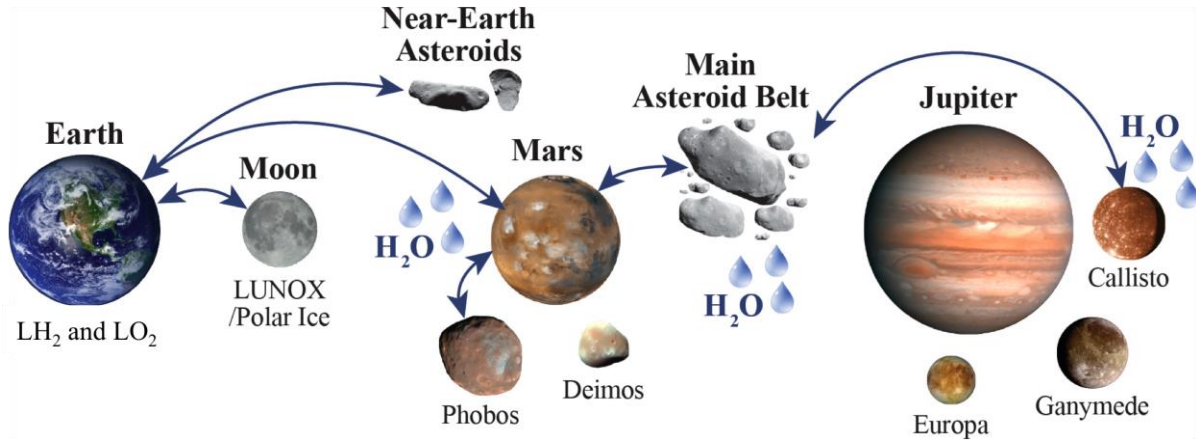

Figure 33. Human Expansion Possibilities using LANTR Propulsion and Extraterrestrial Propellant Resources

In the future, reusable biconic-shaped LANTR-powered ascent/descent vehicles, operating from specially prepared landing sites on Mars, could be used to transport modular payload elements to the surface while resupplying orbiting transfer vehicles with propellants (shown in Fig. 34) needed to reach refueling depots in the asteroid belt. From there, LANTR-powered interplanetary transfer vehicle (ITVs), carrying cargo and passengers, could continue on to the "water-rich" moons of the Jovian system, providing a reliable foundation for the development and eventual human settlement of the Solar System.
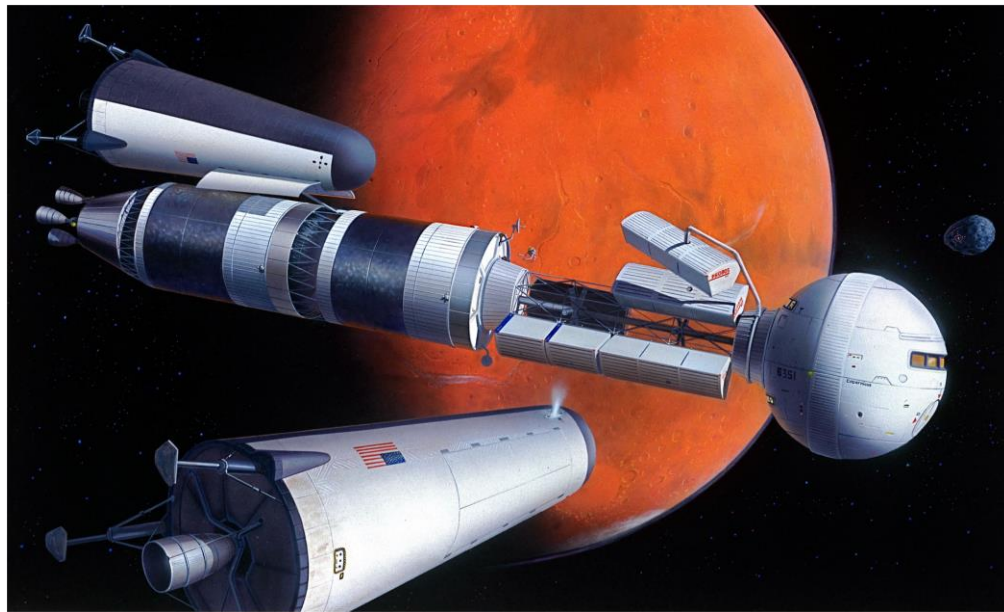

Figure 34. Notional LANTR-powered ITV Unloading Cargo and Loading Propellant
before Departing Mars for the Asteroid Belt

In the nearer term, it is also possible that LANTR propulsion could find its way into NASA's plans for a human mission to Mars. This year is the seventh year in a row that NASA has been funding NTP research and development. Preliminary development plans envision flight-testing a NTPS powered by three 25 klb_f-class NTR engines sometime in the late 2020's. For the Mars mission, two additional tanks of LH_2 – one an in-line tank and the other a drop tank – are added to supplement that onboard the NTPS. Because of LH_2's low density, these additional tanks increase the vehicle's overall size and mass. By adding the afterburner feature to the NTPS and running the engines at a MR ~1 during the LEO departure burn, the amount of LH_2 used during this maneuver can be cut in half. The thrust output of the NTPS is also increased by ~60% – from 75 klb_f to over 120 klb_f reducing gravity losses and eliminating the need for multiple perigee burns during Earth departure. Afterwards the smaller LO_2 drop tank can be jettisoned and LH_2 used for the rest of the mission.

This December marks the 45th anniversary of the Apollo 17 mission to Taurus-Littrow and unfortunately, the termination of both the Apollo and the Rover/NERVA nuclear rocket programs. In the not-so-distant future, the technological progeny from these two historic programs – LUNOX and LANTR – could allow the development of a robust, reusable space transportation system that can be adapted to a wide variety of potential lunar missions using the basic vehicle building blocks discussed in this paper.

The biggest challenge to making this vision a reality, however, will be the production of increasing amounts of LDP and the development of propellant depots for vehicle refueling in LEO and LLO. An industry-operated, privately-financed venture, with NASA as its initial customer, has frequently been mentioned as a possible blueprint for how a commercial LUNOX operation and propellant depot might develop. 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 envisioned. Only time will tell and maybe it will be quicker than any of us can imagine.

Acknowledgments

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