ISRU Water & Oxygen Extraction: Customer Requirements

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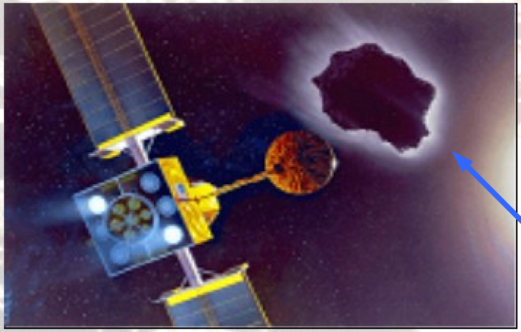
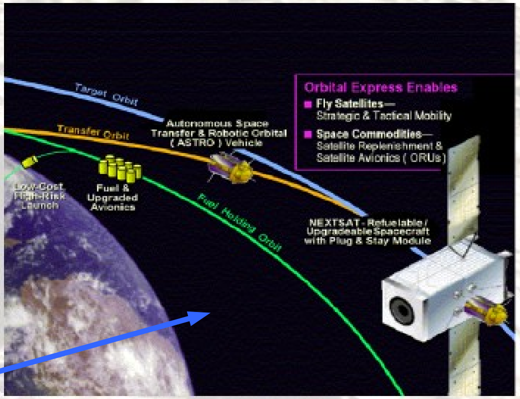
5 June, 2019
Space Solar Power Workshop
International Space Development Conference
Arlington, Virgina

Why do *Customer Requirements* matter?

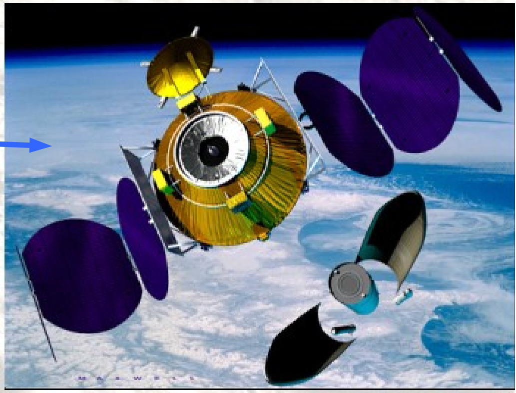
- Space is technology-rich and capital-poor
- The best way to secure commercial investment is to start by *finding a customer*
- Positive ROI (risk-adjusted) for a business case will attract *non-traditional capital*, expanding the size of the space industry

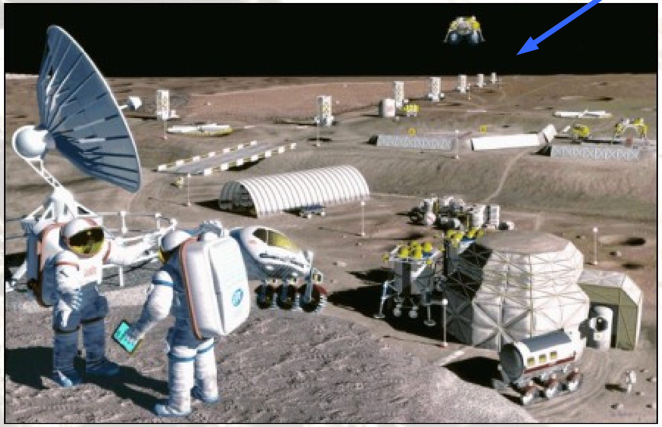
Markets for Lunar Propellant

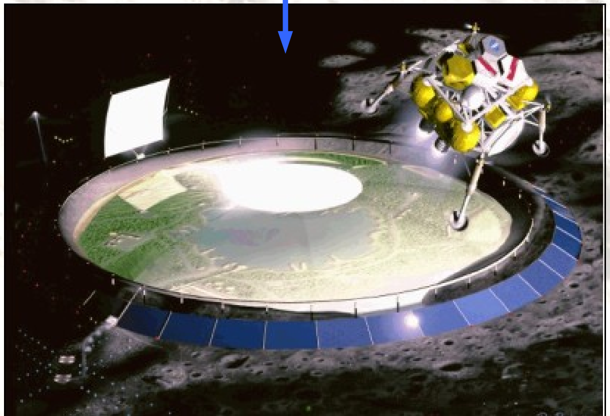


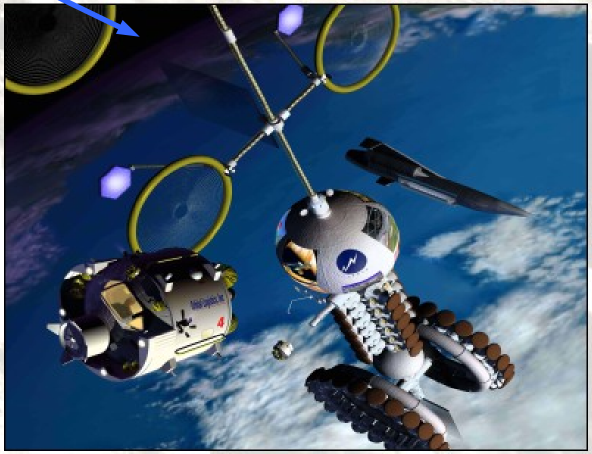


NASA-Science
Military Missions
Debris Management
Satellite Servicing & Refueling
International Space Station
Human Exploration
Space Solar Power
Self-Sustaining Colonies









ISRU Customer: L1 Gateway Circa 2001

propellant, shielding, life support

ISRU Customer: Lunar Base Circa 2019

construction materials, shielding, life support, consumables, agriculture

Image courtesy of SKIDMORE, OWINGS & MERRILL LLP

Financing ISRU infrastructure: Options

- The Government Approach
  - Ask NASA for funding
- The Commercial Approach
  - Start with a customer (LEO-GEO satellite transfer)
  - Engineer and cost a solution
  - Write a business plan
  - Find (equity) investors or talk to the bank (debt)
  - Scale infrastructure to meet demand
  - Generate operating profit

LEO-GEO Propellant Transfer

- ULA announced interest in purchasing propellant in space
- Refueling spacecraft and rocket stages could have **high value to multiple USG customers**

Commercial Lunar Propellant Architecture

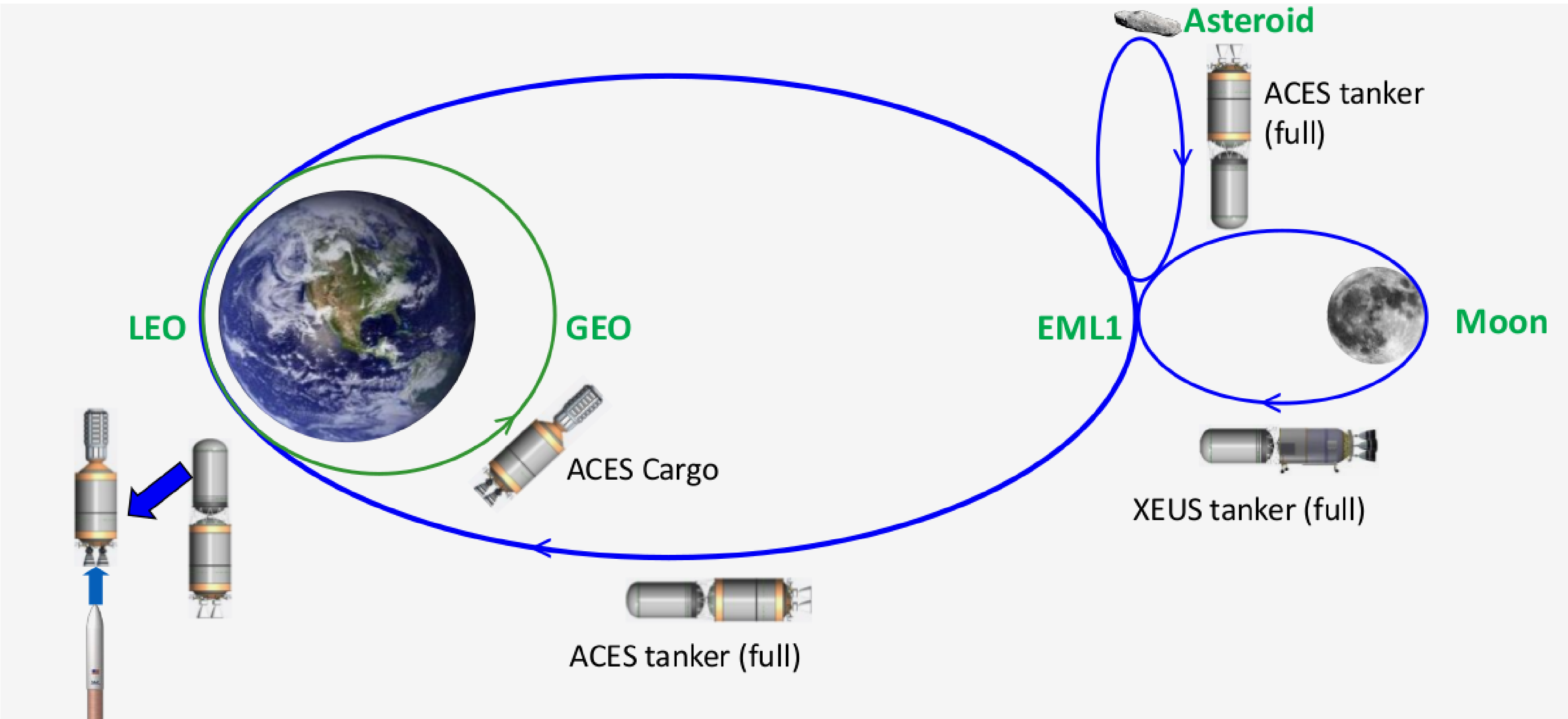
A Collaborative Study of Lunar Propellant Production

http://cislunar.nss.org/wordpress/wp-content/uploads/2018/11/Commercial-Lunar-Propellant-Architecture.pdf

CSM-ULA Lunar Mining Architecture

- In the fall of 2017, ULA engaged the Center for Space Resources at Colorado School of Mines to examine Lunar Mining Architectures
- Architectural Details
  - Three options were evaluated from a technical tradeoff perspective - a single integrated design was selected from the three options
  - The following slides describe the operational and technical assumptions for that baseline design

ULA: Transportation Systems



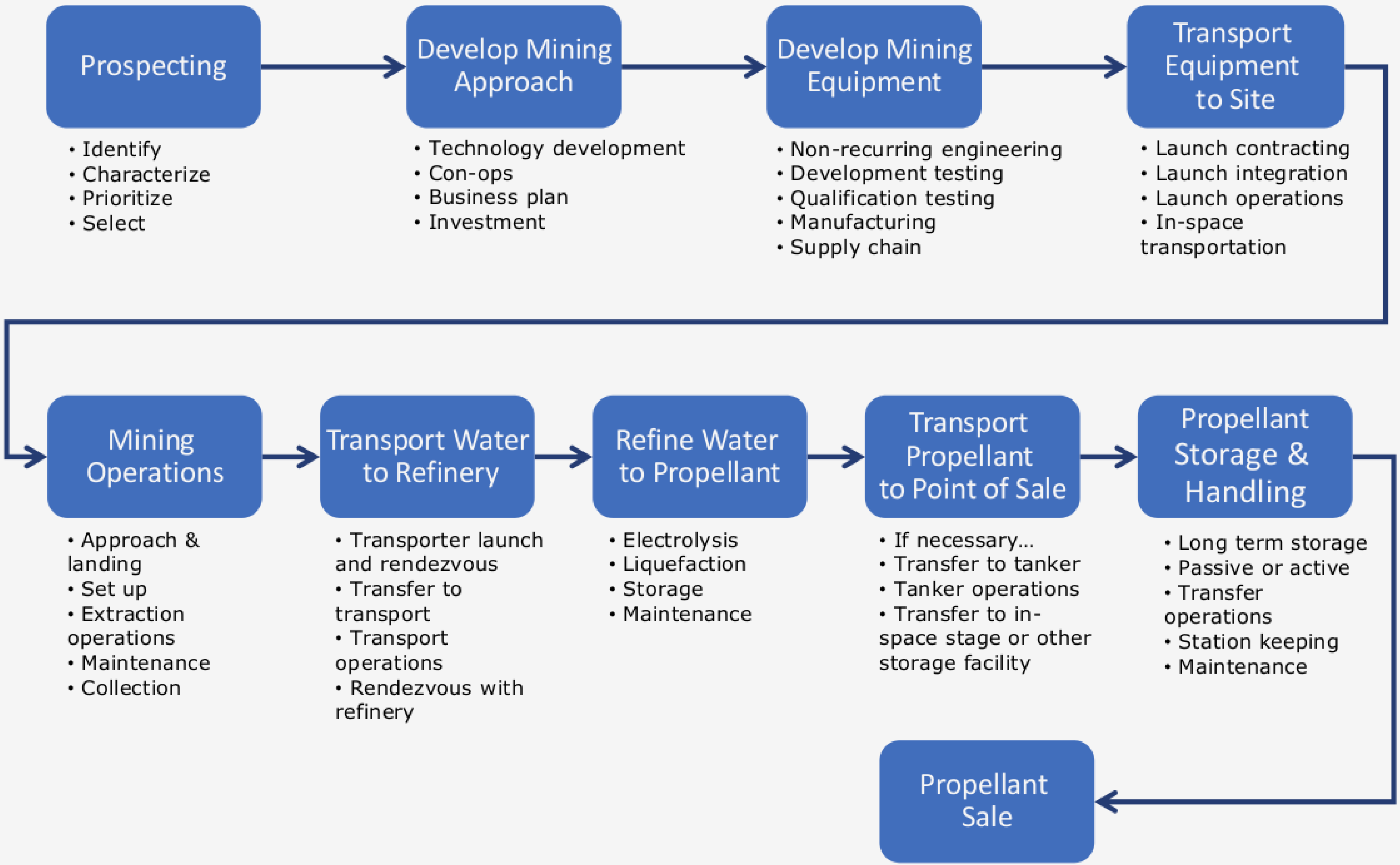
Payload Launch to LEO

Cargo Flow
1. Launch to LEO
2. Refuel Cargo ACES
3. Transport to GEO
4. Deploy cargo

Propellant Flow
1. Mined on moon/asteroid
2. XEUS/ACES transport to EML1
3. Transfer to ACES
4. ACES transport to LEO
5. Transfer to cargo ACES

Graphics courtesy ULA

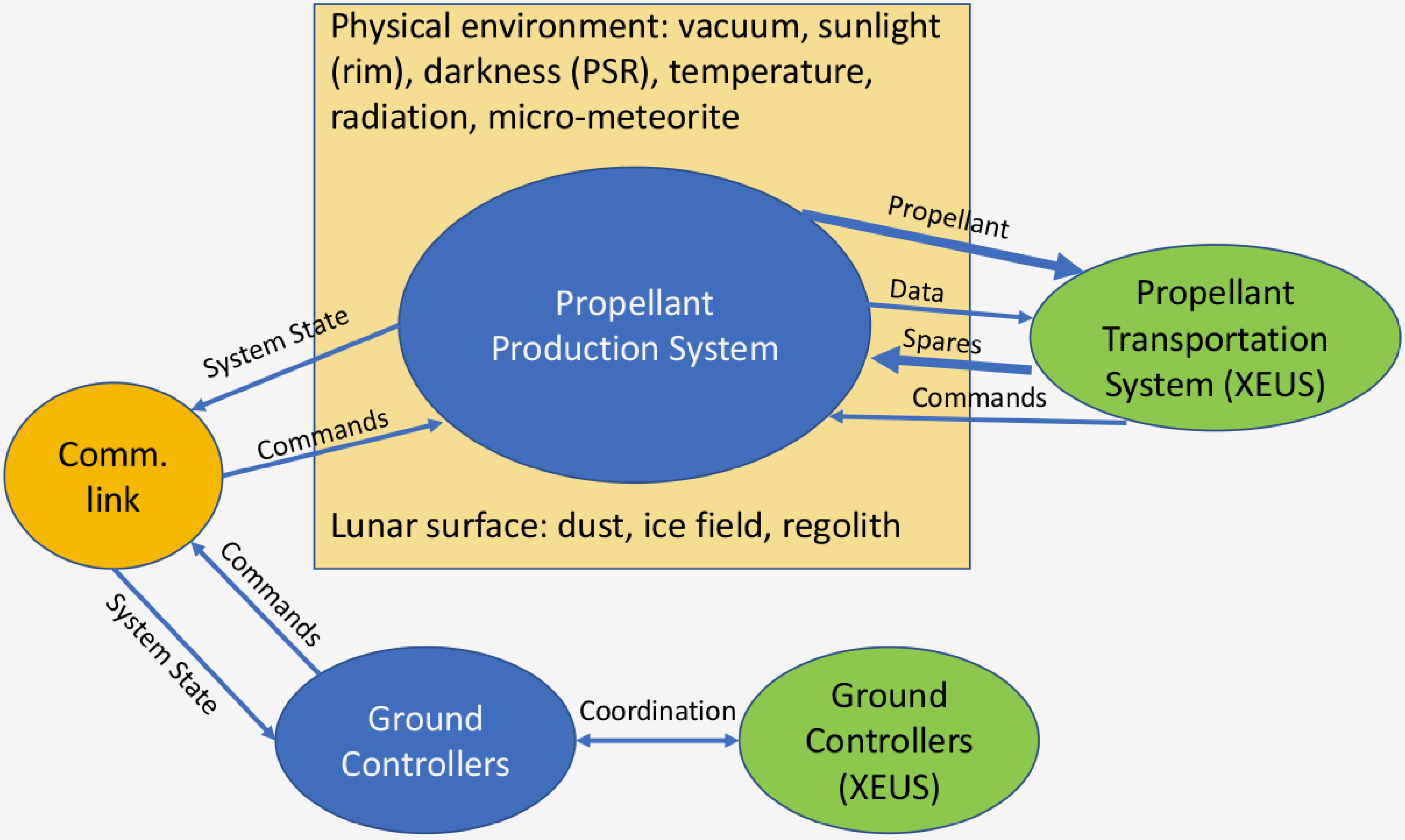
Design Options and ConOps



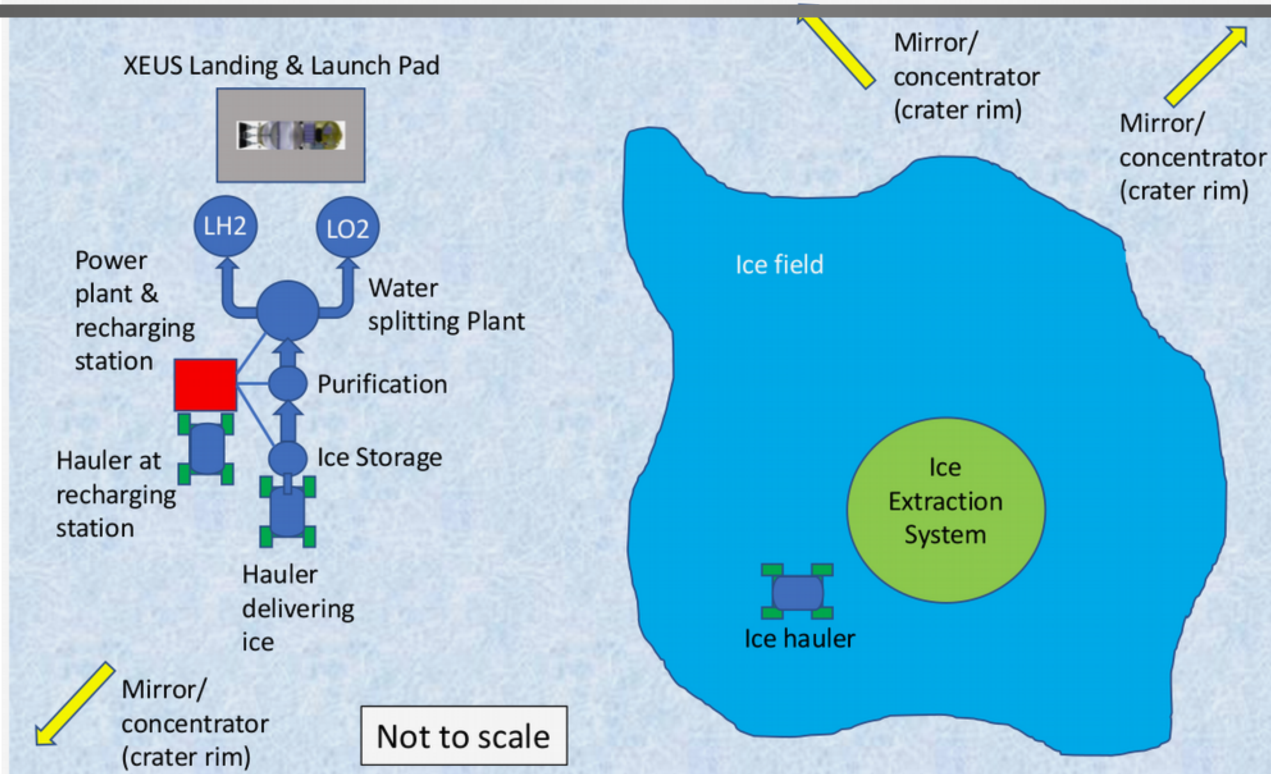
Siting Assumptions

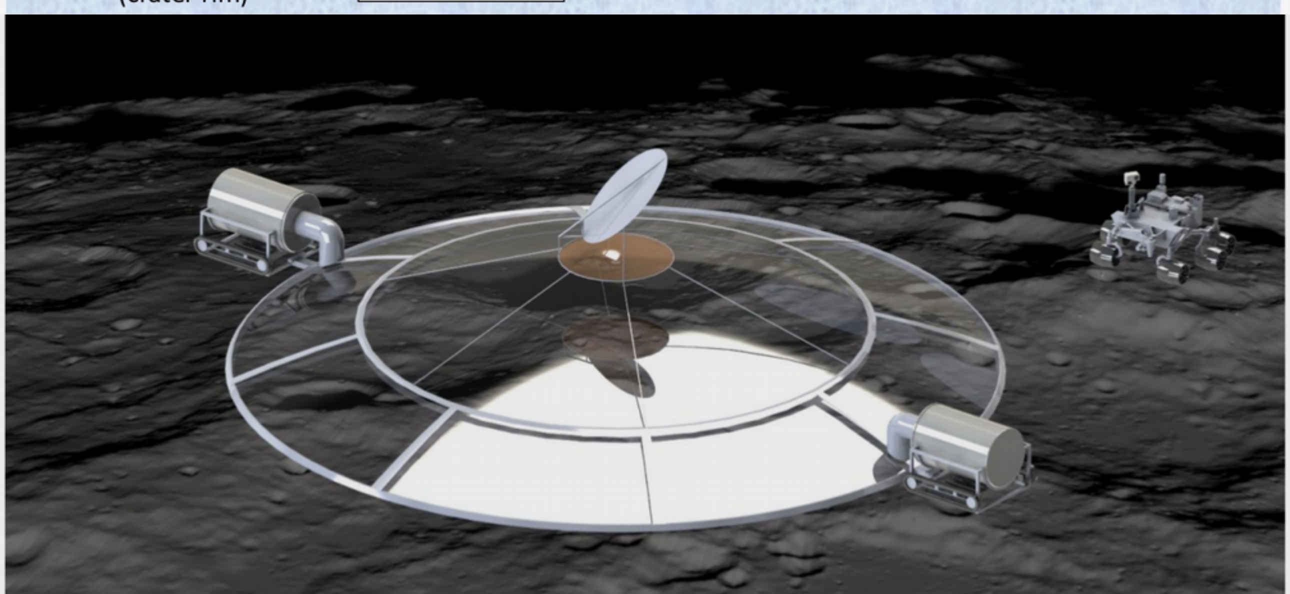
- The PSR will be selected based on the following:
  - Richness of ice field, particularly within the first meter
  - Proximity to nearly permanently lit regions (around crater rim)
- Three locations for the mirror systems chosen based on lighting studies
  - Provide continuous reflected light coverage of the ice field and launch pad/processing area
- The XEUS launch pad and propellant processing and storage area located:
  - Near the ice field to reduce transportation time
  - In a flat, stable, ice-free area to allow XEUS landing and launch

Systems Interfaces



Lunar Surface Architecture

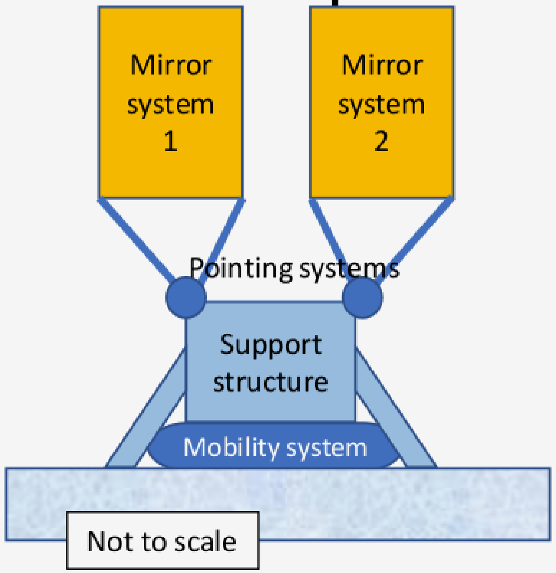


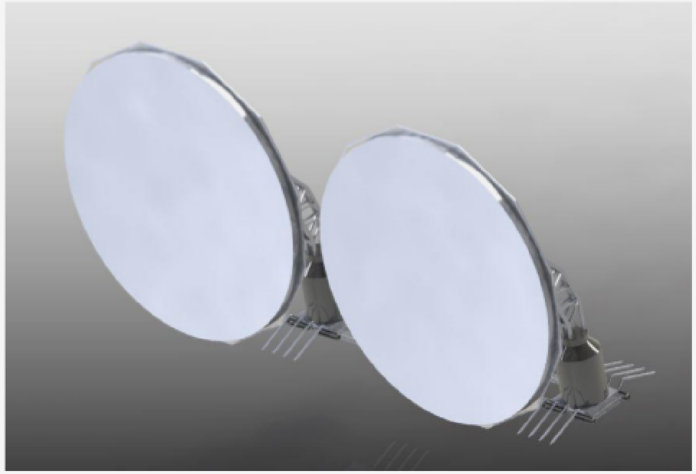


Design Elements

Solar Energy System Concept

- Large mirror array at crater rim in nearly permanently sunlit location
  - Three locations for continuous coverage and some redundancy
  - Exact locations will be determined by ice field geography and lighting studies
- Two mirror assemblies at each location to point at the power station at the refining location and the ice field
- Separately pointable
- Curved to optimally concentrate light at each location
- Mounted to mobility system for initial positioning (setup only)
- Stabilizing feet once positioned
- Mass = 1500 kg + mirrors (option dependent)
- Mirror 1 area: 6000 m2
- Mirror 2 area: 500-4000 m2

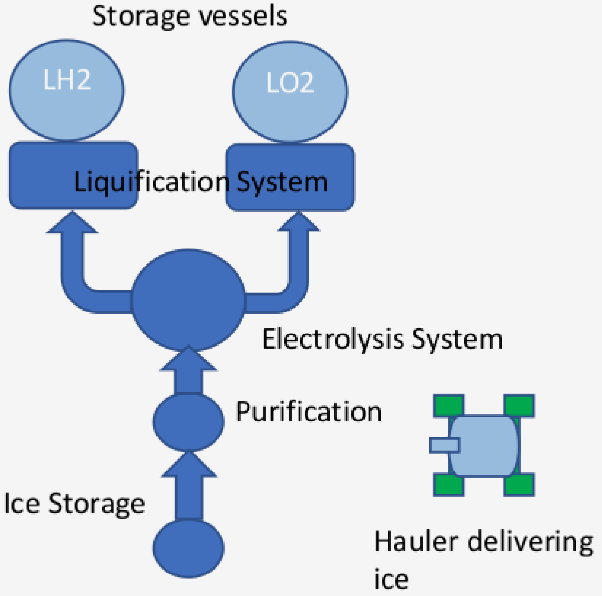


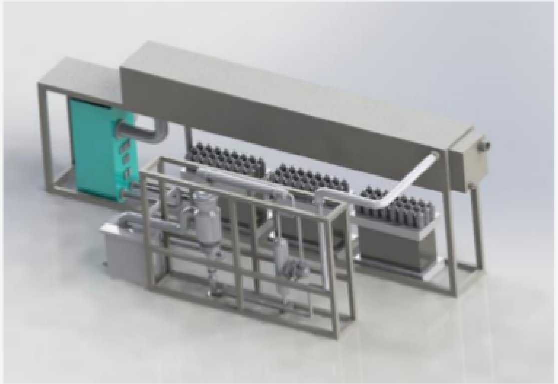


Design Elements

Propellant Processing Concept

- Ice storage vessel receives ice from ice hauler
  - 1000 liter
- Filtration system for purification
- Electrolysis system for splitting
- Liquification system feeds storage vessels
- Mass = 3000 kg ice storage, purification & electrolysis
- Mass = 3000 kg Liquification (physically included with XEUS storage vessels)





Design Elements

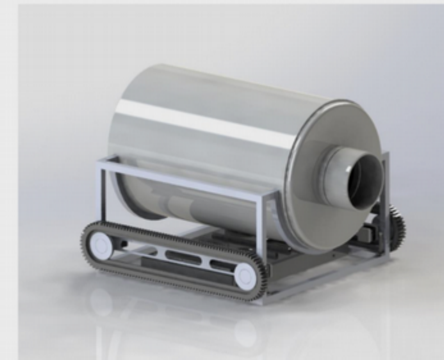
Mobility Systems Concept

- Ice haulers
  - Assume three
  - Deliver ice captured in a cold trap to the processing system
  - Payload mass ≤ 1000 kg (ice plus cold trap tank)
  - Battery powered
  - Steerable
  - Height adjustment
  - Headlights, camera
  - RF receiver
  - Mass = 500 kg
- General purpose vehicle
  - Assume one
  - Same features as ice haulers
  - Robotic manipulator arms for maintenance, set-up and other functions unique to the extraction option
  - Mass = 1000 kg

Ice hauler (w/o cold trap)

Cold Traps

- Function
  - Freeze and contain sublimated water vapor
  - Transport (with mobility system) ice to processing facility
- Concept
  - Three (to match number of ice haulers & allow parallel operations)
  - Aluminum cylindrical tank with hemispherical or elliptical domes
  - 3 m X 1.5 m
  - 300 kg
  - Holds 500 kg ice in the form of frost/snow
  - 1.1 m diameter pipe to connect to capture device and processing plant
    - Non-sealing closure



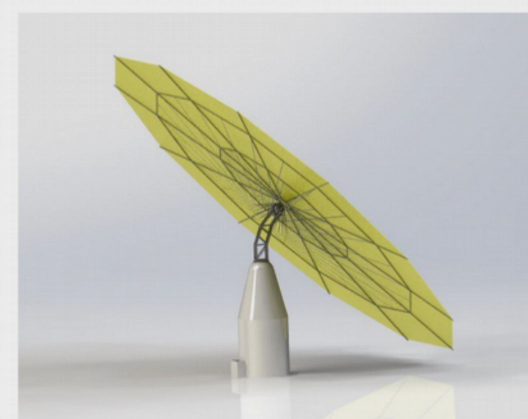
Ice hauler (with cold trap)

Propellant Storage Concept

- Storage system
  - Spent XEUS stages
  - Assume three (provides volume to fuel XEUS and tanker with 50% margin)
- Liquification, conditioning and transfer equipment kitted prior to XEUS launch
- Mass = 1000 kg per XEUS, 3000 kg total (accounted for under propellant processing)

Power System Concept

- PV array
  - Size determined by focusing ability of rim mirror/concentrator
  - Pointable
  - 1.5 Mw power output
- Power conditioning & storage system
- Charging station for mobility systems
- Mass = 4000 kg



ISRU Plant Cost Model Assumptions

- More assumptions:
  - 10 year life of mining/production facility
  - 10% return on sales (ROS)
  - $50k/kg cost of equipment on Earth
  - $35k/kg cost to transport to lunar surface (Vulcan/XEUS)
  - $3k/kg-yr cost to operate plant
- More derived requirements:

Plant mass	40.5 mT	Affordability limit
Plant efficiency	25.5 kg/yr /kg	Annual propellant output per kg of plant HW
Plant development cost	$2.02B	$50,000/kg
Plant delivery cost	$1.47B	$35,000/kg
Total non-recurring cost	$3.49B	Development + delivery

The High Cost of Reliability

- Space industry reliability is expensive
  - Design hardware for maximum service-free lifetime
- Mining industry “wear parts” demonstrate an inverse approach
  - Estimate when they will break and bring N extras
  - Design for maintenance
- Production and Ops Costs for commercial lunar infrastructure could be *dramatically lower* than NASA expectations
- Early architectural choices have significant downstream cost impacts

Comparative Industry Costs

Comparative Costs per Kilogram for Manufactured Systems			
Spacecraft	dry mass (t)	cost $M	**$k/kg**
MSL Rover (Curiosity)	3.8	2500	**658**
GOES-16 weather satellite	5.2	2750	**529**
Telstar 19V	3.0	100	**33.0**
Aircraft			
F-22 Raptor	19.7	339	**17.2**
B-2 Stealth Bomber	71.7	1152	**16.1**
F-18E	13.4	120	**8.9**
F-35A	13.2	94.6	**7.2**
F-15E	20.4	136	**6.7**
Navy Ship (nuclear powered)			
Virginia Class Submarine	7900	3200	**0.41**
Ford-class Aircraft Carrier	100000	13000	**0.13**
Mining Equipment			
Rear Dump Truck (55t)	41.2	0.938	**0.023**
Wheel Loader (7 cu m)	50	0.912	**0.018**
Hydraulic Shovel (4 cu m)	60	1.025	**0.017**
Drill Ship			
GustoMSC PRD12,000 Drillship	45000	710	**0.016**