NASA Oxygen and Water Production Architectures for Early Reusable Lander

Lunar ISRU Workshop

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Lunar ISRU Presentation Overview

EXPLORE MOONtoMARS

- ISRU Overview for Human Lunar Architecture
- Oxygen from Regolith
- Polar Water Prospecting & Mining
- Sustainable Lander and ISRU
- Backup

ISRU Overview for Human Lunar Architecture

Goals for Initial and Long Term Lunar ISRU Consumable Production

EXPLORE MOON to MARS

HEOMD – Human Lunar Lander Reusability and Sustainability

- Early ISRU: Make **10 mT/yr oxygen** from lunar regolith to fuel lander **by 2030** if not sooner
- Sustainable ISRU: Mine **15 mT/yr** water in polar craters to fuel reusable landers by **TBD**

STMD – Strategic Technology Formulation

- Meet strategic thrusts for *Go, Land, Prosper* by addressing Key Capability Challenges for Regolith to Oxygen, Lunar Ice to Water, and Water to Cryogenic Propellant

SMD – Lunar Science and Resource Understanding

- Utilize Commercial Lunar Payload Services (CLPS), instruments, and missions to advance understanding of the Moon, especially volatiles in permanently shadowed regions at the poles for science and exploration

American Leadership and Commercialization of Space

- Promote *SPD-1: Reinvigorating America's Human Space Exploration Program* to lead an innovative and sustainable program of exploration with commercial and international partners (for long-term exploration and utilization of space resources)

ISRU must first be demonstrated on the Moon before it can be mission-critical.

Lunar ISRU Mission Consumables:
Oxygen from Regolith vs Polar Water

EXPLORE MOONtoMARS

- **Oxygen from Regolith**
  - **Lunar regolith is >40% oxygen (O_2) by mass**
  - **Can be incorporated into the architecture from the start with low-moderate risk**
  - **Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth)**
  - Experience from regolith excavation, beneficiation, and transfer applicable to mining Mars hydrated soil/minerals for water and *in situ* manufacturing and constructions
- **Water (and Volatiles) from Polar Regolith**
  - **Form, concentration, and distribution of Water in shadowed regions/craters is not known**
  - **Cannot be incorporated into the architecture from the start with low to moderate risk**
  - **Provides 100% of chemical propulsion propellant mass**
  - **Polar water is "Game Changing" and enables long-term sustainability**
    - Strongly influences design and reuse of cargo and human landers and transportation elements
    - Strongly influences location for sustained surface operations

➢ **Current Plan:** Develop and fly demonstrates for both lunar ISRU consumable approaches
  - Develop oxygen extraction to meet near term sustainability objectives
  - Utilize orbital missions and early lunar surface missions to understand and characterize polar environments, regolith, and water resources to address risks and technology needs

Oxygen Extraction from Regolith

Oxygen from Regolith Mineral Oxides – Comparison of Most Advanced Concepts

	O_2 Extraction			
	H_2 Reduction	CH_4 Reduction	Molten Oxide Electrolysis	Ionic Liquid Reduction
Resource Knowledge	Good - Orbital High Resolution & Apollo Samples			
Site Specificity	Moderate to High (Ilminite & Pyroclastic Glasses Preferred)	Low to Moderate (Iron oxides and Silicates)		
Temperature to Extract	Moderate (900 C)	High (>1600 C)	High (>1600 C)	Low (100+ C)
Energy per Kilogram	High	Moderate	Moderate	?
Extraction Efficiency wt%*	1 to 5	5 to 15	20 to 40	?
TRL	4-5	4-5	2-3	2

*kg O_2/kg bulk regolith

Carbothermal Reduction

Mix carbon into molten regolith at >1650 °C to extract oxygen in the form of carbon monoxide/dioxide

Requires secondary reactor to convert CO/CO_2 to H_2O

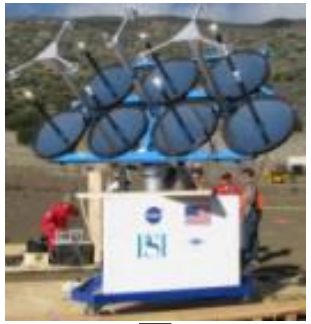
Pros:

- **Will work on regolith anywhere on the Moon**; silicates are very abundant, especially at the Poles
- Higher yield (5 - 15 wt%) reduces excavation and transportation needs
- High TRL- 5; System ground tested
- Technologies highly relevant for Mars ISRU O_2 & CH_4 production

Cons:

- **High temperature and thermal energy** drives need for direct thermal technology (such as solar concentrators)

Solar Concentrator



Mobile Excavator

Inlet Hopper & Transfer

Carbothermal System

Water Electrolysis & Gas Storage

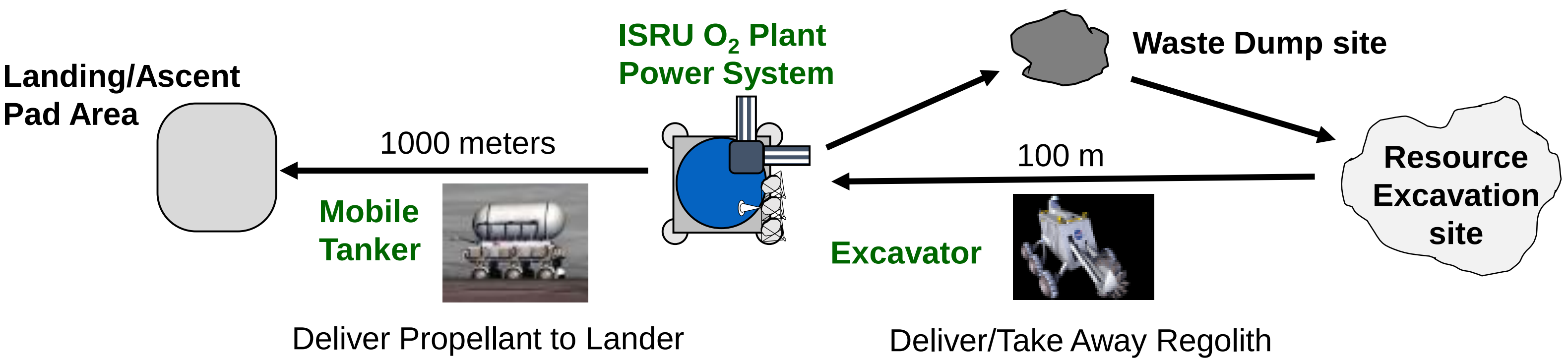
Liquefaction & Cryogenic Storage

Oxygen from Regolith – Full Scale System
Design & Concept of Operation (7.4 continuous months/year)

EXPLORE MOON to MARS

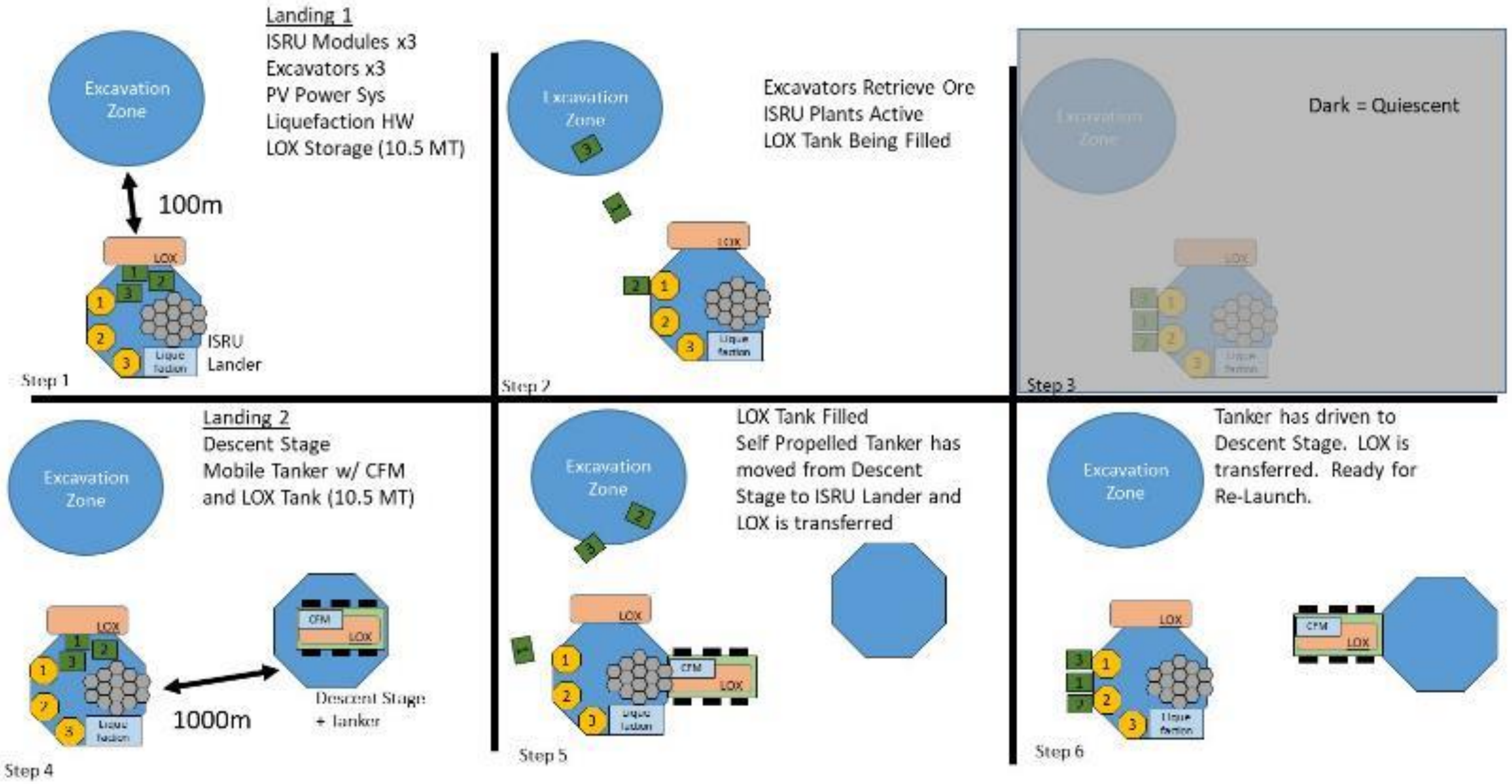
- **Assumed lander had 3.6 mT payload capability and all hardware needed to produce and store O_2 are on a single lander**
  - 2nd lander required to deliver mobile O2 storage and transfer unit
- **Each ISRU module (there are two)** produces 15.6 kg of O_2 per day (3500 mt O_2 per year per module)
- ISRU plant, excavation zone, and dump zone form triangle with 100 m each leg
- Each Excavator
  - Provides 4 deliveries of 35 kg per day to ISRU plant (20 mins total per delivery)
  - Provides 3 disposal runs of 40 kg per day to clear out the two ISRU modules (17 mins total per disposal run)
  - Is charged every 4.5 days (1 kWhr discharged maximum 80% - 50 charge cycles per operating year)
  - Operates via tele-operation/supervised-autonomy with a communication link through the lander to Gateway to Earth
- Electrolysis subsystem converts H_2O into O_2 and H_2
  - 0.65 kg/hr of O_2; H_2 recycled back to methanation reactor
- **Oxygen is liquefied and stored in the descent stage LO_2 tank** (single system for all ISRU modules)
  - 1.3 kg/hr of O_2 (total from two ISRU modules) liquefied and placed in lander tanks
- Solar Concentrator: 22.2 kWth energy delivered to ISRU reactors (2) via fiber optic at 1800 °C
- Electrical Power: 15 kWe (entire system, with 30% growth)
  - Two Ultraflex arrays at 5.4 m diameter
  - Regenerative fuel cell used for nighttime survival during ISRU standby mode (4.6 ‘winter’ months)

Oxygen from Regolith Concept of Operations



Two Landers to Deploy Full Scale Plant

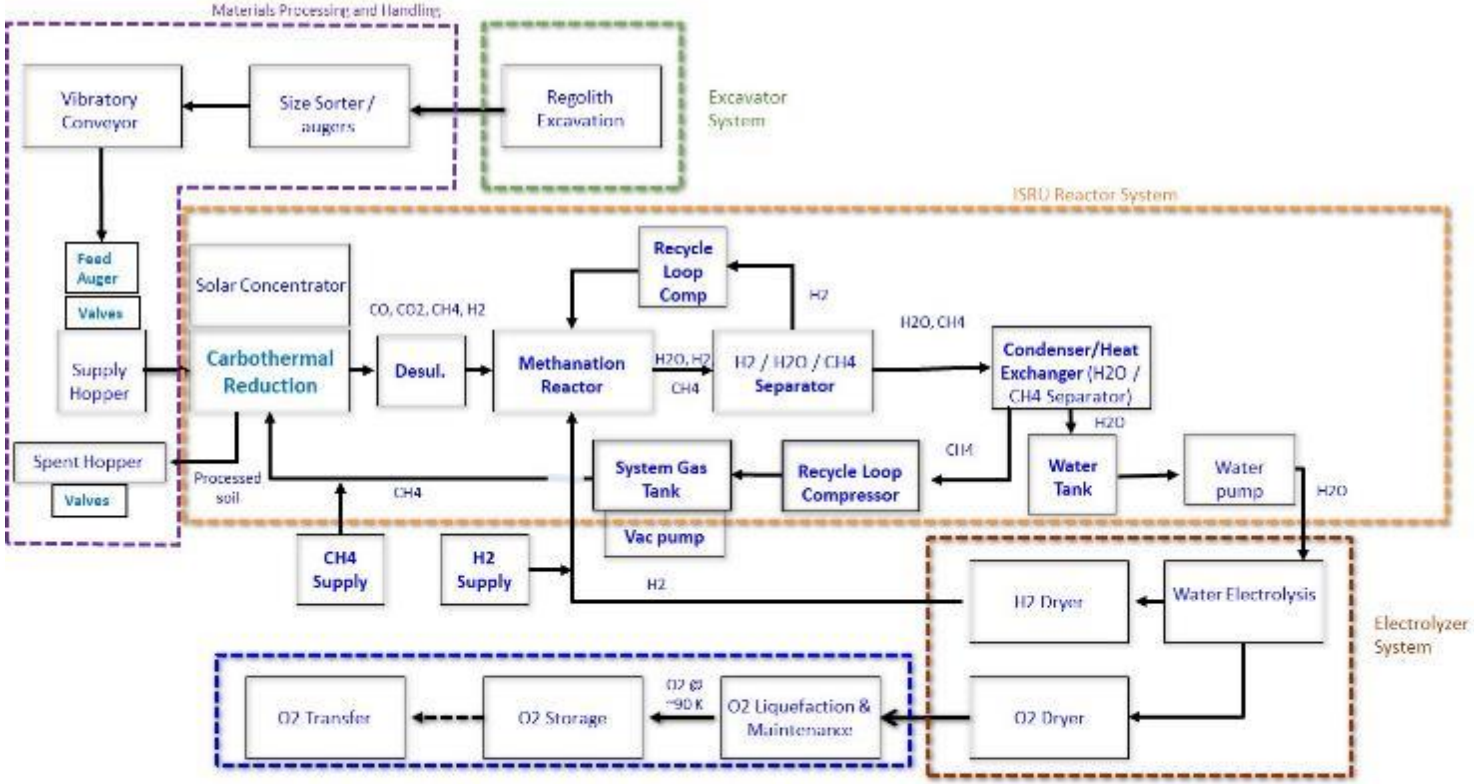
- Lander 1: ISRU O_2 Production Plant, Excavators, & Power System
- Lander 2: O_2 Tanker: O_2 Tanks & Mobile Platform
- *Options:* Where O_2 is liquefied and stored during production
  - Descent tanks
  - Separate tank as payload
  - Mobile tanker

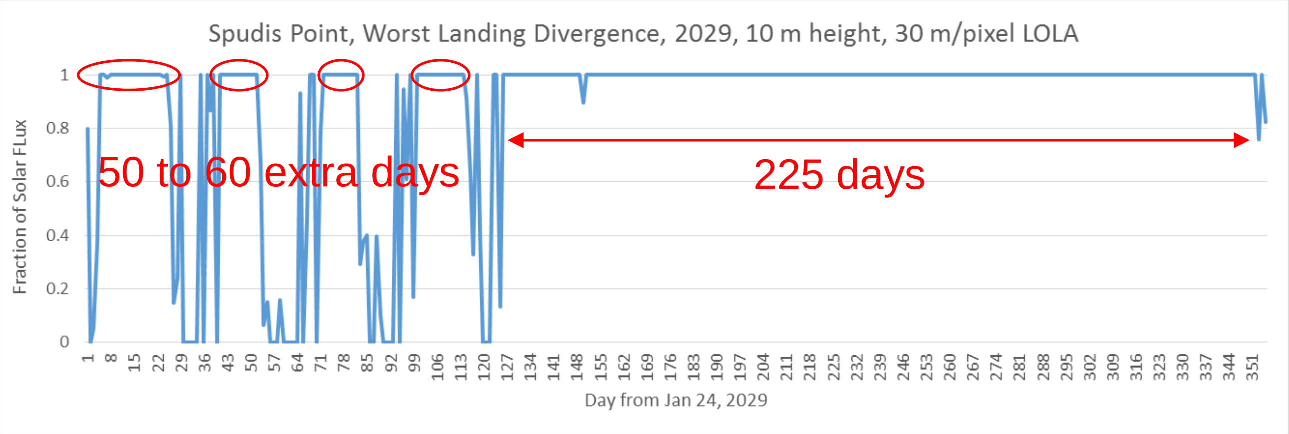


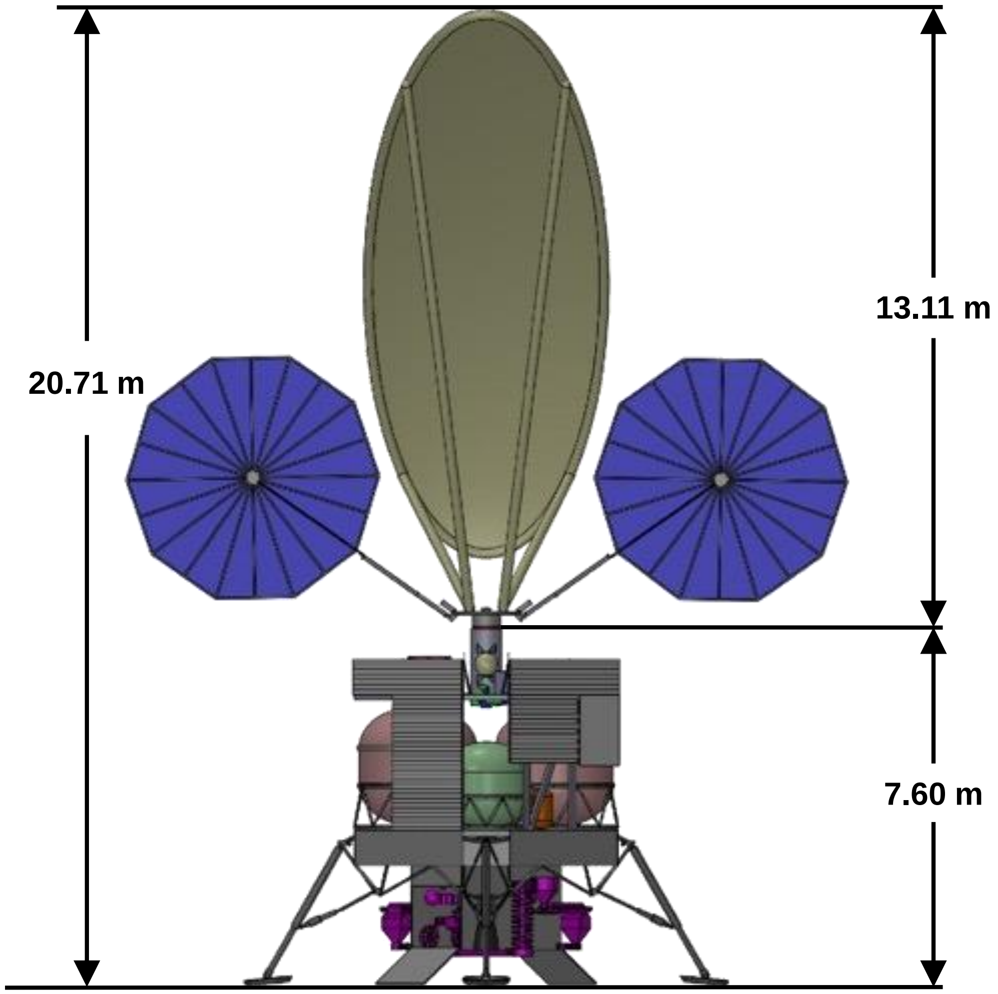
Oxygen from Regolith – Full Scale System

Point of Departure Carbothermal Reduction (7+mT O_2/year)

EXPLORE MOONtoMARS







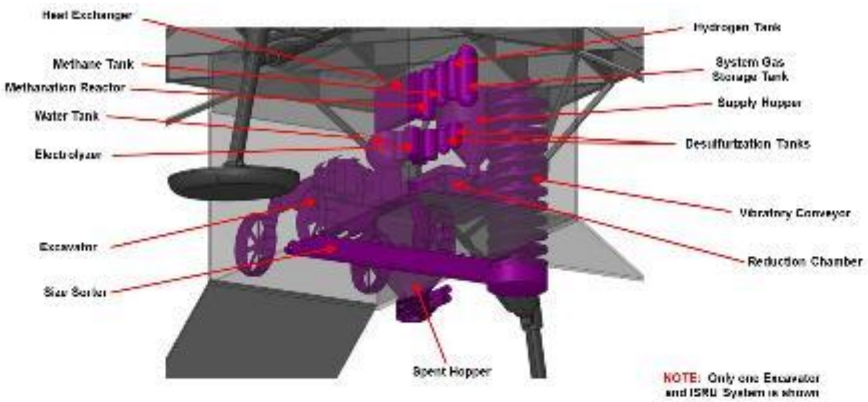
NOTE: Overall Concentrator height is 11.65 m with a width of 5.24 m

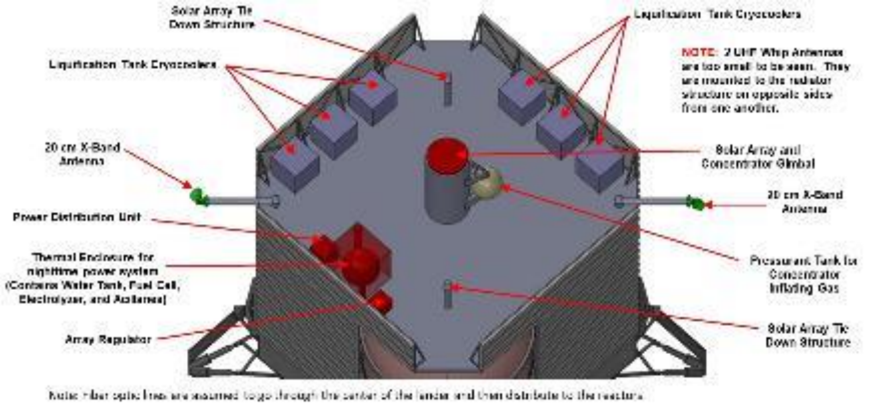
NOTE: Both solar arrays create a width of 15.34 m

Oxygen from Regolith – Full Scale System
Systems Rollup

EXPLORE MOON to MARS

MEL Summary: Case 2 ISRU CD-2018-162	Bus	ISRU System	Excavator System	TOTAL
Main Subsystems	**Basic Mass (kg)**	**Basic Mass (kg)**	**Basic Mass (kg)**	**Total Basic Mass(kg)**
Science	0.0	519.7	200.0	719.7
Attitude Determination and Control	0.0	0.0	0.0	0.0
Command & Data Handling	6.5	18.1	0.0	24.6
Communications and Tracking	42.0	0.0	0.0	42.0
Electrical Power Subsystem	347.3	0.0	12.0	359.3
Thermal Control (Non-Propellant)	340.0	368.2	0.0	708.2
Propulsion (Chemical Hardware)	0.0	115.1	0.0	115.1
Propellant (Chemical)	0.0	0.0	0.0	0.0
Propulsion (EP Hardware)	0.0	0.0	0.0	0.0
Propellant (EP)	0.0	0.0	0.0	0.0
Structures and Mechanisms	774.2	0.0	0.0	774.2
Element Total	***1509.9***	***1021.1***	***212.0***	***2743.0***
Element Dry Mass (no prop,consum)	1509.9	1021.1	212.0	2743.0
Element Propellant	0.0	0.0	0.0	0.0
Element Mass Growth Allowance (Aggregate)	281.9	179.4	43.6	504.8
Additional System Level Growth (For 30% tot)	171.1	127.0	20.0	318.1
Total Wet Mass with 30% Growth	**1962.9**	**1327.4**	**275.6**	**3565.9**





Total payload < 3600 kg lander capability

Oxygen from Regolith – Full Scale System

Powered Equipment List (values are before 30% growth)

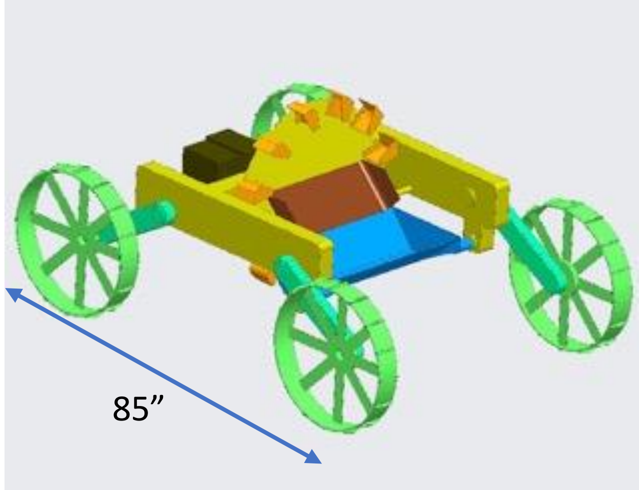
EXPLORE MOON to MARS

Description	Power Mode 1	Power Mode 2	Power Mode 3	Power Mode 4	Power Mode 5	Power Mode 6	Power Mode 7
Case 2 ISRU CD-2018-162	Launch/ Transit and Landing	Commissionin g	Sunlit LOX Production	Sunlit Standby	Night Standby	LOX Transfer	Excavator Recharging
	4 Days	2 Days	7.4 Months	1 - 20 Days	1 - 9 Days	30 Minutes	10 Hours
	(W)	(W)	(W)	(W)	(W)	(W)	(W)
ISRU	32	62	11544	2678	621	2021	298
Bus	11	11	817	1007	438	96	51
Command & Data Handling	10.8	10.8	10.8	10.8	10.8	10.8	10.8
Communications and Tracking	0.0	0.0	85.0	85.0	85.0	85.0	0.0
Electrical Power Subsystem	0.0	0.0	721.0	911.0	342.0	0.0	40.0
Thermal Control (Non-Propellant)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Structures and Mechanisms	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ISRU System	22	52	10727	1672	123	1926	48
O2 Production	0.0	0.0	8080.0	0.0	0.0	0.0	0.0
Command & Data Handling	21.6	47.6	77.6	47.6	47.6	51.6	47.6
Thermal Control (Non-Propellant)	0.0	0.0	2565.2	1620.0	71.9	1620.0	0.0
O2 Storage and Transfer	0.0	4.0	4.0	4.0	4.0	254.0	0.0
Excavator System	0	0	0	0	60	0	200
Excavator	0.0	0.0	0.0	0.0	60.0	0.0	160.0
Electrical Power Subsystem	0.0	0.0	0.0	0.0	0.0	0.0	40.0

Oxygen from Regolith – Full Scale System
Master Equipment List

Description Case 2 ISRU CD-2018-162	Basic Mass (kg)	Growth (%)	Growth (kg)	Total Mass (kg)
ISRU	**2743**	**18%**	**505**	**3248**
Bus	1510	19%	282	1792
Command & Data Handling	6.5	30%	2.0	8.5
Communications and Tracking	42.0	11%	4.4	46.4
Electrical Power Subsystem	347.3	23%	81.5	428.8
Thermal Control (Non-Propellant)	340.0	16%	55.8	395.7
Structures and Mechanisms	774.2	18%	138.2	912.4
ISRU System	1021	18%	179	1200
O2 Production	519.7	17%	86.9	606.6
Command & Data Handling	18.1	30%	5.4	23.5
Thermal Control (Non-Propellant)	368.2	18%	66.3	434.5
O2 Storage and Transfer	115.1	18%	20.7	135.8
Excavator System	212	21%	44	256
Excavator	200.0	20%	40.0	240.0
Electrical Power Subsystem	12.0	30%	3.6	15.6

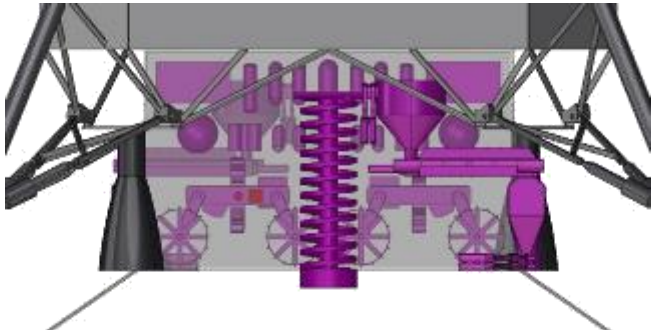
Point of Departure Excavator

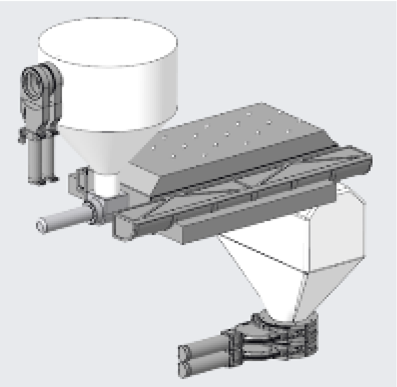


Oxygen from Regolith – BBC

Carbothermal Reduction w/ Solar Concentrator

- Carbothermal Subsystem: **484.1 kg**
  - Reactor based on design by Orbital Technologies Corporation (now part of Sierra Nevada Corp.) scaled down 3.5 mt O_2 / year
  - Reactor bed was re-sized for 14 melt zones
  - Each reactor requires 14 processing zones
  - Assumed 12.1% yield at 1800 °C melt temperature
- Water Electrolysis Subsystem: **122.5 kg**
- Solar Concentrator: **221.2 kg**
  - Requirement: 11.1 kWth energy delivered to each of two ISRU reactors via a 10 m fiber optic run
  - Inflatable: lightest (0.2 kg/m_2), but less accurate – requires secondary concentrator to achieve comparable concentration ratios
- Oxygen Liquefaction/Transfer Subsystem: **135.8 kg**
- **Total Mass: 742.4 kg**



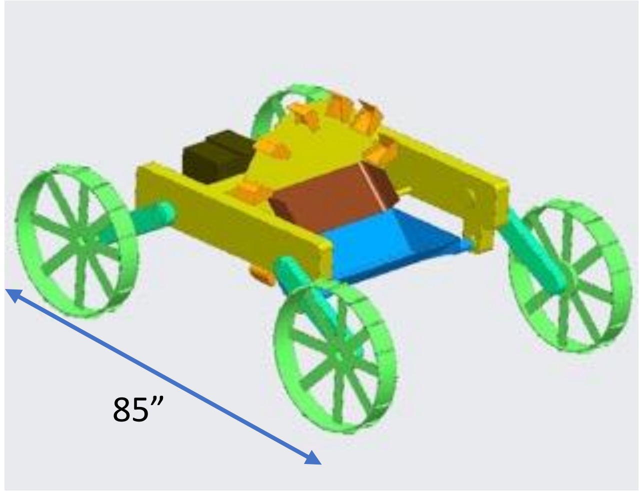


Description Case 2 ISRU CD-2018-162	QTY	Unit Mass (kg)	Basic Mass (kg)	Growth (%)	Growth (kg)	Total Mass (kg)
O2 Production			519.7	17%	86.9	606.6
ISRU Reactor System			193.0	19%	37.6	230.6
Methanation Reactor and Separator	2	10.7	21.4	20%	4.3	25.7
Desulfurization Subsystem	4	10.0	40.0	20%	8.0	48.0
Carbothermal Reduction Chamber	2	45.3	90.6	20%	18.1	108.7
Recycle Loop Compressors	2	0.4	0.8	20%	0.2	1.0
Condenser Heat Exchanger	2	4.3	8.6	20%	1.7	10.3
Hydrogen Tank	2	2.1	4.2	8%	0.3	4.5
Methane Tank	2	2.1	4.2	8%	0.3	4.5
Condenser/Electrolyzer Water Tank	2	7.1	14.2	20%	2.8	17.0
System Gas Tank, with Compressor	2	4.5	9.0	20%	1.8	10.8
Materials Processing and Handling			224.6	13%	28.9	253.5
Supply Hopper	2	9.5	19.0	20%	3.8	22.8
Spent Hopper w/ Valve	2	22.0	44.0	20%	8.8	52.8
Feed Auger w/ Valve	2	22.8	45.6	20%	9.1	54.7
Size Sorter Dump Trough w/ 2 Augers	1	36.0	36.0	20%	7.2	43.2
Vibratory Conveyor	2	40.0	80.0	0%	0.0	80.0
Electrolyzer			102.1	20%	20.4	122.5
Pump	2	1.5	3.0	20%	0.6	3.6
Electrolyzer Subsystem	2	38.9	77.8	20%	15.6	93.4
Dryer Subsystem	2	0.9	1.8	20%	0.4	2.2
Valves and Lines	2	9.7	19.4	20%	3.9	23.3
Semi-Passive Thermal Control			187.5	18%	33.7	221.2
Concentrator	1	34.8	34.8	18%	6.3	41.1
Fiber Optic Lines	1	116.3	116.3	18%	20.9	137.2
Fiber Optic Line Holder	1	10.0	10.0	18%	1.8	11.8
Deployment Gas & Tank	1	26.4	26.4	18%	4.8	31.1
O2 Storage and Transfer			115.1	18%	20.7	135.8
LOx System			115.1	18%	20.7	135.8
LOx System			115.1	18%	20.7	135.8
LOx Liquification System	1	54.0	54.0	18%	9.7	63.7
LOx Intertank Feed System	1	20.9	20.9	18%	3.8	24.7
LOx Refueling System	1	18.7	18.7	18%	3.4	22.1
Valves and Mods to Press. System	1	21.5	21.5	18%	3.9	25.4

Oxygen from Regolith – BBC
Excavator

Excavator Concept

- Excavator design based on Astrobotic Polaris design
- Transverse bucket wheel delivers regolith into central holding tray
- 200 kg excavator tested in gravity-offloading tests
- Digging rate: 0.5 kg/sec
- Baseline driving velocity: 28 cm/s
- Demonstrated payload ratio: 25 – 50 %



Mass Breakdown:

- 128 kg per excavator x 2 = 256 kg (with growth)

Power Breakdown:

- 1 kW-hr battery discharged maximum 80% (50 charge cycles per ‘year’)
- Charge with 100 W for 10 hours using inductive charge plate housed on floor of lander box

Description Case 2 ISRU CD-2018-162	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
		(kg)	(kg)	(%)	(kg)	(kg)
Excavator System			212	21%	44	256
Excavator			200.0	20%	40.0	240.0
Excavation and Processing			200.0	20%	40.0	240.0
Mobile Excavator with transverse bucket wheel	2	100.0	200.0	20%	40.0	240.0
Electrical Power Subsystem			12.0	30%	3.6	15.6
Power Management & Distribution			12.0	30%	3.6	15.6
DC to AC rover recharge	2	4.5	9.0	30%	2.7	11.7
Rover recharge coupling	2	1.5	3.0	30%	0.9	3.9

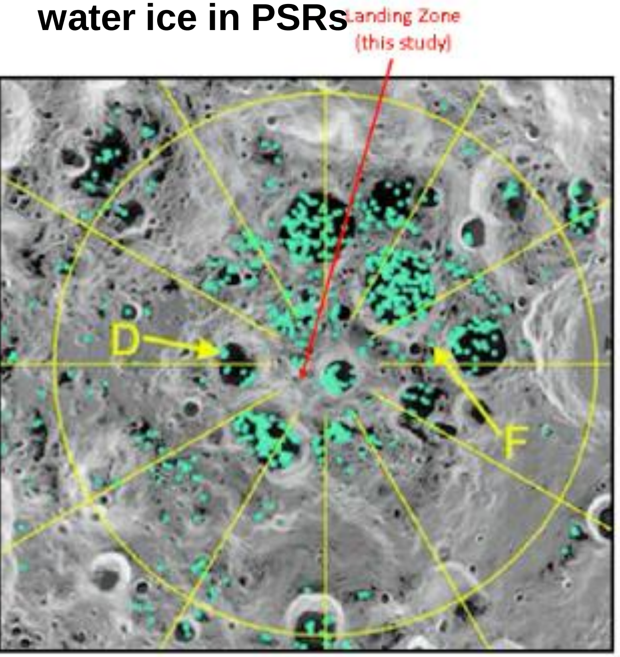
Polar Water Prospecting & Mining

Potential South Pole Landing Sites

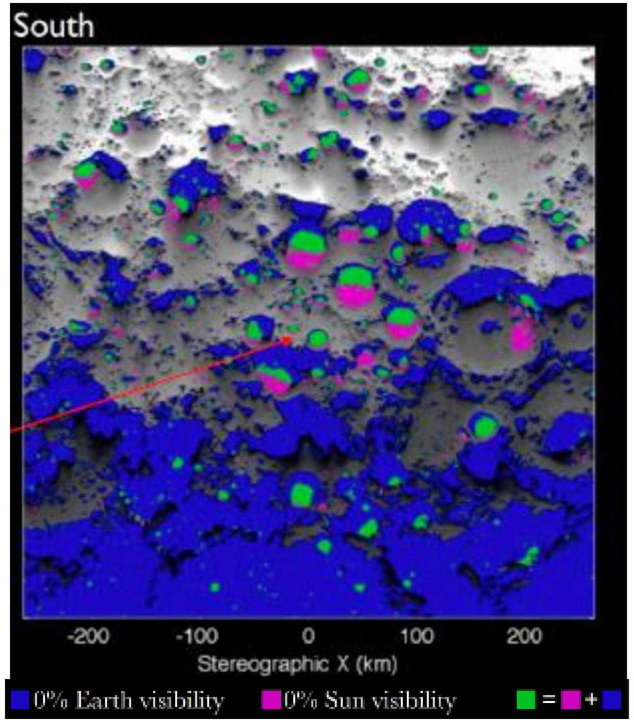
Selection Criteria for Polar Ice

EXPLORE MOON to MARS

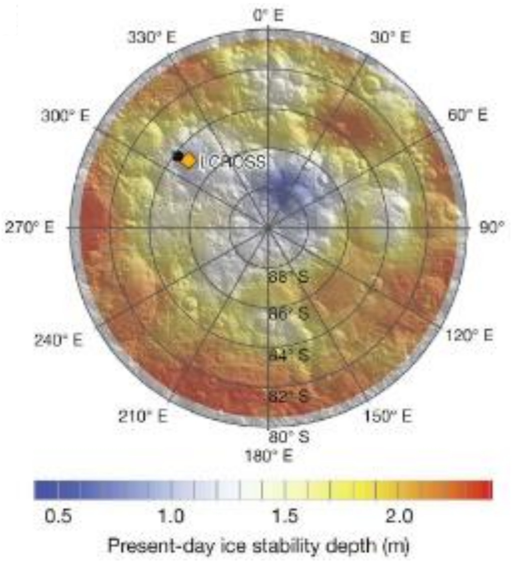
Direct evidence of surface exposed water ice in PSRs



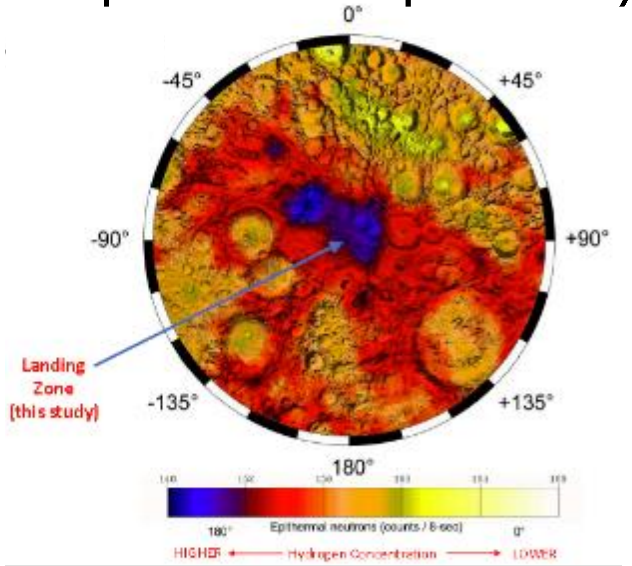
Earth/Sun Visibility



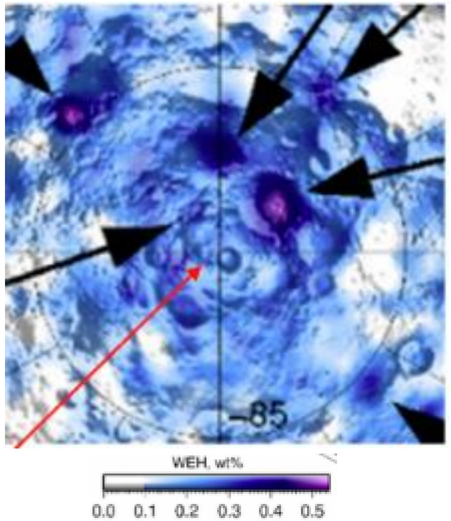
Ice Stability Temperatures



Evidence of Hydrogen (Lunar Prospector Neutron Spectrometer)



LEND Neutron Spectrometer

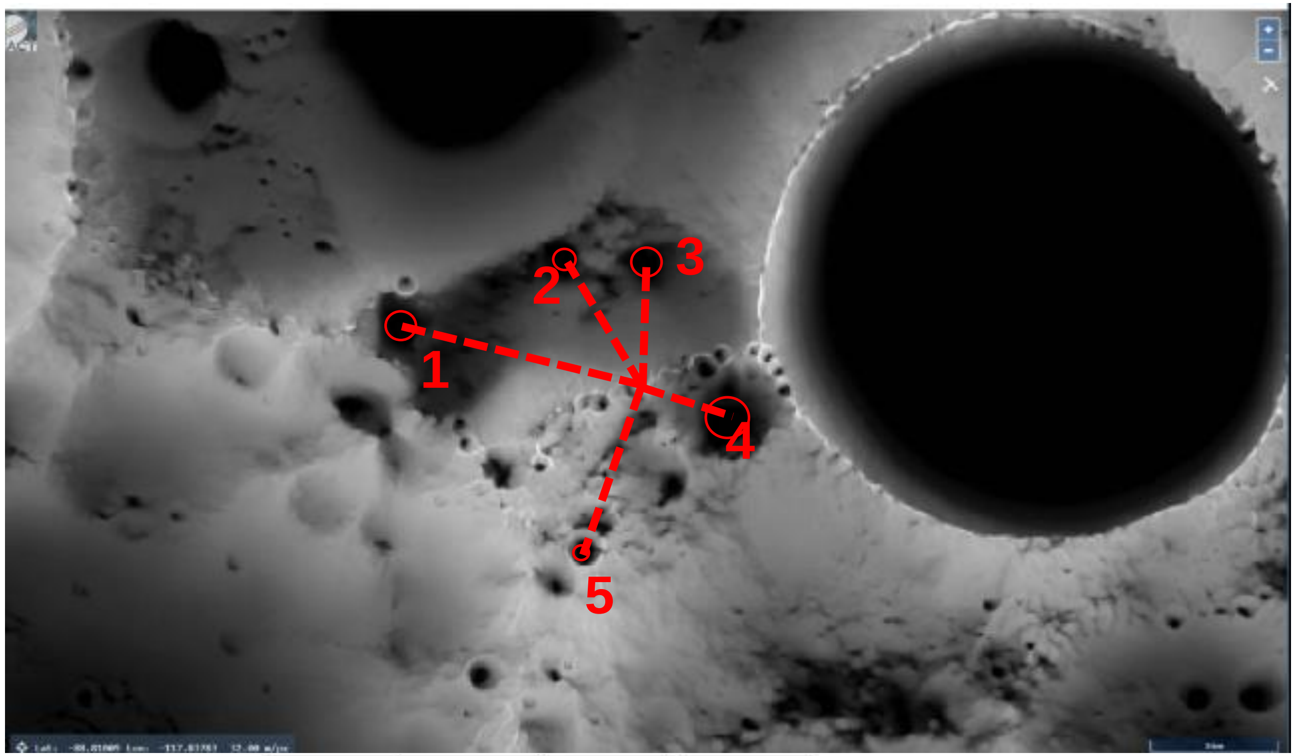


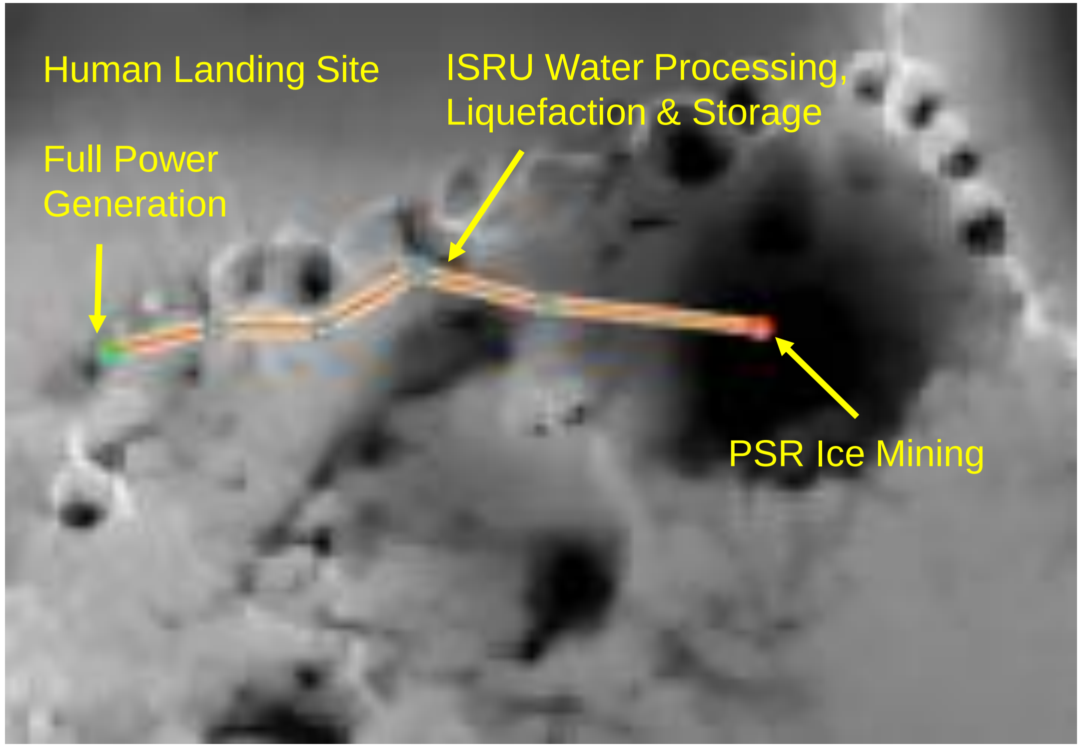
- Access to Sunlight for Infrastructure, Processing, Landing
- Reasonable terrain to Permanently Shadowed Crater (PSR)
- Nearby PSR with strong indications of water (H_2, Thermal Stability, Surface Frost)
- Earth visibility (need is reduced with communications satellite)

Potential South Pole Landing Sites

‘Spudis Ridge’ South Pole

ISRU Ridge Site *Current Baseline



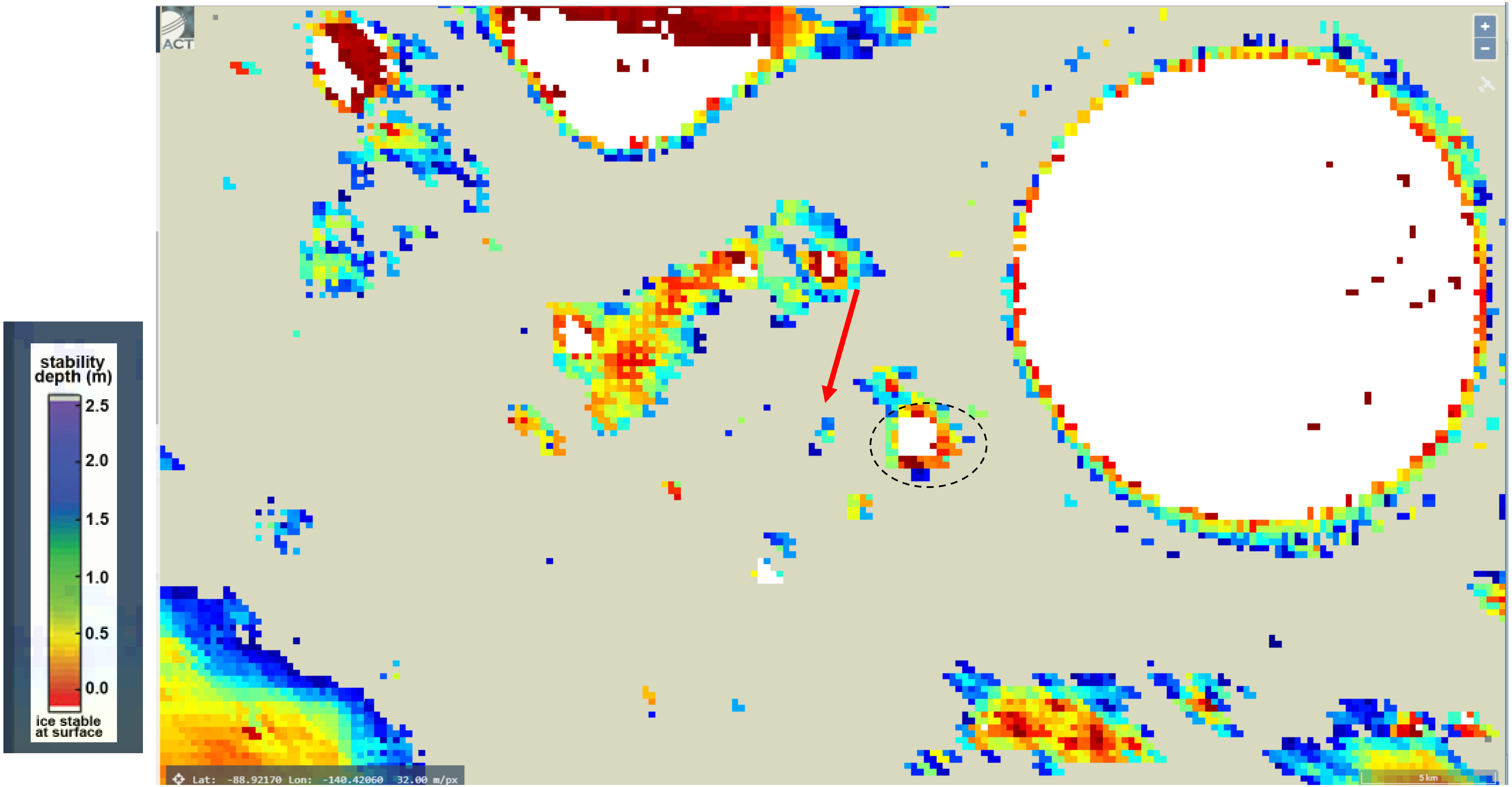


	Distance, m	Max Slope, deg	Approx. dia of PSR ice region, m
PSR 1	9105	14	1000
PSR 2	5654	19	500
PSR 3	4737	21	500
PSR 4	3500	16	1500
PSR 5	6688	21	500

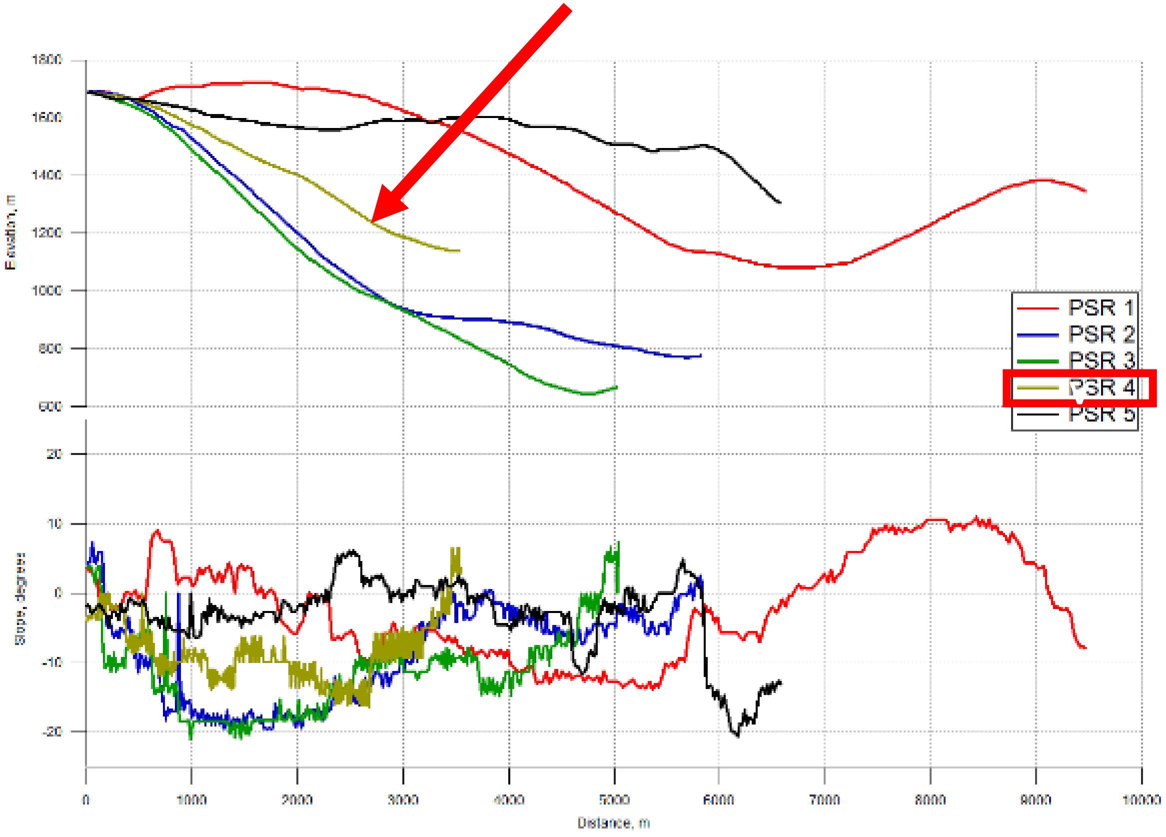
	Distance, m	Max Slope, deg	Approx. dia of PSR ice region, m	Ridge Longitude	Ridge Latitude	PSR Longitude	PSR Latitude
PSR 1 straight	6600	20	1000	-137.34 (222.64)	-89.45	-116.94	-89.38
PSR 4 straight	6500	18	1500			-158.79	-89.57
PSR 4 Ridgeline	6850	15	1500			-158.73	-89.58

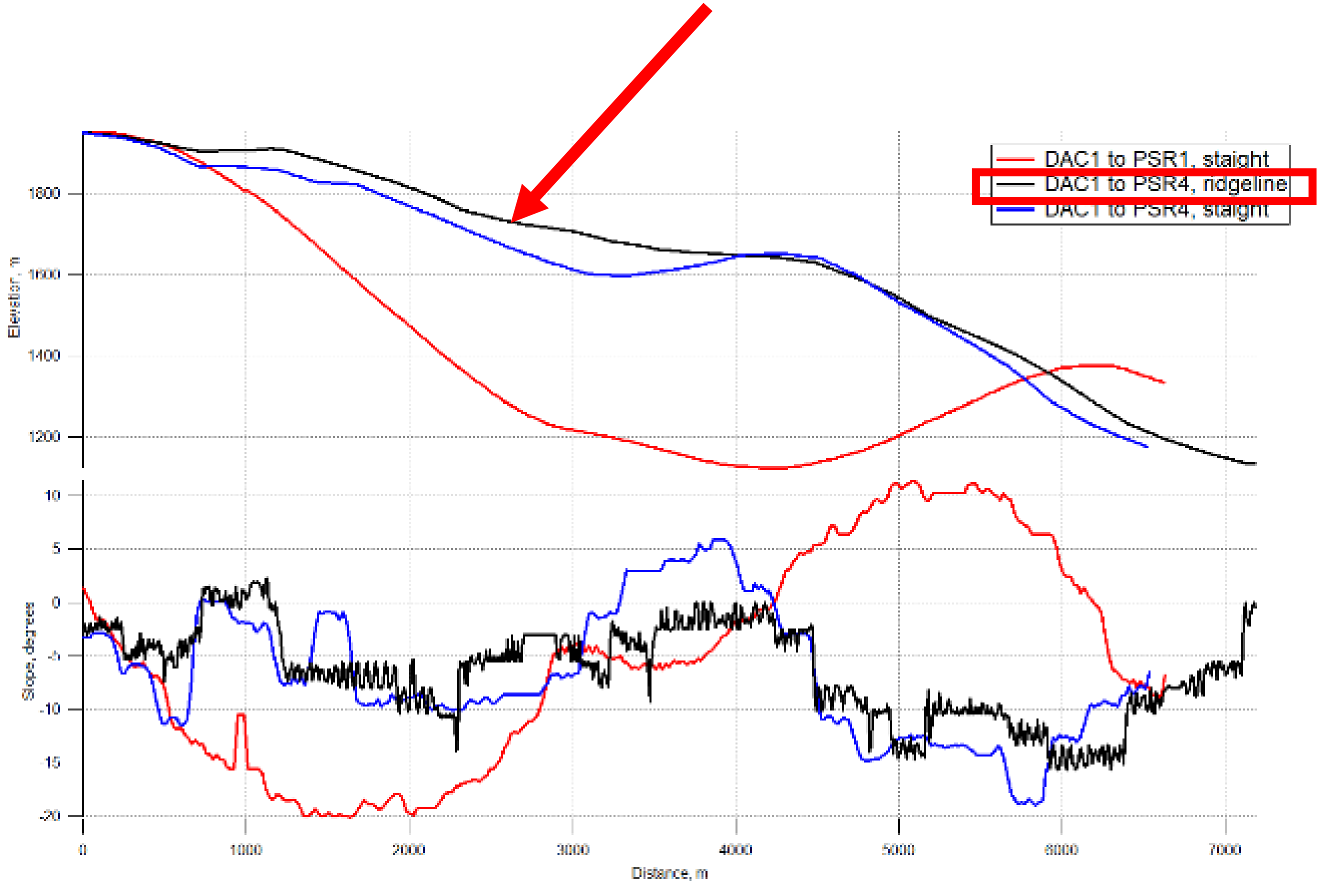
Ice stability depth (Diviner)

- Arrow indicates ridge (sunlight) hardware location
- White areas are surface stable ice



PSRs Near 'Spudis Ridge' and Traverse Paths





Lunar Polar Ice Mining Architecture Options

EXPLORE MOON to MARS

Lunar Polar Water Mining requires:

- Assessable resources in permanently shadow region (PSR)
- Nearby long-duration sunlit area for ISRU and human mission infrastructure
- Sustained communications with Earth (direct or relay)

Options involve Extraction Process and what Hardware/Operations are performed in PSR

Preliminary Study

1. **Icy Regolith is transported to sunlight ridge where it is processed and converted to propellant**
2. **Icy Regolith is processed in PSR; Power is required in PSR**
   - Water is delivered to Propellant production and storage at sunlight ridge
   A. Mobile excavators deliver to a stationary extractor in PSR. Water is delivered out of PSR to production plant using a mobile water tanker.
   B. Excavation and water extraction is housed on mobility platforms that remain in PSR. Water is delivered out of PSR to production plant using a mobile water tanker.
3. **Icy Regolith Excavation/Processing Plant is Mobile**
   - One mobility platform excavates, extracts water, and delivers water outside PSR.
4. **In-situ: Water is removed from the soil without excavating soil**
   - Regolith Process and Power are inside PSR; Water is delivered outside of PSR for Water Processing & Product Storage

'Best' Architecture is predicated on

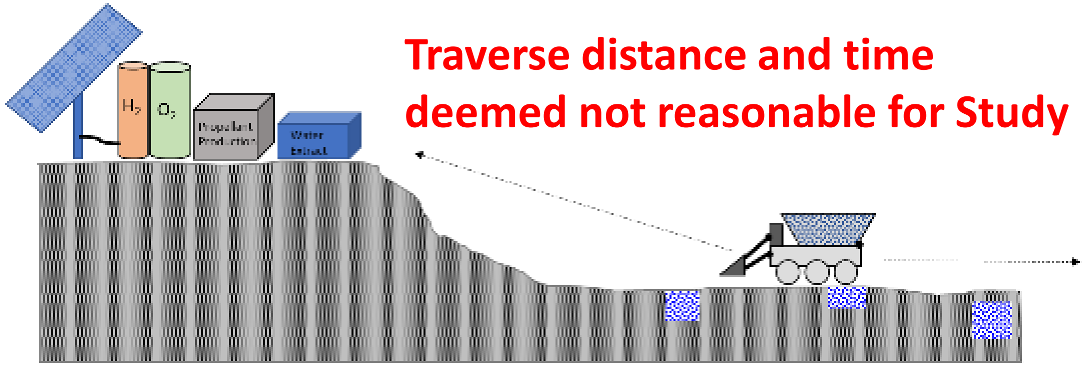
- Mining site selected: resource location and infrastructure location
- Resource properties: hardness and resource concentration, depth, and distribution

Lunar Polar Ice Mining Architecture Options & Technologies

EXPLORE MOON to MARS

1. Icy Regolith is transported to sunlight ridge where it is processed and converted to propellant

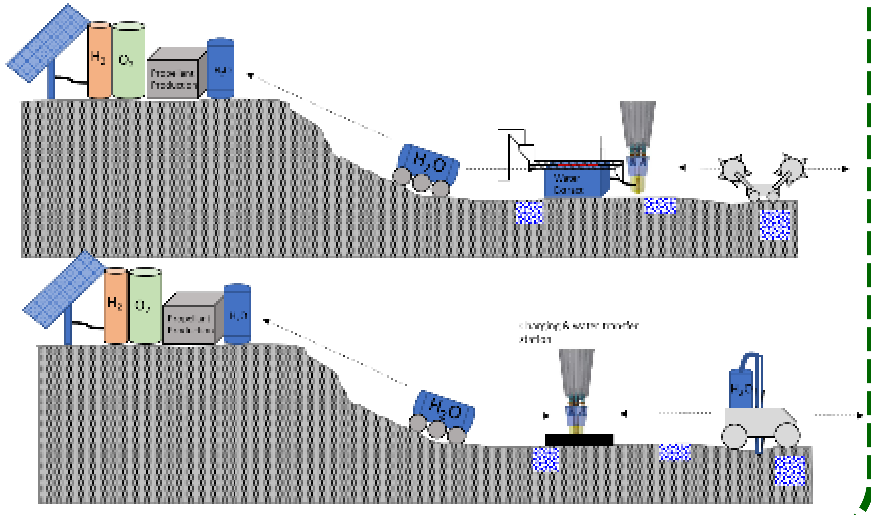
Traverse distance and time deemed not reasonable for Study



2. Icy Regolith is processed in PSR; Power is required in PSR Plant.

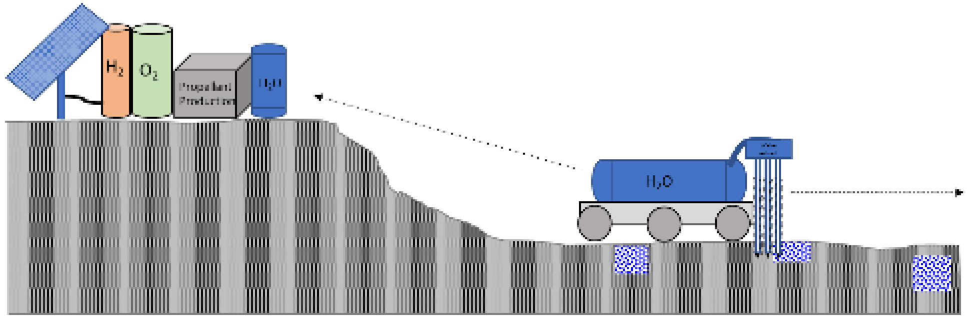
A. Stationary water extraction

B. Mobile water extraction

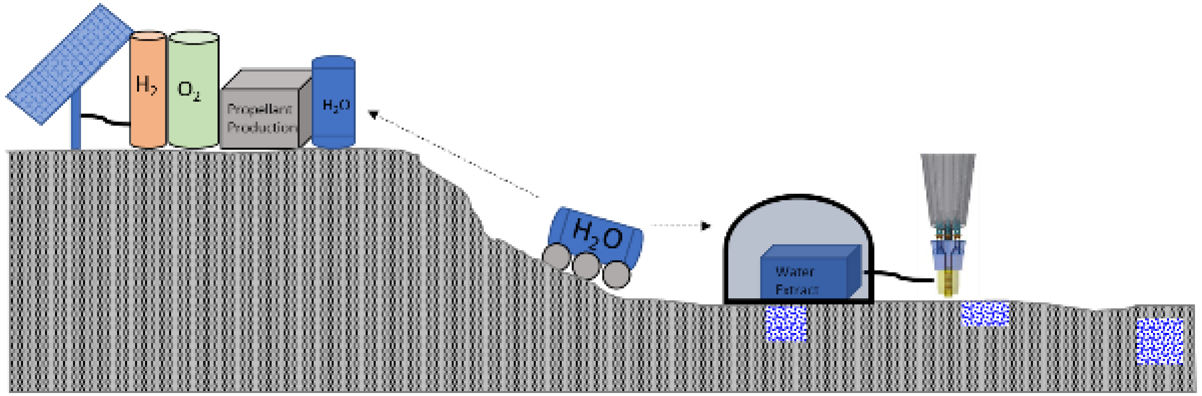


Preliminary Study

3. Icy Regolith Excavation/Processing Plant is Mobile



4. In-situ: Water is removed from the soil without excavating soil



Polar Water Mining Ground Rules & Assumptions

EXPLORE MOON to MARS

- **10 mT of Oxygen and 1.7 mT Hydrogen produced in 1 year**
  - 1 yr = 225 days, consecutive solar availability
  - Need 15.3 mT of Water ; hydrogen is driving requirement (11.3 mT water need to give oxygen)
- **Location: South pole, Shackleton area ("Spudis" ridge)**
  - Propellant plant is in Sunlight location. Water resource is some distance away in PSR
  - Environmental conditions (including traverse distances, slopes, temperatures) at notional Sunlight and PSR locations from Diviner data in Quickmaps software
- State power needs (thermal and electrical) for both Ridge and PSR but mass of power system is NOT included
- Propellant production plant is assumed same for all architectures and located on ridge in sunlight
  - This plant includes everything downstream of (and including) water cleanup (eg. water cleanup, electrolyzer, storage tanks)
  - Transfer of propellant to descent stage is not addressed
- Deployment of equipment is NOT considered in this trade, even though it may influence trade (particularly when PSR emplacement is needed)
- Thermal management is only considered on relevant component level (eg tanks) not on system scale

Polar Ice Mining Study Goals & Approach

Goals

- Trade the different architecture scenarios for Lunar Polar Water ISRU to identify a baseline for a COMPASS study
  - Outcome will also be used for technology development plans, prospecting needs, CLPS demos, etc.
- Examine different Architecture options:
  - Identify baseline hardware for each option
  - Estimate Mass & Power needs for each
  - Identify top level con-ops (needed for mass/power estimates)
- Landing Site set for this study so that terrain, resource availability, and environment conditions can be fixed

Approach: Preliminary study

- Choose baseline hardware/technologies for each architecture
  - Use actual hardware and empirical data when possible (higher TRL hardware will be selected when available)
  - Hardware selected is not optimized solution, selected based on highest fidelity models/hardware
- Examine scenarios based on the following key parametrics
  - Number of trips into the PSR. Fewest number of trips is preferred, but may not be most optimum mass/power solution
  - Water concentration in soil
  - ConOps timelines: Trades include processing time, recharge time, traverse time, etc. Balance these to give a reasonable ConOps

Polar Water Mining Concept Comparisons

EXPLORE MOON to MARS

- **At least 8 concepts are currently being explored including:**
  - **Excavation w/ Auger dryer**
  - **Heated coring auger**
  - Microwave heating
  - Heated Dome

- **Application of concepts are highly dependent on:**

Resource Depth Access: How deep the water resource can be for a given concept to work.

Spatial Resource Definition: Defines the spatial resolution of the resource location needed for successful deployment.

Volatiles retention: How much of the volatiles in the raw material are captured vs lost to the environment.

Material Handling: How much interaction is required with the regolith.

Concepts	Architecture Option			Status	Resource Depth access	Spatial Resource definition	Volatiles retention	Material Handling
	IRSU plant	Mobile	In-situ					
Auger Dryer	X			Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Microwave Vessel	X	?		Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Microwave Zamboni		X	X	Concept Study	Surface	10s of Meters	Low	Low
Vibrating Tray	X	X		Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Coring Auger		X	X	Breadboard Laboratory hardware	Deep (m)	Meters	High	Moderate
Heated Dome			X	Concept Study	Surface	Meter	High	Low
Heated batch (Resolve EBU)	X	?		Field demonstrations	Moderate (cm)	10s of Meters	Low-moderate	High
Water jet/Dome			X	Concept Study	Moderate (cm)	Meter	High	Low

2A. RASSOR with SCD

For baseline scenario 7/10/19: 5% water content, 22 trips out of the PSR, 24hrs water transfer/recharge at sunlit ridge propellant plant.

Mass Breakdown:

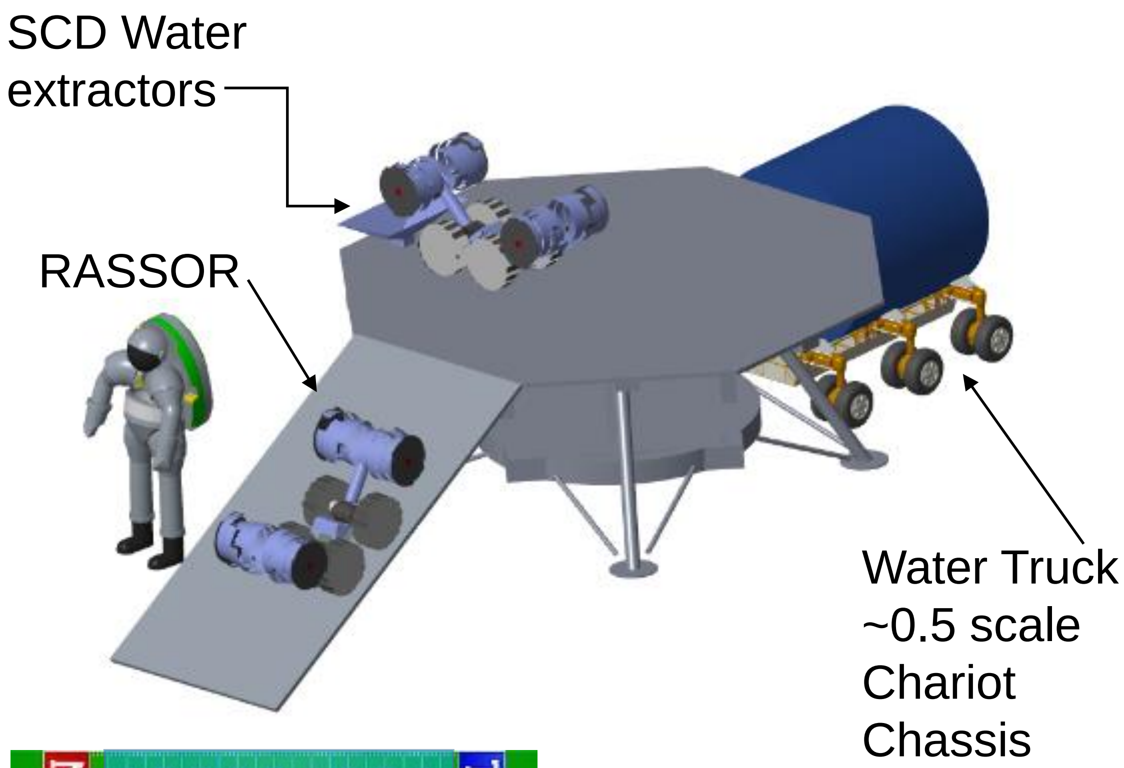
- Excavator: Rassors (2): 86 kg each
- Water extraction: Auger dryer (1): 104 kg*
- Water Tanker: Subscale Chariot (1): 1684 kg*
- Total Mass: 1.96 mT (metric Ton)

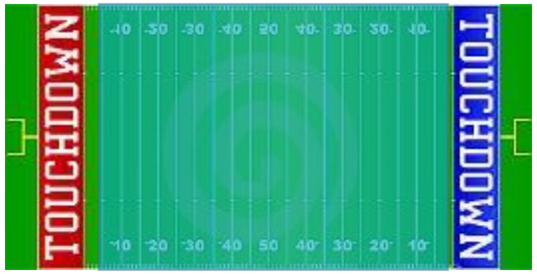
*masses include 15% margin for structure, 20% margin for growth

Power Breakdown:

- PSR Power Total: 12 kW
    - Thermal power (water extraction): 11.7 kW
    - Electrical power: 0.3 kW
- ISRU plant (ridge) Power: 9.6 kW
    - Thermal power (water conditioning): 3.5 kW
    - Electrical power (battery recharge): 6.1 kW
- Total Power: 21.6 kW

Excavation Area/year (5% water by mass): 53.3 x 94 yds





2B. RP Rover with PVEx- BBC

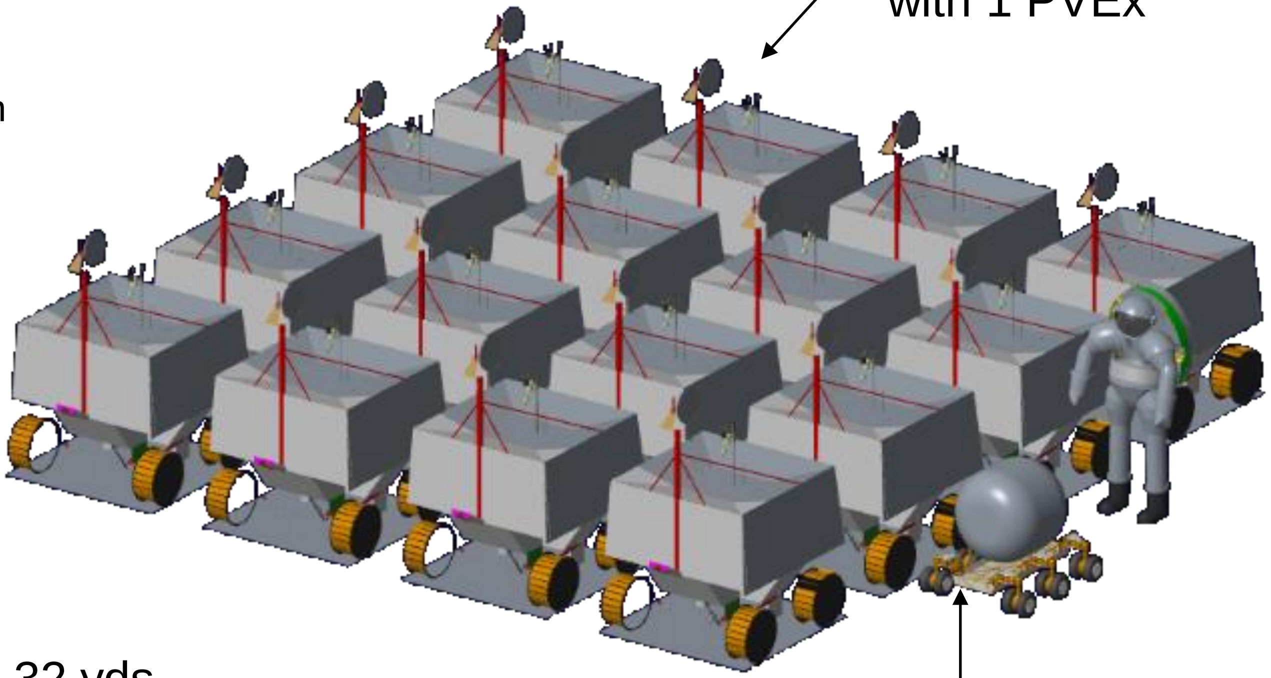
For baseline scenario 7/10/19: 5% water content, 28 trips out of the PSR, 12 hrs water transfer/recharge at sunlit ridge propellant plant.

Mass Breakdown:
- Mobile water extraction (RP + PVEX*): 12 mT (300kg x 40)
- Water Tanker (Subscale Chariot): 1.99 mT*
- Total Mass: 14 mT (metric Ton)

*masses include 15% margin for structure, 20% margin for growth

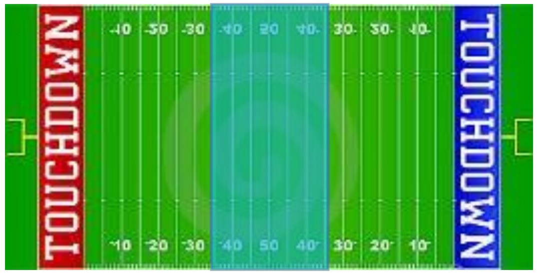
Power Breakdown:
- PSR Power Total: 13.3 kW
  - Battery recharge only
- ISRU plant (ridge) Power: 10.4 kW
  - Battery recharge only
- Power Total: 23.7 kW

RP Mobility Platforms each with 1 PVEx



Water Truck 0.27 scale Chariot Chassis

Excavation Area/year (5% water by mass): 53.3 x 32 yds
- 23000 holes
- 580 holes/PVEx
- 120 holes/day



3. Mobile Water Extraction - BBC

For baseline scenario 7/10/19: 5% water content, 112 trips out of the PSR, 20 hrs water transfer/recharge at sunlit ridge propellant plant.

Mass Breakdown:

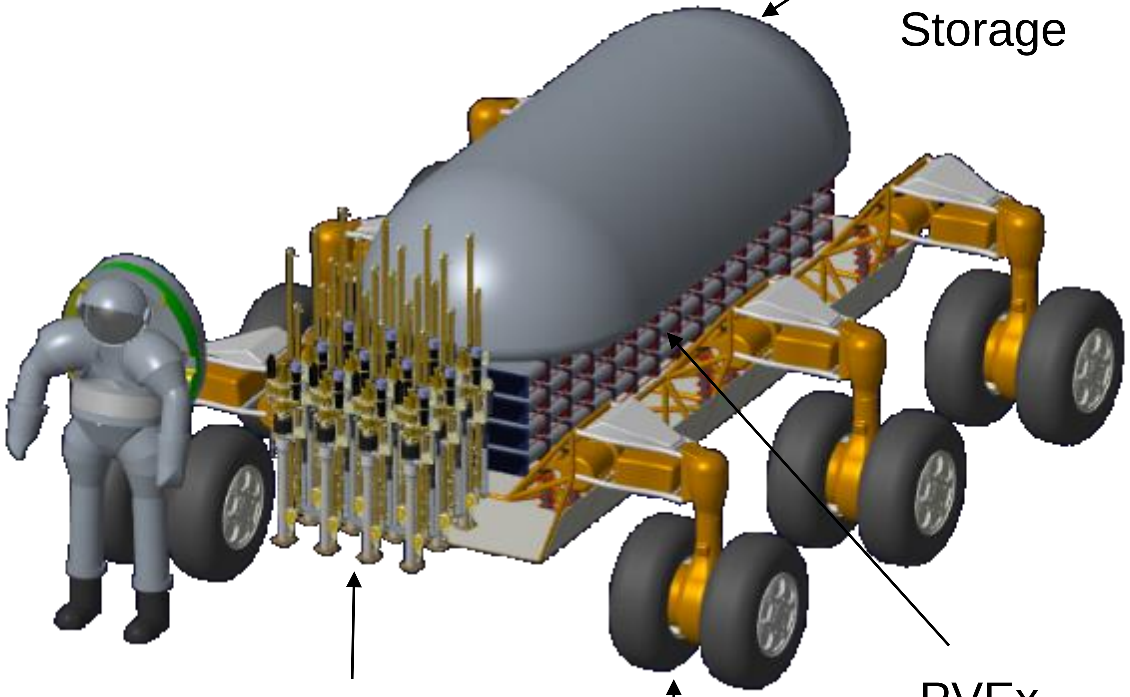
- Empty Chariot Chassis: 2458 kg
- Chariot Payload Subtotal: 1239 kg
    - PVEx Array (14): 210 kg
    - Additional batteries (in addition to chariot baseline): 3567 kg
    - Condenser/Radiator/Storage Tank: 102 kg
    - Margin (15% Structure, 20% Growth): 926 kg
- Total: 7.28 mT (metric Ton)

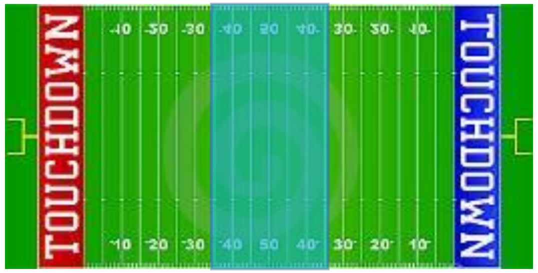
Power Breakdown:

- Chariot Battery Charging, 20hr: 46 kW

Excavation Area/year (5% water by mass): 53.3 x 32 yds

- 23178 holes/year
- 1655 holes/PVEx
- 197 holes/day





Assumptions for Baseline Water Mining Cases

EXPLORE MOON to MARS

For this trade, parameters were chosen to give a moderate power/mass solution to each scenario (semi-optimization). The critical variables are shown for each scenario along with a description of their impact.

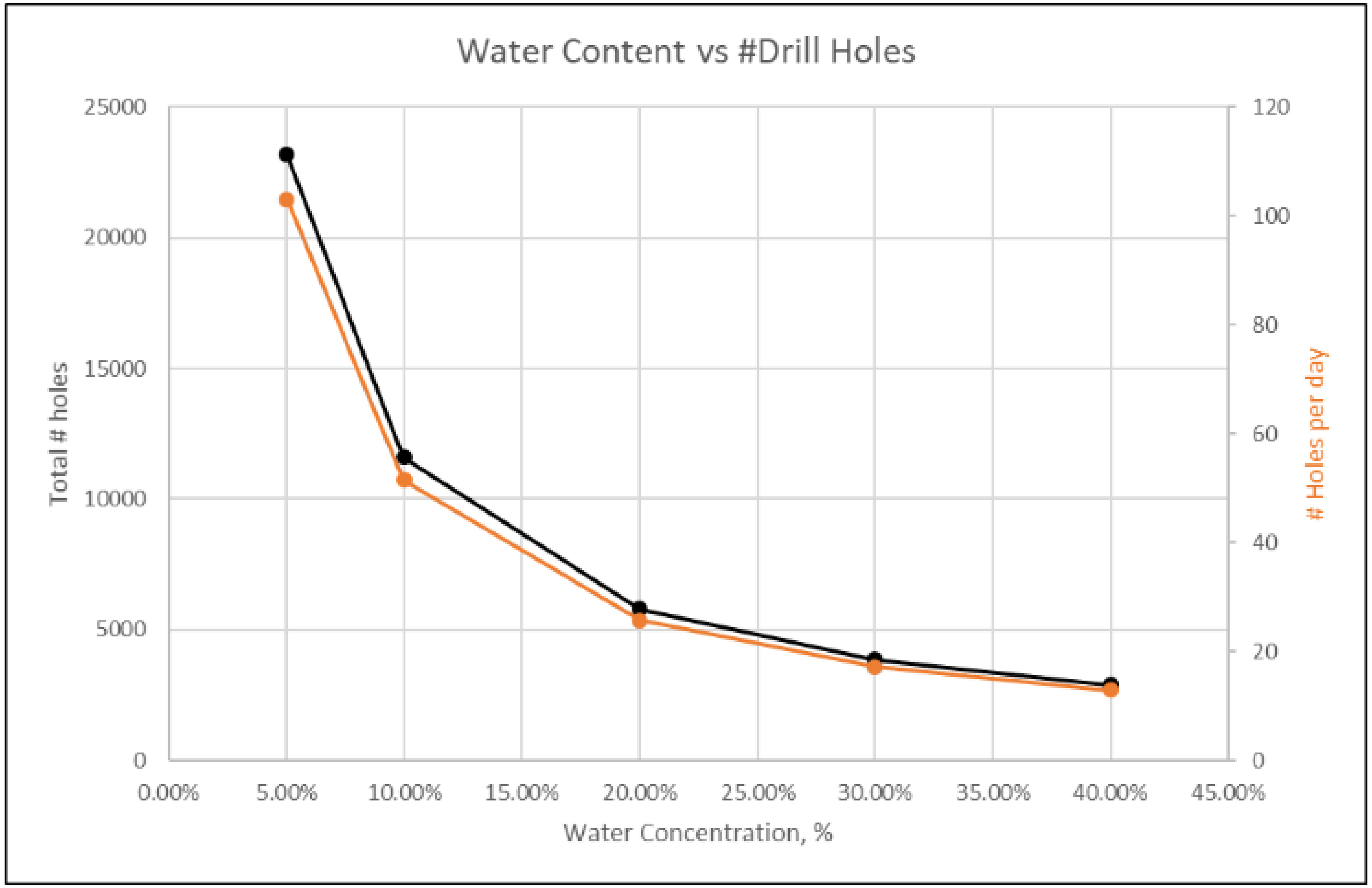
Scenario	2a	2b	3	Impact of parameter
Soil Water content	5%	5%	5%	Higher number reduces mass & power across the board
Number of mobility platforms	3	41	1	For 2a this number is calculated based on amount of soil needed. For 2b it set based on water processing time per PVEX (separate thermal model). For 3 the definition of the scenario is to have 1 platform.
Number of excavators	2	40	14	For 2b and 3 this is the number of PVEX systems, where for 2b there is one PVEX per mobility platform and in 3 all the PVEXs are mounted to one large mobility platform (Chariot)
Days in PSR	10	8	2	Semi optimized number based on mass/power.
Number of trips out of PSR	22	28	112	= days in PSR ÷ 225 days (total production time)
Recharge time in PSR (each excavator)	5hr	5hr	NA	A longer recharge time requires less power from the surface power source. Shorter recharge times allow for faster processing: potentially fewer mobility platforms and/or less water extraction energy (more time for processing = less power)
Recharge time at Ridge	24 hr	12 hr	20 hr	A longer recharge time requires less power from the surface power source. Choice is based on con-ops of system. These numbers are generally the longest time that can be afforded based on earlier assumptions.

2B & 3. Water Extraction plant using Core drill PVEx

Results – Holes Required vs Ice Concentration

EXPLORE MOON to MARS

PVEx is a heated coring drill from Honeybee robotics that combines excavation and water extraction into one tool. It is being considered for an early ISRU CLPS demo. The trade below highlights challenge of using this system for large scale ISRU.



Key Assumptions

- The drill is 5 in diameter, 0.75m. The diameter is larger than the current designed drill (2 in), which would increase production per drill over current SOA.
- The extraction efficiencies are based on empirical data from the SOA 2 in diameter unit.
- Water contents are the average over the entire core length. No distinction was made in the model depth distribution of water.

Key Results:

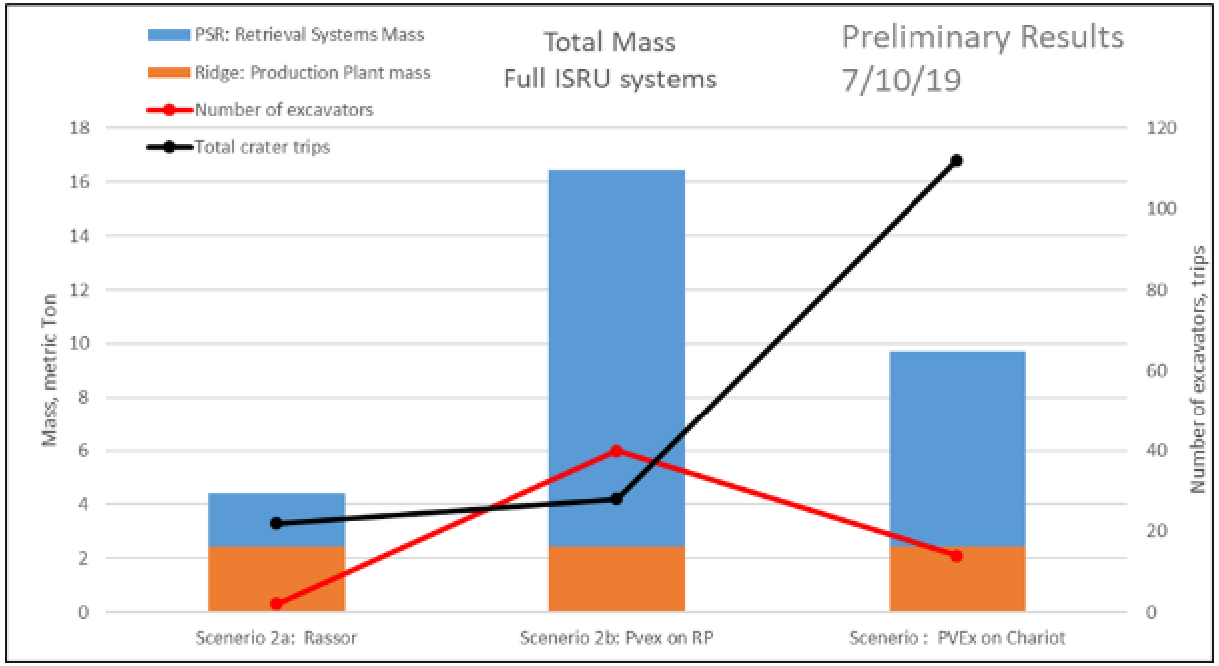
Water Content	Total # drill holes	Drill holes per Day	Drill holes Per Bit
5%	23,000	103	1430
15%	7700	40	480
30%	3800	17	240

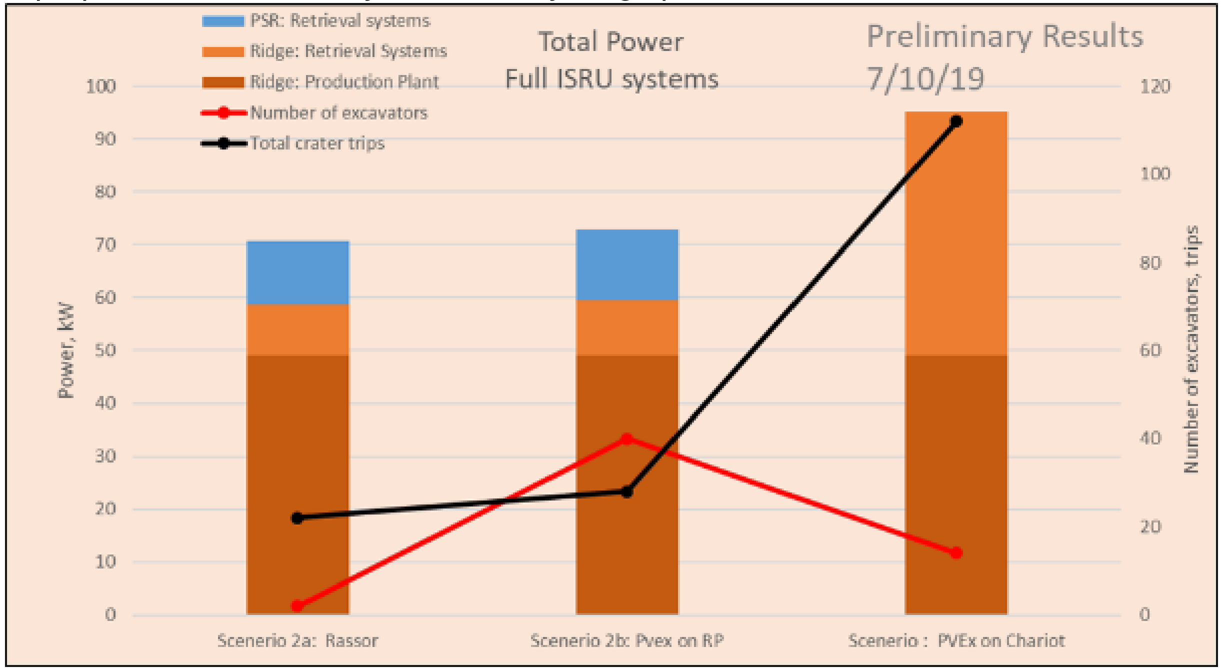
Wear/Life of drill bits may be ~100 holes per bit (rough estimate from Honeybee Robotics). The number of feasible bit changes over the life is TBD.

Trade (2A, 2B, 3) : Baseline Comparison

For this trade, parameters were chosen to give a moderate power/mass solution to each scenario (semi-optimization).

The ridge production plant is the system that processes water into propellants. Retrieval System are anything upstream of this.

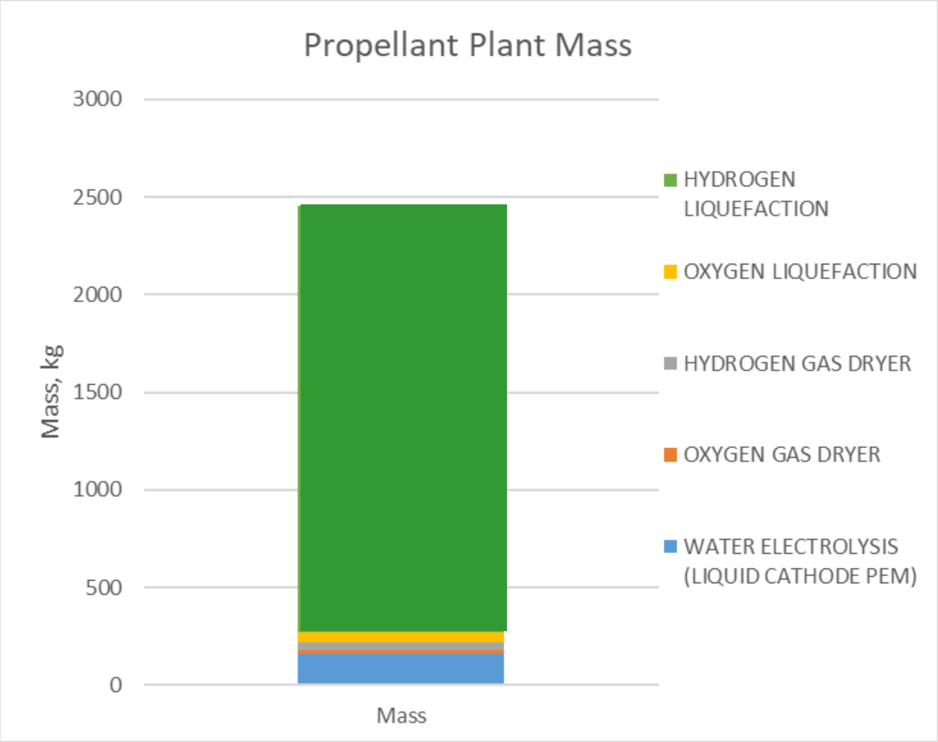


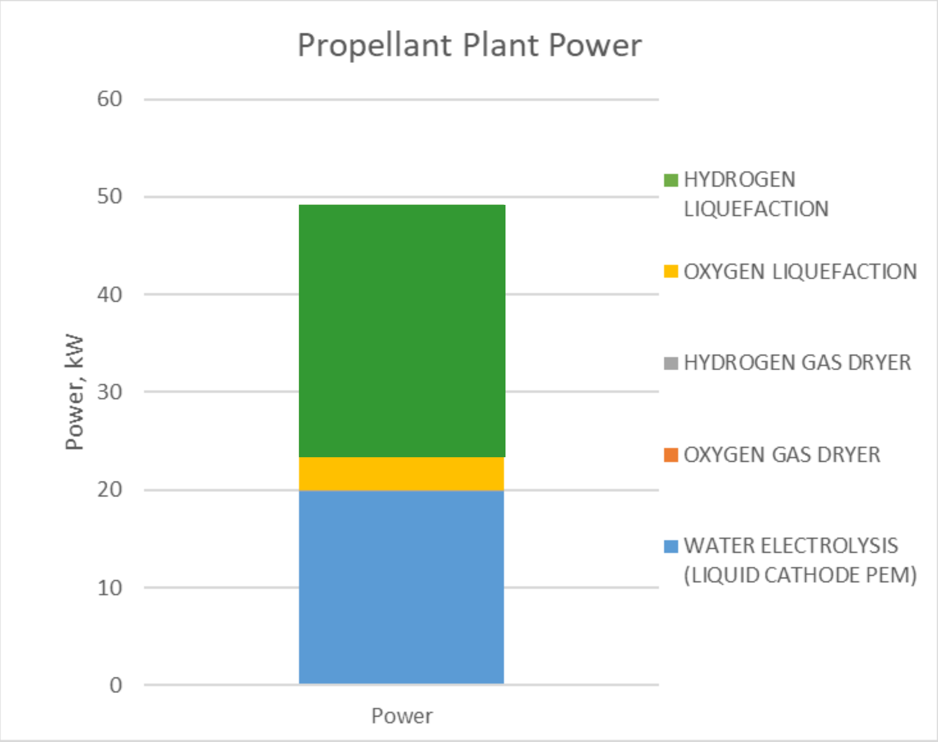


- **Scenario 2a is the best trade in terms of mass and power**
  - Note that the Auger water extractor parameters were set to best case. However when using more conservative numbers 2a remains the lowest mass options while power is comparable (slightly higher) than 2b.
  - Only 2 Rassor systems are needed due to the throughput of the Auger water extractor and the conops timelines. Thus 2a could be done with only 3 mobility systems.
  - Over 90% PSR power requirement is direct thermal power (to extract water). Waste heat could be used to reduce electrical power required.
- **Scenario 2b is highest mass due to large number of mobile excavators.**
  - This could be improved if a different mobility platform is used. The RP mobility platform payload capacity and battery restriction are driving this.
  - Power is comparable to 2a but since water extraction is on a mobile platform all thermal energy must come from the battery. Thus power requirements show here are for battery recharges; frequent recharges offset the large thermal energy requirements.
- **Scenario 3 has the benefit of one mobility platform and no PSR power requirements, but the cost is many trips in/out of the PSR and higher power requirement at the ridge**
  - All the power required is to recharge the Chariot batteries. The recharge time is as high as the conops will allow to reduce this power draw.
  - The system must traverse the PSR every other day due to battery and mass restrictions.

Propellant Production Plant breakdown

The propellant production plant is the same in all scenarios and is located at a fixed location at the sunlit ridge site to leverage solar power option.





- The propellant production plant is same for all scenarios. It is located at the ridge site to leverage solar power.
- The largest mass and power is the hydrogen liquefaction system. **This is a technology development need.**
  - Consulted with CFM personnel to get specifications on existing cyrocooler systems that could meet needs.
  - Other conceptual systems offer better specifications and could be traded to improve estimates
- Water electrolysis remains one of the largest power draws

Initial Observations from Polar Water Mining Study

EXPLORE MOONtoMARS

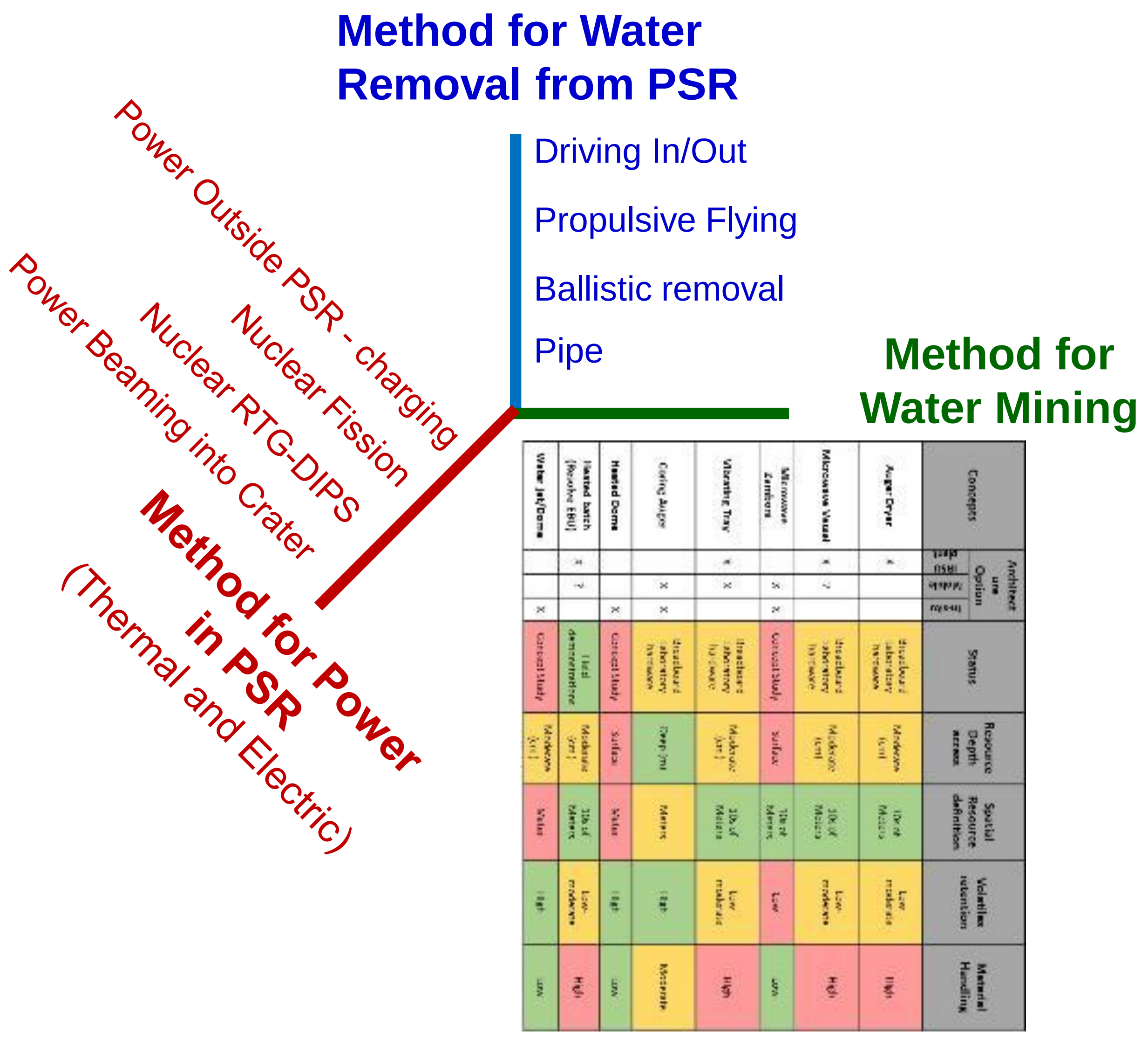
- **Any PSR of significant size requires mobility platform to traverse slopes of around 15 degrees**
  - Some shallower or near PSRs may contain water, but for this study only PSRs that have high probability of surface water were traded
- **All scenarios require multiple trips into PSRs. The capability of mobility platforms for this type of operations are unknown.**
  - The scenario with the fewest number of PSR trips still requires 10 trips at 5.25 km (includes margin for hazard avoidance) each way over 15deg slopes.
  - Consistency of PSR material is unknown… fluffy material will pose greater difficultly
  - Repeating traverses over same path raises significant trafficability concerns:
    - 'Road' construction (surface stabilization) may be needed in the long term
    - Alternative approach to water delivery to infrastructure outside of the PSR
- **Scenario 2A offers the best all around solution**
  - It requires the fewest number of PSR traverses with the lowest total mass. While PSR power is required, 90% of that power requirement is heat that some of which could be recuperated
- **Scenario 2B is the highest mass solution, but power is comparable to 2A.**
  - The number of PSR traverses can be moderate at ~20. But using the current parameters requires ~40 mobility platforms.
- **Scenario 3 has the benefit of one mobility platform and no PSR power source, but the cost is many trips in/out of the PSR**

Polar Mining Study Takeaways

- **Initial Results suggest that there are three main drivers for Water Mining Architecture viability**
  - Method of Water removal from Crater
  - Method of Power in Crater
  - Method of Water Mining

- **Location of Infrastructure (**extended sunlit locations) **and Location of Water** (PSR) **can strongly influences both Method of Water Mining and Method for Power in PSR**
  - Long traverse distances can promote architectures with limited number of trips in/out of PSR for water removal
  - Power in PSR strongly preferred for reducing trips in/out of PSR

- **Method for Water Mining will be highly dependent on concentration/depth of water resource**
  - Hard material may require drilling; however, number of drill holes raises maintenance issues



Next Steps for Polar Water Mining Architecture Evaluation

EXPLORE MOON to MARS

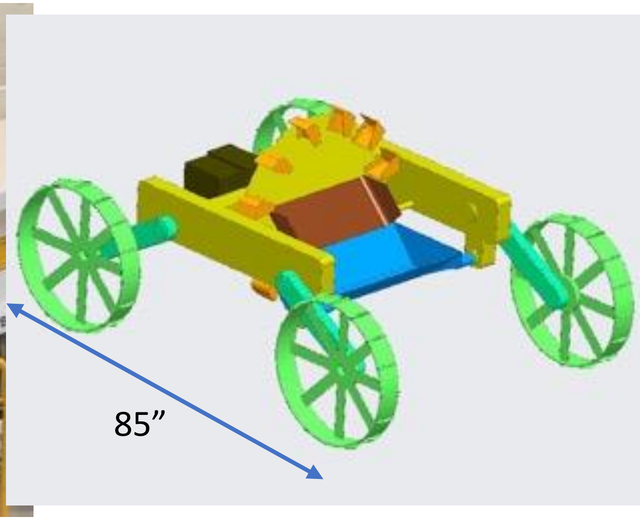
- **Trade different PSR or Sunlight ridge site**
  - Locate ISRU production plant at human landing site
  - Evaluate a closer PSR region
  - Evaluate impact of a deeper water resource
- **Refine models**.
  - Working several improvements and corrections to existing models.
  - Consult with SMEs for subsystems to improve and verify our models: hydrogen liquefaction, mobility platform capabilities, thermal management for water extraction
- **Separate Thermal and Electrical power**
  - Indicate and define where utilization of waste heat is possible for each extraction method evaluated (already done in model but not shown graphically yet)
- **Compare to Oxygen extraction from Regolith systems**
  - Model the mass/power for a baseline system that extracts oxygen from ubiquitous minerals in surface regolith.

Backup

Full O_2 Production Excavator Overview

- Excavator design based on Astrobotic Polaris design
  - Transverse bucket wheel delivers regolith into central holding tray
  - 200 kg excavator tested in gravity-offloading tests
  - Digging rate: 0.5 kg/sec
  - Baseline driving velocity: 28 cm/s
  - Demonstrated payload ratio: 25 – 50 %
- Scale down to ½ the mass
  - Assume same payload *ratio* and driving velocity
  - Assume digging rate cut in half
- Each ISRU module requires 130 kg of fresh regolith each day
  - Four deliveries per day (per module) at 35 kg / load for payload ratio of 35%
- Excavators also need to receive processed regolith (aka, slag) and dispose of in dump zone
  - Slag removed from reactor in form of solid half-spheres ~10 cm diameter
  - Multiple batches of slag nodules held in dump hopper until ready to be removed
  - 115 kg/day of slag (per module) (130 kg of fresh regolith less 12 % oxygen extracted)
  - Three disposal trips per day (per module) at 40 kg / load for payload ratio of 40%

Prototype Astrobotic Polaris excavator in NASA GRC SLOPE Lab

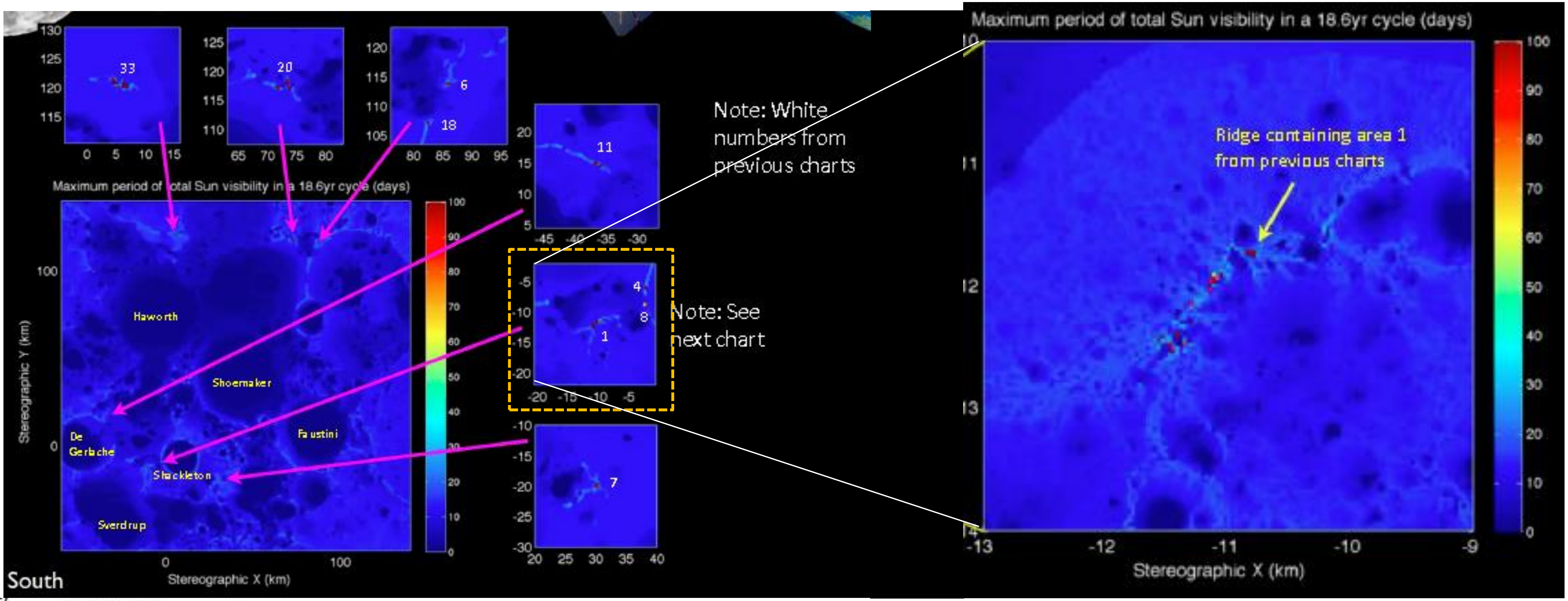


CAD rendering of scaled version (1/2 scale by mass)

Ref 1: Skonieczny, K., “Lightweight Robotic Excavation,” Doctoral Thesis, CMU-RI-TR-13-09, May, 2013.
Ref 2: Thornton, J., “Lightweight Robotic Excavation, Phase 2 Summary Report,” Contract NNX11CB55C, May, 2013

Potential South Pole Landing Sites

Sunlight Near Permanent Shadow



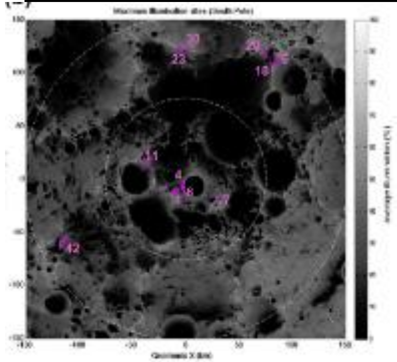


Table 3
List of the 50 most illuminated spots in each pole. In addition to their location (longitude, latitude), we indicate their average illumination and visibility percentage at the surface and 10 m above the surface. Due to this height increase, their rank can change.

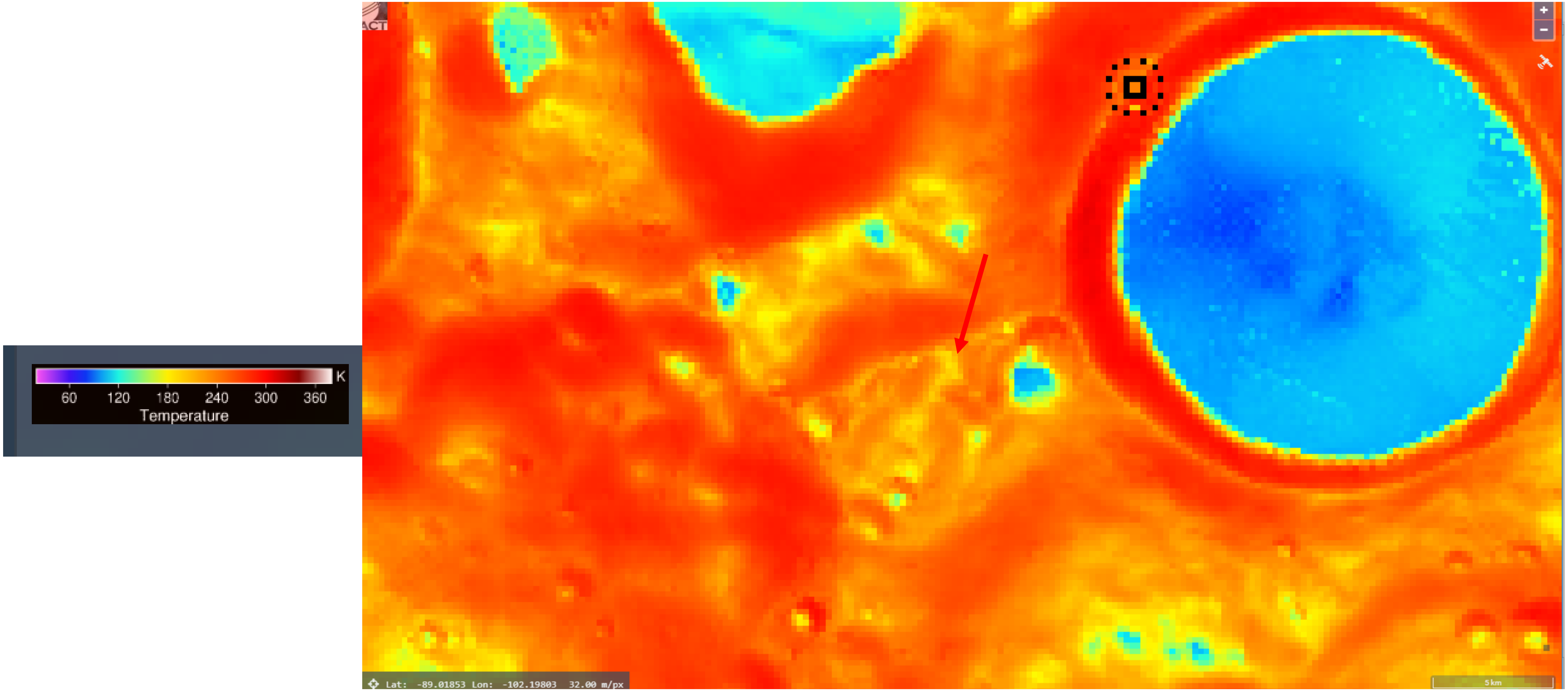
Longitude	Latitude	At surface level			10 m above surface		
		Rank	Average solar illumination (%)	Average solar visibility (%)	Rank	Average solar illumination (%)	Average solar visibility (%)
South pole							
222.69	−89.45	1	89.01	92.66	1	93.10	95.83
222.73	−89.43	2	88.60	91.14	2	92.53	95.24
223.28	−89.44	3	87.13	90.04	3	92.26	94.95
204.27	−89.78	4	86.71	90.46	12	87.41	90.99
203.46	−89.77	5	86.70	90.43	11	87.42	91.00
37.07	−85.30	6	85.95	89.43	14	87.30	89.52
123.64	−88.81	7	85.50	88.20	21	85.59	88.29
197.05	−89.69	8	85.28	88.77	20	85.93	89.33

Landing Zone (this study) 'on ridge'

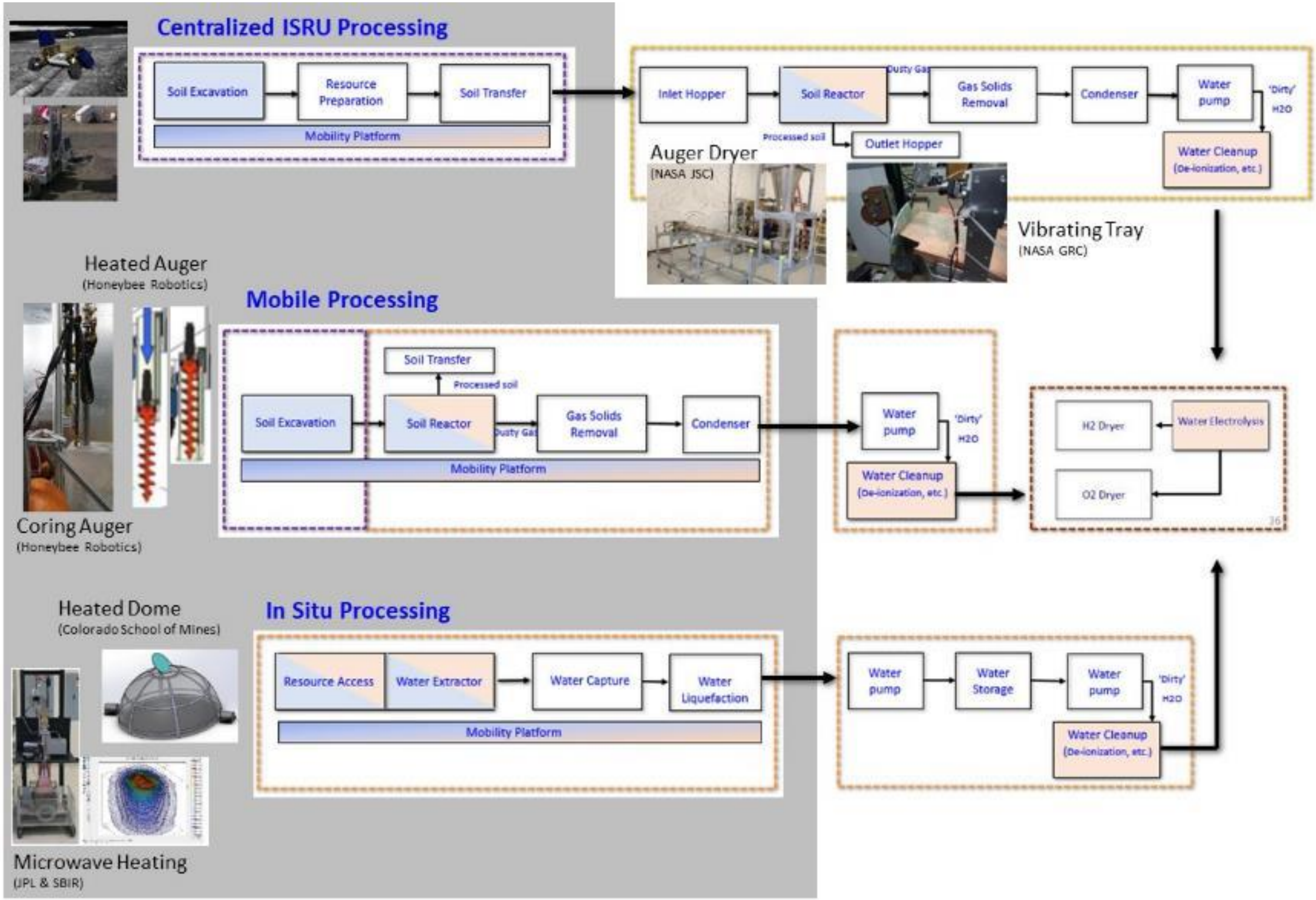
Maximum summer temperatures

- Arrow indicates ridge (sunlight) hardware location
- Blue spots are lowest temperature = highest likelihood for ice

EXPLORE MOONtoMARS



Polar Water Extraction and Processing Options



2A. Excavation & Processing in PSR w/ Power

RASSOR/Extractor/Chariot

RASSOR excavates raw material and delivers to a stationary Auger dryer water extraction unit (co-located with power platform). A Chariot based water tanker collects water from water extraction unit and delivers it to ridge propellent production plant.

Pros

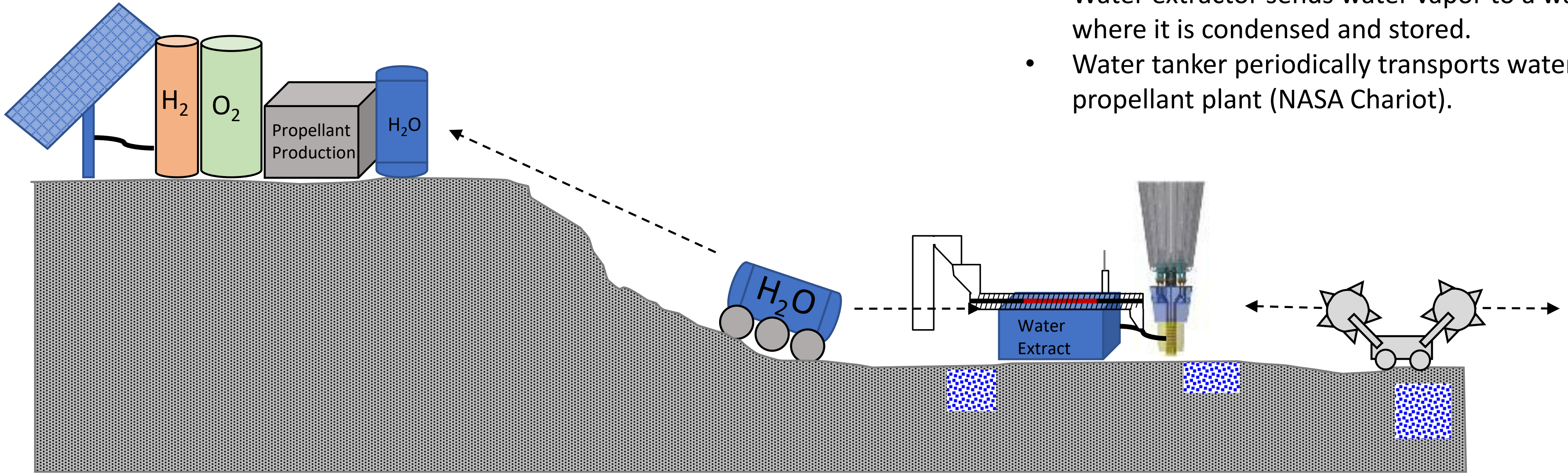
- Icy soil remains in PSR, volatiles loss upon excavation is limited
- Potentially several, smaller excavators making short trips
- Excavators are simple, single function

Cons

- Requires 2 mobility platforms
- Requires secondary power source in crater for water extraction plant and mobility recharging
- Dried material must be transported away
- Water must be transferred 2ce

Baseline:

- Excavator(s) continuously deliver batches of raw soil to a water extraction unit and remove processed soil. Excavators live in PSR. (NASA Rassor)
- Water extractor is at a fixed location in PSR, co-located with a power source. Extractor lives in PSR (NASA Auger Dryer)
- PSR power source for water extraction and battery charging. (Kilopower pictured, but not included in ISRU mass)
- Water extractor sends water vapor to a water tanker where it is condensed and stored.
- Water tanker periodically transports water out of PSR to propellant plant (NASA Chariot).



2B. Excavation & Processing in PSR w/ Power

PVEx/RP/Chariot

EXPLORE MOON to MARS

PVEx drills are mounted to RP mobility platforms. They extract and store water using a heated core drill. They navigate to a PSR power station where they recharge while transferring water to a chariot base water tanker. The water tanker delivers water to the ridge propellant production plant.

Pros

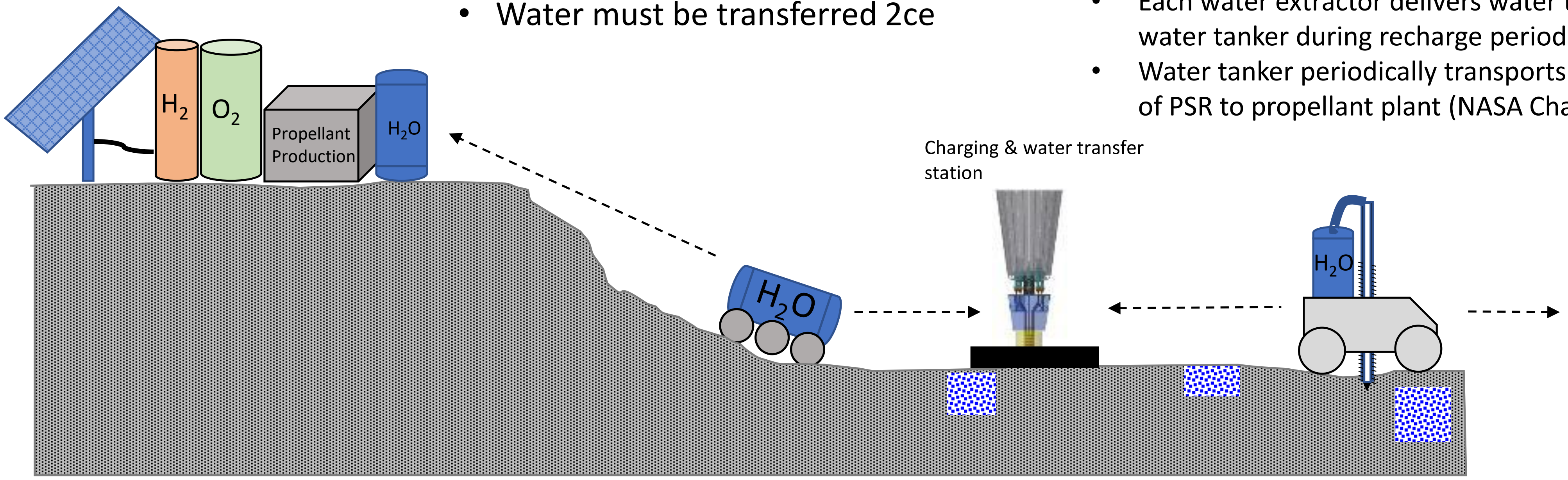
- Icy soil remains in PSR, volatiles loss upon excavation is limited
- Potentially several, smaller excavators making short trips
- Excavators are simple, single function

Cons

- Requires 2 mobility platforms
- Requires secondary power source in crater for water extraction plant and mobility recharging
- Dried material must be transported away
- Water must be transferred 2ce

Baseline:

- Heated coring drill: drill into regolith and heat in place to extract water. Water vapor travels up drill into onboard condenser. (Honeybee PVEX)
- Multiple mobility platforms each support one drill. Lives in PSR. (RP Rover)
- PSR power source for battery charging. (Kilopower pictured, but not included in ISRU mass)
- Each water extractor delivers water to larger water tanker during recharge periods
- Water tanker periodically transports water out of PSR to propellant plant (NASA Chariot)



3. Mobile Water Extraction, Powered Outside of PSR

EXPLORE MOON to MARS

PVEx/Chariot

Mobile platform excavates soil, extracts water, and stores water. Mobile platform operates in PSR and climbs out of crater to deliver to propellant plant.

Pros

- Icy soil remains in PSR, volatiles loss upon excavation is limited
- Dried soil can be immediately disposed

Cons

- Larger mobility platform required with a lot of functionality
  - Likely limited number of mobility platforms which increases failure modes
- Mobility platform must support power intensive processes (drying)

Baseline:

- Multiple Heated coring drills: drill into regolith and heat in place. (Honeybee PVEX)
- Water vapor condensed in water tank (custom design)
- Mobility platform supports water tank, drills, and battery power source (NASA Chariot)
- System travels to production plant site out of PSR to deliver water periodically.