



Texas A&M University-Fluidics for Lunar Operations (FLO)

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Problem

The high delta-V requirements for transporting payloads beyond low Earth orbit force mission planners to sacrifice effective payload capacity, either by requiring more propellants or by limiting payload mass. As a result of this trade-off, transporting payloads to geostationary orbit, the Moon, or Mars, is highly expensive, limiting further exploration and a sustained presence at these locations.

Lunar Railroad Solution

The Lunar Railroad itself is an emerging framework for large-scale lunar development envisioned to produce Liquid Oxygen (LOX) from lunar regolith utilizing a Molten Regolith Electrolysis (MRE) reactor.

The Lunar Railroad enables the energy efficient transportation of raw resources and processed goods, such as LOX, between disperse lunar assets.

Lunar derived oxygen could support support life support systems on the moon like ECLSS system, or it could be condensate into LOX for use as a propellant [1]. Propellant LOX could refuel landers departing from the lunar surface or fuel depots in Geotransfer Orbit, where tugs could utilize the LOX to propel payloads beyond low earth orbit. However, one important component of this concept is the transfer of fluids, like LOX, between different surface assets. This task poses major challenges and these system require testing and modeling prior to any deployment on the lunar surface.

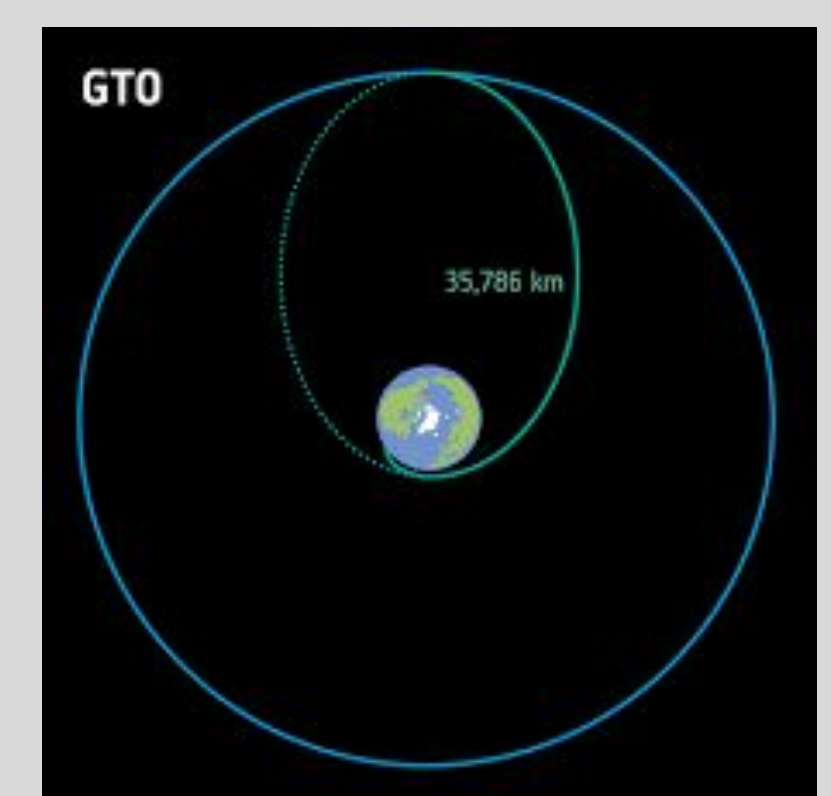
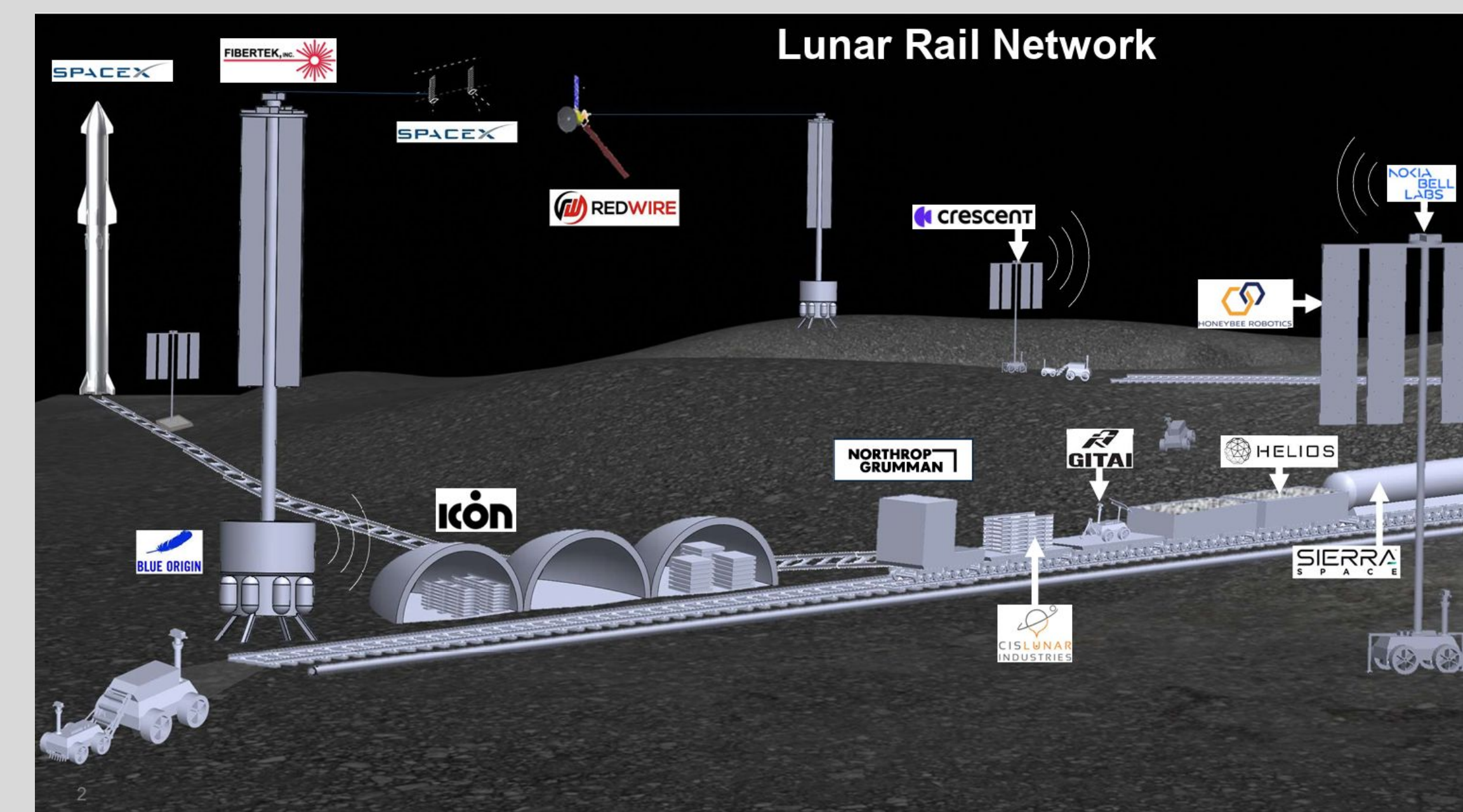


Figure 1: GTO orbit



Objectives / Mission Goals

- Develop system that may safely and efficiently transfer LOX between
 - MRE and train LOX storage
 - LOX Storage and Launchpad systems
- Establish fundamental designs that are scalable for later requirement phases
- Increase human presence in-orbit and on the lunar surface

References:
[1] Texas A&M University, *Lander Integration for Lunar Molten Regolith Electrolysis (LIL-MRE)*, Abstract and Introduction, 2025.
[2] Texas A&M University, *LIL-MRE Design Details and Thermal Management*, pp. L233–L344, 2025.
[3] Texas A&M University, *LIL-MRE Schedule and Integration with Lunar Railroad Infrastructure*, pp. L401–L410, 2025.
[4] Texas A&M University, *LIL-MRE Conclusion and Future Work*, pp. L422–L430, 2025.
[5] NASA Artemis Program and Lunar Railroad Concept Team, *Surface Logistics and Transport Framework for Lunar ISRU*, 2025.
[6] Texas A&M University, *LIL-MRE Challenges and Cryogenic Handling*, pp. L412–L420, 2025.
[7] Lunar Rail Network Infrastructure, Steven Floyd et al. DARPA LunA-10 TA-1 Study

Cryogenic Background Information

Establishing a sustained human presence on the Moon requires reliable oxygen generation and distribution. However, transferring LOX under lunar gravity introduces major challenges. The cryogenic nature of LOX demands precise temperature control to prevent boil-off as well as the use of insulated tanks and transfer lines to maintain stability near 200 K [2]. Surface dust and reduced gravity further complicate connections between landers, depots, and refueling systems [6]. In addition, LOX's reactivity poses challenges when deciding an interior coating to prevent corrosion and protect the pipe's structural integrity. A proper internal coating for the transfer system also prevents contaminants from creating deposits that lower the system's efficiency. Efficient and safe LOX transfer is therefore essential to sustain long-term surface operations, enable refueling for ascent vehicles, and support the Artemis program's goal of a reusable lunar logistics network [5].

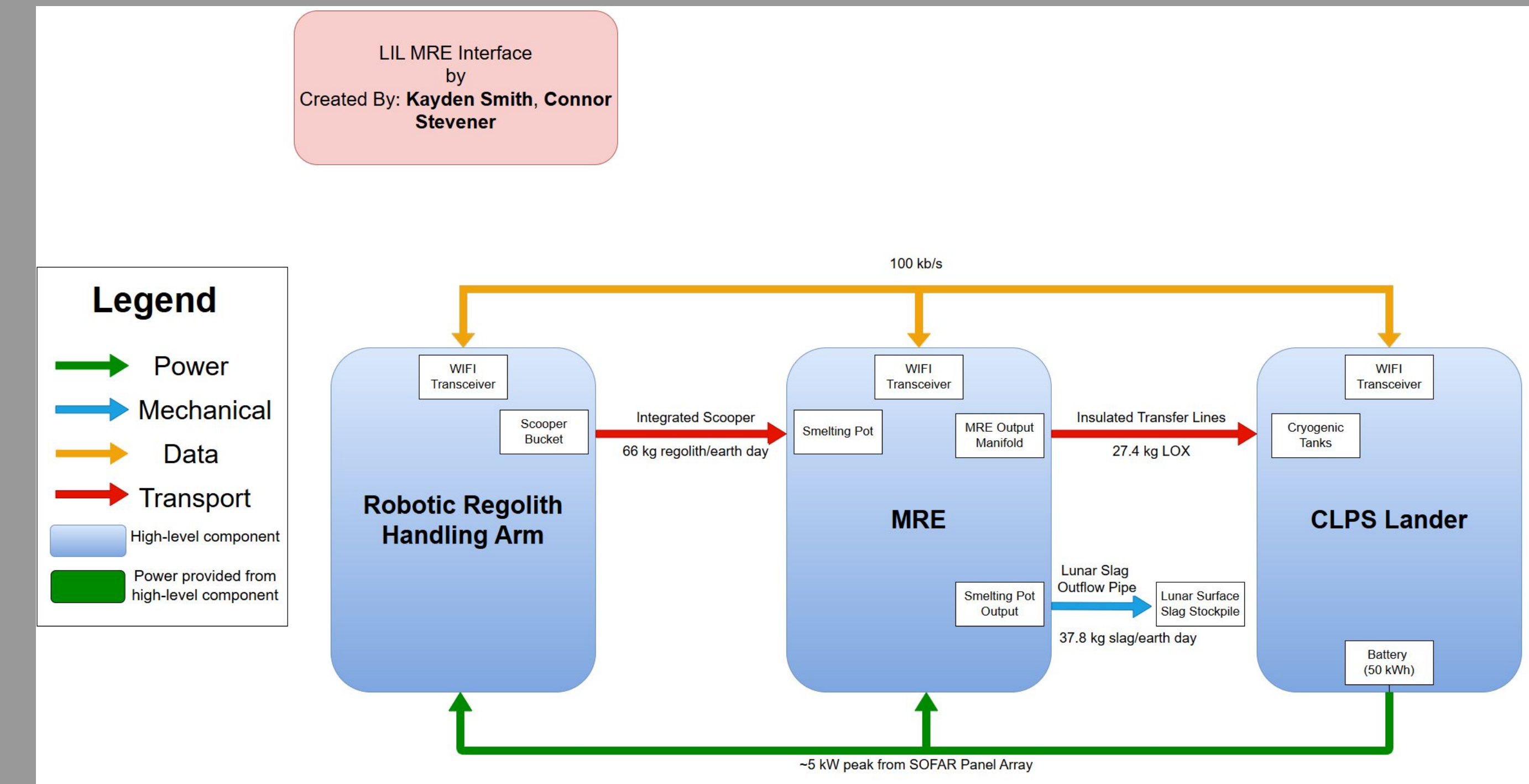


Figure 3: LOX movement flowchart

Considerations

Surface tension and capillary effects vary with gravitational effects. In order to best design a LOX transfer pipe, FLO will consider the following under extensive trade studies once a transfer ConOps is developed factors include:

- Surface energy of material
- Geometry of Pipe Design
- Dust Mitigation with 99% cleaning efficiency
- 2 year minimum operation timeline
- LOX cryogenic temperature (200 K) / supports addition of low-pressure release valves

Material Candidates

The following depicts the kind of considerations taken when selecting appropriate materials.

Pugh Table										
Criteria	Weight	Justification	Bare Aluminum Alloy (Al-2195 / Al-2219, pre-passivated)	Justification I	Anodized Aluminum (Type II, sulfuric acid anodizing)	Justification II	PTFE / PFA Film Liner	Justification III	LOX Certified MXene/Epoxy Nanocomposites	Justification IV
Corrosion Resistance (LOX corrosion rate (µm/year))	0.33	High priority - Aluminum tanks will sit for years underground on the Moon; preventing any corrosion is critical for LOX purity and safety.	3.00	0.1 µm/yr (natural oxide 4–10 nm)	4.00	0.005 µm/yr (oxide 5–25 µm)	5.00	0.000 µm/yr (inert)	1.00	50 µm/year (tested per ASTM G86)
Longevity (years)	0.28	High priority - Tanks must remain functional over long-term storage periods without maintenance.	3.00		4.00	20+ years	5.00	25–30 years	3.00	15 years (limited data from experimental testing)
Cryogenic Stability (Elongation at break %)	0.20	Medium High priority - Liquid oxygen is denser and much cooler than its gaseous state so coating material should be stable in cryogenic conditions.	3.00	10–15 years	2.00	3–8% Elongation	5.00	250–300% Elongation	4.00	50–100% Elongation
Mass	0.09	Medium High - Starship payload is limited; reducing performance.	5.00	No additional coating; tank wall mass only.	4.00	Oxide layer is very thin but slightly	3.00	Film thickness (0.05–0.5 mm) adds slightly	4.00	Thin coating (~0.2–0.3 mm) adds minor
Cost (USD/m²)	0.05	Medium - Important but secondary to safety and performance.	5.00	Commodity aerospace aluminum alloy; standard fabrication; lowest cost baseline. (\$25–40)	4.00	Adds anodizing processing; labor, energy, and QA increase cost by ~2x vs bare Al. (\$60–90)	3.00	Specialty fluoropolymer film; bonding/thermoforming adds cost; moderately priced compared to MXene. (\$80–120)	1.00	High cost due to MXene feedstock; formulation, QC, and low availability; expensive for large-area tanks. (\$300–600)
Accessibility	0.04	Medium priority - Material that is easier to acquire is more efficient for the project.	5.00	Widely available, mature supply chain.	5.00	Easy to source anodized aerospace-grade aluminum.	3.00	Limited vendors, requires bonding expertise; moderate accessibility.	1.00	Experimental, few suppliers, not widely available in aerospace-grade form.
Total	Net Score		3.36		3.63		4.64		2.45	

Figure 4: Example of material trade study

These and further evaluations will determine the proper solution with a higher surface energy to allow for stronger adhesive capillary forces. It should be noted that at significant volume flow, it is expected to simply see additional turbulence within flow.

Further Development

FLO plans to create a Computational Fluid Dynamics (CFD) model utilising Ansys Fluent Simulation Software to evaluate different materials and designs for transferring LOX from surface assets on the lunar surface. Upon completion of fluid analysis with CFD, FLO will use the models to inform and iterate our fluid transfer system designs for further development.

With the information established in previous stages, the next step is to further develop the system's integration into lunar infrastructure. The Lander Integration for Lunar Molten Regolith Electrolysis (LIL-MRE) concept can evolve from a standalone payload into a key element of a surface resource network [1]. Once LOX is reliably produced and stored within the CLPS-class lander, future iterations can include automated transfer lines, cryogenic manifolds, and rail-connected transport tanks to deliver oxidizer to distant sites [2]. This development phase will focus on validating fluid transfer performance under lunar thermal conditions, scaling oxygen production, and synchronizing delivery with surface logistics systems such as the Lunar Railroad and ISRU processing hubs [3]. By refining transfer interfaces and thermal controls, the system can transition from prototype demonstration to an operational node within a reusable lunar supply chain [4].

Model

The model will consist of a simple cylindrical pipe that directly contacts the LOX. The inner shell will be designed with several cooling jackets with integrated temperature/pressure regulation systems. Finally the outer shell will consist of protective shielding fit for protecting transfer from lunar environment. With further development, FLO will maximise the utility of transfer cables contingent on system requirements.

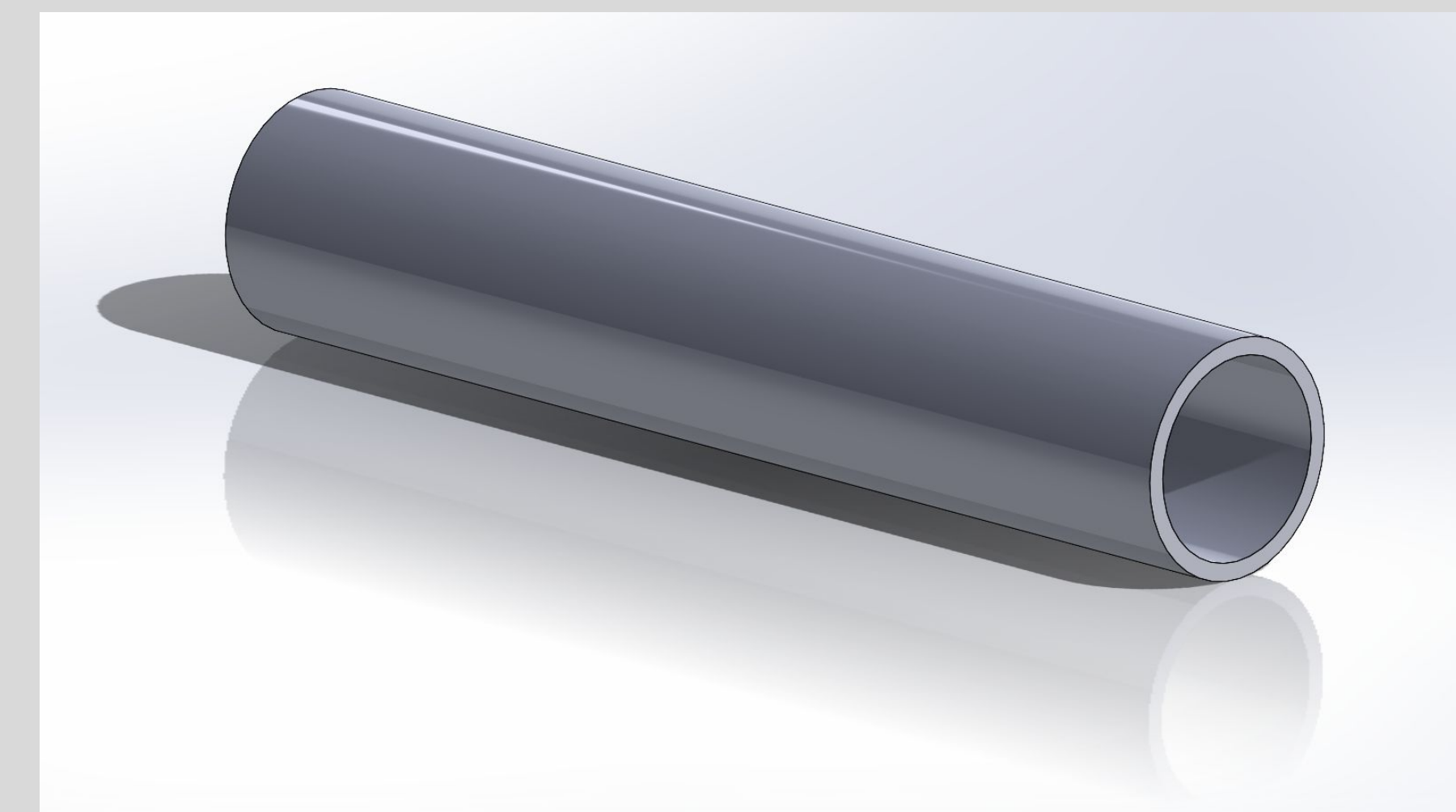


Figure 5: Graphical representation of fluidic model

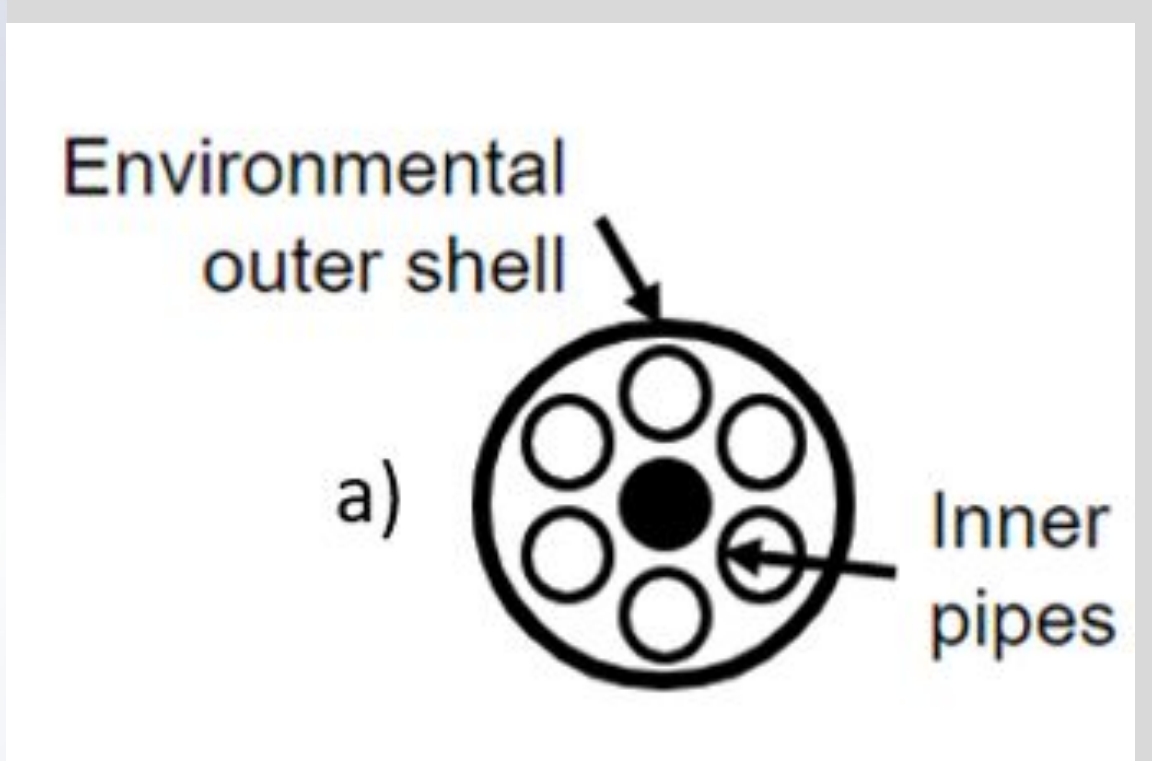


Figure 6: Total pipe cross section [7]

FLO plans to prepare a fluid model and finalize development on fluidic transfer solutions compatible with the lunar railroad.

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