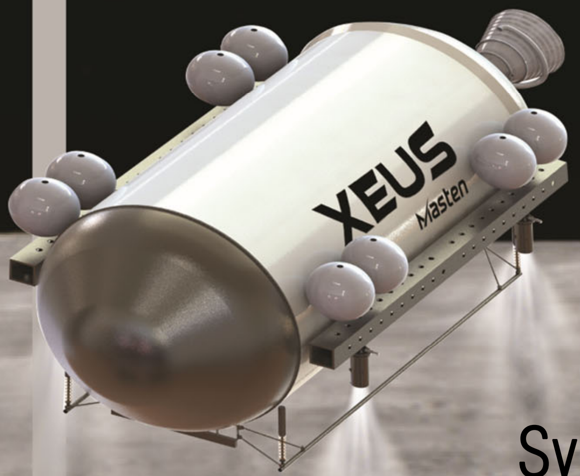
SICSA

CONDITIONS FOR MAKING LUNAR ISRU VALUABLE FOR A MARS-FORWARD FUTURE



Sylvester 'Sly' Hampton | Slyshampton@gmail.com | 5/15/2020

About Me

Sylvester 'Sly' Hampton

2005 – Present | **Eagle Scout**

2013 – 2017 | **B.S. Architecture**

2019 – Present | **Contract Engineer**

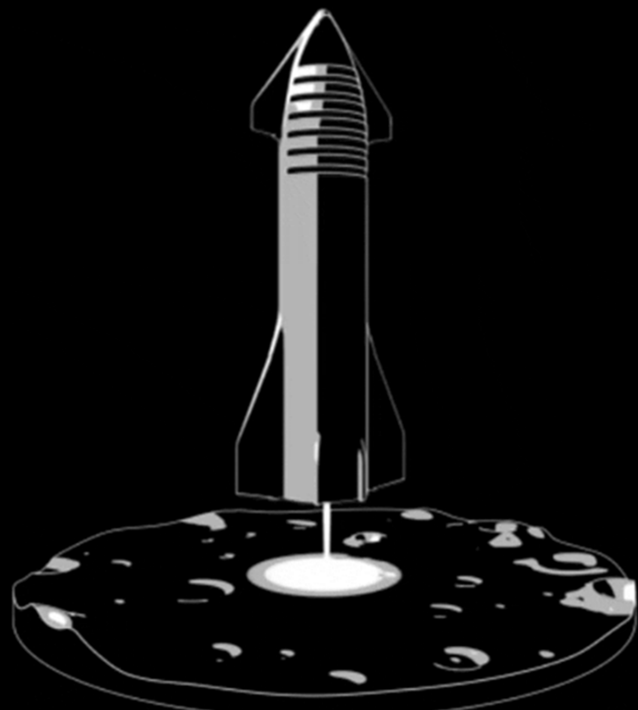
Vision Statement

"To enable humanity's expansion off-Earth for: permanent exploration, development, and settlement towards a *Mars-forward* future."

Previous Research Findings

(Orbital Refueling Depot)

- SpaceX's Starship Architecture
- Lunar propellant sent to LEO is not cost-effective
  - ΔV from LLO to MTO = ~ 1.3 km/s
    - ΔV from Lunar Surface to MTO = ~ 3.03 km/s
  - ΔV from LEO to MTO = ~3.6 km/s
- Large volumes are problematic
  - More infrastructure needed for ISRU plant
    - Greater up-mass cost
  - Ferry propellant back and forth with Starship vessel
    - Higher frequency of launches
- ISRU infrastructure investment is the only net benefit



Research Problem

"What are the CONDITIONS

to make LUNAR ISRU

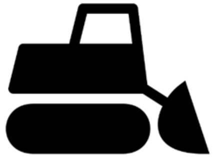
VALUABLE

for a Mars-forward future?"

Top-Level System Elements

ISRU: Water-Ice → Oxidizer & Fuel (in a commercial venture)

Major System Elements:

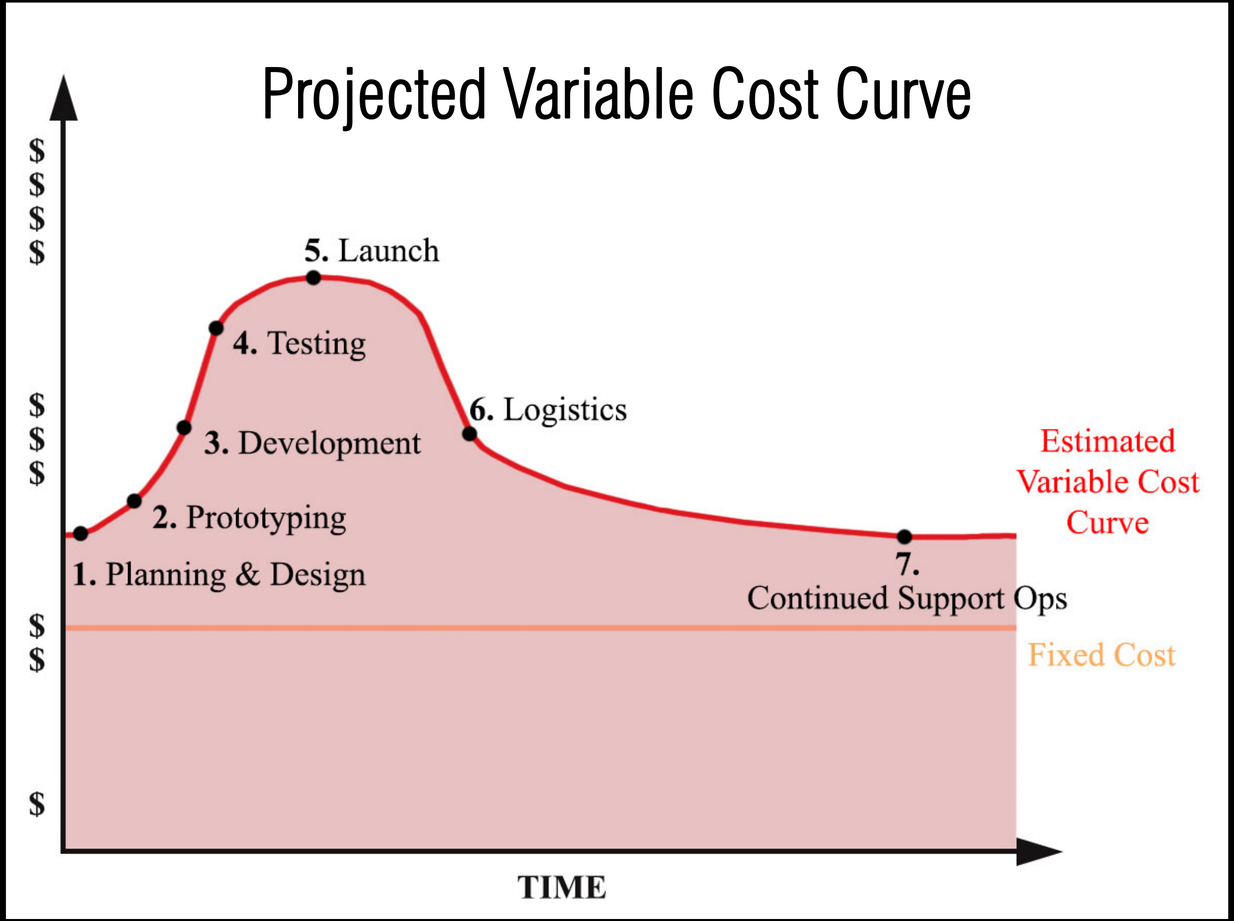


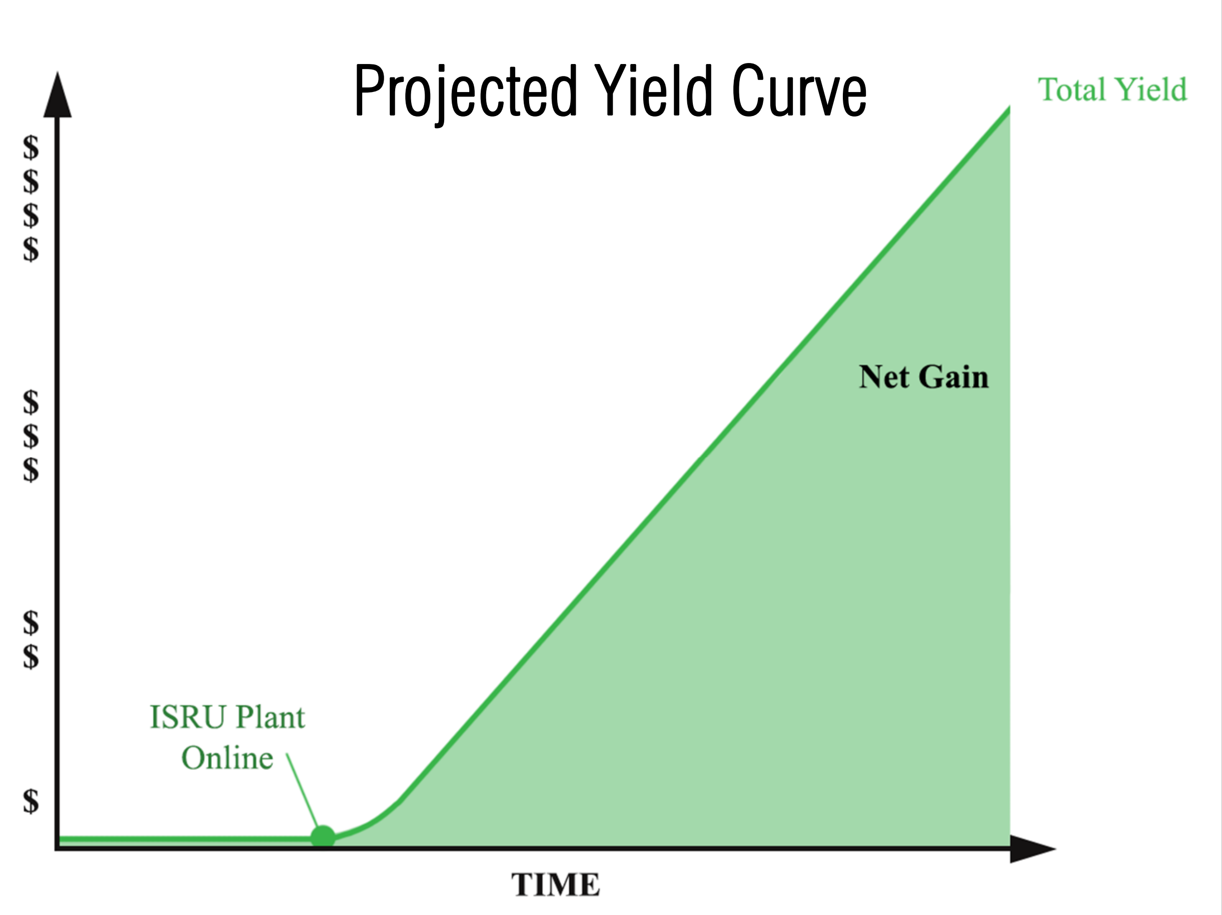
- *Excavation*
- *Transportation*
- Processing
- Storage
- Power Generation

Excavation and Transportation systems are outside of the scope of work, and I do not include them in the energy requirements or trade space

Commercial Viability

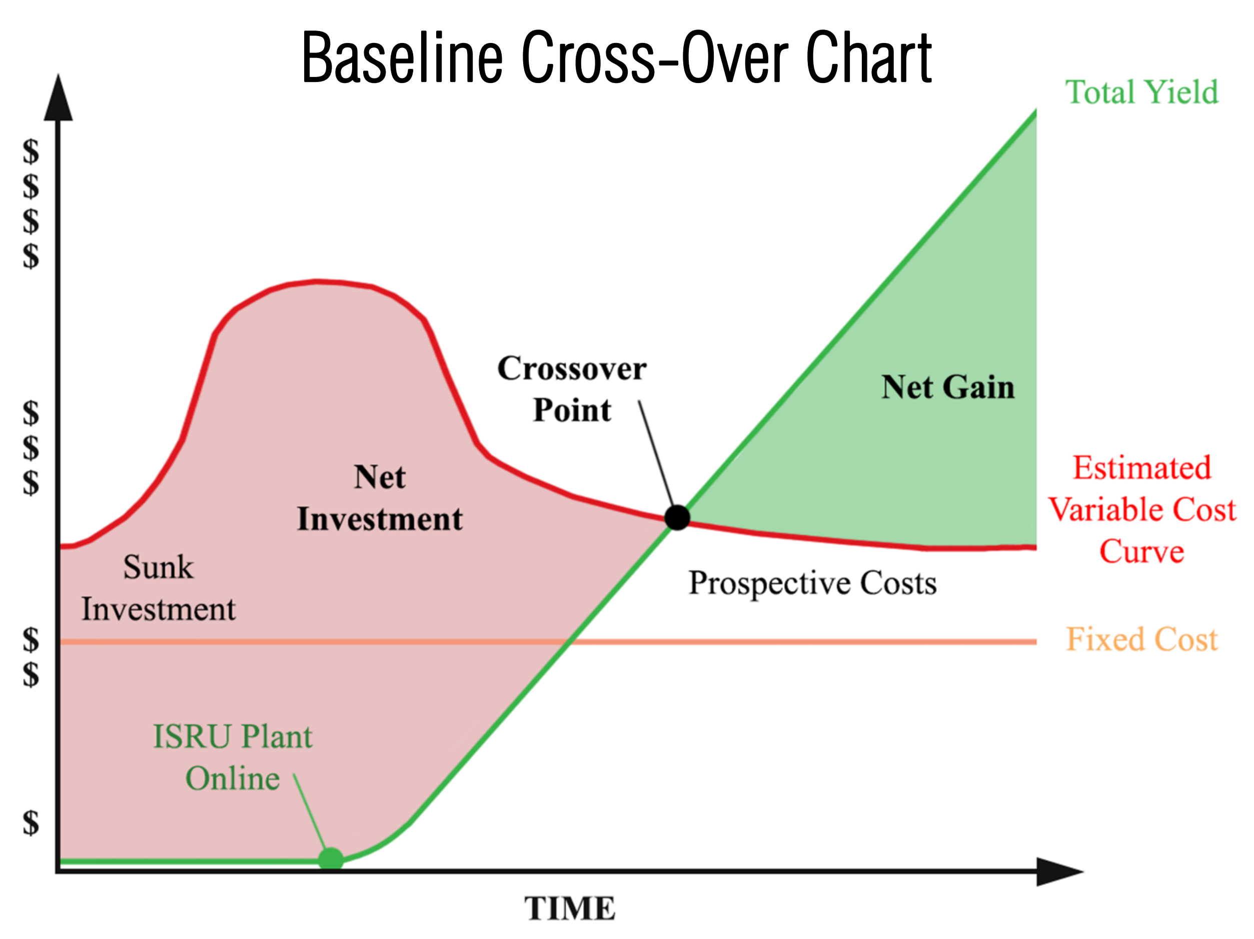
It is important for any commercial-space venture to understand the variable investments costs that must be made early-on, and their expected yield over time to characterize their cross-over point of business viability.

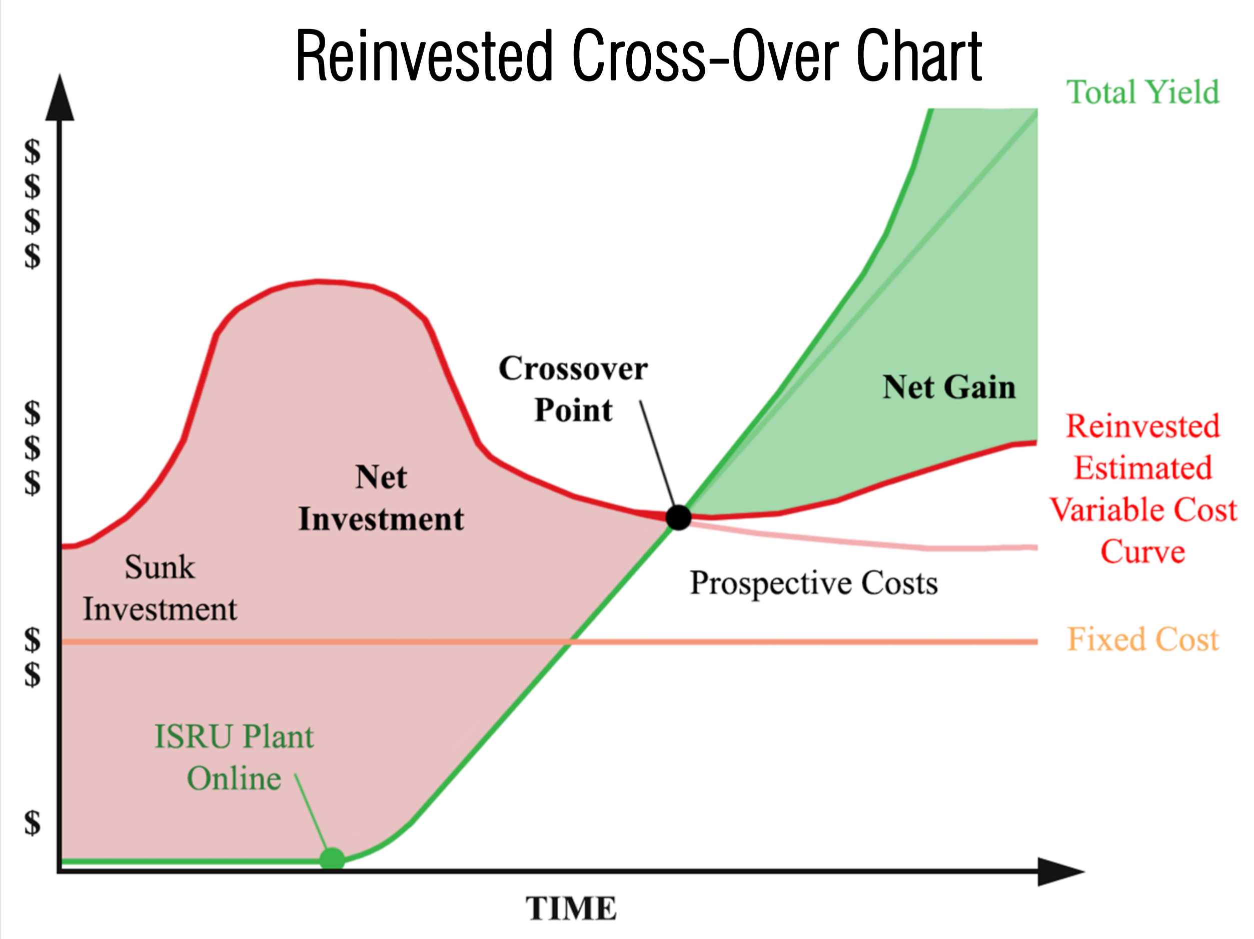




Commercial Viability

At the cross-over point, a business decision can be made to reinvest earnings to improve their overall system's functionality and capabilities. Otherwise, it provides a proof-of-concept and viability, and can be sold off.





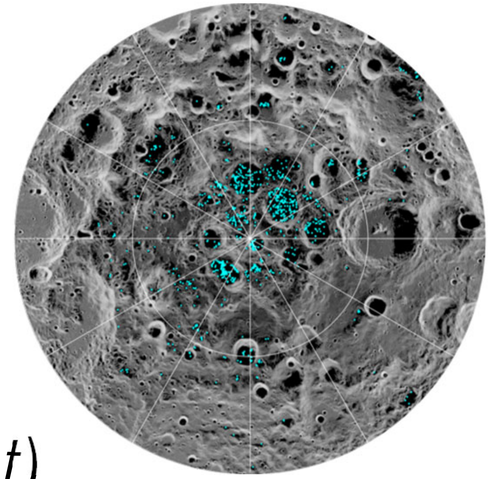
Baseline Assumptions

Existence and ease of accessibility to boundless **water-ice** deposits at the lunar south pole

- Data from LCROSS & LRO have both acquired significant evidence
- NASA's Volatiles Investigating Polar Exploration Rover (VIPER) will investigate the south pole in Dec. 2022.

Market Demand:

- ULA's Advanced Cryogenic Evolved Stage (ACES)
    - Orbital Refueling Depot Architecture
- Masten's Xeus Lunar Lander



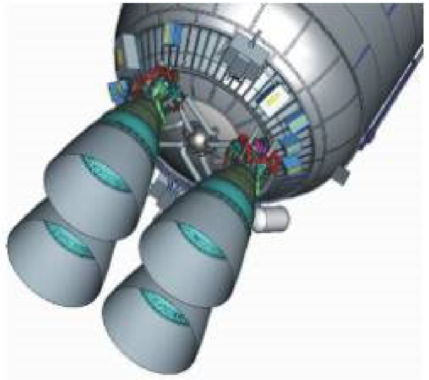
Autonomous Operations *(with minimal, remote, human oversight)*

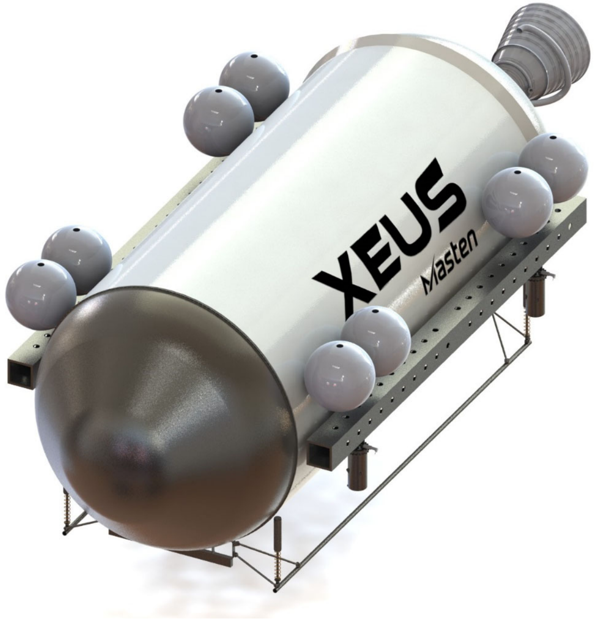
- Nominal operations for entire mission duration

Commercial Architecture

ACES-Xeus based architecture

- LOX/LH_2 Fuel
- ACES: 68MT tank size
  - RL-10 Engine oxidizer-to-fuel ratio (5.88:1)
  - 9.88MT LH_2
  - 58.09MT LOX
- Xeus: 25MT to EML-2 (ORD location)





Processing Plant

- Sublimation & Electrolysis

Cryogenic Storage

- LOX = 90K; LH_2 = 20K

Power Generation System

Commercial Architecture

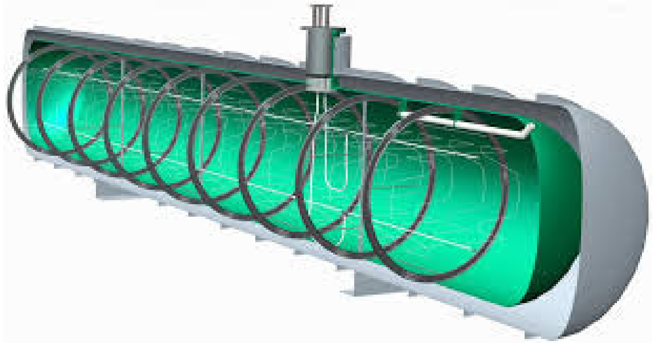
Extraction & Transportation Systems are assumed

- No impact to power generation system requirements or trade decision

Processing System

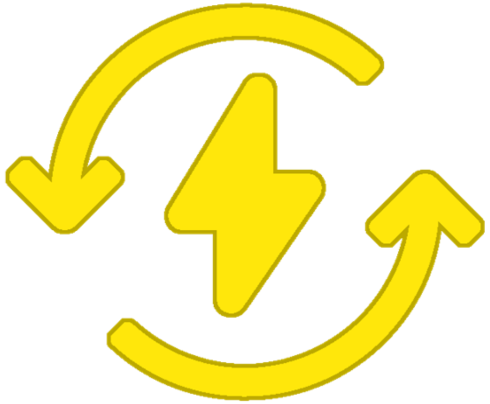
- 10MT of LH_2 (9.88MT tank size + Margin of Error)
- 58.09MT of LOX
- Annual refuel rates of 1x, 2x, and 5x

Cryogenic Storage (IRAS)



- Integrated Refrigeration and Storage | NASA KSC
- Brayton Helium Refrigerator
- Proven technology that can hold LH_2 for indefinite time periods w/out boil-off for ground-based purposes (GODU-LH_2 Project)

Evaluation Metrics & Design Criteria

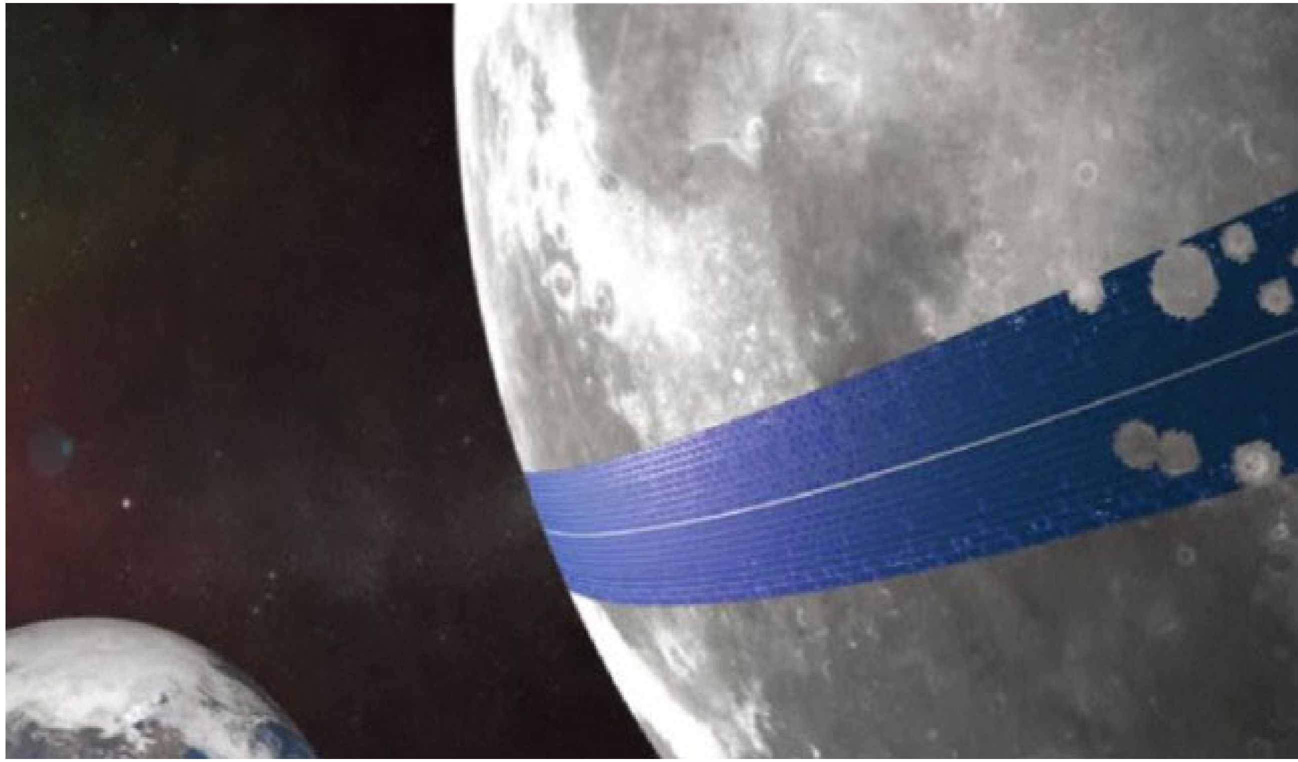


Energy (Power Generation System Trade)

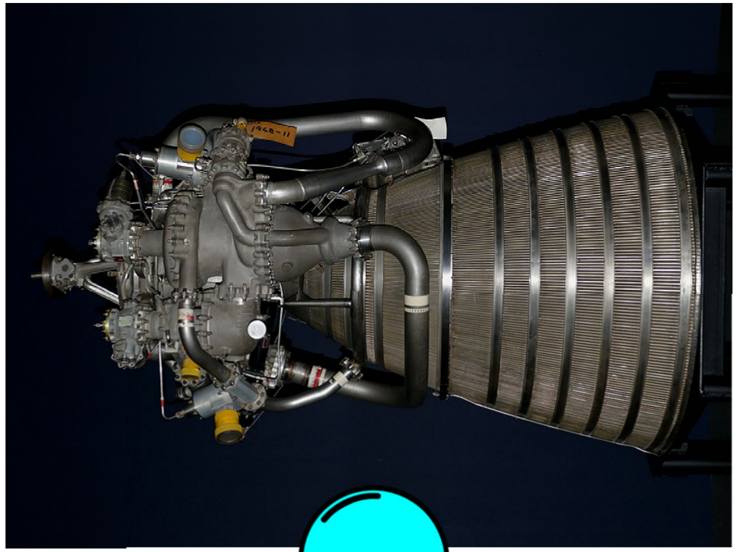
- Output Rate (24-Hr Utility)
- Scalability (Density of kWh capabilities)

Risks

- Nominal Autonomous Operations
  - System level
  - Rendezvous
- Maintenance
  - Redundancy
  - Repairability
- Propellant Transfer Loss
  - ZBO technology and insulation integration



Analyses



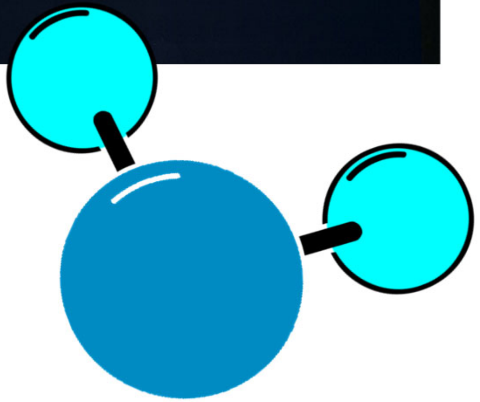
ACES Tank Size = 68MT

- 10MT LH_2 & 58.09MT LOX Needed

Sublimation

- Specific heat change of <110K → 298K *(ΔT = 188K)*

Electrolysis



- $2H_2O_{(l)}$ + Electrical Energy (285.6kJ) → $2H_{2(g)} + O_{2(g)}$
- Propellant ratio ≠ Electrolysis ratio (LH_2 is the bottle neck)

89.93MT of Water-Ice must be processed (including margin of error)

- Surplus of 21.84MT LOX after each refuel cycle
- 89.93MT < Mass of regolith that will be processed (Outside scope)

Brayton He Refrigerator power consumption = 7.69 $kWh/kg_{(LH2)}$

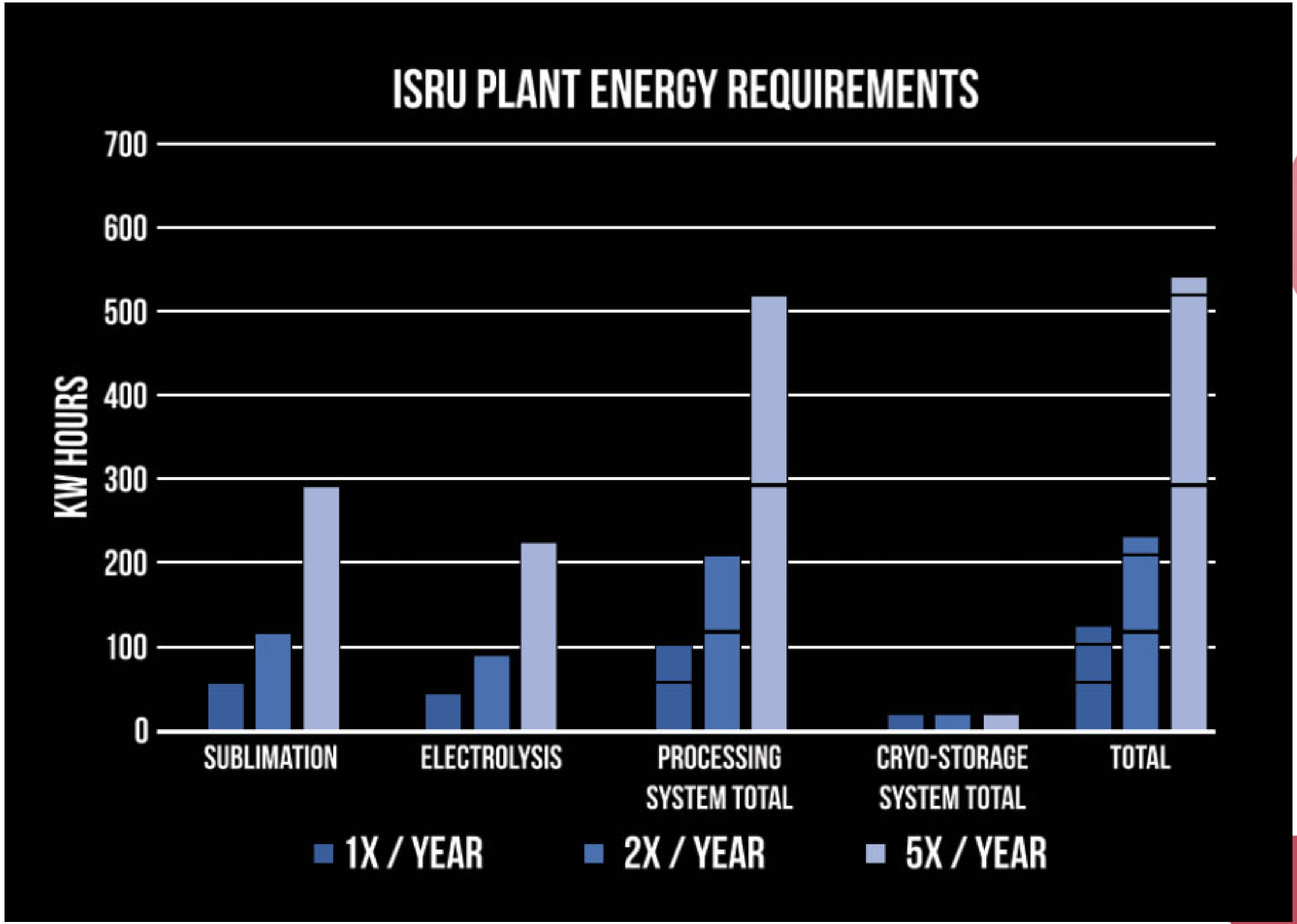
Data Visualization

Total Values:

- 1x/yr. = 126kWh
- 2x/yr. = 230kWh
- 5x/yr. = 543kWh

It is important to note that these are <u>conservative figures</u>.

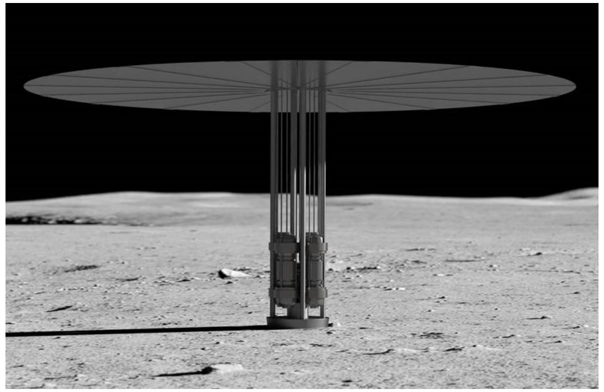
Nuclear fission reactors would be able to redirect their waste heat into the sublimation process, the most energy intensive step, and **reduce the total ΔT** required.



Power Generation Trade Factors

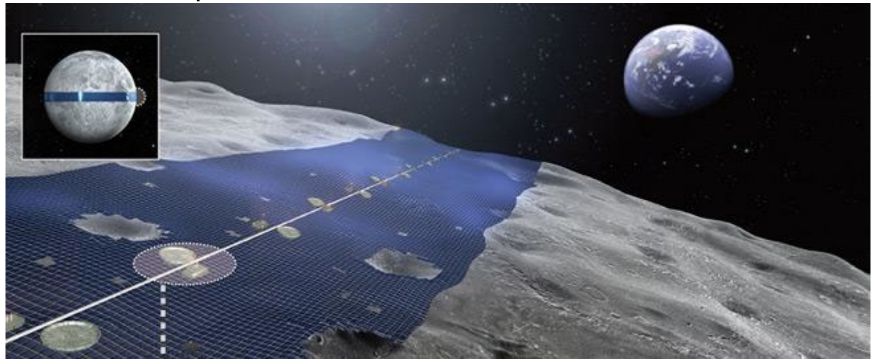
Nuclear Fission

- ✓ Constant & reliable 24hr generation
- ✓ Ancillary benefits of waste heat generation to ease sublimation process
- ✓ >80x more efficient power density (land use)
- ✓ Utility-Scale Power (KRUSTY)
  - Kilopower Reactor Using Stirling Technology
  - KiloPower project led to, a currently under-development, MegaPower project by Los Alamos Labs in conjunction with NASA



Solar (PVAs, Reflectors, Etc.)

- Limited 24hr generation ability
  - Power fluctuations likely
  - On-orbit infrastructure may be required
- Battery backup storage required
  - Additional up-mass
- Inefficient land use
  - Constraints on PVA locations will be set by inclination relative to the sun
  - Surface area that PVA field uses will not be accessible to mine or place other infrastructure



Data Visualization

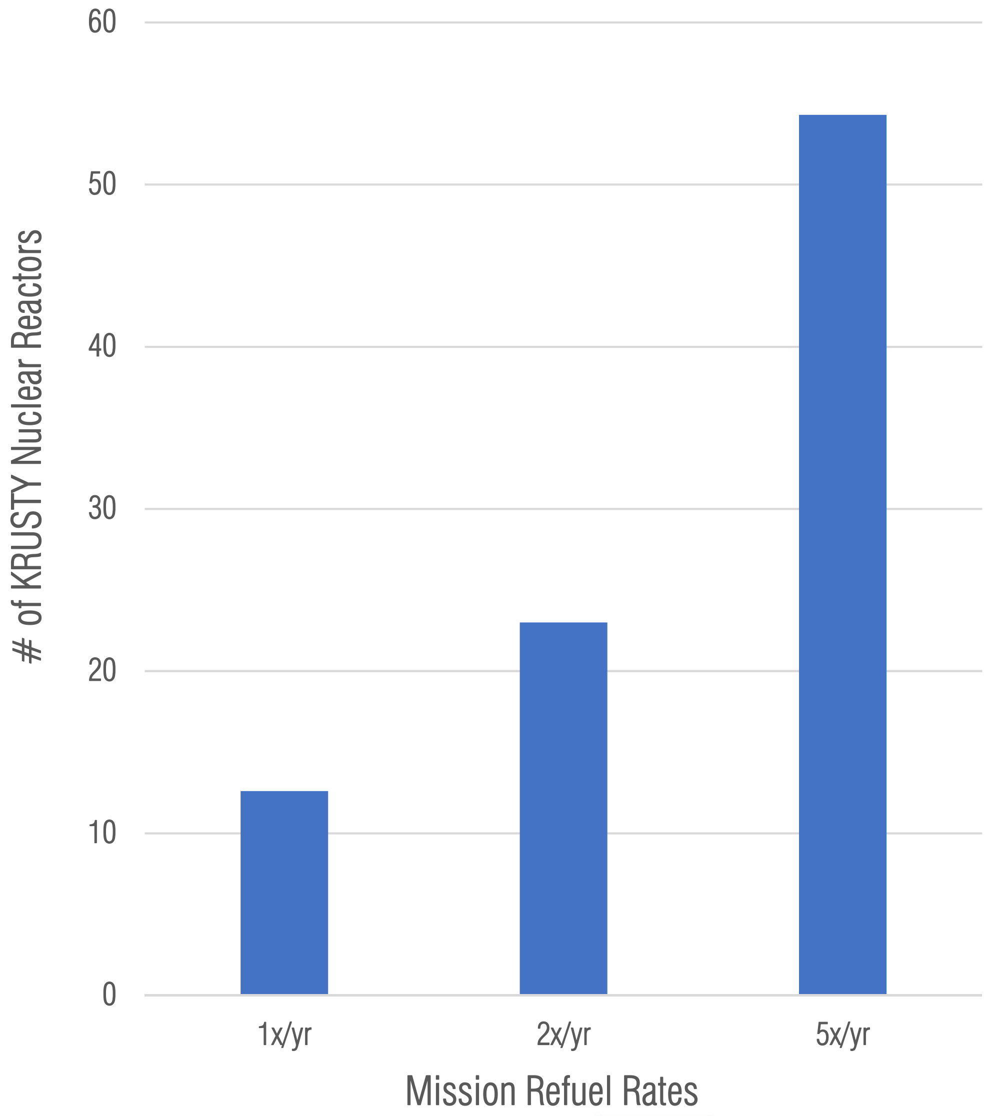
Required Number of Reactors:

- 1x/yr. = 13
- 2x/yr. = 23
- 5x/yr. = 55

# of reactors are <u>over-estimates</u>

- The waste heat from these reactors has not been publicly shared; however, the Stirling engine necessitates the rejection of waste heat, so this is a <u>non-zero figure</u>.

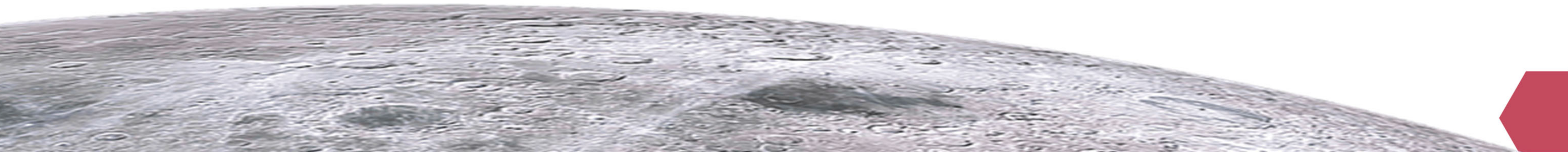
- 2MW reactors may be available in the near future which would bring the reactor number down to one.



Value Proposition

<u>Space Policy Directive 1:</u> Return humans to the Moon, and use it as a test bed for future Mars missions.

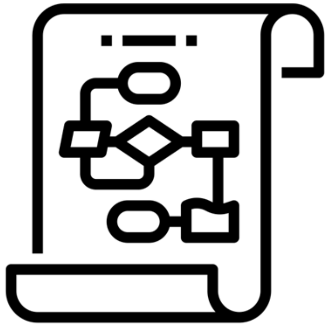
NASA has identified water to be one of the most valuable commodities off-Earth, since it has applications for both human consumption and rocket propellant. This project provides an overview of requirements on a commercial lunar ISRU plant, and a business strategy to become a viable industry, long-term.




Next Steps

Path Forward

- **Design and development** of the **Excavation and Transportation Systems**
    - Incorporate emergent technologies
    - Characterize their power needs
- **Find other revenue sources**
    - Detail how surplus of LOX will be used
    - Specify expected market demand (ACES, Artemis, Gateway, etc.)
- **Develop master plan** of all integrated elements
    - Point A to B, to C… etc.
    - Identify investment costs
    - Determine business case



This research is anticipated to influence students, entrepreneurs, mission planners, and policy makers, by showing viability of off-Earth manufacturing for future space commerce.

UNIVERSITY of HOUSTON
CULLEN COLLEGE of ENGINEERING

SICSA
Sasakawa International Center for Space Architecture

Thank you for listening!

Does anyone have any comments or questions?

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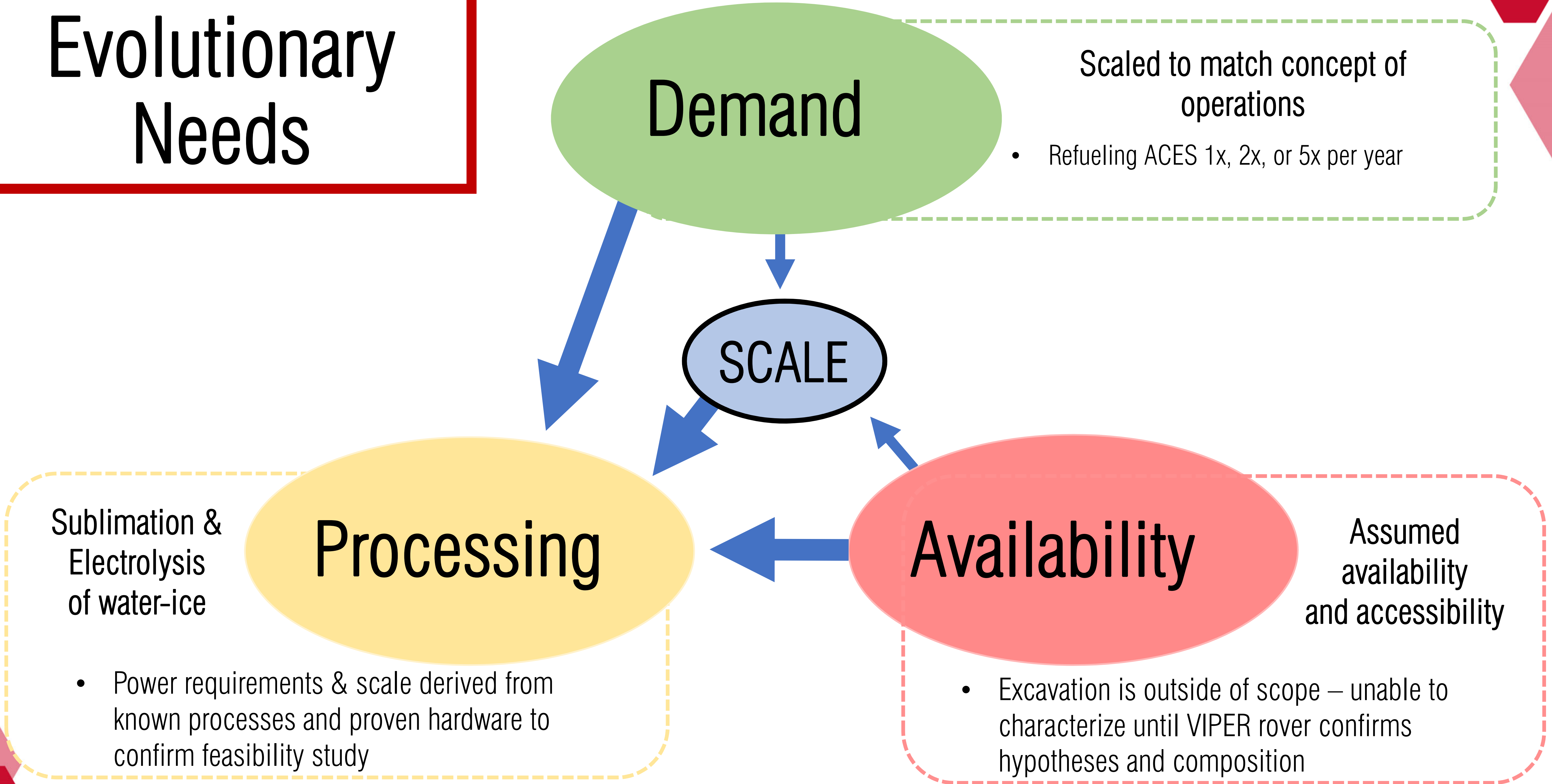
Back-Up Material

Evolutionary Needs



(Initial) Thesis Question

"How would propellant delivered from lunar ISRU compare to SpaceX's baseline Mars Mission Architecture, of Earth to LEO refueling, based on cost and risk?"

At **BEST**, LOX from the moon is ~21% MORE EXPENSIVE than LOX from Earth.

- Launch Cost : ~$20M
- 6 Launches to LEO for Moon Landing
- 150mt / Launch
- Buy/Sell Price: $0.8M/t (= FREE / @ Cost)

1.) $\$20M\,(6) = \$120M$

2.) $\frac{120M}{150mt} = \frac{\$0.8M}{t}$

3.) $\$0.8(150mt) = \$120M$

...

4.) $(940t \times .6) + 150mt = 714mt$

5.) $714mt\,(\$0.8M) = 571.2M$

6.) $\$571.2M + \$120M = \$691.2M$

7.) $\frac{\$691.2M}{714mt} = \$0.97M\ /\mathrm{mt}$

8.) $\boxed{1.21\,(\$0.8M) = \$0.97M}$

ConOps Overview

SpaceX's Baseline DRA

1x: Crewed launch – ***150mt***
5x: Tanker launch, rendezvous, & land

Trans-Mars Injection (TMI)

Gateway Depot

1x: Lunar ISRU Cargo launch – *70mt*
4x: Tanker launch, rendezvous, & land

Trans-Lunar Injection (TLI)
ISRU on Moon for ~2 years (*250mt of LOX/yr*)
1x: Deliver LOX to Gateway in NRHO

1x: Crewed launch – ***150mt***
5x: Tanker launch, rendezvous, & land

LEO to NRHO
Rendezvous/Refuel

Trans-Mars Injection (TMI)

LORD Architecture

1x: Lunar ISRU Cargo launch – *130mt*
5x: Tanker launch, rendezvous, & land

Trans-Lunar Injection (TLI)
ISRU on Moon for ~2 years (*500mt of LOX/yr*)

1x: Moon to LEO parking orbit
1x: Crewed launch to LEO– ***150mt***

Rendezvous/Refuel

Trans-Mars Injection (TMI)

F.O.M. \ DRAs	Baseline	Gateway Depot	LORD
Quantity	∞ | ~$0.15/kg	250mt /yr.	500mt /yr.
Acquisition	+1 Day(s)	~2 Years	~2 Years
ure Development	Status Quo	Adds to Lunar Surface & Gateway Functionality	Critical Infrastructure that brings the Solar System closer to LEO
Risk (LOM or LOC)	Autonomous rendezvous 5x in LEO	~Baseline with added complexity	Higher probability of LOM than LOC
# of Launches	6	≥12	≥ 8
Launch Cost ($M)	~ $131.4	~ $302.22	~ $297.11
Total Score *Lower is better*	11	22	15

1 - Best 2 - Good 3 - Bad 4 - Worst