ENABLING AN INCREASE IN STARSHIP'S PAYLOAD CAPACITY TO LOW EARTH ORBIT (LEO) USING LUNAR DERIVED LIQUID OXYGEN (LULOX) AS ENTRY DESCENT AND LANDING (EDL) LOX. Alice Miller and Jonathan Geifman[1], Helios (Tzur Yigal, Israel), Nicholas J. Bennett[2], PhD Candidate, Australian Centre for Space Engineering Research (ACSER), School of Electrical Engineering and Telecommunications, University of New South Wales (UNSW) (Sydney, NSW, 2052, Australia).

Introduction: A commercial economic model for the extraction of lunar oxygen, independent of artificial projections for future cislunar economy is presented. SpaceX's Starlink is used to demonstrate the model, but any other future mega-constellation is a relevant use case.

Replacing Earth brought Liquid Oxygen (LOX) for Entry Descent & Landing (EDL) with lunar derived liquid oxygen (LULOX), increases Starship's payload capacity to LEO.

This increased payload capacity reduces the number of launches required to maintain the Starlink mega-constellation.

SpaceX plans to deploy 12,000 to 42,000 Starlink Satellites, launched by Starships. A 5 year deorbit regime results in 40-140 launches per annum. Using LULOX for EDL results in a saving of 5-18 Starship launches per annum. This is the potential capturable value.

Actual value to a LULOX supply company will be capturable value minus LULOX production, transportation, storage and supply costs.

LULOX supply scheme: Cislunar space transport vehicles will be based on Starship. A "Lifter to LLO" rocket will supply LULOX from moon production site to a "Transporter to LEO" rocket and receive methane from the Transporter. The "Transporter to LEO" will supply LULOX to a Depot and will receive methane from the Depot.

Methane supply Starships will launch from Earth to the Depot to supply methane for both rockets ("Lifter" and "Transporter").

Sensitivity calculations of the above supply scheme for a LEO orbit of 185 km, have led to the following results:

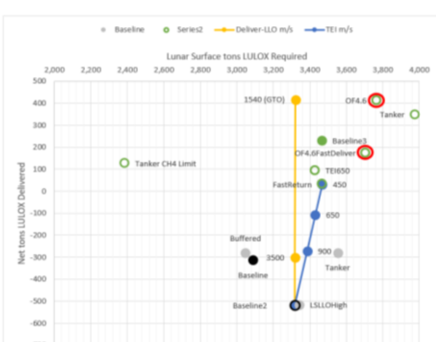

Figure 1: X-axis is lunar surface tons of LULOX required to deliver Y-axis net tons to the customer. Net tons are tons of LULOX supplied in LEO minus CH4 received from Earth.

Various positive Net tons scenarios exist, with up to 400 tons of LULOX supplied in LEO.

Starlink deployment process: Starlink satellites are deployed into about 6 shells, each with a unique orbital inclination and altitude. Altitudes range from about 350 km to about 570 km, inclinations from 42 up to 97 degrees; most satellites are high and around 53 degrees inclination. Each shell is composed of many planes, with each plane hosting a specific number of satellites. A typical Starlink launch currently contains satellites to populate around three planes.

SpaceX takes advantage of an orbital dynamics trick to pay time and avoid the very expensive propulsive plane change. The oblate shape of the Earth has the effect of gradually changing the plane of any orbit, twisting it, known as orbital precession. The effect depends on altitude, inclination, and eccentricity.

SpaceX currently releases all the satellites of a launch into a 290 km circular orbit in a particular deployment plane. Satellites belonging in this plane immediately begin climbing under their own power to their operational altitude, distributing themselves around the orbit as they go. Those destined for other planes raise themselves to around 350 km (presumably to reduce atmospheric drag), where their orbits are processed faster than their destination planes. When their orbit is correctly aligned under their destination plane, they begin their climb. So, for initial deployment with minimum delay, SpaceX launches into an empty plane; the released Starlink satellites fill that plane and the subsequent two planes.

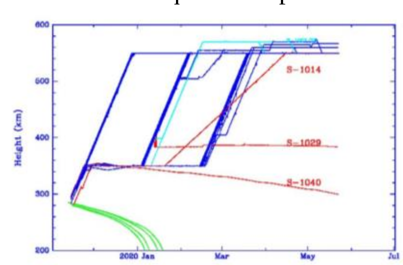

Figure 2: Illustration of a SpaceX launch and deployment of Starlink satellites.

Depot Altitude and Sizing: Sensitivity calculations were performed considering Starlink deployment process, orbital lifetime, inclination and plane changes, precession relative to Starlink Shells and Precession relative to the moon.

Atmospheric drag: Significant atmospheric drag can be generated in low Earth orbits. The force generated depends on properties of the orbiting object and the solar flux.

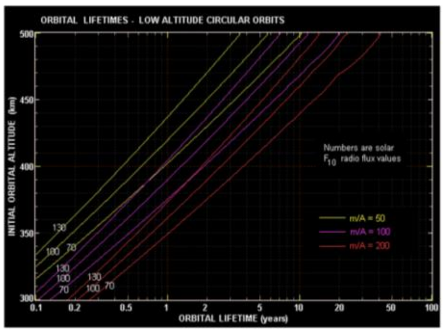

Figure 3: Indicative information on how orbital lifetime varies with altitude, kg/m^2, and solar flux. (https://www.spaceacademy.net.au/watch/debris/orblife.htm)

ETA Space video (https://etaspace.com/orbital-1) of a proposed Depot can be used to estimate that the Depot is of a similar scale to a Centaur upper stage. From Figure 3, one can guestimate that an empty Depot at 290 km, where Starships release their payload and must take on LULOX, will probably last a few weeks. This will probably be less, since a Depot may need to maintain a fixed sun orientation and/or have a sun/Earth shield; both of which would tend to reduce kg/m^2.

Atmospheric drag drives the Depot to a higher altitude than Starship's Starlink depoloyment altitude.

LULOX delivery to LEO to refill Starships is most effective using both LULOX Depots and right-sized "last mile" tankers which will transfer LULOX from the Depot to a starship in its designated deployment orbit.

WSB trajectories: Weak Stability Boundary trajectories (WBS) from LLO to LEO and back were found to be necessary to achieve net positive propellant delivery. WSB trajectories use Earth, Moon, and Sun gravity, therefore, the relative position of all three is significant and limiting, but required delivery cadence could be met

To be in position for every potential WSB a Depot must precess 331 degrees in 29.5 days, 11.22 degrees per day, this is unachievably fast. The fastest precession that will hit the right relative location at the right time for the 53-degree inclinations is at 910 km, this will hit every third opportunity, every 88.5 days a transfer is possible.

A 910 km Depot will precess about 0.75 degrees per day relative to the 53-degree Starlink shells, so it will take 480 days to precess over every shell. If Starlink lifetimes are 5 years, and SpaceX will be repopulating three consecutive shells at a time, then they only need access to a particular shell every 1826 days, about 3.8 Depot cycles. So, a single Depot per inclination shell might well be enough

The high propellant cost of orbital plane changes forces multiple Depots, one per inclination, or set of very close inclinations. Within an inclination, astrodynamics constraints force the timing of possible deliveries from the Moon to a Depot. To increase the delivery frequency, one must increase the number of Depots in the inclination.

Summary: The most likely scenario for LULOX supplier to support Starlink utilizes Weak Stability Boundary trajectories both ways, aerobraking into Earth orbits, one Depot per inclination group at an altitude of around 910 km (to synch with WSB opportunities), dedicated CH4 tankers launching from Earth to supply the Depots, and relatively small last-mile tankers to deliver LOX to Starships in 290 km orbits. SpaceX would need to coordinate their launch campaign around the precession of the Depots, and the timing seems to be a reasonable fit for likely Starlink replacement flights.

Future work to be done: The orbital dance logic seems to make sense, however high fidelity numerically propagated orbital simulations need to be computed to confirm the basic scheme, to explore any constraints on lunar landing after TLI, and to characterize how much "slack" there is in WSBs to accommodate the precession of Depots. Ideally one would model all the elements of the logistics network over an extended period to verify the practicality and sustainability of the business case.