RLSO 2

Robotic Lunar Surface Operations 2 Study Overview

Presenter: Alex Austin

Jet Propulsion Laboratory
California Institute of Technology

RLSO 2 Study Participants:

JPL
Alex Austin
John Elliott
Scott Howe
Raul Polit Casillas
Miles Smith
Gerald Voecks
Mar Vaquero
Brent Sherwood
Aaron Parness

NASA Ames
Tony Colaprete
Terry Fong

University of Central Florida
Phil Metzger

Honeybee Robotics
Kris Zacny
Vincent Vendiola

Ceres Robotics
Mike Sims

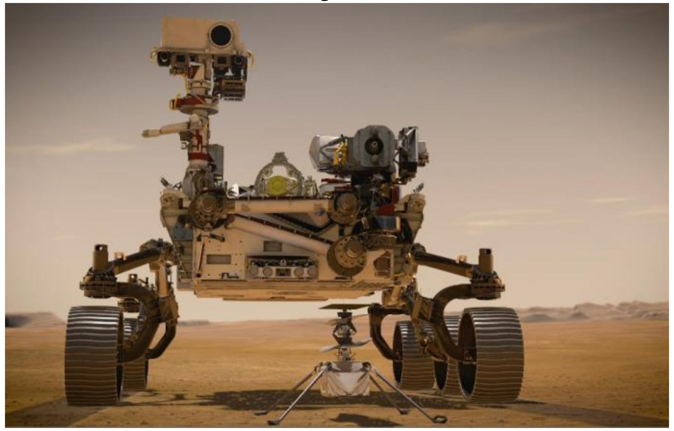
Astronaut Consultants
Harrison Schmitt
Sandra Magnus

JPL Introduction

Earth Science

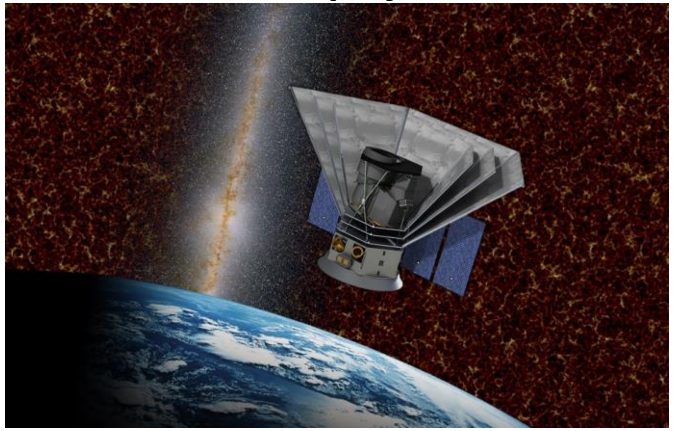
NASA-ISRO Synthetic Aperture Radar (NISAR)

Planetary Science



Mars Perseverance Rover and Ingenuity Helicopter

Astrophysics



Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx)

Jet Propulsion Laboratory
California Institute of Technology

About Me – Alex Austin

- Worked at JPL for 5 years
- Bachelors and Masters degrees in Aerospace Engineering from Rensselaer Polytechnic Institute
- Originally from Rochester, New York
- Lead Engineer for Team Xc, JPL's SmallSat and CubeSat engineering team
- Lead of the Robotic Lunar Surface Operations 2 Study
- Hobbies: Skiing, hiking, cooking, playing with my cat

Aerospace Architecture, Construction and Engineering – Key Considerations

- **Aerospace systems are extremely mass and volume constrained** – they must be launched on a rocket from Earth and transported to the Moon's surface!
- **Aerospace systems must be extremely reliable** – there is no easily accessible garage to fix them!
- **Aerospace systems must perform the greatest number of functions possible** – we don't have the luxury of sending a lot different systems!
- **Aerospace systems must bring everything that they need with them** – there are no gas stations or grocery stores!
- **Aerospace Systems have to deal with crazy environments** – there is no air and the temperatures vary from -300°F to 225 °F!

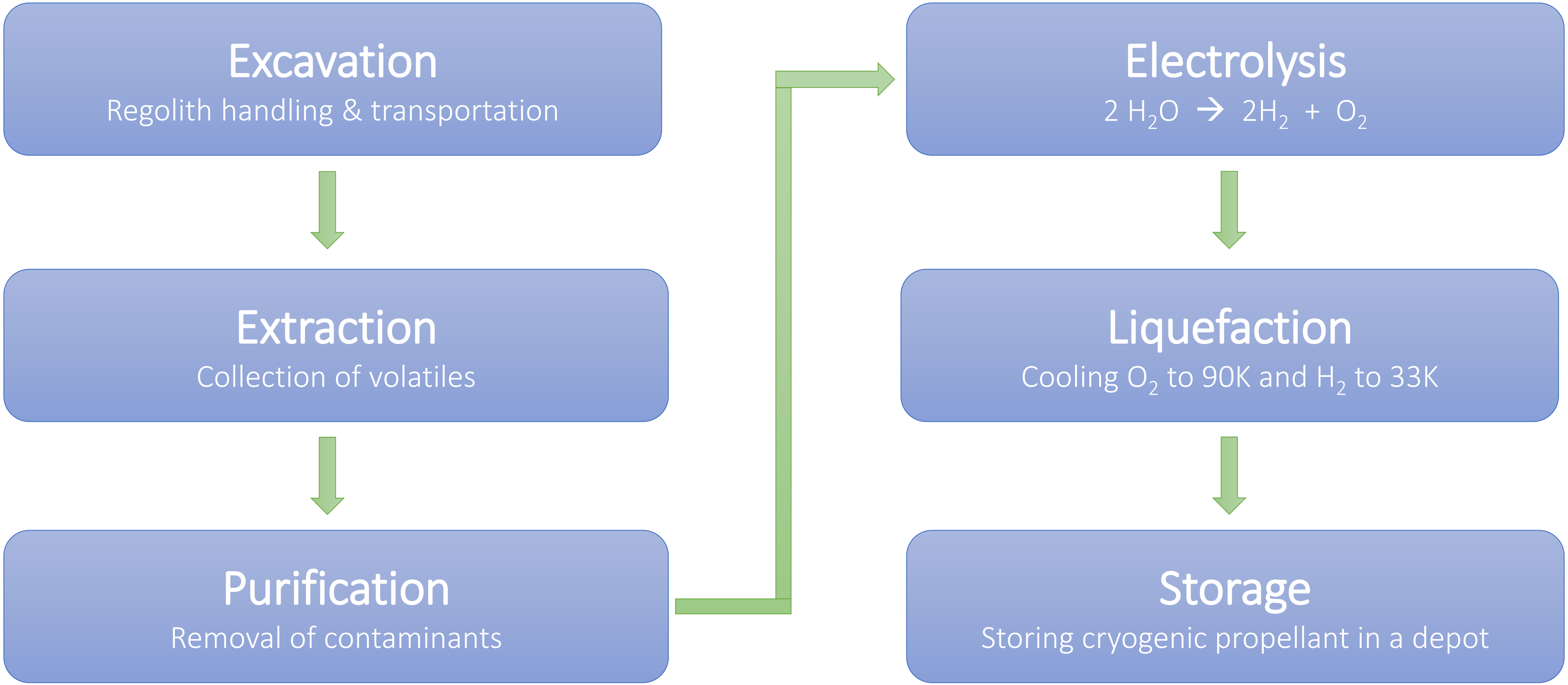
Goals and Assumptions of RLSO2 Study

Overarching goal: Build an understanding of the architecture of a sustainable lunar base with ISRU for the production of propellant, as well as compare potential different architecture options.

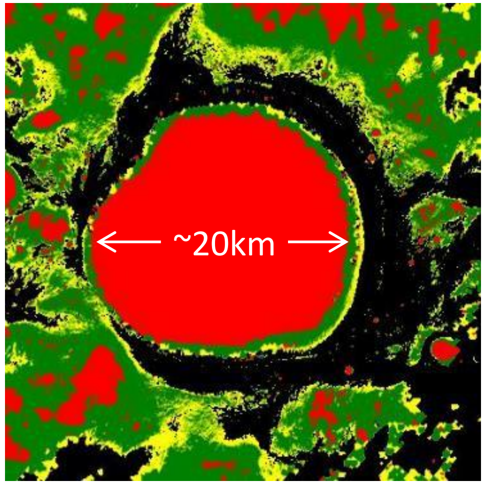
Initial assumptions:

- South Pole location, with ISRU based on the collection of water ice
- Support a crew of four for at least 30-day stays, four times per year
- Lunar Gateway is used as staging point in orbit for base construction and operations
- Focus first on establishing ISRU capability, followed by science and exploration activities

How to go from lunar regolith to rocket propellant…



Lunar Polar Ice Resources



- Type 1
- Type 2
- Type 3
- Type 4

- Bin by water-stability depth into four terrain types
- Map areas that have 20-m DEM and high-res thermal models
- Illustrated: Hermite-A crater, lunar north pole

	Water concentration (wt%)	Depth beneath the surface (cm)	Water-containing column (cm)	Total water excavated (kg/m^3)	Extraction area for 10 t of water (m^2), @30% patchy
Type 1a PSR regolith	2	20-100	80	7.2	1,400
Type 1b PSR surface frost	100	0 - 0.002	0.002	0.006	> 1.5M
Type 2 PLR buried regolith	1	40-100	60	2.7	3,700
Type 3 PLR deeper regolith	0.5	60-100	40	0.9	12,000
Type 4 Lunation-lit regolith	0	--	0	0	n/a

Most of the water-ice exists at the poles of the Moon

But the highest resource concentration is in permanent darkness!

Major Elements of an ISRU Lunar Base

Energy System – >500 kW capacity, near-100% duty cycle, modular units landed intact, then connected via cables or laser

Habitat System – 30-day visits: hab, logistics, workshop, EVA, regolith-shield superstructure

Construction & Maintenance Robots – Mobile robots for site preparation, base construction, and maintenance

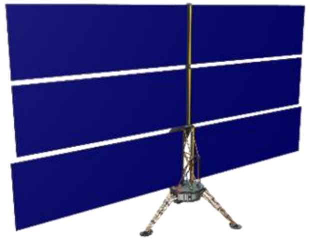
ISRU Mining System – Mobile robots that reach, excavate, beneficiate, and transport lunar regolith (or extract resource onboard and transport it)

ISRU Extraction System – Processor that separates frozen volatiles from lunar regolith

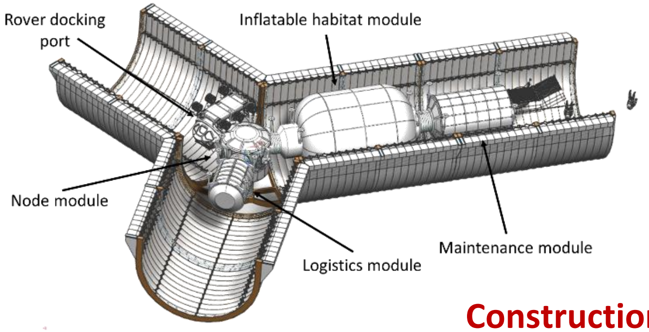
ISRU Volatiles Processing System – Plant that separates water from other volatiles, and cracks it into H_2 and O_2

ISRU Depot System – Plant that liquefies, cryogenically stores, and distributes cryogenic propellant to reusable landers

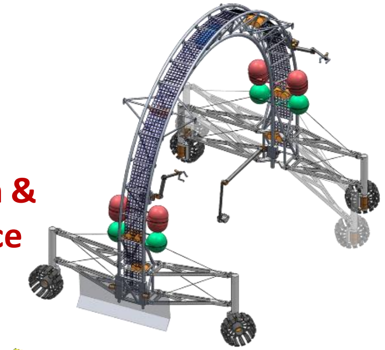
Lander System – Reusable, refuelable lander, reusable landing pad, and ground support systems



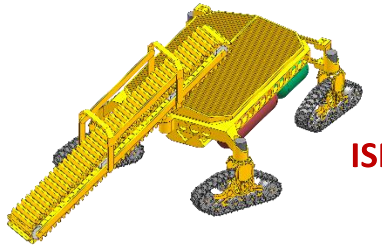
Energy System



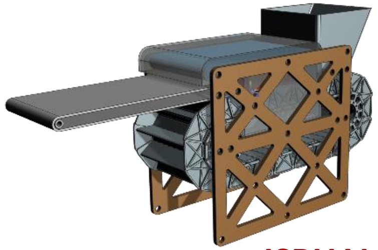
Habitat System



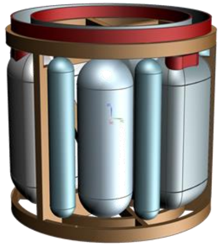
Construction & Maintenance Robots



ISRU Mining System

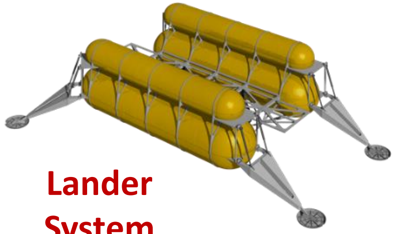


ISRU Volatile Extraction System



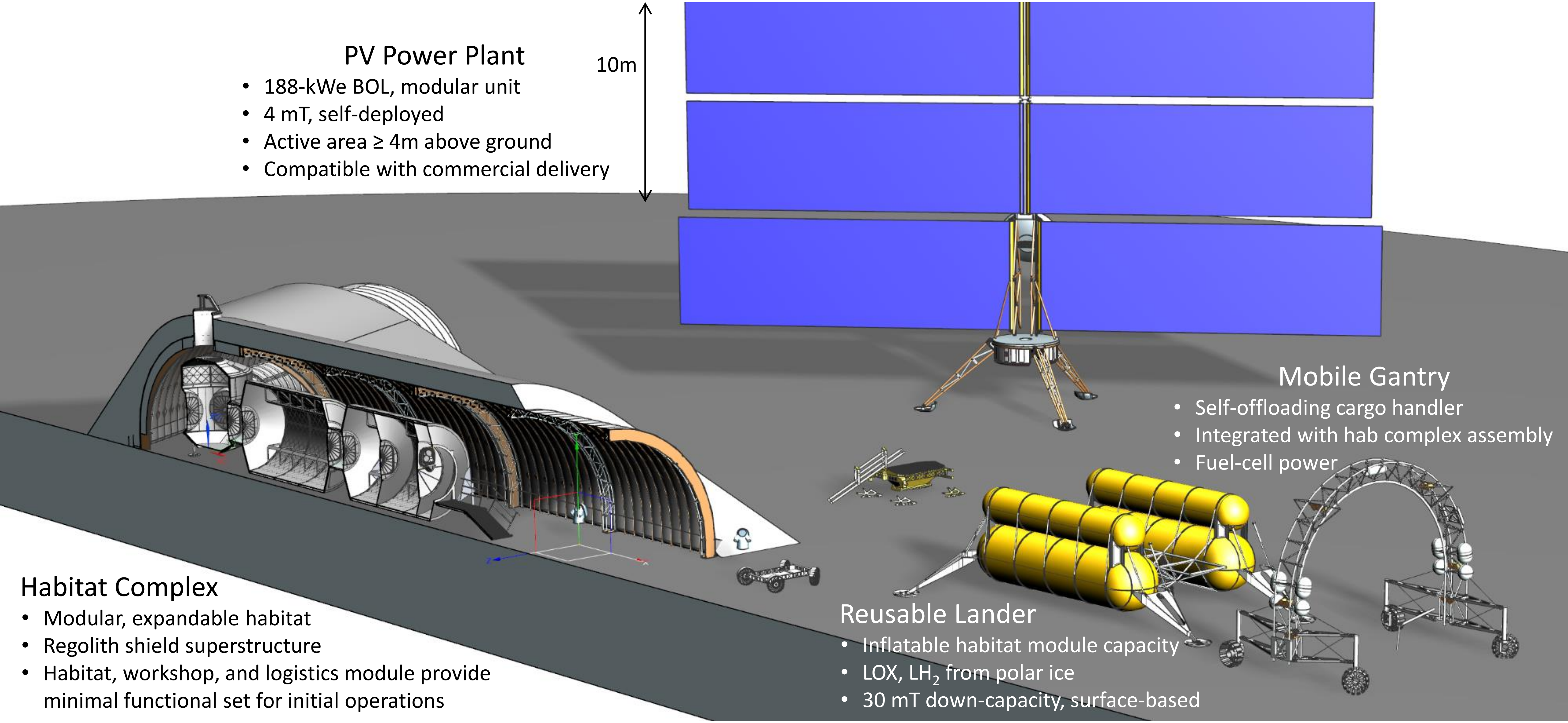
ISRU Processing System

Propellant Storage Depot



Lander System

Lunar Base Element Designs to Scale



PV Power Plant

- 188-kWe BOL, modular unit
- 4 mT, self-deployed
- Active area ≥ 4m above ground
- Compatible with commercial delivery

Mobile Gantry

- Self-offloading cargo handler
- Integrated with hab complex assembly
- Fuel-cell power

Habitat Complex

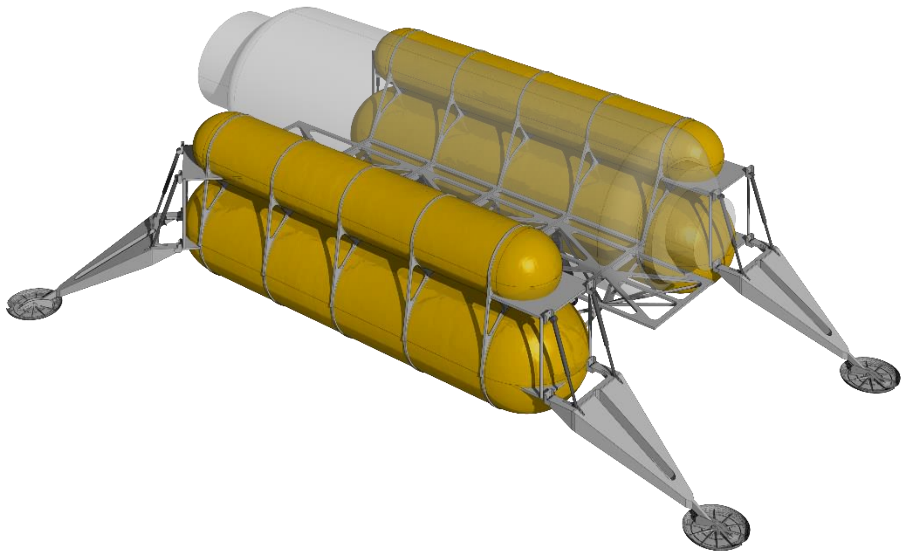
- Modular, expandable habitat
- Regolith shield superstructure
- Habitat, workshop, and logistics module provide minimal functional set for initial operations

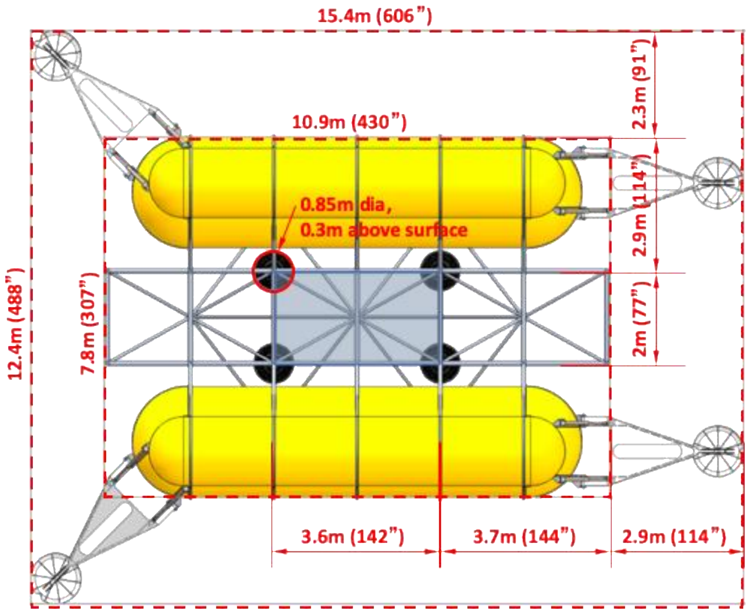
Reusable Lander

- Inflatable habitat module capacity
- LOX, LH_2 from polar ice
- 30 mT down-capacity, surface-based

Reusable Lander

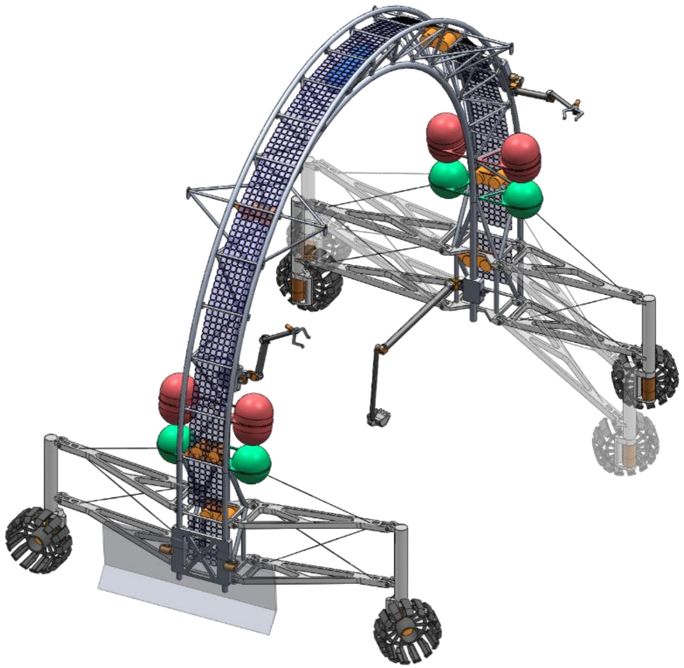
- Sized to carry 30 metric ton payload from Gateway to surface and then return empty to Gateway
- LOX/LH2 propulsion system with zero-boiloff cryocoolers
- Single-stage vehicle for maximum reusability
- Side slung tanks allow payload to be carried close to the ground, making offloading easier

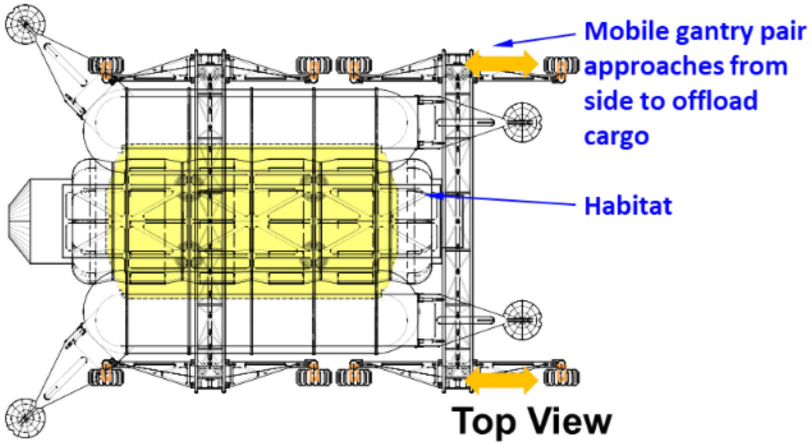


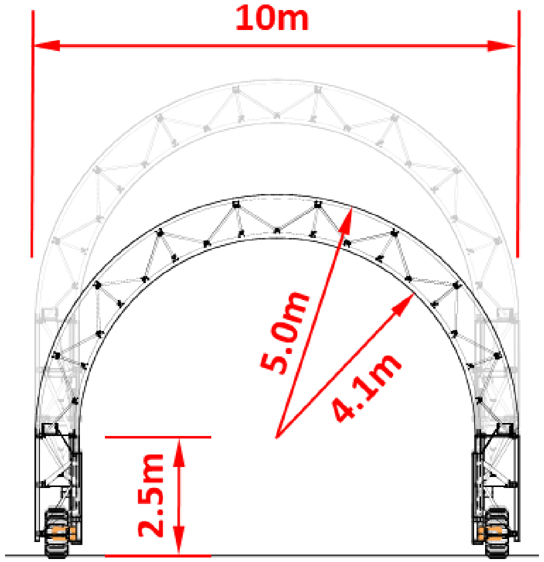


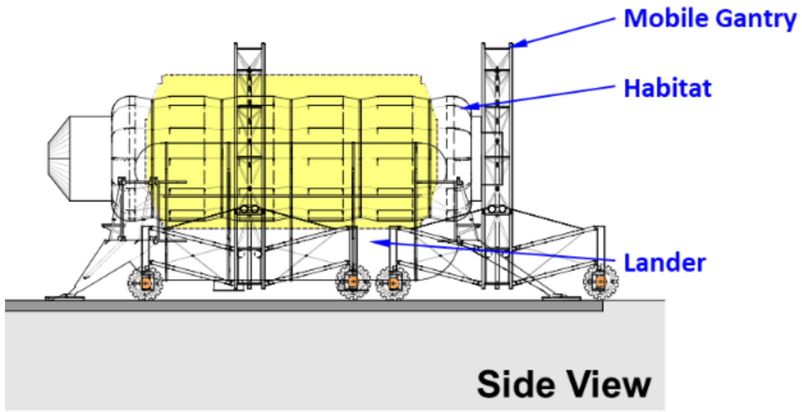
Mobile Gantry

- Mobile Gantry element is multifunctional to support site preparation, base construction, and maintenance tasks
- Many interchangeable tools (winches, scoops, robotic arms, etc.)
- Fuel cell powered with solar array backup
- Two units can be used together to offload heavy payloads from the lander



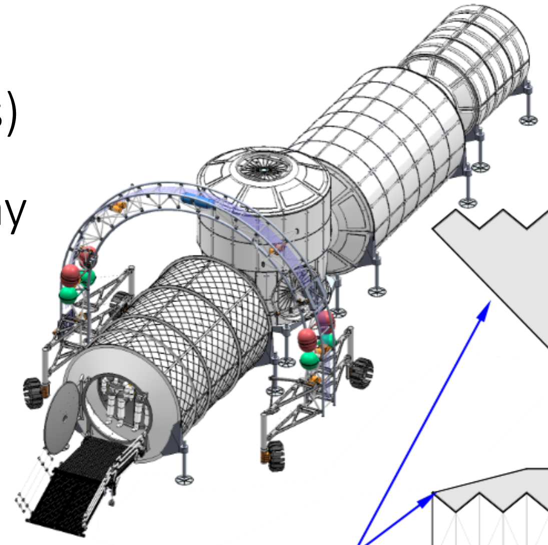


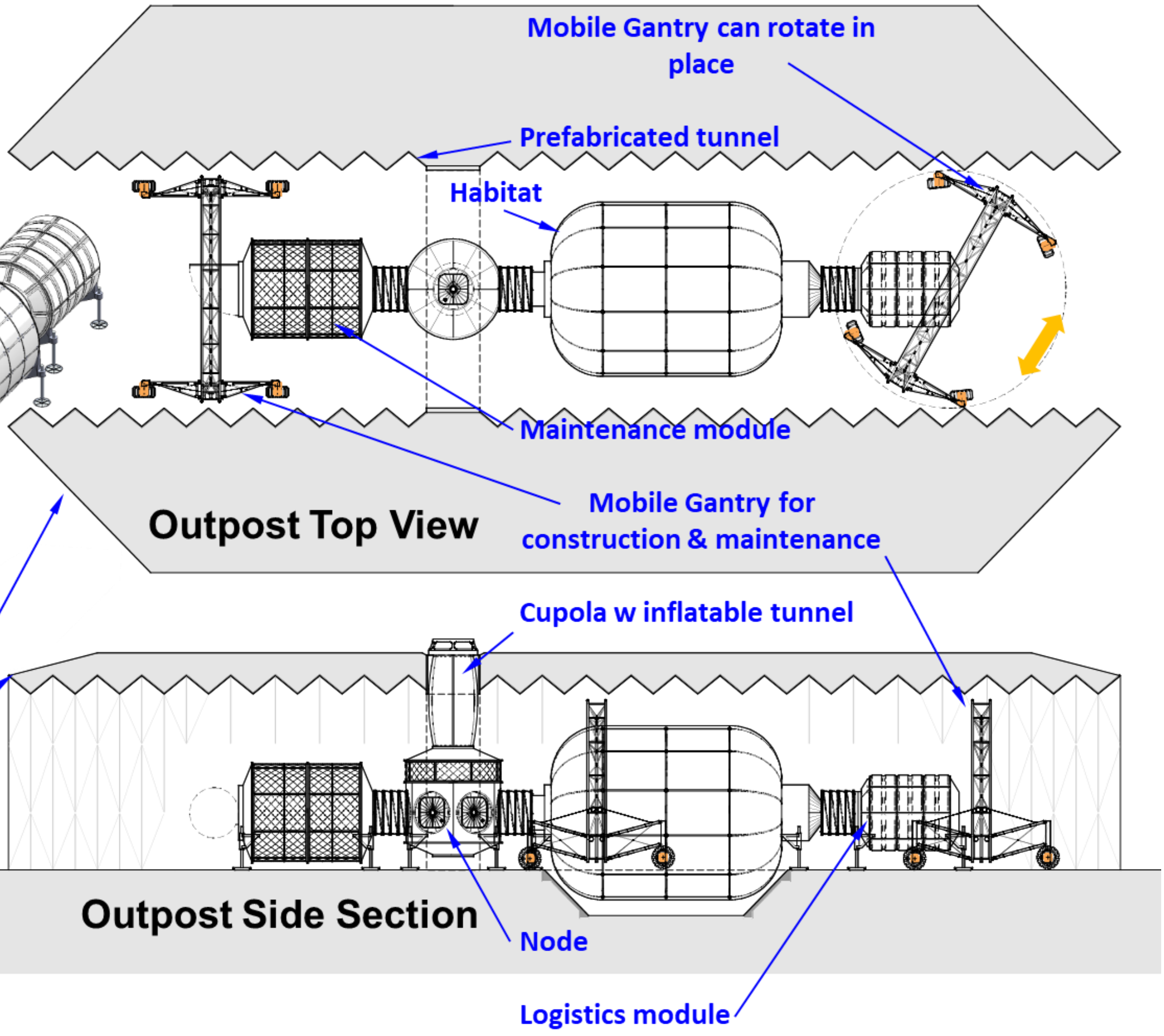




Habitat Complex

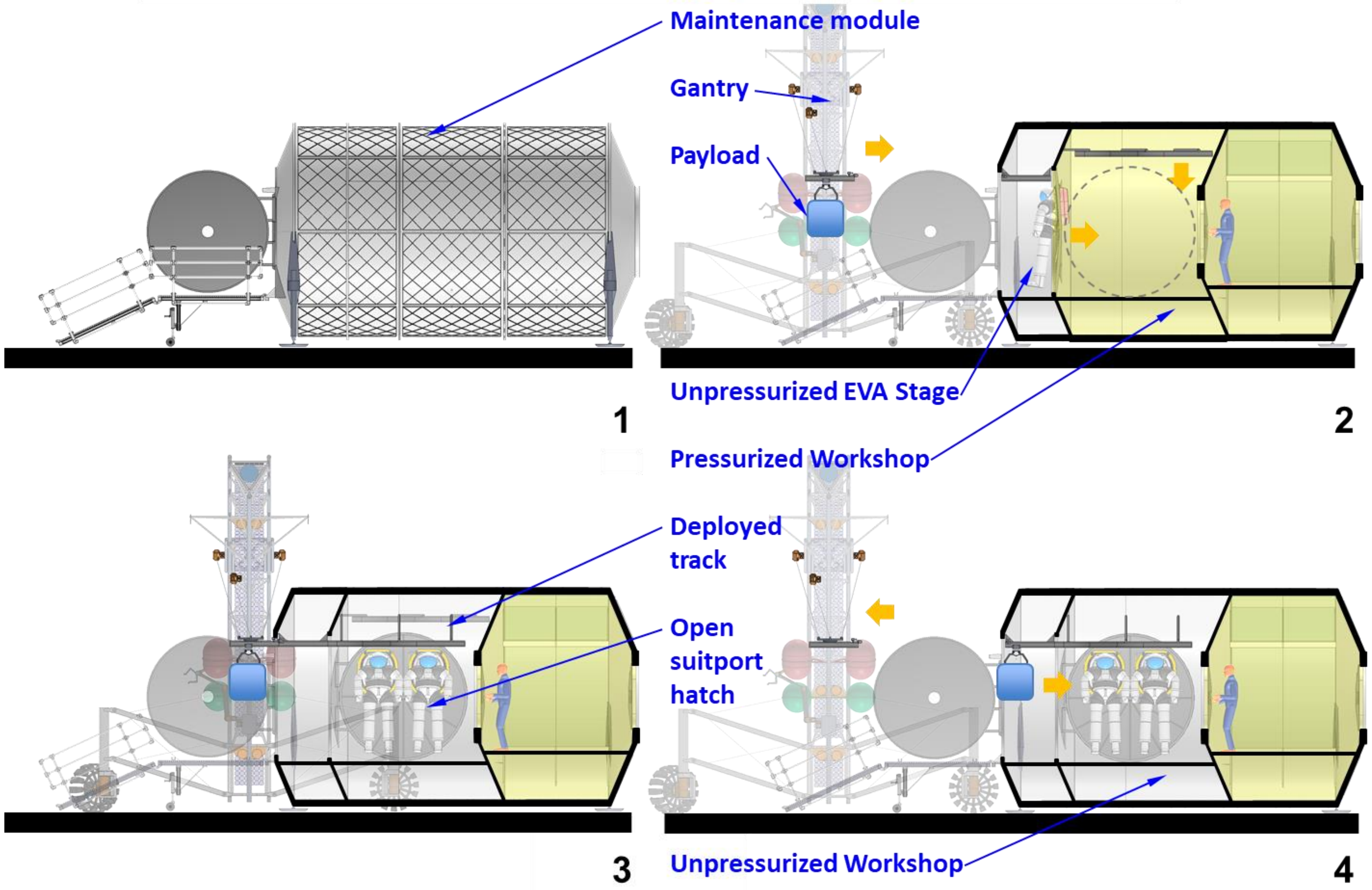
- Minimum habitat complex for ISRU base operations (Habitat, Maintenance, and Logistics modules)
- Supports a crew of 4 for a 30 day stay on the lunar surface
- Housed inside a deployable tunnel structure with regolith shielding to protect from harmful radiation
- Emplaced by mobile gantry elements
- Expandable infrastructure allows for new modules (e.g. science laboratory) to be added over time





Robotic Maintenance Approach

- Much of crew visit time will need to be devoted to maintenance of ISRU and other base elements
- Mobile Gantry is able to remove subassemblies of other robotic elements and transport them to pressurized maintenance module, minimizing the need for crew EVA
- Multi-zoned maintenance module provides lunar dust mitigation

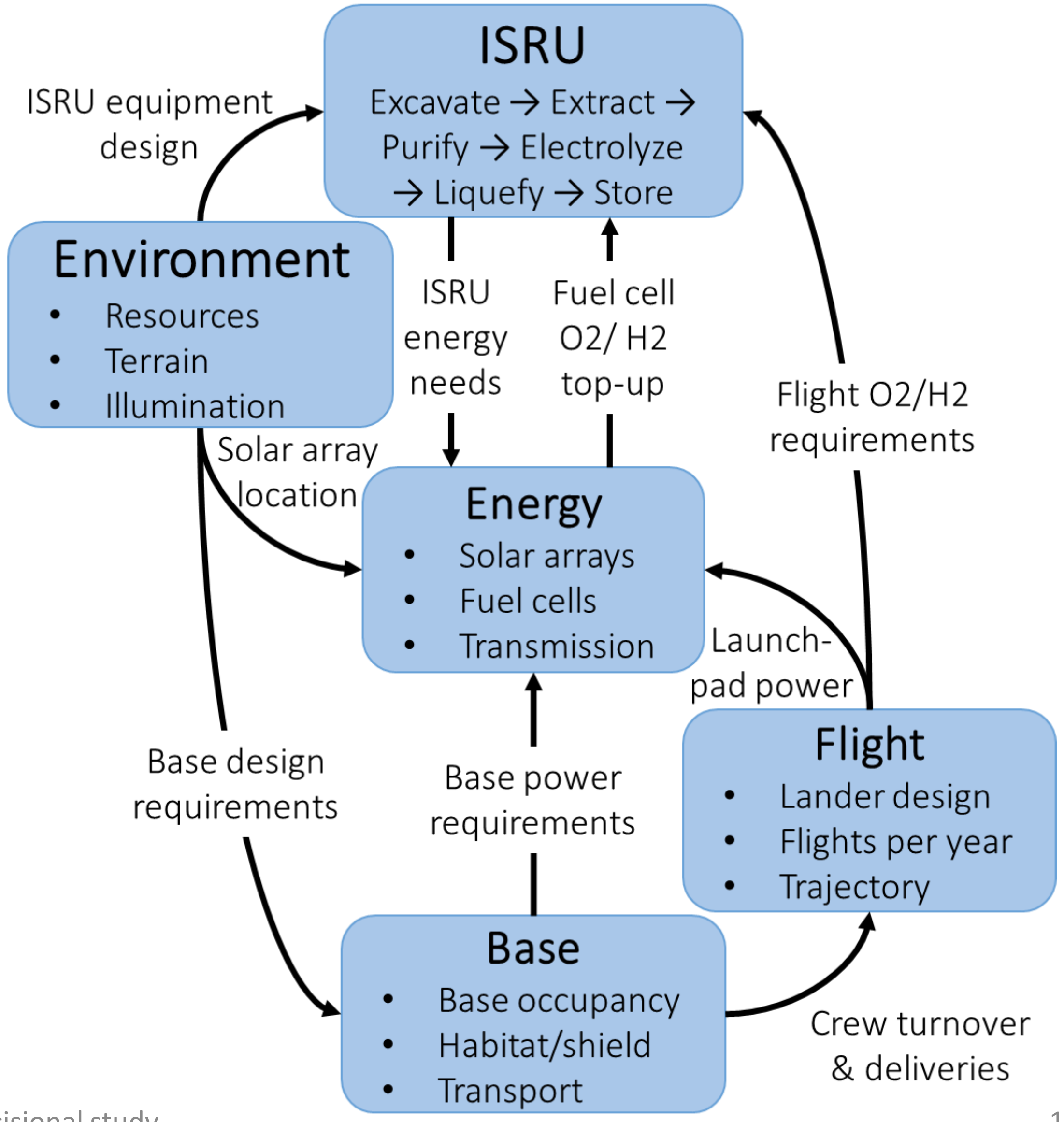


A lunar base is an interconnected system

Each major element of the base system impacts all of the other elements

- Habitat and astronaut systems
- ISRU techniques and elements
- Energy system architectures
- Lunar lander designs

What might seem like a small change in one area can have a large impact across other areas



Key Takeaways

- **Aerospace systems have very different requirements and constraints from those on Earth.** These can be very challenging, but that also makes them exciting – don’t be afraid of the challenge!
- **Water-ice at the Moon provides a potentially useful resource** – if you can use this, it could decrease what has to brought from Earth, but the trade-off is that it is difficult to access and process.
- **A Lunar Base requires a number of different interconnected elements**, which can get quite overwhelming – consider focusing on certain pieces.

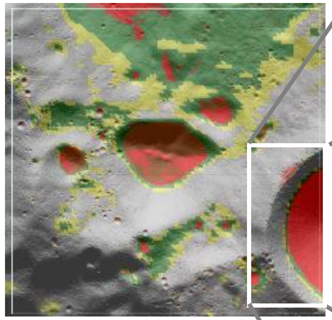
Thank you!

Backup – Potential Lunar Base Architecture Options

Option 1 – Deep Shackleton, PSR

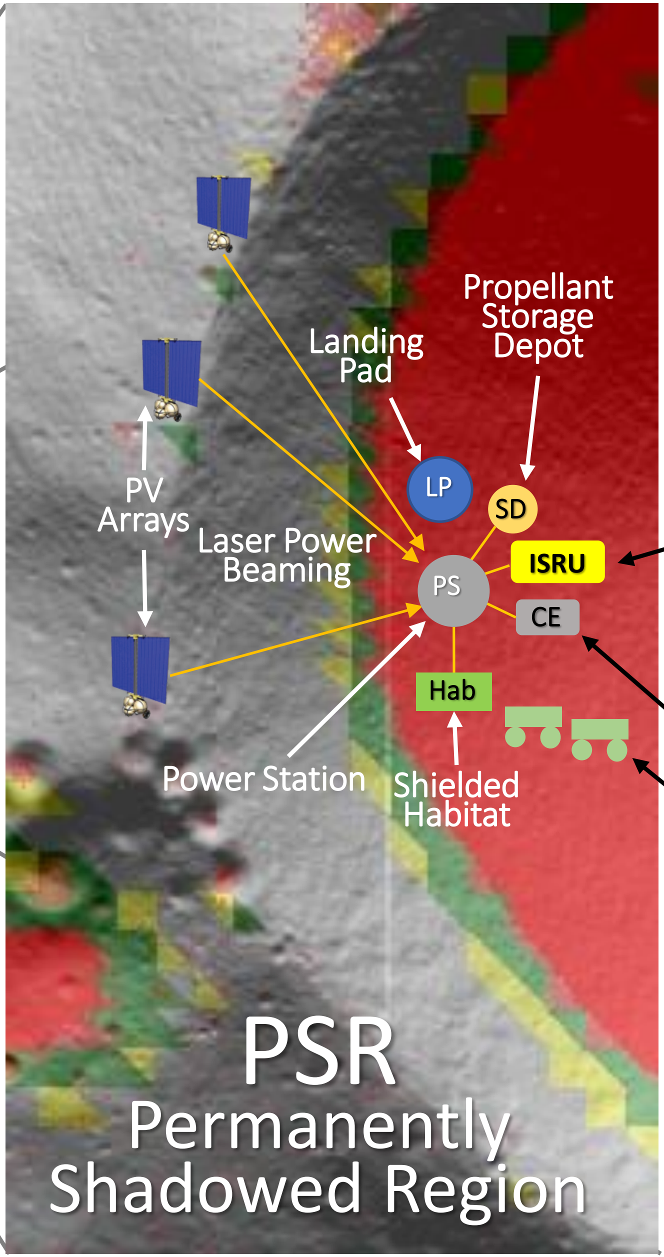
Type 1a Resource

2 wt% water ice, found 20 – 100 cm down



Power Infrastructure

- Multiple PV rim stations yield high lunation duty cycle
- Laser power beaming to central station
- Cable distribution to base elements
- Mobile elements use fuel cells, recharge at central station



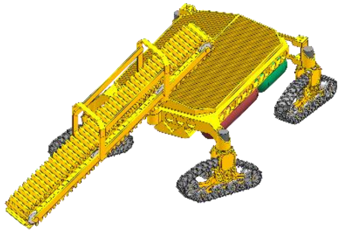
Reach, remove, and haul regolith resource <1 km to ISRU base

ISRU Plant
Purification
Electrolysis
Liquefaction

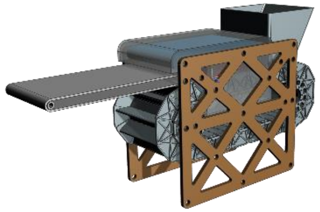
Central Volatile Extractor

Fuel Celled Dig/Haul Robots

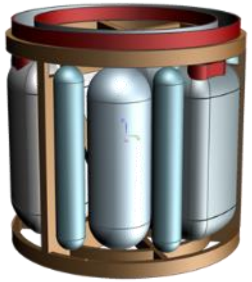
Excavation – Dig & Haul robots



Extraction – Central unit

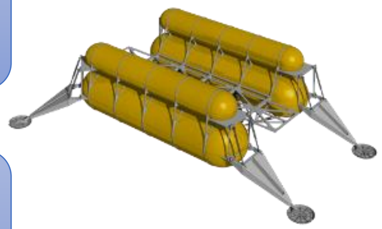


Purification – RO & EDI



Electrolysis – PEM or SOXE

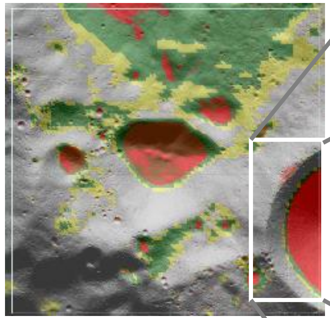
Liquefaction – Turbopumps & Coolers

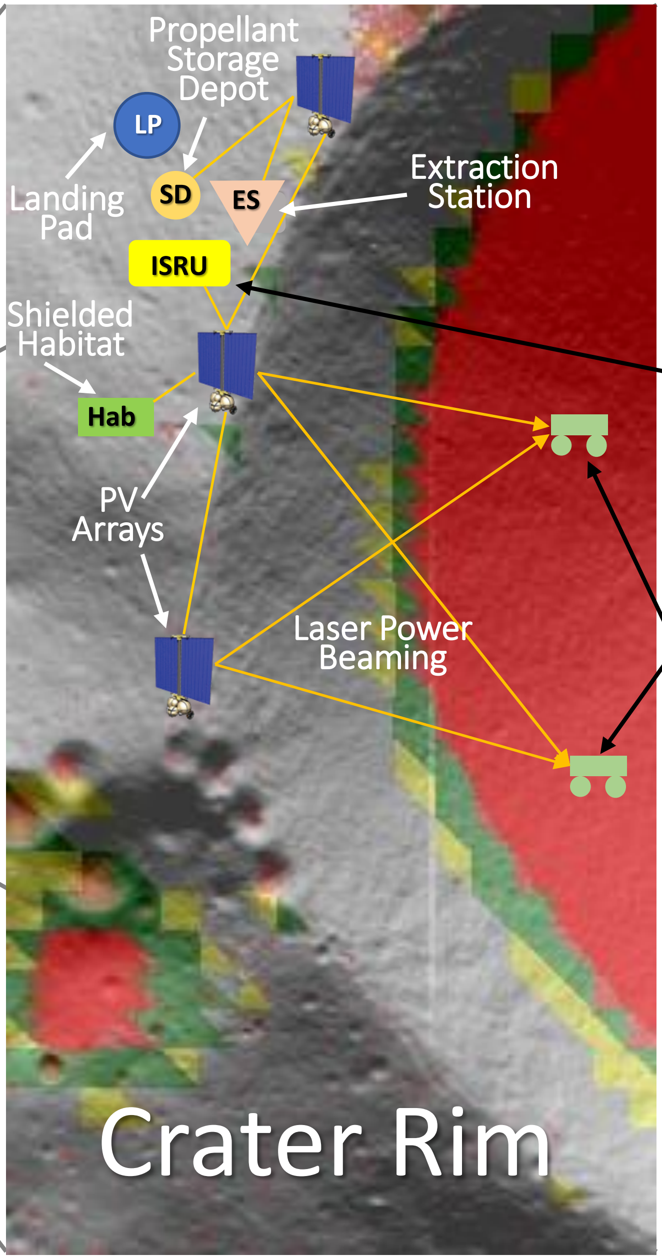


Storage – Depot at landing pad

Option 2 – Shackleton Slope, into the PSR

Type 1a Resource
2 wt% water ice, found
20 – 100 cm down





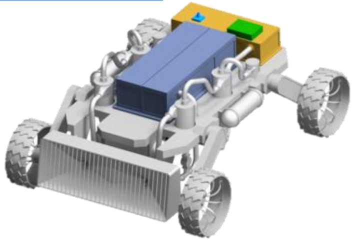
Power Infrastructure
- Multiple PV rim stations yield high lunation duty cycle
- Power cables to base elements
- Laser power beaming to excavators inside PSR
- Fuel-celled base robots

Haul beneficiated resource <10 km up and out of the crater

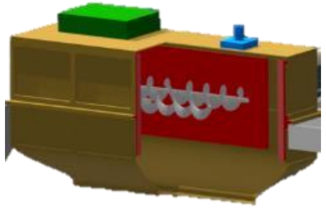
ISRU Plant
Purification
Electrolysis
Liquefaction

Beam-powered Roving Beneficiators

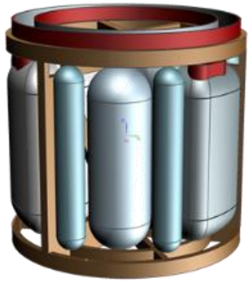
Excavation
Pneumatic beneficiator



Extraction
Heating w/ agitation

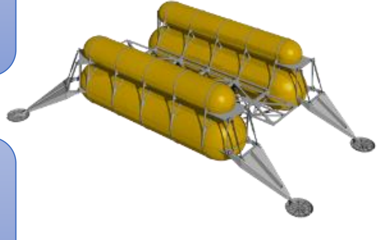


Purification
RO & EDI



Electrolysis
PEM or SOXE

Liquefaction
Turbopumps & Coolers

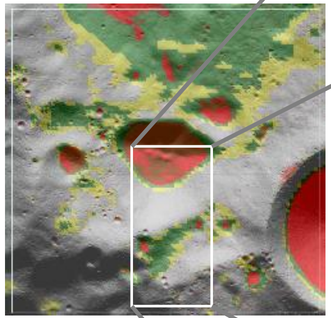


Storage
Depot at landing pad

Option 3 – Shackleton West Ridge, PLR Ice Fields

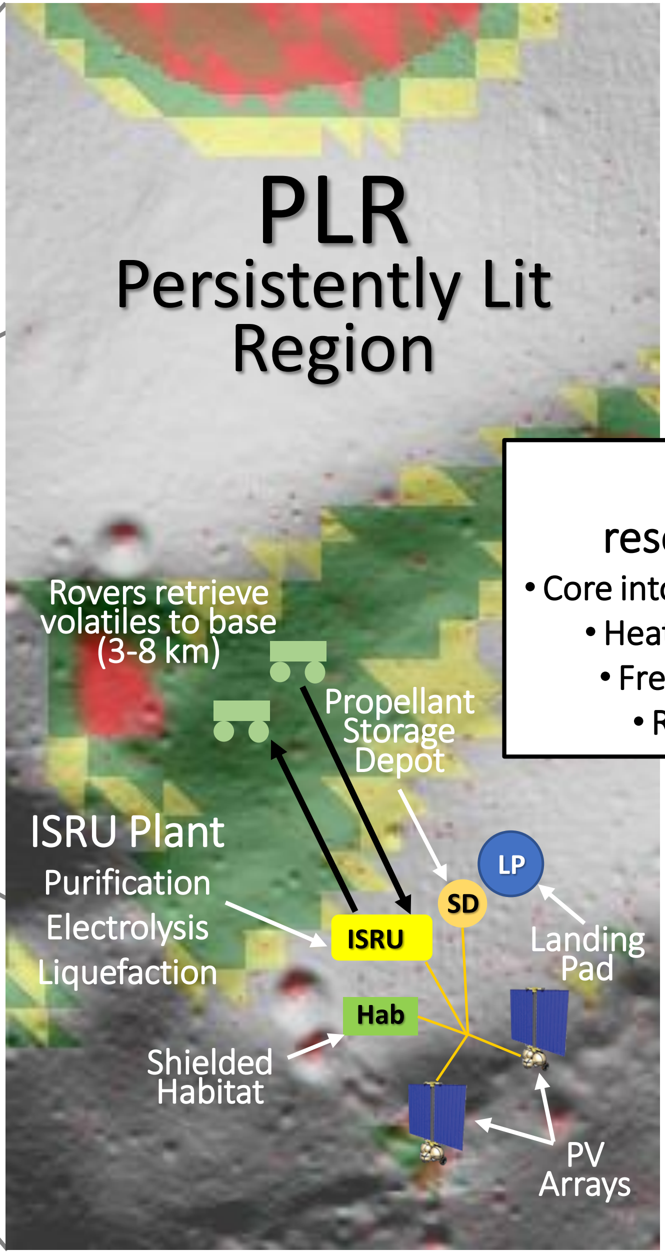
Type 2 resource

1 wt% water ice, found 40 – 100 cm down



Power Infrastructure

- Multiple PV stations yield high lunation duty cycle
- Solar/fuel cell mobility
- Excavator + Extractor rover and base robots



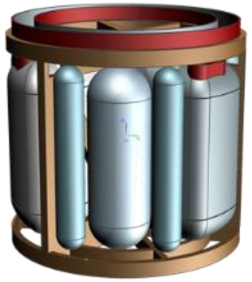
Fleet of resource rovers

- Core into the buried resource
- Heat the cores in situ
- Freeze the volatiles
- Return to base

Transport frozen volatiles to base (3-8 km)

Excavation + Extraction
In situ extraction by coring rover

Purification
RO & EDI



Electrolysis
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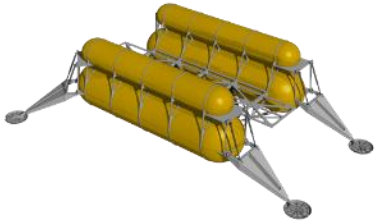

General Mass and Energy Requirements