Commercialization and Human Settlement of the Moon and Cislunar Space Enabled by ISRU, Fission Surface Power, and Advanced In-Space Propulsion Systems.

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Introduction: Over 50 years have passed since the movie *2001: A Space Odyssey* debuted in April 1968. In the film, Dr. Heywood Floyd flies to a large artificial gravity space station orbiting Earth aboard a commercial space plane. He then embarks on a commuter flight to the Moon arriving there 25 hours later. Today, on the 50th anniversary of the Apollo 11 lunar landing, the images portrayed in *2001* remain well beyond our capabilities and *2100: A Space Odyssey* seems a more appropriate title for Kubrick and Clarke's film. This paper looks at the key technologies, systems, and supporting infrastructure (in-situ resource utilization (ISRU), fission surface power (FSP), advanced in-space propulsion, and orbiting propellant depots), that could be developed by NASA and the private sector over the next 30 years allowing the operational capabilities presented in *2001* to be achieved, albeit on a more spartan scale.

Options for Lunar-Derived Propellant (LDP): The processing of lunar polar ice (LPI) deposits for propellant production – specifically liquid oxygen (LO_2) and hydrogen (LH_2) – can help reduce the launch mass requirements from Earth and can enable a reusable, space transportation system (LTS). Large quantities of LPI (estimated at several billion metric tons (t)) are believed to exist in the extremely cold (~25-50 K), permanently shadowed regions near the poles. These ice deposits represent a valuable resource provided they can be economically accessed, mined, processed and stored. In a recent study [1], in-situ thermal mining of the icy regolith using directed sunlight, followed by cold trap capture of the sublimated water vapor, was the preferred approach for extraction. The study identified an annual propellant demand and associated water production rate of ~2460 t/yr. With water's composition (8:1 O/H mass ratio) and the assumed propellant mixture ratio (O/H MR ~5:1) for the chemical engines, it is necessary to produce and electrolyze ~6.7 t of lunar water each day to produce the 1640 t of LO_2/LH_2 propellant needed annually. The total electrical power required for the propellant production operation was ~2.1 MW_e (including ~1.38 MW_e for electrolysis) plus ~800 kW_t used for the thermal mining.

Volcanic Glass. Lunar-derived LO_2 (LLO_2) can also be produced from iron oxide-rich volcanic glass beads using the hydrogen reduction process. Reduction experiments conducted by Allen et al. [2] have shown the glass beads to be an attractive feedstock material producing oxygen yields of ~4.3 to 4.7 wt%. This volcanic glass is also found in vast quantities at numerous pyroclastic deposits located on the lunar nearside. At the smallest of these, Taurus-Littrow, located at the southeastern edge of the Mare Serenitatis, the existing deposits could produce well in excess of a billion metric tons of LLO_2. To produce a 1000 t/yr of LLO_2 annually, the estimated electrical power for mining and processing is ~1.5 to 2 MW_e [3]. The additional LH_2 needed for propulsion would be supplied by Earth or by processing mare regolith for solar wind implanted (SWI) volatiles. Megawatt-class FSP power systems will be essential providing continuous "24/7" power to processing plants, evolving human settlements, and other commercial activities that develop on the lunar near and farside.

Lunar Transportation System Elements: As the production levels of LDP increase, reusable, surface-based lunar landing vehicles (LLVs) will replace expendable systems in the LTS reducing the launch mass for each mission. The LLVs use LO_2/LH_2 chemical rocket engines and provide cargo and crew "orbit-to-surface" access. They will also be used to transport LDP to depots in lunar polar (LPO) and equatorial orbits (LLO) once they are established. For short transit time missions to the Moon, advanced propulsion will be essential for the in-space lunar transfer vehicle (LTV) element. The nuclear thermal rocket (NTR) can satisfy this role initially. It uses LH_2 propellant and has a high thrust / high specific impulse (I_{sp} ~900 s) capability – twice that of today's best chemical rocket, the RL10B-2. To take advantage of the mission benefits of refueling with LLO_2 and LLH_2 for Earth return, a variant of the conventional NTR is introduced into the LTS [3].

LOX-Augmented NTR (LANTR): The bipropellant LANTR engine utilizes its divergent nozzle section as an afterburner into which oxygen is injected and supersonically combusted with the reactor-heated hydrogen emerging from the engine's sonic throat. By varying the O/H MR, LANTR engines can operate over a range of thrust and I_{sp} values while the reactor core power level remains relatively constant. Although the LANTR engine can operate at higher I_{sp} than the state-of-the-art RL10B-2 chemical engine, the LANTR is ~9.5x heavier and requires additional shielding mass to reduce crew radiation exposure.

Space-based Crewed Cargo Transport (CCT) and Commuter Shuttle: Space-based, reusable

LTVs that use LANTR engines and refuel with LDP offer unique mission capabilities including a short transit time CCT (shown in Fig.1) that can deliver varying amounts of cargo (from 10 to 40 t) to lunar orbit depending on the desired transit times out and back. The CCT elements include a common three engine propulsion stage carrying LH_2 propellant, an in-line LO_2 tank assembly, a 4-sided truss with attached payload, and a forward habitat module. Carrying only Earth-supplied LH_2, the RL10B-2 CCT can deliver 20 t of cargo to LLO, refuel with ~60.9 t of LLO_2, then return to LEO. The 1-way transit time out and back is ~51.5 hours.

Lunar Commuter Shuttle: By replacing the CCT's habitat and payload elements with a 20 passenger transport module (PTM), a commuter shuttle service similar to that portrayed in *2001* appears possible, allowing 1-way trip times to and from the Moon under 33 hours [3]. Once in orbit, the PTM detaches from the shuttle and is picked up by a Sikorsky-style LLV that delivers it to the lunar surface where it is transferred to a surface vehicle for transport to the lunar base. The LANTR shuttle refuels with ~80.4 t of LLO_2 then returns to LEO. If only 1% of the estimated LDP obtained from LPI and volcanic glass deposits were available for use in lunar orbit, such a supply could support routine commuter flights to the Moon for many thousands of years!

Orbiting Space Transportation Nodes (STNs): Space-based LTVs would operate between STNs located in LEO, LLO and LPO. Besides providing a propellant depot and cargo transfer function, the STN (Fig. 1) offers a convenient staging location where propellant, cargo and passengers can be dropped off and/or picked up. A fission power system with twin reactors provides the STN with abundant power for habitat module life support, facility operations, and onboard cryofluid management and transfer activities.

Mining Requirements Using Volcanic Glass and LPI Feedstock: The LDP production demands and associated mining requirements will depend on the mission type, ΔV requirement, and frequency of occurrence. The estimated mining area and feedstock throughput for a 1000 t/yr LLO_2 production facility using volcanic glass is ~2800 m^2 and 25,000 t/yr assuming a 4% O_2 yield [3]. Using thermal mining of icy regolith, with a 4% ice content and 25 kg/m^2 yield [1], an estimated mining area of ~45,000 m^2 will produce 1000 t/yr of LLO_2 plus 125 t/yr of LLH_2.

Synergies with Lunar He-3 Mining: The production of LLO_2 from volcanic glass deposits will have synergy with an evolving He-3 mining industry. For every kg of He-3 collected, ~18.2 t of important SWI volatiles are produced as by-products [4] including H_2 (6.1 t), H_2O (3.3 t), He-4 (3.1 t), CO (1.9 t), CO_2 (1.7 t), CH_4 (1.6 t), and N_2 (0.5 t) that can supplement propulsion and life support needs.

References:

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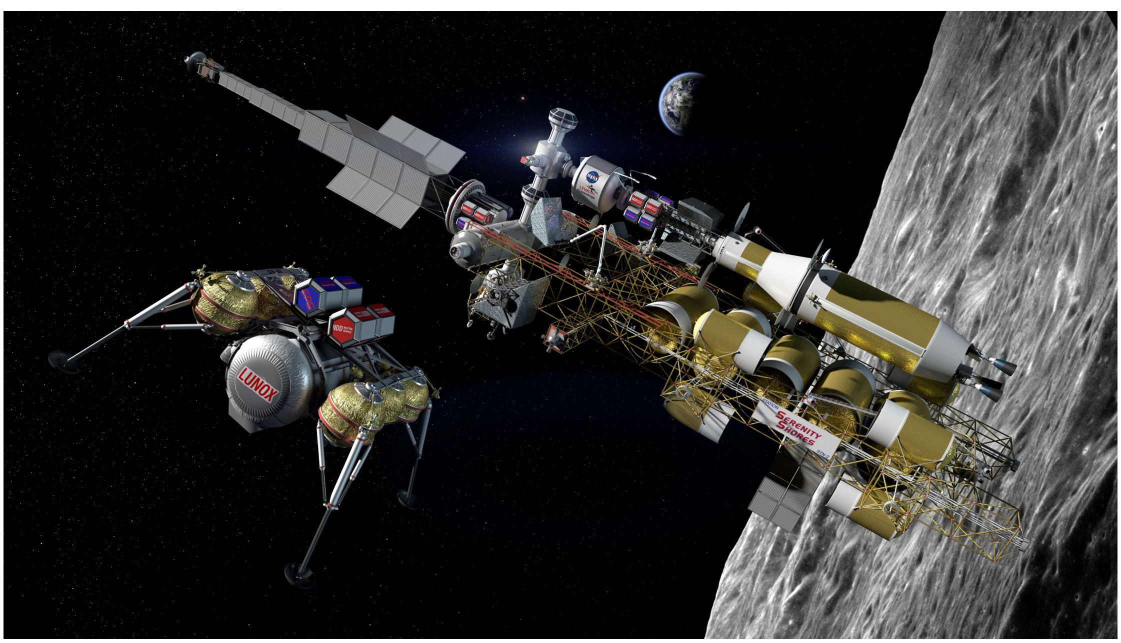

Figure 1. Payload being unloaded from a CCT and LLO2 propellant being delivered to a lunar STN.