Commercial and Human Settlement of the Moon and Cislunar Space – A Look Ahead at the Possibilities Over the Next 50 Years

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Over 50 years have passed since the movie *2001: A Space Odyssey* debuted in April 1968. In the film, Dr. Heywood Floyd flies to a large artificial gravity space station orbiting Earth aboard a commercial space plane. He then embarks on a commuter flight to the Moon arriving there 25 hours later. Today, on the 50th anniversary of the Apollo 11 lunar landing, the images portrayed in *2001* still remain well beyond our capabilities. This paper examines key technologies and systems (in-situ resource utilization, fission power, advanced chemical and nuclear propulsion), and orbiting infrastructure elements (providing a propellant depot and cargo transfer function), that could be developed by NASA and the private sector in future decades allowing the operational capabilities presented in *2001* to be achieved, albeit on a more spartan scale. Lunar-derived propellants (LDPs) will be essential to reducing the launch mass requirements from Earth and developing a reusable lunar transportation system (LTS) that can allow initial outposts to evolve into settlements supporting a variety of commercial activities like in-situ propellant production. Deposits of icy regolith found within permanently shadowed craters at the lunar poles can supply the feedstock material to produce liquid oxygen (LO_2) and hydrogen (LH_2) propellant needed by surface-based lunar landing vehicles (LLVs) using chemical rocket engines. Along the Moon's nearside equatorial corridor, iron oxide-rich volcanic glass beads from vast pyroclastic deposits, together with mare regolith, can provide the materials to produce lunar-derived LO_2 plus other important solar wind implanted (SWI) volatiles, including H_2 and helium-3. Megawatt-class fission power systems will be essential for providing continuous "24/7" power to processing plants, evolving human settlements, and other commercial activities that develop on the Moon and in orbit. Reusable LLVs will provide cargo and passenger "orbit-to-surface" access and will also be used to transport LDP to Space Transportation Nodes (STNs) located in lunar polar (LPO) and equatorial orbits (LLO). Spaced-based, reusable lunar transfer vehicles (LTVs), operating between STNs in low Earth orbit (LEO), LLO, and LPO, and able to refuel with LDPs, can offer unique mission capabilities including short transit time crewed cargo transports. Even a commuter shuttle service similar to that portrayed in *2001* appears possible, allowing 1-way trip times to and from the Moon as short as 24 hours. The performance of LTVs using both RL10B-2 chemical rockets, and a variant of the nuclear thermal rocket (NTR), the LO2-Augmented NTR (LANTR), are examined and compared. The bipropellant LANTR engine utilizes its divergent nozzle section as an afterburner into which oxygen is injected and supersonically combusted with reactor-heated hydrogen emerging from the engine's sonic throat. If only 1% of the LDP obtained from icy regolith, volcanic glass, and SWI volatile deposits were available for use in lunar orbit, such a supply could support routine commuter flights to the Moon for many thousands of years! This paper provides a look ahead at what might be possible in the not too distant future, quantifies the operational characteristics of key in-space and surface technologies and systems, and provides conceptual designs for the various architectural elements discussed.

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Nomenclature

°C / °K	=	temperature (in degrees Celsius / Kelvin)
ELH_2	=	Earth-supplied Liquid Hydrogen
IMLEO	=	Initial Mass in Low Earth Orbit
klb_f	=	thrust (1000's of pounds force)
LLO_2 / LLH_2	=	Lunar-derived Liquid Oxygen / Liquid Hydrogen
LUNOX	=	another name for LLO_2
NERVA	=	Nuclear Engine for Rocket Vehicle Applications (program)
O/H MR	=	Oxygen-to-Hydrogen Mixture Ratio
SLS / HLV	=	Space Launch System / Heavy Lift Vehicle (future commercial options)
t	=	metric ton (1 t = 1000 kg)
ΔV	=	velocity change increment (km/s)

1.0 Introduction and Background

More than 50 years have passed since Stanley Kubrick and Arthur C. Clarke's movie *2001: A Space Odyssey* debuted in April 1968 [1]. For many of us this film brought to life the exciting possibilities awaiting humankind beyond the Apollo program – images of commercial space planes, large orbiting space stations and commuter flights to sprawling settlements on the Moon depicted in Figure 1. Before the year's end, Apollo 8 astronauts would orbit our celestial neighbor ten times on Christmas Eve, followed seven months later by the historic lunar landing mission of Apollo 11 on July 20, 1969. The images of astronauts, spacecraft and rovers traversing the stunning alien landscapes of Hadley Rille, Descartes, and Taurus Littrow that followed on Apollo missions 15, 16 and 17, reinforced a vision of future lunar exploration consistent with that portrayed in *2001*. After all NASA would have over 30 years to develop the necessary technologies. Unfortunately, national support and public interest in the Apollo program soon waned. Apollo missions 18, 19 and 20 were canceled, and the funding for a post-Apollo program that envisioned artificial gravity space stations in both Earth and lunar orbit, a permanent lunar base, and a nuclear rocket-powered human mission to Mars never materialized.

NASA and its partner nations did construct the *International Space Station (ISS)* but the reusable Space Shuttle has now been retired for eight years, after three decades of operation, and the Agency does not currently possess the systems to send humans to the lunar surface as it once did. NASA is developing the SLS and the *Orion* spacecraft for transporting astronauts to lunar orbit sometime in the 2024-25 timeframe. It has also developed a National Space Exploration Campaign report [2] that outlines the Agency's plans for an innovative and sustainable program of exploration that includes commercial and international partners. The opportunities for commercial involvement are widespread and include: (1) continued cargo and crew launch services to low Earth orbit (LEO); (2) private sector operation of the *ISS*, and/or other free-flying platforms/stations to support a robust future LEO economy; (3) lunar payload delivery services with landers ranging in size from small surface science missions to human landing missions; and (4) the demonstration of key technologies (e.g., in-situ resource utilization (ISRU), fission surface power, advanced in-space propulsion) needed for long-term exploration, commercial development, and eventual settlement of the Moon.

Although a "Journey to Mars" [3] sometime in the late 2030's remains the stretch goal for NASA, there is another destination of interest to the greater worldwide space community – it is the Moon. Located just 3 days from Earth, the Moon 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. Abroad, a Space Resources Initiative is being funded by the Luxembourg Space Agency [4], and plans for human surface missions and settlements on the Moon in the 2025 – 2030 timeframe are being openly discussed in Europe, China, and Russia [5,6,7]. In the United States, a number of private companies – Bigelow Aerospace (BA) [8], SpaceX [9], United Launch Alliance (ULA) [10], and Blue Origin [11] – are also discussing commercial ventures to the Moon, along with possible public-private partnerships with NASA.

In early March 2017, Bigelow Aerospace announced its plans [8] 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 possessing ~330 m^3 of internal volume once inflated. The company went on to say that a variant of the BA-330 module could also be placed in LLO to serve as a transportation node and/or refueling depot for astronauts and spacecraft making their

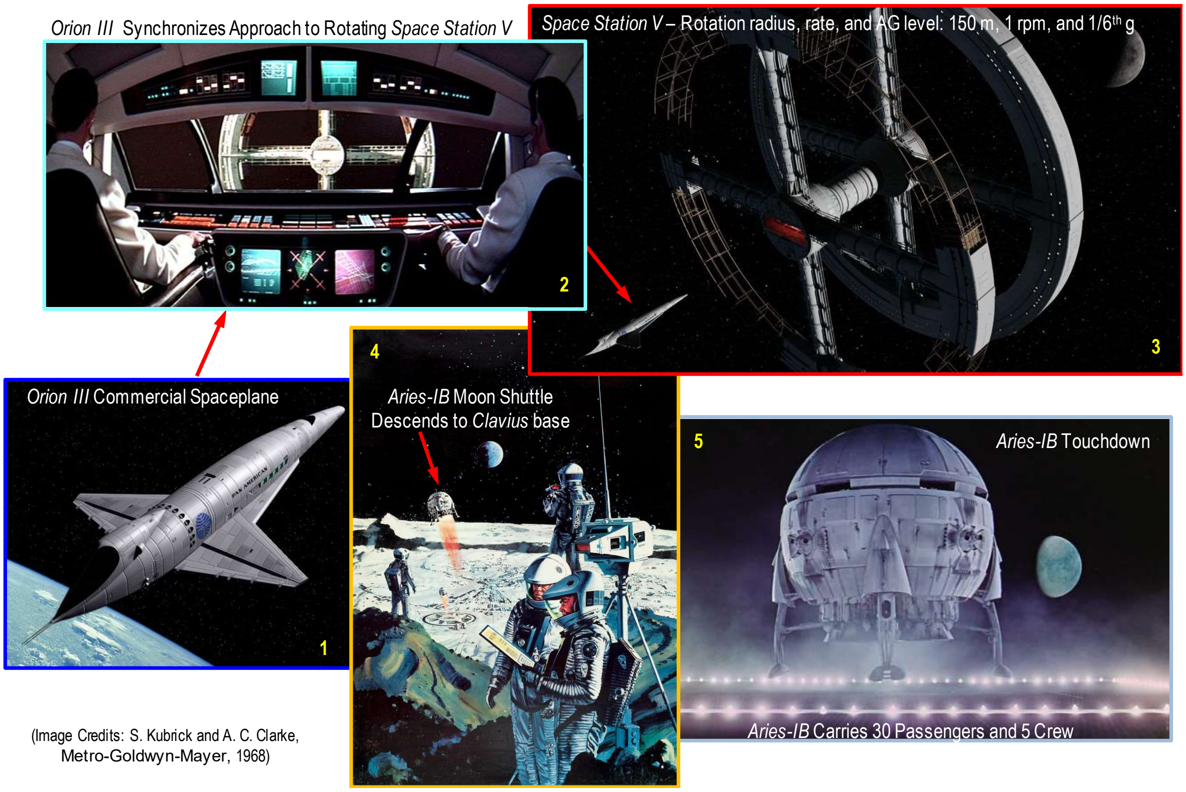


Figure 1. Images from *2001: A Space Odyssey* – Dr. Floyd's Commuter Flight to the Moon

way to and from the Moon and the lunar surface (LS). In mid-September 2018, SpaceX announced its new plan [12] to send the first tourist, a Japanese billionaire, on a trip around the Moon sometime in 2023 using its Big Falcon Rocket. This renewed interest in the Moon by US industry and international rivals prompted the Trump Administration to implement Space Policy Directive-1 in December 2017 [13] directing NASA to lead an innovative space exploration program to send American astronauts back to the Moon for long term exploration and use, and eventually on to Mars. The schedule for returning American astronauts to the Moon was accelerated this past March, when Vice President Pence, speaking on behalf of the President, directed NASA to return American astronauts to the lunar surface by 2024. He also suggested the lunar south pole as the destination – a region thought to contain abundant water ice inside the permanently shadowed craters (PSCs) that exist there [14].

Lunar-derived propellant (LDP) production – specifically LLO_2 and LLH_2 – has been identified as a key technology offering significant mission leverage [15] and it figures prominently in ULA's plan for developing a cislunar space economy [10]. Similarly, Blue Origin's Jeff Bezos is developing a large lunar lander, called the *Blue Moon*, capable of delivering up to ~4536 kg of payload to the lunar surface [16]. Powered by LO_2/LH_2 engines, it would also be able to use LDPs once they become available. Samples returned from different sites on the Moon during the Apollo missions have shown that the lunar regolith has significant oxygen content. The iron oxide-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. [17]. Post-Apollo lunar probe missions have also provided orbital data indicating the existence of large quantities of water ice trapped in deep PSCs located at the Moon's poles [18].

So the stage is now set. NASA has been directed to return to the Moon for long term exploration and use, and companies, large and small, are anxious to start doing business on the Moon [19]. What will the outcome of this next chapter in humankind's exploration of the Moon be? Today, during this 50th anniversary year of the Apollo 11 lunar landing, the images in Figure 1, depicting Dr. Floyd's commuter flight to the Moon, remain a source of inspiration to the author (SKB). In this paper we examine the key technologies, systems, and supporting infrastructure that could be developed by NASA and the private sector over the next several decades that could allow the operational capabilities portrayed in *2001* to be achieved, albeit on a more spartan scale.

The paper includes the following topics. First, the benefits and options for using LDPs are discussed. Then the two primary feedstock materials under consideration – icy regolith obtained from polar PSCs, and volcanic glass beads from vast pyroclastic deposits on the lunar nearside – are reviewed, and proposed concepts for their mining are discussed. Next, system descriptions of the two candidate propulsion options – the LO_2/LH_2 RL10B-2 engine and a variant of the NTR, the LO_2-Augmented NTR (or LANTR) – are presented, along with their currently existing and projected performance characteristics. The mission and transportation system ground rules and assumptions used in the LTS analyses are then provided, followed by a discussion of the important role that space transportation nodes (STNs) are expected to play in supporting a reusable, space-based LTS. Concepts for crewed cargo transports (CCTs) and commuter shuttles are then presented along with the refueling requirements needed to support missions with varying trip times to polar (LPO) and equatorial lunar orbits (LLO). A comparison of the LDP production and mining requirements using icy regolith and volcanic glass follows, and the synergy with an evolving helium-3 mining industry is also discussed. The paper ends with a summary of our findings and some concluding remarks.

2.0 Benefits of Using and Options for Producing Lunar-Derived Propellants

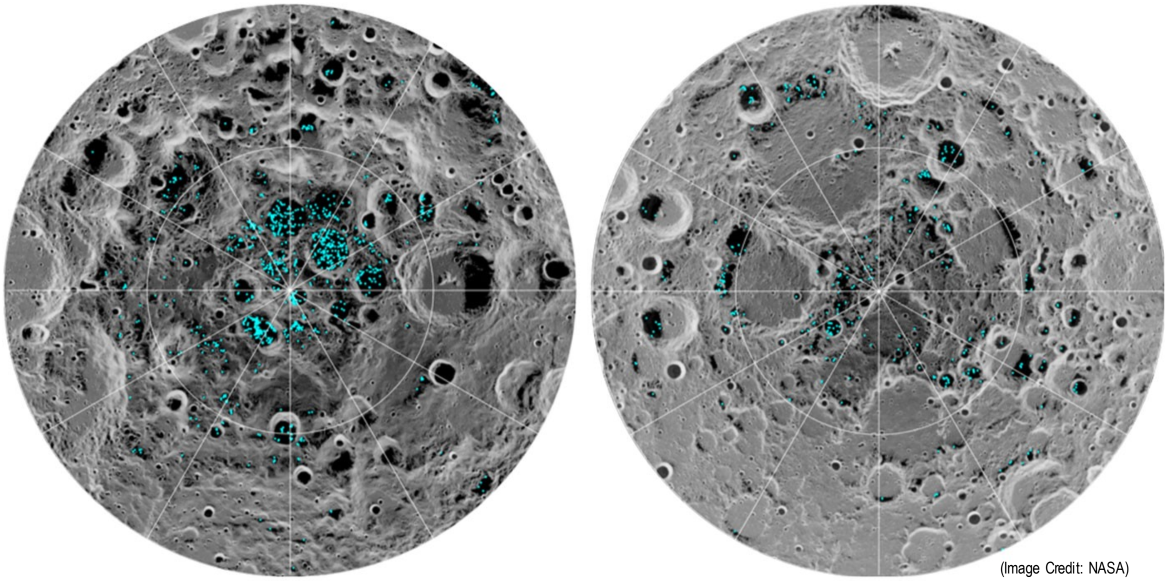
Previous studies conducted by NASA and its contractors [20,21] have indicated a substantial benefit from using LDPs – specifically LLO_2 in the lunar space transportation system. In a LTS using LO_2/LH_2 chemical rockets, ~6 kilograms (kg) of mass in LEO is required to place 1 kg of payload on the LS. Of this 6 kg, ~70% (4.2 kg) is propellant, of which ~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 and utilize LLO_2 from processed lunar volcanic glass, or LLO_2 and LLH_2 from the electrolysis of lunar water (LH_2O) derived from lunar polar ice (LPI), can provide a significant mission benefit. By providing a local source of oxygen and hydrogen 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.

2.1 LPI: Estimated Quantities and Locations

Watson et al. first conjectured about the existence of water ice at the lunar poles in 1961 [22]. Later in 1979, Arnold [23] estimated the mass of water deposited in the pole's PSCs over the last 2 billion years at ~10 to 100 billion metric tons and concluded that the Moon's poles might provide an abundant water resource for future exploitation. The sources for this water were attributed to micrometeoroids, solar wind proton reduction of lunar regolith, and comets.

In the post-Apollo era, the *Clementine* [24], *Lunar Prospector* [25], *Chandrayaan-1* [26], *Lunar Reconnaissance Orbiter* (*LRO*) [27] and *Lunar CRater Observation and Sensing Satellite* (*LCROSS*) [28] lunar probe and impact missions have provided data indicating the existence of trapped water ice within a number of deep PSCs found near the Moon's poles. On the basis of the data provided by these spacecraft, estimates of the water ice concentrations in the polar regolith varied from ~0.7 to 8.5 wt% and the total quantity of LPI at both poles ranged from ~600 million to ~2 billion metric tons. Recently, the existence of surface water ice at the Moon's poles was confirmed and reported by Li et al., [29] whose team took a fresh look at data from NASA's Moon Mineralogy Mapper (M3) instrument that flew on the *Chandrayaan-1* spacecraft. Figure 2 shows the distribution of surface ice at the Moon's south (Fig. 2a) and north poles (Fig. 2b). The turquoise dots represent the ice locations, and the gray scale corresponds to the surface temperature, with the darker gray representing colder areas and the lighter gray indicating warmer locations. As is evident, the ice is present at the coldest and darkest spots on the lunar surface within 20 degrees of both poles, and is more abundant in the south, where it's principally found at the bottoms of PSCs. In the north, the ice appears more widely dispersed and less concentrated.

While considerable enthusiasm has been expressed about mining and processing LPI for rocket propellant, and using it to create a space-faring cislunar economy [30], the "ground truth" about LPI will need to be established before this enthusiasm is warranted. Robotic surface missions more capable than the *Resource Prospector* mission, cancelled by NASA in April 2018 [31], will need to be sent to potential resource sites of interest to quantify the physical state of the water ice (e.g., its concentration in the regolith), its vertical thickness and areal extent, and the levels of soil contamination. The depth, slope and interior thermal environment of the PSCs must also be assessed.



a) Lunar South Pole b) Lunar North Pole

Figure 2. Location of Surface Water Ice at the Moon's Polar Regions

2.2 Environmental Conditions and Proposed Concepts for Mining Lunar Polar Ice

The PSCs where LPI exists can be deep and extremely cold, posing major engineering challenges for mining and processing the ice-bearing regolith. Figure 3 shows the relative location, dimensions and depth of a large PSC – Shackleton crater in the south polar region. To put the operating temperature conditions into perspective, the world's 10 coldest mines are located in Russia, and all but one of these are located in Russia's Sakha Republic – a region in the country's extreme north that contains vast diamond, coal, and gold resources [32]. At the coldest of these mines, Sarylakh, the temperatures can drop to nearly -50 °C (~223 °K). By contrast, the temperatures inside the PSCs are ~30 to 50 °K – more than 5 times colder than the coldest mines on Earth! In fact, the coldest temperature in the Solar System was measured in the crater, Hermite (shown in Fig. 4), located near the Moon's north pole [33] – a

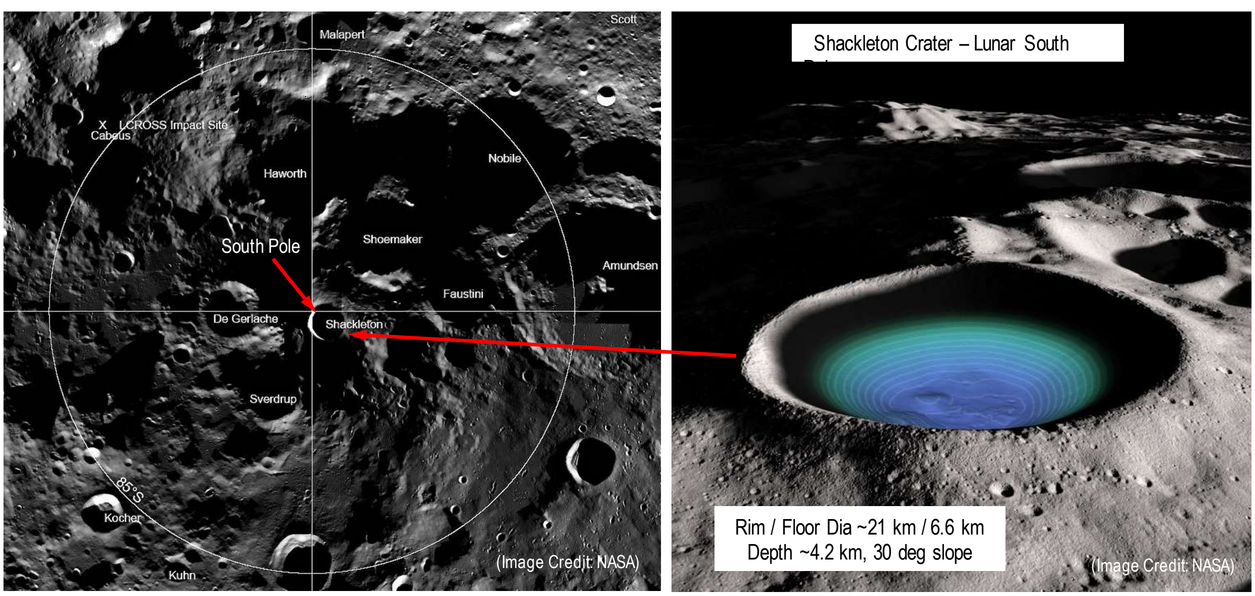


Figure 3. Lunar South Polar Region and Features of Nearby Shackleton Crater

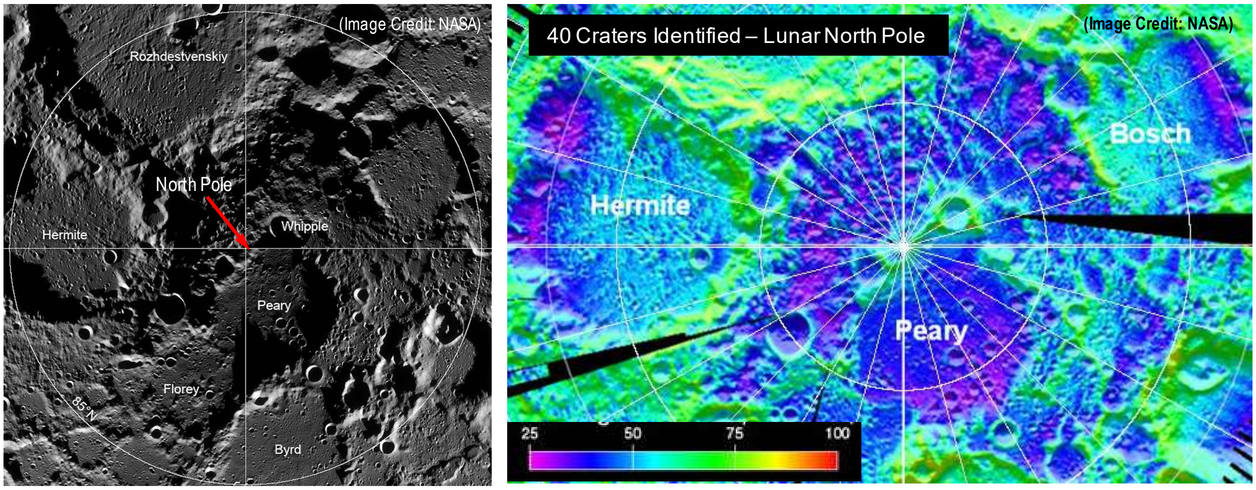


Figure 4. Lunar North Polar Region and Measured Temperatures in Nearby Craters

temperature of ~26 °K (-247 °C) recorded by the *LRO* in 2009. Similar cold temperatures were also found in the nearby craters Peary and Bosch (also shown in Fig. 4) as well as at the bottoms of several PSCs located in the Moon's south polar region. All are candidates for LPI deposits and potential mining.

In addition to working in dark, extremely cold surroundings where metals can become brittle, mining equipment must be designed to operate in a hard vacuum, on electricity rather than petrol, and in gravity that is $1/6^{th}$ that of Earth. It must also tolerate an increased radiation environment, and the abrasive nature of the lunar dust, which can cause increased rubbing friction, wreak havoc on machinery, and adheres to everything it touches.

Surface mining is the most common approach to mineral extraction here on Earth with excavation being a key component. To determine the effect of different ice-regolith mixtures on the excavation process, Gertsch et al. [34,35] conducted load-penetration tests on samples of the lunar regolith simulant (JSC-1) containing varying levels of water ice content (from 0 to ~12 wt%). The samples were compacted and cooled to 77 °K using LN_2 to simulate conditions expected in lunar cold traps. From the test measurements, Gertsch et al. matched the different ice-regolith mixtures to the following types of terrestrial mined rocks: (1) at 0 to ~0.3 wt% ice, the mixture behaves like weak coal that is easy to excavate; (2) at ~0.6 to 1.5 wt% ice (similar to that measured by *Lunar Prospector*), the mixture behaves like weak shale or mudstone and is readily excavatable; (3) at ~8.4 wt% ice (similar to that measured by *LCROSS*), the mixture behaves like moderate-strength limestone and sandstone and is excavated using mechanical excavators; and (4) at ~10 to 12 wt% ice, the mixture behaves like strong limestone, sandstone, and high-strength concrete, which requires massive excavators.

So what kind of equipment will be required to mine icy regolith? The mining process typically involves the following operations: fragmentation, excavation, loading, hauling, and resource separation. Mechanical mining methods frequently combine multiple operations into a single machine. For example, a mechanical excavator can be designed to excavate and transport the feedstock material to the resource extraction plant. An innovative approach for regolith excavation is currently being developed by NASA known as the Regolith Advanced Surface Systems Operations Robot, or RASSOR for short [36]. RASSOR's primary purpose is to excavate and transport regolith but it can also climb over rocks and traverse steep slopes.

Because of the Moon's low gravity, the mass of an excavation vehicle using traditional terrestrial methods does not provide enough reaction force to enable the excavation blade to penetrate the regolith. The RASSOR 2 prototype (shown in Fig. 5), uses counter-rotating bucket drums positioned at the front and rear of its central mobility chassis to provide near-zero horizontal and minimal vertical net reaction force allowing it to load, haul, and dump regolith under extremely low gravity conditions with high reliability [37]. During the loading process, RASSOR's front and rear bucket drums excavate regolith using scoops mounted on the drums' exteriors that sequentially take multiple cuts of regolith while rotating at approximately 20 revolutions per minute [37]. When RASSOR's bucket drums are filled, it raises its arms (Fig.5a) allowing the central mobility chassis to drive to the processing facility. Once there, it unloads the collected regolith by spinning its drums in reverse allowing the regolith to pour out into the collection bin (Fig. 5b). On a robotic precursor mission [36], RASSOR would be tele-operated and powered by batteries that are recharged at the lander in between mining cycles. For future production-class mining, autonomous operation and higher capacity batteries or a hydrogen/oxygen fuel cell system could power each vehicle. The onboard hydrogen

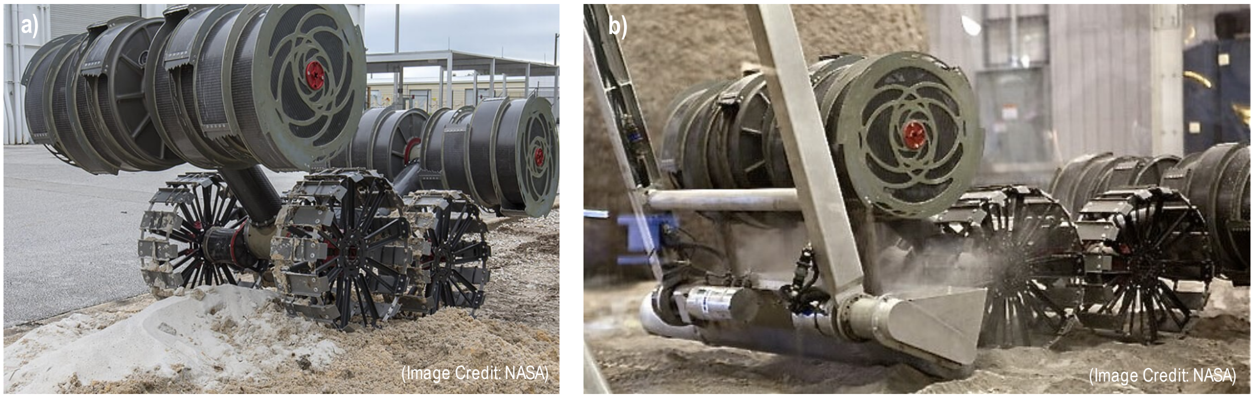


Figure 5. RASSOR 2 Prototype – With Rotating Bucket Drums Raised (a) and Being Emptied into a Dump Bin (b)

and oxygen tanks would be refilled, and the leftover water reprocessed at an electrolysis station powered by a surface nuclear power plant.

An alternative approach to excavating and transporting icy regolith has been proposed and analyzed by the Colorado School of Mines (CSM) [38], and used in a recent collaborative study on commercial lunar propellant production [39]. Known as "thermal mining," this in-situ approach uses directed sunlight from the crater rim to heat the surface of the icy regolith, or the subsurface using heating elements, producing sublimated water vapor that is captured within a dome-shaped tent enclosure covering the heated surface (shown in Fig. 6). The vapor is then vented into "cold trap" ice haulers for transport to a central processing plant for water purification and subsequent electrolysis to produce the LLO_2 and LLH_2 propellants used by surface-based LLVs. The purified LH_2O can also be shipped to orbiting STNs for conversion to propellant there.

In the commercial lunar propellant production study [39], an annual water production rate of ~2460 t/yr was identified. With water's 8:1 O/H mass ratio, and an assumed O/H MR of ~5:1 for their chemical engines, it was necessary to produce and electrolyze ~6.7 t of LH_2O each day to produce the ~1640 t of LO_2/LH_2 propellant needed annually. The total electrical power needed for propellant production was ~2.1 MW_e (including the ~1.38 MW_e for electrolysis) plus ~800 kW_t used for the thermal mining. Using a 4% ice content and 25 kg/m^2 yield [39], an estimated mining area of ~98,400 m^2 is needed to produce ~2187 t/yr of LLO_2 plus ~273 t/yr of LLH_2.

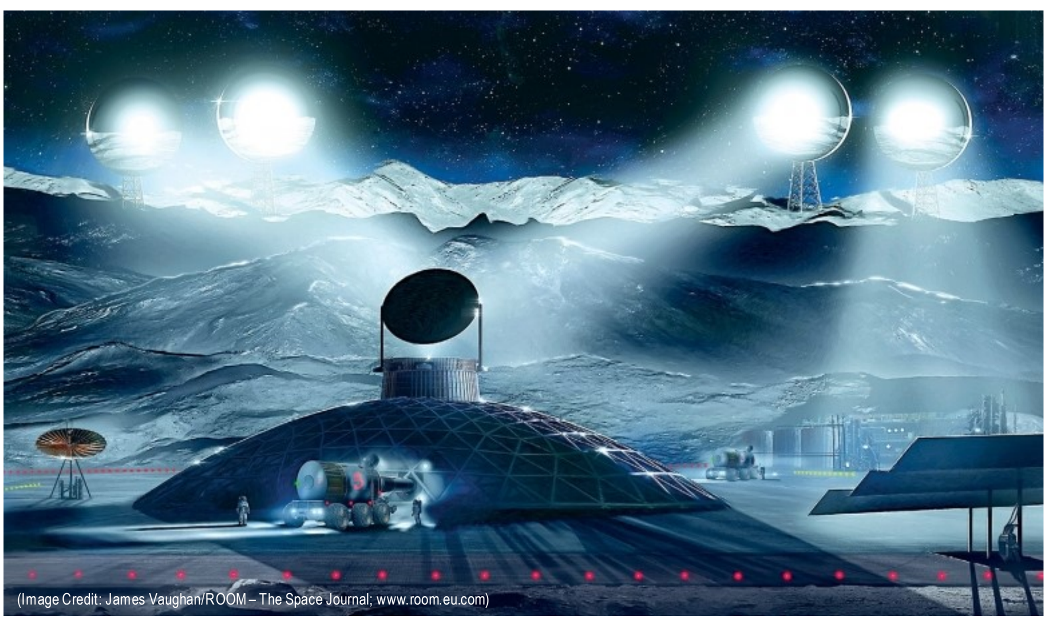


Figure 6. Artist's Concept for a LPI Thermal Mining Operation at the Lunar South Pole

2.3 LUNOX: Extraction Efficiency, Plant Characteristics and Siting Location

As discussed above, much of the information regarding LPI is based on the analysis and interpretation of orbital data obtained from past robotic science missions. By contrast, samples brought back on the Apollo missions have shown that nearly half the mass (~43%) of the Moon's surface material is oxygen [15] and at least 20 different techniques [40,41] have been identified for its extraction. The reduction of iron oxide in the mineral "ilmenite" ($FeTiO_3$) and 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:

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

The water is then electrolyzed to produce oxygen and the hydrogen is recycled back to the processing plant to react with more feedstock material. From an extensive set of hydrogen reduction experiments conducted by Allen et al. [42,43], "ground truth" for oxygen release was established using 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 abundance in the soil as shown in Figure 7. 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 an Fe content of ~17.8 wt%. The orange and black beads shown in Figure 7a have identical elemental compositions, but the black beads are largely crystalline while the orange beads are largely glass. Reduction of the orange glass beads produced an oxygen yield of ~4.3 wt% whereas the black crystalline beads produced ~4.7 wt%, the highest for any of the samples (Fig. 7b) [43]. Assuming the same hydrogen reduction process, volcanic glass feedstock, and a conservative oxygen yield of 4 wt%, 1 t of LUNOX can be produced by processing 25 t of volcanic glass – a significant improvement over previous estimates.
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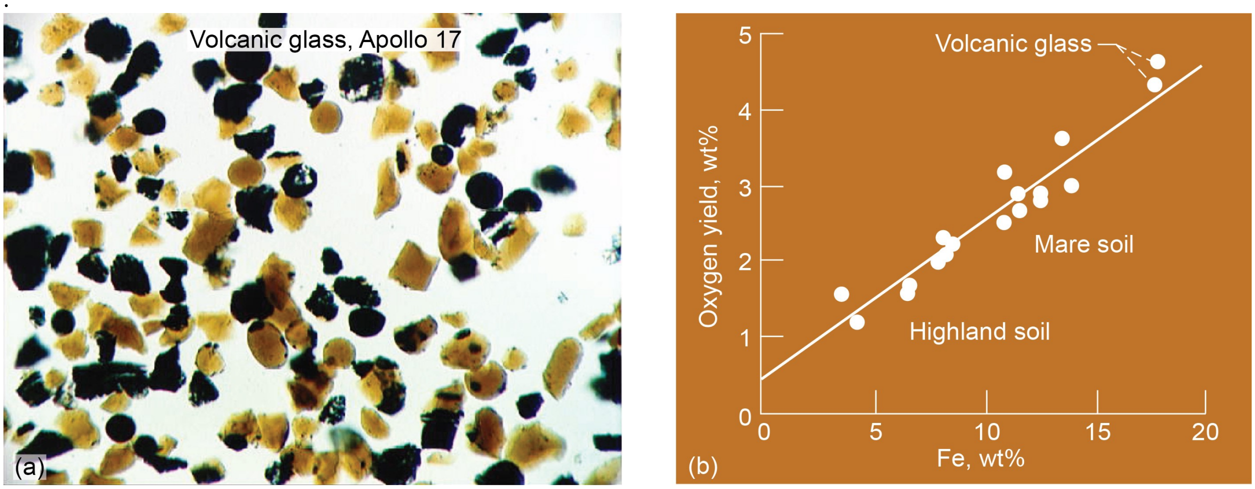

Figure 7. Volcanic Glass Beads and Oxygen Yields from Full Range of Apollo samples [43]

The key activities involved at a LUNOX production plant are depicted in Figure 8. Tele-operated 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 fission power system located a safe distance away (11) from the plant and the regolith-covered habitat module (12) occupied by the plant workers.

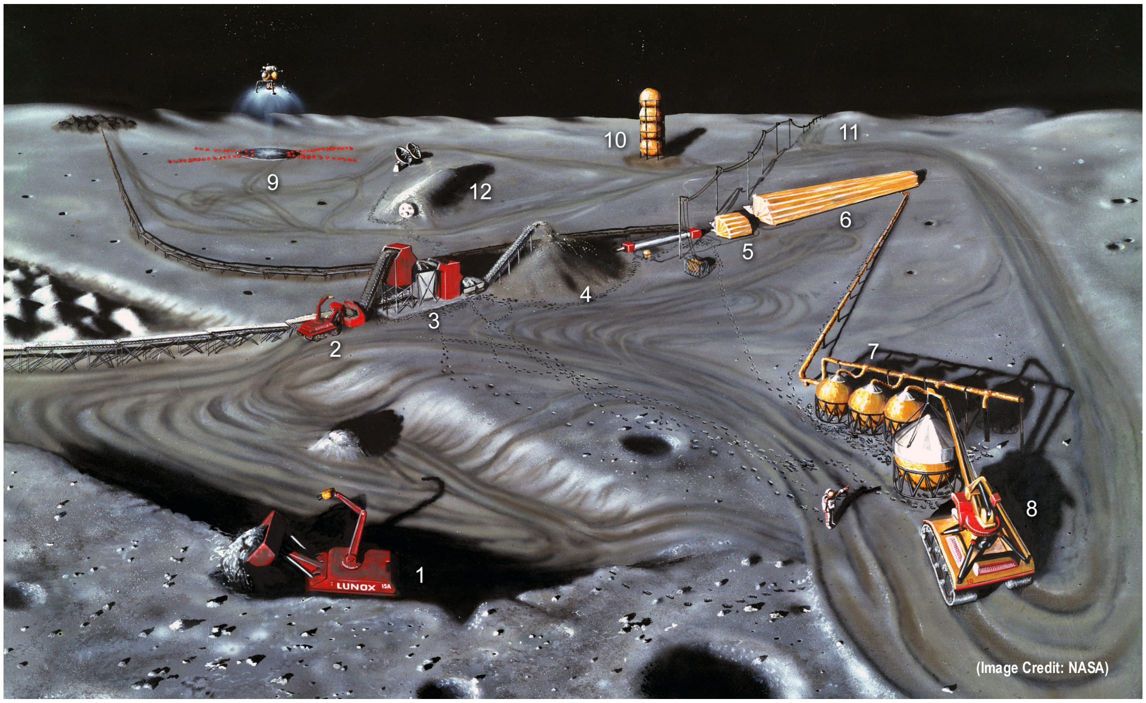

Figure 8. Activities at a LUNOX Production Plant Processing Ilmenite-bearing Feedstock Materials (ca. 1983)

A detailed conceptual design study of a lunar oxygen pilot plant was performed for NASA by Christiansen et al. of Eagle Engineering in 1988 [41]. The study selected a three-stage fluidized bed reactor for its hydrogen reduction processing plant because of its simplicity and well understood reaction chemistry, and ilmenite as the feedstock material. 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 1500 t/year. Key trades and sensitivity analyses were also conducted including evaluations on: (1) soil or basalt feedstock; (2) solar photovoltaic arrays with regenerating fuel 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. Additional information on the concept of operations for the fluidized bed hydrogen reduction plant is provided elsewhere [44].

In the Eagle Engineering study, the LUNOX plant is supplied by two tele-robotic 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 dumps its load into the process feed bin and collects a load of either screened soil or tailings (unprocessed ilmenite, rutile and iron) from the plant's discharge bin. It then dumps these materials at the appropriate collection area and returns to the mining site to begin the cycle over again. For a plant using soil feedstock (with ~7.5 wt% ilmenite), ~327 t of soil required processing for each ton of LUNOX produced [41].

Unfortunately, the Eagle Engineering study performed in 1988 was unable to benefit from the subsequent hydrogen reduction experiments conducted by Allen et al. [43] 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 [45] using demonstrated and complementary gamma ray spectrometry [46] and multispectral imaging [47] 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 327 t required using the ilmenite-bearing soil feedstock. According to Allen et al., volcanic glass is an attractive feedstock material 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. More importantly, 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 Hawke et al, [48] and Gaddis et al [49]. 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 dark mantle deposits (DMDs) 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).

The author's 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 well in excess of a billion metric tons of LUNOX using the hydrogen reduction process, a 4.5 wt% oxygen yield and a 5-m mining depth. The facility image, shown in Figure 9, was developed and first presented by the author in 1997 [50] 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, and towards the top, modular production units, resembling oil rigs on Earth, generate copious amounts of LUNOX which are stored in well-insulated tanks adjacent to the facility. At the top, 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. Lastly, fission power reactors – positioned within nearby craters with surface radiators located overhead – 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 tele-operated surface vehicles, production units and habitat modules even during the 2-week lunar night. As the production capacity of the LUNOX enterprise increases, additional supporting commercial activities are expected to emerge including metals processing (e.g., iron and titanium), power generation, maintenance and operations of surface-based LLVs and LLO STNs, and eventually even a lunar tourism industry complete with routine commuter flights to and from the Moon.

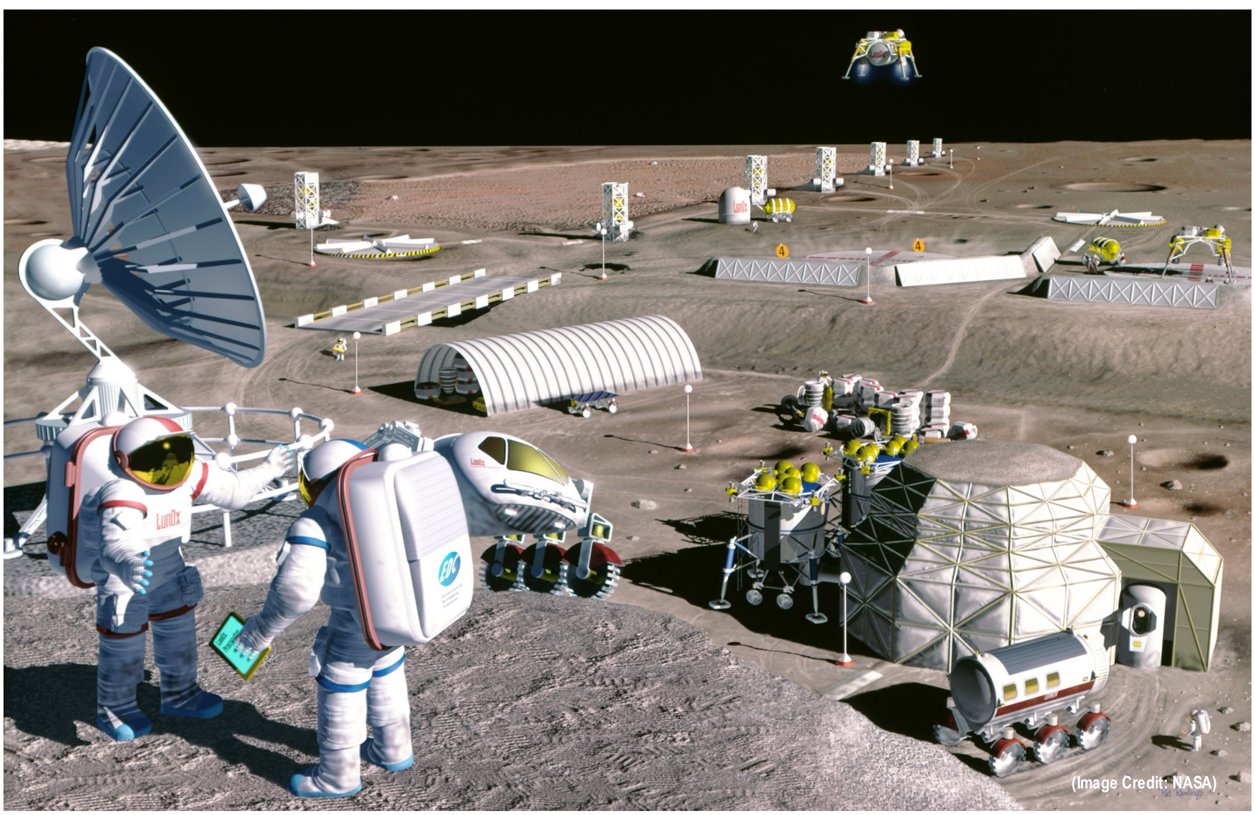

Figure 9. Conceptual Commercial LUNOX Facility Bordering on the Taurus-Littrow DMD [50]

3.0 Propulsion System Options: RL10B-2 and LO_2-Augmented NTR (LANTR)

The capabilities of two propulsion technologies have been examined in this paper. The first option is “now technology” and is represented by the LO_2/LH_2 RL10B-2 engine [51]. Derived from the long line of proven RL10 engines, the RL10B-2 has been the “workhorse” of the commercial launch industry powering the upper stages of the medium and heavy-lift versions of the United Launch Alliance’s Delta IV launch vehicle, as well as, the upper stage of the Delta III. It features the world’s largest extendible carbon-carbon nozzle allowing the RL10B-2 to achieve the highest specific impulse (I_{sp}) of any cryogenic engine – 465.5 s. Pictures of the RL10B-2 engine, with its nozzle retracted and deployed, are shown in Figure 10. In this stowed configuration, the engine length is ~2.2 m (86.5 in). When deployed the engine length is ~4.15 m (163.5 in), and the nozzle exit diameter is ~2.15 m (84.5 in). From an operational standpoint, the service life and total number of engine starts for the RL10B-2 are reported [52] to be 3500 s and 15 starts. Additional characteristics of the engine are listed Table 3 of Sect. 4.

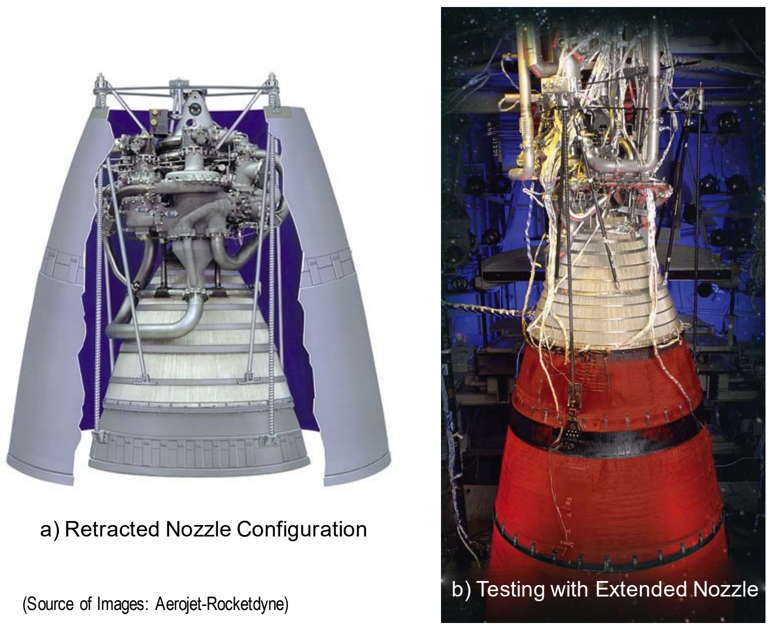

Figure 10. RL10B-2 Engine with Carbon-Carbon Nozzle Stowed and Deployed

The second propulsion option considered in this paper is the nuclear thermal rocket (NTR) – an important propulsion technology for Mars missions that is receiving considerable attention and funding from NASA at present. The NTR uses a compact fission reactor core containing uranium (U)-235 fuel to generate 100s of megawatts of thermal power (MW_t) required to heat the LH_2 propellant to high exhaust temperatures for rocket thrust [53]. In an “expander cycle” engine (shown in Fig. 11), high pressure LH_2 flowing from a turbopump assembly (TPA) is split into two paths: the first path cools the engine’s nozzle, pressure vessel, neutron reflector, and control drums, and the second path cools 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 for thrust generation.

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.

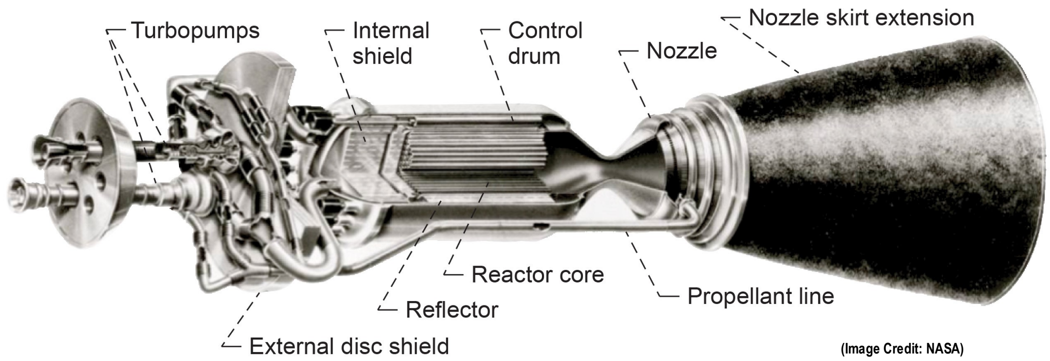

Figure 11. Key Features of Expander Cycle NTR Engine with Dual LH_2 Turbopumps

The motivation for considering the NTR in this study is simple – it is a proven technology with a specific impulse nearly twice that of the RL10B-2. During the Rover/NERVA program (1955-1972), a technology readiness level (TRL~5-6) was achieved [53]. Twenty rocket reactors were designed, built and ground tested in integrated reactor / engine tests that demonstrated: (1) a wide range of thrust levels (~25, 50, 75 and 250 klb_f); (2) high temperature carbide-based nuclear fuels that provided hydrogen exhaust temperatures up to 2550 K (*achieved in Pewee*); (3) sustained engine operation (*over 62 minutes for a single burn achieved in the NRX-A6*); as well as (4) accumulated lifetime at full-power; and (5) restart capability (*>2 hours with 28 startup and shutdown cycles achieved in the NRX-XE experimental engine*).

Near the end of the Rover/NERVA program, a Small Nuclear Rocket Engine (SNRE) [53] design was developed by the Los Alamos National Laboratory. Although it was not built, the SNRE incorporated all of the lessons learned from the program's 20 previous reactor designs and test results. SNRE-class engines are used this study with each engine producing ~16.5 klb_f of thrust with a I_{sp} of ~900 s. The total engine length is ~5.8 m with its ~1.8-m-long radiation-cooled, retractable nozzle section fully extended. The nozzle area ratio (NAR), exit diameter, and engine thrust-to-weight ratio are 300:1, ~1.53 m, and ~3.02, respectively.

Because the SNRE is a monopropellant engine that uses only LH_2 in its reactor core, 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 LO_2-Augmented NTR (or LANTR)," a LH_2-cooled NTR outfitted with an O_2 "afterburner nozzle" and feed system [50,54,55]. Combining NTR and supersonic combustion ramjet engine technologies, LANTR is a versatile, high-performance engine with unique capabilities and can take full advantage of the mission leverage provided by using LDPs by allowing "bipropellant" operation.

3.1 LANTR: An Enhanced NTR with Bipropellant Capability

In order to utilize LLO_2 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 (GO_2) to injectors positioned inside the afterburner nozzle downstream of the throat [50,54,55]. 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."* A simplified schematic of LANTR engine operation is illustrated in Figure 12a.

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 using a "cascade" scramjet injector developed by Aerojet (now Aerojet Rocketdyne) [55]. A three-zone staged injection approach [55] 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.

Figure 12b shows 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 an O/H MR <2 to simulate a NTR. The water-cooled, copper test nozzle had a NAR of 25:1 and used 3 wedge-shaped injectors (two of which are visible in Figure 12b). These 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 [55].

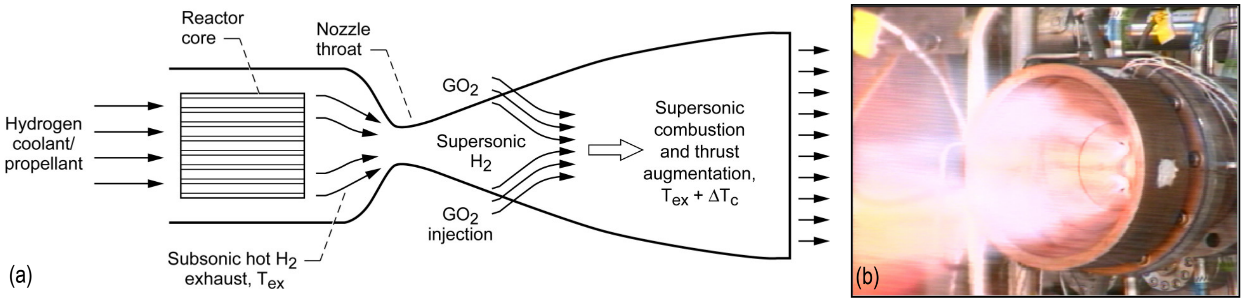

Figure 12. Simplified LANTR Schematic and "Proof-of-Concept" Test Article [55]

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 from 16.5 to ~56.8 klb_f (over 344%) while the I_{sp} decreases from 900 to 516 s (~57%) which is still ~50 s higher than that achieved in today's high performance RL10B-2 engine [51]. Additional performance characteristics of the SNRE-class LANTR are listed Table 3 of Sect. 4.

The thrust augmentation feature of LANTR means that large-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 using multiple perigee-burns during the Earth departure maneuver). Lastly, the increased use of high-density LO_2 in place of low-density LH_2, and the ability to resupply LANTR vehicles with LLO_2 prior to Earth return, are expected to significantly reduce vehicle size and mass while increasing delivered payload.

Table 1. SNRE and 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 Temperature (T_{ex}) = 2734 °K, Chamber Pressure = 1000 psi, and NAR = 300:1

4.0 Mission, Payload and Transportation System Ground Rules and Assumptions

Specific mission and payload (PL) 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 requirements 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), lunar orbit capture (LOC), trans-Earth injection (TEI), and Earth orbit capture (EOC), smaller ΔV maneuvers are needed for propellant settling, vehicle mid-course correction maneuvers, and LTV-STN rendezvous and docking (R&D), separation, and station keeping.

Table 2. Mission and Payload Ground Rules and Assumptions

• Crewed Cargo Transport (CCT) using RL10B-2 chemical or LANTR propulsion delivers cargo from LEO to LPO or LLO, with 3 days in lunar orbit (~40- to 72-hr one-way transit times) • Commuter shuttle using RL10B-2 or LANTR propulsion delivers Passenger Transport Module (PTM) from LEO to LPO or LLO, then back to LEO (one-way transit times of ~36 hr or less) • Fast cargo delivery shuttle using RL10B-2 propulsion delivers priority cargo container (PCC) from LEO to LLO, then back to LEO (one-way transit times of ~30 hr or less)	• Reusable CCT delivers varying amounts of cargo, depending on the transit times, to and from lunar orbit; CCT refuels with LDP provided at lunar STN before returning to LEO STN • Reusable commuter shuttle delivers PTM to lunar orbit for subsequent delivery to the lunar surface by LLV; shuttle refuels with LDP at lunar STN before returning to LEO space station with another PTM • Reusable fast cargo shuttle delivers PCC to LLO for subsequent delivery to the lunar surface by LLV; shuttle refuels with LDP at lunar STN before returning to LEO space station with another PCC
• CCT, commuter, and fast cargo shuttle missions depart from LEO, capture into an equatorial or polar lunar orbit, then return to LEO	• LEO: 407 km circular, 28.5 deg inclination • LLO: 300 km circular, equatorial • LPO: 300 km circular, polar
• Primary mission velocity change ΔV maneuvers: RL10B-2 or LANTR engines used • Additional ΔV requirements: Advanced Material Bipropellant Rocket (AMBR) RCS thrusters used to perform non-primary propulsion maneuvers as well as primary burn maneuvers under 100 m/s	• 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 • STN separation & station keeping: ~10 m/s
• Lunar Landing Vehicle (LLV) masses: - Single-stage LO_2-LH_2 LDAVs carry crew and PL from lunar orbit to the lunar surface (LS); - Sikorsky-style LLVs transport PTMs and PCCs from lunar orbit to the LS and back again; - Sikorsky-style "tanker" LLVs transport LDPs or LH_2O to lunar STN then return to the LS	• LDAV crew cab and dry mass: 8.6 t • Crew (4) and EVA suits: 0.8 t • LDAV propellant load: 22.5 t • LDAV surface payload: 5.0 t • Sikorsky-style LLV dry mass: 10.9 t • Sikorsky-style LLV propellant load: 40.0 t • LLO_2/LH_2O wet tank mass: 30.0 t • LLH_2 wet tank mass: 9.5 t
• CCT PL masses:	• Habitat module: 9.9 t • Star truss with RMS: 11.5 t • Outbound PL (multiple pallets & containers carried on each flight): 2.5 t (large cargo pallet) 0.68 t (small container) • Crew (4) and EVA suits: 0.80 t • Returned samples: 0.25 t
• Commuter shuttle PL mass: • Fast cargo delivery shuttle PL mass:	• PTM: 15 t (includes 2 crew & 18 passengers) • PCC: 7.5 t (includes 5.0 t of priority cargo)

A variety of PLs are delivered to and returned from the Moon by the different LTVs examined in this paper. For the reusable, space-based crewed cargo transport (CCT), a habitat module that supports a crew of four is positioned at the front of the vehicle. Connecting the habitat module to the rest of the CCT is a "star truss" that has four concave sides to accommodate multiple large PL pallets and smaller containers. The forward circular truss ring also has a remote manipulator system (RMS) with twin arms attached to it as shown in Fig. 13a. For the commuter shuttle application, the CCT's habitat module, star truss and PL pallets are removed and replaced with a passenger transport module (PTM) (Fig. 13b) that carries 18 passengers and 2 crew members. For rapid delivery of priority cargo, the PTM is replaced by a priority cargo container (PCC) (shown in Fig. 13c) that has the same outer mold line as the PTM but has half the mass.

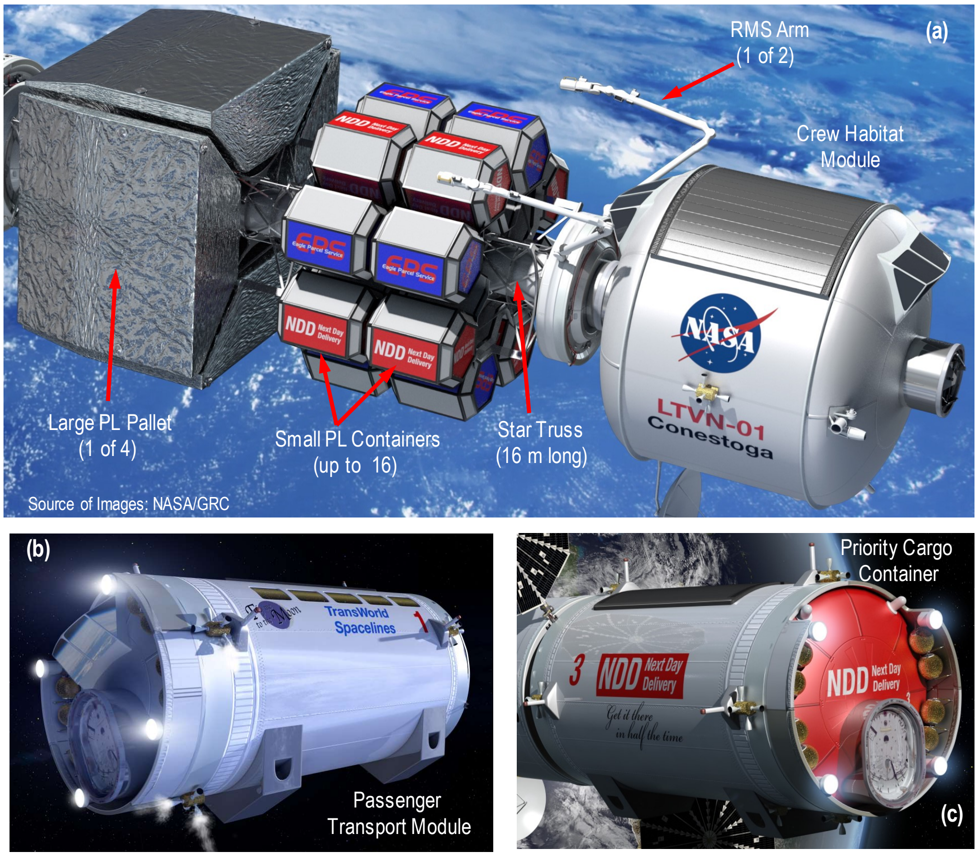

Figure 13. Payload Elements Carried by the CCT, Commuter, and Priority Cargo Shuttles

Surface-based lunar landing vehicles (LLVs) using LO_2/LH_2 chemical rockets are envisioned to provide cargo and crew "orbit to surface" access. They will also be used to transport LDPs to STNs in LPO and equatorial LLO once they are established. A "heritage" single stage lunar descent and ascent vehicle (LDAV) design [56], developed during NASA's earlier Space Exploration Initiative studies, can carry a crew of four and deliver 5 t of surface PL stored in two 2.5-t PL pallets mounted on each side of the crew cab. Autonomous and semi-autonomous Sikorsky-style LLVs, with side-mounted engines and propellant tanks, and PL attached to the underside of the LLV structure, are used for transporting tanks of LDP or LH_2O to orbiting STNs, as well as, PTMs and PCCs from orbit to settlements on the LS, and back again. The dry masses, propellant loadings, and PLs carried by the LDAV and Sikorsky-style LLVs are shown in Table 2.

Table 3 lists the key ground rules and assumptions used on the two main elements of the in-space lunar transportation system – the propulsion stage (PS) and forward in-line propellant tank (shown in Figure 14). The PS tank carries only LH_2 and is powered by a 3-engine cluster of RL10B-2 or LANTR engines. A smaller diameter in-line tank, with conical adaptor, is located forward of the PS and carries only LO_2. It is assumed that the PS and in-line LO_2 tank carry only Earth-supplied propellants when departing LEO but are able to refuel with LDPs – either LLO_2 from a LLO STN, or both LO_2 and LH_2 from a LPO STN, for the return to Earth. Details on the RL10B-2 and LANTR engines, used for primary maneuvers, were provided in Sect. 3 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 LANTR engine cooldown after each major propulsive maneuver.

Table 3. Transportation Systems Ground Rules and Assumptions

RL10B-2 performance parameters	• Engine design: Expander cycle • Propellants: LH_2 and LO_2 • O/H MR: 5.88:1 • Thrust: 24.75 klb_f • Exhaust temperature: ~3165 ° K • Chamber pressure: 640 psi • Nozzle area ratio: 280:1 • Specific impulse: 465.5 s • Engine T/W ratio: ~37.3 • Engine length: 4.15 m
SNRE & LANTR performance parameters	• Engine design: NERVA-derived, expander cycle • Fuel type: UC-ZrC composite • Propellants: LH_2 (NTR), LH_2 and LO_2 (LANTR) • Thrust: 16.5 klb_f (SNRE-class engine using only LH_2) 26.5 to 56.8 klb_f (LANTR, O/H MR = 1 to 5) • Exhaust temperature: ~2734 ° K (with ~2860 ° K peak temperature) • Chamber pressure: 1000 psi • Nozzle area ratio: 300:1 • Specific impulse range: 900 to 516 s with LANTR (MR = 0 to 5) • Engine T/W ratio: ~3.02 to 9.02 for LANTR (MR = 0 to 5) • Engine length: 5.8 m
Propellant margins	• Cooldown (LANTR): 3% of LH_2 propellant used for each burn • Performance reserve: 1% on ΔV • Tank trapped residuals: 2% of total tank capacity
Reaction control system (propellant settling, mid-course correction burns, lunar orbit operations, and primary maneuvers under ~100 m/s)	• Propulsion type: AMBR 200 lb_f thrusters • Propellant: nitrogen tetroxide (N_2O_4) and hydrazine (N_2H_2) • Nominal I_{sp}: 335 seconds
LH_2 cryogenic tanks and passive thermal protection system	• Material: Aluminum-Lithium (Al-Li) • Tank OD: 7.6 m (LH_2) and 4.6 m (LO_2) • Tank L: 15.65 m (core PS tank) and 7.95 m (in-line LO_2 tank) • Geometry: Cylindrical with root 2/2 ellipsoidal domes • Insulation: 1-in SOFI (~0.78 kg/m^2) + 60 layers of MLI (~0.90 kg/m^2)
Active cryofluid management and 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 (for 7.6-m OD tank)
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 m^2 arrays, second set of arrays provides power to mission payloads • "Keep-alive" power supplied by lithium-ion battery system
Dry weight contingency factors	• 30% on NTR system and composite structures (e.g., saddle and star trusses) • 15% on established propulsion, propellant tanks, and spacecraft systems
SLS, SLS upgrade, HLV launch requirements: – Usable payload delivered to LEO – Cylindrical payload envelope	• ~73 t (SLS) and 105 to 110 t (for SLS-1B / future commercial HLV) • 7.6 m OD x ~26.5 m L

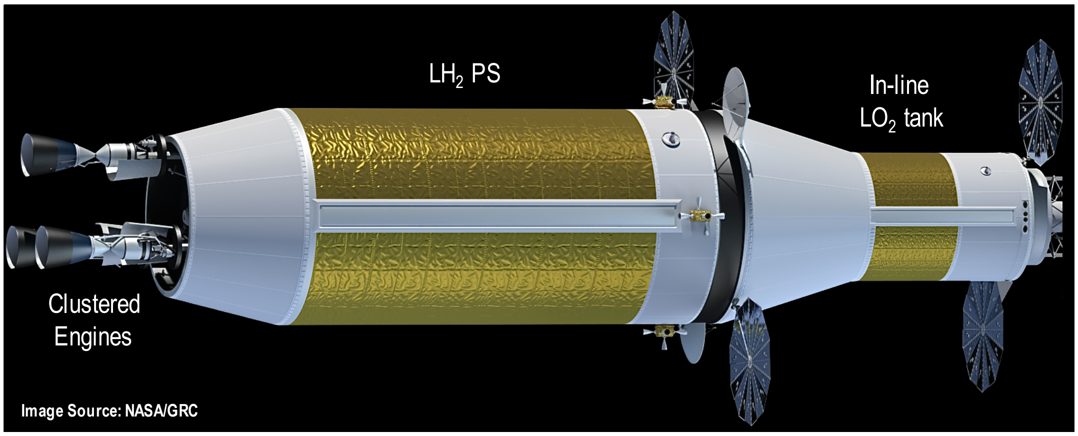

Figure 14. Key LTV System Elements – the LH$_2$ Propulsion Stage (PS) and In-Line LO$_2$ Tank

For the smaller auxiliary maneuvers, a storable bipropellant reaction control system (RCS) with Advanced Material Bipropellant Rocket (AMBR) thrusters is used (details in Table 2). A split RCS is used with approximately half the AMBR thrusters and bipropellant mass located on the PS and the other half located at the front end of the in-line LO$_2$ tank just behind the mission-specific PL (shown in Figure 14).

The LH$_2$ propellant carried in the PS is stored in the same "state-of-the-art" Al/Li LH$_2$ propellant tank being developed for the Space Launch System (SLS) and its upgrade (SLS-1B) to support future human exploration missions. The tank dimensions are 7.6-m OD by ~15.65-m length (L) and it carries ~39.8 t of LH$_2$ propellant. Tank sizing assumes a 30-psi ullage pressure, 5g axial and 2.5g lateral launch loads, a safety factor of 1.5, and a 3% ullage factor. For cryofluid management, the tank uses a combination spray-on foam (SOFI) and multilayer insulation (MLI) system for passive thermal protection. A zero boil-off (ZBO) "reverse turbo-Brayton" cryocooler system is also added to eliminate boil-off during the mission. The cryocooler system mass and power requirements are sized to remove ~42 watts of heat penetrating the 60-layer MLI system while the PS is in LEO where the highest tank heat flux occurs. To remove this heat, the two-stage cryocooler system requires ~5.3 kW$_e$ for operation. Also housed within and mounted to the PS's forward cylindrical adaptor section are the RCS, avionics, batteries, two deployable circular PVAs, electrical connections, a forward docking system, and the Brayton cryocooler and radiator system (shown in Figure. 14).

The second major element of the LTV system is the forward in-line LO$_2$ tank and its conical adaptor connecting it to the PS. The tank dimensions are 4.6-m OD by ~7.95-m L and it carries ~111.2 t of LO$_2$ propellant. The LO$_2$ tank and adaptor section use the same Al/Li alloy, sizing, and launch load assumptions as well. The LO$_2$ tank uses only a passive thermal protection system since it is drained after the LOC burn and is subsequently refueled with LLO$_2$ before the trip back to LEO. The in-line tank element and its adaptor section also include forward and rear docking adaptors, quick-connect propellant feed lines, electrical conduits along the tank length, and forward RCS. Two sets of circular solar photovoltaic arrays (PVAs) – each producing ~14 kW$_e$ – are baselined on the LTV with one set supplying the primary electrical power needed for all key LTV subsystems and the second set providing power for the different mission PLs considered here.

Table 3 also provides the assumed "dry weight contingency" (DWC) factors, along with the launch vehicle requirements for delivered mass to LEO and the shroud cylindrical payload envelope. 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 PS mass (~73 t) and size (~7.6-m OD and ~26.5-m L) determines the required lift capability and the usable shroud PL volume for the upgraded SLS-1B / future commercial HLV. For the CCT mission discussed in Sect. 6.0, the habitat module (~6.5-m OD by ~8.5-m L) and star truss (~16-m L) can be launched together, or the truss can be launched together with the in-line LO$_2$ tank and its adaptor (~11.5-m L).

5.0 Growth Mission Possibilities Enabled by Space Transportation Nodes and LDP Refueling

Commercial space transportation nodes (STNs), providing propellant and cargo transfer services in LEO and lunar orbit, will be key to realizing a robust, reusable LTS in the second half of the 21st century. Supplied with LO_2 and LH_2 propellants from Earth, delivered by a new generation of low cost, reusable heavy lift vehicles, and LDPs from the Moon, strategically positioned STNs will become transportation hubs for a variety of LTVs operating in cislunar space. A concept design for a LEO STN, called *Oasis*, is shown in Figure 15 along with the key features it needs to function as a propellant and cargo transfer hub. It is here that LTVs like the crew cargo transport (CCT) (shown docked to *Oasis* in Fig. 15) will be resupplied with propellant and cargo for their next scheduled delivery to the Moon. A fission power system (FPS) [57] is used to supply the high electrical power *Oasis* needs (~0.5-1 MW_e) for cargo and propellant transfer operations, onboard cryofluid management, and habitat module life support. It uses liquid metal-cooled, fast spectrum reactors with uranium nitride fuel, Brayton power conversion, and a deployable, fold-out radiator system, that can be collapsed allowing the entire FPS to be launched on a single SLS launch.

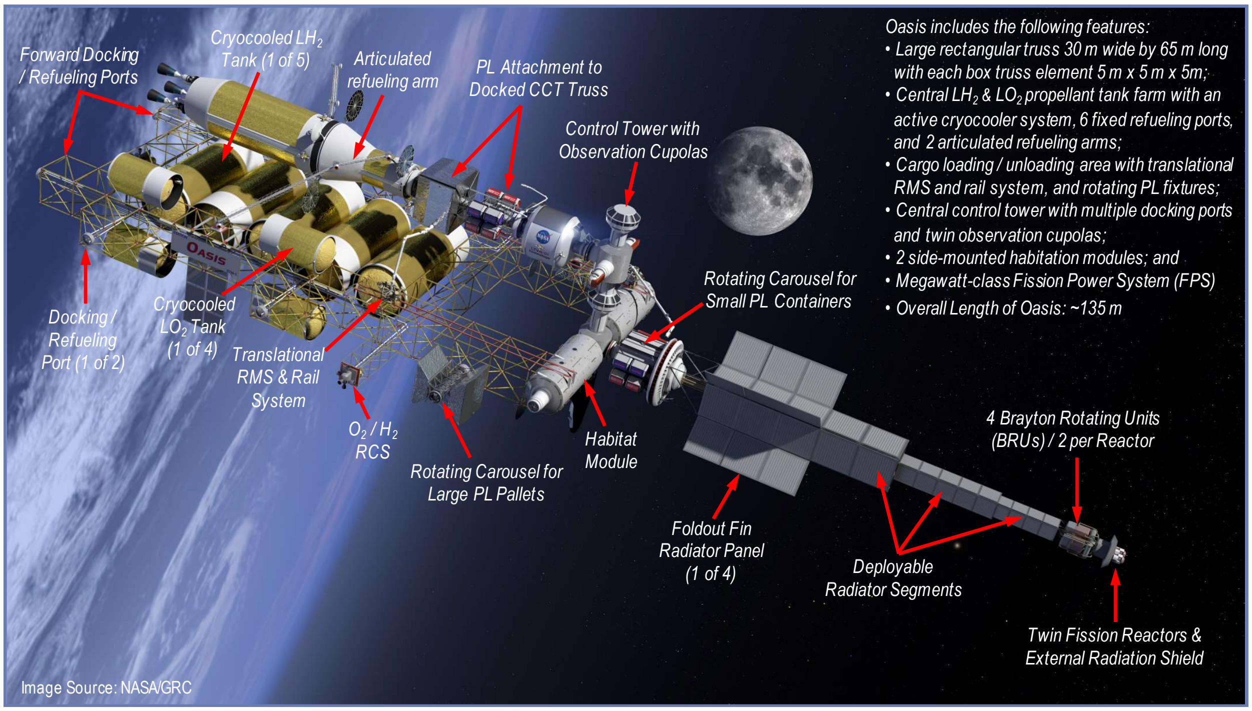

Figure 15. *Oasis* Commercial LEO STN – Key Features and Activities

As LDP production levels increase and operation of surface-based LLVs become routine, development of commercial STNs would be expected in both polar and equatorial lunar orbits. Because abundant deposits of volcanic glass are located at a number of sites just north of the lunar equator, a STN established in equatorial LLO could be routinely supplied with LUNOX by tanker LLVs operating from LUNOX production facilities. Similarly, lunar water (LH_2O), derived from processing icy regolith at the poles, could be transported to a STN in LPO by water tanker LLVs. Here the water would be electrolyzed and the LDPs stored for subsequent use. Besides providing their propellant and cargo transfer function, lunar STNs will also provide convenient staging locations where CCTs and commuter shuttles can drop off cargo and passengers that would then be picked up by LLVs for transport to the LS.

The LLO STN, *Serenity Shores*, shown in Figure 16, derives its name from the FeO-rich volcanic glass DMD located at the southeastern edge of the *Sea of Serenity*. It is a clone of *Oasis* and has all of the same features needed to unload cargo from arriving CCTs destined for the LS. While cargo is being unloaded, the CCT would be refueled with LLO_2, delivered by LUNOX tanker LLVs, for its return to Earth. Both activities are shown in Figure 16. Periodic shipments of ELH_2 would supply the STN with the LH_2 needed by the LLVs. For the LPO STN, higher electrical power levels from the FPS are also likely to support onboard water electrolysis and propellant production.

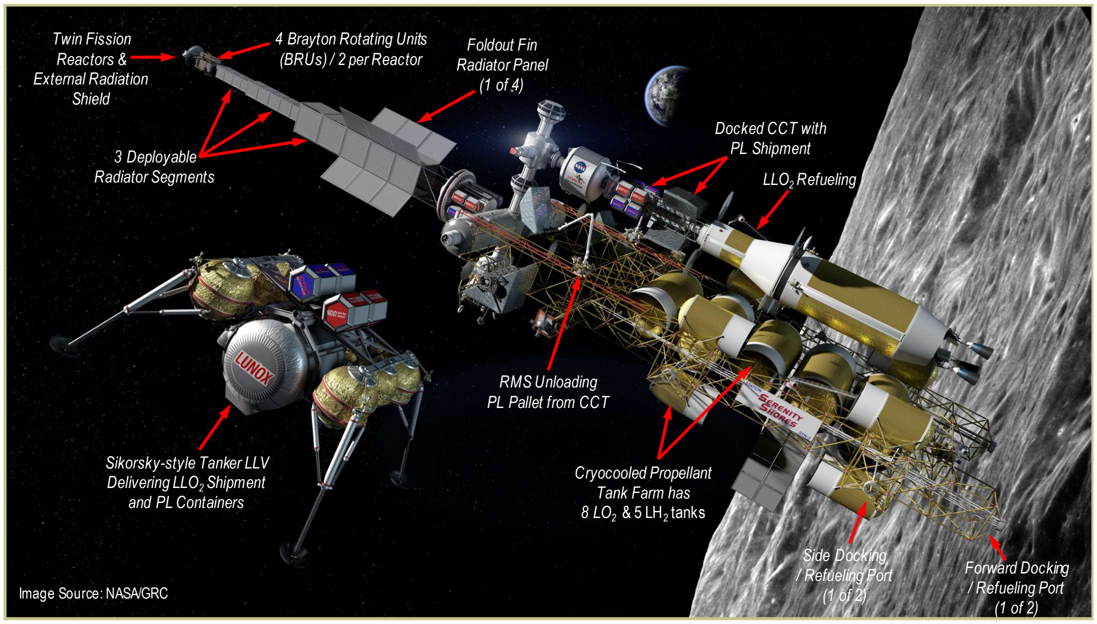

Figure 16. *Serenity Shores* Commercial LLO STN – Key Features and Activities

One-way transit times to and from the Moon on the order of ~72 hr 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 Figure 17 shows, decreasing the Earth-to-Moon transit time from 72 to 36 hours increases the outbound ΔV requirement from ~4.0 to 4.9 km/s and the total roundtrip ΔV requirement by ~1.8 km/s. Decreasing 1-way flight times from 72 to 24 hr increases the round trip ΔV requirement by ~4.9 km/s, to ~12.9 km/s! As a result, long lifetime engines and LDP for refueling will be needed for LTVs of reasonable size.

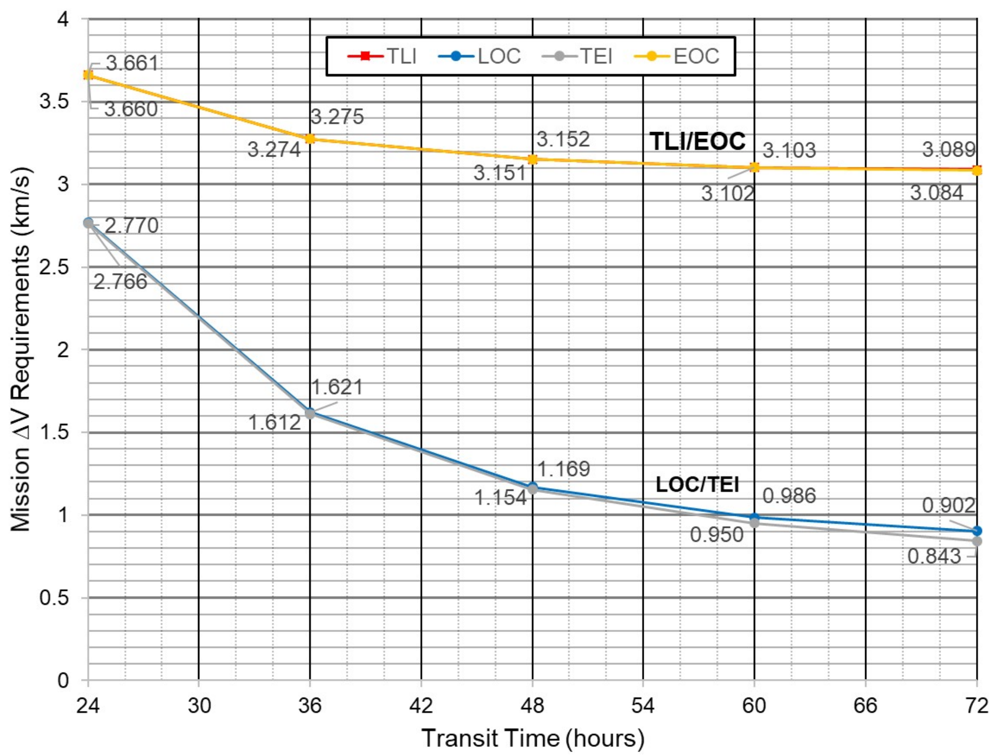

Figure 17. Variation of Mission ΔV Values with Flight Time (LEO to LLO to LEO)

To access the STN in its assumed 300-km circular LPO, a three-burn LOC maneuver is utilized. The first burn captures the CCT or commuter shuttle into a highly elliptical orbit around the Moon with a perigee altitude of 300 km – the same as the final parking orbit. A second burn is then performed at apogee to change the plane of the orbit to match the inclination of the desired parking orbit – in this case 90° for LPO. The third and final burn is performed near perigee to lower the orbit's apogee resulting in the final 300-km circular LPO. The duration of the LOC maneuver can range from several hours to a day to complete. A short 2.5-hr duration is baselined in this paper but it requires a larger total capture ΔV.

Like the capture maneuver, TEI requires three burns and 2.5 hr to complete. The first burn raises the apogee of the orbit, resulting in a highly elliptical orbit around the Moon. The second burn is a plane change burn performed near apogee that adjusts and aligns the plane of the elliptical orbit from 90° to that needed for departure. The third and final burn is again performed near perigee and after it's completed, the LTV has escaped the Moon and is on its trajectory back to Earth.

Figure 18 shows the variation in mission ΔV for flights to and from LPO as a function of transit time but does not include the additional 2.5hr required for the LPO insertion and departure maneuvers. Decreasing the Earth-to-Moon transit time from 72 to 36 hours increases the outbound ΔV requirement from ~4.2 to 4.9 km/s and the total roundtrip ΔV requirement by ~2.6 km/s. Decreasing the 1-way flight times further to 24 hr increases the round trip ΔV requirement by ~5.6 km/s, to ~14.2 km/s, indicating the extreme difficulty of performing fast transit missions to LPO involving short insertion and departure times.

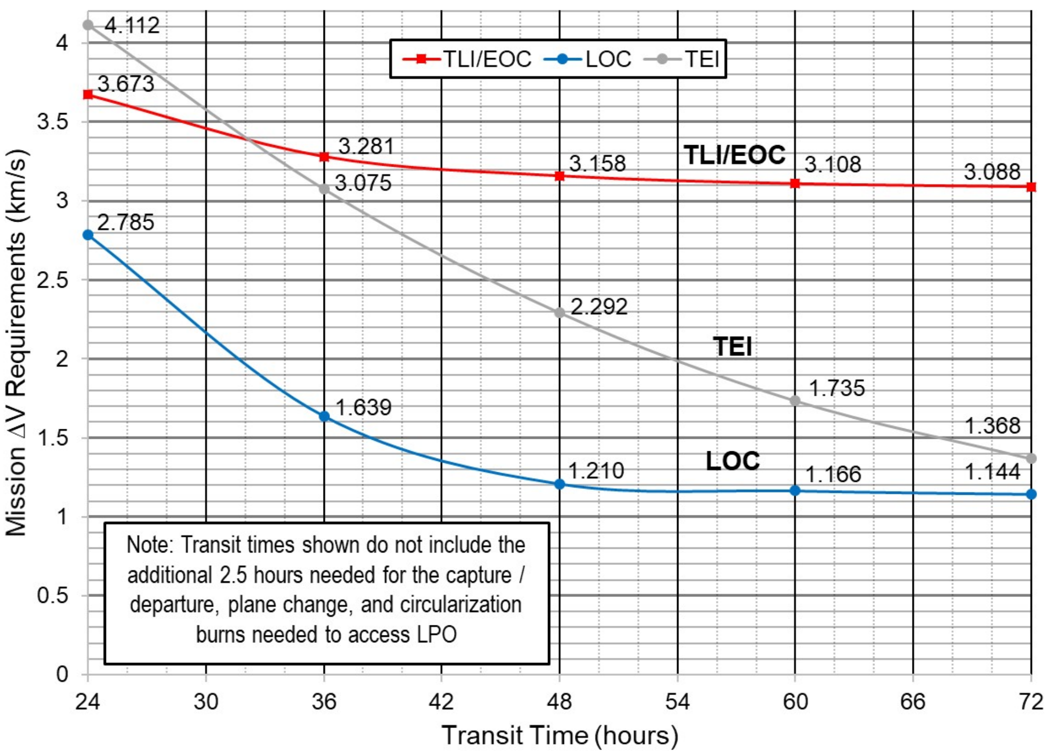

Figure 18. Variation of Mission ΔV Values with Flight Time (LEO to LPO to LEO)

6.0 *Conestoga* – A Reusable, Space-based Crewed Cargo Transport (CCT)

The original Conestoga wagon was a freight wagon developed in Lancaster County, Pennsylvania in the early 1700s [58] 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 Figure 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) [59]

Named after its earlier ancestor, the *Conestoga* crewed cargo transport, shown in Figure 20, is a space-based, reusable LTV that uses a clustered 3-engine propulsion stage (PS) and can refuel with LDPs. *Conestoga* has its own dedicated habitat module that supports a crew of four and has a mass of ~10 t. Two crewmembers operate the vehicle and manage the unloading of the PL. The other two represent rotating crewmembers on assignment at the lunar base or the lunar STN. Connecting the habitat module to the rest of the CCT is a 16-m long, four-sided star truss that can carry a variety of different payloads ranging in size from the small PL container weighing ~675 kg to the larger, wedge-shaped PL pallet weighing 2.5 t. To accommodate the large, wedge-shaped pallets, the sides of the star truss are also concave – a feature similar to the upward curving ends of the Conestoga wagon's bed, although not for the same reason. In Figure 20, *Conestoga* is outfitted with 4 large PL pallets and 16 small shipping containers for a total PL mass of 20 t.

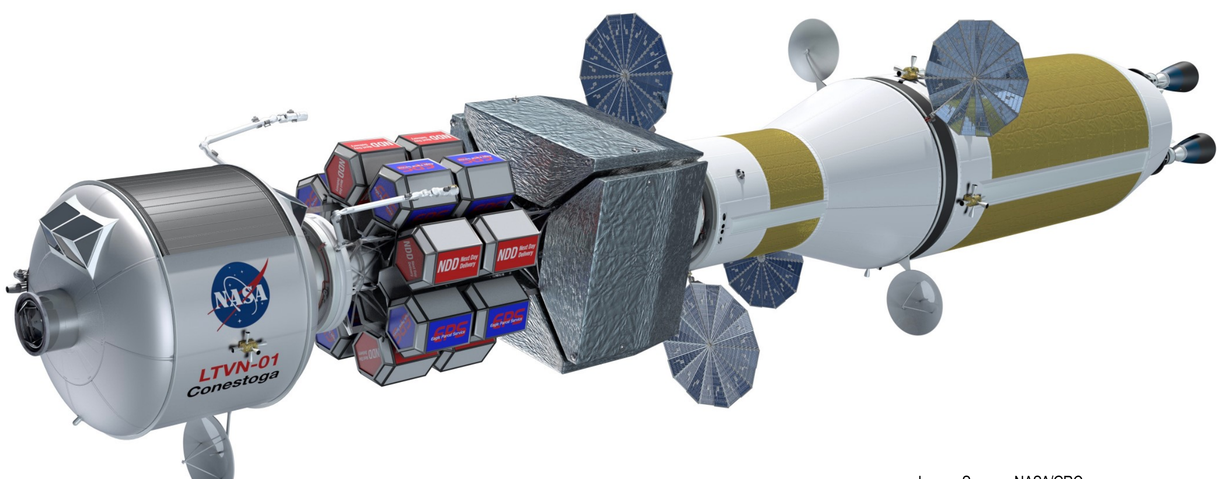

Image Source: NASA/GRC

Figure 20. *Conestoga* – A Space-based Crewed Cargo Transport uses a Common PS and In-Line LO_2 Tank

Attached to the star truss's 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 (visible in Fig. 21), the crew can use these manipulator arms to unload and attach cargo to co-orbiting LLVs when operating away from the lunar STN. Refueling ports and twin PVAs are also located at the forward ends of both the PS and in-line LO_2 tank assembly for refueling in LEO and lunar orbit, and for powering the PS and forward habitat. Other key features and dimensions of *Conestoga's* four main elements are shown in Figure 21.

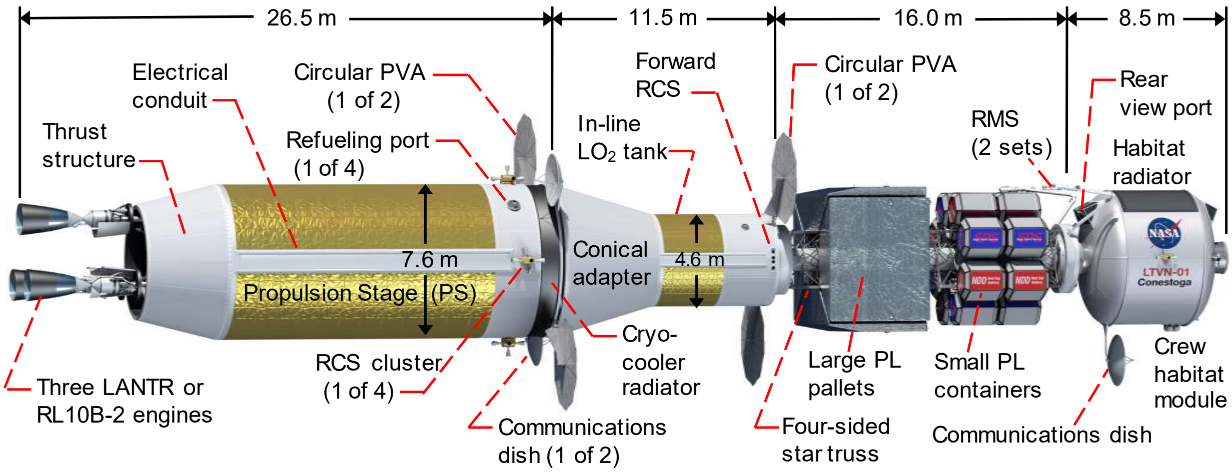

Figure 21. Key Features and Dimensions for the *Conestoga* Crewed Cargo Transport

The *Conestoga* CCT is a versatile vehicle that can deliver varying amounts of cargo (from 10 to 40 t) to lunar orbit depending on the desired transit times out to the Moon and back. Once loaded with cargo and propellant, *Conestoga* separates from the LEO STN (Fig. 22a), performs the TLI burn and departs for the Moon (Fig. 22b). After capture into either lunar equatorial or polar orbit, *Conestoga* rendezvous and docks with the lunar STN where its PL is removed, and its propellant tank(s) are refueled for the trip back to Earth as shown earlier in Figure 16.

As mentioned previously, the performance of the Conestoga CCT using both LANTR and chemical RL10B-2 engines is examined in this study. The RL10B-2 engines operate at a fixed thrust level, O/H MR, and specific impulse. The LANTR engines, however, are sized with the appropriate hardware mass (pumps, controls, lines, etc.) to allow operation over the full range of O/H MRs from 0 to 5 during the mission. A multidisciplinary analysis and mission assessment code (MAMA) with optimization capability [60] is used to determine the propellant requirements for the various missions examined. By giving the optimizer control over the O/H MRs used for the individual mission burns, initial propellant loading and refueling amounts, one can find the minimum propellant requirements needed to complete the mission. Depending on the specified mission objective, the optimizer can be used to minimize the total propellant, Earth-supplied propellant, or lunar-supplied propellant usage. Alternatively, one can explore other possibilities by giving the optimizer control over cargo mass or transit times. Using this capability, one can determine the maximum cargo that can be delivered for a given mission scenario and vehicle configuration,

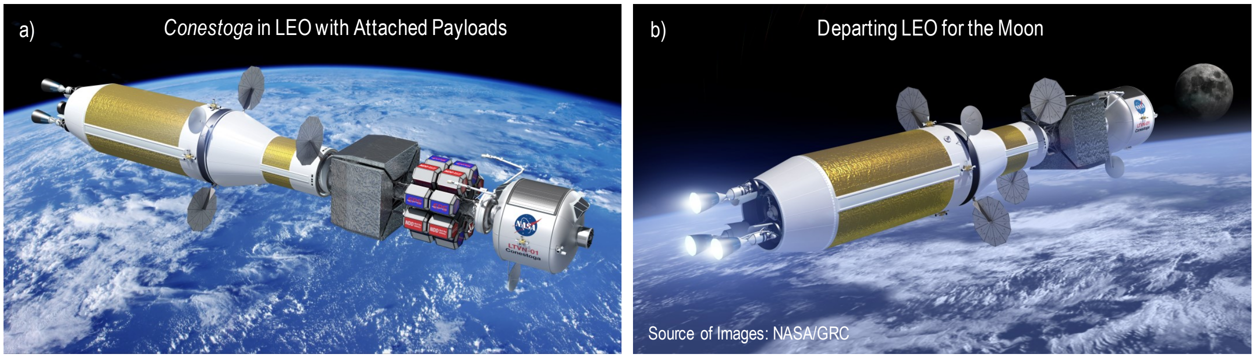

Figure 22. *Conestoga* Crewed Cargo Transport Mission – LEO STN Separation and Departure for the Moon

along with the propellant and refueling requirements. In contrast to only using LLO_2 for CCT refueling in LLO [44], access to both LPI-derived LO_2 and LH_2 in LPO opens up the mission trade space, and the addition of LLH_2 can be leveraged to reduce the IMLEO and total propellant requirements for various mission types despite the larger ΔV needed to access LPO.

Table 4 provides a comparison of CCT mission trip times to LPO and LLO using different propulsion options. Also shown are the total mission ΔV, engine burn time, IMLEO, and the propellant requirements in both LEO and lunar orbit, for the different mission scenarios. All the cases shown use the same common PS and in-line LO_2 tank assembly as that shown in Figures 14 and 21.

In Case 1, the mission objective is to determine the minimum amount of LO_2 and LH_2 propellant required for a LANTR-propelled *Conestoga* CCT to deliver 20 t of PL to LPO. The transit time to the Moon is 72 hr followed by an additional 2.5 hr required to complete the 3-burn LPO insertion maneuver. The mission begins with the CCT filling its LH_2 PS and in-line LO_2 tank with ~39.8 t of LH_2 and ~62.2 t of LO_2 (~56% of maximum capacity) at the LEO STN. During the outbound mission leg, the CCT's LANTR engines run H_2-rich (O/H MR ~2.6, I_{sp} ~604 s for TLI, and MR ~0.4, I_{sp} ~818 s for LOC), and burn all of the loaded LO_2 and ~81.2% of the LH_2 (~32.3 t). This includes the additional LH_2 needed for engine cooldown after each burn. The MR and I_{sp} values listed for LOC are the averaged values for the 3-burn, LPO insertion maneuver.

Following insertion, *Conestoga* rendezvous and docks with the LPO STN. Here its cargo is unloaded and its propellant tanks are refilled (at an 8:1 ratio) with ~54.3 t of LLO_2 and ~6.8 t of excess LLH_2 produced during the electrolysis of LH_2O delivered to the STN by tanker LLVs. The ~6.8 t of "top off" LLH_2 supplements the ~6.7 t of ELH_2 remaining in *Conestoga's* PS. After refueling, *Conestoga* picks up 250 kg of lunar samples, separates from the STN, performs the 3-burn LPO departure maneuver, and begins its 72-hr trip back to Earth.

Table 4. CCT Missions Options, Trip Times, ΔV Budgets, Burn Times, and LDP Refueling Needs

Case Description *	Objective	Transit Times/Orbits**/ Mission ΔV***and Burn Times	LH_2 Propulsion Tank and In-line LO_2 Tank	Start Mass and Propellant Needs
1. LANTR Crewed Cargo Transport (CCT) with 9.9 t-hab module and 16-m star truss carries 20 t of cargo to LPO	Determine the minimum LO_2 and LH_2 required (both in LEO and in LPO) to deliver 20 t of cargo to LPO assuming an 8:1 refueling ratio	72-hr 1-way transit times LEO → LPO → LEO ΔV ~8.378 km/s Engine Burn Time ~29.7 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~186.3 t; ~62.24 t LO_2 and ~39.8 t LH_2 supplied at LEO STN; ~54.3 t LLO_2 and ~6.78 t LLH_2 supplied at LPO STN
2. RL10B-2 CCT with 9.9 t-hab module and 16-m star truss carries 20 t of cargo to LPO	Determine the minimum LO_2 and LH_2 required (both in LEO and in LPO) to deliver 20 t of cargo to LPO assuming an 8:1 refueling ratio	72-hr 1-way transit times LEO → LPO → LEO ΔV ~8.490 km/s Engine Burn Time ~42.2 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~192.5 t; ~103.5 t LO_2 and ~20.5 t LH_2 supplied at LEO STN; ~55.6 t LLO_2 and ~6.95 t LLH_2 supplied at LPO STN
3. LANTR CCT with 9.9 t-hab module and 16-m star truss carries 20 t of cargo to LPO	Determine the minimum transit time, and the LO_2 and LH_2 required, to deliver 20 t of cargo to LPO assuming an 8:1 refueling ratio	~39.2-hr 1-way transit times LEO → LPO → LEO ΔV ~10.865 km/s Engine Burn Time ~34.1 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~234.6 t; ~111.2 t LO_2 and ~39.8 t LH_2 supplied at LEO STN; ~109 t LLO_2 and ~13.63 t LLH_2 supplied at LPO STN
4. RL10B-2 CCT with 9.9 t-hab module and 16-m star truss carries 20 t of cargo to LPO	Determine the minimum transit time, and the LO_2 and LH_2 required, to deliver 20 t of cargo to LPO assuming an 8:1 refueling ratio	~41.7-hr 1-way transit times LEO → LPO → LEO ΔV ~10.550 km/s Engine Burn Time ~57.6 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~202.9 t; ~111.2 t LO_2 and ~24.0 t LH_2 supplied at LEO STN; ~104.8 t LLO_2 and ~13.1 t LLH_2 supplied at LPO STN
5. LANTR CCT with 9.9 t-hab module and 16-m star truss carries 20 t of cargo to LLO	Determine the LO_2 required (both in LEO and LLO) to deliver 20 t of cargo to LLO	72-hr 1-way transit times LEO → LLO → LEO ΔV ~8.049 km/s Engine Burn Time ~25.3 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~195.3 t; ~74.7 t LO_2 and ~39.8 t LH_2 supplied at LEO STN; ~54.9 t LLO_2 supplied at LLO STN
6. RL10B-2 CCT with 9.9 t-hab module and 16-m star truss carries 20 t of cargo to LLO	Determine the LO_2 and LH_2 required (both in LEO and LLO) to deliver 20 t of cargo to LLO	72-hr 1-way transit times LEO → LLO → LEO ΔV ~8.145 km/s Engine Burn Time ~40.9 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~191.5 t; ~99.6 t LO_2 and ~26.6 t LH_2 supplied at LEO STN; ~54.65 t LLO_2 supplied at LLO STN
7. LANTR CCT with 9.9 t-hab module and 16-m star truss carries 20 t of cargo to LLO	Determine the minimum transit time, and the LO_2 required to deliver 20 t of cargo to LLO	~45.9-hr 1-way transit times LEO → LLO → LEO ΔV ~8.883 km/s Engine Burn Time ~25.3 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~231.8 t; ~111.2 t LO_2 and ~39.8 t LH_2 supplied at LEO STN; ~71.0 t LLO_2 supplied at LLO STN
8. RL10B-2 CCT with 9.9 t-hab module and 16-m star truss carries 20 t of cargo to LLO	Determine the minimum transit time, and the LO_2 and LH_2 required to deliver 20 t of cargo to LLO	~51.5-hr 1-way transit times LEO → LLO → LEO ΔV ~8.710 km/s Engine Burn Time ~45.7 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~206.2 t; ~111.2 t LO_2 and ~29.7 t LH_2 supplied at LEO STN; ~60.9 t LLO_2 supplied at LLO STN

*Cases 1 – 8 use a common LH_2 PS and in-line LO_2 tank assembly; Propellant depots assumed in LEO, LPO, and LLO; LANTR engines use optimized MRs out and back; RL10B-2 engines operate at fixed MR = 5.88:1; **LEO – 407 km, LPO and equatorial LLO – 300 km; ***Total round trip mission ΔV values include g-losses

On the inbound mission leg, *Conestoga's* engines run O_2-rich (MR ~5.0, I_{sp} ~516 s for TEI, and ~3.9 and ~557 s for EOC) and burn all of the available LO_2 (~54.3 t) and LH_2 (~13.5 t) remaining in *Conestoga's* tanks. For this mission, the IMLEO is ~186.3 t consisting of the PS (~73 t), the in-line LO_2 tank assembly and adaptor (~71 t), the star truss assembly with its RMS (~11.5 t) and attached PL (20 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 is ~8.378 km/s, and the total engine burn time is ~29.7 min, which includes the following individual burn times: ~14.1 min (TLI), ~6.8 min (LOC), ~2.2 min (TEI), and ~6.6 min (EOC).

Case 2 has the same mission objective as Case 1 but here the *Conestoga* uses three RL10B-2 engines on its PS. In contrast to the LANTR engines, the RL10B-2 engines operate with a fixed thrust = 24.75 klb_f, O/H MR = 5.88:1, and I_{sp} = 465.5 s out and back. Before departing the LEO STN with its 20 t of cargo, *Conestoga's* LH_2 PS and in-line LO_2 tank are filled with ~20.5 t of LH_2 and ~103.5 t of LO_2 (~52% and 93% of their maximum capacities). During the outbound transfer to LPO, *Conestoga* burns all of its available LO_2 (~101.2 t) and 84% of LH_2 (~17.2 t). After R&D with the STN, *Conestoga* again transfers its PL, picks up its returning lunar samples, and refuels with ~55.6 t of LLO_2 and ~6.95 t of excess LLH_2 satisfying the 8:1 refueling ratio, and supplementing the ~2.5 t of LH_2 remaining in the PS. On the inbound mission leg, the RL10B-2 engines use all 55.6 t of LO_2 and 9.45 t of LH_2.

The IMLEO for Case 2 is ~192.5 t which includes the PS (~39 t), the in-line LO_2 tank assembly (~111.7 t), the star truss assembly with its RMS (~11 t) and attached PL (20 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 is ~8.490 km/s, and the total engine burn time is ~42.2 min with the individual burn times as follows: ~22.5 min (TLI), ~4.7 min (LOC), ~4.3 min (TEI), and ~10.7 min (EOC).

There are several noticeable differences between Cases 1 and 2, the first being the PS mass. For the RL10B-2 CCT, the PS mass is ~53% that of the LANTR CCT. This is due to the heavier mass of a LANTR engine (~9.5 times that of its RL10B-2 counterpart) and the need for additional shield mass on each engine to reduce crew radiation exposure during the mission. Despite its lower PS mass, the RL10B-2 CCT's engines operate at a lower I_{sp} (465.5 s) and require ~22 t of additional propellant at the start of the mission. By contrast, the LANTR engines in Case 1 operate at low MRs and much higher I_{sp}-values during the TLI and LOC maneuvers resulting in a lower propellant consumption and IMLEO. A final significant difference between Cases 1 and 2 is the engine burn time. With its larger propellant loading out and back, and lower I_{sp}, the total engine burn time for the RL10B-2 CCT (~42.2 min), is 12.5 min longer than the LANTR option. The reported performance characteristics of the RL10B-2 engine [51], indicate a service life of ~3500 s (~1 hr) and the number of starts at 15. For a truly reusable space-based LTS, the engine service life and number of starts will need to be increased by a factor of ~5 -10 to avoid costly and time-consuming engine replacements over the lifetime of the LTV.

In Case 3, the mission objective is to determine the minimum transit time required for the LANTR-powered *Conestoga* CCT to deliver its cargo to LPO, along with the propellant needed in LEO and LPO to accomplish this objective. For this case, the 1-way transit times to and from the Moon are reduced from 72 to ~39.2 hr not including the additional 2.5 hr required for the 3-burn LPO insertion and departure maneuver. At the start of the mission *Conestoga's* LH_2 PS and in-line LO_2 tank are filled to their maximum capacity and its engines run O_2-rich on the outbound mission leg (O/H MR ~4.4 for TLI, and ~3 for LOC). During the outbound mission leg, the CCT uses all of its available LO_2 (~108.9 t) and ~70% of its LH_2 (~23.6 t) including that needed for engine cooldown. At the STN, *Conestoga* refuels with ~109 t of LLO_2 and ~13.63 t of excess LLH_2 at the specified 8:1 refueling ratio. This top off LLH_2 supplements the ~11.7 t of LH_2 remaining in the PS for Earth return. On the inbound mission leg, the LANTR engines again run O_2-rich (MR ~5 and ~3.8 for TEI and EOC, respectively) and use all the remaining propellant (~109 t of LO_2 and ~25.34 t of LH_2) in *Conestoga's* tanks. The mission IMLEO is ~234.6 t, which includes the PS (~72.7 t), the in-line LO_2 tank assembly (~119.6 t), the star truss assembly with its RMS (~11.5 t) and attached PL (20 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 is ~10.864 km/s, and the total engine burn time is ~34.1 min, which includes the following individual burn times: ~13.3 min (TLI), ~4.3 min (LOC), ~9.5 min (TEI), and ~7 min (EOC).

Case 4 has the same mission objective as 3 but uses RL10B-2 engines. With the lower performance of the engines, the 1-way transit times are slightly longer at ~41.7 hr, but the IMLEO is lower at ~202.9 t due primarily to the lower mass of the PS at ~42.3 t. Also, because the LANTR engines run O_2-rich in Case 3, their I_{sp} advantage for this more demanding mission is reduced. As a result, the RL10B-2 option requires less propellant loading in both LEO and LPO. The total mission ΔV is also slightly lower at ~10.550 km/s (due to reduced gravity losses), but the total engine burn time is near the service lifetime of the RL10B-2 at ~57.6 min, which includes the following burn times: ~23.6 min (TLI), ~5.8 min (LOC), ~17.3 min (TEI), and ~10.9 min (EOC).

In Cases 5 through 8, the CCT operates between LEO and equatorial LLO, uses only ELH_2, and refuels with only LLO_2 before returning to Earth. In Case 5, the mission objective is to determine the minimum amount of LO_2 propellant required (both in LEO and LLO) for a LANTR-powered CCT to deliver 20 t to LLO. The 1-way transit time to and from the Moon is again 72 hr. For this mission, the CCT's LH_2 tank is filled to maximum capacity (~39.8 t) and its in-line LO_2 tank to ~67% capacity (~74.7 t) at the LEO STN. During the outbound mission leg, the CCT's LANTR engines run at O/H MR and I_{sp} values of ~3.3 and ~604 s for TLI, and ~1.5 and ~818 s for LOC, and burn all of the available LO_2 (~72.4 t) and ~66% of the LH_2 (~25.7 t), including that needed for engine cooldown.

Following capture, *Conestoga* rendezvous and docks with the LLO STN, unloads it cargo, and refills its in-line LO_2 tank with ~54.8 t of LLO_2 propellant routinely delivered to the STN by LLO_2 tanker LLVs. After refueling *Conestoga* picks up 250 kg of lunar samples, separates from the STN, performs the TEI maneuver, and begins its 72-hr trip back to Earth. On the inbound mission leg, *Conestoga's* engines run O_2-rich (MR ~4.3, I_{sp} ~541 s for TEI, and ~4.2 and ~544 s for EOC) and burn all of the loaded LLO_2 and the remaining ~13.3 t of LH_2 in the PS tank. For this mission, the IMLEO is ~195.3 t which includes the PS (~71.3 t), the in-line LO_2 tank assembly (~81.7 t), the star truss with its RMS (~11.5 t) and attached PL (20 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 is ~8.049 km/s, and the total engine burn time is ~25.3 min, which includes the following individual burn times: ~12.9 min (TLI), ~3.8 min (LOC), ~2.4 min (TEI), and ~6.2 min (EOC).

In Case 6, the CCT uses RL10B-2 engines and again delivers 20 t of cargo to LLO in 72 hr. However, because the engines operate with a higher O/H MR (5.88:1) that is constant throughout the mission, the objective here is to determine the minimum LO_2 and LH_2 refueling required at the LEO and LLO STNs to accomplish the mission. Before TLI, the RL10B-2 CCT loads ~99.6 t of LO_2 and ~26.6 t of LH_2 at the LEO STN. During the outbound mission leg, the engines burn all of the available LO_2 (~97.3 t) and ~64% of the available LH_2 (~16.55 t). The CCT then rendezvous and docks with the LLO STN, unloads it cargo and refuels with ~54.6 t of LLO_2. It then picks up 250 kg of lunar samples, separates from the STN, performs the TEI maneuver, and begins its 72-hr trip back to Earth. On the inbound mission leg, the CCT burns the loaded LLO_2 and the ~9.3 t of LH_2 remaining in the PS. The IMLEO for this case is ~191.5 t which includes the PS (~43.6 t), the in-line LO_2 tank assembly (~106.3 t), the star truss with its RMS (~10.8 t) and attached PL (20 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 is at ~8.145 km/s and the total engine burn time is ~40.9 min, which includes the following burn times: ~22.3 min (TLI), ~3.9 min (LOC), ~4.3 min (TEI), and ~10.4 min (EOC).

In Case 7, the mission objective is to determine the minimum transit time required for the LANTR-powered CCT to deliver its 20 t cargo to LLO, along with the propellant needed in LEO and LLO to accomplish this objective. For this case, the 1-way transit times to and from the Moon are reduced from 72 to ~45.9 hr. At the beginning of the mission the CCT's PS LH_2 tank and in-line LO_2 tank are filled to their maximum capacity and its engines run O_2-rich on the outbound mission leg (with O/H MR and I_{sp} values of ~4.9 and ~517 s for TLI, and ~3.4 and ~573 s for LOC). During the transfer to LLO, the CCT uses all of its available LO_2 (~108.9 t) and ~62.5% of its LH_2 (~24.3 t) including that needed for engine cooldown. After rendezvous and docking with the LLO STN, the CCT unloads its cargo and refuels with ~71 t of LLO_2. It then picks up returning lunar samples, separates from the STN, and performs the TEI maneuver to begin the 45.9-hr trip back to Earth. On the inbound mission leg, the LANTR engines run O_2-rich (MR ~5 and I_{sp} ~516 s for both TEI and EOC), burning all the loaded LO_2 (~71 t) and the remaining LH_2 (~14.62 t) in the CCT's propellant tanks. The mission IMLEO is ~231.8 t, which includes the PS (~71.3 t), the in-line LO_2 tank assembly (~118.2 t), the star truss assembly with its RMS (~11.5 t) and attached PL (20 t), the habitat module (9.9 t), consumables (~0.1 t), plus the crew and passengers with their EVA suits (~0.8 t). The total mission ΔV is ~8.883 km/s, and the total engine burn time is ~25.3 min, which includes the following individual burn times: ~12.2 min (TLI), ~3.6 min (LOC), ~3.5 min (TEI), and ~6 min (EOC).

Case 8 has the same mission objective as 7 but here the CCT uses RL10B-2 engines to deliver its 20 t of cargo to LLO. For this case, the 1-way transit time is slightly longer than Case 7 at ~51.5 hr but the IMLEO is more than 25 t lower at ~206.2 t due to both the lower mass of the PS (~46.7 t) and the LH_2 propellant loading required in LEO (~29.7 t versus ~39.8 t for the LANTR option). Also, because the LANTR engines again run O_2-rich in Case 7, the I_{sp} gap between the LANTR and RL10B-2 engines is reduced leading to a lower propellant loading requirement in both LEO and LLO for the RL10B-2 option. The total mission ΔV is also slightly lower at ~8.710 km/s (due to reduced gravity losses), but the total engine burn time is longer at ~45.7 min, which includes the following individual burn times: ~24.4 min (TLI), ~4.9 min (LOC), ~5.8 min (TEI), and ~10.6 min (EOC).

Summary of Findings: For CCT missions to LPO using both LANTR and RL10B-2 propulsion, refueling with LPI-derived LO_2 and LH_2 helps reduce IMLEO and the resupply propellants that need to be delivered to the LEO STN. With 72-hr transit times, LANTR engines can run H_2-rich outbound and O_2-rich inbound lowering the CCT's refueling requirements in both LEO and LPO, and the total burn time on its engines to just under 30 min. When using RL10B-2 engines, with their higher O/H MR, the CCT requires more LO_2 at the beginning of the mission resulting in a slightly larger IMLEO. The engine burn time for the mission is also longer, just over 42 min. For minimum transit time CCT missions on the order of 40 hr, the LANTR engines run O_2-rich out and back narrowing their I_{sp} advantage over the RL10B-2. This plus the heavier mass of the LANTR engines and their shielding increases the IMLEO for CCTs using this option compared to those using RL10B-2 engines. For CCT missions to LLO, the same general trends are observed, although without the additional ΔV required to access and depart from LPO, the total mission ΔVs are noticeably lower, especially for the minimum transit time missions, as are the engine burn times for both options.

With improvements in engine service lifetime, and the availability of LDPs at strategically positioned STNs in lunar polar and equatorial orbits, *Conestoga-class* CCTs, like those shown in Figure 23, can provide the basis for a robust and flexible LTS that offers a wide range of cargo delivery capability and transit times. 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.

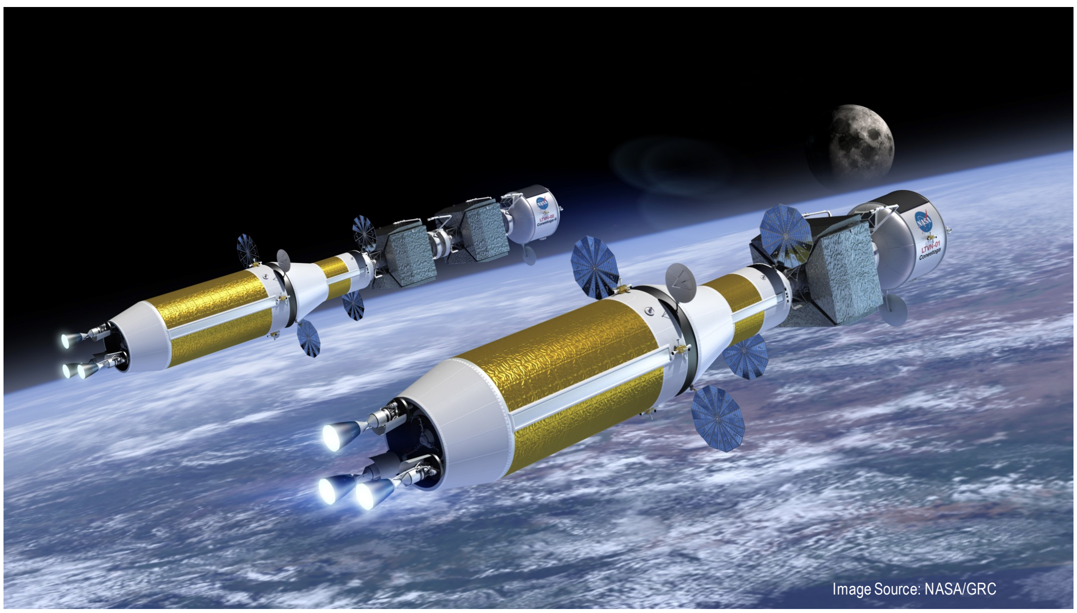

Figure 23. *Conestoga-class* Crewed Cargo Transports Departing LEO for the Moon

7.0 Feasibility of Commuter Shuttle Missions to the Moon

In *2001: A Space Odyssey* [1], Dr. Heywood Floyd must attend an important meeting – a meeting on the Moon. He departs from a large AG space station orbiting Earth and arrives there 25 hr later [61] 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, more than 50 years later, the images portrayed in Kubrick and Clarke's film remain well beyond our capabilities and *2100: A Space Odyssey* seems a more appropriate title for the movie. In this section, the feasibility and requirements for commuter flights to the Moon using advanced chemical and LANTR propulsion, along with LDPs, are evaluated to see if the operational capabilities presented in *2001* can be achieved albeit on a more spartan scale.

A 24-hr 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-hr layover in San Francisco. As Figure 17 shows, decreasing the Earth-to-Moon transit time from 72 to 36 hr increases the outbound ΔV requirement from ~4.0 to 4.9 km/s and the total roundtrip ΔV requirement by ~1.8 km/s. Decreasing the flight time from 72 to 24 hr each way increases the round trip ΔV requirement by ~4.9 km/s, to ~12.9 km/s! At these higher velocities, free return trajectories are also no longer available, so multiple engines will be required to improve reliability and increase passenger safety.

What might a typical commuter flight to the Moon involve? It might originate from a future commercial artificial gravity station (AGS) like *Ad-Venture* shown below in Figure 24. Operating in LEO, *Ad-Venture* is powered by a 2.5 MW_e FPS [57] and has facilities supporting a variety of activities including zero-gravity R&D, manufacturing, emerging cislunar industries, and space tourism. The rotation rate (ω = 2 rpm) and radius (~37.5 m) of *Ad-Venture's* habitation modules produce a $1/6^{th}$g AG level providing Earth tourists the opportunity to experience what it would be like to live on the Moon. Similarly, long-time lunar colonists and individuals born on the Moon in the future could also travel to LEO to experience Earth's beauty "up close and personal" while being exposed to a comfortable lunar gravity environment.

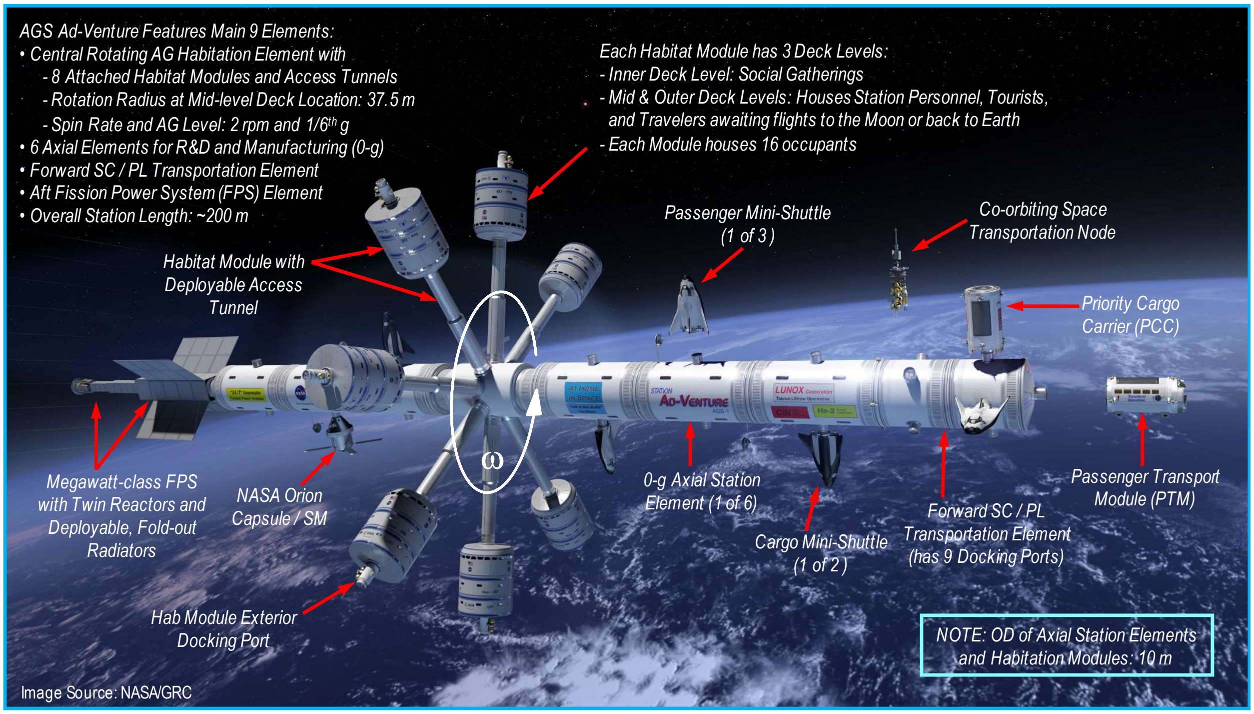

Figure 24. Features, Characteristics, and Activities at Commercial AGS *Ad-Venture*

Ad-Venture also functions as a transportation hub for flights to and from the Moon. Its forward transportation element has multiple docking ports to accommodate a variety of spacecraft (SC) and PLs. A possible scenario for a commuter flight to the Moon might start with passengers boarding an Earth-to-orbit (ETO) mini-shuttle for a flight to *Ad-Venture* shown in Figure 25a. There they would enter a PTM containing its own life support, power, instrumentation and control, and RCS. The PTM provides the "brains" for the commuter shuttle and is home to the 18 passengers and 2 crewmembers operating it while on route to the Moon. After undocking from *Ad-Venture* (Fig. 25b), the PTM rendezvous and docks with the refueled shuttle awaiting it a safe distance away (Fig. 25c). Shortly thereafter, following system checkout, the shuttle fires its engines to depart LEO and the commuter flight to the Moon begins (Fig. 25d).

Following the ~1-1.5-day transfer, the shuttle captures into lunar orbit where the PTM detaches and docks with a waiting "Sikorsky-style" LLV (Fig. 26a) that delivers it to the lunar surface. The "orbit to surface" transfer time is assumed to be ~1 hr. From here the PTM is lowered to a "flatbed" surface vehicle (Fig. 26b) 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 Fig. 26c and the lower right corner of Fig. 9). This scenario is reversed on the return trip to Earth (Fig. 26d). During the PTM transfer to the lunar surface and back again, the *Serenity Shores* STN (Fig. 16) supplies the shuttles with the LDPs needed for their return to Earth.

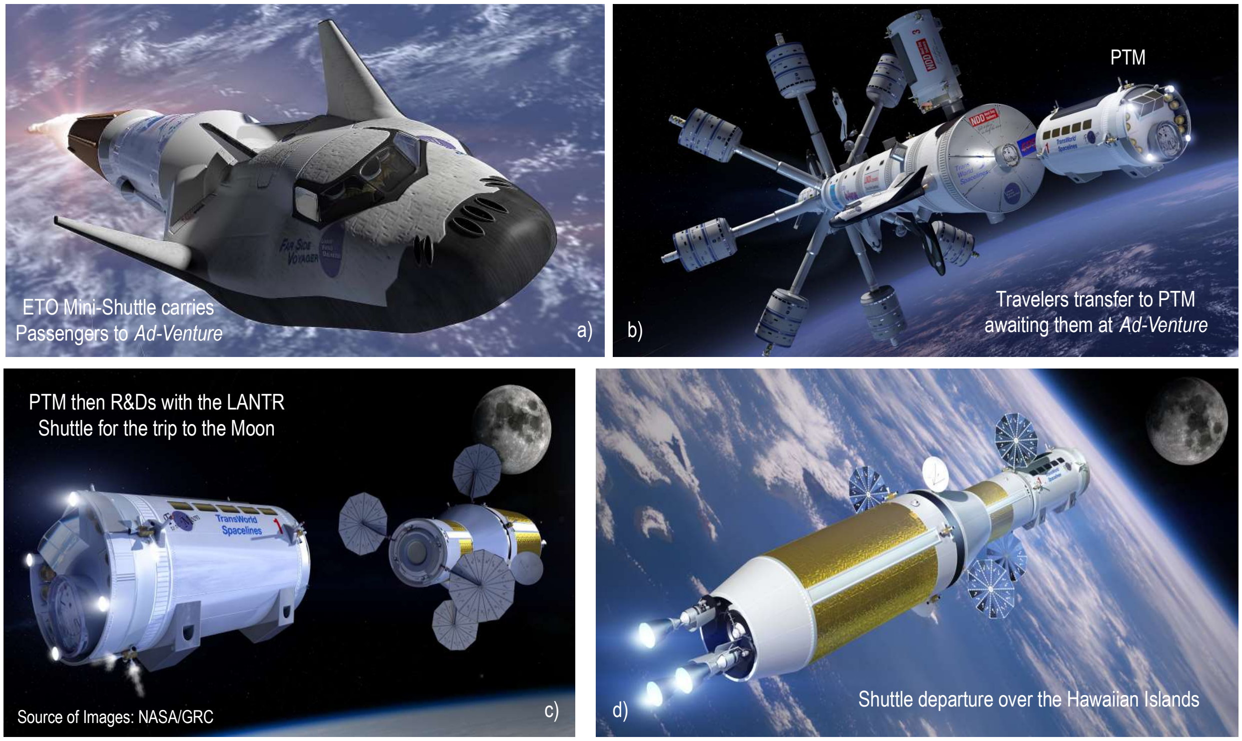

Figure 25. Commuter Shuttle Mission to the Moon – Liftoff, LEO Operations, and Departure Mission Phases

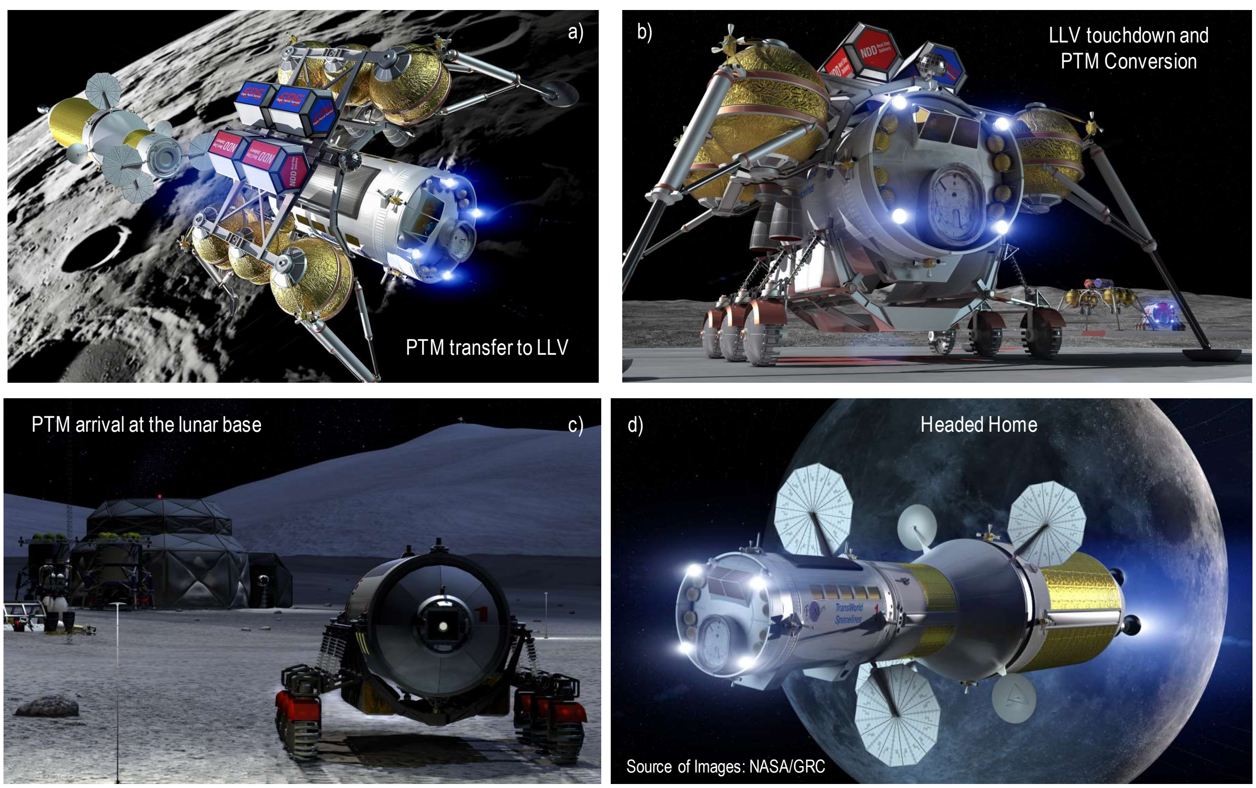

Figure 26. Commuter Shuttle Mission to the Moon – Arrival, Landing, and Return Mission Phases

The commercial commuter shuttle we envision utilizes the same PS, engine types, and in-line LO_2 tank assembly used on the *Conestoga* CCT shown in Figure. 20. 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 Figure 27). The fully loaded PTM has an estimated mass of ~15 t and its OD and length are ~4.6 m by ~8 m, respectively.

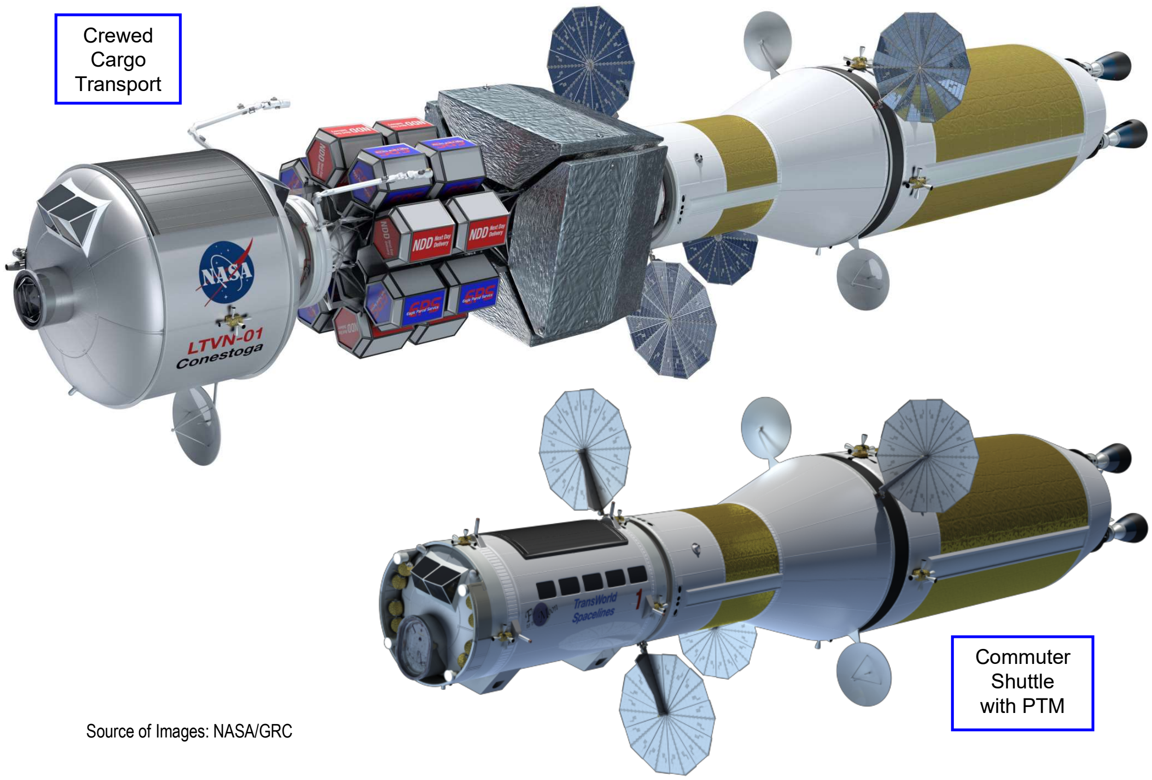

Figure 27. Relative Size of a CCT and Commuter Shuttle using a Common PS and In-Line LO_2 Tank Assembly

Table 5 provides a sampling of the different chemical and LANTR shuttle missions to LPO and LLO considered in this study. The mission objective for Cases 1 through 8 is to reduce trip time, and determine the LDP refueling requirements, engine burn times, and IMLEO needed to achieve the times shown. Cases 1 through 8 use the same PS, clustered engines, and in-line LO_2 tank assembly used on the *Conestoga-class* vehicles summarized in Table 4.

In Case 1, a LANTR-powered commuter shuttle transports the PTM to and from LPO and then refuels with LLO_2 and the excess LLH_2 produced during the electrolysis of LH_2O delivered to the polar STN by water tanker LLVs. The ~33.5-hr 1-way transit times to and from LPO include the additional 2.5-hr for the LPO insertion and departure maneuvers used in this study. To reach the Moon in ~31 hours, the shuttle's LH_2 PS and in-line LO_2 tank are filled to their maximum capacity and its LANTR engines run O_2-rich on the outbound mission leg (O/H MR ~5 for TLI, and ~4 for LOC). During the outbound mission leg, the shuttle uses ~98% of its available LO_2 (~108.9 t) and ~60% of its LH_2 (~23.6 t) including that needed for engine cooldown. At the STN, the shuttle refuels with ~109 t of LLO_2 and ~13.63 t of excess LLH_2 available after water electrolysis to supplement the ~15.3 t of LH_2 remaining in the PS for Earth return. On the inbound mission leg, the shuttle's engines again run O_2-rich (MR ~4.6 and ~3 for TEI and EOC, respectively) and use ~109 t of LO_2 and ~28.9 t of LH_2 including cooldown. The mission IMLEO is ~207.5 t, which includes the PS (~72.8 t), the in-line LO_2 tank assembly and conical adaptor (~119.7 t), and the PTM (15 t). The total mission ΔV is ~12.326 km/s, and the total engine burn time is ~34.1 min, which includes the following individual burn times: ~11.3 min (TLI), ~4.1 min (LOC), ~11.4 min (TEI), and ~7.3 min (EOC).

Case 2 uses RL10B-2 engines on the shuttle's propulsion stage to transport the PTM to and from LPO and again assumes an 8:1 refueling ratio. The 1-way transit times are slightly longer at ~36.6 hr (including the additional 2.5 hr for the LPO insertion and departure maneuvers) but the IMLEO is substantially lower at ~141.4 t, which includes the PS (~36.6 t), the in-line LO_2 tank assembly and adaptor (~89.8 t), and the PTM (15 t). The reduced IMLEO is

Table 5. Fast Shuttle Mission Options, Trip Times, ΔV Budgets, Burn Times, and LDP Refueling Needs

Case Description *	Objective	Transit Times/Orbits**/ Mission ΔV***and Burn Times	LH_2 Propulsion Tank and In-line LO_2 Tank	Start Mass and Propellant Needs
1. LANTR commuter shuttle carrying 15 t Passenger Transport Module (PTM) to LPO then back to LEO	Determine the minimum transit time, and the LO_2 and LH_2 required, to deliver the PTM to and from LPO assuming an 8:1 refueling ratio	~33.5-hr 1-way transit times LEO $\rightarrow$ LPO $\rightarrow$ LEO ΔV ~12.326 km/s Engine Burn Time ~34.1 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~207.5 t; ~111.2 t LO_2 and ~39.75 t LH_2 supplied at LEO STN; ~109 t LLO_2 and ~13.63 t LLH_2 supplied at LPO STN
2. RL10B-2 commuter shuttle carrying 15 t PTM to LPO then back to LEO	Determine the minimum transit time, and the LO_2 and LH_2 required, to deliver the PTM to and from LPO assuming an 8:1 refueling ratio	~36.6-hr 1-way transit times LEO $\rightarrow$ LPO $\rightarrow$ LEO ΔV ~11.688 km/s Engine Burn Time ~51.1 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~141.4 t; ~82.8 t LO_2 and ~19.4 t LH_2 supplied at LEO STN; ~109 t LLO_2 and ~13.63 t LLH_2 supplied at LPO STN
3. RL10B-2 commuter shuttle carrying 15 t PTM to LPO then back to LEO	Determine the minimum transit time, and the LO_2 and LH_2 required, to deliver the PTM to and from LPO assuming a 5.88:1 refueling ratio	~36.6-hr 1-way transit times LEO $\rightarrow$ LPO $\rightarrow$ LEO ΔV ~11.691 km/s Engine Burn Time ~48.8 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~126.4 t; ~74.3 t LO_2 and ~13 t LH_2 supplied at LEO STN; ~109 t LLO_2 and ~18.53 t LLH_2 supplied at LPO STN
4. LANTR commuter shuttle carrying 15 t PTM to LLO then back to LEO	Determine the minimum transit time, and the LO_2 required, to deliver the PTM to and from LLO	~33.1-hr 1-way transit times LEO $\rightarrow$ LLO $\rightarrow$ LEO ΔV ~10.419 km/s Engine Burn Time ~25.3 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~204 t; ~111.2 t LO_2 and ~39.75 t LH_2 supplied at LEO STN; ~80.3 t LLO_2 supplied at LLO STN
5. RL10B-2 commuter shuttle carrying 15 t PTM to LLO then back to LEO	Determine the minimum transit time, and the LO_2 and LH_2 required, to deliver the PTM to and from LLO	~31.1-hr 1-way transit times LEO $\rightarrow$ LLO $\rightarrow$ LEO ΔV ~10.966 km/s Engine Burn Time ~50 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~181.9 t; ~111.2 t LO_2 and ~32.31 t LH_2 supplied at LEO STN; ~76.5 t LLO_2 supplied at LLO STN
6. RL10B-2 shuttle carries a 7.5 t Priority Cargo Container (PCC) to LLO then back to LEO	Determine the minimum transit time, and the LO_2 and LH_2 required, to deliver a PCC to and from LLO	~27.1-hr 1-way transit times LEO $\rightarrow$ LLO $\rightarrow$ LEO ΔV ~12.053 km/s Engine Burn Time ~49.1 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~173.6 t; ~111.2 t LO_2 and ~31.8 t LH_2 supplied at LEO STN; ~73.3 t LLO_2 supplied at LLO STN
7. LANTR commuter shuttle carrying 15 t PTM to LLO then back to LEO	Determine the minimum transit time, and the LO_2 and LH_2 required, to deliver the PTM to and from LLO assuming a 6.39:1 refueling ratio	24-hr 1-way transit times LEO $\rightarrow$ LLO $\rightarrow$ LEO ΔV ~13.030 km/s Engine Burn Time ~36.3 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~204.1 t; ~111.2 t LO_2 and ~39.75 t LH_2 supplied at LEO STN; ~109 t LLO_2 and ~17.05 t LLH_2 supplied at LLO STN
8. RL10B-2 commuter shuttle carrying 15 t PTM to LLO then back to LEO	Determine the minimum transit time, and the LO_2 and LH_2 required, to deliver the PTM to and from LLO assuming a 5.88:1 refueling ratio	~24.9-hr 1-way transit times LEO $\rightarrow$ LLO $\rightarrow$ LEO ΔV ~12.839 km/s Engine Burn Time ~56.9 min	7.6 m OD x ~15.65 m L (~39.75 t LH_2) 4.6 m OD x ~7.95 m L (~111.2 t LO_2)	IMLEO ~168.8 t; ~111.2 t LO_2 and ~19.32 t LH_2 supplied at LEO STN; ~102.1 t LLO_2 and ~17.36 t LLH_2 supplied at LLO STN

*Cases 1 – 8 use a common LH_2 PS and in-line LO_2 tank assembly; Propellant depots assumed in LEO, LPO, and LLO; LANTR engines use optimized MRs out and back; RL10B-2 engines operate at fixed MR = 5.88:1; **LEO – 407 km, LPO and equatorial LLO – 300 km; ***Total round trip mission ΔV values include g-losses

attributed to the lower dry mass of the RL10B-2's PS (~52.5% that of the LANTR PS) and the lower LH_2 and LO_2 propellant loading of the shuttle (~67.7% that of the LANTR shuttle) at the start of the mission. The heavier mass of a LANTR engines and the need for additional shielding mass on each engine are key contributors to the larger LANTR PS dry mass. The LANTR shuttle also carries the maximum LH_2 and LO_2 propellant loading in its tanks at the start of the mission to achieve its fast transit times and to satisfy the specified LDP refueling ratio of 8:1 discussed above.

The RL10B-2-powered commuter shuttle in Case 2 operates with a fixed thrust = 24.75 klb_f, O/H MR = 5.88:1 and I_{sp} = 465.5 s out and back. At mission start, the shuttle's PS LH_2 and in-line LO_2 tanks contain ~19.4 t of LH_2 and ~82.8 t of LO_2 (~48.8% and ~74.5%, respectively, of their maximum capacities). During the outbound mission leg, the shuttle uses ~80.6 t of LO_2 and ~13.7 t of LH_2. At the STN, the shuttle again refuels with ~109 t of LLO_2 and ~13.63 t of excess LLH_2 produced during water electrolysis to supplement the ~4.9 t of LH_2 remaining in the PS for Earth return. On the inbound mission leg, the shuttle's RL10B-2 engines use ~109 t of LO_2 and ~18.54 t of LH_2. The total mission ΔV is ~11.688 km/s, and the total engine burn time is ~51.1 min which is ~50% longer than the LANTR shuttle. The individual burn times are as follows: ~16.8 min (TLI), ~4.9 min (LOC), ~19.6 min (TEI), and ~9.8 min (EOC).

Case 3 examines the impact of increasing the refueling ratio of the RL10B-2 shuttle from 8:1 to 5.88:1, the operational O/H MR for the RL10B-2 engine. Although the transit times remain the same, increasing the amount of LLH_2 produced at the STN from ~13.63 t to 18.53 t, further decreases the IMLEO to ~126.4 t, which includes the PS (~30.2 t), the in-line LO_2 tank assembly (~81.2 t), and the PTM (15 t). By overproducing on the LH_2O transported to and electrolyzed at the LPO STN, the propellant resupply requirements at the LEO STN are reduced below that required in Case 2. During the outbound mission leg, the shuttle now uses ~72 t of LLO_2 and ~12.2 t of LH_2. At the STN, it refuels with ~109 t of LLO_2 and ~18.53 t of excess LLH_2 required by the shuttle for Earth return while also satisfying the 5.88:1 refueling ratio. The total mission ΔV is ~11.691 km/s, and the total engine burn time is ~48.8 min which includes the following individual burn times: ~16.8 min (TLI), ~4.9 min (LOC), ~19.6 min (TEI), and ~9.8 min (EOC). The low IMLEO and larger shuttle departure mass from LPO are reflected in the burn times shown for TLI and TEI.

Case 4 shows the fastest transit times to and from LLO achievable by a LANTR commuter shuttle using only ELH_2 and refueled LUNOX. By fully loading the shuttle's LH_2 and LO_2 propellant tanks to their maximum capacities of ~39.8 t and ~111.2 t, respectively before TLI, refueling with ~80.3 t of LUNOX, and operating the LANTR engines O_2-rich (O/H MR = 5, I_{sp} ~516 s) out and back, the LANTR shuttle can achieve one-way transit times just under 33 hr. The IMLEO is ~204 t, which includes the PS (~71.1 t), the in-line LO_2 tank assembly and adaptor section (~117.9 t), and the PTM (15 t). The total mission ΔV is ~10.4 km/s, and the total mission burn time is ~25.3 min, which includes the following individual burn times: ~11 min (TLI), ~3.5 min (LOC), ~5.1 min (TEI), and ~5.7 min (EOC).

Case 5 shows the fastest transit times to and from LLO achievable by a RL10B-2 commuter shuttle again using only ELH_2 and LUNOX refueling before returning to Earth. Before TLI, the shuttle's LH_2 and LO_2 propellant tanks are loaded with ~32.3 t and ~111.2 t of fuel and oxidizer, respectively, and its engines (again operating at an O/H MR = 5.88:1 and I_{sp} = 465.5 s) burn ~108.9 t of LO_2 and ~18.52 t of LH_2 on the outbound mission leg. The shuttle then refuels with ~76.5 t of LUNOX at the LLO STN which it burns with the ~13 t of LH_2 remaining in the shuttle's PS on the way back to Earth. The shuttle can achieve one-way transit times of ~31 hr and its IMLEO is ~181.9 t, which includes the PS (~49.2 t), the in-line LO_2 tank assembly (~117.7 t), and the PTM (15 t). The lower IMLEO is again attributed to lighter mass of the RL10B-2 engines used on the shuttle's PS, and the narrowing of the I_{sp} gap between the LANTR and RL10B-2 shuttle systems. Lastly, the total mission ΔV is ~10.966 km/s, and the total mission burn time is ~50 min – approximately twice that of the LANTR shuttle – with individual burn times as follows: ~22.6 min (TLI), ~6.8 min (LOC), ~10.5 min (TEI), and ~10.1 min (EOC).

Case 6 looks at a variant of the commuter shuttle that focuses on delivering high priority cargo to the Moon as fast as possible. Today, on their website for international shipping [62], UPS advertises 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 [63], the company promises free 2-day shipping on your purchases.

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, originally developed by Orbital ATK. *Cygnus* is an automated cargo vehicle [64] designed to transport supplies to the *ISS*. 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 [64].

The priority cargo container (PCC) used in Case 6 has the same outer mold line as the PTM shown in Figure 27 and, like the PTM, draws its electrical power from the twin PVAs located at the front end of the shuttle's in-line LO_2 tank assembly. Figure 28 depicts a next-day-delivery (NDD) priority cargo shuttle flight departing LEO for the Moon. *The cargo shuttle can deliver a 7.5 t PCC to and from LLO, with 1-way transit times just over 27 hr using RL10B-2 engines, LUNOX refueling, and only ELH_2 for the round trip mission.* Before TLI, the shuttle's LH_2 and LO_2 propellant tanks are loaded with ~31.8 t and ~111.2 t of fuel and oxidizer, respectively. The shuttle then burns ~108.9 t of LO_2 and ~18.52 t of its available LH_2 (~31 t) during the outbound mission leg. After arriving in LLO, the PCC detaches from the shuttle and docks with a waiting Sikorsky-style LLV for delivery to the LS in the same manner as the PTM. The shuttle then refuels with ~73.2 t of LUNOX at the LLO STN and awaits another PCC to deliver back to LEO. On the inbound mission leg, the cargo shuttle burns all of its loaded LUNOX and the remaining ~12.45 t of ELH_2 in the cargo shuttle's PS tank. The IMLEO for this priority cargo shuttle mission is ~173.6 t, which includes the PS (~48.5 t), the in-line LO_2 tank assembly (~117.6 t), and the PCC (7.5 t). The total mission ΔV is ~12.053 km/s, and the total mission burn time is ~49.1 min which includes the following burn times: ~22.1 min (TLI), ~7.2 min (LOC), ~11.1 min (TEI), and ~8.7 min (EOC).

Case 7 looks at the minimum transit times possible for the LANTR commuter shuttle mission using LUNOX plus additional LLH_2 to supplement the ELH_2 provided for the mission. At the start of the mission, the shuttle's LH_2 and LO_2 propellant tanks are loaded to their maximum capacities of ~39.8 t and ~111.2 t, respectively. During the outbound mission leg, the shuttle's LANTR engines operate at O/H MR ~4.5, I_{sp} ~535 s during TLI, and MR ~2.1, I_{sp} ~633 s during LOC, burning all of shuttle's available LO_2 and ~31.6 t of its ELH_2 leaving ~7.4 t remaining in the PS tank. The shuttle refuels with ~109 t of LUNOX and ~17 t of LLH_2 at the LLO STN, picks up another PTM, and

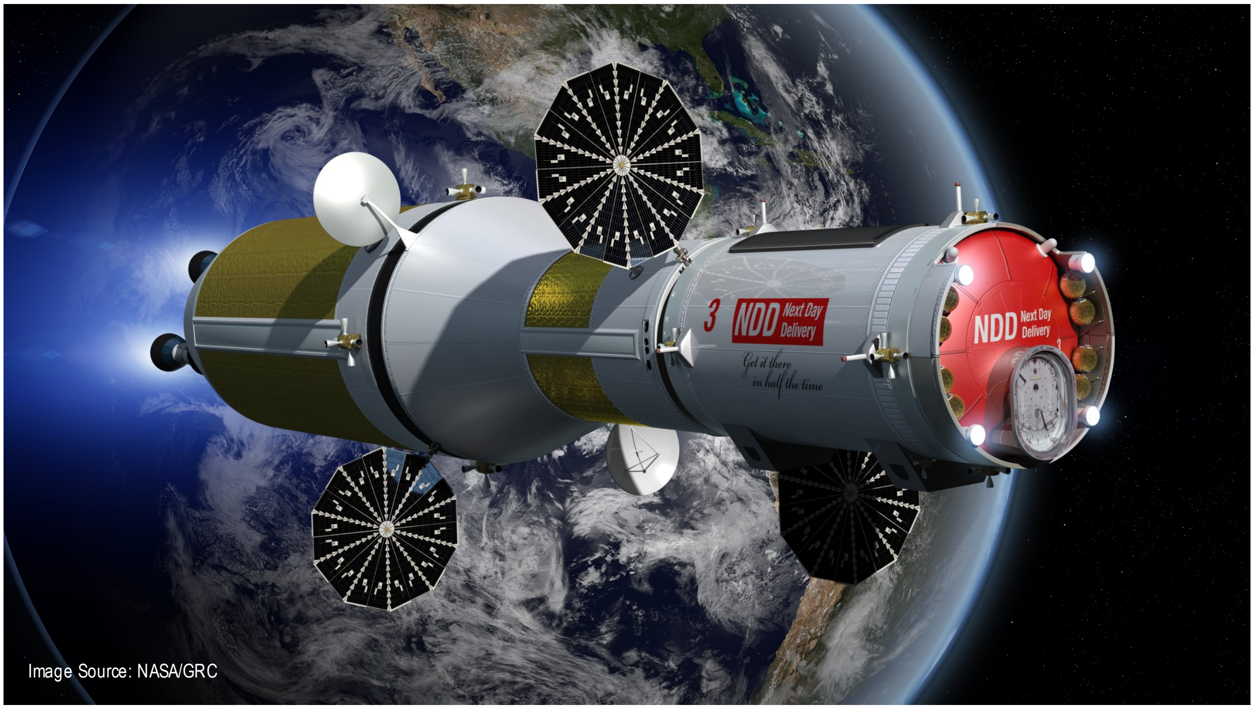

Figure 28. Priority Cargo Delivery Vehicle Departing LEO for the Moon

returns to Earth. During the inbound mission leg, the LANTR engines operate O_2-rich (O/H MR ~5.0, I_{sp} ~516 s during TEI, and MR ~4.1, I_{sp} ~549 s during EOC), burning all of shuttle's onboard propellants (~109 t of LUNOX and ~24.4 t of combined LLH_2 and ELH_2). *With the existing tank sizes and the conditions outlined above, the LANTR commuter shuttle can achieve one-way transit times of 24 hr.* The IMLEO is ~204.1 t, which includes the PS (~71.1 t), the in-line LO_2 tank assembly and adaptor section (~118 t), and the PTM (15 t). The total mission ΔV is ~13.030 km/s, and *the total mission burn time is ~36.3 min*, which includes the following individual burn times: ~12.6 min (TLI), ~7.8 min (LOC), ~8.9 min (TEI), and ~7 min (EOC).

Case 8 uses RL10B-2 engines on the commuter shuttle and has the same mission objective as Case 7, to determine the minimum transit times possible using LUNOX and LLH_2 during the mission. Prior to TLI, the shuttle's LH_2 and LO_2 propellant tanks are loaded with ~19.3 t and ~111.2 t, respectively. During the outbound mission leg, the shuttle's RL10B-2 engines (operating at O/H MR ~5.88:1and I_{sp} ~465.5 s out and back), burn all of the available LO_2 and LH_2 (~108.9 t and ~18.52 t, respectively) contained in the shuttle's propellant tanks. The shuttle then refuels with ~102.1 t of LUNOX and ~17.36 t of LLH_2 at the LLO STN, picks up another PTM, and returns to Earth. During the inbound mission leg, the RL10B-2 engines burn all of available propellant loaded onto the shuttle prior to TEI. *With the existing tank sizes and the conditions outlined above, a commuter shuttle powered by RL10B-2 engines can achieve one-way transit times to LLO of ~24.9 hours – about an hour longer than the 25-hr trip taken by Dr. Floyd in 2001 which included landing on the Moon as well.* The IMLEO is ~168.8 t, which includes the PS (~36.1 t), the in-line LO_2 tank assembly and adaptor section (~117.7 t), and the PTM (15 t). The total mission ΔV is ~12.839 km/s, and the total mission burn time is ~56.9 min, which includes the following individual burn times: ~21.9 min (TLI), ~7.5 min (LOC), ~16.4 min (TEI), and ~11.1 min (EOC).

Lastly, it is interesting to note that during the 24-hr LANTR-powered shuttle flight to the Moon (Case 7), the acceleration levels experienced by passengers during the major mission burns will range from: ~0.36g to 0.73g for the TLI burn, ~0.49g to 0.76g for the LOC burn, ~0.41g to 0.71g for the TEI burn, and ~0.65g to ~1.29g for the EOC burn. For the ~25-hr RL10B-2 shuttle flight to the Moon (Case 8), the acceleration levels passengers experience will be more modest at ~0.20g to 0.46g (for TLI), ~0.46g to 0.82g (for LOC), ~0.21g to 0.38g (for TEI), and ~0.38g to ~0.85g (for EOC).

8.0 Estimated Total LDP Mission Needs, Mining Area and Processing Requirements

In Sects. 6 and 7, CCT and commuter shuttle missions to LPO and LLO were examined and compared. For LPO missions we assume that LPI deposits are mined and processed to produce LH_2O that is then transported to a LPO STN using reusable tanker LLVs. At the STN the LH_2O is electrolyzed to produce both LLO_2 and LLH_2 that is then stored for subsequent use by the LTS elements.

Because of water's composition (8:1 O/H mass ratio), ~1.125 t of LH_2O must be produced and electrolyzed for every ton of LLO_2 required for LTV refueling. Additional water must also be produced to supply the LDP the tanker LLVs need to deliver water to the lunar STN. In this paper the LLVs use throttled LO_2/LH_2 chemical rockets operating at an O/H MR of 5.5:1 and I_{sp} of 450 s. As a result, it will be necessary to overproduce on water to supply the required amounts of LH_2 needed by the LLVs unless additional ELH_2 is supplied to the STN for their use.

To determine the range of LDP needed at both the orbiting STN and surface LPI mining and processing facility, it is necessary to look at the different mission types, their transit times, and frequency of occurrence. The needs of the various LLVs supporting each mission type must also be taken into account. To illustrate this point, we examine a specific LANTR CCT mission scenario in more detail using Case 1 from Table 4 as our baseline CCT mission. We also assume the CCT delivers 20 t of cargo to LPO six times a year. Table 6 summarizes the LDP and LH_2O required to support this mission scenario. The CCT delivers 20 t of cargo (equivalent to eight 2.5 t PL pallets) to the LPO STN where it is unloaded and subsequently attached to four LDAVs (each carrying two pallets) for transport to the LS. After transferring its cargo, the CCT refuels with ~54.3 t of LLO_2 and ~6.8 t of top-off LLH_2 at the STN then returns to LEO. Fifteen tanker LLV flights originating from the polar propellant production facility supply the STN with the required quantities of LH_2O consistent with the return propellant needs of the CCT over the course of the year. We assume here that the water is electrolyzed at the STN and the propellant then stored for CCT use.

Supporting six CCT flights/yr between LEO and LPO will require annual LDP and LH_2O production rates of ~1,509 and ~1,951 t/yr, respectively. Approximately 367 t of LLO_2 and LLH_2 propellant is required by the LANTR CCT, ~543 t by the LDAVs transporting cargo from LPO to the LS, and ~599 t by the tanker LLVs delivering LH_2O to the STN. For an electrolysis rate of ~1 t/day, the electrical power at the STN needed just for electrolysis (P_e) is estimated to be ~0.205 MW_e with the electrolysis power (in MW_e) equal to ~0.2042 x (H_2O electrolysis rate, t/day). The corresponding power level and electrolysis rate supporting LDAV and LLV tanker operations at the polar propellant facility is ~0.886 MW_e and ~4.34 t/day, respectively.

Table 6. Total LDP & LH_2O Required to Support 6 LANTR CCT Flights Every Year

72-hr 1-way transits (4 crew, 9.9 t hab module, 16 m truss, 20 t cargo delivered to LPO):	
• LANTR CCT**: (54.3 t LLO_2 + 6.8 t LLH_2 /mission)	
x (6 missions/year)	= 326 t LLO_2/yr
	+ 41 t LLH_2/yr
	367 t LH_2O/yr
• LDAV*+: (19.1 t LLO_2 + 3.5 t LLH_2/flight)	
x (6 flights/LDAV/year) x 4 LDAVs	= 459 t LLO_2/yr
	+ 84 t LLH_2/yr
• LLV*#: (33.8 t LLO_2 + 6.1 t LLH_2/flight)	
x (5 flights/LLV/year) x 3 LLVs	= 507 t LLO_2/yr
	+ 92 t LLH_2/yr
Total LDP Production	= 1,509 t/yr
Total LH_2O Required	= 1,951 t/yr

**CCT also "tops off" its PS with excess LLH_2 produced from water electrolysis at 8:1 ratio; 72-hr transit time does not include the 2.5 hr long "3-burn" LOC maneuvers into and out of LPO.
*O/H MR = 5.5:1, I_{sp} = 450 s, ΔV_{desc} = 2.115 km/s and ΔV_{asc} = 1.985 km/s assumed.
+Each crewed LDAV flight picks up 5 t of PL at the LPO STN, then returns to the LS.
#LLV tanker transports ~25 t of LH_2O to LPO STN, then return to LS with empty 5-t tank.

Figure 29 shows a curve of the LH_2O production rate versus required mining area needed to support a sampling of LANTR and RL10B-2 CCT and commuter shuttle missions discussed in Sects. 6 and 7. The curve assumes the use of thermal mining with a 4 wt% water ice content in the regolith and a yield of 25 kg/m^2. The requirements for specific missions are plotted along the curve and additional mission details are provided in the color-coded boxes to the right of the curve. Details include the mission transit times and frequency, refueling ratio, the amount of LH_2O to be electrolyzed for use by the particular CCT or commuter shuttle and its supporting LLVs, and the associated electrolysis power (P_e) needed on the STN and the LS. Also shown on the curve are the requirements for the LANTR CCT mission discussed above in Table 6 (purple box) and the Commercial Lunar Propellant Study [39]. Finally, it should be noted that the total LS power requirement will include components for thermal mining, cold-trap ice hauler operation and recharging, LH_2O storage and purification, electrolysis, and propellant storage.

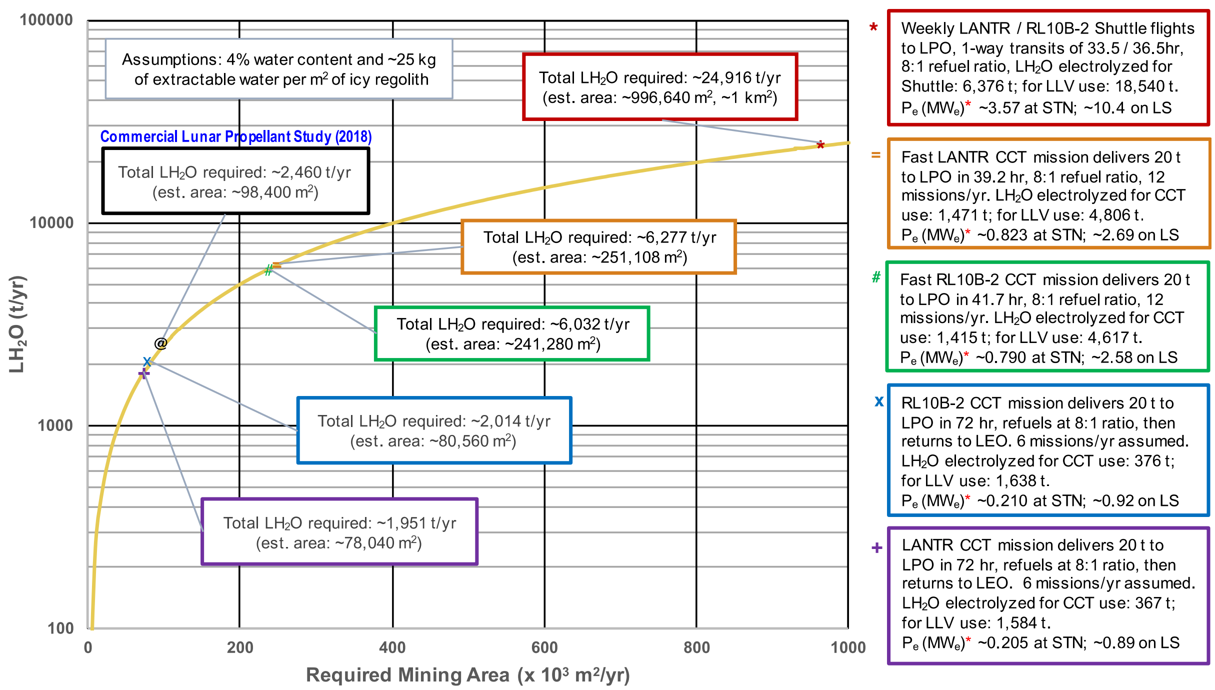

Figure 29. LH_2O Production Rates and Required Mining Areas for Various LPO Mission Options

For CCT and commuter shuttle missions to LLO, we assume that LLO_2, or LUNOX, is produced from vast deposits of volcanic glass located on the lunar nearside and then routinely transported from the LS to a STN located in equatorial LLO, again using reusable tanker LLVs. As discussed previously, for LLO missions we assume the LTVs use only ELH_2 and refuel with LUNOX only before returning to Earth. As a point of comparison to Table 6, Table 7 shows the total LUNOX and ELH_2 required for a similar CCT mission to LLO (Case 6 in Table 4) but using RL10B-2 instead of LANTR engines. As before the CCT delivers 20 t of cargo to the LLO STN where it is unloaded and subsequently attached to four LDAVs for transport to the LS. The CCT then refuels with ~54.7 t of LUNOX at the STN before returning to LEO. Just over thirteen tanker LLV flights supply the STN with the required quantities of LUNOX consistent with the return propellant needs of the CCT over the course of the year.

To accommodate the six CCT flights per year and the LLV flights supporting it, an annual LUNOX production rate of ~1,234 t/yr is required (shown in Table 7). Approximately 329 t of LUNOX is used by the RL10B-2 CCT, ~459 t by the four LDAVs transporting cargo from the STN to the LS, and ~446 t by three LUNOX tanker LLVs, each flying ~4 to 5 resupply missions to the STN over the course of a year. While the CCT is supplied with all the LH_2 it needs for the mission at the LEO STN, additional shipments of LH_2 to the LLO STN will be required to supply the LLV flights. The ~165 t of ELH_2 can be supplied using two NTR tanker vehicles [44], each carrying ~28 t of LH_2 and flying three flights to the LLO STN each year.

Table 7. Total LUNOX and ELH_2 Required to Support 6 RL10B-2 CCT Flights Every Year

72-hr 1-way transits (4 crew, 9.9 t hab module, 16 m truss, 20 t cargo delivered to LLO):	
• RL10B-2 CCT**: (54.7 t LUNOX/mission) x (6 missions/yr)	= 329 t LUNOX/yr
• LDAV*+: (19.1 t LUNOX + 3.5 t ELH_2/flight) x (6 flights/LLV/year) x 4 LDAVs	= 459 t LUNOX/yr + 84 t ELH_2/yr
• LLV*#: (33.8 t LUNOX + 6.1 t ELH_2/flight) x (4.4 flights/LLV/year) x 3 LLVs	= 446 t LUNOX/yr + 81 t ELH_2/yr
Total LUNOX Production	= 1,234 t/yr
Total ELH_2 Required	= 165 t/yr

**RL10B-2: O/H MR = 5.88:1, and I_{sp} = 465.5 s; CCT uses 3 engines.
*O/H MR = 5.5:1, I_{sp} = 450 s, ΔV_{desc} = 2.115 km/s and ΔV_{asc} = 1.985 km/s assumed.
+Each crewed LDAV flight picks up 5 t of PL at the LPO STN, then returns to the LS
#LLV tanker transports ~25 t of LUNOX to LLO STN, then returns to LS with empty 5-t tank.

Table 8 shows the LUNOX and ELH_2 requirements for an ambitious ~31-hr RL10B-2 commuter shuttle mission to LLO (Case 5 in Table 5). To support weekly commuter flights, annual LUNOX production levels of ~11,909 t/yr is required. Approximately 3,978 t of LUNOX is used by the commuter shuttles, ~5,378 t by LUNOX tanker LLVs flying just over 3 resupply missions to the LLO STN each week over the course of a year (Fig. 30a), and ~2,553 t is used by the same Sikorsky-style LLVs to transport arriving and departing PTMs to and from the LS (Fig. 30b). For these more demanding LUNOX architectures the increasing amounts of ELH_2 required to support LLV operation and methods of delivering it to LLO are concerns. A potential solution to the LH_2 resupply issue is discussed in more detail shortly.

Table 8. Total LUNOX and ELH_2 Required for Weekly RL10B-2 Commuter Flights to LLO

31.1-hr 1-way transits carrying a 15-t, 20-person PTM:	
• RL10B-2 shuttle**: (76.5 t LUNOX mission/week) x (52 weeks/year)	= 3,978 LUNOX/yr
• LLV*+: (33.8 t LUNOX + 6.14 t ELH_2 /flight) x (3.06 LLV flights/week) x (52 weeks/year)	= 5,378 t LUNOX/yr + 977 t ELH_2/yr
• LLV*#: (49.1 t LUNOX + 8.9 t ELH_2 /round trip flight/week) x (52 weeks/year)	= 2,553 t LUNOX/yr + 463 t ELH_2/yr 2,584 t LUNOX/yr
Total LUNOX Production	= 11,909 t/yr
Total ELH2 Required	= 1,440 t/yr

**RL10B-2: O/H MR = 5.88:1, I_{sp} = 465.5 s; Shuttle uses 3 engines.
*O/H MR = 5.5:1, I_{sp} = 450 s, ΔV_{desc} = 2.115 km/s and ΔV_{asc} = 1.985 km/s assumed.
+ LLV tanker transports ~25 t of LUNOX to LLO; returns to LS with empty 5-t tank.
# Total for LLV delivery of PTM from LLO to LS plus the PTM return from the LS to LLO.

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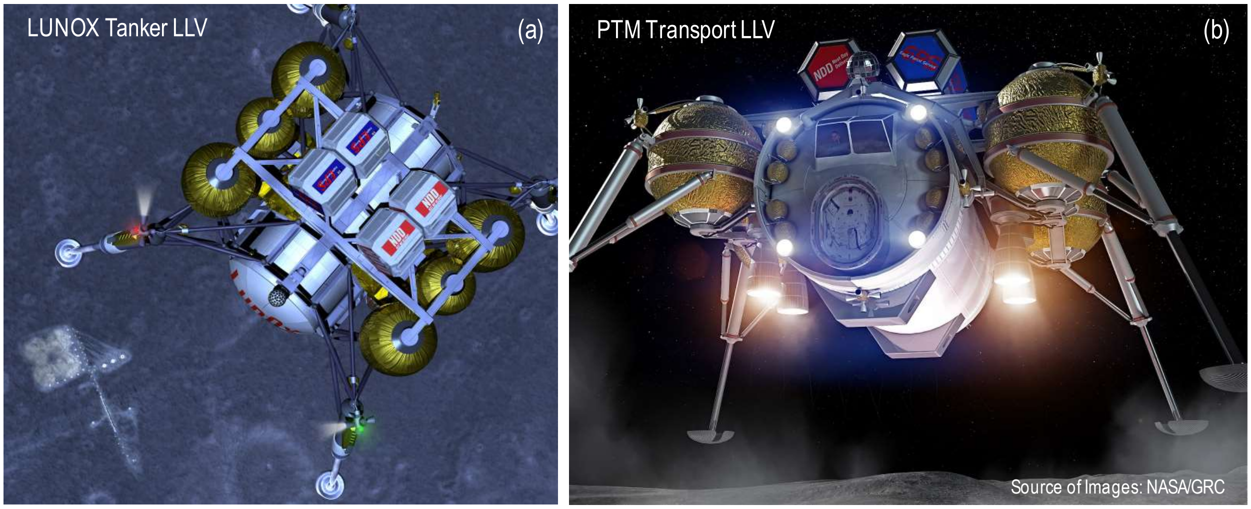

Figure 30. Tanker and PTM Transport LLVs – Key Elements of the Commuter Shuttle Architecture

A preliminary assessment of plant mass, power level, feedstock throughput has been made assuming a LUNOX operation employing 12 production plants each with a capacity of 1000 t/yr. Table 9 compares the characteristics for two different LUNOX plants – one based on hydrogen reduction of ilmenite [41], and the other on "iron rich" volcanic glass [44]. 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 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 ~1.5 MW_e includes power for the mining and processing equipment, and includes 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 liquefiers.

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 excavator/loader loaders and four haulers. To produce ~12,000 t of LUNOX annually to support the weekly commuter shuttle service outlined in Table 8, a glass throughput of ~300,000 t/yr and a soil mining rate of ~4 t per hour per excavator/loader at each plant will be required. This rate assumes the same 35% mining duty cycle used for the ilmenite processing plant [41] and corresponds to mining operations during ~70% of the available lunar daylight hours (~3067 hours per year).

Although this number is large, it is modest compared to current terrestrial coal and lunar helium-3 (He-3) mining activities proposed in the past. For example, the production rate for coal in the United States in 2017 exceeded 700 million tons, which is understandable when one realizes that a single 1000 MW_e coal-fired power plant consumes about ninety 100-ton train cars of coal per day! In 1986, Wittenberg et al. [65] published a paper suggesting that an abundant source of He-3 – estimated at ~1 million metric tons – exists on the Moon implanted in the surface regolith by the solar wind. Since then, an impressive body of scientific and engineering research has been developed [66] by the University of Wisconsin's Fusion Technology Institute (FTI) supporting the case for He-3 mining on the Moon [67]. This lunar resource can play an important role in meeting Earth's future energy demands given the fact that 1 t of He-3 burned with abundant deuterium (D) found in the Earth's oceans can produce ~10 GW_e-yr of electrical energy. To support a DHe-3 based fusion power economy generating ~250 GWe-yr of electrical energy in the 2035 to 40 timeframe will require processing ~3 billion tons of regolith to produce the ~25 t of He-3 needed annually [68]. The mining requirements for a more modest He-3 production rate of 5 t/yr are shown in Table 9.

Table 9. 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, and each miner producing 33 kg He^3 per year)	= 2700 t
• 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)	= 6.0×10^8 t/yr

8.1 Synergy Between Commercial LUNOX Production and a Developing Lunar He-3 Industry

As mentioned above, an estimated million metric tons of solar-wind-implanted (SWI) He-3 is embedded in the near-surface lunar regolith. It is divided roughly equally between the maria and the highlands [61] although the highest concentrations of He-3 are found in mare regoliths that are rich in titanium-oxide (TiO_2), which is contained in the mineral ilmenite ($FeTiO_3$) [69]. Approximately 90% of the He-3 is concentrated in small < 50 micron size particles, which constitute ~45% of the lunar regolith. By heating the soil to temperatures of ~700 °C [70], ~85% of the He-3 trapped within these fine particles can be extracted via thermal desorption. Cameron [71] identified Mare Tranquillitatis and Mare Serenitatis, on the eastern nearside, and Oceanus Procellarium and Mare Imbrium, on the western nearside, as areas rich in titanium and therefore candidate sites for He-3 mining. Hawke et al., [48] have pointed out that these regions may be too heterogeneous with sizable impact craters and excavated rock fragments in the upper 2 m of the regolith, making these areas less attractive for mining. As an alternative site, they propose that ilemenite-rich pyroclastic mantling deposits be considered. These deposits are large in their regional extent, tens of meters thick, and numerous on the lunar nearside. The regolith is also uniformly fine-grained (~40 micron particles) and relatively rock free making it ideal for lunar mining activities.

The University of Wisconsin's FTI has spent considerable time and effort in designing an automated, multi-function, lunar miner that is self-contained, compact, and lightweight [72,73]. The Mark II lunar miner concept shown in Figure 31 has a mass of 18 t and is capable of producing 33 kg of He-3 per year while operating during the lunar days to take advantage of beamed solar power (~200 kW_e) used for its process energy and operation. Excavation of the regolith is accomplished using a bucket wheel excavator that sweeps out a 120° arc ahead of the miner opening up a trench ~11 m wide and ~3 m deep. A conveyor transports the regolith inside the miner where the larger aggregate material is separated out and regolith beneficiation, down to sub-50 micron particles, occurs using a fluidized bed [73]. These fine-grained particles are then heated to 700 °C to remove the He-3. A recuperator cools the regolith back down to 100 °C, allowing ~85% of the process heat to be recovered. The miner then spreads the cooled regolith back onto the surface filling in the mined area behind it as it moves forward (shown in Figure 31). In 1994, Wittenberg also proposed an in-situ option [74] for extracting lunar soil volatiles similar to thermal mining.

During He-3 extraction significant quantities of other volatiles are also produced (see Table 10). Along with the He-3, these volatiles are collected, compressed into cylinders mounted on each of the miners, and later separated out and liquefied at a nearby central processing station. The liquefied He-3 is then shipped back to Earth for use in DHe-3 fusion reactors. A fission power system is used at the processing station allowing continuous "24-7" operation. Later, a DHe-3 fusion reactor can be used with deuterium supplied from Earth.

An important fact not to be overlooked is the 6.1 t of LH_2 and 3.3 t of LH_2O produced as "by-products" for each kg of He-3 fuel collected. As the He-3 production rate increases over time, these by-products can eliminate the need for ELH_2 for the commuter shuttle mission shown in Table 8. By electrolyzing the LH_2O, an additional 0.367 t of LH_2 can be produced providing 6.467 t of LH_2 and 2.933 t of LO_2 for each kg of He-3 mined. The 1440 t shortfall in LH_2 can be readily made up using seven Mark II miners producing ~231 kg of He-3 annually. This production rate is ~22 times lower than the 5 t/yr rate shown in Table 9 resulting in a lower mass and power requirement for the miners of ~126 t and ~1.4 MW_e, respectively. The total throughput of regolith is also reduced to ~28 million tons with each miner excavating an area of ~1 km^2 each year. For the 5 t/yr He-3 mining example shown in Table 9, the excavation area would be ~150 km^2.

Figure 31. Automated Mark II Lunar Miner for Extracting He-3 and SWI Volatiles [75]

Table 10. Gaseous Volatiles Released During Heating of Lunar Ilmenite to ~700 °C [68]

Isotope, Molecule, or Compound	t of Volatile Released per kg of He-3
H_2	6.1
H_2O	3.3
He-4	3.1
CO	1.9
CO_2	1.7
CH_4	1.6
N_2	0.5
Total Volatiles =	18.2

As mentioned previously, Mare Tranquillitatis is an attractive potential site for He-3 mining. With its titanium-rich regolith and large surface area estimated at ~190,000 km^2, this region could contain ~7,100 t of He-3 [76]. To the northwest is Mare Serenitatis, another potential He-3 mining location and also a candidate site for LUNOX production using iron-rich volcanic glass.

The Taurus-Littrow DMD (Fig. 32) – located at the southeastern edge of the Mare Serenitatis (~21°N, ~29.5°E), approximately 30 km west of the Apollo 17 landing site – is the author's proposed site for a commercial LUNOX facility. 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 each side), a mining depth of ~5 m, a soil density for the volcanic glass of ~1.8 g/cm^3, and a MMR of 25 to 1 (equivalent to a 4% O_2 yield), Figure 33 shows that the Taurus-Littrow DMD could produce ~720 million tons of LUNOX.

Figure 33 also shows that the mining areas needed to support commuter flights to the Moon are not unrealistic at ~0.033 km^2 and ~0.167 km^2 for 1 to 5 flights/week, respectively. Even at five times the higher rate of ~60,000 t/yr, there are sufficient LUNOX resources at this one site to support ~25 commuter flights carrying 450 passengers each week for the next ~2,400 years and more sites containing even larger quantities of iron-rich pyroclastic glass have been identified [24]. For 25 flights per week, ~36,000 t/yr of LLH_2 would be needed to fuel the tanker and transport LLVs. This amount of LLH_2 is consistent with a He-3 production rate of ~5.6 t/yr, – slightly larger than the 5 t/yr example in Table 9, but well below the 25 t/yr requirement to support a DHe-3 based fusion power economy [68].

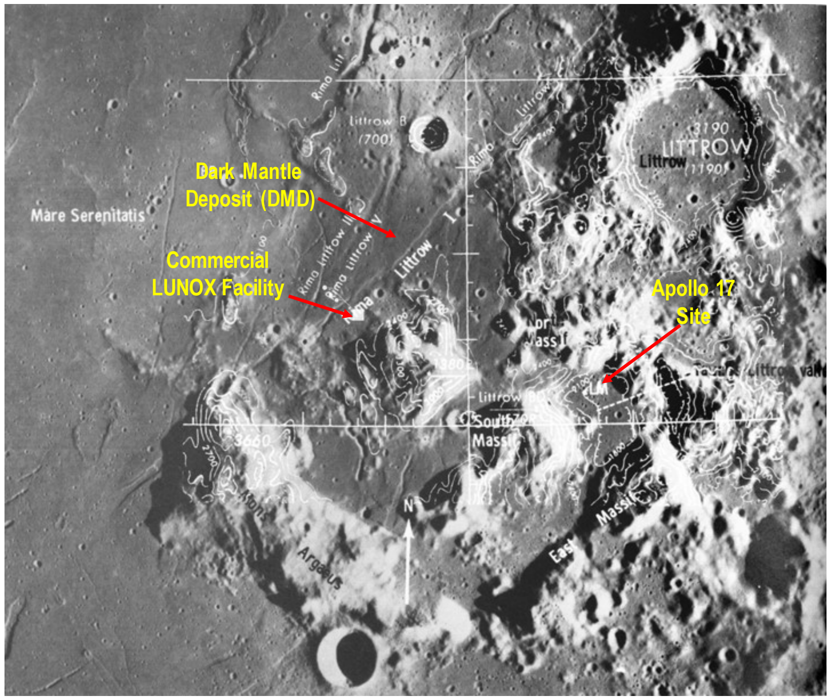

Figure 32. Apollo 17 Landing Site and Major Geographic Features of the Taurus-Littrow Region

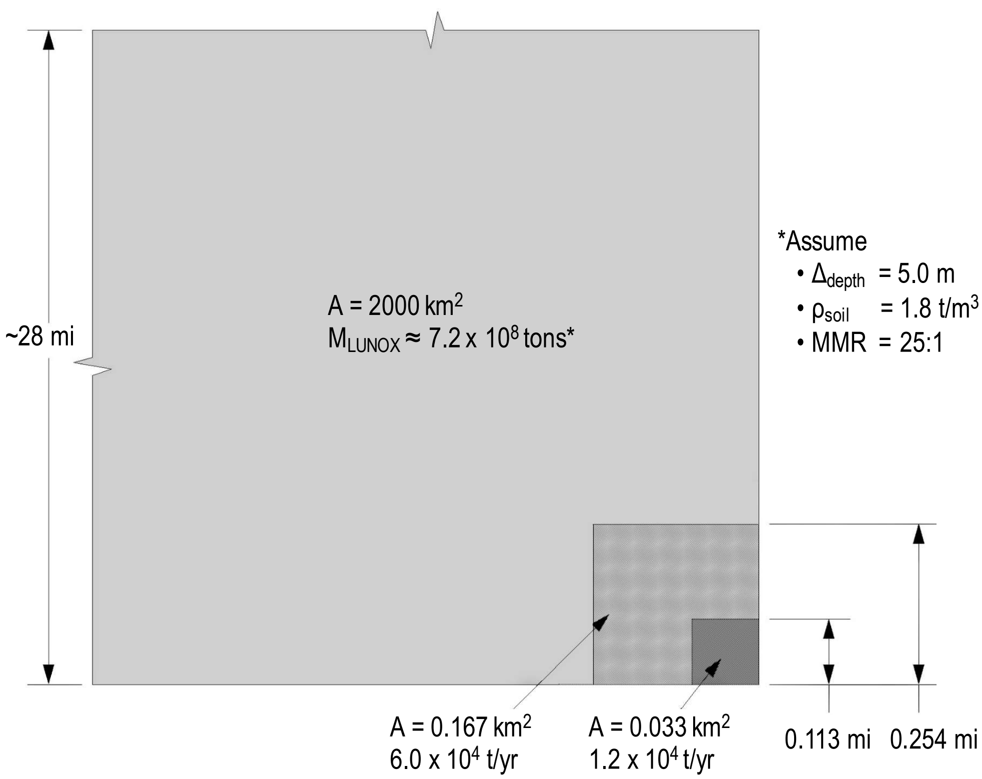

Figure 33. Required Mining Areas and LUNOX Production Rates to Support Routine Commuter Flights to the Moon

8.2 Dr. Floyd's 25-hr Flight to the Moon – Is it Possible and What's Required?

By decreasing the PS LH_2 tank length to ~8.15 m for the RL10B-2 shuttle option, 24-hr transit times appear possible if LLH_2 is again provided from He-3 mining to refuel not only the LLVs but the commuter shuttle as well. Table 11 shows the LUNOX and LLH_2 requirements needed for a 24-hr RL10B-2 commuter shuttle mission to LLO. For this truly ambitious commuter shuttle capability, a LUNOX production rate of ~16,871 t/yr is required which includes ~5,057 t for the shuttle and ~11,814 t for the propellant transfer and PTM delivery LLVs. In this architecture, transporting LH_2O to the STN to obtain the necessary amount of LLH_2 for the shuttle requires a large amount of power (~4.3 MWe) for electrolysis so shipments of smaller amounts of LLH_2 to the STN is preferred.

Table 11. Total LUNOX and LLH_2 Needed for Weekly RL10B-2 Commuter Flights to LLO

24-hr 1-way transits carry a 15-t, 20-person PTM: (1-hr "orbit to LS" transfer not included)

• RL10B-2 shuttle**: (97.24 t LUNOX + 16.54 t LLH_2/mission)	
x (1 mission/week) x (52 weeks/year)	= 5,057 t LUNOX/yr
	+ 860 t LLH_2/yr
• LLV*α: (21.0 t LUNOX + 3.82 t LLH_2 / LLV flight)	
x (2.22 LLV flights/week) x (52 weeks/year)	= 2,424 t LUNOX/yr
	+ 441 t LLH_2/yr
• LLV*+: (33.8 t LUNOX + 6.14 t LLH_2 / LLV flight)	
x (3.89 LLV flights/week) x (52 weeks/year)	= 6,837 t LUNOX/yr
	+ 1,242 t LLH_2/yr
• LLV*#: (49.1 t LUNOX + 8.92 t LLH_2 /round trip flight/week)	
x (52 weeks/year)	= 2,553 t LUNOX/yr
	+ 464 t LLH_2/yr
NOTE: Total Engine Burn Time for Shuttle Mission ~54.2 min	Total LUNOX Production = 16,871 t/yr
	Total LLH_2 Required = 3,007 t/yr

**RL10B-2 shuttle refuels with LUNOX and LLH_2 at a 5.88:1 ratio; LH_2 tank L reduced to 8.15 m
*O/H MR = 5.5:1, I_{sp} = 450 s, ΔV_{desc} = 2.115 km/s and ΔV_{asc} = 1.985 km/s assumed.
αLLV LLH_2 tanker transports ~7.5 t of LLH_2 to LLO; returns to LS with empty 2-t tank.
+LLV LUNOX tanker transports ~25 t of LUNOX to LLO; returns to LS with empty 5-t tank.
#Total for LLV delivery of PTM from LLO to LS plus PTM return from the LS to LPO.

Assuming a LUNOX production rate of ~17,000 t/yr, the required mining areas needed to support 24-hr commuter flights to the Moon are ~0.047 km^2 and ~0.236 km^2 for 1 to 5 flights/week, respectively. Even at five times the higher rate of ~85,000 t/yr, the Taurus-Littrow DMD can still supply sufficient LUNOX to support 25 commuter flights to the Moon each week for the next ~1,700 years. For acquisition of the needed LLH_2, ~14 to 71 He-3 miners would be required to support a flight rate of 1 to 5 flights/week. To supply LLH_2 to five competing lunar space lines would require ~353 miners and providing an annual He-3 production rate of ~11.6 t/yr.

8.3 Where Does One Begin?

While ~500 kg of He-3 (the yearly output from 15 miners) can keep five 1000-MW_e DHe-3 fusion power plants operating continuously for a year, this number of plants will not spring into existence overnight. In reality, the capabilities of tomorrow's LTS will evolve over time, in a synergistic manner, as the production rates for the commercial LUNOX enterprise and developing He-3 industry grow. As an example, consider the mission scenario outlined in Table 12. A *Conestoga* CCT using RL10B-2 engines delivers two Mark III He-3 miners [77] to the LLO STN in 72 hr. Each miner has a mass of ~13 t which includes a 30% DWC. The CCT then refuels with ~56 t of LUNOX before returning to LEO 3 days later. Two Sikorsky-style LLVs pick up the miners and deliver them to a new central processing facility being built to separate the He-3 and other lunar volatiles. Here the automated miners are checked out before being deployed to their selected mining site. Three tanker LLVs, operating from an established LUNOX facility, deliver 75 t of LUNOX to the STN to refuel the CCT. The LUNOX requirement for

Table 12. Total LUNOX & ELH_2 Required to Support RL10B-2 CCT He-3 Miner Mission

72-hr 1-way transits (4 crew, 9.9 t hab, 16 m truss, delivers 2-13 t He-3 miners to LLO):	
• RL10B-2 CCT**: (55.9 t LUNOX/mission) x (1 mission/yr)	= 55.9 t LUNOX/yr
• LLV*+: (25.4 t LUNOX + 4.62 t ELH_2/flight) x (2 flights/mission) x (1 mission/yr)	= 50.8 t LUNOX/yr + 9.2 t ELH_2/yr
• LLV*#: (33.8 t LUNOX + 6.14 t ELH_2/flight) x (3 flights/mission) x (1 mission/yr)	= 101.4 t LUNOX/yr + 18.4 t ELH_2/yr
Total LUNOX Production	= 208.1 t/yr
Total ELH_2 Required	= 27.6 t/yr

**RL10B-2: O/H MR = 5.88:1, I_{sp} = 465.5 s; CCT uses 3 engines.
*O/H MR = 5.5:1, I_{sp} = 450 s, ΔV_{desc} = 2.115 km/s and ΔV_{asc} = 1.985 km/s assumed.
+Two cargo LLVs pick up PL at LLO STN; each returns to LS with a 13 t He-3 miner.
#LLV tanker transports ~25 t of LUNOX to LLO STN, then returns to LS with empty 5-t tank.

this mission is modest at ~208 t, and the ~28 t of ELH_2 can be supplied by a single NTR tanker. After a year of operation, the two miners supply the volatiles to produce 66 kg of He-3, ~427 t of LLH_2 and ~194 t of LLO_2 after electrolyzing the ~218 t of LH_2O into its constituent elements. With this amount of LLH_2 now available, and the production rate of LUNOX increasing annually, the CCT flight rate can also be increased in year 2 allowing additional miners and cargo to be delivered to the Moon to support the continued growth of lunar settlements, LUNOX production facilities, and a developing He-3 mining industry.

9.0 Summary and Concluding Remarks

The commercialization and human settlement of the Moon and cislunar space will be greatly aided by the development and utilization of ISRU, fission power systems (FPS), reusable propulsion systems, and the strategic positioning of STNs in LEO, lunar equatorial and polar orbits. Reusable propulsion systems imply long operating lifetimes – 10s of hours not 10s of minutes. Lunar derived propellants (LDPs), specifically LLO_2 and LLH_2 derived from polar ice deposits, are receiving a lot of attention. However, there are other source materials for LDPs that should not be overlooked. Vast deposits of volcanic glass on the lunar nearside can supply well in excess of 25 billion tons of LUNOX, and, longer term, ~5 billion tons of SWI volatiles can be recovered, for propellant and life support use, from the lunar regolith during He-3 mining.

The combination of LDP with advanced chemical and LANTR propulsion can lead to a robust LTS with unique mission capabilities that include short transit time crewed cargo transports and commuter flights to the Moon. Chemical propulsion exists now but LANTR propulsion offers some unique features. They include a variable thrust and I_{sp} capability, shorter total mission burn times (~50% that of chemical), bipropellant operation, and the use of high density LO_2 leads to smaller LTVs. However, LANTR engines are heavier, require radiation shielding, and the mission Con-Ops must deal with engine cooldown and management of the associated cooldown thrust that can last for hours. Also, for ambitious lunar missions, LANTR engines typically run O_2-rich lowering their I_{sp} and the performance benefit they have over chemical propulsion. Indeed, for many of the CCT and commuter shuttle missions examined in this paper, those using the RL10B-2 engine show overall performance comparable to or better then missions using LANTR.

Scalable, megawatt-class FPSs will be another key technology needed on the Moon. While nearly continuous solar power may be available at a few select sites at the lunar poles, only FPS can satisfy the requirements for abundant "24/7" electrical power, at low mass mass, needed for the continued growth of commercial activities in LEO, lunar orbit, and on the lunar surface. A design concept has been developed for a 2.5 MW_e FPS that uses a liquid metal-cooled, fast spectrum reactor with uranium nitride fuel, Brayton power conversion, and a deployable, fold-out radiator system, that can be collapsed allowing the entire system to be launched on a single SLS launch.

The next biggest challenge to making the vision we've presented a reality will be the production of increasing amounts of LDP from multiple sources, and the development of strategically positioned STNs for vehicle refueling in LEO, LLO, and LPO. Besides providing a propellant depot and cargo transfer function, orbiting STNs offer convenient staging locations where propellant, cargo, and passengers can be dropped off and/or picked up.

An industry-operated, privately financed venture, with NASA as its initial customer, has frequently been mentioned as a possible blueprint for how a commercial lunar propellant production facility and orbital 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 it may be quicker than any of us can imagine.

In this 50th anniversary year of the Apollo 11 mission, it is comforting to know that work is underway on many of the technologies and systems discussed in this paper. Hopefully, in the not too distant future, the technological progeny from these development efforts will be able to provide the traveling public the same type of space transportation capability portrayed in *2001: A Space Odyssey* and in Clarke's novel [61] by the same name. Imagine future Dr. Floyds having the opportunity to make "…utterly without incident and in little more than one day, the incredible journey of which men had dreamed of for two thousand years…" a routine flight to the Moon.

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