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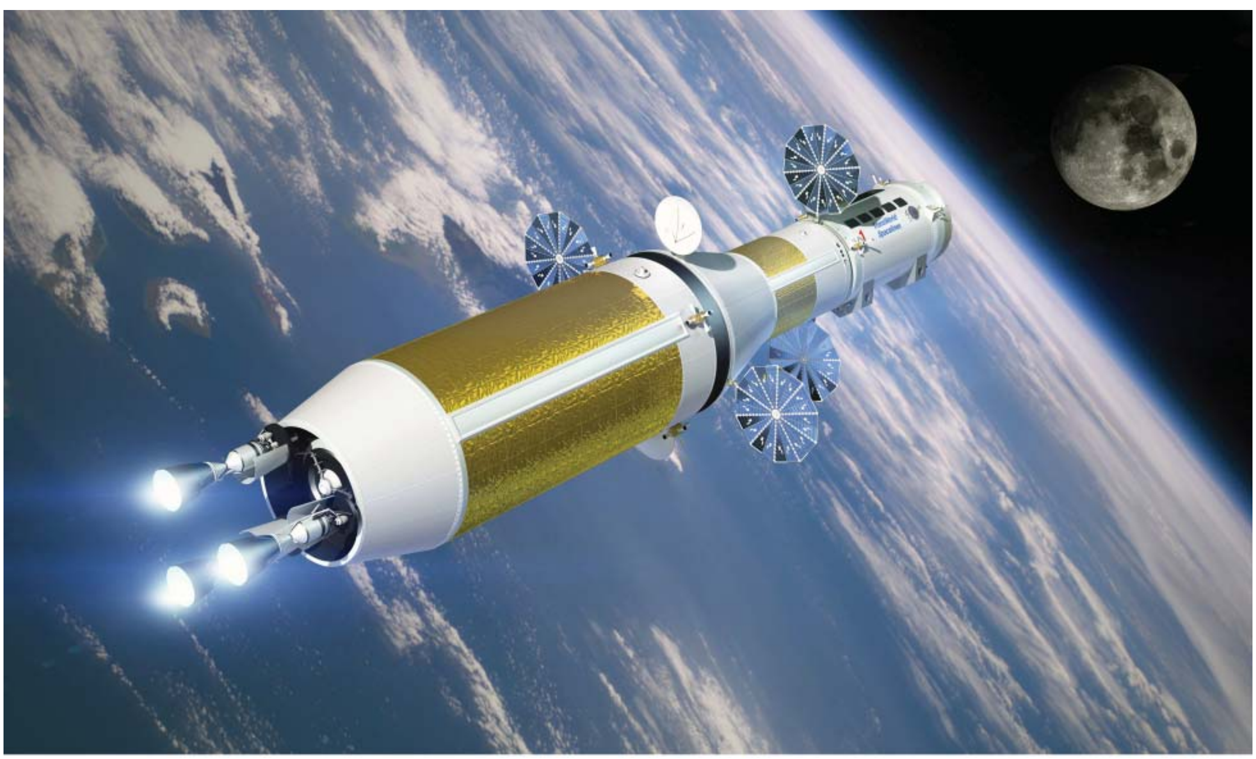

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## Summary

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

transfer vehicle designs, along with the increasing demands on $LLO_2$ production as mission complexity and velocity change $\Delta V$ requirements increase. A comparison of vehicle features and engine operating characteristics, for both NTR and LANTR engines, is also provided along with a discussion of the propellant production and mining requirements associated with using FeO-rich volcanic glass as source material.

## 1.0 Introduction

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

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

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

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

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

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

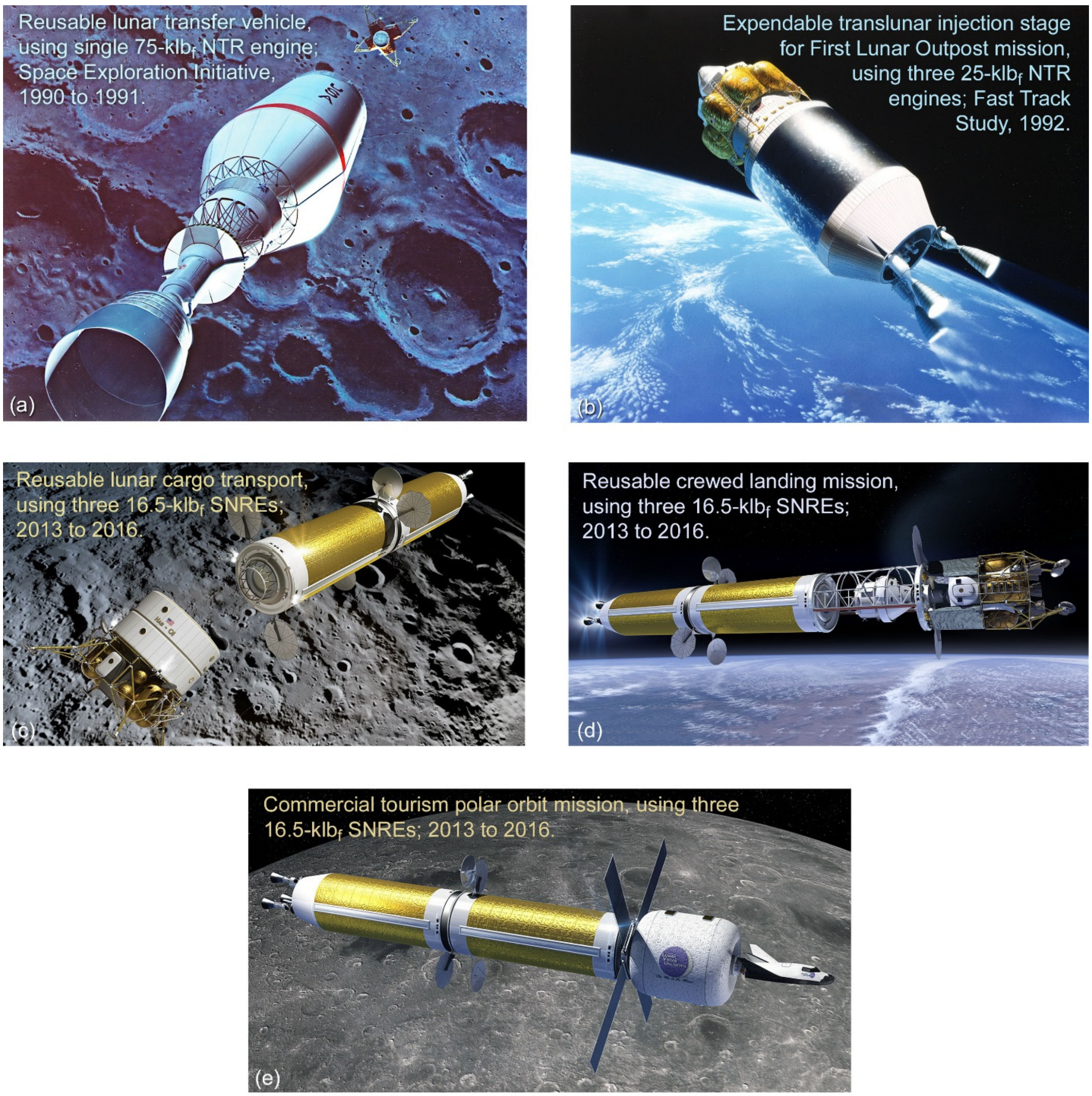



Figure 1.—Past and recent examples of crewed, cargo, and commercial lunar transfer vehicles designed by NASA Glenn Research Center showing transition away from single large to multiple smaller engines.

The nuclear thermal rocket (NTR) achieves its high specific impulse by using $LH_2$ to maintain the reactor fuel elements at their required operating temperature and then exhausting the heated hydrogen gas exiting the reactor out the engine's nozzle to generate thrust. Because the NTR is a monopropellant engine, a key question emerges: "How can the high performance of the NTR and the leverage potential of LDP best be exploited?" The answer is found in the $LO_2$-augmented NTR (or LANTR), a $LH_2$-cooled NTR outfitted with an $O_2$ "afterburner nozzle" and feed system (Refs. 18 to 20). Combining NTR and supersonic combustion ramjet engine technologies, LANTR is a versatile, high-performance engine that can enable a robust nuclear LTS with unique capabilities and can take full advantage of the mission leverage provided with using LDPs by allowing bipropellant operation.

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

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

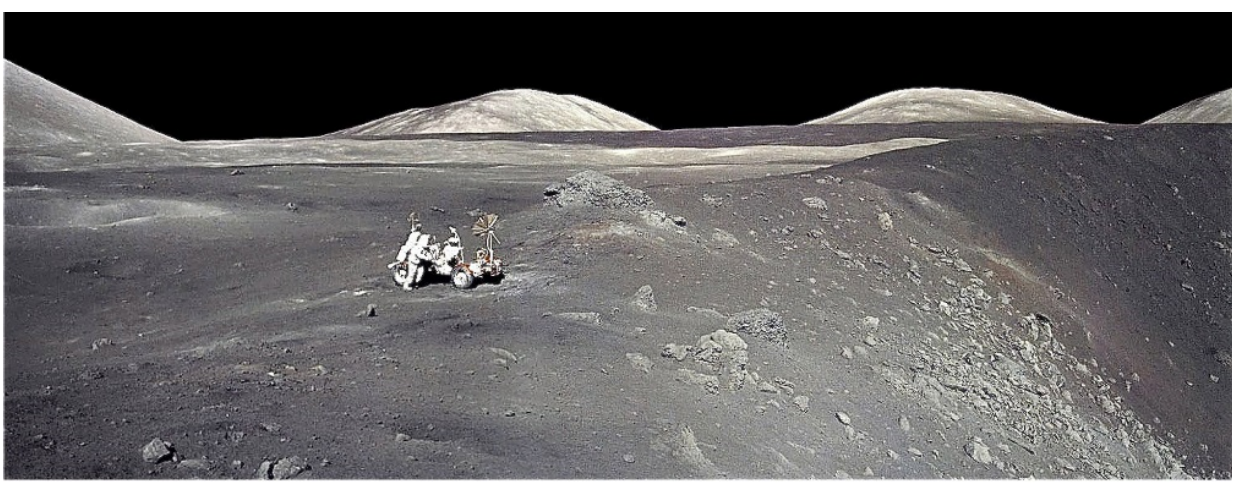


Figure 2.—Astronaut Harrison Schmitt collects samples of dark mantle material at Shorty Crater (Taurus-Littrow landing site on Moon) during Apollo 17 mission.

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

In view of these facts, this report focuses on LUNOX and volcanic glass as the primary LDP and feedstock material. The potential mission benefits and issues associated with using LPI will be examined in a follow-on report. This report provides a summary of our ongoing analysis results to date and touches on the following topics: First, the oxygen extraction process and yields from candidate feedstock materials, system mass and power requirements, siting locations, and features of a commercial LUNOX production plant are discussed. Next, a system description of the NTR and the LANTR concept are presented along with performance projections for the engine as a function of the oxygen-to-hydrogen mixture ratio (O/H MR) used in the afterburner nozzle. The mission and transportation system ground rules and assumptions used in the analysis are then provided and used in an evolutionary mission architecture that illustrates the benefits of using LANTR and LUNOX technologies quantifying them in terms of reduced vehicle size, launch mass, and required engine burn times. The potential for a robust, reusable LTS that includes short-transit-time crewed cargo transports (CCTs) and commuter shuttles is discussed after that along with the refueling needs, LUNOX production rates, and mining requirements needed to support these more demanding and higher $\Delta V$ missions. The report ends with some thoughts on the possibilities for future human expansion into the solar system using LANTR propulsion and locally produced extraterrestrial propellant and then some concluding thoughts.

Acronyms and symbols used in this report are listed in the appendix to aid the reader.

## 2.0 LUNOX: Its Benefits, Extraction Efficiency, Plant Characteristics, and Siting Locations

Previous studies conducted by NASA and its contractors (Refs. 27 and 28) 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 kg of mass in LEO is required to place 1 kg of payload (PL) on the LS. Of this 6 kg, ~70% (4.2 kg) is propellant and ~85.7% of this mass (3.6 kg) is oxygen, assuming the engines operate with an O/H MR of 6:1. Since the cost of placing a kilogram of mass on the LS is ~6 times the cost of delivering it to LEO (Ref. 11), the ability to produce LUNOX from processed lunar material can provide a significant mission benefit. By providing a local source of oxygen for use in life support systems, fuel cells, and chemical rocket engines used on lunar landing vehicles (LLVs), the initial mass in low Earth orbit (IMLEO), launch costs, and LTS size and complexity can all be reduced. Greater quantities of higher value cargo (e.g., people, propellant processing equipment, and scientific instruments) can also be transported to LEO and on to the Moon instead of bulk propellant mass, further reducing LTS costs.

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

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

The water is then electrolyzed to produce oxygen, and the hydrogen is recycled back to the processing plant to react with more feedstock material (Refs. 29 and 30). In the hydrogen-reduction experiments

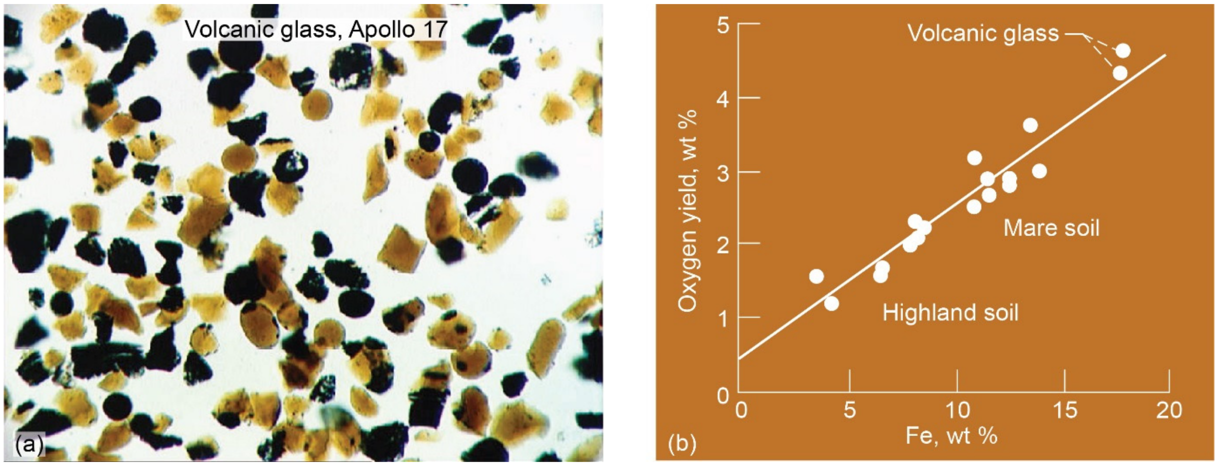



Figure 3.—Volcanic glass beads from Apollo 17 mission and oxygen yields from full range of Apollo samples (Ref. 22).

conducted by Allen et al. (Refs. 21 and 22), oxygen release was measured from samples of lunar soil and volcanic glass beads returned by the Apollo missions. The results indicated that oxygen can be produced from a wide range of lunar soils and is strongly correlated with the iron abundance in the soil as shown in Figure 3. Iron-rich highland soils produced the smallest amount of oxygen, ~1 to 2 wt%, whereas 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 3(a) 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. 3(b)) (Ref. 22). Assuming the same hydrogen-reduction process, volcanic glass feedstock, and a conservative oxygen yield of 4 wt%, 1 t (=1000 kg) of LUNOX could be produced by processing ~25 t of volcanic glass—a significant improvement over previous estimates.

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

The key activities involved at a LUNOX production plant are depicted in Figure 4. 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 LS 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-hr, 7-day/week plant operation is provided by a nuclear fission reactor located a safe distance (11) away from the plant and the regolith-covered habitat module (12) occupied by the plant workers.

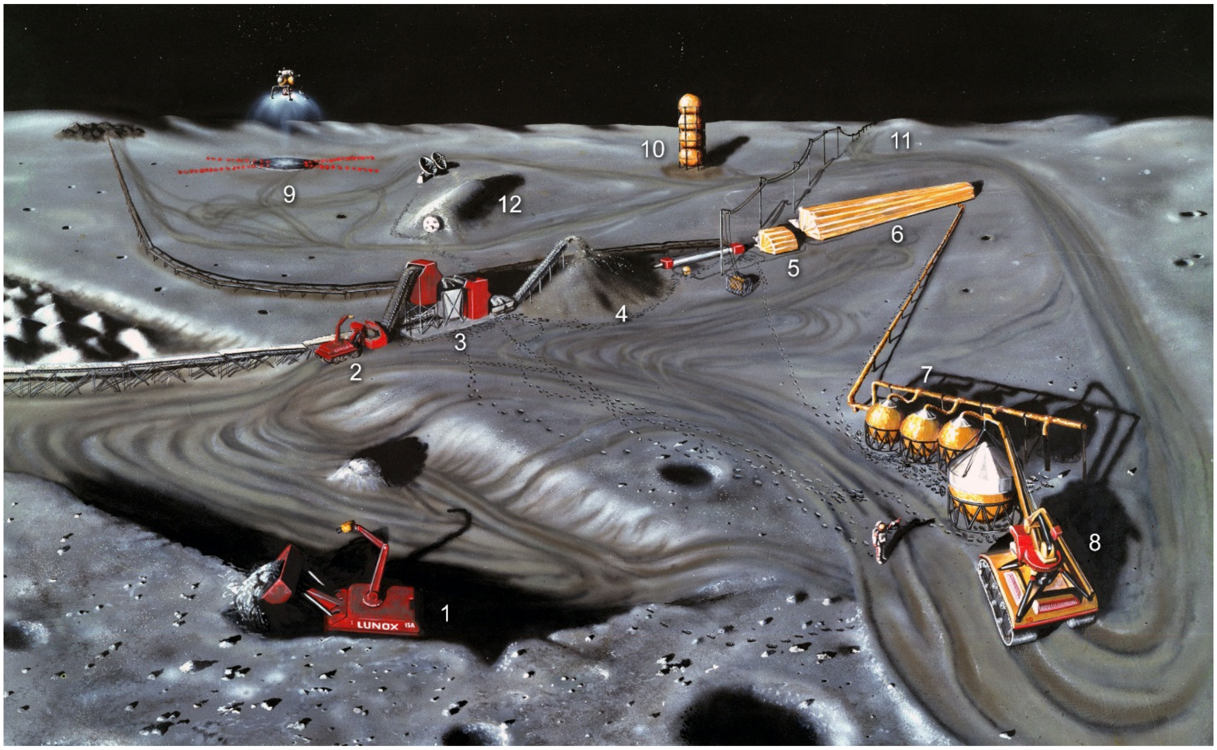


Figure 4.—Activities at future LUNOX production plant: processing ilmenite-bearing feedstock materials (ca. 1983).

A detailed conceptual design study of a lunar oxygen pilot plant was performed for NASA by Christiansen et al. of Eagle Engineering in 1988 (Ref. 30). The study selected hydrogen reduction of ilmenite as the baseline concept because of process simplicity and well understood reaction chemistry. It developed computer models for the mining, beneficiation, and processing equipment that allowed estimates of the mass and power required for both a pilot plant producing 24 t/yr of LUNOX and larger production plants producing up to 1500 t/yr. Key trades and sensitivity analyses were also conducted including evaluations on (1) soil or basalt feedstock; (2) solar photovoltaic arrays (PVAs) 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.

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

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

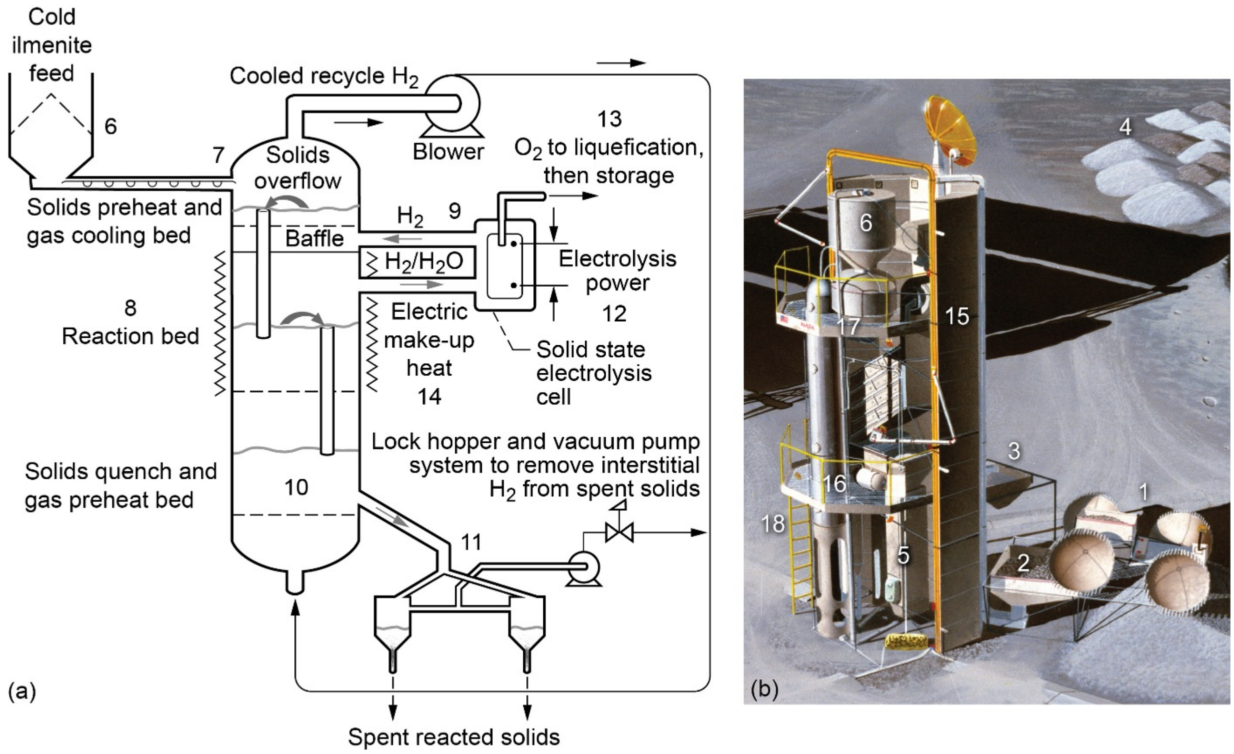



Figure 5.—Schematic and Illustration of LUNOX pilot plant utilizing continuous fluidized-bed reactor for ilmenite reduction with hydrogen.

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

The Eagle Engineering study considered both an ilmenite-rich basalt feedstock (containing ~33 wt% ilmenite) and a soil feedstock (~7.5 wt% ilmenite) in assessing plant performance. With basalt feedstock, ~186 t of mined material is required per ton of LUNOX produced. Using lower ilmenite content soil feedstock eliminated the need to crush and grind tons of rock for ilmenite extraction, but it increased the mining mass ratio (MMR) to ~327 t of soil per ton of LUNOX. Estimates of LUNOX plant mass and power consumption levels for a soil feedstock system obtained from the Eagle Engineering study (Ref. 30) are shown in Figures 6 and 7 as a function of the annual production rate. The 35% duty cycle assumes that mining operations occur during 70% of the available lunar daylight hours (~3067 per year).

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

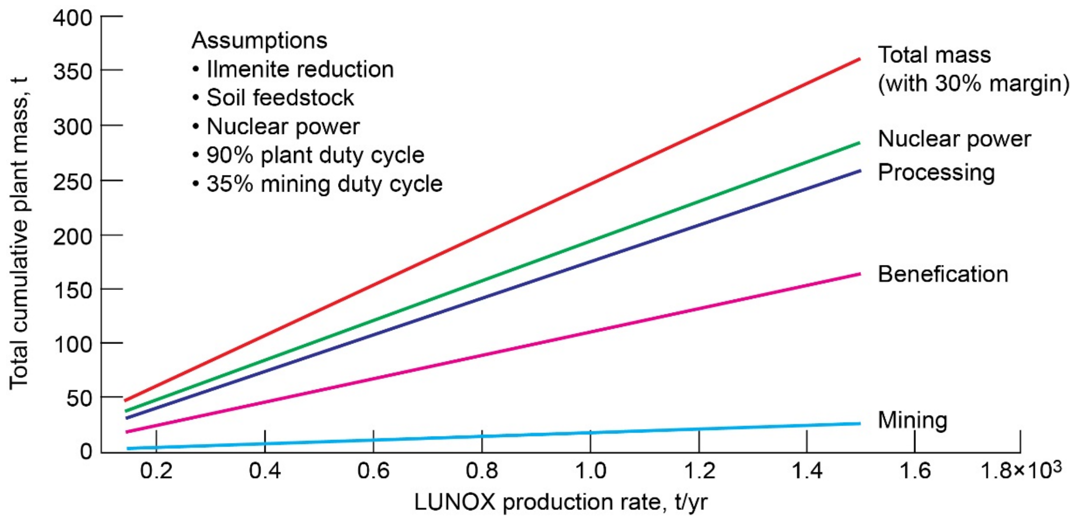



Figure 6.—Variation of LUNOX production plant component mass with annual production rate.

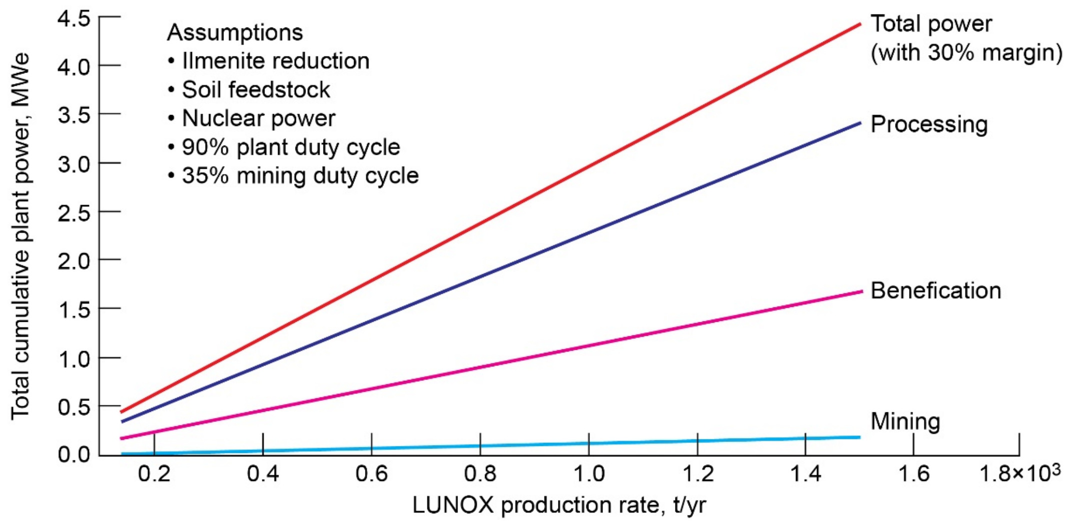



Figure 7.—Variation of LUNOX production plant power consumption with annual production rate.

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 MMR required using the ilmenite-bearing soil discussed above. According to Allen et al., volcanic glass is an attractive feedstock option because it is uniformly fine grained, reacts rapidly, and can be fed directly into the LUNOX production plant with little or no processing prior to reduction. There is another important reason to consider as well: it exists in large quantities.

A significant number of large pyroclastic deposits, thought to be the result of continuous, Hawaiian-style, fire-fountain eruptions from large surface vents, have been identified on the lunar nearside by Gaddis et al. (Ref. 24). These deposits are of regional extent and are composed largely of crystallized black beads, orange glass beads, or a mixture of the two. Noteworthy large deposits located just north of the lunar equator include: (1) the Aristarchus Plateau (~49,015 $km^2$), (2) Southern Sinus Aestuum (~10,360 $km^2$), (3) Rima Bode (~6620 $km^2$), (4) Sulpicius Gallus (~4320 $km^2$), (5) Southern Mare Vaporum (~4130 $km^2$), and (6) Taurus-Littrow (~2940 $km^2$).

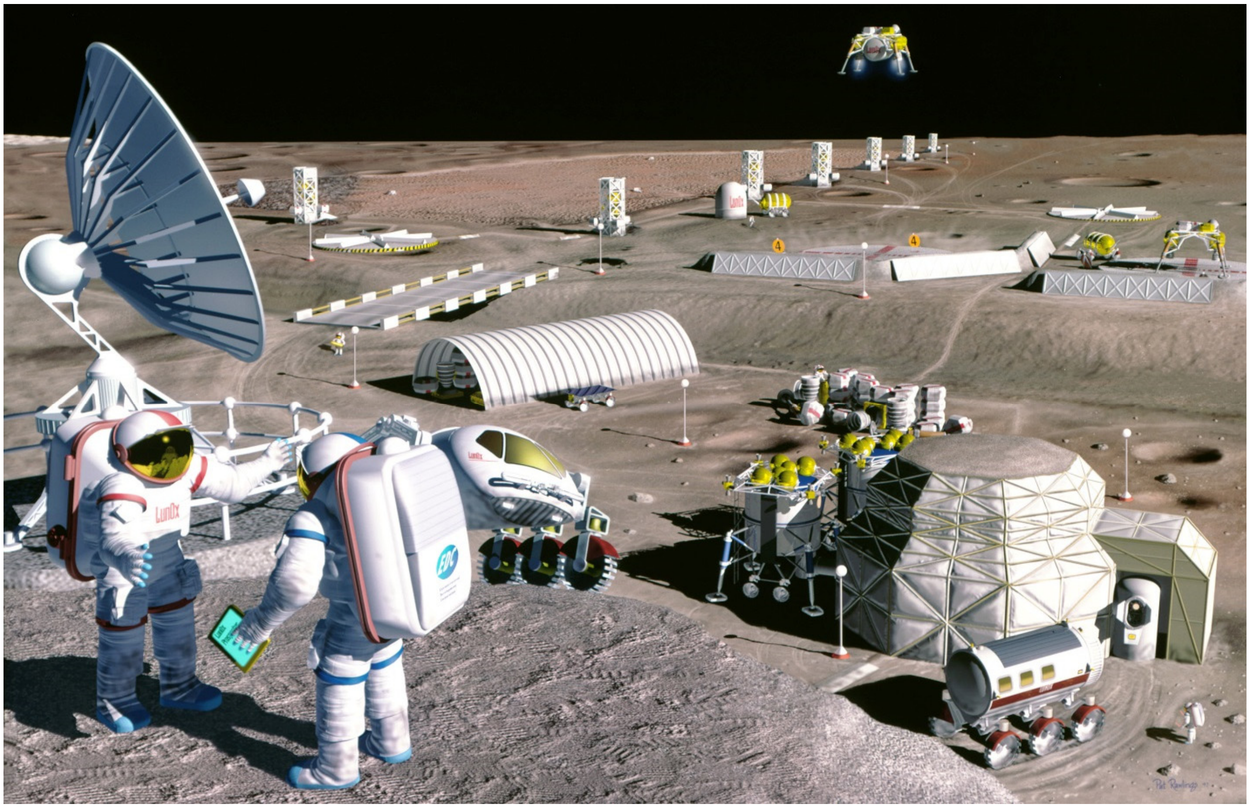


Figure 8.—Conceptual commercial LUNOX facility bordering Taurus-Littrow site dark mantle deposit.

Just like 20 years ago, our choice for siting a commercial LUNOX facility is the Taurus-Littrow DMD near the southeastern edge of Mare Serenitatis (~21° N, ~29.5° E), approximately 30 km west of the Apollo 17 landing site. This deposit of largely black crystalline beads covers ~3000 $km^2$, is thought to be tens of meters thick, and could yield hundreds of millions of tons of LUNOX using the hydrogen-reduction process. The facility image (Fig. 8) was developed and first presented in the author’s 1997 33rd Joint Propulsion Conference paper (Ref. 18) and has appeared in publications and magazines numerous times since then. Depicted in the lower left foreground are two lunar industrialists discussing planned expansions at the LUNOX facility, 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, nuclear fission reactors, positioned within craters and having overhead surface radiators, 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 production capacity increases, the LUNOX enterprise can expand its commercial operations to include metals processing (e.g., iron and titanium), power generation, maintenance, as well as the operations of surface-based LLVs and LLO propellant depots and eventually even a lunar tourism industry complete with routine commuter flights to and from the Moon.

## 3.0 NTR and LANTR System Description and Performance Characteristics

The NTR uses a compact fission reactor core containing enriched uranium- (U-) 235 fuel to generate hundreds of megawatts of thermal power ($MW_t$) required to heat the $LH_2$ propellant to high exhaust temperatures for rocket thrust (Ref. 35). In an “expander cycle” engine (Fig. 9), high-pressure $LH_2$ flowing from a turbopump assembly (TPA) is split into two paths, with the first cooling the engine’s nozzle, pressure vessel, neutron reflector, and control drums and the second path cooling the engine’s core support tie-tube (TT) 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 (FEs). 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), and then expanded out a high-area-ratio nozzle (~300:1) 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.

Recent studies showing the benefits of NTP for a variety of exploration and commercial lunar missions (Refs. 16 and 17) have used a common NTP stage (NTPS) employing a cluster of three small nuclear rocket engines (SNREs). The engine’s reactor core is composed of hexagonal-shaped FEs and core support TTs developed and tested during the Rover/NERVA program (Ref. 35). Each FE was fabricated using a graphite matrix material that contained the U-235 fuel in the form of either coated particles of uranium carbide ($UC_2$) or a dispersion of uranium and zirconium carbide (UC-ZrC) referred to as “graphite composite” (GC) fuel (Fig. 10).

This higher performance GC fuel was developed as a *“*drop-in replacement*”* for the coated-particle fuel and was tested in the Nuclear Furnace 1 (NF–1) element test reactor (Ref. 35) near the end of the Rover program. The GC elements achieved a peak power density of ~5 $MW_t$/L (~5000 $MW_t/m^3$) and a peak fuel temperature of ~2700 K. The GC elements also demonstrated better corrosion resistance than the standard coated-particle FEs used in the previous Rover/NERVA (Nuclear Engine for Rocket Vehicle Applications) reactor tests. This improved resistance of the GC fuel was attributed to its higher coefficient of thermal expansion that more closely matched that of the protective ZrC coating, thereby helping to reduce coating cracking. Electrical-heated composite FEs were also tested by Westinghouse in hot hydrogen at 2700 K for ~600 min—equivalent to ten 1-hr cycles.

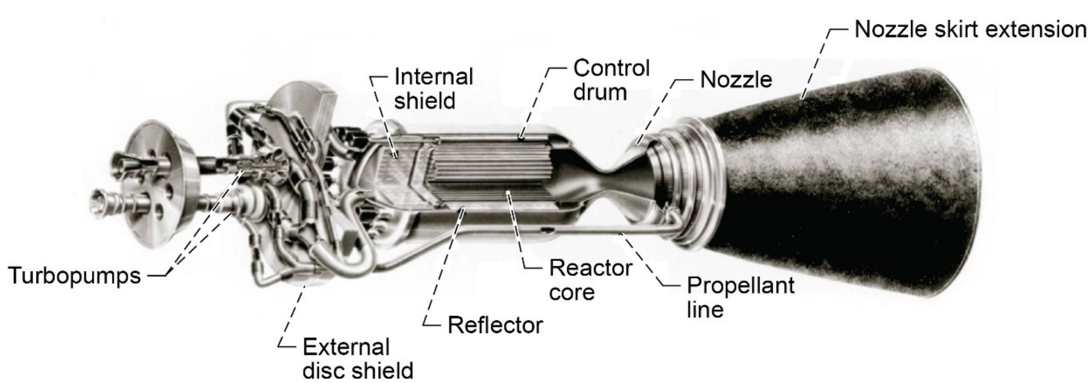



Figure 9.—Expander cycle NTR engine with dual $LH_2$ turbopumps.

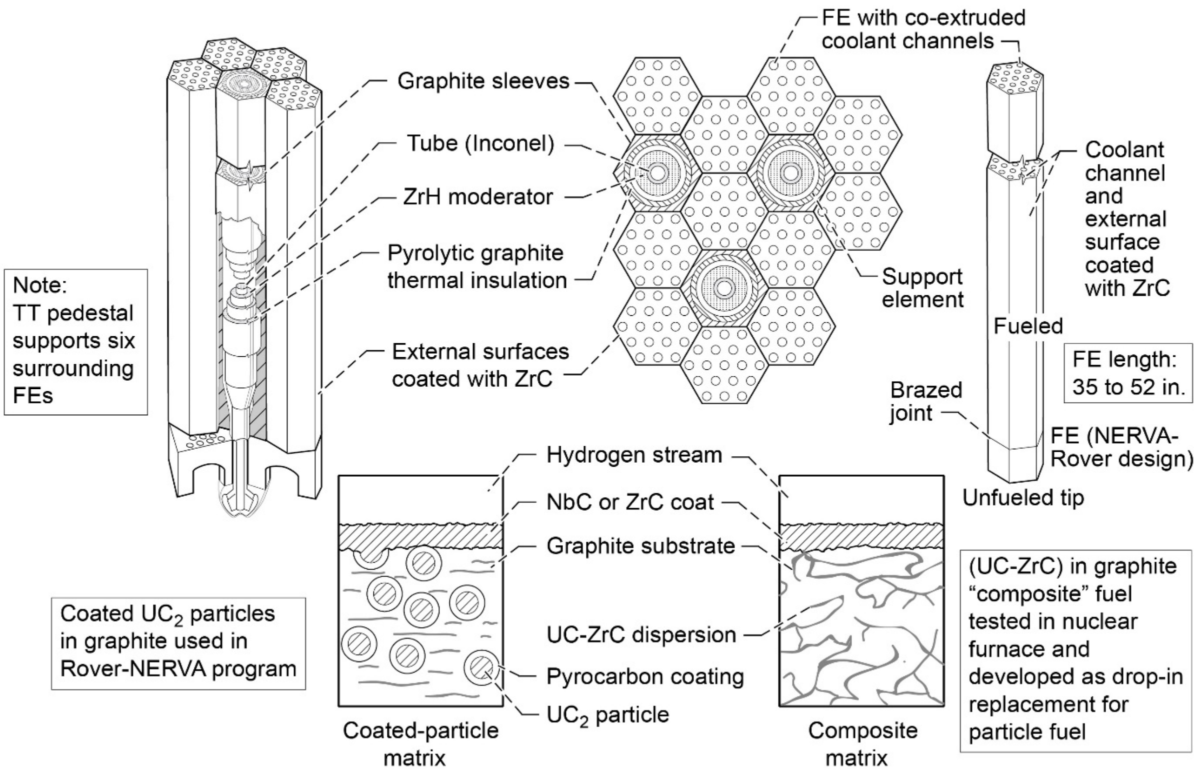



Figure 10.—Coated particle and graphite composite SNRE fuel element (FE) and tie-tube (TT) arrangement.

Heritage Rover/NERVA FEs had hexagonal cross sections (~0.75 in. across the flats) and 19 axial coolant channels (Fig. 10) that were coated with niobium carbide (NbC) initially, then with zirconium carbide (ZrC), using a chemical vapor deposition process. This protective coating, applied to the FE's exterior surfaces as well, helped to reduce coating cracking, hydrogen penetration, and subsequent erosion of the graphite matrix material. Individual elements were 1.32 m (52 in.) in length and produced ~1 $MW_t$ during steady-state, full-power operation. Also included in the engine's reactor core were hexagonal-shaped TT elements that provided structural support for six surrounding FEs (Fig. 10). A coaxial Inconel tube inside the TT carries hydrogen coolant that is also used to supply a source of heated hydrogen for turbine drive power in the SNRE's expander cycle engine design. A sleeve of zirconium hydride (ZrH) moderator material is also incorporated into each TT (Fig. 10) to help increase core reactivity and allow construction of smaller, lower thrust engine systems like the SNRE design (Ref. 35) developed by the Los Alamos National Laboratory near the end of the Rover/NERVA program.

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

The baseline SNRE used in this study has a nominal power output of ~365 $MW_t$, an average power density of ~3.44 $MW_t$/L, and produces ~16.5 $klb_f$ (1 $klb_f$ = 1000 pounds force) of thrust. The reactor core has 564 FEs and 241 TTs and is surrounded by a 14.7-cm-thick perimeter neutron reflector, resulting in a pressure vessel OD of ~98.5 cm. With a fuel loading of ~0.6 g/cm$^3$, the FEs contain ~60 kg of 93% enriched U-235. The GC fuel operates at a peak temperature of ~2860 K, and the corresponding hydrogen exhaust temperature is ~2734 K. With a chamber pressure of 1000 psia, a hydrogen flow rate of ~8.30 kg/s

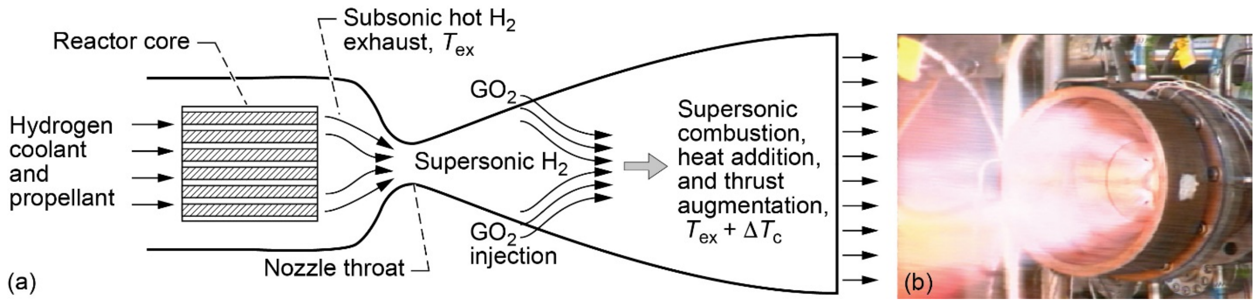



Figure 11.—Simplified LANTR schematic and simulated proof-of-concept test article photograph (Ref. 36).

and a nozzle area ratio (NAR) of ~300:1, the engine's specific impulse $I_{sp}$ is ~900 s. The total engine length is ~5.8 m with the ~1.8-m-long radiation-cooled, retractable nozzle section fully extended. The nozzle exit diameter is ~1.53 m and the engine's thrust-to-weight ratio is ~3.02.

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

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

A simplified schematic of LANTR engine operation is illustrated in Figure 11. Also shown is a photograph of a nonnuclear, "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 three wedge-shaped injectors (two of which are visible in Fig. 11) (Ref. 36). These tests and follow-on tests with a 50:1 NAR 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 (Ref. 20).

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 (Table I) while the reactor core produces a relatively constant power output. As the MR varies from 0 to 5, the engine thrust level for the SNRE increases by over 344%—from 16.5 to ~56.8 $klb_f$—while the $I_{sp}$ decreases by ~57%—from 900 to 516 s—which is still 54 s higher than that achieved by today's best $LO_2/LH_2$ chemical engine, the RL10B–2 (Ref. 37). This thrust augmentation feature 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, or g-losses (thereby eliminating the need for and concern over multiple perigee burn Earth departure maneuvers). Lastly, the increased use of high-density $LO_2$ in place of low-density $LH_2$, and the ability to resupply, or reoxidize, LANTR vehicles with LUNOX prior to Earth return, are expected to significantly reduce vehicle size and mass while increasing delivered PL.

TABLE I.—SNRE AND LANTR PERFORMANCE CHARACTERISTICS AS FUNCTION OF O/H MIXTURE RATIO[a]

| O/H mixture ratio | Specific impulse,[b] $I_{sp}$, s | Thrust augmentation factor | Thrust, $lb_f$ | Engine mass, $lb_m$ | Engine thrust/weight |
|---|---|---|---|---|---|
| 0 | 900 | 1.0 | 16,500 | 5462 | 3.02 |
| 1 | 725 | 1.611 | 26,587 | 5677 | 4.68 |
| 2 | 637 | 2.123 | 35,026 | 5834 | 6.00 |
| 3 | 588 | 2.616 | 43,165 | 5987 | 7.21 |
| 4 | 552 | 3.066 | 50,587 | 6139 | 8.24 |
| 5 | 516 | 3.441 | 56,779 | 6295 | 9.02 |

[a]Acronyms are defined within report and in appendix.
[b]Fuel exit and hydrogen exhaust temperature = 2734 K, chamber pressure = 1000 psia, and nozzle area ratio = 300:1.

# 4.0 Mission, Payload, and Transportation System Ground Rules and Assumptions

Specific mission and PL ground rules and assumptions used in this report are summarized in Table II, which provides information about the different lunar mission scenarios along with the assumed parking orbits at Earth and the Moon. Specific trajectory details and $\Delta V$ budgets for the different missions examined are provided within the appropriate sections of the report. In addition to the large $\Delta V$ requirements for the primary propulsion maneuvers like translunar injection (TLI), lunar orbit capture (LOC), trans-Earth injection (TEI), and Earth orbit capture (EOC), smaller $\Delta V$ maneuvers are needed for propellant settling, vehicle midcourse correction maneuvers, orbital operations in LLO (including rendezvous and docking (R&D) of the lunar transfer vehicle (LTV) with surface-based LLVs or with the lunar propellant depot), and lastly, LTV-depot separation and station keeping.

A variety of different PLs are also considered. On initial “all $LH_2$” NTR crewed landing missions, a forward-mounted saddle truss is used to connect the PL elements to the transfer vehicle’s in-line tank. The truss is open on its underside, and its forward adaptor ring provides a docking interface between the multipurpose crew vehicle (MPCV) and the single-stage $LO_2/LH_2$ lunar descent and ascent vehicle (LDAV) (Fig. 12(a)). The LDAV is a “heritage” design (Ref. 38) analyzed in considerable detail during NASA’s earlier Space Exploration Initiative studies. It carries a crew of four plus 5 t of surface PL stored in two 2.5-t PL pallets mounted on each side of the crew cab. The LDAV mass breakdown including the propellant loading and landed PL is shown in Table II. On the lunar landing mission analyzed here, the crew collects and returns ~100 kg of samples.

For the reusable, space-based CCT missions using LANTR propulsion and LUNOX on the Earth return mission leg, the LTV carries a habitat module that supports a crew of four. 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 LLO propellant depot. Connecting the habitat module to the rest of the LANTR LTV is a “star truss” that has four concave sides to accommodate four PL pallets (Fig. 12(b)). The forward circular truss ring also has a remote manipulator system (RMS) with twin arms attached to it. Using the habitat module’s rear viewing window, the crew uses these arms to unload and attach the transport’s cargo to the depot or to a co-orbiting LLV transferring crew and awaiting cargo delivery.

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

TABLE II.—MISSION AND PAYLOAD GROUND RULES AND ASSUMPTIONS[a]

| | |
|---|---|
| • Crewed lunar landing using NTR (3-day transits to and from Moon with 3 to 14 days on surface)<br><br>• CCT using LANTR (1.5- to 3-day transits to and from Moon with 3 days in LLO)<br><br>• LANTR commuter shuttle carries PTM (one-way transit of 36 hr or less)<br><br>• Rapid commuter shuttle and priority cargo delivery system using LANTR (24- and 48-hr transit times for passenger and priority cargo mission legs, respectively) | • Reusable LTV carries MPCV, reusable LLV and surface PL to LLO; returns MPCV and spent LLV to EEO; *Orion* capsule used for crew recovery at mission end<br><br>• Reusable, LANTR LTV transports habitat module, crew, and varying amounts of cargo, depending on the transit times to and from LLO; LTV refuels with LUNOX at LLO depot before returning to Earth<br><br>• Reusable, LANTR LTV transport a PTM to LLO for subsequent delivery to the LS by LLV; LTV refuels with LUNOX at LLO depot before returning to Earth with another PTM<br><br>• Reusable LANTR LTV delivers PTM to LLO then returns priority cargo back to LEO; LTV refuels with LUNOX at LLO depot before returning to Earth; PTM and cargo PLs alternate going out and back |
| • NTR and LANTR missions depart from LEO, then capture and depart from equatorial LLO<br>• NTR missions return to EEO, and LANTR missions return to LEO | • LEO: 407 km circular<br>• LLO: 300 km equatorial<br>• 3.24-hr EEO: 407 by 9050 km<br>• 24-hr EEO: 407 by 71,310 km |
| • Primary mission velocity change increment $\Delta V$ maneuvers: NTR or LANTR engines used<br>• Additional $\Delta V$ requirements: AMBR RCS thrusters used to perform nonprimary propulsion maneuvers | • $\Delta V$ budgets for different missions discussed in relevant sections<br>• Propellant settling burn: ~1 m/s<br>• Midcourse correction: ~10 m/s<br>• Lunar orbit rendezvous and docking and maintenance: ~40 m/s<br>• Depot separation and station keeping: ~10 m/s |
| • Crewed landing mission PL masses:<br>Reusable NTR LTV delivers *Orion* MPCV and single-stage $LO_2$-$LH_2$ LDAV to LLO; LDAV carries four crew and 5 t of PL to LS; LTV with *Orion* MPCV, LDAV, and surface samples returned to 24-hr EEO | • *Orion* MPCV: 13.5 t<br>• Saddle truss assembly (STA): 7.2 t<br>• LDAV crew cab and dry mass: 8.6 t<br>• Crew (4) and EVA suits: 0.8 t<br>• LDAV propellant load: 20.9 to 22.4 t<br>• LDAV surface PL: 5.0 t<br>• Returned samples: 0.1 t |
| • CCT PL masses:<br>Reusable LANTR LTV delivers a habitat module, crew, and cargo (10 to 20 t, depending on transit time) from LEO to LLO, then returns to LEO | • Habitat module: 9.9 t<br>• Single star truss with RMS: 5.29 t<br>• Outbound PL (4 to 8 cargo pallets) 2.5 t each<br>• Crew (4) and EVA suits: 0.80 t<br>• Returned samples: 0.25 t |
| • Commuter shuttle PL mass:<br>Reusable LANTR LTV delivers PTM from LEO to LLO then back again<br>• PTM and priority cargo masses: Reusable LANTR LTV delivers PTM to LLO then returns to LEO with priority cargo shipment; PLs alternate out and back | • PTM: 15 t (includes 2 crew and 18 passengers)<br><br>• PTM: 15 t (“one-way” transit time for the PTM is 24 hr)<br>• Cargo container: 7.5 t (includes 5.0 t of priority cargo) (“one-way” transit time for cargo is 48 hr) |

[a]Acronyms are defined within report and in appendix.

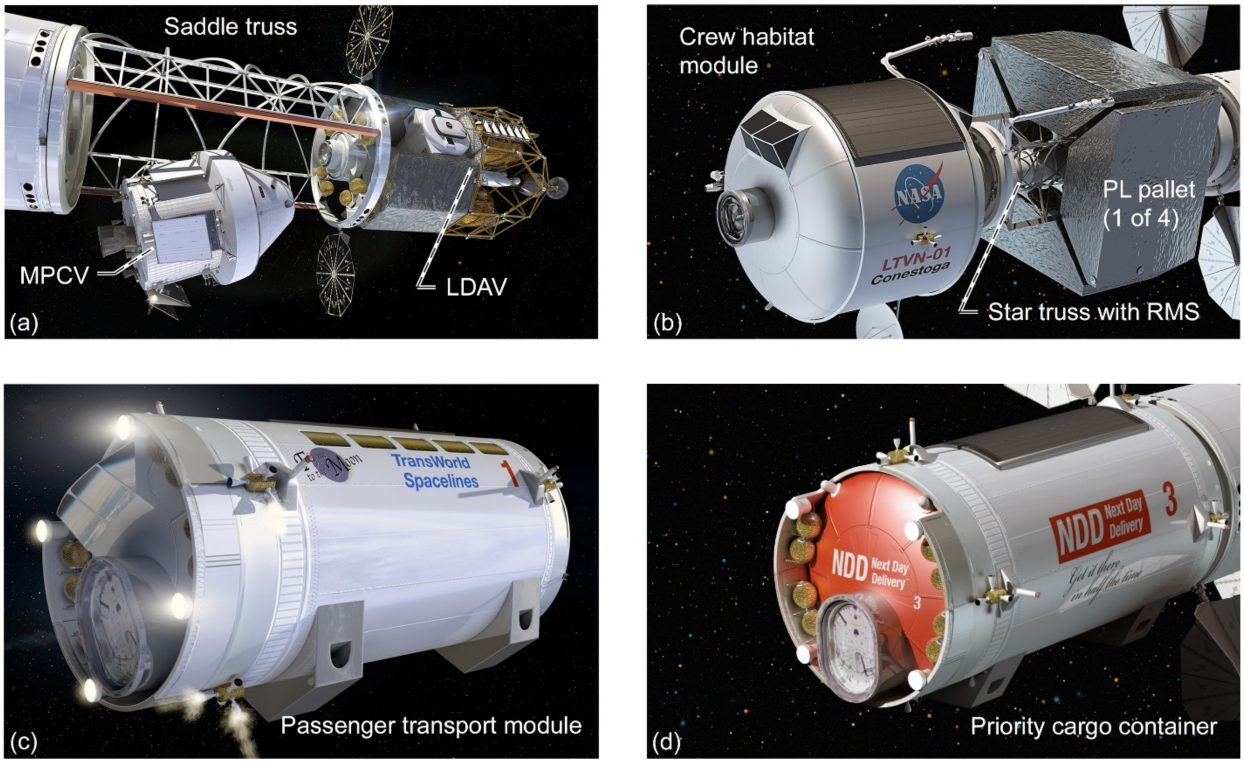



Figure 12.—Payload elements carried by NTR and LANTR lunar transfer vehicles.

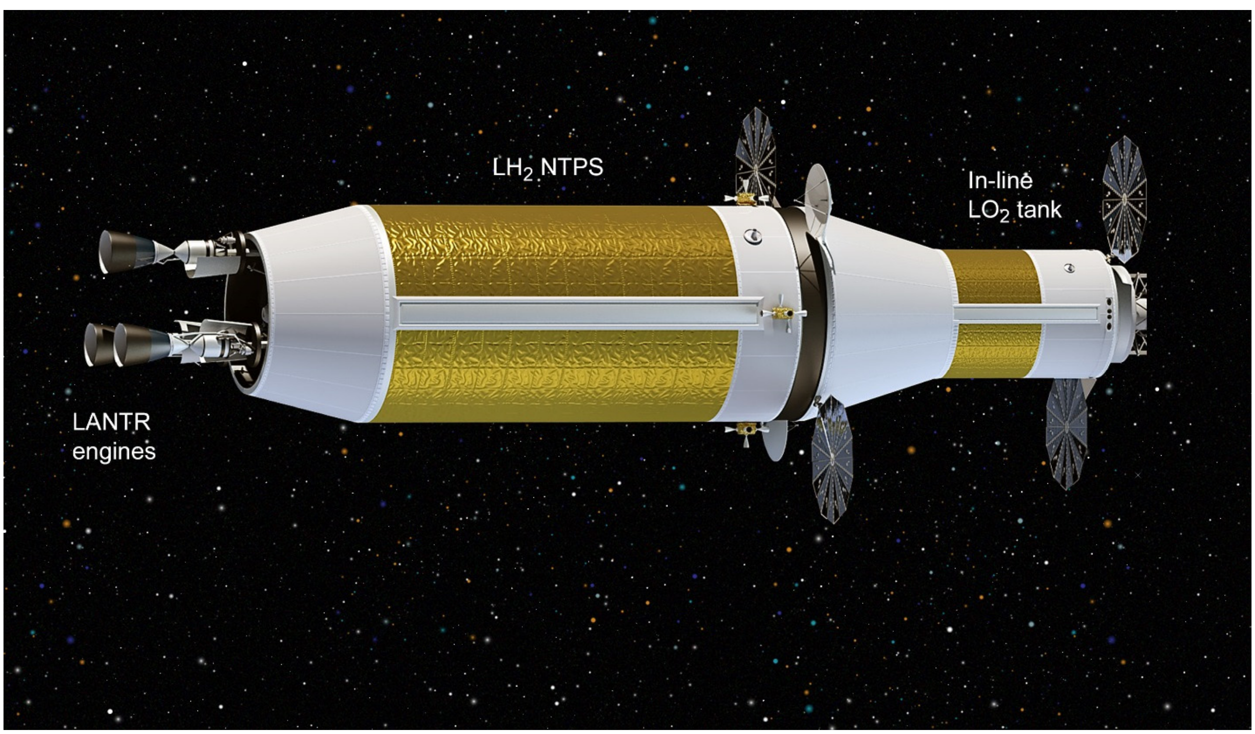



Figure 13.—Key elements of LANTR lunar transfer vehicle system: $LH_2$ NTPS and in-line $LO_2$ tank.

Table III lists the key ground rules and assumptions used in the NTR and LANTR transportation system elements. The NTPS carries only $ELH_2$ and uses a three-engine cluster of SNRE-class engines initially before transitioning over to LANTR operation. The smaller diameter in-line $LO_2$ tank located in front of the NTPS carries Earth-supplied $LO_2$ on the way out to the Moon but refuels with LUNOX for the return to Earth. Details on the NTR and LANTR engine design and performance are provided in Section 2.0 and are summarized in Table III. The total mission $LH_2$ and $LO_2$ propellant loadings consist of the usable propellant plus performance reserve and tank-trapped residuals. Additional $LH_2$ is also provided for engine cooldown after each major propulsive maneuver.

For the smaller auxiliary maneuvers performed, a storable bipropellant reaction control system (RCS) with Advanced Material Bipropellant Rocket (AMBR) thrusters is used (details in Table III). The LANTR LTV utilizes a split RCS with approximately half the AMBR thrusters and bipropellant mass located on the rear NTPS and the other half located at the front end of the in-line $LO_2$ tank just behind the mission-specific PL.

TABLE III.—NTR AND LANTR TRANSPORTATION SYSTEM GROUND RULES AND ASSUMPTIONS[a]

| | |
|---|---|
| NTR and LANTR characteristics | • Engine (fuel type): NERVA-derived (UC-ZrC composite)<br>• Propellants: $LH_2$ (NTR), $LH_2$ and $LO_2$ (LANTR)<br>• Thrust level: 16.5 $klb_f$ (SNRE-class engine using only $LH_2$)<br>26.5 to 56.8 $klb_f$ (LANTR, O/H MR = 1 to 5)<br>• Fuel element length: 0.89 m (SNRE baseline)<br>• Exhaust temperature: ~2734 K (with 2860 K peak temperature)<br>• Chamber pressure: ~1000 psi<br>• Nozzle area ratio: ~300:1<br>• Specific impulse range: $I_{sp}$ = 900 to 516 s with LANTR (MR = 0 to 5) |
| Propellant margins | • Cooldown: 3% of usable $LH_2$ propellant<br>• Performance reserve: 1% on $\Delta V$<br>• Tank trapped residuals: 2% of total tank capacity |
| RCS<br>(propellant settling, midcourse correction burns, and lunar orbit operations) | • Propulsion type: AMBR 200-$lb_f$ thrusters<br>• Propellant: nitrogen tetroxide ($N_2O_4$) and hydrazine ($N_2H_2$)<br>• Nominal $I_{sp}$: 335 s |
| $LH_2$ cryogenic tanks and passive thermal protection system | • Material: Aluminum-lithium (Al/Li)<br>• Tank<br>– Outer diameter (OD): 7.6 m ($LH_2$); 7.6 m and 4.6 m ($LO_2$)<br>– Length (L): 15.65 m (core NTPS and in-line $LH_2$ tanks)<br>5.23 to 7.95 m ("in-line" $LO_2$ tank)<br>• Geometry: Cylindrical with $\sqrt{2}/2$ ellipsoidal domes<br>• Insulation: 1-in. SOFI (~0.78 $kg/m^2$)<br>+ 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<br>• 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 PLs<br>• "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)<br>• 15% on established propulsion, propellant tanks, and spacecraft systems |
| SLS and SLS upgrade launch requirements:<br>– Usable PL delivered to LEO<br>– Cylindrical PL envelope | <br>• ~70 t (SLS) and 105 to 110 t (upgrade)<br>• 7.6 m OD by ~26.5 m L |

[a]Acronyms and symbols are defined within report and in appendix.

The $LH_2$ propellant carried in the NTPS is stored in the same "state-of-the-art" Al-Li $LH_2$ propellant tank being developed for the Space Launch System (SLS) or alternative heavy lift vehicle (HLV) to support future human exploration missions. Sizing of the $LH_2$ tank assumes a 30-psi ullage pressure, 5g axial and 2.5g lateral launch loads, and a safety factor of 1.5. A 3% ullage factor is also assumed. The in-line $LO_2$ tank with its rear conical adaptor section uses the same sizing and launch load assumptions. All tanks use a combination spray-on foam (SOFI) and multilayer (MLI) insulation system for passive thermal protection. A zero boil-off (ZBO) "reverse turbo-Brayton" cryocooler system is used on the NTPS to eliminate boil-off after the NTPS has been refueled with $ELH_2$ and during the course of the mission. A passive thermal protection system is used on the in-line $LO_2$ tank since it is drained after the LOC burn and is subsequently refueled with LUNOX before the trip back to LEO. The heat load on the NTPS hydrogen tank is largest in LEO and determines the size of the ZBO cryocooler system. Two sets of circular solar PVAs—each producing ~14 $kW_e$—are baselined 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 III also provides the assumed dry weight contingency (DWC) factors, along with the requirements for delivered mass to LEO and the shroud cylindrical PL envelope for the upgraded SLS or HLV. A 30% DWC is used on the NTR and LANTR systems and advanced composite structures (e.g., stage adaptors and trusses) and 15% on heritage systems (e.g., Al-Li tanks, RCS, etc.). The NTPS mass (~70 t) and size (~7.6-m OD and ~26.5-m length (L)) determines the required lift capability and the usable shroud PL volume for the upgraded SLS. The combined saddle truss (~13.7-m L) and LDAV (~9.6-m L) used on the crewed landing mission (Fig. 12(a)) has this same approximate length. On the CCT mission discussed in Section 7.0, the habitat module (~6.5-m OD and ~8.5-m L) and star truss (~11-m L) can be launched together, or the truss can be launched together with the in-line $LO_2$ tank and its conical adaptor (~11.5-m L).

## 5.0 Performance Impact of Integrating LANTR and LUNOX Into the LTS Architecture

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

The NTPS, with its three 16.5-$klb_f$ SNREs, is the "workhorse" element of the cargo and crewed NLTVs shown in Figures 14(a) and (b), respectively. It has a 7.6-m-OD by ~15.7-m-long Al-Li tank that carries ~39.8 t of $LH_2$ propellant. Housed within and mounted on the forward cylindrical adaptor section of the NTPS are the RCS, avionics, batteries, two deployable circular PVAs, a docking system, and a reverse turbo-Brayton cryocooler system for ZBO $LH_2$ storage. The cryocooler system mass and power requirements increase with tank diameter and are sized to remove ~42 W of heat penetrating the 60-layer MLI system while the stage is in LEO, where the highest tank heat flux occurs. To remove this heat load, the two-stage cryocooler system requires ~5.3 $kW_e$ for operation.

The second major element is an in-line Al-Li propellant tank that connects the NTPS to the forward PL element. It has the same OD and length $LH_2$ tank as that used in the NTPS and supplies an additional ~39.8 t of $LH_2$ propellant used during for the 2-perigee burn TLI maneuver. The in-line tank element also includes forward and aft cylindrical adaptor sections that house quick connect propellant feed lines, electrical connections, a RCS along with docking and PL adaptors. A ZBO cryocooler system is not used on the in-line $LH_2$ tank since it is drained during the TLI maneuver. The total length of the in-line element is ~20.7 m.

### 5.1 Reusable Lunar Cargo Delivery and Propellant Tanker Missions

Using the NTPS and in-line tank discussed above, the cargo transport can deliver an ~64.5-t fully integrated habitat lander with surface mobility to LLO then return to Earth for refueling and reuse. Three SLS–1B launches deliver the vehicle and PL elements to LEO where assembly occurs via autonomous R&D. The cargo transport then departs from LEO (characteristic energy $C_3$ ~−1.678 km$^2$/s$^2$ and TLI velocity change $\Delta V_{TLI}$ ~3.214 km/s including a g-loss of ~117 m/s) and captures into a 300-km circular LLO (arrival $C_3$ ~1.151 km$^2$/s$^2$ and LOC velocity change $\Delta V_{LOC}$ ~906 m/s including g-loss) approximately 72 hr later.

Once in orbit, the habitat lander separates from the cargo transport (Fig. 14(a)) and descends to the surface, landing autonomously at a predetermined location on the Moon. The habitat lander uses $LO_2/LH_2$ chemical engines and is equipped with either wheels or articulated landing gear, allowing movement in both the vertical and horizontal directions so the lander can either "drive or walk" short distances from the landing site. Assuming a LUNOX production plant and lander can be configured to fit within the SLS–1B PL shroud, the habitat lander can be replaced by a 36-t wet LLV stage capable of delivering ~28 t from LLO to the LS. According to Figure 6, a LUNOX plant mass of ~28 t corresponds to a production capacity of ~175 t/yr assuming volcanic glass as feedstock. This mass includes the mining and processing equipment with a 30% margin but does not include any beneficiation hardware. The fission surface power system mass is also not included here because it is delivered and predeployed on an earlier mission. Without any attached PL, the cargo NLTV can also function as a propellant tanker, delivering ~25.6 t of $LH_2$ to a LLO depot on each round-trip mission.

After PL separation and a day or so in LLO, the cargo transport performs a TEI burn (departure $C_3$ ~0.945 km$^2$/s$^2$ and $\Delta V_{TEI}$ ~857 m/s including g-loss) and returns to Earth 72 hr later. On final approach, it performs the EOC burn (arrival $C_3$ ~−1.755 km$^2$/s$^2$ and $\Delta V_{EOC}$ ~366 m/s) and captures into a 24-hr elliptical Earth orbit (EEO) with a 407-km perigee by 71,310-km apogee. Postburn engine cooldown thrust is then used to assist in orbit lowering. Afterwards, an auxiliary tanker vehicle operating from a LEO propellant depot, rendezvous and docks with the cargo vehicle and supplies it with the additional $LH_2$ propellant needed for final orbit lowering and rendezvous with the LEO transportation node and propellant depot, where it is refurbished and resupplied before its next mission.

The cargo NLTV has an IMLEO of ~187.8 t consisting of the NTPS (~68.3 t), the in-line tank element (~52 t), and the habitat lander (~64.5 t) with its connecting structure (~3.0 t). The mission requires five primary burns by the SNRE engines that use ~74.8 t of $LH_2$ propellant. With ~49.5 klb$_f$ of total thrust and $I_{sp}$ ~900 s, the total engine burn time is ~50 min. For the propellant tanker mission, the IMLEO is ~121.2 t and the total engine burn time is ~34 min.

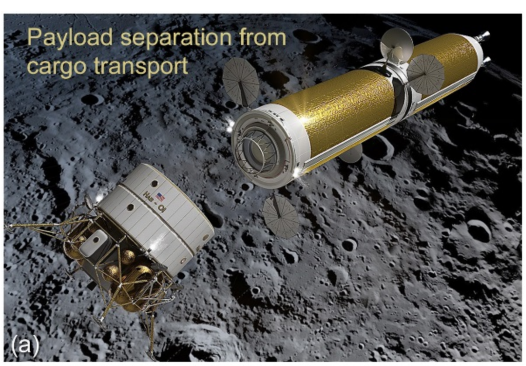




Figure 14.—Reusable NTR cargo delivery and crewed lunar landing vehicles.

## 5.2 Reusable Crewed Lunar Landing Mission

On the crewed landing mission, the NLTV (Fig. 15(a)) carries a forward-mounted saddle truss assembly (STA) that connects the PL elements to the transfer vehicle's in-line tank. The truss is open on its underside, and its forward adaptor ring provides a docking interface between the *Orion* MPCV and the single-stage $LO_2$-$LH_2$ LDAV as shown in Figure 14(b). The LDAV carries a crew of four plus 5 t of surface PL stored in two "swing-down" pallets mounted on each side of the crew cab (Fig. 15(b)).

Three SLS–1B launches are used to deliver the two NTR vehicle elements and the PL element to LEO for assembly via autonomous R&D. The PL element includes the connecting STA plus the LDAV with its surface cargo containers. In addition to a front and rear docking capability, the STA's forward adaptor ring also carries twin PVAs and a RCS. Once assembled, the *Orion* MPCV and crew are launched, and they rendezvous with the NLTV positioning itself inside the STA and docking with the LDAV using the docking port and transfer tunnel mounted to the STA's forward adaptor ring (Fig. 12(a)). After the 2-perigee burn TLI burn ($C_3$ ~–1.516 km$^2$/s$^2$ and $\Delta V_{TLI}$ ~3.214 km/s including a g-loss of ~110 m/s), the crew begins its 3-day coast to the Moon. Although the crewed NLTV carries a significant amount of PL mass (the STA, MPCV, and "spent" LDAV) back from the Moon, it uses the same ~15.7-m-long in-line tank to supply the required amount of $LH_2$ propellant needed for this reusable mission. After its 72-hr transit, the NLTV performs the LOC burn (arrival $C_3$ ~1.217 km$^2$/s$^2$ and $\Delta V_{LOC}$ ~913 m/s including g-loss) inserting itself and its PL into LLO.

Once in LLO, the crew enters the LDAV and separates from the transfer vehicle. After separation, the LDAV's two PL pallets are rotated 180° and lowered into their landing position in preparation for descent to the LS (Fig. 15(b)). The $\Delta V$ budget used in the Martin Marietta LDAV design (Ref. 38) is $\Delta V_{des}$ ~2.115 km/s and $\Delta V_{asc}$ ~1.985 km/s for the descent and ascent velocity changes, respectively. The LDAV uses five RL10A–4 engines operating with a $I_{sp}$ ~450 s, and ~13.5 t of $LO_2$/$LH_2$ propellant is expended during the descent to the surface.

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

The crewed lunar landing mission has an IMLEO of ~176.6 t that includes the NTPS (~68.7 t), the in-line tank assembly (~51.8 t), the STA (~7.2 t), the wet LDAV (~29.5 t) with its surface PL (~5 t), the *Orion* MPCV (~13.5 t), consumables (~0.1 t), and four crewmembers (~0.8 t includes suits for lunar extravehicular activity (EVA)). At departure, the $LH_2$ propellant loading in the NTPS and the in-line tank are at their maximum capacity of ~39.8 t. The overall length of the crewed NLTV is ~74 m. Like the cargo mission, the crewed landing mission requires five primary burns by the NTPS using ~74.8 t of $LH_2$ propellant, and the total engine burn time is again ~50 min.

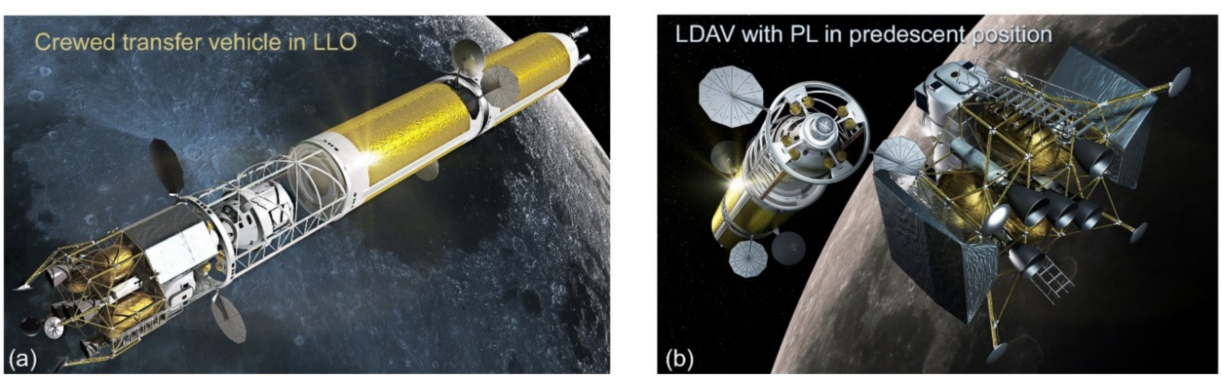



Figure 15.—Crewed lunar landing mission: crewed transfer vehicle capture into LLO and LDAV landing preparation.

## 5.3 Impact of Using LUNOX to Refuel Surface-Based LDAVs and In-Space NLTVs

Figure 16 shows the variation in NLTV size, IMLEO, increased mission capability, and engine burn time resulting from the development and utilization of $LLO_2$. Figure 16(a) shows the reusable, crewed NLTV discussed above. It departs from LEO and captures into a 300-km equatorial LLO. At the end of the mission, the NLTV returns to Earth with the spent LLV and captures into a 24-hr EEO because it has a much lower $\Delta V$ requirement. In order to return to LEO, the NLTV would need an additional ~118 t of $LH_2$ propellant, requiring the insertion of a star truss with four attached drop tanks between the vehicle's in-line tank and forward PL. The additional mass of the extra truss, propellant, and tanks nearly doubles the vehicle's IMLEO to ~347.8 t!

The first significant step in LUNOX production occurs when lunar outpost assets and $LLO_2$ production levels become sufficient to support a LS-based LDAV. By not having to transport a "wet" LDAV to LLO on each flight, the crewed NLTV now has a lower starting mass in LEO (~146 t) plus sufficient onboard propellant to allow a single-burn departure from LEO and a return to a lower, higher energy ~3.25-hr EEO (407-km perigee by 9050-km apogee with $\Delta V_{EOC}$ ~1793 m/s including a g-loss of ~35 m/s) as shown in Figure 16(b).

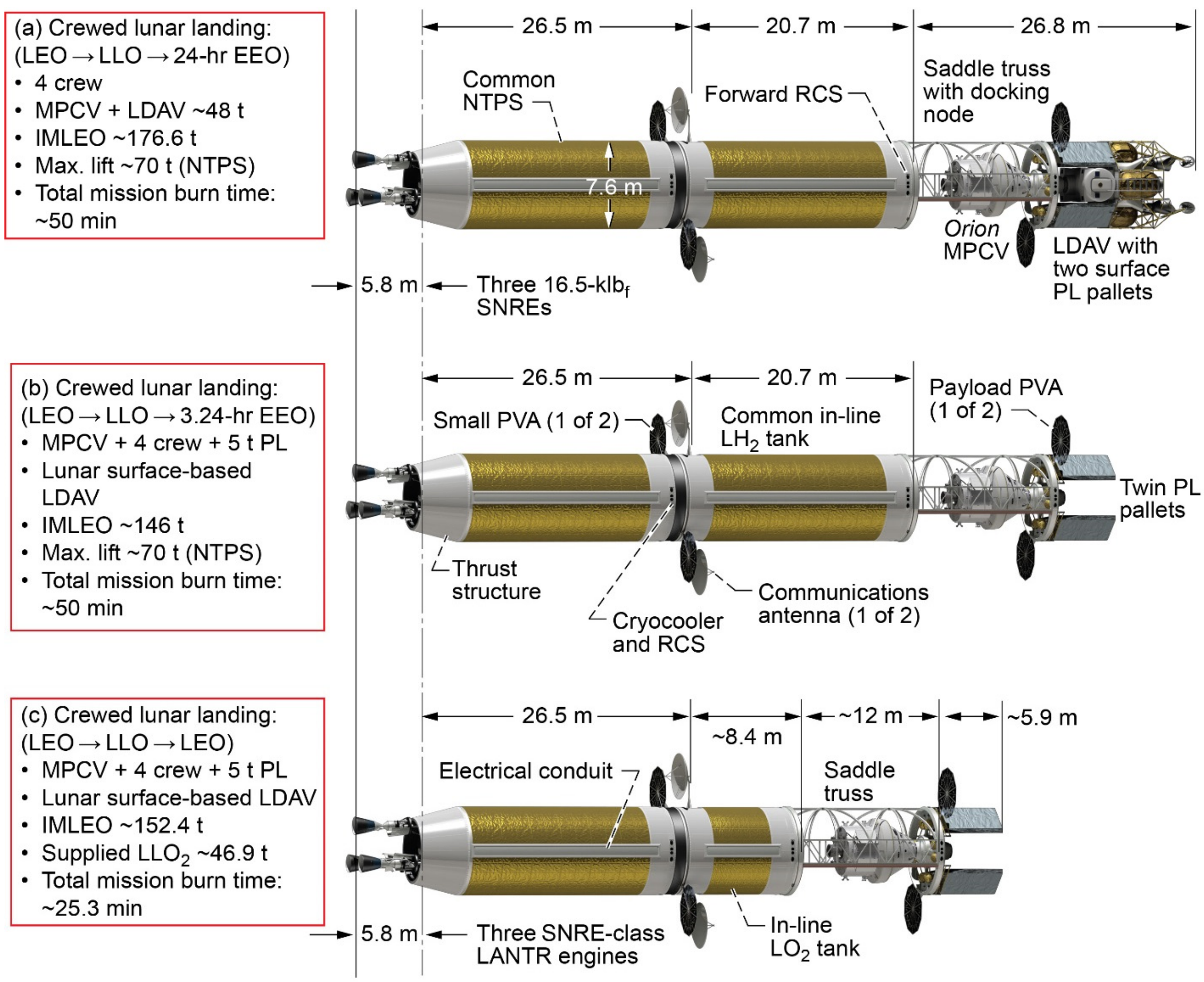



Figure 16.—Variation in NLTV size, IMLEO, mission capability, and engine burn time resulting from development and utilization of $LLO_2$ and transition to LANTR operation.

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

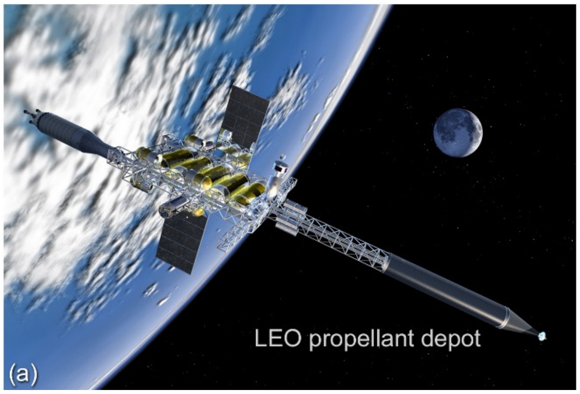
As LUNOX production increases further and a propellant depot is established in LLO, it will be routinely supplied with both $LLO_2$ transported from the LS by specialized LUNOX tanker LLVs and $ELH_2$ delivered by NTR tanker vehicles operating between LEO and LLO. At this point, the NLTV's SNREs are refitted with afterburner nozzles and $LO_2$ feed systems, and the large in-line $LH_2$ tank used in the two previous vehicles is replaced by a smaller $LO_2$ tank (Fig. 16(c)). The $LO_2$ tank, consisting of two √2/2 ellipsoidal domes, is ~5.23 m long and has a 7.6-m OD that is compatible with the saddle truss diameter. The corresponding tank volume can hold ~163.5 t of $LO_2$, which is excessive for the landing mission under consideration here. Using ~49 t of LEO-supplied $LO_2$ for TLI and LOC, refueling with ~47 t of $LLO_2$ prior to Earth return, and using only $ELH_2$ out and back, a crewed LANTR LTV is smaller and ~24 t lighter than the NLTV shown in Figure 16(a). It is also capable of returning back to LEO—a significant advance in performance capability.

The LANTR engines used in this study are sized with the appropriate hardware mass (pumps, controls, lines, etc.) for the maximum O/H MR operation to allow the full range of MRs from 0 to 5 to be accessible during the mission. It is also important to note that with $LO_2$ augmentation, the total engine burn time for the LANTR LTV option is nearly cut in half. This is because of the fixed $LH_2$ loading in the NTPS (~39.8 t) and the specified hydrogen flow rate (~8.3 kg/s) through each engine. It is this bipropellant operation, LUNOX refueling capability, and use of optimized MRs out and back that allow the LANTR system to achieve its superior performance while also reducing the LTV's size and mass.

## 6.0 Growth Mission Possibilities Using Depots and LUNOX Refueling

Over time we envision the development of a totally space-based LTS with different types of NLTVs operating between transportation nodes and/or propellant depots located in LEO (Fig. 17(a)) and LLO (Fig. 17(b)). Because abundant deposits of volcanic glass are located at sites just north of the lunar equator, we envision that a depot will be established in equatorial LLO initially and will be routinely supplied with LUNOX from tanker LLVs operating between LLO and the LS. A propellant depot in LLO could also evolve into a key transportation node, providing a convenient staging location where NTR tanker vehicles, CCTs, and commuter shuttles can drop off $ELH_2$, cargo, and passengers that would then be picked up by LLVs for transport to the LS.

One-way transit times to and from the Moon on the order of ~72 hr would be normal initially. Eventually, however, as lunar outposts grow into permanent settlements staffed by visiting scientists, engineers, and administrative personnel representing both government and private ventures, more frequent flights of shorter duration could become commonplace. As shown in Figure 18, cutting transit times between LEO and LLO in half to ~36 hr will require the mission's total $\Delta V$ budget to increase by ~25% (from ~8 to 10 km/s). As a result, versatile LANTR engines with adequate supplies of LUNOX for refueling will be key to ensuring LTVs of reasonable size.



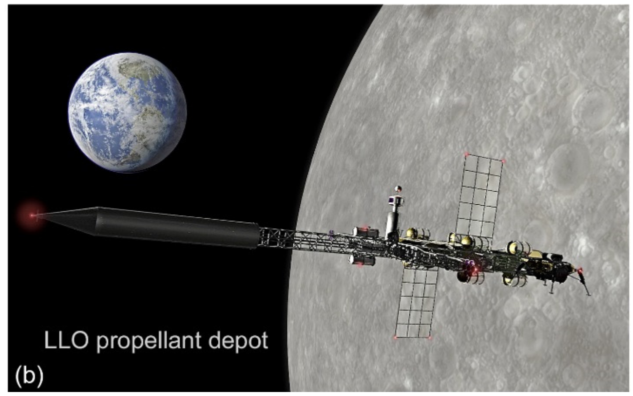



Figure 17.—Propellant depots in LEO and LLO: critical elements for robust lunar transportation system.

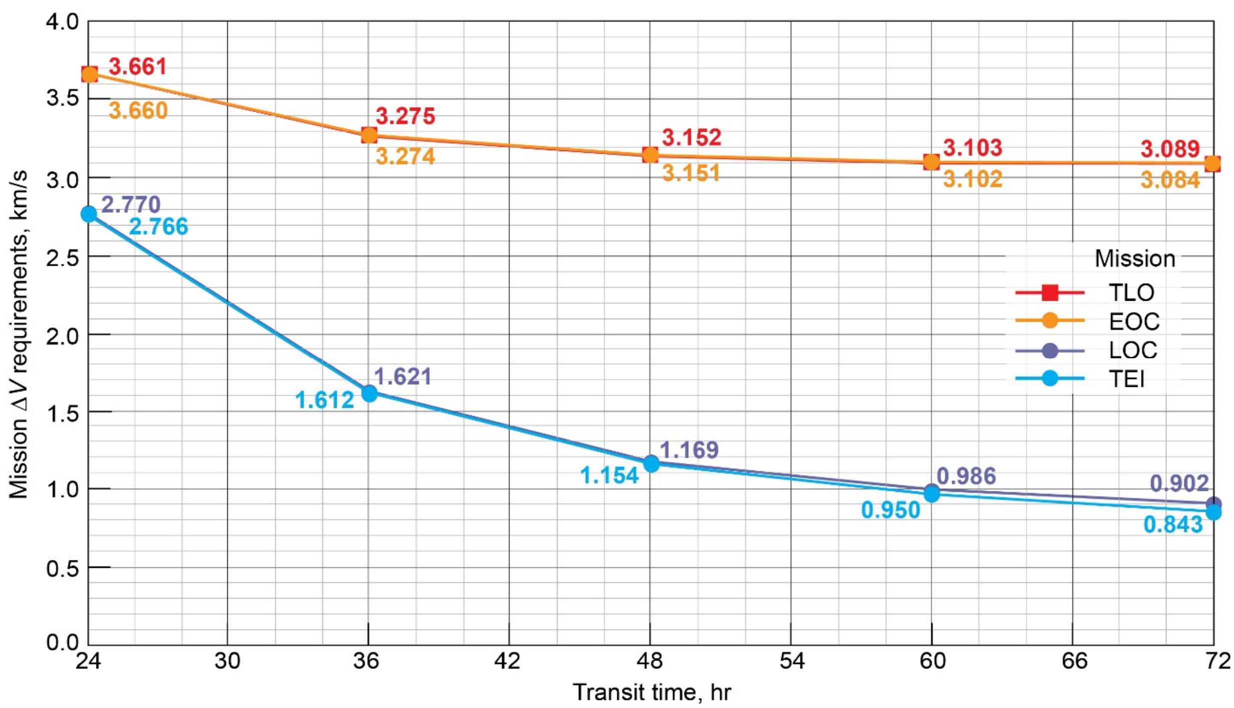



Figure 18.—Variation in primary-maneuver $\Delta V$ values with flight time.

# 7.0 *Conestoga*—A Reusable, Space-Based Crewed Cargo Transport

The original Conestoga wagon was a freight wagon developed in Lancaster County, Pennsylvania, in the early 1700s (Ref. 39) and used extensively in Pennsylvania and the nearby states of Maryland, Ohio, and Virginia for more than 150 years. It was designed for hauling heavy loads—up to 6 t—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 (Fig. 19).

Named after its earlier ancestor, the *Conestoga* CCT shown in Figure 20 is a space-based, reusable LTV that uses LANTR propulsion and refuels with LUNOX propellant. *Conestoga* has its own dedicated habitat module that supports a crew of 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 LLO propellant depot. Connecting the habitat module to the rest of the LANTR LTV is a four-sided star truss that has four PL pallets attached to it, each weighing up to ~2.5 t. To accommodate the wedge-shaped geometry of the cargo pallets, the sides of the star truss are concave—a feature similar to the upward curving ends on the Conestoga wagon bed, though not for the same design reason. 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. Using the habitat module's rear viewing window, the orbiting LDAV transferring crew and awaiting cargo delivery. Key features and dimensions of the *Conestoga* are shown in Figure 21, and major mission activities are shown in Figure 22.

Figure 19.—Conestoga wagons, the "ships of inland commerce," were used from 1700s to early 1900s to transport settlers, farm produce, and freight across Pennsylvania and neighboring states (image ca. 1910). Courtesy of Landis Valley Village & Farm Museum, Pennsylvania Historical Museum Commission.

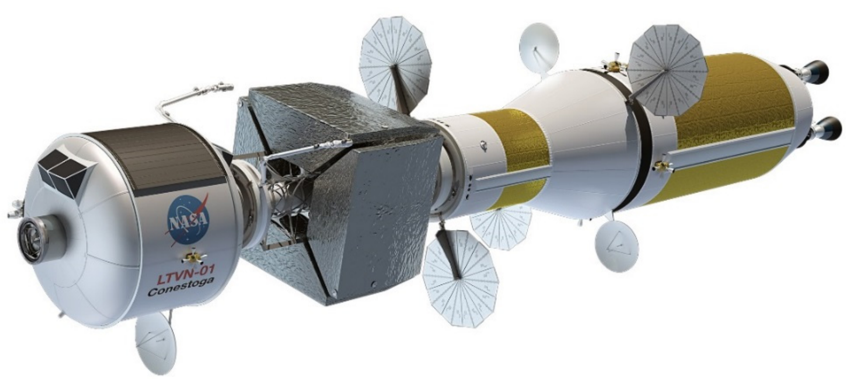



Figure 20.—*Conestoga*: Space-based crewed cargo transport, using common NTPS and in-line $LO_2$ tank.

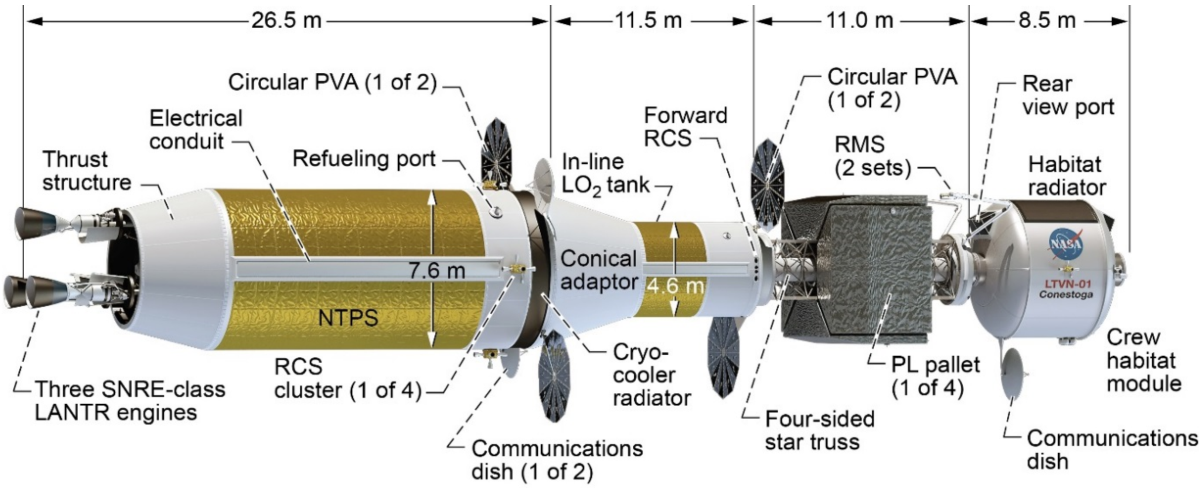



Figure 21.—Key features and dimensions of *Conestoga* crewed cargo transport.

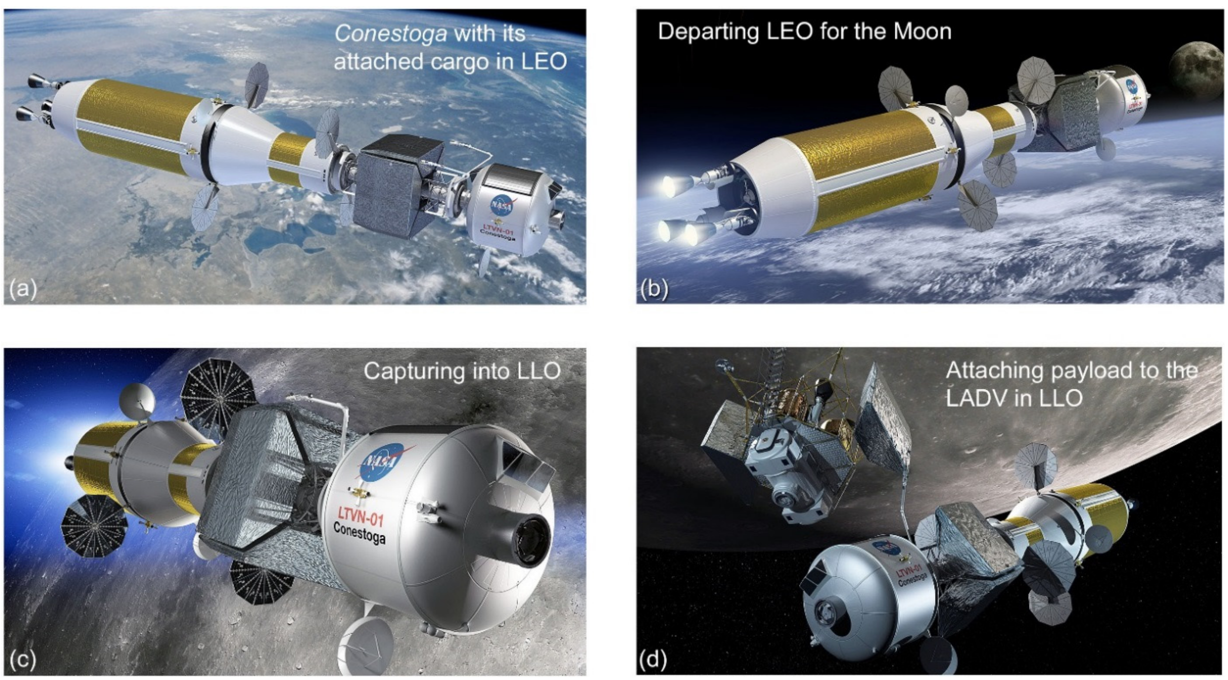



Figure 22.—*Conestoga* crewed cargo transport mission: LEO, outbound, and LLO operations.

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

In this study, the *Conestoga's* NTPS is limited to a LEO launch mass of ~70 t, which includes ~39.8 t of $LH_2$ contained in the NTPS's propellant tank. With this fixed value, the outbound and return O/H MRs used by the LANTR engines are optimized to achieve the desired mission performance. The multidisciplinary analysis and mission assessment code (MAMA) with optimization capability (Ref. 40) is used to determine the customized $LO_2$ tank size and LUNOX refueling requirement for a particular mission application, or for a fixed $LO_2$ tank size it can be used to determine the maximum delivered PL and LUNOX refueling needed for a desired trip time. For a fixed $LO_2$ tank size and PL, the shortest trip time and LUNOX refueling needed can also be determined. A variety of other trades have also been conducted.

Table IV provides a sampling of different crewed cargo missions, vehicle types, and trip times that have been examined as well as the associated LUNOX refueling requirements. All the cases shown use the same common three-engine NTPS described previously in Section 4.0 and shown in Figure 21. Case 1, the crewed lunar landing mission discussed in Section 5.0 and shown in Figure 16(c), carries the *Orion* MPCV and 5 t of cargo. It uses an oversized in-line $LO_2$ tank consisting of two 7.6-m-OD ellipsoidal domes and requires ~47 t of LUNOX for Earth return.

Case 2 is a space-based CCT similar to *Conestoga*. It has its own dedicated habitat module weighing 9.9 t, plus a star truss that has two 2.5-t PL pallets attached to it. The $LO_2$ tank is smaller (~4.6-m OD and ~3.4-m L) and is customized for this particular application, resulting in a lower IMLEO (~131 t) and LUNOX refueling requirement (~35 t).

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

*Case 4 is the defining mission used to establish the required performance and sizing for the Conestoga crewed cargo transport*. Case 4 not only cuts the one-way transit times to 36 hr, but it also doubles the amount of cargo delivered to the LLO to 10 t. To meet these demanding mission objectives, the LANTR engines run "$O_2$ rich" on both the outbound mission leg (O/H MR = 5 and $I_{sp}$ ~ 516 s for TLI; MR = 4.1 and $I_{sp}$ ~ 550 s for LOC) and return mission leg (MR = 5 and $I_{sp}$ ~ 516 s for both the TEI and EOC burns). The $LO_2$ tank length increases to 7.95 m, and it holds ~111.2 t of $LO_2$ just prior to mission start. This tank length is fixed for all subsequent *Conestoga*-class missions. After dropping off its cargo and picking up 250 kg of lunar samples, *Conestoga* refuels with ~74.9 t of LUNOX for the return trip home. For this mission, *Conestoga* has an IMLEO of ~214.3 t, consisting of the NTPS (~71 t), the in-line $LO_2$ tank and conical adaptor (~117.2 t), the star truss assembly with its RMS (~5.3 t) and attached PL (10 t), the habitat module (9.9 t), consumables (~0.1 t), plus the two crew and two passengers with their EVA suits (~0.8 t). The total mission $\Delta V$ to go from LEO to LLO then back to LEO again is ~9.92 km/s including g-losses. With the augmented thrust levels provided by the LANTR engines (~56.8 $klb_f$ per engine at MR = 5), the burn times for the individual maneuvers are ~11.5 min (TLI), ~3.8 min (LOC), ~4.4 min (TEI), and ~5.6 min (EOC), totaling ~25.3 min. *This total burn time is essentially fixed by the available amount of $LH_2$ in the NTPS and the ~8.3-kg/s specified $LH_2$ flow rate for each engine. What varies in the different cases presented in this report is the amount of $LO_2$ supplied in LEO and LLO and the different O/H MRs used by the LANTR engines to achieve the mission objectives*.

Case 5 illustrates the mission flexibility with the *Conestoga* CCT and its LANTR engines. With its fixed-size tanks able to carry ~39.8 t of $LH_2$ and up to ~111.2 t of $LO_2$, *Conestoga* can operate as both a cargo delivery and tanker vehicle. By increasing the LEO to LLO transit time back to 72 hr, and operating the LANTR engines $O_2$ rich both out and back (again at O/H MR = 5 and $I_{sp}$ ~516 s), *Conestoga* can deliver 10 t of cargo and transfer ~9.62 t of $LH_2$ propellant from its NTPS to the LLO depot. For the return trip back to LEO, it refuels with ~54 t of LUNOX. The IMLEO required for this mission is ~194.1 t and the total mission $\Delta V$ is ~8.04 km/s. The burn times for the individual maneuvers are 9.9 min (TLI), ~1.9 min (LOC), ~2.1 min (TEI), and ~5.2 min (EOC) totaling ~19.1 min. *By transferring ~9.6 t of $LH_2$ propellant from the NTPS during this mission, there is less available for the engines to use, so the total mission burn time decreases and the LANTR engines operate at MR = 5 to compensate*.

TABLE IV.—LANTR CREWED CARGO MISSION OPTIONS, TRAJECTORY AND $\Delta V$ BUDGETS, AND LUNOX REFUELING NEEDS[a]

| Case description[b] | Objective | Trajectory and orbits[c] | In-line $LO_2$ tank | Results |
|---|---|---|---|---|
| 1. Crewed LANTR LTV with MPCV and 12-m saddle truss carrying 5 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 5 t cargo to LLO | 72-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~7.984 km/s | 7.6-m OD by ~5.23-m L<br>(~163.5 t $LO_2$) | IMLEO ~152.4 t<br>~48.8 t $LO_2$ supplied in LEO<br>~46.9 t $LLO_2$ refueling in LLO |
| 2. LANTR crewed cargo transport (CCT) with 9.9-t habitat module and 11-m star truss carrying 5 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 5 t cargo to LLO using alternative LTV configuration | 72-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~7.996 km/s | 4.6-m OD by ~3.4-m L<br>(~35.9 t $LO_2$) | IMLEO ~131.1 t<br>~35.9 t $LO_2$ supplied in LEO<br>~35.1 t $LLO_2$ refueling in LLO |
| 3. LANTR CCT with 9.9-t habitat module and 11-m star truss carrying 5 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 5 t cargo to LLO while cutting transit times to 36 hr | 36-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~9.838 km/s | 4.6-m OD by ~6.1-m L<br>(~81.2 t $LO_2$) | IMLEO ~177.4 t<br>~81.2 t $LO_2$ supplied in LEO<br>~71.6 t $LLO_2$ refueling in LLO |
| 4. LANTR CCT with 9.9-t habitat module and 11-m star truss carrying 10 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 10 t cargo to LLO while cutting transit times to 36 hr | 36-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~9.920 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~214.3 t<br>~111.2 t $LO_2$ supplied in LEO<br>~74.9 t $LLO_2$ refueling in LLO |
| 5. LANTR CCT with 9.9-t habitat module and 11-m star truss carrying 10 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 10 t cargo and $LH_2$ propellant to LLO with transit times of 72 hr | 72-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~8.038 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~194.1 t<br>~90.8 t $LO_2$ supplied in LEO<br>~9.62 t $LH_2$ to LLO depot<br>~54 t $LLO_2$ refueling |
| 6. LANTR CCT with 9.9-t habitat module and two 11-m star trusses carrying 20 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 20 t cargo to LLO with transit times of 72 hr | 72-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~8.057 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~189.6 t<br>~71.0 t $LO_2$ supplied in LEO<br>~52.1 t $LLO_2$ refueling in LLO |
| 7. LANTR CCT with 9.9-t habitat module and two 11-m star trusses carrying 20 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 20 t cargo to LLO in shortest transit time | ~44.2-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~9.017 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~230.0 t<br>~111.2 t $LO_2$ supplied in LEO<br>~70.9 t $LLO_2$ refueling in LLO |
| 8. LANTR CCT with 9.9-t habitat module and two 11-m star trusses carrying 40 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 40 t cargo to LLO with transit times of 72 hr | 72-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~8.064 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~250.7 t<br>~109.8 t $LO_2$ supplied in LEO<br>~60.3 t $LLO_2$ refueling in LLO |

[a]Acronyms and symbols are defined within report and in appendix.
[b]Cases use common $LH_2$ NTPS (7.6-m OD by ~15.7-m L). Propellant depots are assumed in LEO and LLO. LANTR engines use optimized O/H MRs out and back.
[c]Altitude: 407 km (LEO) and 300 km (LLO, equatorial). Total round-trip mission $\Delta V$ values shown include g-losses.

For the same one-way transit time of 72 hr, Case 6 shows that a *Conestoga*-class vehicle can double the amount of cargo delivered to LLO from 10 to 20 t. Shown in Figure 23, the *Conestoga-II* is a heavy, CCT that adds a second 11-m-long star truss and RMS and four more 2.5-t PL pallets to the vehicle configuration. This addition results in an increase in the vehicle's overall length from ~57.5 to ~68.5 m. Departing from LEO, the *Conestoga-II*'s LANTR engines operate for ~12.3 min at an O/H MR = 3.4 and $I_{sp}$ of ~573 s. During lunar orbit capture, the engines operate fuel rich for ~4.4 min with a MR = 0.9 and the $I_{sp}$ at ~737 s. Once in orbit, the crew unloads the forward PL pallets first. This allows an unobstructed view of the rear PL section from the habitat module's rear viewing port during the unloading process. After picking up samples, the *Conestoga-II*'s $LO_2$ tank is refueled with ~52.1 t of LUNOX. On the return leg of the mission, the engines operate for ~2.2 min at MR = 4.7 and $I_{sp}$ ~527 s during the TEI maneuver. For EOC, the engines operate for ~6.4 min at MR = 3.8 and $I_{sp}$ ~558 s. The total mission $\Delta V$ is ~8.06 km/s, and the total burn time on the engines is ~25.3 min.

Even with 20 t of delivered PL, additional performance capability is still possible using the *Conestoga-II* vehicle. Since its $LO_2$ tank is only filled to ~64% of maximum capacity in Case 6, faster trip times are possible by taking advantage of the extra propellant capacity that exists within the vehicle design. By increasing the $LO_2$ loading to its maximum capacity of 111.2 t before TLI and increasing the LUNOX refueling to ~70.9 t before TEI, Case 7 shows that faster one-way transit times—on the order of ~44.2 hr—are possible even when carrying 20 t of cargo. For this mission, the LANTR engines operate at O/H MR ~4.9 and $I_{sp}$ ~519 s for TLI and MR ~3.5 and $I_{sp}$ ~568 s for LOC. On the return leg, the engines operate at MR = 5 and $I_{sp}$ ~ 516 s for both the TEI and EOC burns. The IMLEO for the *Conestoga-II*'s fast 20-t cargo delivery mission is ~230 t, the total mission $\Delta V$ is ~9.02 km/s, and the total mission burn time is again ~25.3 min. The burn times for the individual maneuvers are ~12.2 min (TLI), ~3.6 min (LOC), ~3.6 min (TEI), and ~5.9 min (EOC).

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

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

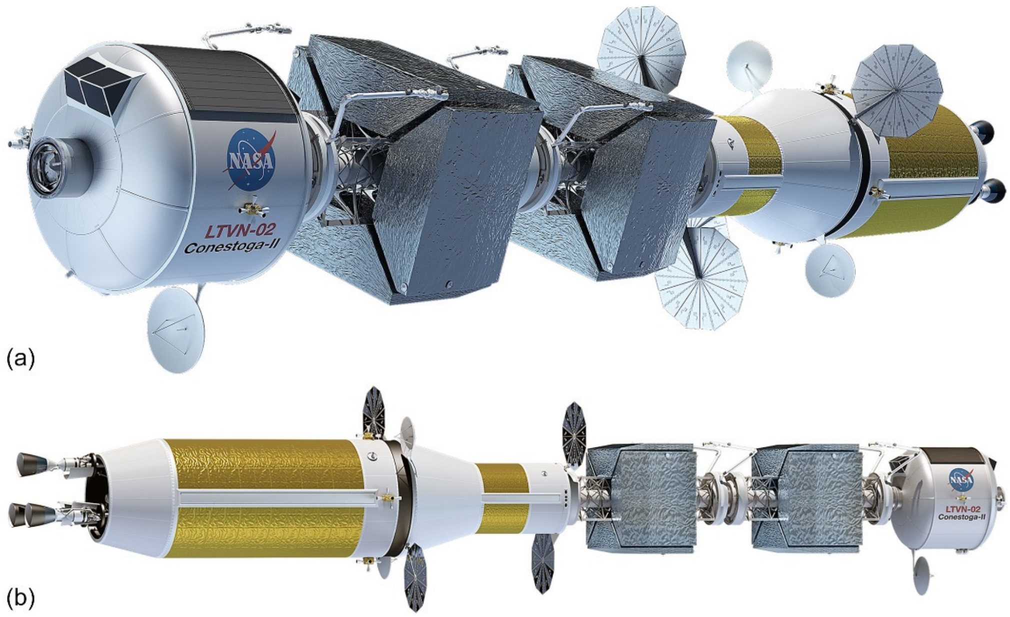



Figure 23.—*Conestoga-II* heavy crewed cargo transport isometric and elevation views.

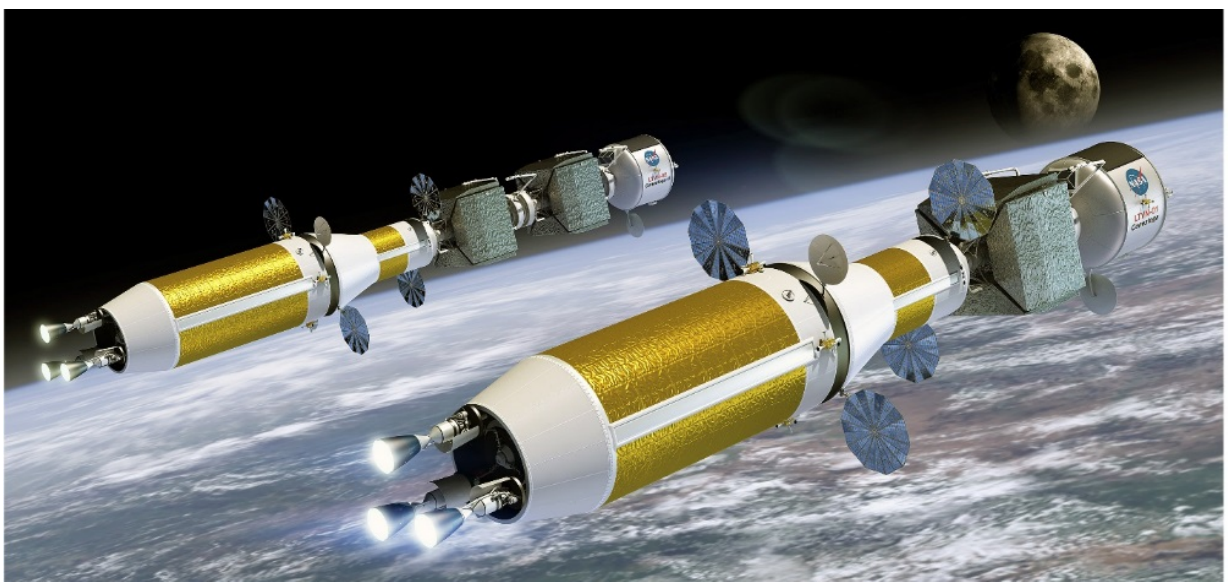


Figure 24.—*Conestoga*-class crewed cargo transports departing LEO for Moon.

## 8.0 Commuter Shuttle Mission Feasibility

In the movie “2001: A Space Odyssey,” released by MGM in 1968 (Ref. 41), Dr. Heywood Floyd departs from a huge artificial gravity space station orbiting Earth and bound for the Moon. He arrives there 24 hr later (Ref. 42) 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, 50 years later, the images portrayed in Stanley Kubrick and Arthur C. Clarke’s film remain well beyond our capabilities, and “2100: A Space Odyssey” seems a more appropriate title for the movie. In this section, we evaluate the feasibility and requirements for commuter flights using LANTR propulsion and LUNOX propellant to see if the operational capabilities presented in “2001: A Space Odyssey” 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, DC, to Melbourne, Australia, with a 3-hr layover in San Francisco. As Figure 18 shows, decreasing the LEO-to-LLO transit time from 72 to 24 hr increases the outbound $\Delta V$ requirement from ~4 to 6.4 km/s and the total round-trip $\Delta V$ requirement by ~4.8 km/s! Increasing the flight time to 36 hr each way decreases this additional $\Delta V$ requirement by 37.5% to ~1.8 km/s. Also, at these higher velocities, free return trajectories are no longer available, so multiple engines will be required to improve reliability and increase passenger safety.

How might a typical commuter flight to the Moon proceed? A possible scenario might start with passengers boarding a future Earth-to-orbit shuttle for a flight to a future commercial artificial gravity station (AGS) shown in Figure 25(a). There they would enter a PTM containing its own life support, power, instrumentation and control, and RCS. The PTM provides the “brains” for the LANTR-powered shuttle and is home to the 18 passengers and 2 crewmembers operating it while on route to the Moon. After departing the AGS (Fig. 25(b)), the PTM docks with the fully fueled LANTR shuttle awaiting it a safe distance away (Fig. 26(a)). At the appropriate moment, the LANTR engines are powered up, and the shuttle climbs rapidly away from Earth (Fig. 26(b)). For a 36-hr flight to the Moon, the acceleration experienced by the passengers during Earth departure will range from ~0.4g to ~0.8g near the end of the TLI burn.

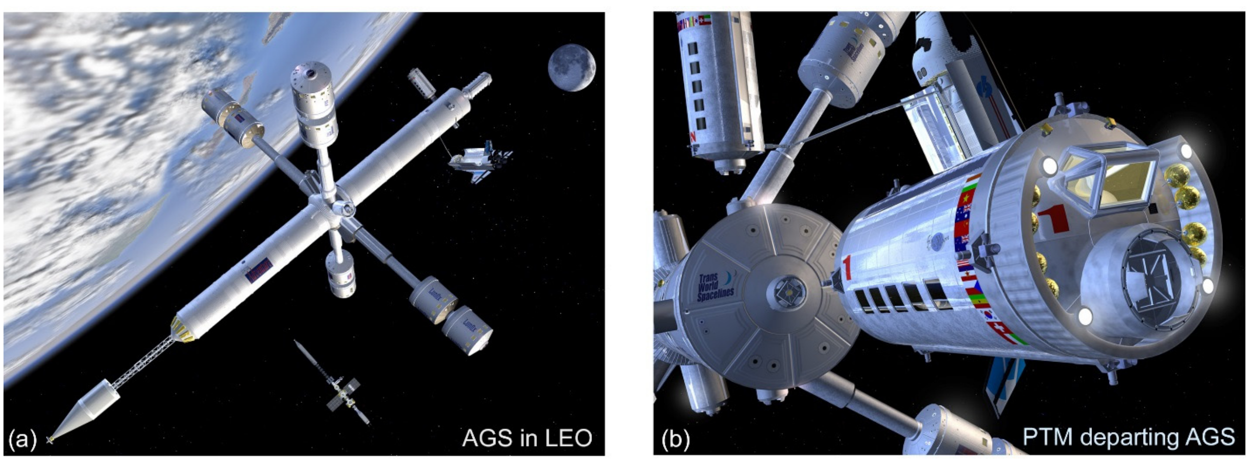



Figure 25.—Future commercial artificial gravity station (AGS) provides transportation hub for PTMs arriving and departing from LEO.

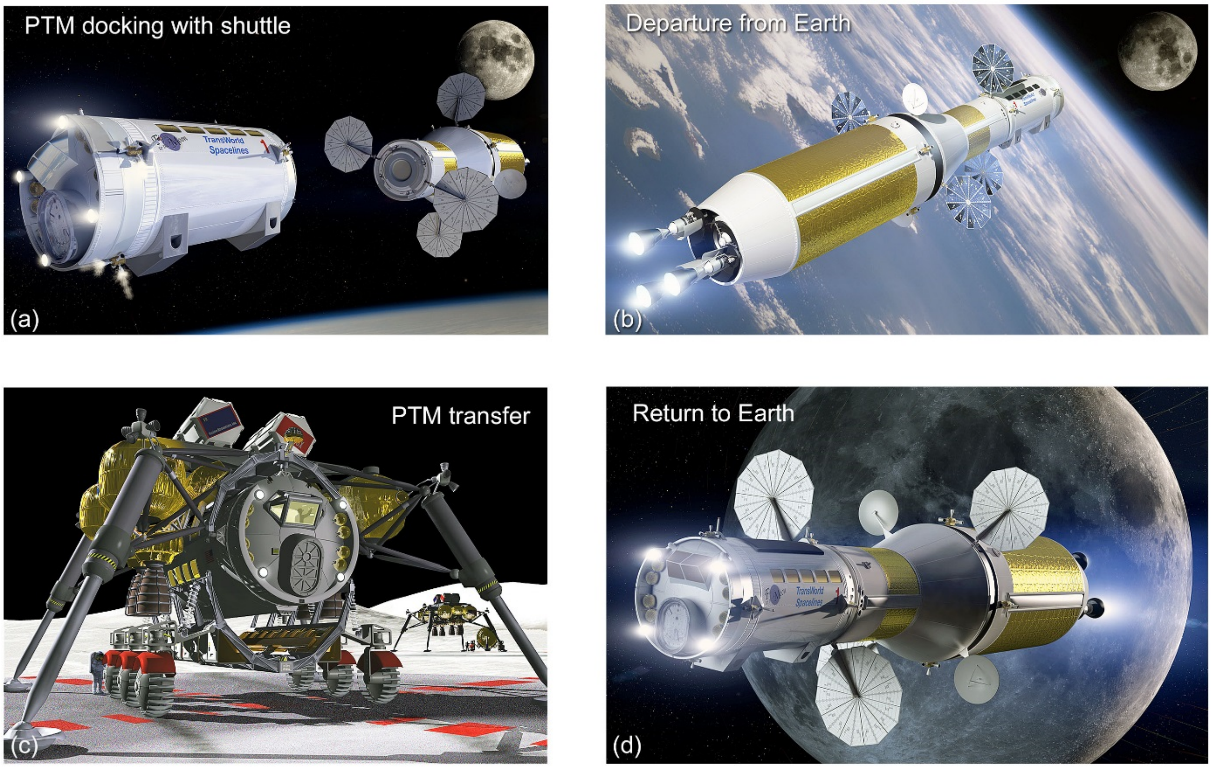
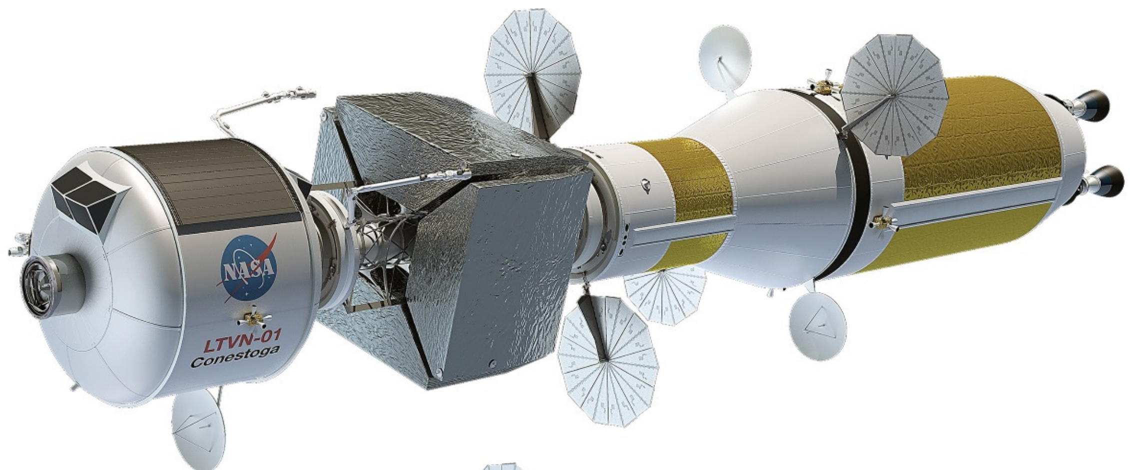


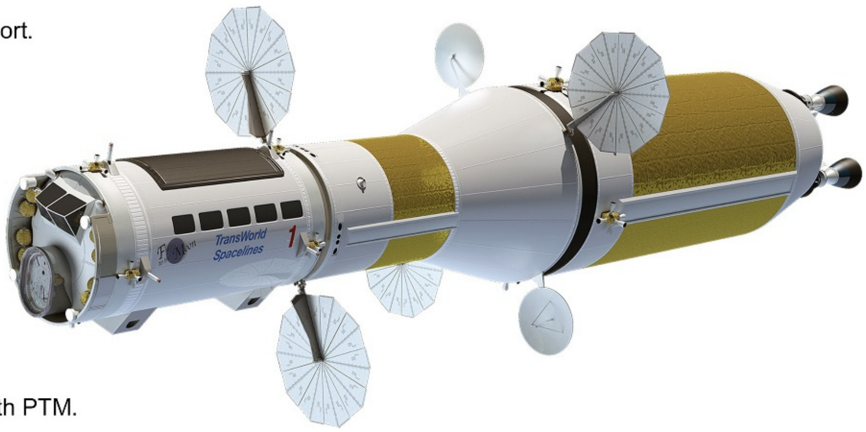
Figure 26.—Various phases of LANTR commuter shuttle mission to Moon.

Following the 36-hr transfer, the LANTR shuttle arrives in LLO where the PTM detaches and docks with a waiting Sikorsky-style LLV. A commercial propellant depot (Fig. 17(b)) provides a convenient staging node for LLO operations supplying the LANTR shuttle with LUNOX for Earth return and the LLV with Earth-supplied $LH_2$ needed to deliver the PTM to the LS. From here the PTM is lowered to a flatbed surface vehicle (Fig. 26(c)) and electronically engaged providing the PTM with surface mobility. The PTM then drives itself to the lunar base airlock for docking and passenger unloading (shown in the lower right corner of Fig. 8). This scenario is reversed on the return trip to Earth (Fig. 26(d)). At the end of the flight, the passengers will also experience a bit of excitement as peak acceleration levels can reach ~1.4g at the end of the LEO capture burn.

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




(a) Crewed cargo transport.




(b) Commuter shuttle with PTM.

Figure 27.—Relative sizes of *Conestoga* crewed cargo transport and LANTR commuter shuttle using same NTPS and in-line $LO_2$ tank assembly.

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

TABLE V.—LANTR COMMUTER SHUTTLE MISSION OPTIONS, TRAJECTORY AND $\Delta V$ BUDGETS, AND LUNOX REFUELING NEEDS[a]

| Case description[b] | Objective | Trajectory and orbits[c] | In-line $LO_2$ tank | Results |
|---|---|---|---|---|
| 1. LANTR commuter shuttle carrying 15-t PTM to LLO then back to LEO | Determine $LLO_2$ refueling needed to deliver 15-t PTM to and from LLO with transit times of 36 hr | 36-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~9.835 km/s | 4.6-m OD by ~5.4-m L<br>(~69.3 t $LO_2$) | IMLEO ~160.6 t<br>~69.3 t $LO_2$ supplied in LEO<br>~67.9 t $LLO_2$ refueling in LLO |
| 2. LANTR commuter shuttle carrying 15-t PTM to LLO then back to LEO | Minimize $LLO_2$ refueling needed to deliver 15-t PTM to and from LLO with transit times of 36 hr | 36-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~9.924 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~203.5 t<br>~111.2 t $LO_2$ supplied in LEO<br>~55.7 t $LLO_2$ refueling in LLO |
| 3. LANTR commuter shuttle carrying 15-t PTM to LLO then back to LEO | Minimize LEO $LO_2$ fueling needed to deliver 15-t PTM to and from LLO with transit times of 36 hr | 36-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~9.914 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~168.2 t<br>~76.1 t $LO_2$ supplied in LEO<br>~72.8 t $LLO_2$ refueling in LLO |
| 4. LANTR commuter shuttle carrying 15-t PTM to LLO then back to LEO | Minimize total mission $LO_2$ needed to deliver 15-t PTM to and from LLO with transit times of 36 hr | 36-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~9.913 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~169.7 t<br>~77.6 t $LO_2$ supplied in LEO<br>~70.2 t $LLO_2$ refueling in LLO |
| 5. LANTR commuter shuttle carrying 15-t PTM to LLO then back to LEO | Determine $LLO_2$ refueling needed to deliver PTM to and from LLO with shortest transit times possible | 32.8-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~10.481 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~203.3 t<br>~111.1 t $LO_2$ supplied in LEO<br>~80.4 t $LLO_2$ refueling in LLO |
| 6. LANTR commuter shuttle carrying 15-t PTM to LLO then back to LEO | Determine $LLO_2$ and $ELH_2$ refueling needed to deliver the PTM to and from LLO with transit times of 24 hr | 24-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~13.051 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~203.7 t<br>~111.2 t $LO_2$ supplied in LEO<br>~109.0 t $LLO_2$ refueling in LLO<br>~17.0 t $ELH_2$ refueling in LLO |
| 7. Super-fast LANTR shuttle carrying 15-t PTM to LLO then back to LEO | Determine $LLO_2$ and $ELH_2$ refueling needed to deliver the PTM to LLO then back to LEO as fast as possible | 19.2-hr one-way transit times<br>LEO → LLO → LEO<br>$\Delta V$ ~15.353 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~203.5 t<br>~111.2 t $LO_2$ supplied in LEO<br>~108.8 t $LLO_2$ refueling in LLO<br>~38.3 t $ELH_2$ refueling in LLO |

[a]Acronyms and symbols are defined within report and in appendix.
[b]Cases 1 to 7 use common $LH_2$ NTPS (7.6-m OD by ~15.7-m L). Propellant depots are assumed in LEO and LLO. LANTR engines use optimized O/H MRs out and back.
[c]Altitudes: 407 km (LEO), 300 km (LLO, equatorial). Total round-trip mission $\Delta V$ values shown include g-losses.

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

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

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

Case 5 focuses on achieving the fastest transit times possible by taking full advantage of the extra propellant capacity that exists in the vehicle's in-line $LO_2$ tank. By increasing the commuter shuttle's $LO_2$ loading to its maximum capacity of ~111.2 t before TLI, refueling with ~80.4 t of LUNOX before TEI, and operating the LANTR engines $O_2$ rich (O/H MR = 5) out and back, the shuttle can decrease its one-way transit time from 36 to 32.8 hr. The additional $LO_2$ loading prior to TLI increases the required IMLEO to ~203.3 t, which includes the NTPS (~71 t), the in-line $LO_2$ tank assembly and adaptor section (~117.3 t), and the PTM (15 t). The decreased transit time increases the total mission $\Delta V$ by ~0.567 km/s to ~10.5 km/s. The total mission burn time is ~25.3 min, and the individual burn times are ~11 min (TLI), ~3.5 min (LOC), ~5.1 min (TEI), and ~5.7 min (EOC).

Case 6 is similar to Case 5 except that it also uses some of the $ELH_2$ delivered to the LLO depot by NTR tankers to "top off" the shuttle's NTPS before returning to Earth. By resupplying the shuttle with ~111.2 t of $LO_2$ before TLI, refueling it with ~109 t of $LLO_2$ and ~17 t of $ELH_2$ before TEI, and operating $O_2$-rich on the way back to Earth, the 24-hr trip to the Moon taken by Dr. Floyd in "2001: A Space Odyssey" becomes possible. The IMLEO for this case is ~203.7 t including the NTPS (~70.9 t), the in-line $LO_2$ tank assembly (~117.8 t), and the PTM (15 t). The total $\Delta V$ required for this 24-hr shuttle capability is ~13.1 km/s with g-losses. *With the additional $LH_2$ supplied to the NTPS, the total engine burn time also increases to ~36.3 min*, which includes burn times of ~12.9 min (TLI), ~7.5 min (LOC), ~8.9 min (TEI), and ~7.0 min (EOC).

Case 7 is similar to Case 6 with the exception that it uses a larger amount of $ELH_2$ during the return to Earth, allowing the shuttle's transit times to be shortened even further, down to ~19.2 hr. For this super-fast, "medical-emergency-type" case, the shuttle is resupplied with ~111.2 t of $LO_2$ and ~39.8 t of $LH_2$ before TLI, then refueled to near maximum capacity with ~108.8 t of LUNOX and ~38.3 t of $ELH_2$ before TEI. The engines are also operated $O_2$ rich during the TLI and TEI burns, and $H_2$ rich during the LOC and EOC burns. The IMLEO is ~203.5 t, which includes the NTPS (~70.8 t), the in-line $LO_2$ tank assembly and adaptor section (~117.7 t), and the PTM (15 t). The 19.2-hr transit times to the Moon and back increases the total mission $\Delta V$ by an additional ~2.3 km/s to ~15.4 km/s including the g-losses. *With the available $LH_2$ provided during the mission, the total burn time on the LANTR engines increases to ~50.1 min* with individual burn durations of ~13.8 min (TLI), ~11.5 min (LOC), ~13.7 min (TEI), and ~11.1 min (EOC).

# 9.0 Alternating Priority Cargo Delivery Missions

In addition to a commercial shuttle service for passengers, it is also likely that similar services will be developed for delivering high-priority cargo. Today, on their website for international shipping (Ref. 43), 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 (Ref. 44), the company promises free 2-day shipping on your purchases.

This section examines the performance impact of alternating outbound and return deliveries of a PTM and priority cargo shipment on the same shuttle flight. The shipping container we envision has a gross mass of ~7.5 t and carries ~5 t of cargo within its pressurized volume. The container is scaled from the *Cygnus* spacecraft, developed by Orbital ATK. *Cygnus* is an automated cargo vehicle (Ref. 45) designed to transport supplies to the International Space Station. It has a dry mass of ~5 t and can carry up to 3.5 t of cargo in its pressurized cargo module. An attached service module provides auxiliary propulsion and up to 4 $kW_e$ of electrical power using two photovoltaic arrays (PVAs) (Ref. 45).

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

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

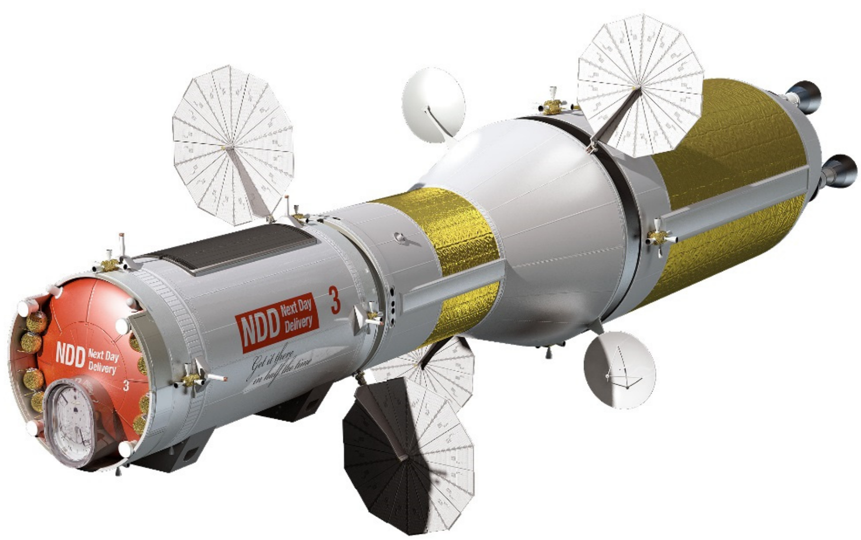



Figure 28.—Priority cargo delivery vehicle using LANTR shuttle system.

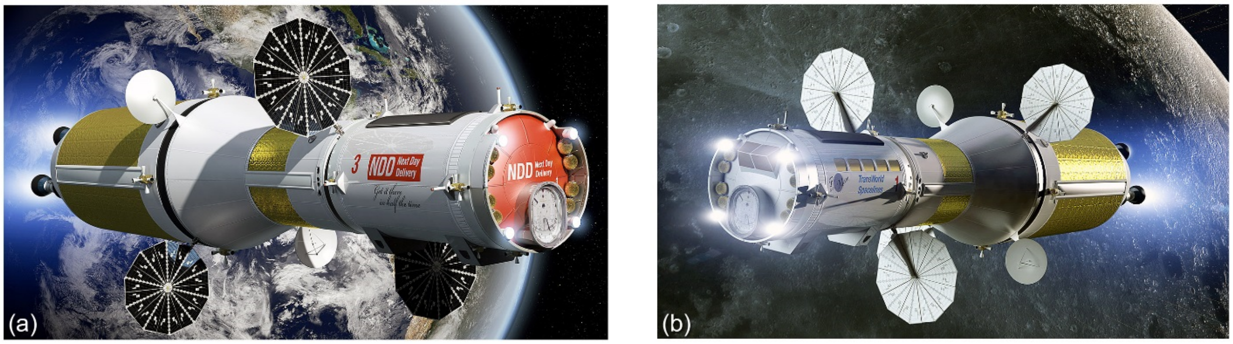



Figure 29.—Alternating priority cargo container and PTM payloads from Earth to Moon and back on same LANTR shuttle flight.

TABLE VI.—ALTERNATING PTM–PCC MISSION OPTIONS, TRIP TIME POSSIBILITIES AND $\Delta V$ BUDGETS, AND LUNOX REFUELING NEEDS[a]

| Case description[b] | Objective | Trajectory and orbits[c] | In-line $LO_2$ tank | Results |
|---|---|---|---|---|
| 1. Alternating PTM out to LLO followed by priority cargo delivery back to LEO using three LANTR engine NTPSs | Determine $LLO_2$ refueling needed to deliver 15-t PTM to LLO then 7.5-t PCC back to LEO | LEO → LLO transit time: 36 hr<br>LLO → LEO transit time: 36 hr<br>$\Delta V$ ~9.910 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~157.6 t<br>~66.0 t $LO_2$ supplied in LEO<br>~55.1 t $LLO_2$ refueling in LLO |
| 2. Alternating priority cargo delivery to LLO followed by PTM back to LEO using three LANTR engine NTPSs | Determine $LLO_2$ refueling needed to deliver 7.5-t PCC out to LLO then 15-t PTM back to LEO | LEO → LLO transit time: 36 hr<br>LLO → LEO transit time: 36 hr<br>$\Delta V$ ~9.909 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~146.5 t<br>~62.2 t $LO_2$ supplied in LEO<br>~64.8 t $LLO_2$ refueling in LLO |
| 3. Alternating PTM out to LLO followed by priority cargo delivery back to LEO using two LANTR engine NTPSs | Determine $LLO_2$ refueling needed to deliver 15-t PTM to LLO then 7.5-t PCC back to LEO | LEO → LLO transit time: 24 hr<br>LLO → LEO transit time: 48 hr<br>$\Delta V$ ~10.959 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~191.2 t<br>~105.3 t $LO_2$ supplied in LEO<br>~44.7 t $LLO_2$ refueling in LLO |
| 4. Alternating priority cargo delivery to LLO followed by PTM back to LEO using two LANTR engine NTPSs | Determine $LLO_2$ refueling needed to deliver 7.5-t PCC out to LLO then 15-t PTM back to LEO | LEO → LLO transit time: 48 hr<br>LLO → LEO transit time: 24 hr<br>$\Delta V$ ~10.951 km/s | 4.6-m OD by ~7.95-m L<br>(~111.2 t $LO_2$) | IMLEO ~144.7 t<br>~65.9 t $LO_2$ supplied in LEO<br>~93.2 t $LLO_2$ refueling in LLO |

[a]Acronyms and symbols are defined within report and in appendix.
[b]Cases use common $LH_2$ NTPS (7.6-m OD by ~15.7-m L). Propellant depots are assumed in LEO and LLO. LANTR engines use optimized O/H MRs out and back.
[c]Altitude: 407 km (LEO), 300 km (LLO, equatorial). Total round-trip mission $\Delta V$ values shown include g-losses.

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

In the second set of PTM–PCC delivery missions (Cases 3 and 4), the same in-line $LO_2$ tank is used, but the NTPS now uses only two LANTR engines. The transit times are set for PTM delivery at 24 hr and for the PCC delivery at 48 hr. Like Case 1, Case 3 delivers the PTM on the outbound leg and then the

PCC on the return leg. Because of the faster transit time used on the PTM mission leg, ~105.3 t of $LO_2$ must be supplied to the shuttle prior to TLI. Similarly, the LUNOX refueling requirement needed is reduced to ~44.7 t because of the PCC's smaller mass and extended transit time for the return to Earth. The IMLEO for this mission is ~191.2 t, which includes the NTPS (~65.2 t), the in-line $LO_2$ assembly and adaptor section (~110 t), and the PTM (15 t). The total mission $\Delta V$ is ~10.959 km/s, and the total engine burn time increases to ~37.8 min. The burn times for the individual maneuvers are ~17.9 min (TLI), ~10.8 min (LOC), ~3.2 min (TEI), and ~5.9 min (EOC).

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

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

## 10.0 Mining and Processing Requirements and Estimated LUNOX Reserves

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

To support weekly commuter flights to the Moon annual LUNOX production levels of ~12,540 t/yr will be required (see Table VII). Approximately 4190 t of LUNOX is used by the LANTR shuttle, ~6140 t by four second-generation Sikorsky-style LUNOX tanker LLVs (Fig. 30) flying one resupply mission to the LLO depot each week over the course of a year, and ~2220 t used by the same Sikorsky-style LLVs to transport arriving and departing PTMs to and from the LS. Each LLV has a dry mass of ~10.9 t and a maximum $LO_2/LH_2$ propellant capacity of ~35 t.

TABLE VII.—TOTAL LUNOX REQUIRED FOR WEEKLY COMMUTER FLIGHTS[a]
[32.8-hr one-way transits (15-t, 20-person PTM).]

| | |
|---|---|
| LANTR shuttle | |
| (80.5 t LUNOX/mission/week) × (52 weeks/year) | 4,186 t/yr |
| LLV[b] | |
| LLV[c] (29.5 t LUNOX/flight) × (1 flight/LLV/week) × (4 LLVs) × (52 weeks/year) | 6,136 t/yr |
| LLV[d] (42.7 t LUNOX)/(round trip flights/week) × (52 weeks/year) | 2,220 t/yr |
| Total LUNOX rate | 12,542 t/yr |

[a]Acronyms and symbols are defined within report and in appendix.
[b]O/H MR = 6 and $I_{sp}$ = 465 s. Descent and ascent velocity changes $\Delta V_{desc}$ = 2000 m/s and $\Delta V_{asc}$ = 1900 m/s assumed.
[c]LLV tanker transports ~25 t of LUNOX to LLO; returns to LS with empty 5-t tank.
[d]Total for LLV delivery of PTM from LLO to LS plus PTM return from LS to LLO.

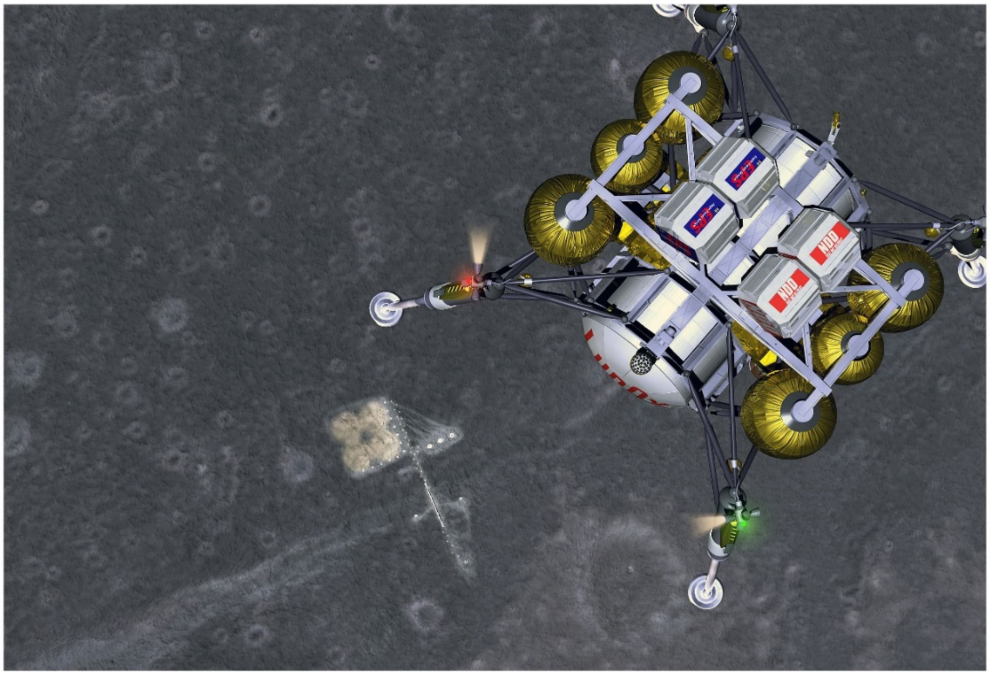


Figure 30.—Tanker LLV lifts off from commercial facility, delivering LUNOX to depot in LLO.

TABLE VIII.—COMPARISON OF DIFFERENT LUNAR MINING CONCEPTS SHOWING PLANT MASS, REQUIRED OPERATING POWER, AND MINING RATES[a]

| | |
|---|---|
| Hydrogen reduction of ilmenite (LUNOX production, 1000 t/yr) | |
| Plant mass (mining, beneficiation, processing, and power) | 244 t |
| Power requirements (mining, beneficiation, and processing) | 3.0 $MW_e$ |
| Regolith throughput | |
| (assumes soil feedstock at 7.5 wt% ilmenite and MMR of 327 t of soil per ton of LUNOX) | $3.3\times10^5$ t/yr |
| Hydrogen reduction of iron-rich volcanic glass (LUNOX production, 1000 t/yr) | |
| 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 4% $O_2$ yield and MMR = 25 to 1) | $2.5\times10^4$ t/yr |
| Lunar helium-3 extraction: ($He^3$ production, 5 t/yr) | |
| Mobile miners (150 miners required, each weighing 18 t, and each miner producing $He^3$ at 33 kg/yr) | 2700 t |
| Power requirements (200 kW direct solar power/miner) | 30.0 $MW_e$ |
| Regolith throughput | |
| (processing and capture of solar-wind-implanted volatiles occurs aboard the miner) | $7.1\times10^8$ t/yr |

[a]Acronyms are defined within report and in appendix.

A preliminary assessment of plant mass, power level, feedstock throughput, and required mining area has been made assuming a LUNOX operation employing 13 modular units, each with a production capacity of 1000 t/yr. Table VIII compares the characteristics for two LUNOX plants—one based on hydrogen reduction of ilmenite (Ref. 30), and the other on iron-rich volcanic glass feedstock. The advantages of using volcanic glass feedstock are apparent, having mass and power requirements that are 43% and 50% lower than that of an ilmenite-reduction plant using a soil feedstock. Included in the volcanic-glass-reduction plant mass of ~105.3 t is the mining (~9.6 t) and processing equipment (84.6 t), both of which include a 30% dry weight contingency (DWC), plus the fission reactor power source (~11.1 t). The plant power requirement of ~1.52 $MW_e$ includes ~10.7 $kW_e$ for the mining equipment and ~1509 $kW_e$ for the processing equipment. Both values again include a 30% margin. The process power dominates, is a function of the LUNOX production rate, and is primarily associated with the electric heaters, electrolysis cell, and oxygen liquifiers as discussed in Section 2.0 and pointed out in Figure 5.

Using the low-end 4% $O_2$ yield obtained from orange and black volcanic glass beads still translates into more than an order-of-magnitude reduction in the amount of mined material. The mining equipment used at each 1000 t/yr production plant consists of two front-end loaders and four haulers. To produce ~13,000 t of LUNOX annually will require a glass throughput of ~$3.25\times10^5$ t/yr and a soil mining rate at each production plant of just under 6 t/hr per loader assuming the same 35% mining duty cycle used in the ilmenite processing plant results. This duty cycle corresponds to mining operations during ~70% of the available lunar daylight hours (~3067 hr each year).

Although this number is large, it is modest compared to terrestrial coal and proposed lunar helium-3 mining activities. For example, with a single 1000-$MW_e$ coal-fired power plant consuming about sixty 100-t train cars of coal per day, the annual U.S. production rate for coal exceeds 500 million tons! Similarly, past proposals for mining helium-3 on the Moon (Ref. 46) to support a future fusion-based power economy in the United States would require the processing of ~2.8 billion tons of regolith to obtain the estimated 20 t of helium-3 needed annually (see Table VIII).

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

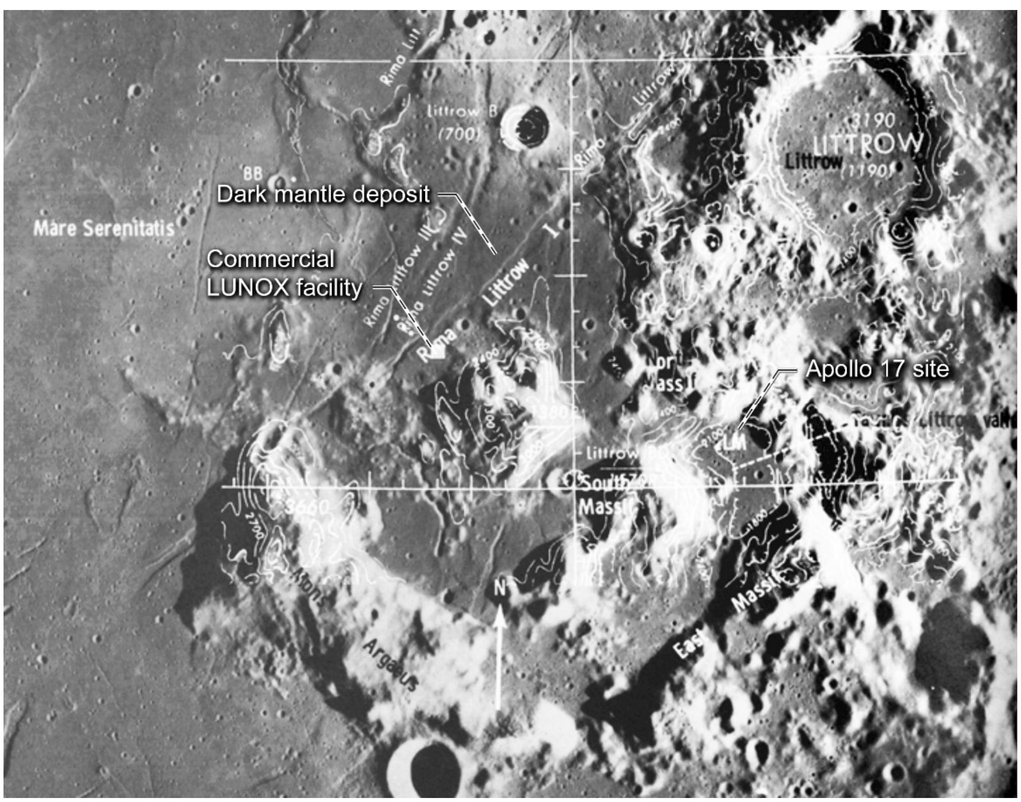


Figure 31.—Apollo 17 landing site and major geographic features of Taurus-Littrow region.

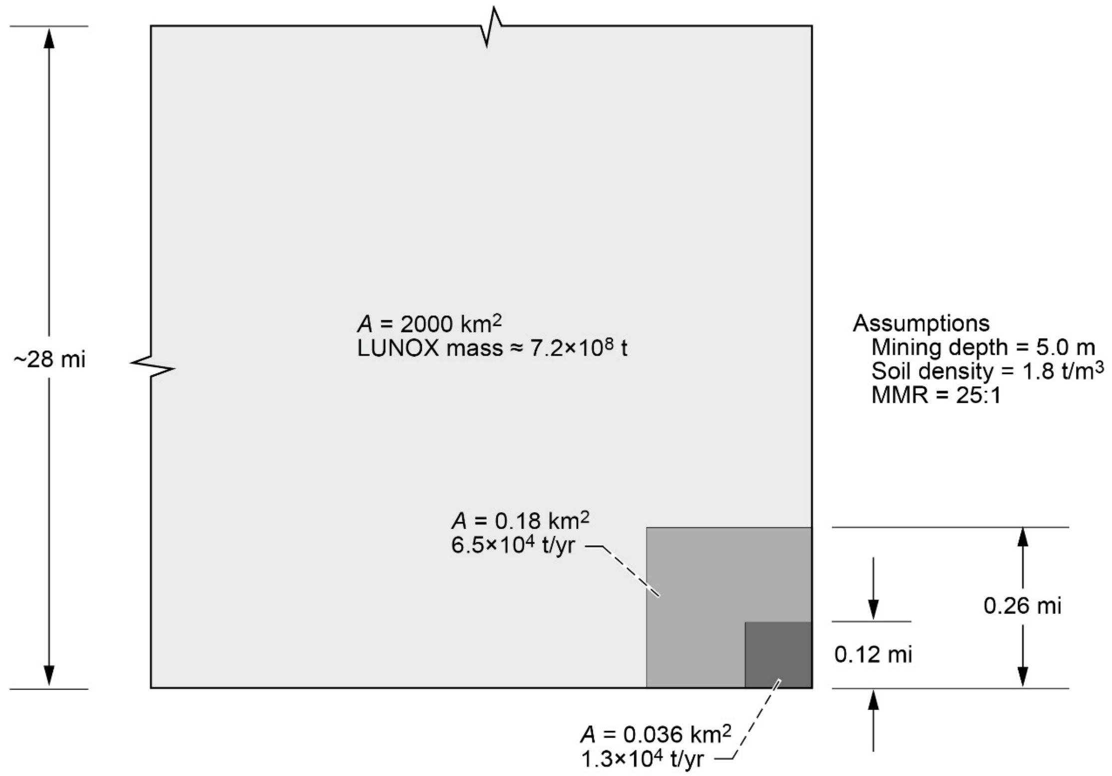



Figure 32.—Required mining areas *A* and LUNOX production rates to support routine commuter flights to Moon.

## 11.0 A Look Ahead

Whereas others have discussed more conventional space transportation systems supported by propellant depots (Ref. 47), the performance capability resulting from combining the two "high-leverage" technologies, LANTR and LUNOX, is quite extraordinary. For example, to perform the same 36-hr commuter shuttle mission with the same propellant tank volumes used in Case 3 of Table V, an all-$LH_2$ NTP system would require an effective $I_{sp}$ of ~1575 s, which is equivalent to that postulated for an advanced gaseous-fuel-core NTR system.

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

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

In the nearer term, it is also possible that LANTR propulsion could find its way into NASA's plans for a human mission to Mars. The year 2018 is the eighth year in a row that NASA has been funding NTP research and development. Preliminary development plans envision flight testing a NTPS powered by three 25-$klb_f$-class NTR engines sometime in the late 2020s. For the Mars mission, two additional tanks of $LH_2$—one an in-line tank and the other a drop tank—are added to supplement the NTPS.

Because of $LH_2$'s low density, these additional tanks increase the vehicle's overall size and mass. By adding the afterburner feature to the NTPS and running the engines at an O/H MR ~1 during the LEO departure burn, the amount of $LH_2$ used during this maneuver can be cut in half. The thrust output of the NTPS is also increased by ~60%, from 75 $klb_f$ to over 120 $klb_f$, reducing g-losses and eliminating the need for multiple perigee burns during Earth departure. Afterwards the smaller $LO_2$ drop tank can be jettisoned and $LH_2$ used for the rest of the mission.

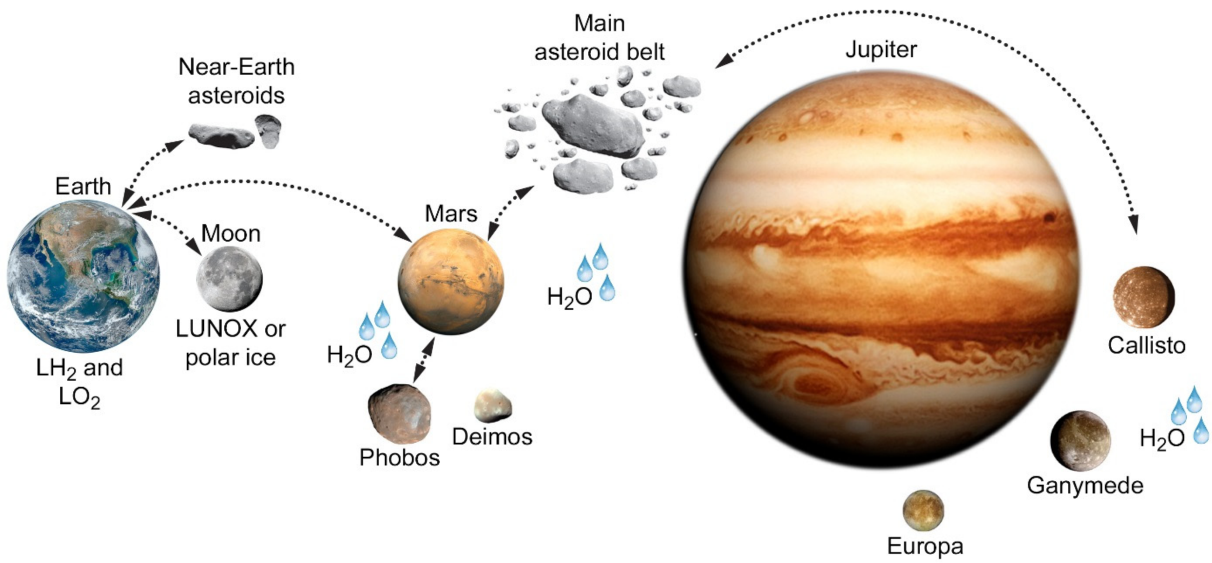



Figure 33.—Human expansion possibilities using LANTR propulsion and extraterrestrial propellant resources.

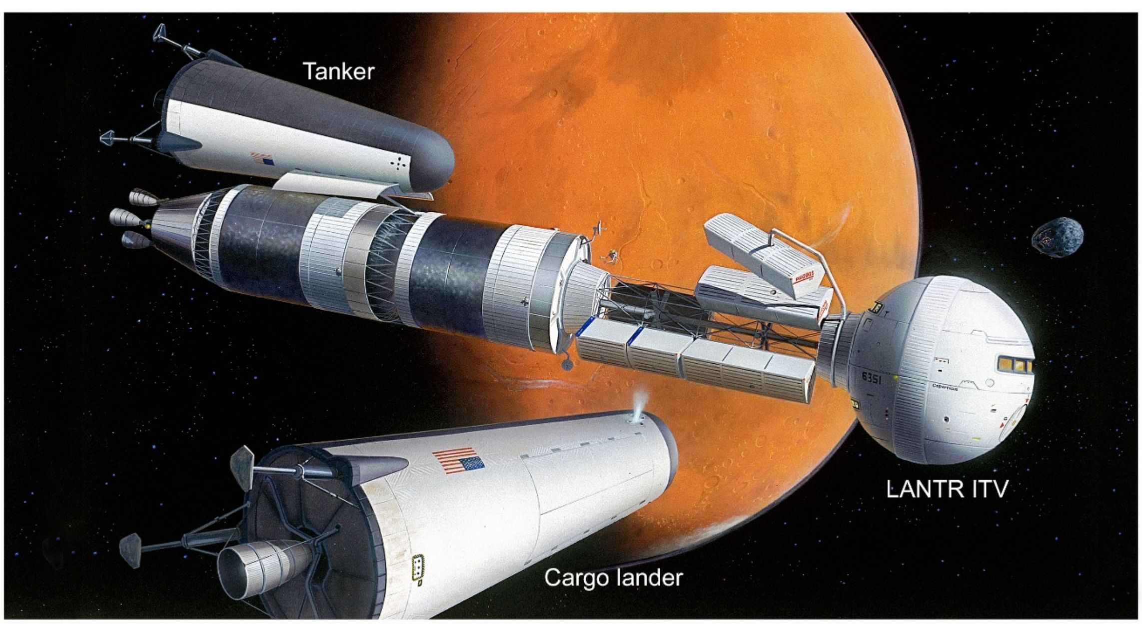



Figure 34.—Conceptual LANTR interplanetary transfer vehicle unloading cargo and loading propellant before departing Mars for asteroid belt.

## 12.0 Concluding Remarks

The nuclear thermal rocket (NTR) offers significant benefits for lunar missions and can take advantage of the mission leverage provided from using lunar-derived propellant (LDP)—specifically, lunar-derived liquid oxygen (LUNOX)—by transitioning to the liquid-oxygen- ($LO_2$-) augmented NTR (LANTR). Using this enhanced NTR system has many advantages. It provides a variable thrust and specific impulse $I_{sp}$ capability, shortens engine burn times, extends engine life, and allows combined liquid hydrogen and oxygen ($LH_2$ and $LO_2$, respectively) operation. Its use together with adequate supplies of LUNOX, extracted from abundant reserves of FeO-rich volcanic glass, can lead to a robust nuclear lunar transportation system (LTS) that evolves over time and has unique mission capabilities. The examples discussed in this report include short-transit-time crewed cargo transports, commuter shuttles, and priority cargo delivery systems operating between transportation nodes and/or propellant depots located in low Earth orbit (LEO) and low lunar orbit (LLO).

December 2017 marked the 45th anniversary of the Apollo 17 mission to Taurus-Littrow and unfortunately, the termination of both the Apollo and the Rover/NERVA nuclear rocket programs. In the not-so-distant future, the technological progeny from these two historic programs—LUNOX and LANTR—could allow the development of a robust, reusable space transportation system that can be adapted to a wide variety of potential lunar missions using the basic vehicle building blocks discussed in this paper.

The biggest challenge to making this vision a reality, however, will be the production of increasing amounts of LDP and the development of propellant depots for vehicle refueling in LEO and LLO. An industry-operated, privately financed venture, with NASA as its initial customer, has frequently been mentioned as a possible blueprint for how a commercial LUNOX operation and propellant depot might develop. With industry interested in developing cislunar space and commerce and with competitive forces at work, the timeline for developing this capability could well be accelerated beyond anything currently being envisioned. Only time will tell and maybe it will be quicker than any of us can imagine.

# Appendix—Nomenclature

| | |
|---|---|
| AGS | artificial gravity station |
| AMBR | Advanced Material Bipropellant Rocket |
| BA | Bigelow Aerospace |
| CCT | crewed cargo transport |
| DMD | dark mantle deposit |
| DWC | dry weight contingency |
| EEO | elliptical Earth orbit |
| $ELH_2$ | Earth-supplied liquid hydrogen propellant |
| EOC | Earth orbit capture |
| EVA | extravehicular activity |
| FE | fuel element |
| GC | graphite composite |
| HLV | heavy lift vehicle |
| IMLEO | initial mass in low Earth orbit |
| ITV | interplanetary transfer vehicle |
| L | length |
| LANTR | $LO_2$-augmented NTR |
| LDAV | lunar descent and ascent vehicle |
| LDP | lunar-derived propellant |
| LEO | low Earth orbit (= 407 km circular/28.5° inclination) |
| $LLH_2$ | lunar liquid hydrogen |
| LLO | low lunar orbit (= 300 km circular/equatorial) |
| $LLO_2$ | lunar liquid oxygen |
| LLV | lunar landing vehicle |
| LOC | lunar orbit capture |
| LPI | lunar polar ice |
| LS | lunar surface |
| LTS | lunar transportation system |
| LTV | lunar transfer vehicle |
| LUNOX | lunar-derived liquid oxygen; another name for $LLO_2$ |
| MAMA | multidisciplinary analysis and mission assessment (code) |
| MLI | multilayer insulation |
| MMR | mining mass ratio |
| MPCV | multipurpose crew vehicle |
| NAR | nozzle area ratio |
| NERVA | Nuclear Engine for Rocket Vehicle Applications (program) |
| NLTV | Nuclear-powered lunar transfer vehicle |
| NTP | nuclear thermal propulsion |
| NTPS | NTP stage |
| NTR | nuclear thermal rocket |
| O/H MR | oxygen-to-hydrogen mixture ratio |
| OD | outer diameter |
| PCC | priority cargo container |
| PL | payload |
| PTM | passenger transport module |
| PVA | photovoltaic array |
| R&D | rendezvous and docking |
| RCS | reaction control system |

| | |
|---|---|
| RMS | remote manipulator system |
| SEC | Shackleton Energy Company |
| SLS | Space Launch System |
| SNRE | small nuclear rocket engine |
| SOFI | spray-on foam insulation |
| STA | saddle truss assembly |
| TEI | trans-Earth injection |
| TLI | translunar injection |
| TPA | turbopump assembly |
| TT | tie tube |
| ULA | United Launch Alliance |
| ZBO | zero boil-off |
| $\Delta V$ | velocity change increment, km/s |
| $\Delta V_{asc}$ | ascent velocity change |
| $\Delta V_{des}$ | descent velocity change |

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