SPACE COMMODITY TRADING ON THE MOON AND WITH OTHER SOLAR SYSTEM LOCATIONS.

J. B. Greenblatt, Emerging Futures, LLC, 2726 Eighth St., Berkeley, CA 94710 USA, jeff@emerging-futures.com.

Introduction: A thriving space economy will be built upon *in situ* resource utilization and trade with other solar system locations. Elements must include human life support commodities (water, air and food), basic structural materials (metals, concrete, glass, plastics, plant fibers), inorganic (acids, bases) and organic chemicals, nutrients [(bioavailable nitrogen (N), potassium (K) and phosphorus (P)], propellants [hydrogen (H_2)/oxygen (O_2), methane (CH_4)/O_2, etc.] for rockets and surface mobility, power [silicon (Si) for solar photovoltaics], and small amounts of rare elements for specialized applications. Maximum recycling of nearly all materials will be essential to minimize energy, mass, labor and cost requirements.

The Moon: Here we focus on the Moon as the focal point of a space economy, and examine which types of commodities would be available natively for surface use and/or export, and which materials must be imported from Earth, asteroids or other locations. Some preliminary mass flow estimates based on the existence of a large (50,000 person) lunar settlement [1], and ongoing Mars settlement (20,000 people/yr.) are developed at the end to provide context.

Lunar regolith is abundant in metals [calcium (Ca), aluminum (Al), magnesium (Mg), iron (Fe), titanium (Ti)], Si, O_2, water (at the poles), sulfur and sunlight, but lacks large concentrations of carbon (C), N, and most other elements, including some critical to basic human activities (K, P, halogens, etc.) While small amounts of some of these elements, particularly in mare-based KREEP deposits, might be sufficient for limited industrial use, the lack of C, and probably N, represent severe limitations that can likely only be redressed through material imports.

Moreover, while water is likely present in sufficient amounts (~3 Gt) [2] to provide for nearly unlimited surface needs, resources are insufficient to support sustainable large-scale export to drive a space economy. Therefore, we focus on export of lunar O_2, which is available in abundance from metal oxides, rather than H_2/O_2 propellant, along with refined metals and limited amounts of other materials.

Interplanetary trading: In Figure 1 we show simple flows of commodities among Earth, Moon, Mars, near-Earth asteroids and orbital locations. Due to Earth's deep gravity well, only limited quantities of commodity materials not available elsewhere are sent into space. These include elements rare on the Moon, complex materials such as electronics, and possibly carbon (if sufficient quantities of the element cannot be supplied from locations with lower escape velocities, such as Mars or near-Earth asteroids). In the near term, propellant fuels (H_2, CH_4) might also need to be supplied from Earth to orbital locations for spacecraft refueling, but in the long term, these commodities will be more economically supplied from other locations.

Mars and near-Earth asteroids. These celestial bodies might also be able to supply metals and volatiles, but many basic metals can likely be supplied in abundance from the Moon, along with O_2 which provides an important component to an in-orbit propellant resupply economy.

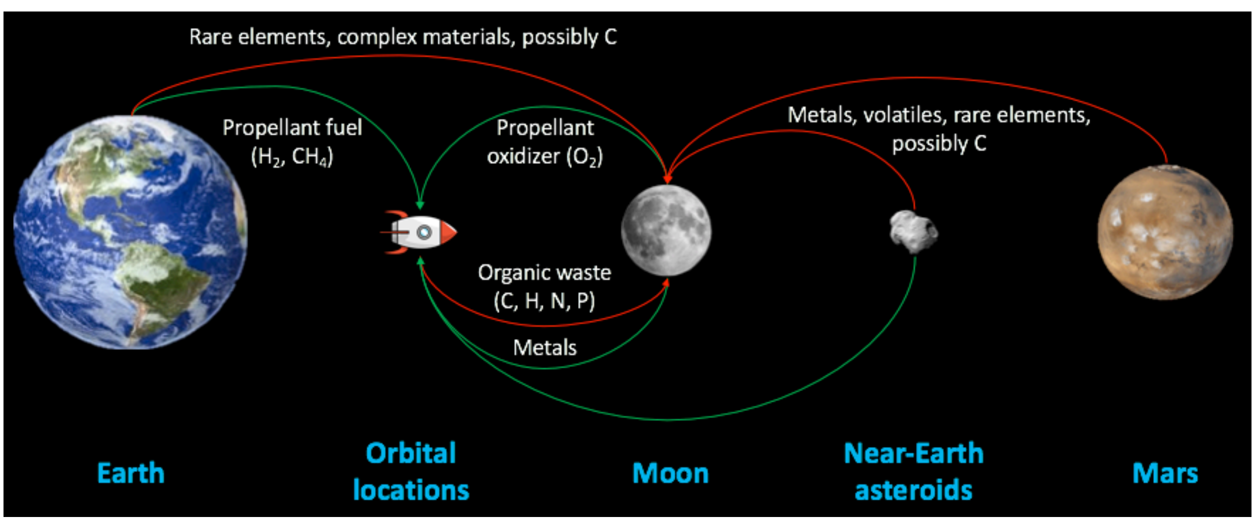

Figure 1. Some interplanetary material trade flows

Carbon and nutrient deficits. To supply elements deficient on the Moon (mainly C), we propose that carbon waste recovered from in-orbit activities such as human transport between Earth and Mars be collected and delivered to the lunar surface, after recycling of water, oxygen and other useful commodities. Humans produce ~0.3 kg/day C, mainly from exhaled CO_2; urine and feces contribute little additional C but valuable concentrations of N, P and K [3].

Mars transport spacecraft: One million people transported to Mars over 50 years is an annual flow of 20,000 people/yr. or 430 spacecraft each carrying 100 people every synodic period (2.14 yrs.). Assuming the average journey takes 4 months, the fleet produces 730 t/yr. C, 30 t/yr. N and ~7 t/yr. each P and K. A fleet of SpaceX Big Falcon Rockets (BFR) would require 172 kt/yr. O_2 + 48 kt/yr. CH_4 in low Earth orbit (LEO) to propel them to Mars [4]. We assume spacecraft dry mass is 75% Al (64 t), 20 yr. lifetime and 10% fleet redundancy. Replacement of old spacecraft therefore requires 1.5 kt/yr. Al.

Lunar settlement: Because virtually all lunar water is estimated to be located at the poles whereas lunar activities would likely be desirable to locate elsewhere, we propose that instead of transporting water up to 2,700 km from pole to equator, the water is electrolyzed at the poles and the H_2, with 11% of the mass of water, transported via suborbital "surface hopper" rocket, whereas the produced O_2 is exported to space to provide propellant oxidant for Mars transport or other spacecraft. At receipt locations, regolith processing would produce Si, metals and O_2 sufficient to reconstitute water, with ample quantities left over for breathing air or other uses. See Figure 2.

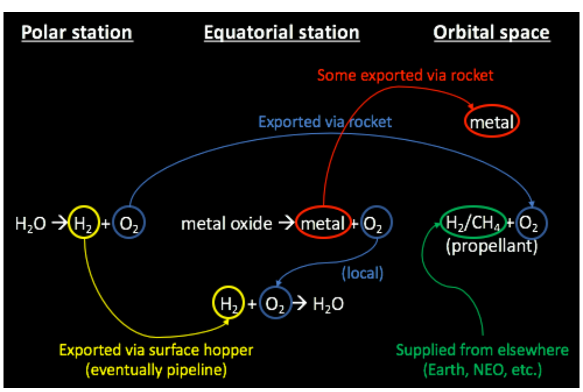

Figure 2. Material flows on and from the Moon

For a lunar settlement population of 50,000 [1] and assuming 99% water recycling, human plus agricultural water use requires 201 kt/yr. An additional 342 kt/yr. is required for H_2/O_2 propellant used to export 188 kt/yr. O_2 plus 1.5 kt/yr. refined Al to the Earth-Moon L1 Lagrange point, as well as transport of 23 kt/yr. H_2 from pole to equator. Producing this propellant would require 730 MW. Power for regolith processing and settlement needs would be additional.

Carbon requirements. Assuming 33% additional C required for non-food uses (plant fiber, animal feed, organic chemicals, etc.) and 90% overall recycling of C, the settlement would require 730 t/yr., exactly equal to that produced by the spacecraft fleet. Higher recycling rates would require less C imports.

Regolith processing. To provide sufficient O_2 will require 485 kt/yr. raw regolith, assuming 43% oxygen by mass [2] with 90% O_2 recovery. Assuming lower recovery rates (50%) for other elements and average lunar concentrations in regolith [2], 51 kt/yr. Si, 32 kt/yr. Al, 24 kt/yr. Fe and 32 kt/yr. other metals will be recovered. Replacing old spacecraft would require 5% of produced Al, leaving ample supplies of this and other metals for surface infrastructure or other space-based applications.

Lunar pipeline. In the long term, building a pole-to-equator H_2 pipeline is advantageous. We estimate, based on reasonable pipe dimensions and 25% redundancy, this would require 109 kt of steel, or 4.5 years of settlement Fe production, but save 62 MW and 46 kt/yr. of water for propelling surface hoppers. Assuming steel contains 1% C, 1.1 kt or 1.5 years of C imports would be also required.

Orbital propellant depots: The envisioned system would supply 188 kt/yr. O_2 to L1. If subsequently transported to LEO, this would be ample to replenish propellant oxidant for a fleet of Mars transport spacecraft, provided that propellant fuel (e.g., CH_4 or H_2) is supplied from elsewhere (Earth, Mars, carbon-rich asteroids, etc.). The advantage of supplying O_2 from space is to greatly reduce the number of propellant launches from Earth, and hence cost. We estimate that each BFR requires ~6 propellant launches to refuel in orbit [4]; with lunar-supplied O_2, propellant launches could shrink to ~1.3.

References:

[1] Greenblatt J. B. (2017) Comparative analysis of human settlements on the Moon and Mars, Emerging Futures, LLC. https://tinyurl.com/moonvsmars.

[2] Crawford, I. A. (2015) Lunar Resources: A Review, *Progress in Physical Geography*, 39: 137-167. DOI: 10.1177/0309133314567585.

[3] Rose C., Parker A., Jefferson B., Cartmell E. (2015) The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology, *Critical Reviews in Environmental Science and Technology*, 45:1827–1879.

[4] *Wikipedia*, BFR (rocket), accessed 9 March 2018. https://en.wikipedia.org/wiki/BFR_(rocket).