In-Situ Resource Utilization options for the Moon and Mars

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What is In-Situ Resource Utilization (ISRU)?

Living Off the Land:

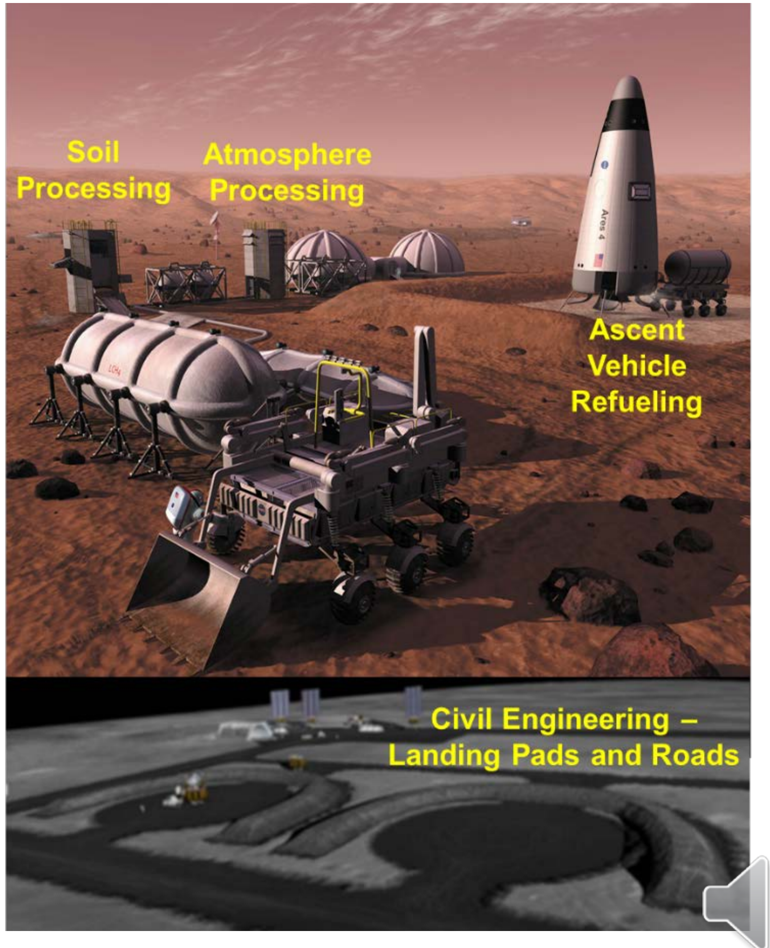
ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' (local) resources to create products and services for robotic and human exploration

Resource Examples

- Water
- Oxygen
- Hydrogen
- Carbon
- Metals
- Silicon
- Nitrogen
- Regolith/Rock
- Discarded materials

Product Examples

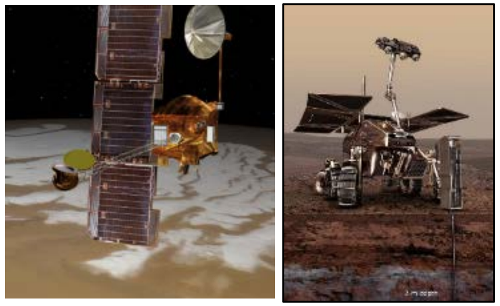
- Propellant
- Life Support Consumables
- Feed stock for:
  - Additive manufacturing
  - Construction
- Agriculture substrate and/or fertilizer



- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

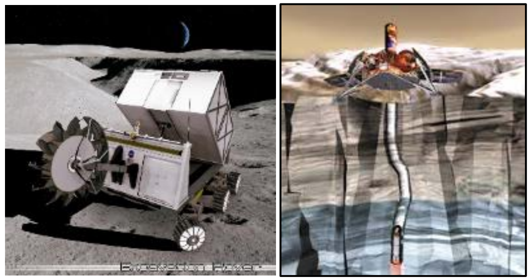
In-Situ Resource Utilization (ISRU) encompasses:

Resource Assessment (Prospecting)



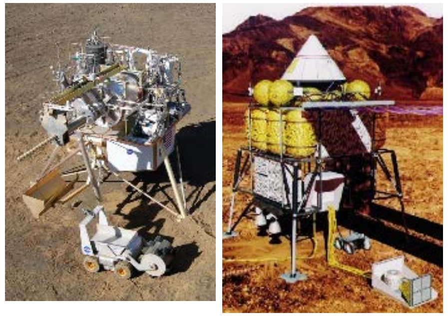
Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition



Drilling, excavation, transfer, and preparation/ beneficiation before processing

Resource Processing/ Consumable Production



- Propellants, life support gases, fuel cell reactants, etc.

Processing resources into products with immediate use or as feedstock for construction & manufacturing

In Situ Manufacturing

Production of feedstock potentially derived from one or more processed resources for use in manufacturing of replacement parts, complex products, machines, and integrated systems.

In Situ Construction

Civil engineering, infrastructure emplacement and structure construction using materials produced from in situ resources

- Radiation shields, landing pads, roads, berms, habitats, etc.

In Situ Energy

Generation and storage of electrical, thermal, and chemical energy with in situ derived materials

- Solar arrays, thermal storage and energy, chemical batteries, etc.

How Making Propellants on Planetary Surfaces Saves on Launches and Cost (Gear Ratio Effect)

Every 1 kg of propellant made on the Moon or Mars saves 7.5 to 11.2 kg in LEO

Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

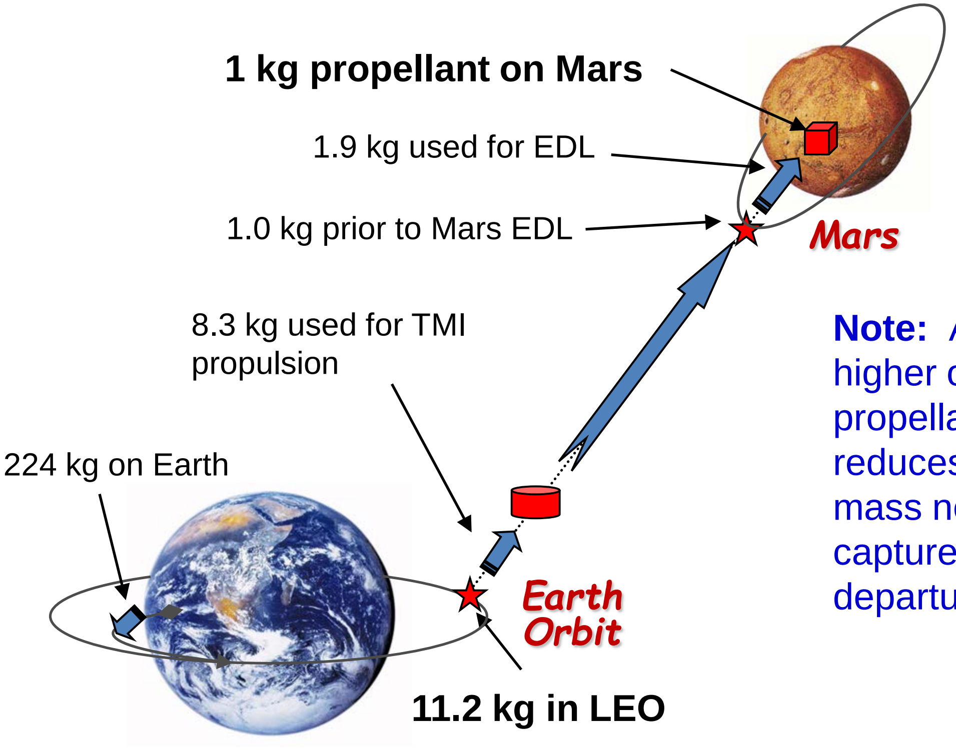
- Savings depend on in-space transportation approach and assumptions; previous Mars gear ratio calculations showed only a 7.5 kg saving
- 25,000 kg mass savings from propellant production on Mars for ascent = 187,500 to 282,500 kg launched into LEO

Mars Crew Ascent Mission

Oxygen only	75% of ascent prop. mass:	20 to 23 mT
Methane + Oxygen	100% of ascent prop. mass:	25.7 to 29.6 mT

Moon Lander: Surface to NRHO

- Crew Ascent Stage (1 way): 3 to 6 mT O_2
- Single Stage (both ways): 40 to 50 mT O_2/H_2



1 kg propellant on Mars

1.9 kg used for EDL

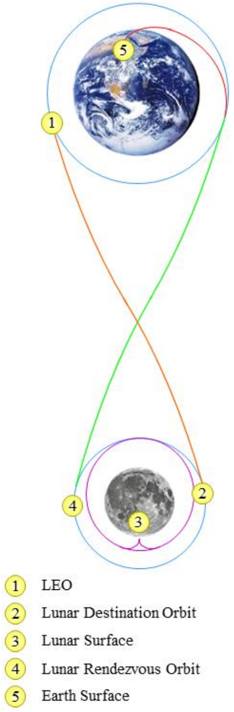
1.0 kg prior to Mars EDL

8.3 kg used for TMI propulsion

224 kg on Earth

11.2 kg in LEO

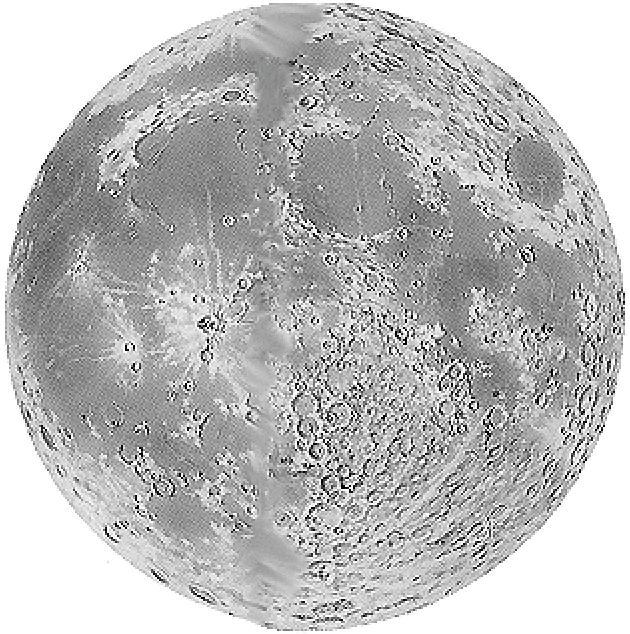
Note: Ascent to higher orbit with ISRU propellant also reduces propellant mass needed for orbit capture (TLI/TMI) and departure burns (TEI)



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

Estimates based on Aerocapture at Mars

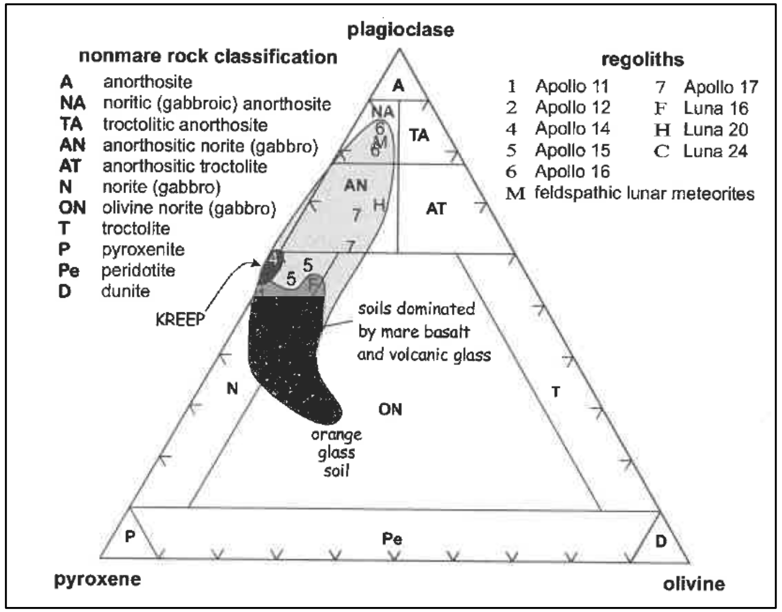
Lunar ISRU



Lunar Resources

Lunar Regolith

- **>40% Oxygen by mass**
  - Silicate minerals make up over 90% of the Moon
- Regolith
  - Mare: Basalt (plagioclase, pyroxene, olivine)
  - **Highland/Polar: >75% anorthite, iron poor**
- Pyroclastic Glass
- KREEP (Potassium, Rare Earth Elements, Phosphorous)
- Solar Wind Implanted Volatiles

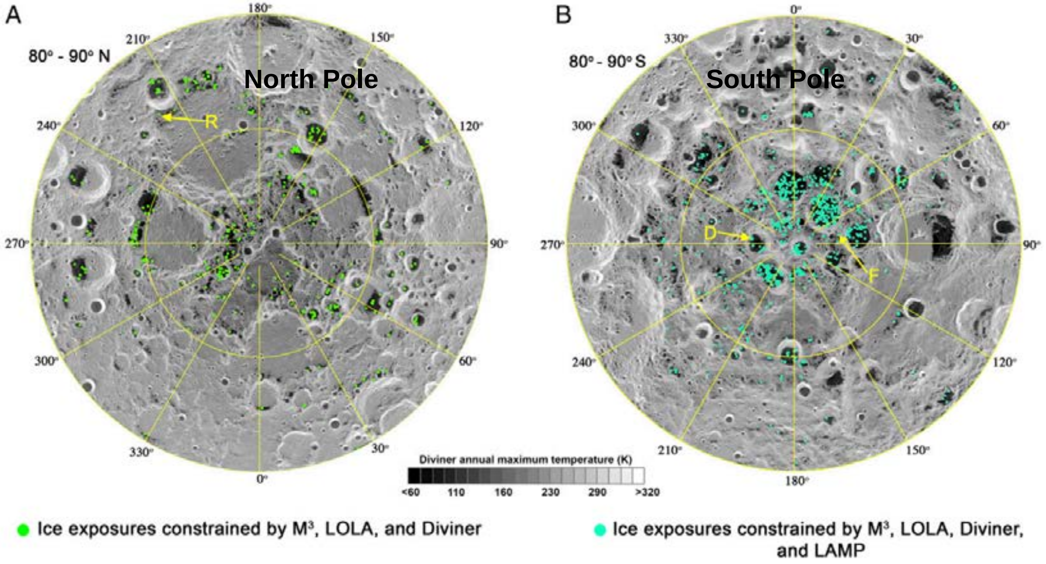


From *New Views of the Moon*

Polar Water/Volatiles

- LCROSS impact estimated **5.5 wt%** water along with other volatiles
- Green and blue dots show positive results for surface water ice and temperatures <110 K using orbital data.

➢ *Without direct measurements, form, concentration, and distribution of water is unknown*



Li et. al, (2018), *Direct evidence of surface exposed water ice in the lunar polar regions*

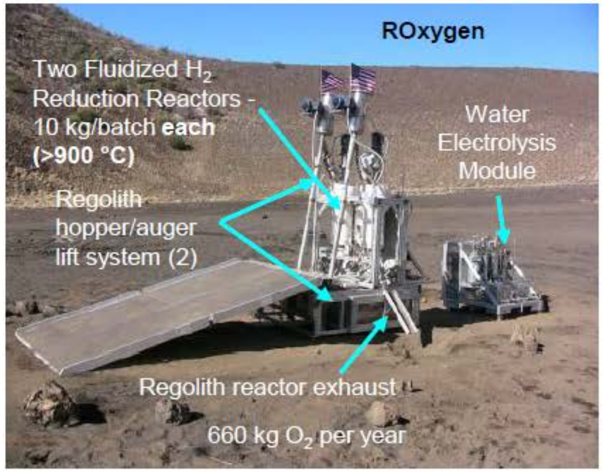
	Concentration (%wt)*
H_2O	5.5
CO	0.70
H_2	1.40
H_2S	1.74
Ca	0.20
Hg	0.24
NH_3	0.31
Mg	0.40
SO_2	0.64
C_2H_4	0.27
CO_2	0.32
CH_3OH	0.15
CH_4	0.03
OH	0.00
H_2O (adsorb)	0.001-0.002
Na	

Table courtesy of Tony Colaprete

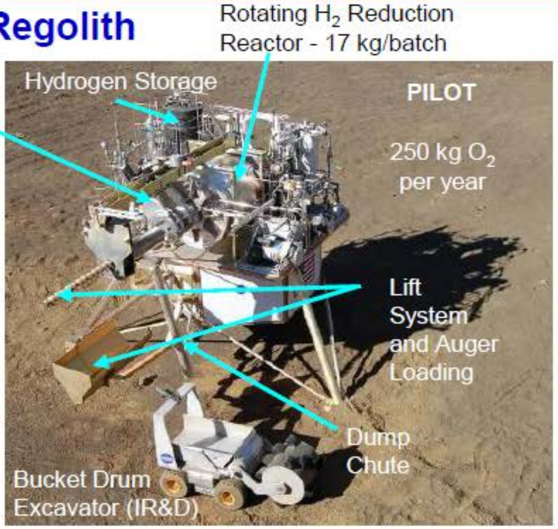
Oxygen extraction- methods

- Oxygen is bound to minerals within the regolith: Iron and Silica oxides
- Can be obtained from surface regolith at any location
    - Easy access, readily available, but moderate yield
    - High energy processes required to process material
    - Reacted byproduct may have potential as construction feedstock
- Sample return from Apollo provides solid chemical characterization
- Oxygen alone provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth)

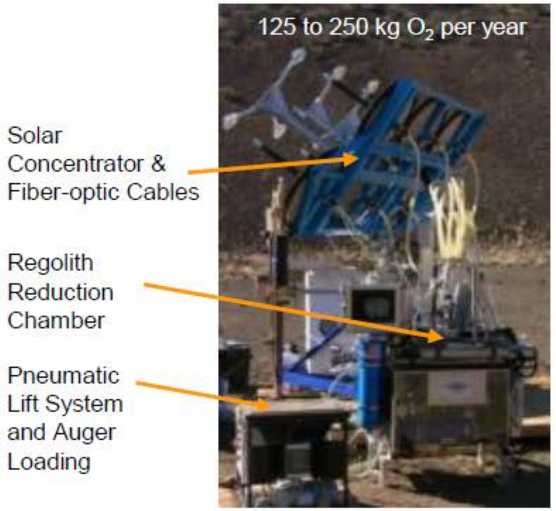
Hydrogen Reduction of Regolith



1. Heat Regolith to >900 C
2. React with Hydrogen to Make Water
3. Crack Water to Make O_2

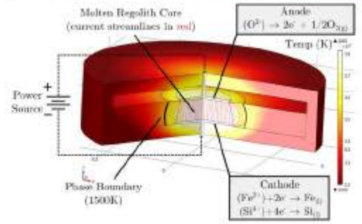


Carbothermal Reduction of Regolith



1. Melt Regolith to >1600 C
2. React with Methane to produce CO and H_2
3. Convert CO and H_2 to Methane & Water
4. Crack Water to Make O_2

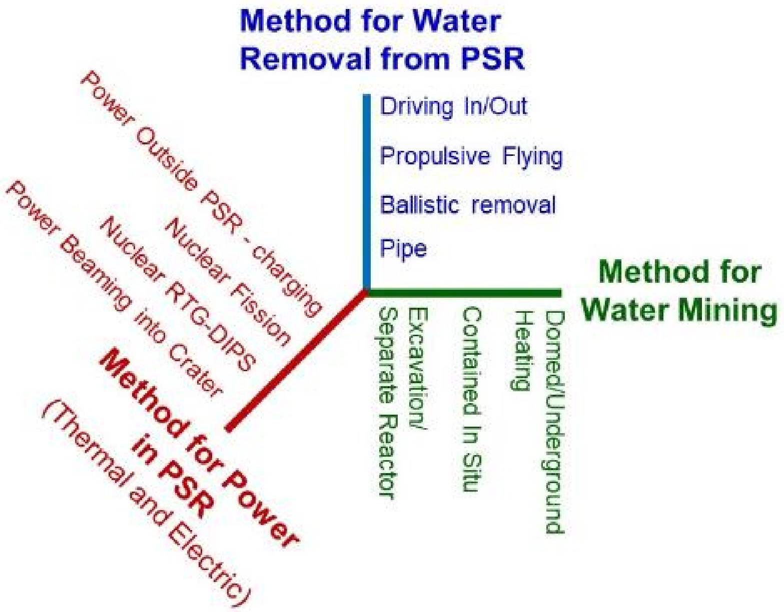
Molten Electrolysis of Regolith

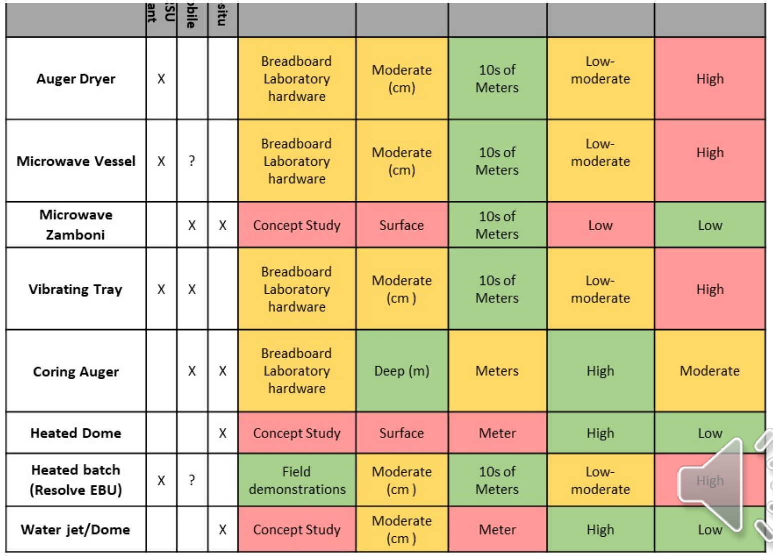


1. Melt Regolith to >1600 C
2. Apply Voltage to Electrodes To Release Oxygen

Mining Polar Water: Overview

- **Ice has been identified at the permanently shadowed regions at the Lunar poles**
    - Regolith is ~5 wt% according to LCROSS data
- **Water would provide:**
    - Both fuel and oxidizer for propulsion (Hydrogen/Methane + Oxygen)
    - Options for radiation protection, food production, etc. over what is available from lunar regolith
- **Available at specific locations that support ice stability**
    - Shadowed regions; temperatures can be 70K
    - Permanently shadowed regions (PSR) (shallower/more extensive ice stability potential) are craters with significant slopes for traverse-ability
- **Distribution and characteristics of ice is not well known at this time.**
- **Application of mining technologies are highly dependent on:**
    - **Resource Depth Access**: How deep the water resource can be for a given concept to work.
    - **Spatial Resource Definition:** How homogenous is the resource
    - **Resource Geotechnical Properties**: How hard and porous is the icy regolith
    - **Volatiles Retention:** How much of the volatiles are captured vs lost to the environment.
    - **Material Handling:** How much interaction is required with the regolith.

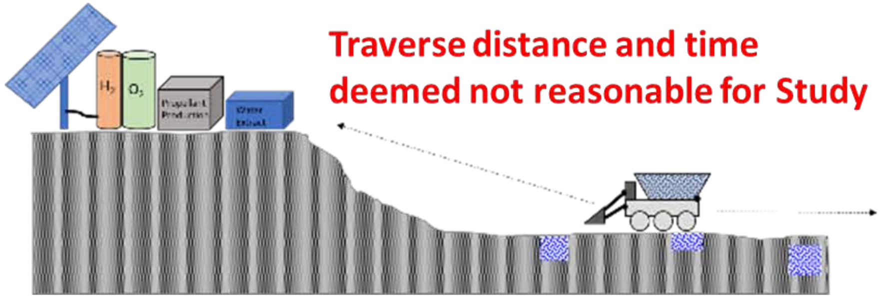




	SU ant	bile	situ					
Auger Dryer	X			Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Microwave Vessel	X	?		Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Microwave Zamboni		X	X	Concept Study	Surface	10s of Meters	Low	Low
Vibrating Tray	X	X		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

Lunar Water Architectures

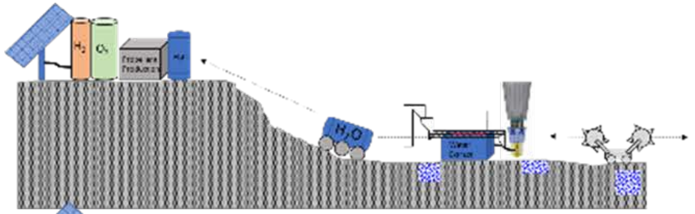
1. Icy Regolith is transported to sunlight ridge where it is processed and converted to propellant



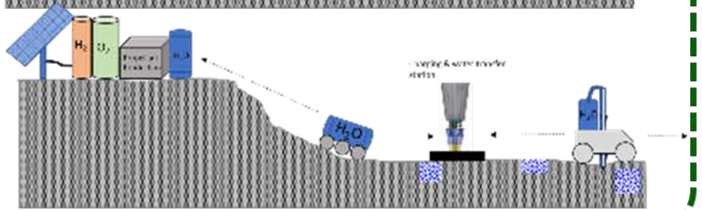
Traverse distance and time deemed not reasonable for Study

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

A. Stationary water extraction

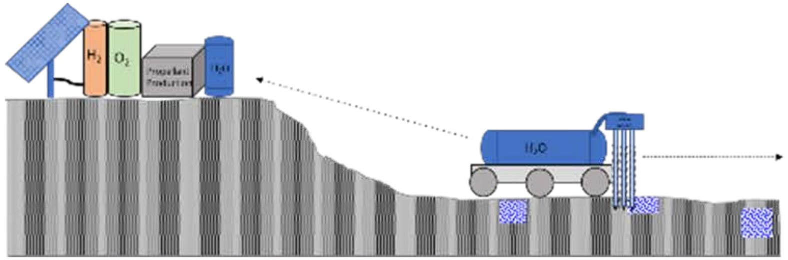


B. Mobile water extraction

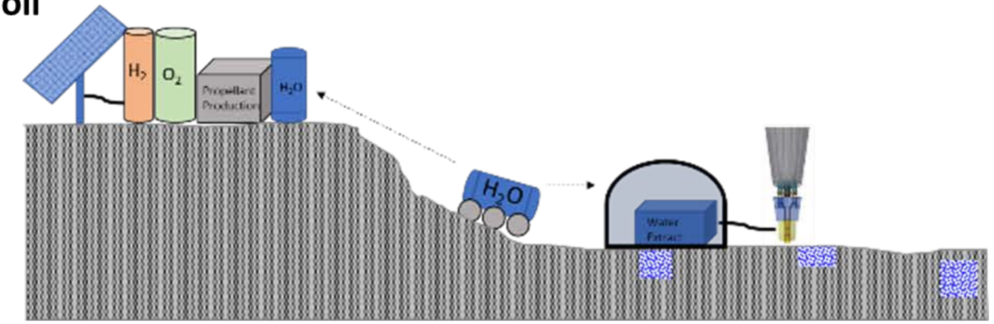


Preliminary Study

3. Icy Regolith Excavation/Processing Plant is Mobile



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



Threshold Criteria for a Lunar Water Reserve

ISRU System	
ISRU Requirement	**Criteria**
Water Concentration	≥2 wt. % to a 1 wt. % detection limit
Water Depth distribution	5 to 100 cm, ≤10 cm increments
Overburden depth	5 to 50 cm ≤10 cm increments
Lateral distribution	500 m radius
Target yield	15 tons water per lander

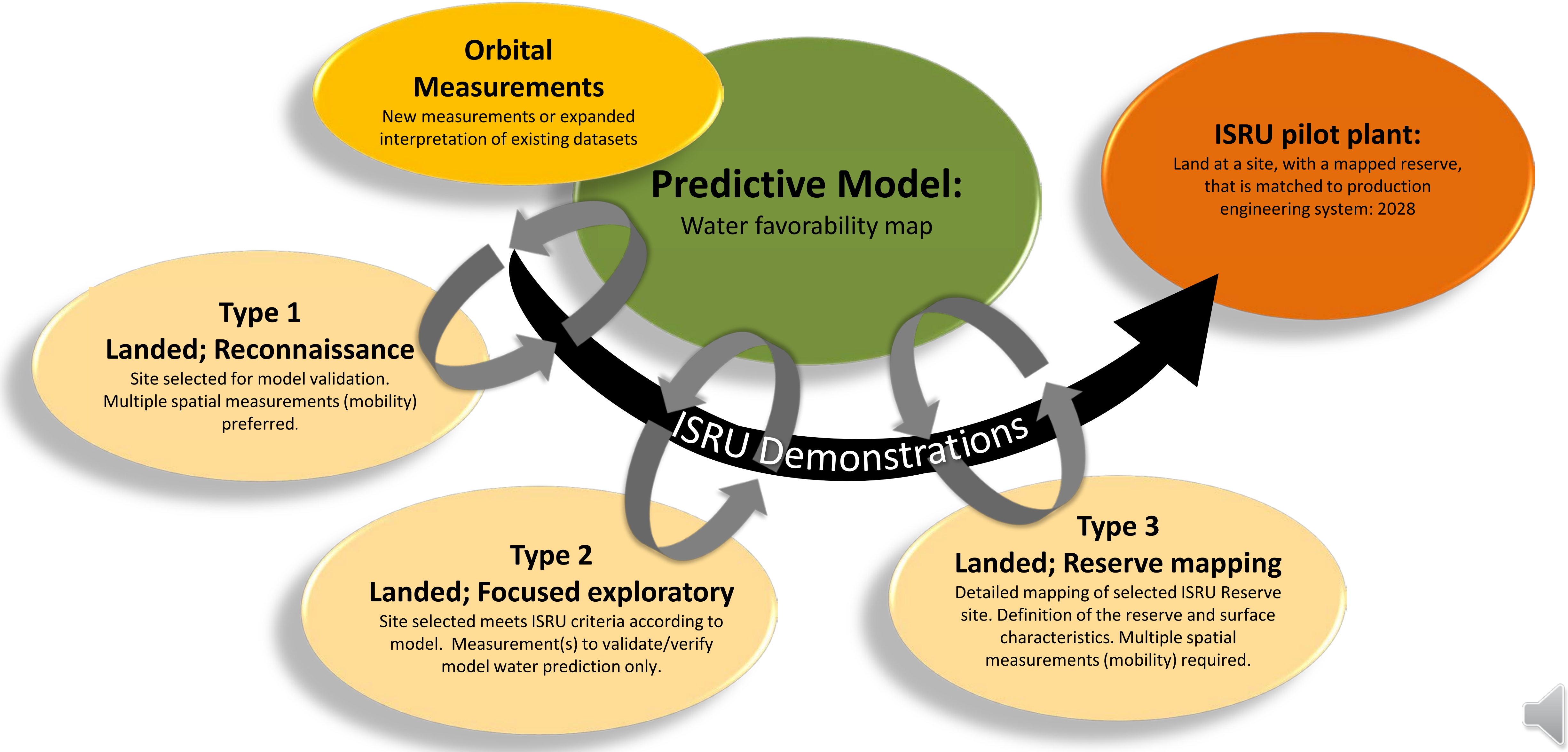
- Criteria according to current ISRU system models which use current technologies and architecture concepts
- Criteria consider breakpoints where benefits as compared to Oxygen from Regolith (O2R) fall off

Knowledge Gaps	
Cohesive Strength (c, kPa)	Compressive Strength (MPa)
Internal Friction Angle (Ø, degrees)	Water Release Temperature profile
Particle size distribution (µm)	Other volatiles at temperature (e.g. contaminants)
Soil bulk density (g/cm^3)	

Human Landing Systems		
Lander Requirement	**Initial**	**Sustained**
Daylight Operations	continuous light	50 hours darkness (threshold) 191 hours (goal)
Surface Access	84° S – 90° S	global
Habitation Capability	two crew for 8 earth days	four crew lunar sortie with pre-emplaced surface infrastructure
EVA Excursion Duration	lasting a minimum of 4 hours	lasting a minimum of 8 hours
Landing Site Vertical Orientation	vertical orientation of 0 to 8° (threshold) and 0 to 5° (goal) from local vertical for surface operations.	
Landing Accuracy	landing within 100 m (3-sigma) of target landing site	
Surface Operations	operating on the lunar surface for a minimum of 6.5 Earth days	
EVA Excursions per Sortie	at least two (threshold) and five (goal) surface EVA excursions per sortie.	
Scientific Payload Return to Lunar Orbit	returning scientific payload of at least 35 kg and 0.07 m^3 volume (threshold) and 100 kg and 0.16 m^3 volume (goal)	

- For infusion of ISRU into Human campaign, the HLS site requirement must be considered : ISRU reserves must have adequate proximity to HLS sites
- Information per HLS BAA Appendix H requirements

Resource Assessment:
Measurement Strategy



Orbital Measurements
New measurements or expanded interpretation of existing datasets

Predictive Model:
Water favorability map

ISRU pilot plant:
Land at a site, with a mapped reserve, that is matched to production engineering system: 2028

Type 1
Landed; Reconnaissance
Site selected for model validation. Multiple spatial measurements (mobility) preferred.

ISRU Demonstrations

Type 2
Landed; Focused exploratory
Site selected meets ISRU criteria according to model. Measurement(s) to validate/verify model water prediction only.

Type 3
Landed; Reserve mapping
Detailed mapping of selected ISRU Reserve site. Definition of the reserve and surface characteristics. Multiple spatial measurements (mobility) required.

ISRU Lunar Development and Demonstration Timeline

Reconnaissance, Prospecting, Sampling | **Resource Acquisition & Processing** | **Pilot Consumable Production**

Sub-system Demonstrations: Investigate, sample, and analyze the environment for mining and utilization.

Follow The Natural Resources:
Demonstrations of systems for extraction and processing of raw materials for future mission consumables production and storage.

Sustainable Exploration:
Scalable Pilot - Systems demonstrating production of consumables from in-situ resources in order to better support sustained human presence.


CLPS Drill Down Select

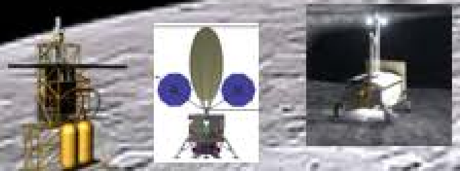

High-fidelity Simulant Production


Oxygen from Lunar Simulant Ground Demos

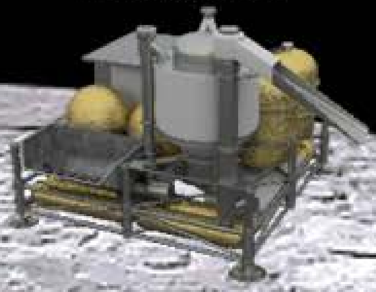
Polar Resources Ice Mining Experiment (Prime-1) on CLPS

Volatiles Investigation Polar Exploration Rover (VIPER)

ISRU Subsystem Consumables Extraction Demos



Scalable Pilot - ISRU Systems for Consumable Production



2019

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PRIME-1 & VIPER

First Steps toward surface understanding of Polar Water and Volatiles

Polar Resources Ice Mining Experiment (Prime-1) on CLPS

- CLPS mounted payload to detect volatiles at 1-m depth in 2022
- Instruments include:
  - Mass Spectrometer Observing Lunar Operations (MSolo)
  - The Regolith and Ice Drill for Exploring New Terrain (TRIDENT)

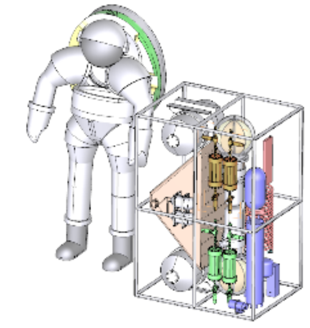
Volatiles Investigation Polar Exploration Rover (VIPER)

- Dec. 2023 mid-lunar day at South Pole
- Measure volatiles at the lunar poles and acquire new key data on lateral and vertical distribution
  - Neutron Spectrometer System (NSS)
  - NIRVSS IR Spec
  - Msolo Mass Spec
  - TRIDENT Drill
- Build lunar resource maps for future exploration sites
  - Long duration operation (months)
  - Traverse 10’s km

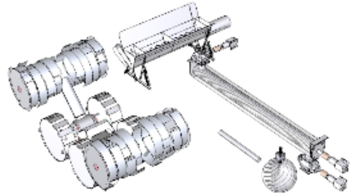
Mars ISRU

Mars Resources

Atmosphere Processing

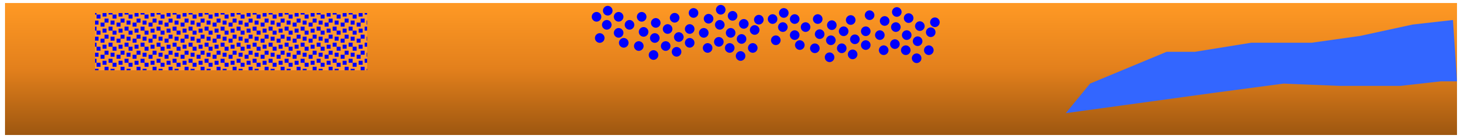


Granular Regolith Processing for Water



Gypsum/Sulfate Processing for Water

Icy Regolith Processing for Water



Atmosphere
- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- >95% Carbon Dioxide
- Temperature: +35 C to -125 C
- Everywhere on Mars; Lower altitude the better
- Chemical processing similar to life support and regenerative power

Mars Garden Variety Soil
- Low water concentration 1-3%
- At surface
- Granular; Easy to excavate
- 300 to 400 C heating for water removal
- Excavate and transfer to centralized soil processing plant
- Most places on Mars; 0 to +50 Deg. latitude

Gypsum or Sulfates
- Hydrated minerals 5-10%
- At Surface
- Harder material: rock excavation and crushing may be required
- 150 to 300 C heating for water removal
- Localized concentration in equatorial and mid latitudes

Subsurface Ice
- 90%+ concentration
- Subsurface glacier or crater: 1 to 3 m from surface
- Hard material
- 100 to 150 C heating for water removal
- Downhole or on-rover processing for water removal
- Highly selective landing site for near surface ice or exposed crater; >40 to +55 Deg. latitude

Increasing Complexity, Difficulty, and Site Specificity

Propellant Production on Mars

Oxygen

- Resource: Atmospheric CO_2
- Reaction:
  - Solid Oxide Electrolysis
  - Reverse Water Gas Shift
- Accounts for 75% of propellant mass
  - Mixture ratio: 3.5 (O/F) for Methane

Solid Oxide CO_2 Electrolysis (SOE)

$$2\,CO_2 \xrightarrow{900 - 1000\ C} 2\,CO + O_2 \quad \text{[Pt catalyst]} \longrightarrow O_2$$

Reverse Water Gas Shift (RWGS)

$$CO_2 + H_2 \overset{400 - 650\ C}{\rightleftharpoons} CO + H_2O \quad \text{[catalyst]} \longrightarrow H_2O$$

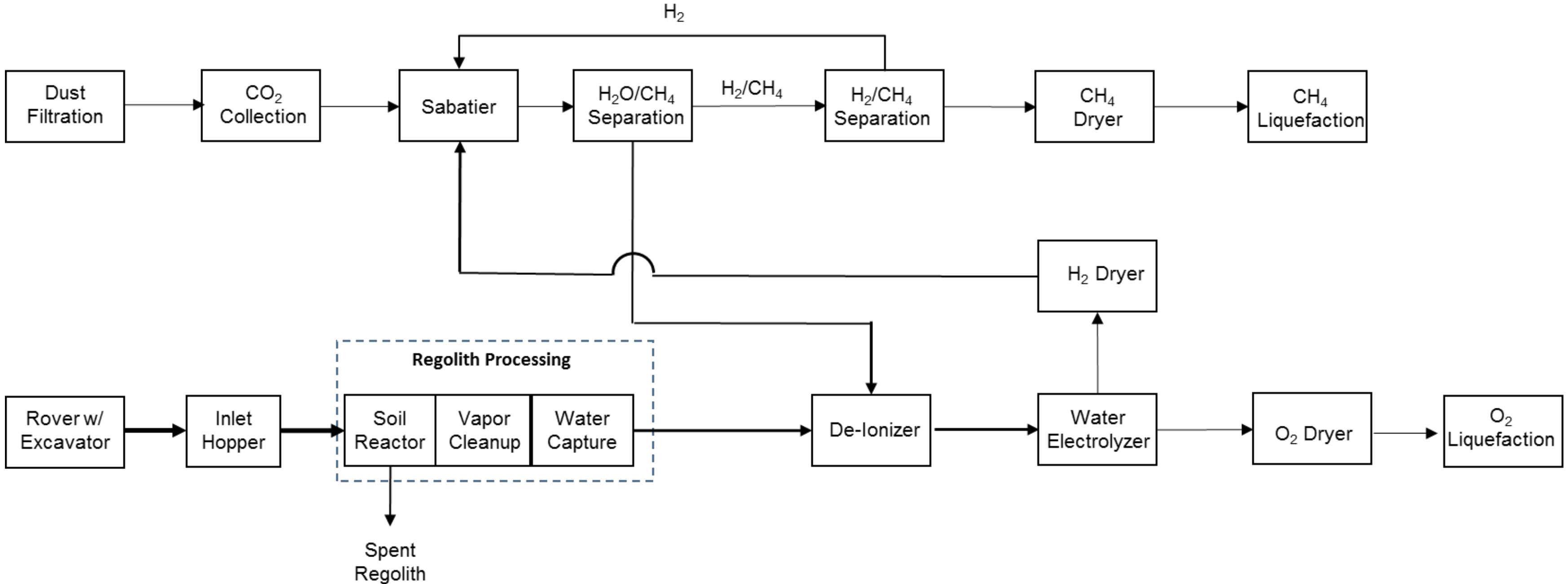
Methane

- Resource:
  - Atmospheric CO_2 + Water
- Reaction:
  - Water Electrolysis + Sabatier
- Closes loop: All propellants for ascent + excess oxygen
  - Sabatier produces at a 4:1 ratio

$$2\,H_2O + CO_2 \rightarrow 2\,O_2 + CH_4$$

Soil: $2H_2O \rightarrow 2H_2 + O_2$

Sabatier: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$



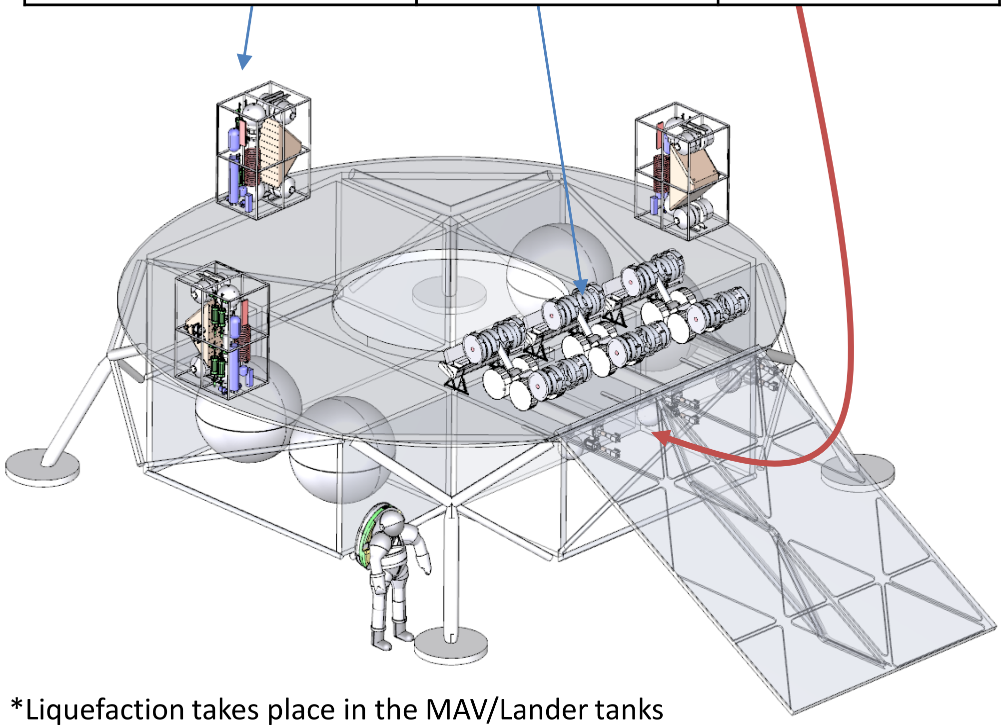
Evolvable Mars Campaign: ISRU Case Study

- Evolvable Mars Campaign
  - Pre-deployed Mars ascent vehicle (MAV)
  - 4 crew members
  - Propellants: Oxygen & Methane
- Production rate based on a mission timeline of 480 days (16 months)
  - ISRU system arrives one launch opportunity ahead of humans
  - MAV must be fully fueled before human departure from earth
- Water from low yield hydrated surface material
- ISRU system does not include: Power source, Radiators/ system thermal management, Propellant Tanks, communications. Significant additional margin on mass and power to cover TBD system design feature like support structure, thermal management, etc.

		Total mass needed	Rate at 480days continuous operation
Requirement:	CH_4	6978 kg	0.61 kg/hr
Reactants needed to meet requirement:	H_2O	15701 kg (785,050 kg 2% soil)	1.36 kg/hr (68.2 kg/hr soil@2%)
	CO_2	19190 kg	1.67 kg/hr
Results in:	O_2	27912 kg total (22728 kg propellant, 5184 kg leftover)	2.43 kg/hr

Approach: Production requirement met by 3 independent ISRU systems including:

3 Propellant production (atmosphere processing/water electrolysis) modules	3 mobile RASSOR excavators	3 regolith processing (water production) modules

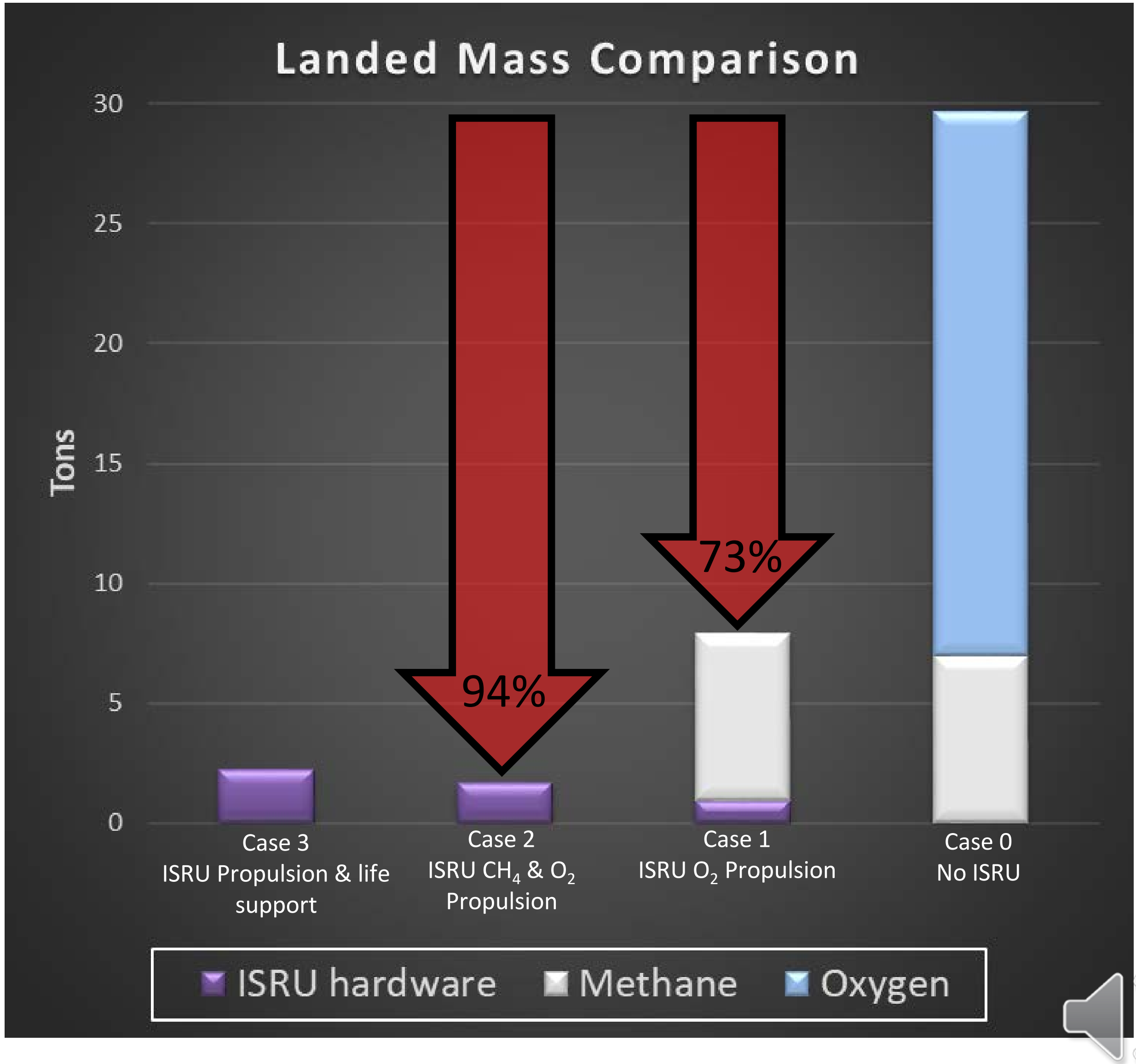


*Liquefaction takes place in the MAV/Lander tanks

Kleinhenz, J.E. and Paz, A. *An ISRU Propellant Production System to Fully Fuel a Mars Ascent Vehicle*. AIAA SciTech Forum 2017. American Institute for Aeronautics and Astronautics. AIAA-2017-0423

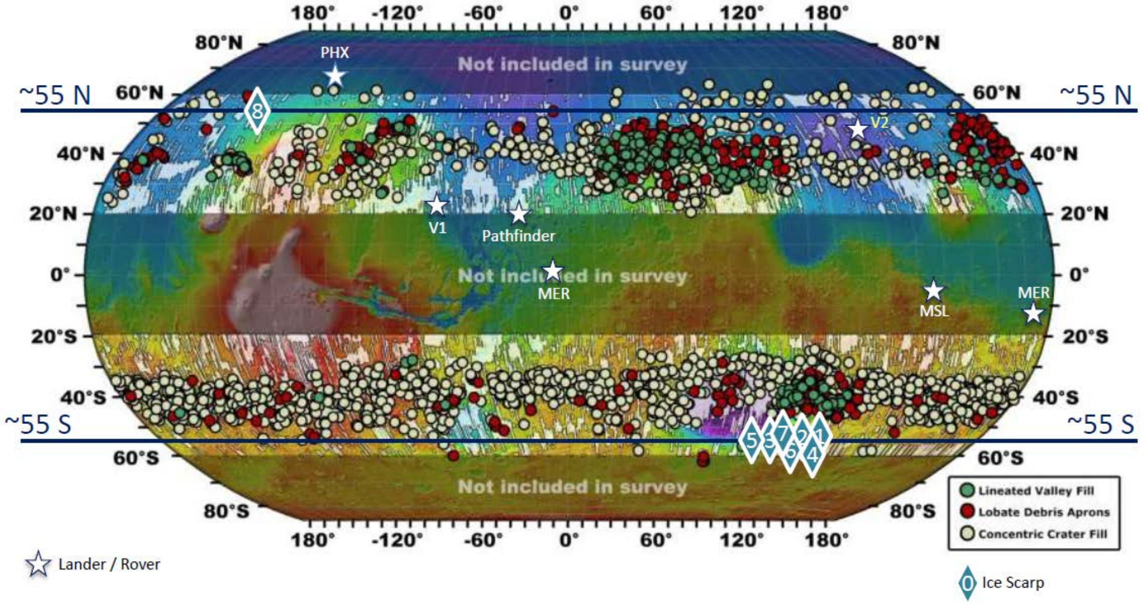
EMC Case Study Results: Overall Mass comparison

- Three production scenarios:
  - Case 0: No ISRU, all propellant from Earth
  - Case 1: O_2 produced from CO_2 atmosphere, fuel from earth
  - Case 2: All propellants produced with ISRU
  - Case 3: All propellants and life support consumables for 4 crew produced with ISRU
- Mass reductions are compared to total ascent propellants only
  - Masses represent ISRU hardware (1 - 2mT) and any landed propellant
- Mass savings in LEO is about 10kg per ever 1 kg of propellant produced
  - LEO Mass savings on the order of 300 mT with full ISRU system (Case 2)
  - Reduces cost and eliminates several heavy lift launch vehicles
  - NOTE: This study is with low yield, ubiquitous surface regolith (not site specific)

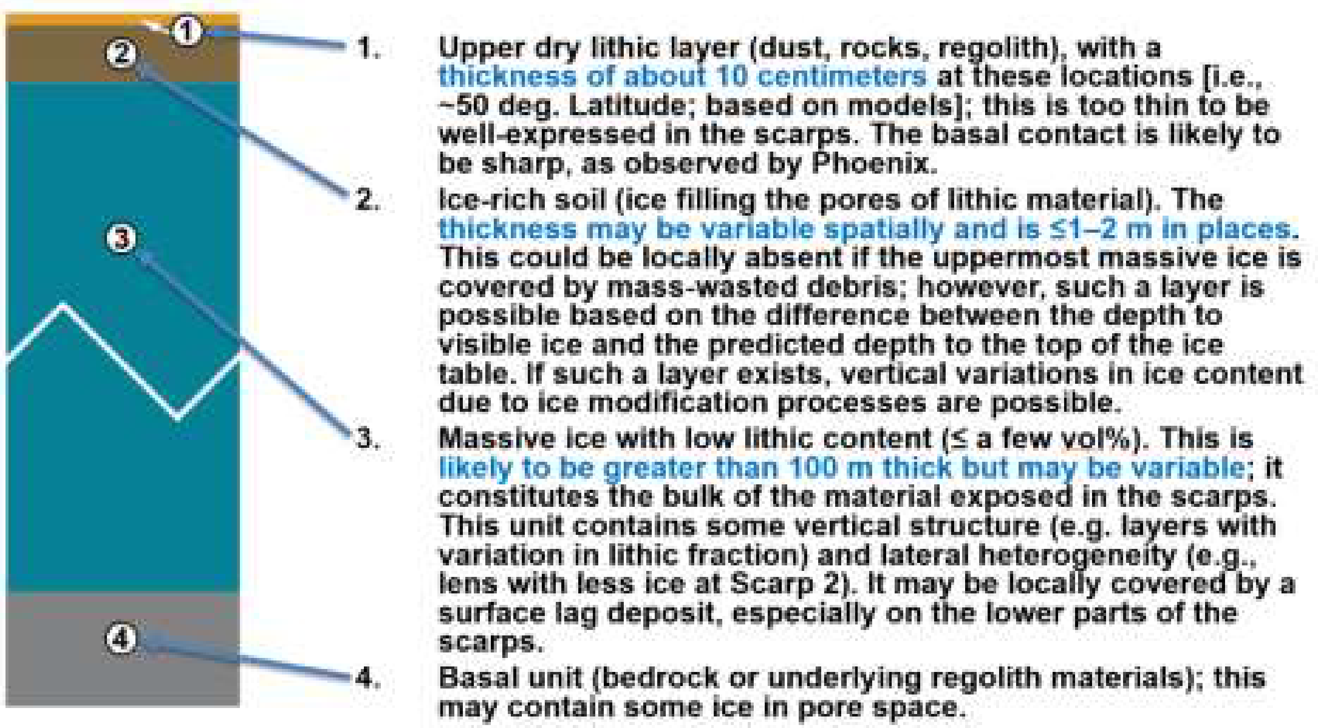


Kleinhenz, J.E. and Paz, A. *An ISRU Propellant Production System to Fully Fuel a Mars Ascent Vehicle*. AIAA SciTech Forum 2017. American Institute for Aeronautics and Astronautics. AIAA-2017-0423

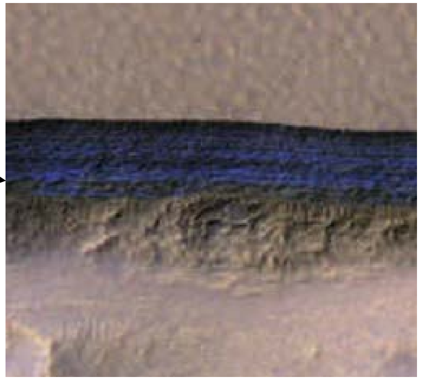
Mars Ice



- The circles Represent terrain features consistent with terrestrial glacial feature
- The Diamonds are recently discovered ice scarps (‘roadcuts’ showing exposed ice)



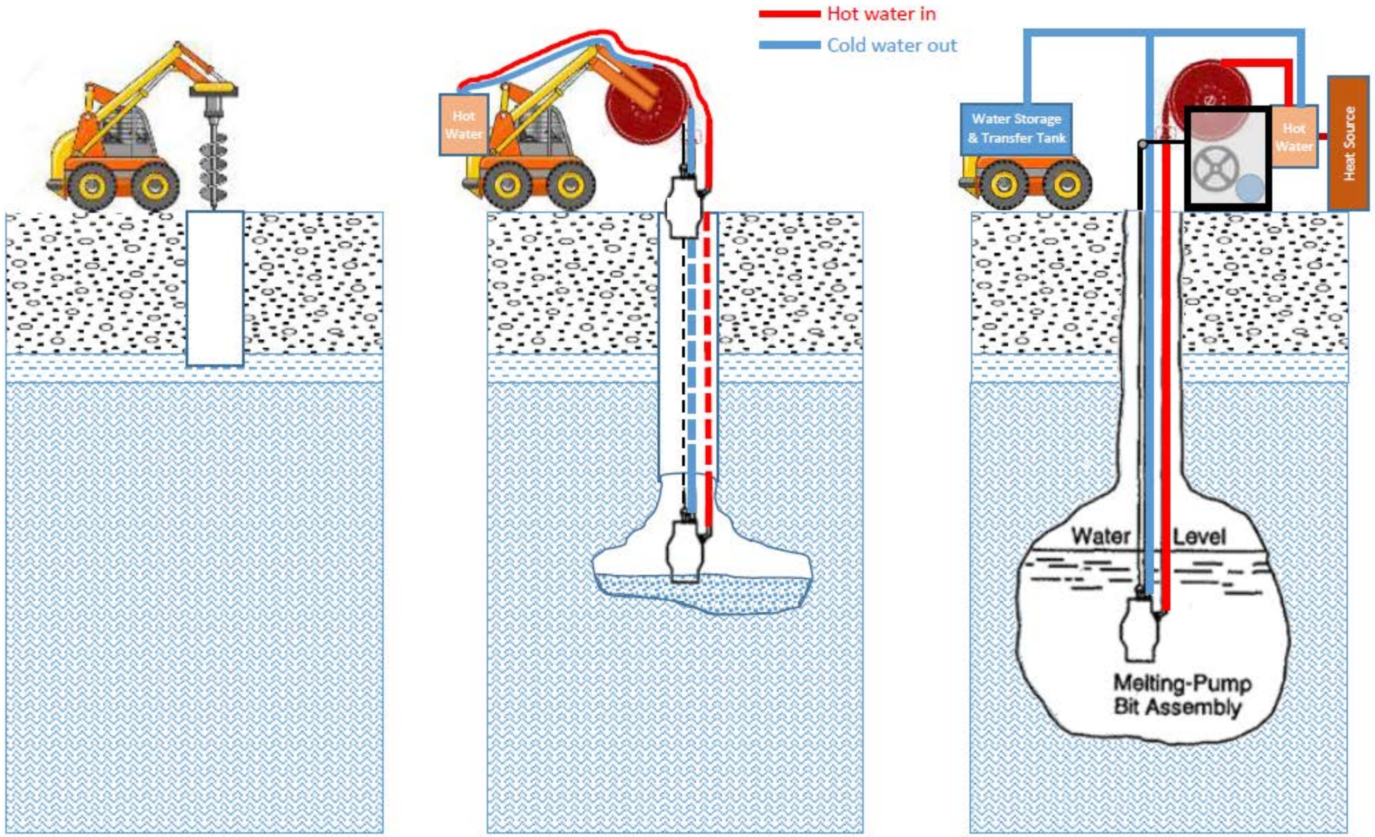
1. Upper dry lithic layer (dust, rocks, regolith), with a thickness of about 10 centimeters at these locations [i.e., ~50 deg. Latitude; based on models]; this is too thin to be well-expressed in the scarps. The basal contact is likely to be sharp, as observed by Phoenix.
2. Ice-rich soil (ice filling the pores of lithic material). The thickness may be variable spatially and is ≤1–2 m in places. This could be locally absent if the uppermost massive ice is covered by mass-wasted debris; however, such a layer is possible based on the difference between the depth to visible ice and the predicted depth to the top of the ice table. If such a layer exists, vertical variations in ice content due to ice modification processes are possible.
3. Massive ice with low lithic content (≤ a few vol%). This is likely to be greater than 100 m thick but may be variable; it constitutes the bulk of the material exposed in the scarps. This unit contains some vertical structure (e.g. layers with variation in lithic fraction) and lateral heterogeneity (e.g., lens with less ice at Scarp 2). It may be locally covered by a surface lag deposit, especially on the lower parts of the scarps.
4. Basal unit (bedrock or underlying regolith materials); this may contain some ice in pore space.



Dundas, C. M., et al. “Exposed subsurface ice sheets in the Martian mid-latitudes,” *Science* 359, 12 Jan 2018, pp. 199-201. doi: 10.1126/science.aao1619

Mars Subsurface Ice Mining: Rodwell

- Mars also has subsurface glaciers at higher latitudes. This is site specific resource
- This ice could with within top 5m
- Rodwells are in use terrestrially (Antarctic field stations) for water generation from subsurface ice sheets.
- System modeling for a Mars Rodwell has also been studied (Hoffman, 2018) which:
  - Leveraged CRREL's (Cold Regions Research and Engineering Laboratory) numeric model for Rodwell design.
    - Testing in 2018/2019 to get Mars relevant parameters to modify model
  - Initial Mass estimate for Mars Rodwell was ~5 mT



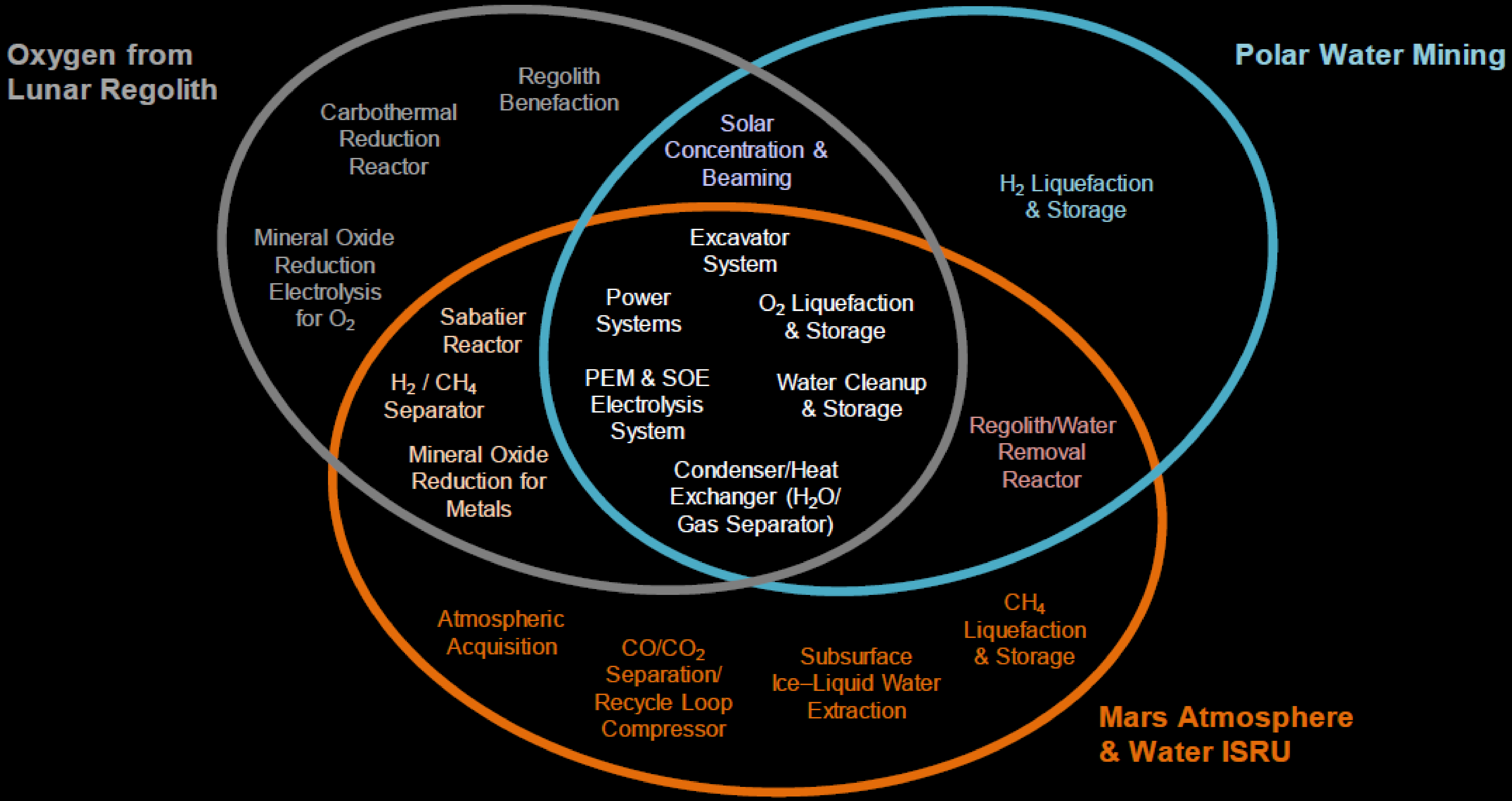
Phase 1: Drill through overburden into top of ice.

Phase 2: Melt into ice. Begin forming water pool.

Phase 3: Steady state operation.

Stephen J. Hoffman, Alida D. Andrews and Kevin D. Watts
Simulated Water Well Performance on Mars, AIAA 2018-5293,
https://doi.org/10.2514/6.2018-5293

ISRU Technology Synergy



Oxygen from Lunar Regolith

Polar Water Mining

Mars Atmosphere & Water ISRU

Carbothermal Reduction Reactor

Regolith Benefaction

Mineral Oxide Reduction Electrolysis for O_2

Solar Concentration & Beaming

H_2 Liquefaction & Storage

Excavator System

Power Systems

O_2 Liquefaction & Storage

Sabatier Reactor

H_2 / CH_4 Separator

PEM & SOE Electrolysis System

Water Cleanup & Storage

Mineral Oxide Reduction for Metals

Condenser/Heat Exchanger (H_2O/ Gas Separator)

Regolith/Water Removal Reactor

Atmospheric Acquisition

CO/CO_2 Separation/ Recycle Loop Compressor

Subsurface Ice–Liquid Water Extraction

CH_4 Liquefaction & Storage