RLSO 2

Robotic Lunar Surface Operations 2

2019

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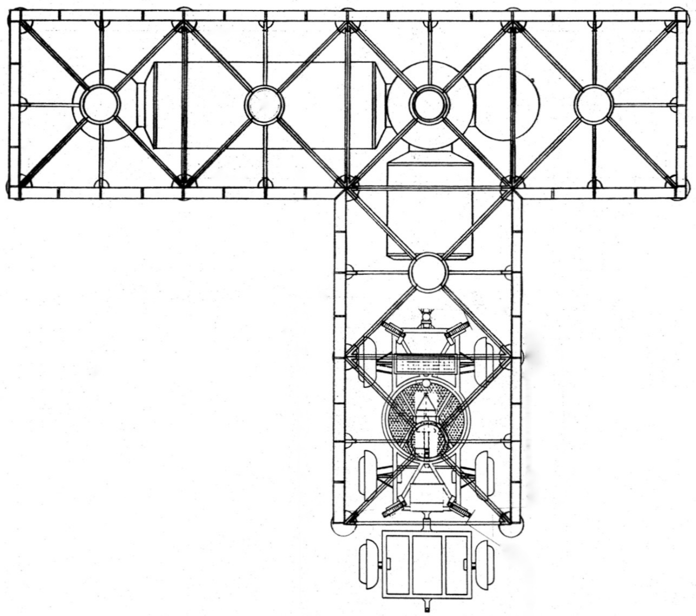
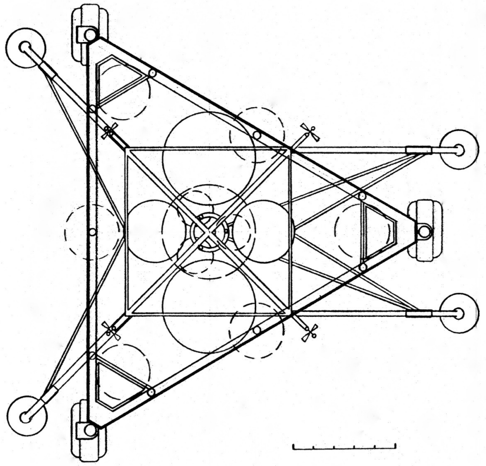
RLSO – 1989 Boeing study for NASA ARC

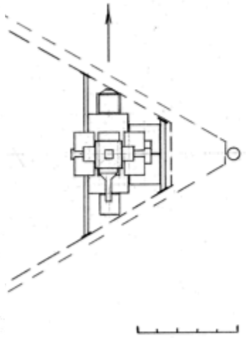
“Develop a concept for a LLOX-producing lunar base that would be built by robots before human crews arrive”

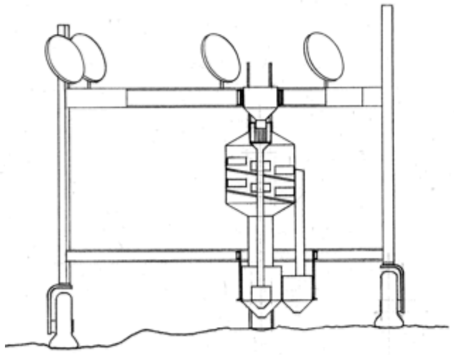
Integrated element designs.

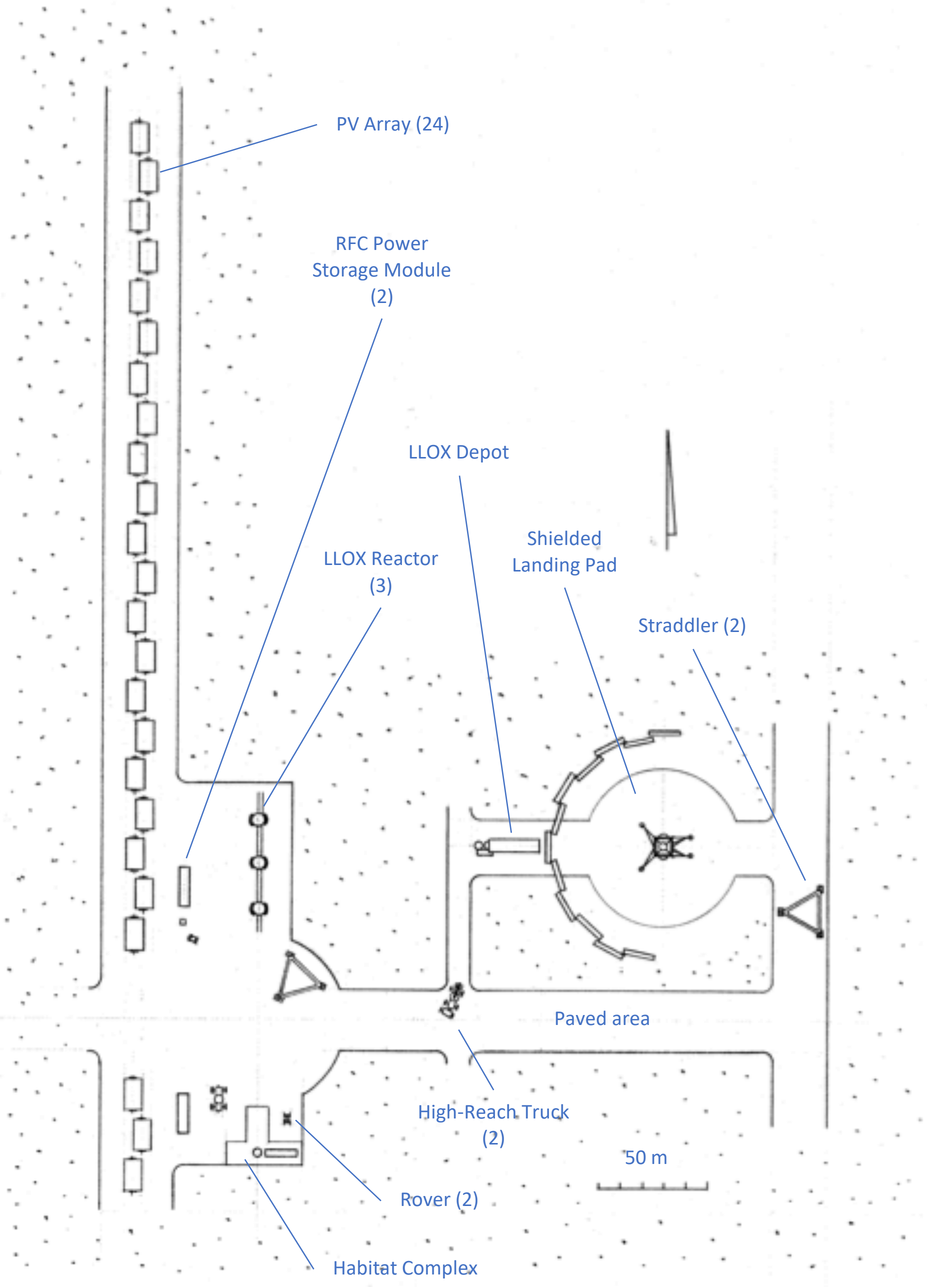
Quantified operations analysis.











What would RLSO look like today?

- Lunar polar volatiles, including ice
- ISS experience, international collaboration
- SPD-1, Moon Village, commercial actors, private capital
- SLS, Orion, Gateway, CLPS, Blue Moon
- Modern tools: spreadsheets, CAD, performance models

Functional decomposition of ice-based propellant ISRU

Excavation
Regolith handling & transportation

Extraction
Collection of volatiles

Purification
Removal of contaminants

Electrolysis
$2\ H_2O \rightarrow 2H_2 + O_2$

Liquefaction
Cooling O_2 to 90K and H_2 to 33K

Storage
Storing cryogenic propellant in a depot

Major elements of an ISRU base

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

Habitat System – Minimal functions, 30-d visits: hab, logistics, workshop, EVA, regolith-shield superstructure

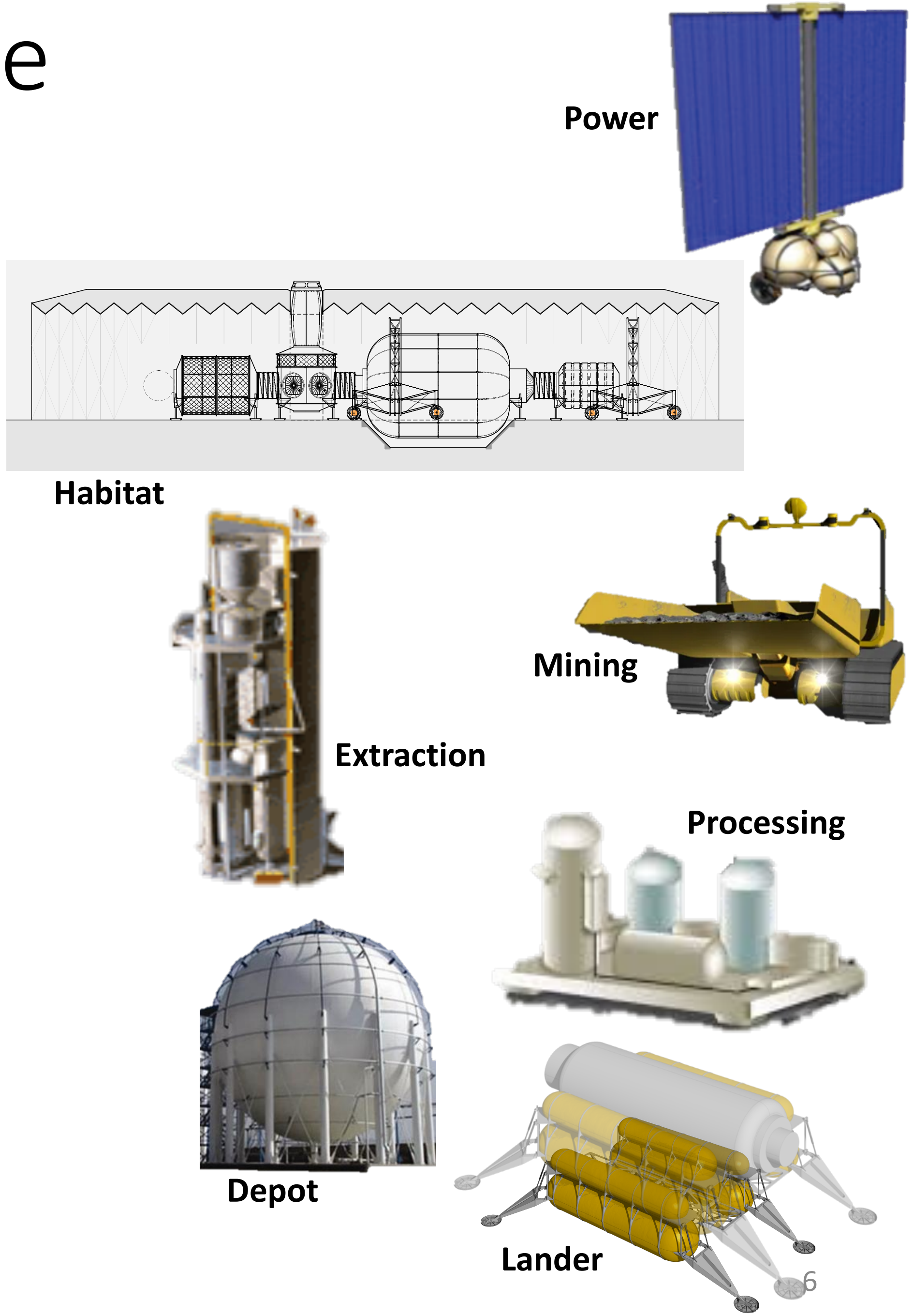
ISRU Mining System – Mobile robots that reach, excavate, beneficiate, and transport lunar regolith (or extract resource onboard and transport it)

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

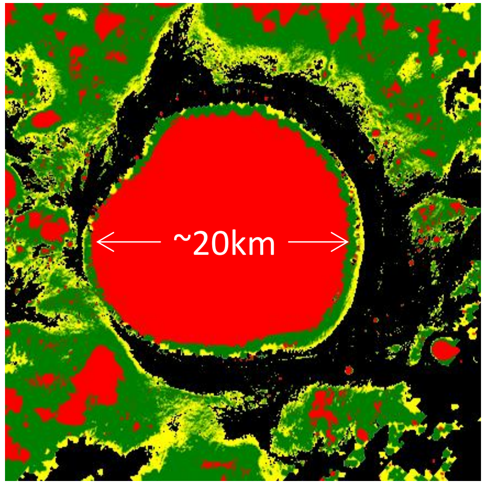
ISRU Volatiles Processing System – Plant that separates water from other volatiles, and cracks it into H_2 and O_2

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



Polar ice resources



- 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

	Total Fractional Area (%)	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	9	2	20-100	80	7.2	1,400
Type 1b PSR surface frost	9	100	0 - 0.002	0.002	0.006	> 1.5M
Type 2 PLR buried regolith	28	1	40-100	60	2.7	3,700
Type 3 PLR deeper regolith	7	0.5	60-100	40	0.9	12,000
Type 4 Lunation-lit regolith	56	0	--	0	0	n/a

Initial ISRU Requirements

Water need

- Lander flights per year: 4
- Propellant required per flight: 40,000 kg
- Water required per flight: **51,500 kg** (6:1 engine ratio vs. 8:1 water mass ratio)
- Water need: 206,000 kg/yr = **1,130 kg/d** @ half-time operations

Resource need

- Type 1: **0.15 m^3 (~210 kg)** per kg of H_2O yield
- Type 2: **0.40 m^3 (~600 kg)** per kg of H_2O yield

Regolith need

- Type 1: 240,000 kg/d @ half-time
- Type 2: 680,000 kg/d @ half-time

Initial Energy Requirements

Volatiles processing minimum: **10.5 kWh per 1 kg of water**

- 2 kWh/kg for extraction from regolith
- 6.5 kWh/kg for electrolysis: H_2O into H_2 and O_2
- 2 kWh/kg for liquefaction: H_2 and O_2 into LH_2 and LOX

ISRU energy: **2,200,000 kWh/yr**

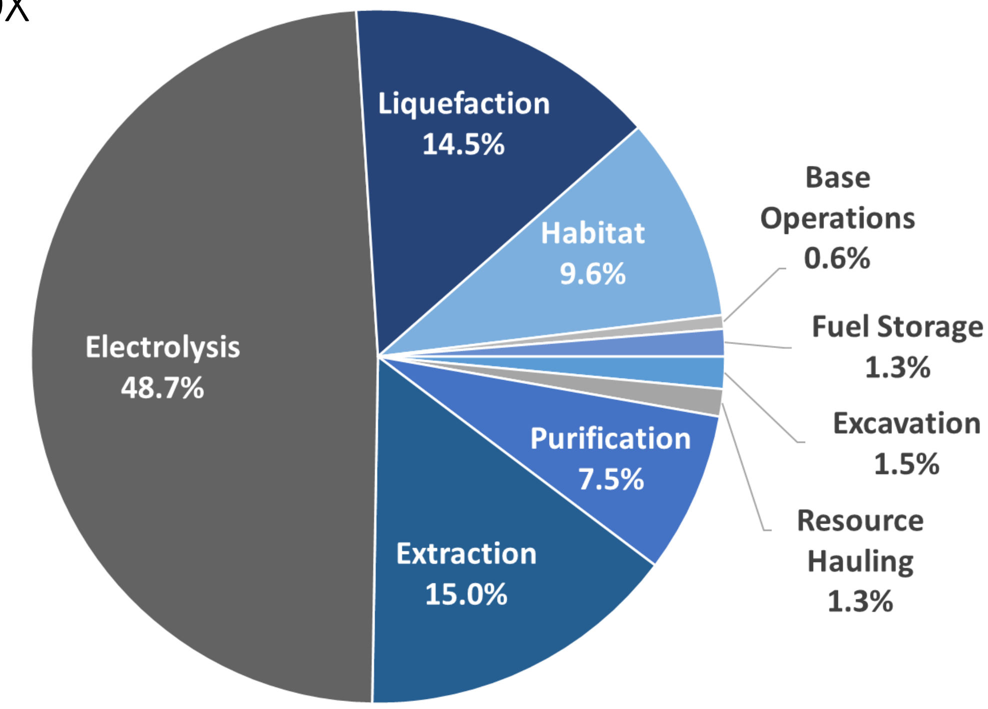
- Quantity of water required: 206,000 kg/yr

ISRU power: **500** kW @ half-time ops (4,380 hr)

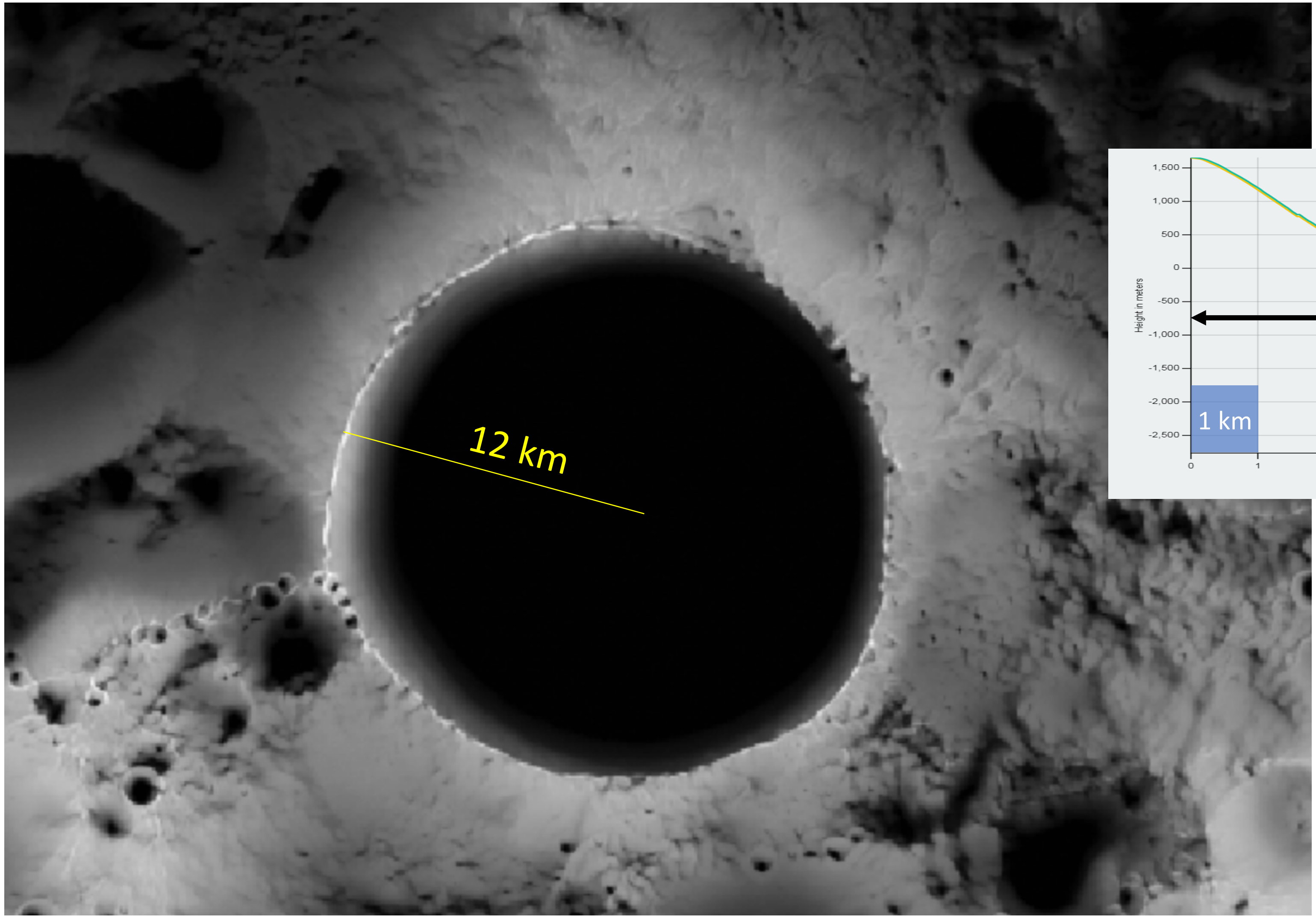
Other energy requirements include:

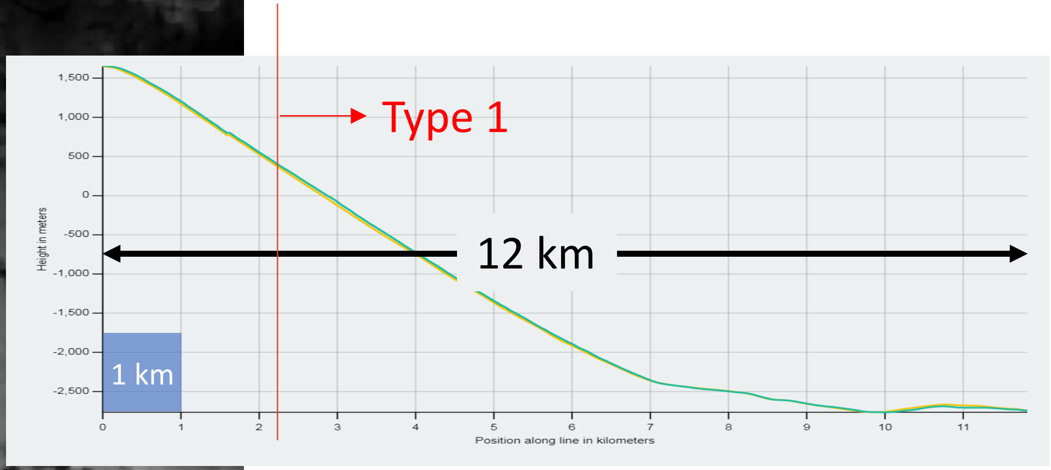
- Excavation, hauling, cryogenic storage
- Hab-complex sustained operation
- General mobility and base operations

Total base power need: ≥600 kW



Shackleton Crater

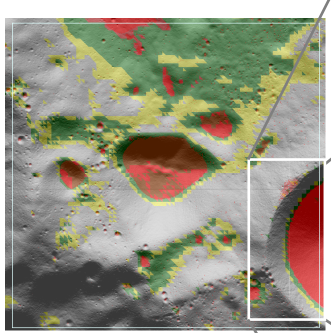




Option 1 – Deep Shackleton, PSR

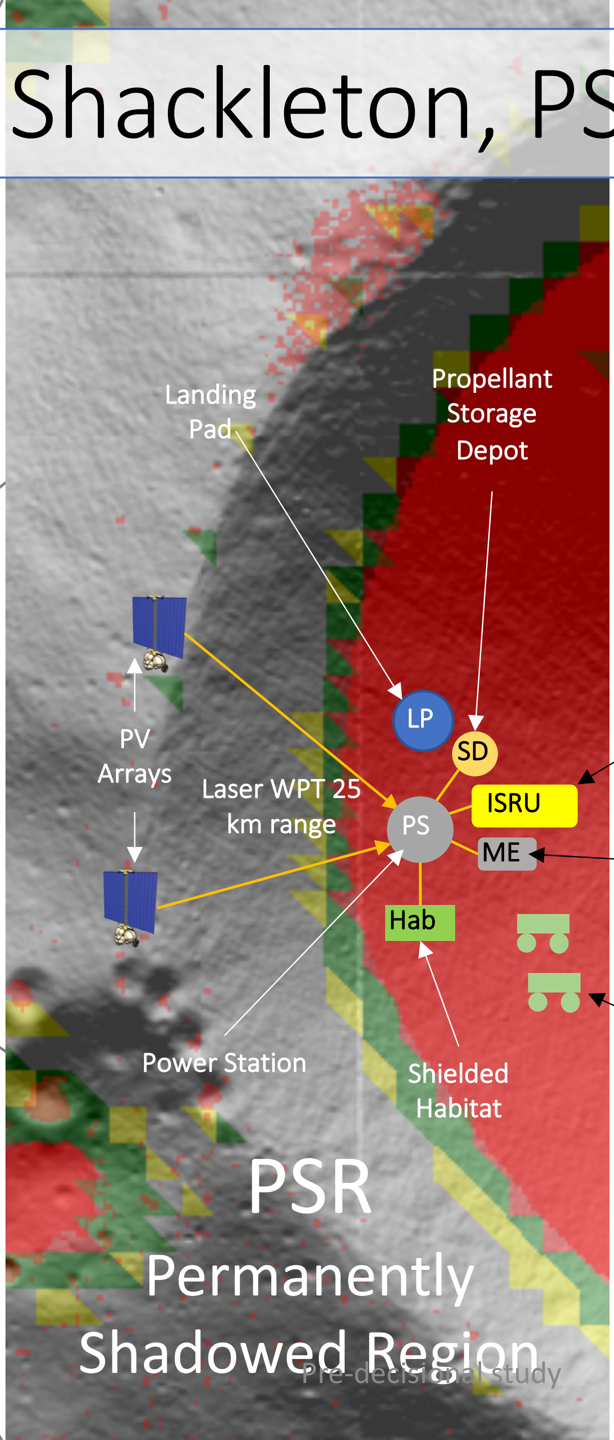
Type 1a Resource

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



Power Infrastructure

- Multiple PV rim stations yield high lunation duty cycle
- Laser WPT to central power 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 Microwave Extractor

Fuel Celled Dig/Haul Robots

Excavation
Dig & Haul robots

Extraction
Central microwave unit

Purification
Processing plant

Electrolysis
PEM or SOXE

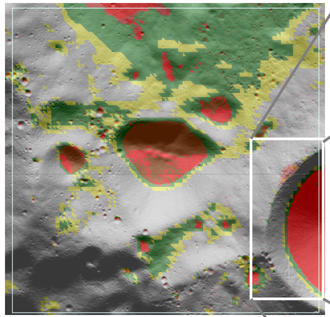
Liquefaction
Turbopumps & Coolers

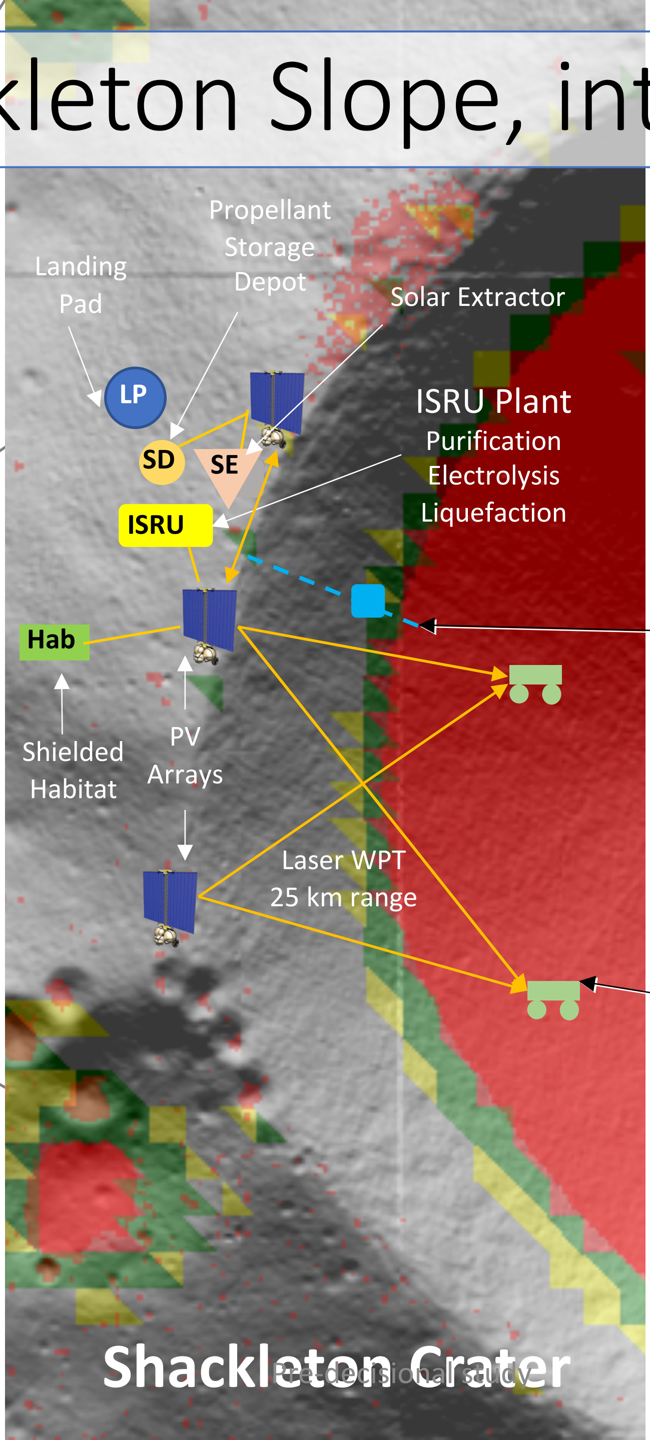
Storage
Depot at landing pad

Option 2 – Shackleton Slope, into the PSR

Type 1a resource

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





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

Resource "escalator"

Passive solar sublimation

Beam-powered Roving Beneficiators

Excavation
Roving beneficiator
Pneumatic collection

Extraction
Solar baking

Purification
Processing plant

Electrolysis
PEM or SOXE

Liquefaction
Turbopumps
& Coolers

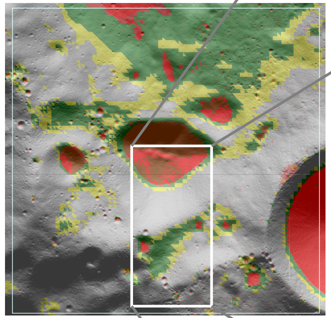
Storage
Depot at landing pad

Power Infrastructure

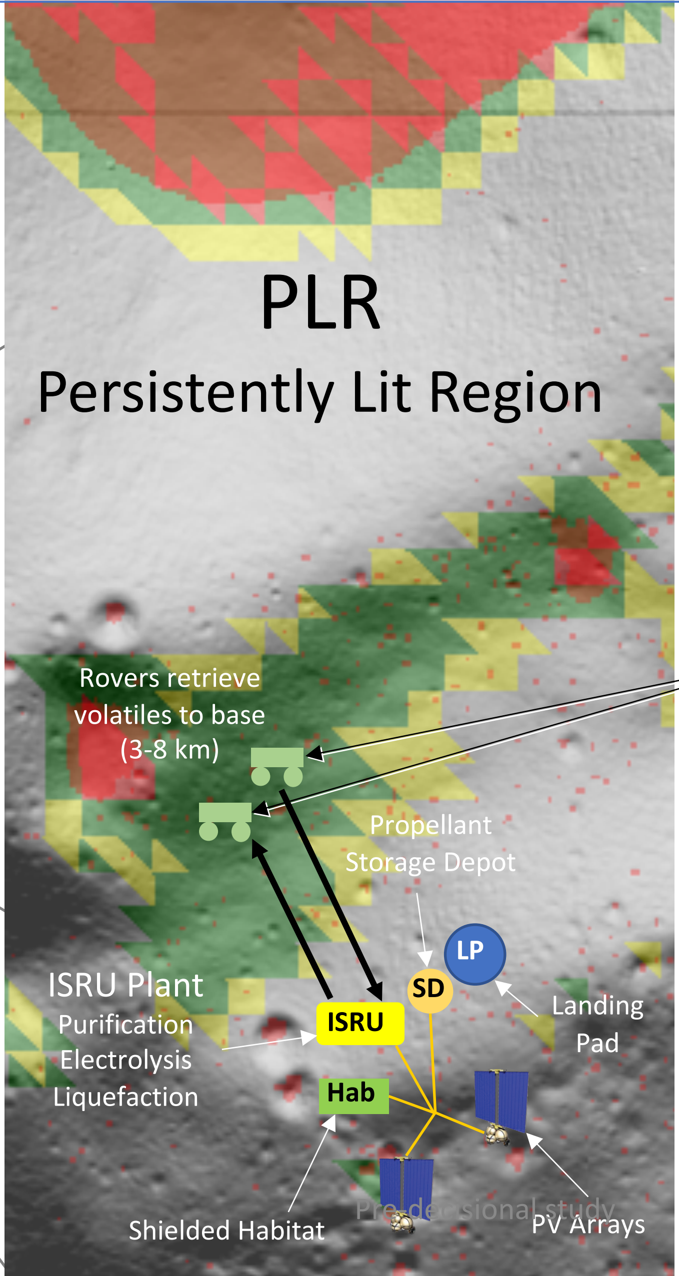
- Multiple PV rim stations yield high lunation duty cycle
- Power cables to base elements
- Laser WPT to excavators inside PSR
- Fuel-celled base robots

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 Retriever and base robots



Transport frozen volatiles to base (3-8 km)

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

Excavation + Extraction
In situ extraction by coring rover

Purification
Processing plant

Electrolysis
PEM or SOXE

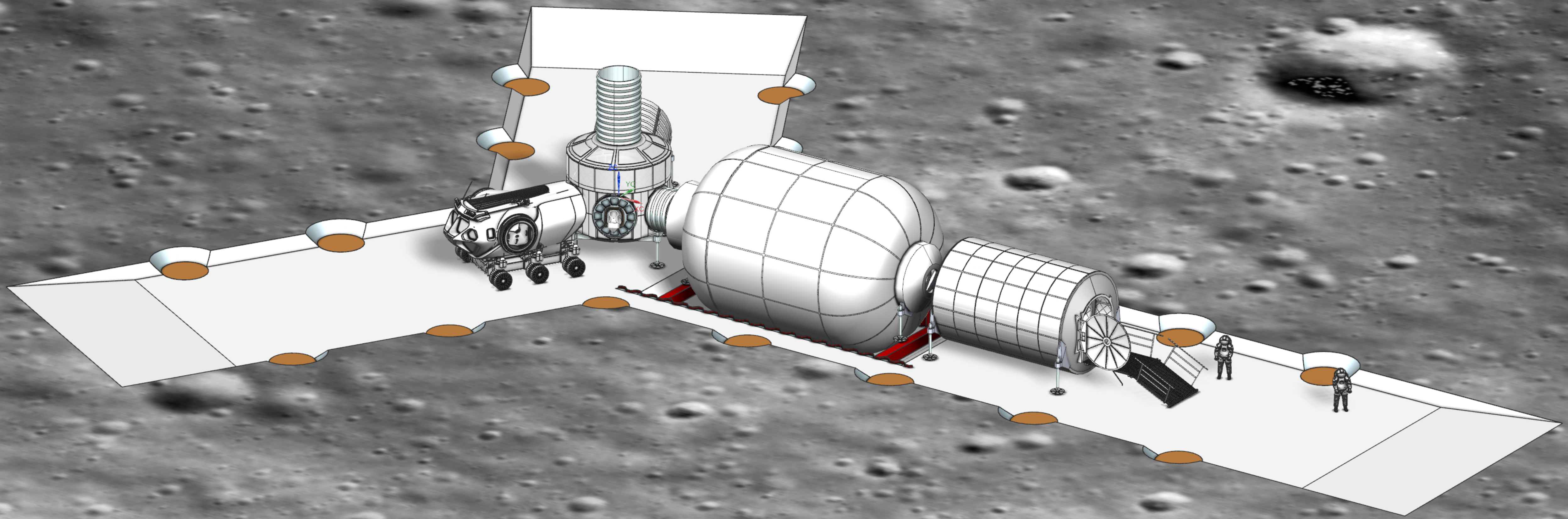
Liquefaction
Turbopumps & Coolers

Storage
Depot at landing pad

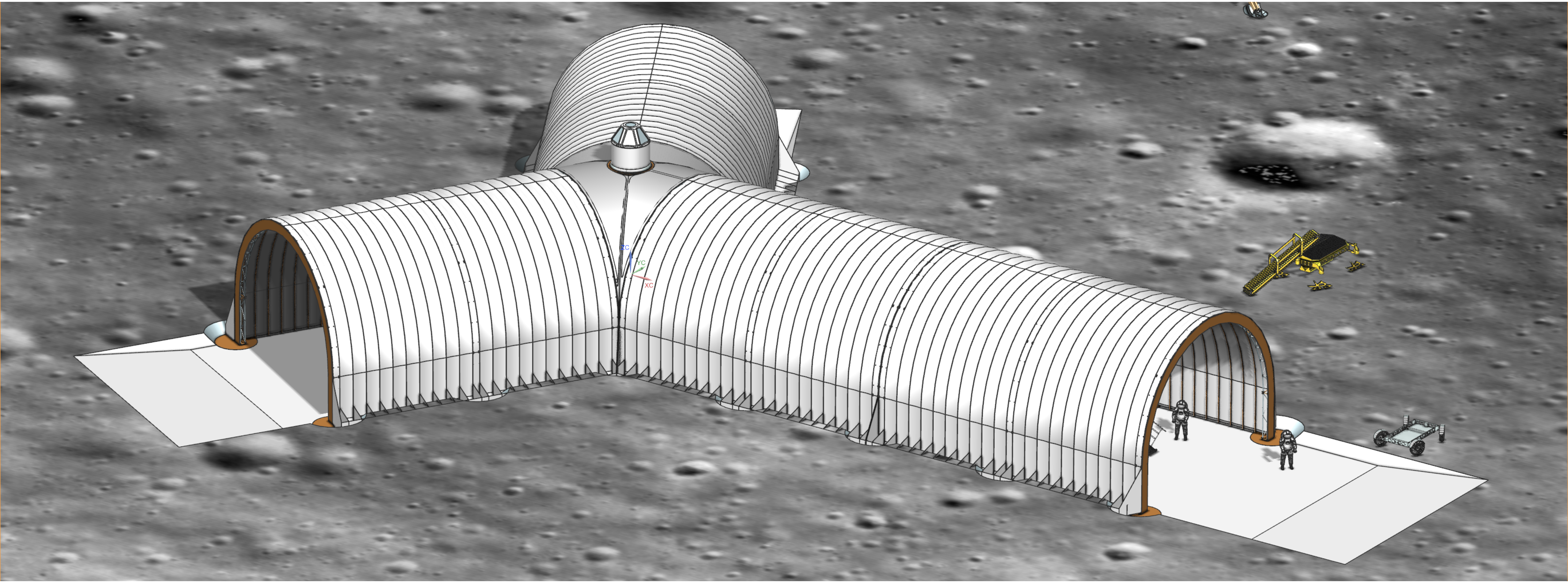
Option comparison

Option	Best attributes	Worst attributes
1. Deep Shackleton	• Best quality resource, with minimal overburden removal • Stable operating environment: dark, 70K • Creates market for power beamers	• Base cannot access regional exploration sites • Base is permanently dark
2. Shackleton Slope	• Best quality resource, with minimal overburden removal • Base can support exploration excursions	Resource must be brought several km up and out of crater
3. Shackleton West Ridge	• Avoids crater slopes • Proximate sunlight and shadow • 0.5m/px LROC imagery • Creates market for mining rovers	"Half-quality" resource, buried deeper

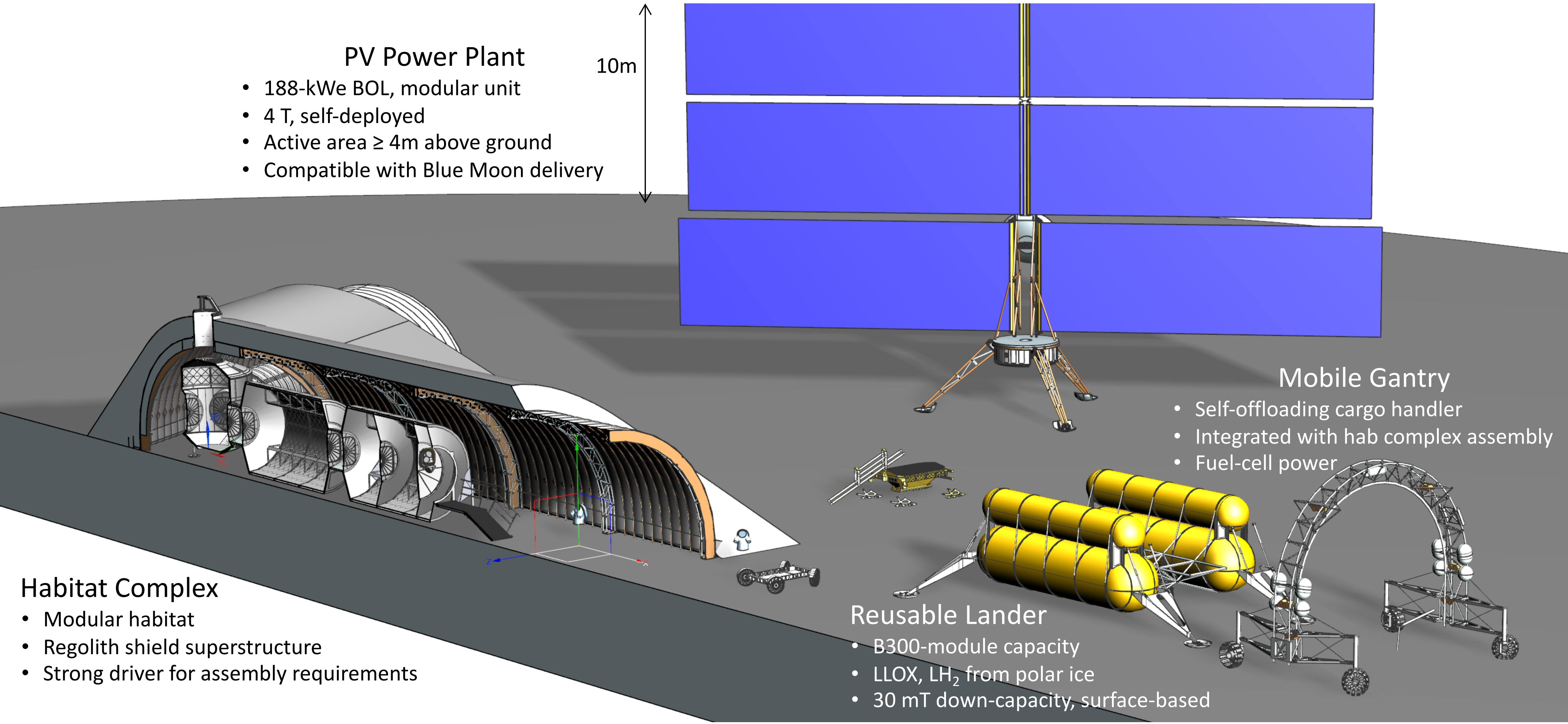
Habitat complex: commercial product lines, LER, Suitlocks, robotic-accessible workshop



Shielded without burying complex equipment



Assembled by self-offloading gantry robot



PV Power Plant
- 188-kWe BOL, modular unit
- 4 T, self-deployed
- Active area ≥ 4m above ground
- Compatible with Blue Moon delivery

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

Habitat Complex
- Modular habitat
- Regolith shield superstructure
- Strong driver for assembly requirements

Reusable Lander
- B300-module capacity
- LLOX, LH_2 from polar ice
- 30 mT down-capacity, surface-based

Emergent findings

Nuclear power useful for production-scale ISRU would have to be MWe class

“Best” ice resource and location may not be in a PSR

Potential competitive roles for commercial actors

- Power providers, extraction rovers

Empirical knowledge gaps with high leverage

- Vertical distribution at m scale – wt% of ice as a function of depth
- Horizontal distribution at km scale – patchiness of resource “field”
- Geotechnical properties – “coffee grounds and sugar” or cryo-permafrost
- Diffusion rate – trapping vs losing the resource from heating in situ
- Agitation loss coefficient – losing the resource from handling it

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