In-Situ Resource Utilization (ISRU)

Living off the Land on the Moon and Mars

ACS National Meeting& Exposition

Robert D. Green

Julie Kleinhenz

NASA Glenn Research Center, Cleveland, OH

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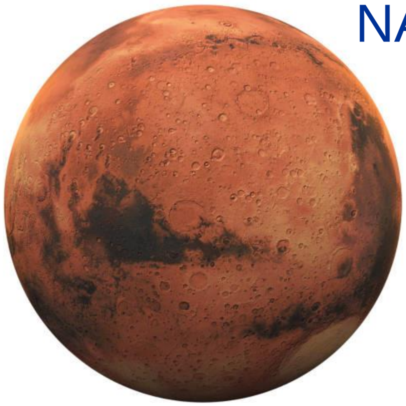
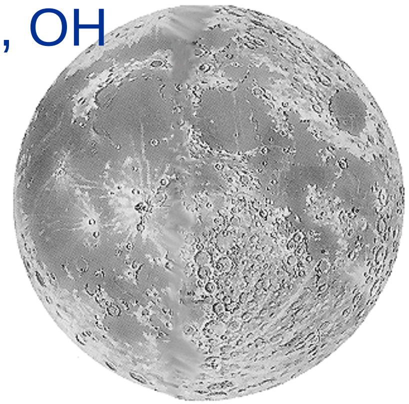




What is *In Situ* Resource Utilization (ISRU)?

Living Off the Land:

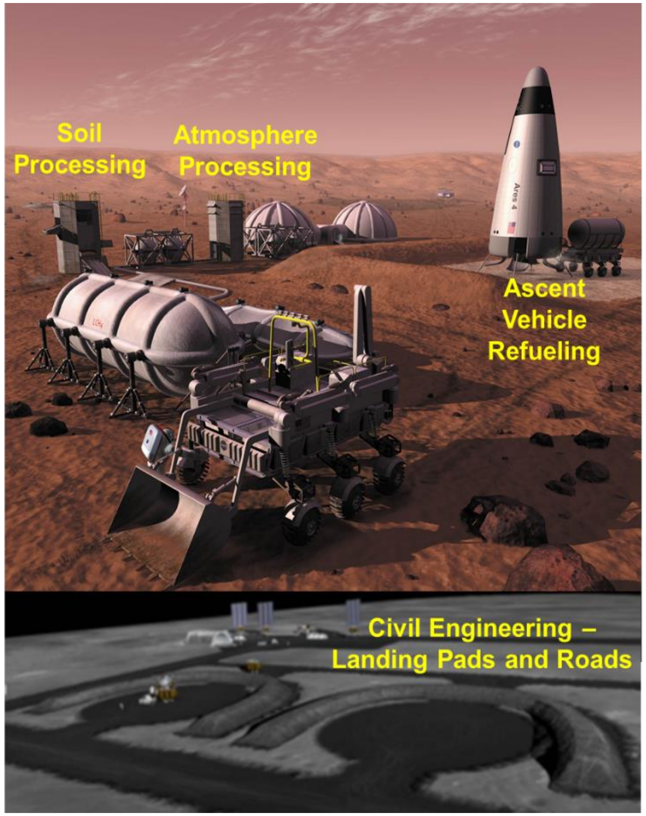
ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' (local) resources to create products and services for robotic and human exploration

Resource Examples

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

Product Examples

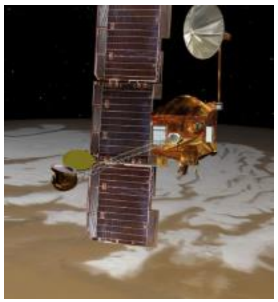
- Propellant
- Life Support Consumables
- Feed stock for:
  - Additive manufacturing
  - Construction
- Agriculture substrate and/or fertilizer



- **'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

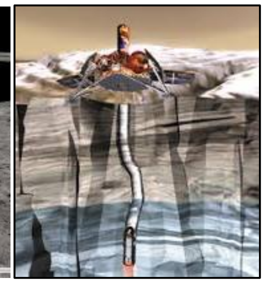
In Situ Resource Utilization (ISRU) encompasses:

Resource Assessment (Prospecting)



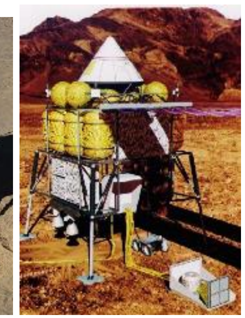

Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition

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

Resource Processing/ Consumable Production

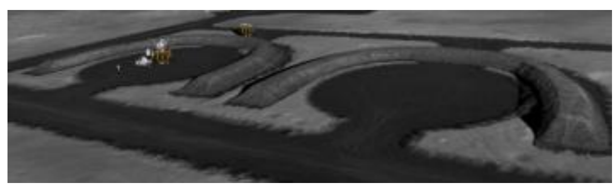
- Propellants, life support gases, fuel cell reactants, etc.

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.

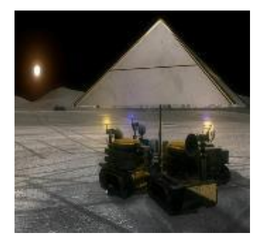
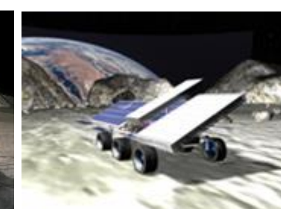
In Situ Construction



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.

ISRU: Make It vs Bring It!

It Changes How We Explore Space

Increases Mission Performance

- Launch mass savings/Lander size reduction (>7.5 kg saving per 1 kg produced on Moon/Mars surface)
- Longer stays, increased EVA, or increased number of crew over baseline with ISRU consumables
- Increased payload-to-orbit or delta-V for faster rendezvous with fueling of ascent vehicle
- Increased and more efficient surface nighttime and mobile fuel cell power architecture with ISRU

Increases Sustainability and Decreases Life Cycle Costs

- Potential reuse of landers with in-situ propellants can provide significant cost savings
- Enables in-situ growth capabilities in life support, habitats, powers, etc.
- Enables path for commercial involvement and investment

Reduces Mission and Crew Risk

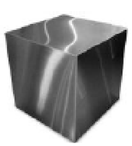
- Minimizes/eliminates life support consumable delivery from Earth – Eliminates cargo delivery failure issues & functional backup to life support system
- Increases crew radiation protection over Earth delivered options – *In-situ* water, plastic, and/or regolith
- Can minimize impact of shortfalls in other system performance – Launch vehicles, landers, & life support
- Minimizes/eliminates ascent propellant boiloff leakage issues – *In-situ* refueling
- Minimizes/eliminates landing plume debris damage – Civil engineering and construction
- Decreased logistics and spares brought from Earth – *In situ* manufacturing

Increases Science

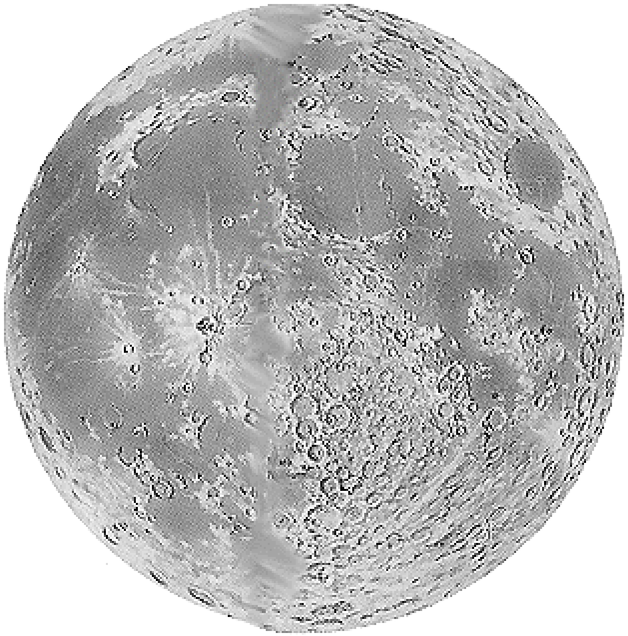
- Greater surface location and science sample collection access thru in-situ fueled hoppers
- Greater access to subsurface samples thru ISRU excavation and trenching capabilities
- Increased science payload per mission by reducing launch payload mass/consumables

ISRU Must Be Considered from the Start or Benefits & Cost Reductions are Minimized

Primary Resources of Interest for Human Exploration

	 Moon	 Mars	 Asteroids	Uses
Water (Hydrogen) 	Icy Regolith in Permanently Shadowed Regions (PSR) Solar wind hydrogen with Oxygen	Hydrated Soils/Minerals: Gypsum, Jarosite, Phylosilicates, Polyhdrated Sulfates Subsurface Icy Soils in Mid-latitudes to Poles	Subsurface Regolith on C-type Carbonaceous Chondrites	▪ Drinking, radiation shielding, plant growth, cleaning & washing ▪ Making Oxygen and Hydrogen
Oxygen 	Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite	Carbon Dioxide in the atmosphere (~96%)	Minerals in Regolith on S-type Ordinary and Enstatite Chondrites	▪ Breathing ▪ Oxidizer for Propulsion and Power
Carbon (Gases) 	▪ CO, CO_2, and HC's in PSR ▪ Solar Wind from Sun (~50 ppm)	Carbon Dioxide in the atmosphere (~96%)	Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites	▪ Fuel Production for Propulsion and Power ▪ Plastic and Petrochemical Production
Metals 	Minerals in Lunar Regolith ▪ Iron/Ti: Ilmenite ▪ Silicon: Pyroxene, Olivine, Anorthite ▪ Magnesium: Mg-rich Silicates ▪ Al: Anorthitic Plagioclase	Minerals in Mars Soils/Rocks ▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite ▪ Silicon: Silica, Phyllosilicates ▪ Aluminum: Laterites, Aluminosilicates, Plagioclase ▪ Magnesium: Mg-sulfates, Carbonates, & Smectites, Mg-rich Olivine	Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids	▪ *In situ* fabrication of parts ▪ Electical power generation and transmission

Note: Rare Earth Elements (REE) and Platinum Group Metals (PGM) are not driving Resources of interest for Human Exploration



LUNAR ISRU

Lunar Resources

- **Oxygen from Regolith**
  - Oxygen is bound to minerals within the regolith: Iron and Silica oxides
  - Can be obtained from surface and Mare regolith
    - Easy access, readily available, but relatively low yield
    - High energy processes required to process material
    - Reacted byproduct has high 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)

- **Water from Polar Regolith**
  - Ice has been identified at the permanently shadowed regions at the Lunar poles
    - Regolith is ~5 wt% according to LCROSS data
    - Recent data from Moon Mineralogy Mapper (M(3)) indicates up to 30 wt% in some craters
  - Distribution and characteristics of ice is not well known without ground-truth
  - 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

Lunar Polar Water

- Accessing ice requires accessing permanently shadowed craters
  - Maximum annual temperature < 110 K
  - Crater slope and lack of sunlight for solar power
- Depth distribution of Ice TBD
  - Surface processing possible for frost
  - Subsurface methods may be required

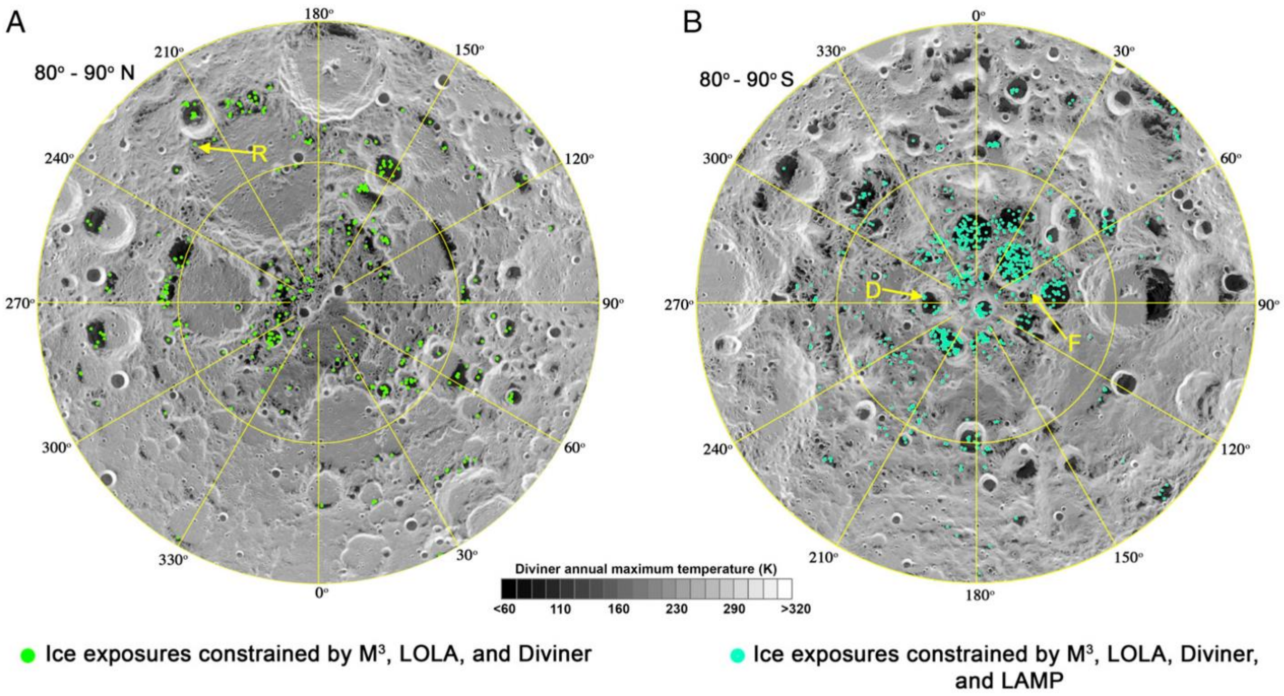
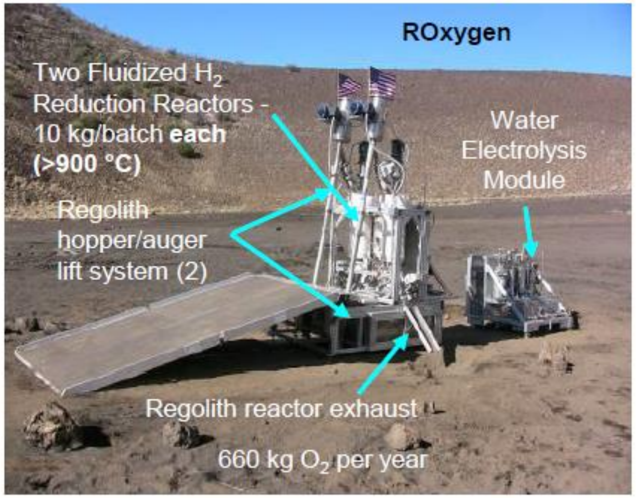


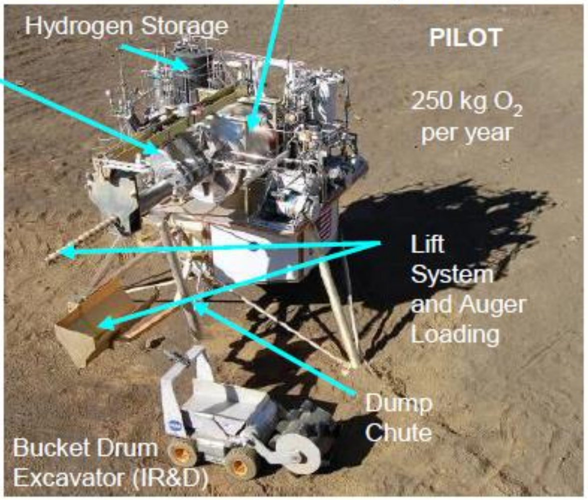
Fig. 4. Distribution of water-ice-bearing pixels (green and cyan dots) overlain on the Diviner annual maximum temperature for the (*A*) northern- and (*B*) southern polar regions. Ice detection results are further filtered by maximum temperature (<110 K), LOLA albedo (>0.35) (12), and LAMP off and on band ratio (>1.2, only applicable in the south) (13). Each dot represents an M (3) pixel, ~280 m × 280 m.

Lunar Oxygen Extraction

Hydrogen Reduction of Regolith



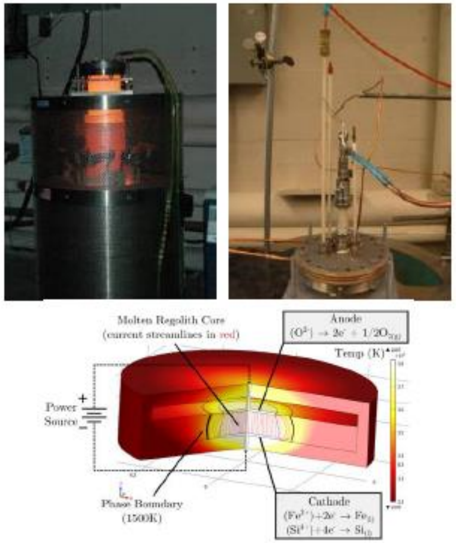
1. Heat Regolith to >900 C
2. React with Hydrogen to Make Water
3. Crack Water to Make O_2



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

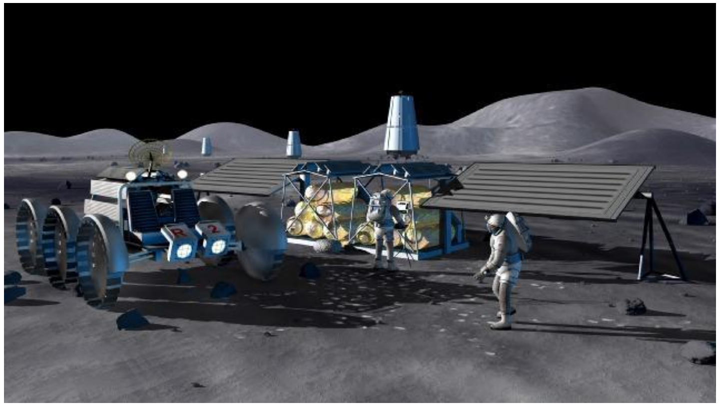
Molten Electrolysis of Regolith



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

Lunar ISRU applications

- Consumable production
  - Chemical propellants for robotic and human vehicles
  - Life support (O_2 and H_2O)
  - Fuel Cell reactants
- Site preparation/Civil engineering
  - Radiation protection (H_2O and/or Regolith)
  - Landing pads, berms for plume mitigation
  - Road clearing for payload emplacement

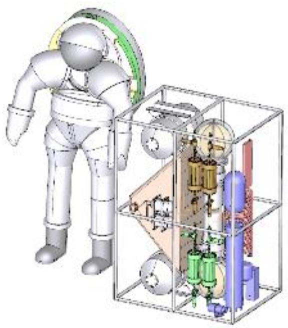


- Mars Forward
  - Demonstrate compatible technologies like
    - Excavation, material handling, thermal processing, cryogenic fluid storage and transfer, etc.
    - Autonomous operations: e.g. Land empty ascent vehicle and produce propellant prior to human presence
    - Link to Gateway mission concepts provide for Gateway/lunar sorties or Mars transit

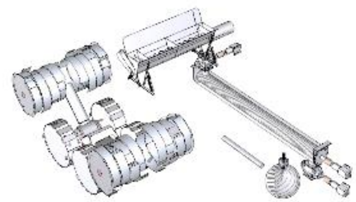
MARS ISRU

Mars Resources

Atmosphere Processing

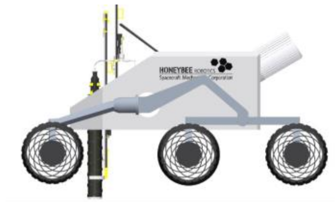


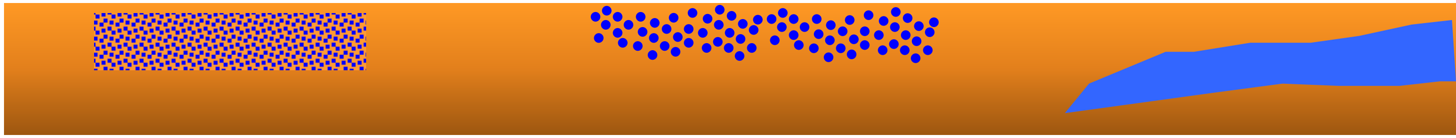
Granular Regolith Processing for Water



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

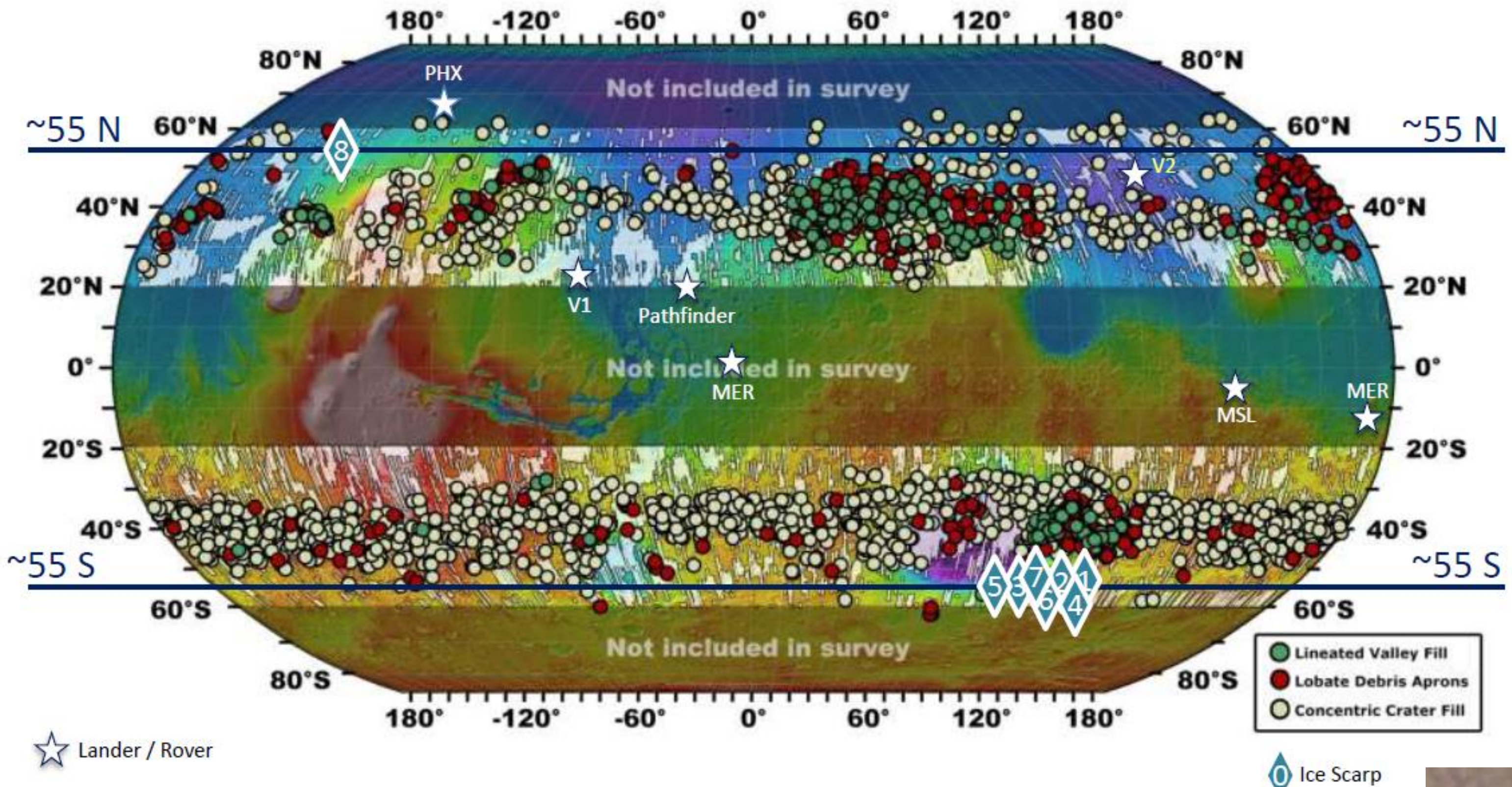
- Hydrated minerals 5-10%
- **At Surface**
- **Harder material:** rock excavation and crushing may be required
- **150 to 250 C heating for water removal**
- **Localized concentration in equatorial and mid latitudes**

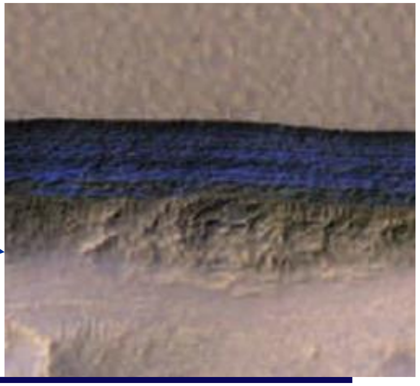
Subsurface Ice

- **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

Mars Ice





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

Propellant Production on Mars

Oxygen

- Resource: Atmospheric CO_2
- Reaction:
  - Solid Oxide Electrolysis
  - Reverse Water Gas Shift

Solid Oxide CO_2 Electrolysis (SOE)

$$2\,CO_2 \xrightarrow{800-1000\ C} 2\,CO + O_2 \quad \text{[Ni catalyst]} \rightarrow O_2$$

Reverse Water Gas Shift (RWGS)

$$CO_2 + H_2 \xrightleftharpoons{400-650\ C} CO + H_2O \quad \text{[Fe catalyst]} \rightarrow H_2O$$

- Accounts for 75% of propellant mass
  - Mixture ratio: 3.5:1

Methane

- Resource:
  - Atmospheric CO_2 + Water
- Reaction:
  - Water Electrolysis + Sabatier

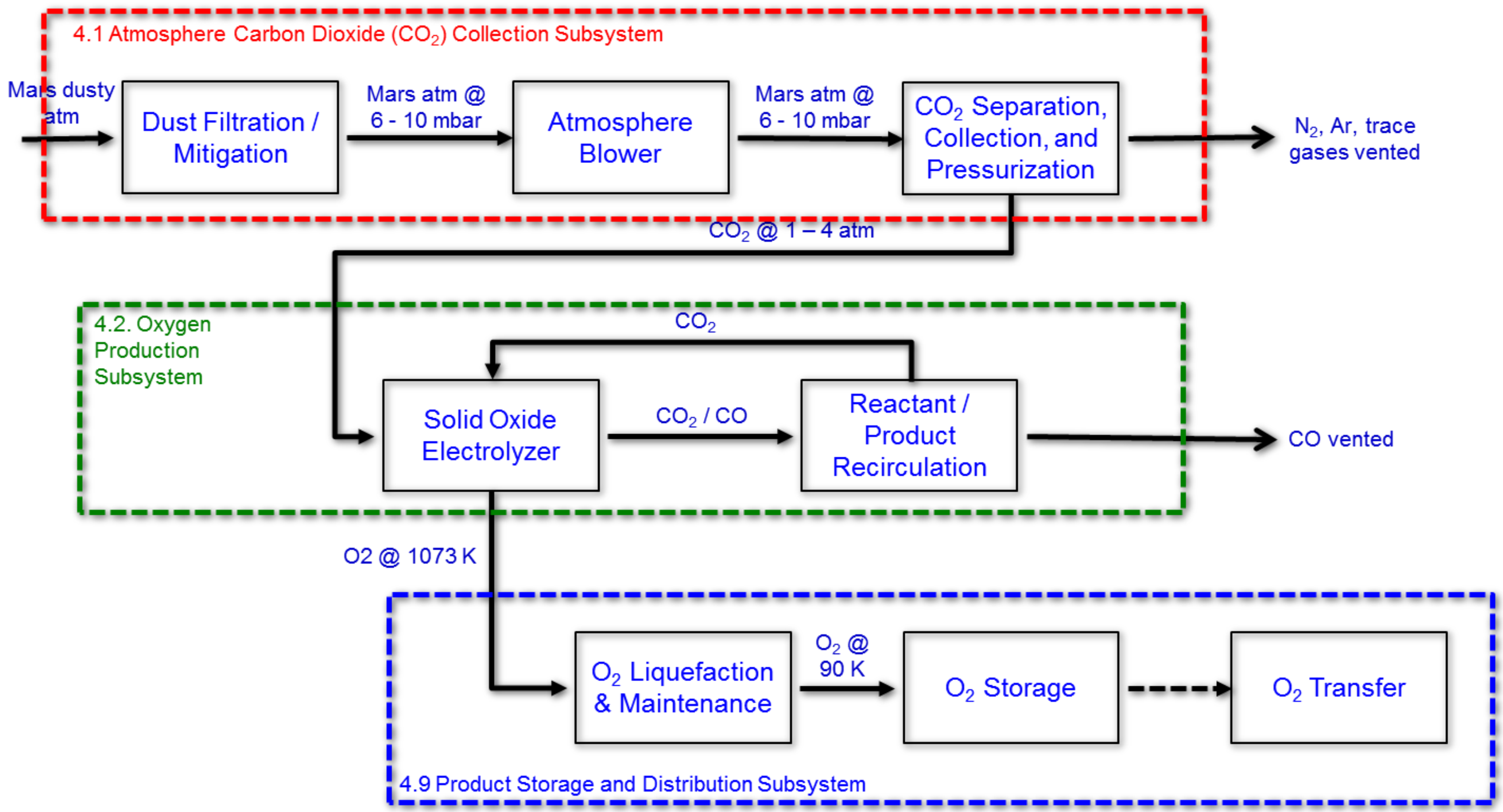
$$2\,H_2O + CO_2 \rightarrow 2\,O_2 + CH_4$$

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

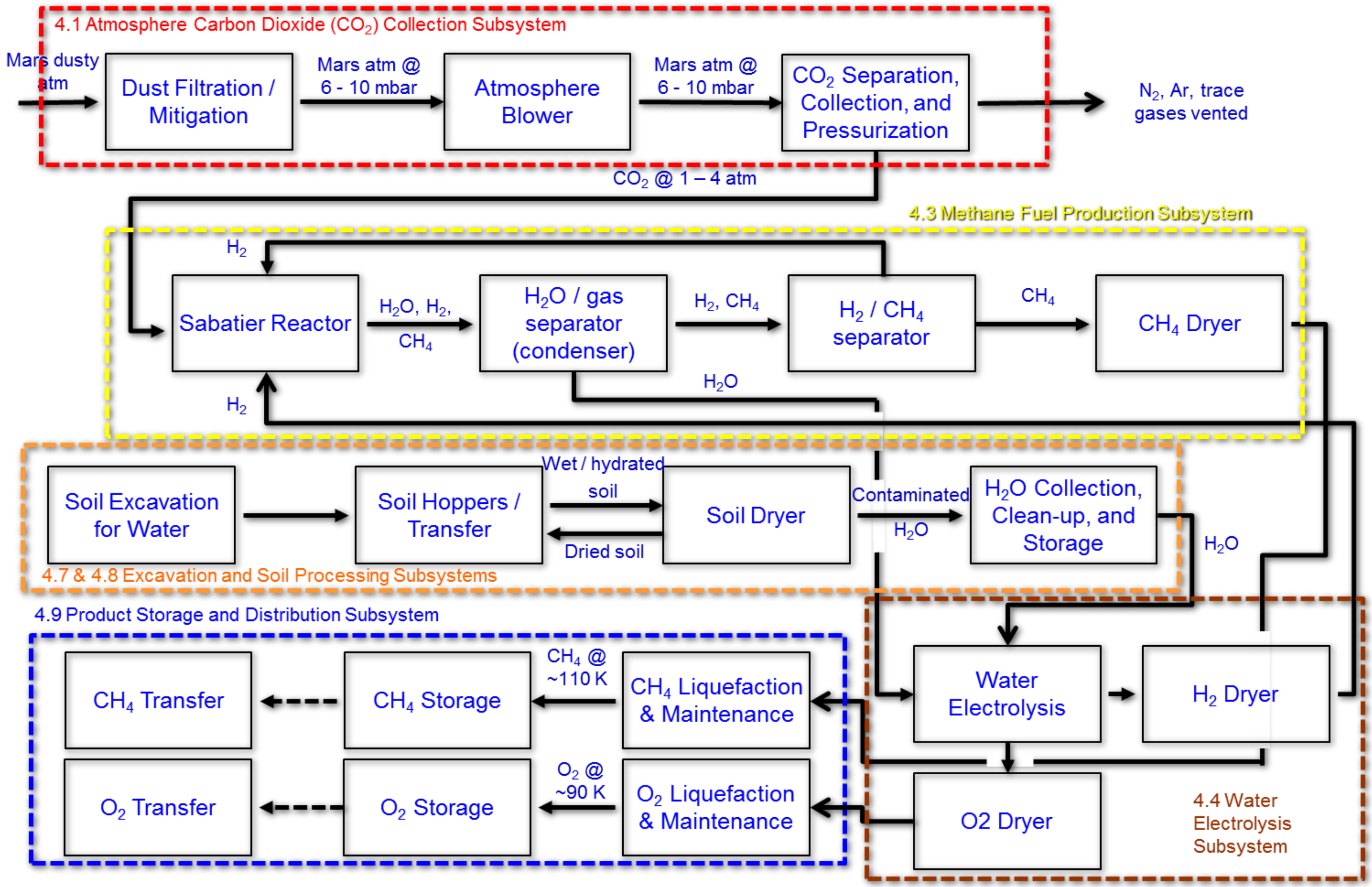
Sabatier: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

- Closes loop: All propellants for ascent + excess oxygen
  - Sabatier produces at a 4:1 ratio

Oxygen production from atmosphere integrated system (solid oxide electrolysis option)



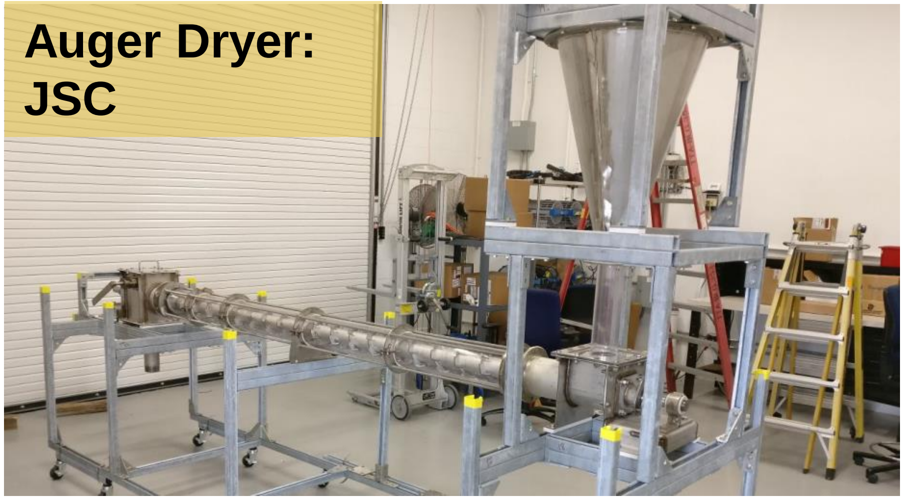
Oxygen and methane production from atmosphere and soil water integrated system



Examples of Technologies

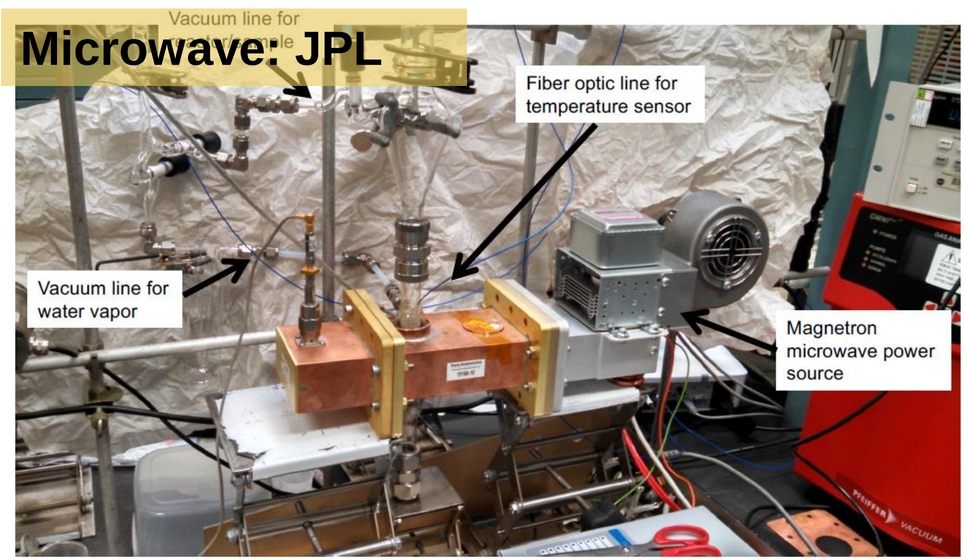
	Subsystem	Components	Heritage
Excavation	Excavation	RASSOR 2.0 excavator – Bucket drum rover	KSC prototype hardware, laboratory tests in regolith simulants
Regolith Processing	Regolith Processing	Auger Conveyor Dryer – heated auger with gas loop for continuous regolith processing	JSC design concept – numerical sizing model, conceptual CAD
		Vapor cleanup – Membrane separator	COTS
		Water collection – Cold trap	JSC design concept- numerical sizing model
Propellant Production	CO_2 Acquisition	Cryofreezer	COTS –flight heritage KSC cold head conceptual design numerical sizing
	Sabatier	Microchannel Sabatier	Solicited: Battelle PNNL
		Regenerative Gas dryer, desiccant	JSC development hardware
		CH_4/H_2 separator	Solicited: Hamilton Sunstrand
	Electrolysis	PEM electrolysis stack, Cathode feed	Giner Inc.
		Deionizer	COTS
		Inlet pump, mircorpump	COTS
		Regenerative Gas dryer, desiccant	JSC development hardware
	Liquefaction	Cryocooler	COTS

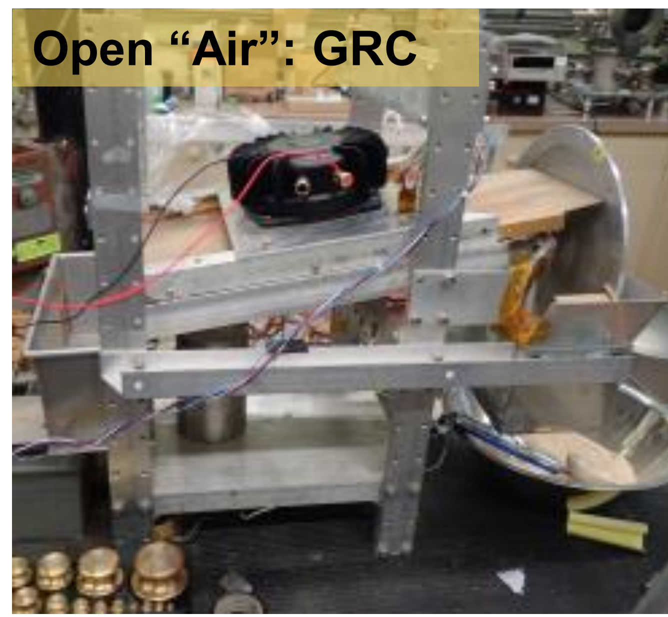
Soil Processing Technologies for Hydrated Surface material



Examples of technologies to process granular surface material for resource extraction.

- Designed for Mars surface material: low yield hydrates (1.5% to 10% water)
- In-house efforts





NASA ISRU system study example: Evolvable Mars Campaign

- 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
- Assumptions:
  - Water from low yield hydrated surface material
  - Regolith transferred to fixed processing site
  - Liquefaction in MAV tanks
  - Modular systems: 3 operating at 40% each
  - Estimates do NOT include:
    - Power source
    - Radiators

		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

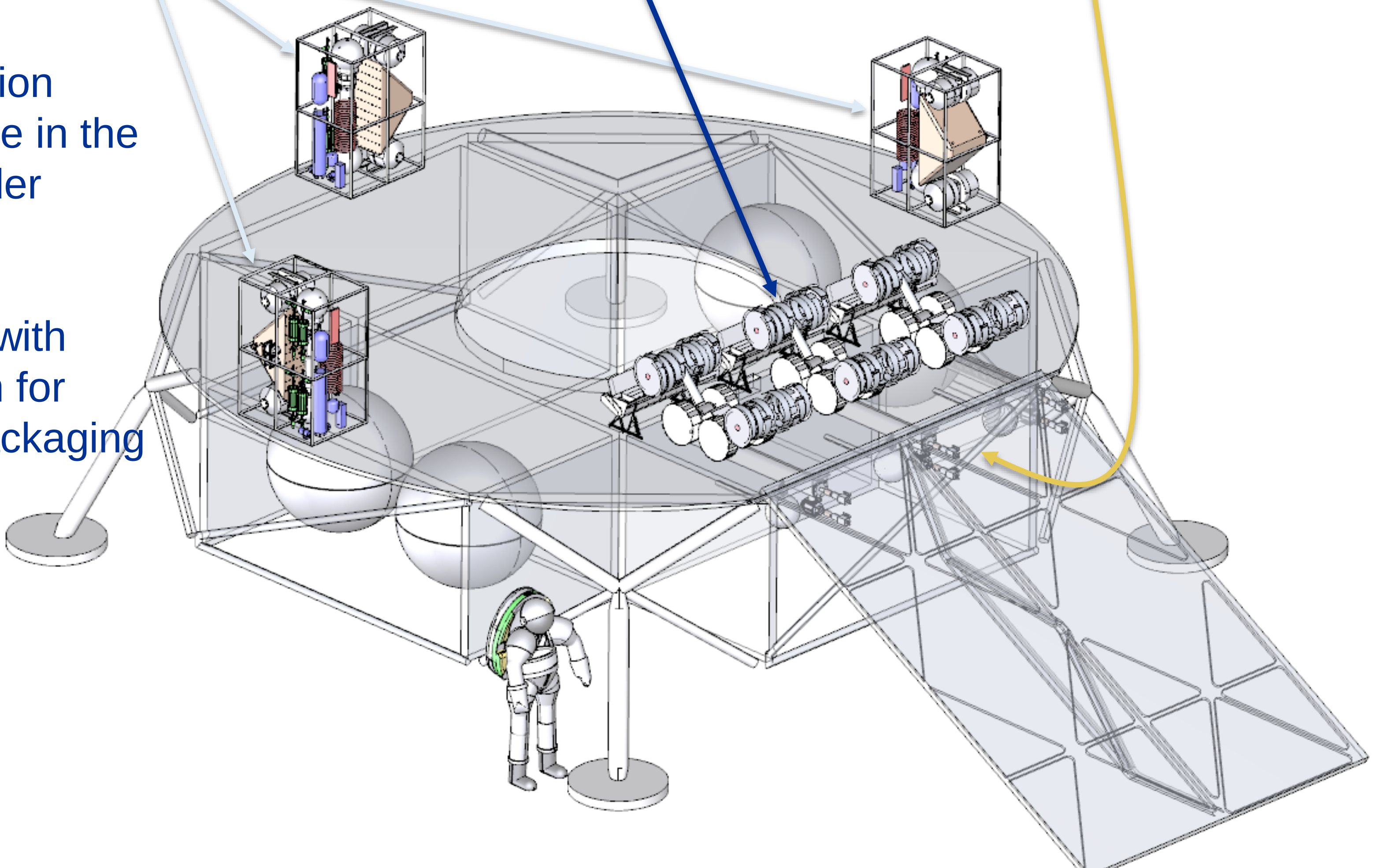
Notional Packaging: Full ISRU System

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

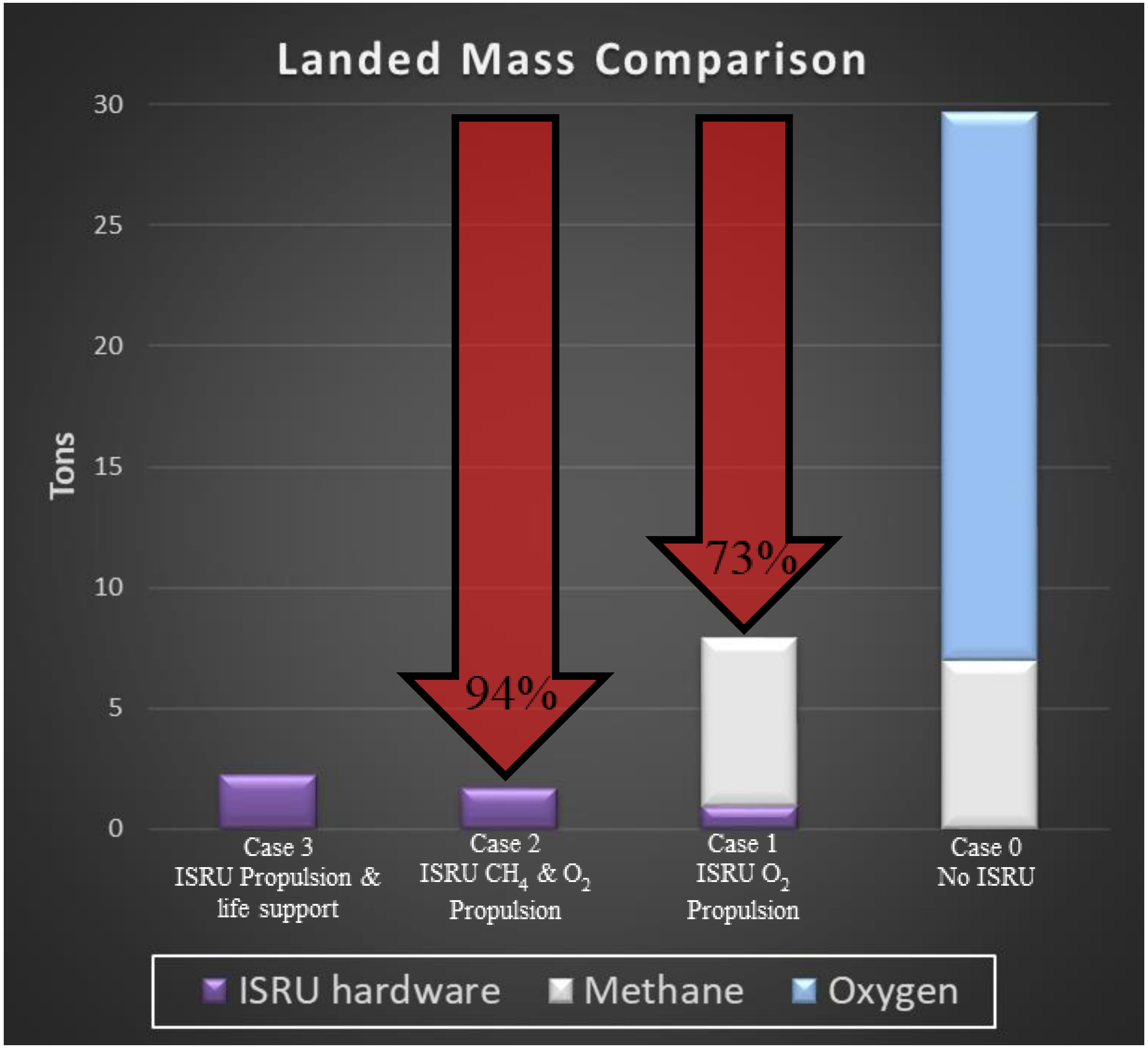
*Liquefaction takes place in the MAV/Lander tanks

*Working with MAV team for current packaging



Overall Mass comparison

- Mass reductions are compared to total ascent propellants only
- 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
  - Reduces cost and eliminates several heavy lift launch vehicles



Leverage (Gear) Ratios using ISRU

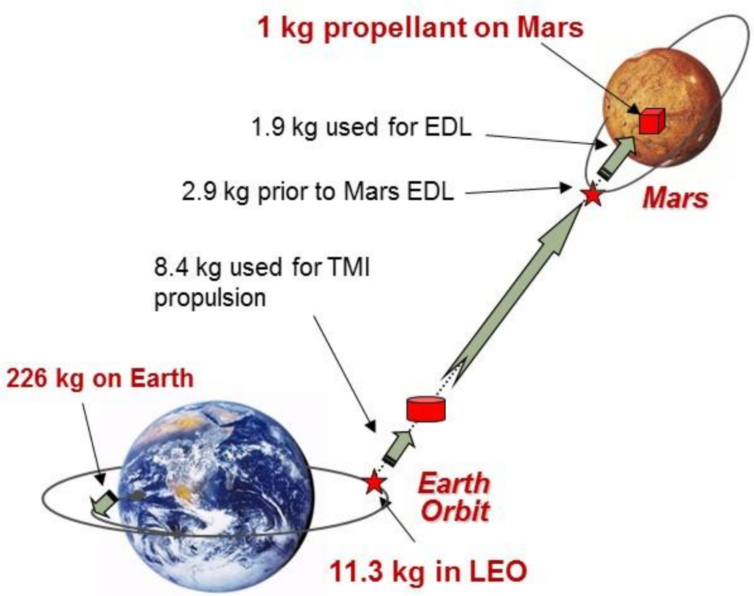
Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

Potential 334.5 mT launch mass saved in LEO = 3 to 5 SLS launches avoided per Mars Ascent

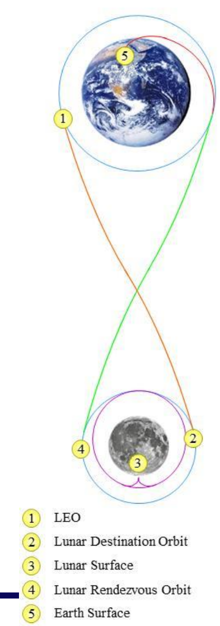
Mars mission

- Oxygen only — 75% of ascent propellant mass; 20 to 23 mT
- Methane + Oxygen — 100% of ascent propellant mass: 25.7 to 29.6 mT

Regeneration of rover fuel cell reactant mass



Estimates based on Aerocapture at Mars



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

HIGHLIGHT AN ISRU TECHNOLOGY – SOLID OXIDE ELECTROLYSIS OF CO_2

Solid oxide electrolysis of carbon dioxide

Brief description:

CO_2 disassociates into CO and oxygen ions (O^{2-}) on cathode,

$$CO_2 + 2e^- \rightarrow CO + O^{2-}$$

O^{2-} ions transport across YSZ membrane and recombine to form O_2 on anode:

$$O^{2-} \rightarrow 1/2O_2 + 2e^-$$

Materials/catalysts (typical):

Cathode: Ni-YSZ (Nickel-Yttria-doped Zirconia cermet), Ni-doped ceria (Ni with samaria or gadolinia doped ceria cermet)

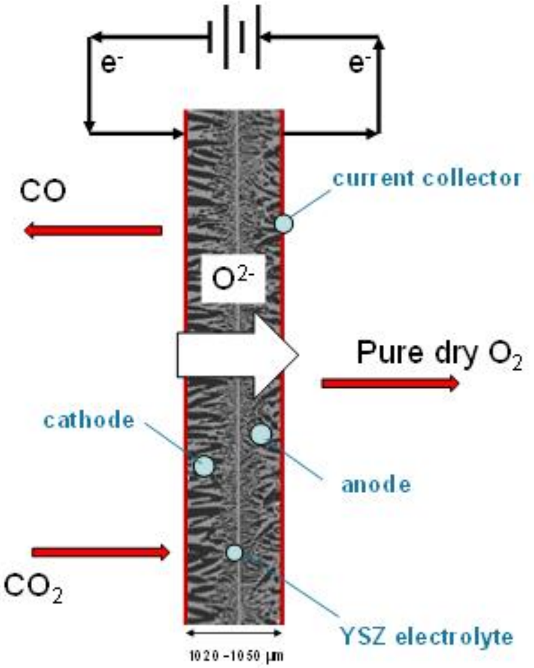
Anode: LSCF (lanthanum strontium cobalt ferrite), LSM (lanthanum strontium manganite), $La_{1-x}Sr_xMnO_3$

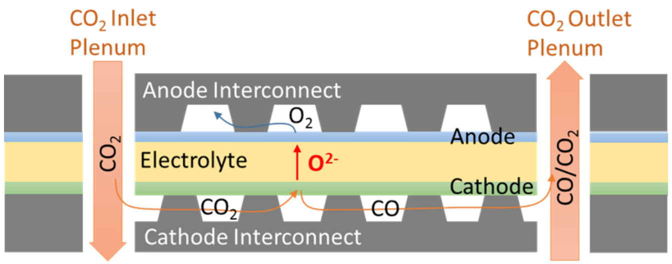
Electrolyte: YSZ (yttria stabilized zirconia), ScSZ (scandia stabilized zirconia)

Interconnect: Chromium/iron/yttrium alloy

Some Advantages:

- Solid state electrochemical process (no moving parts).
- Produces pure dry oxygen (important for liquefaction).
- Does not require hydrogen (or water source).

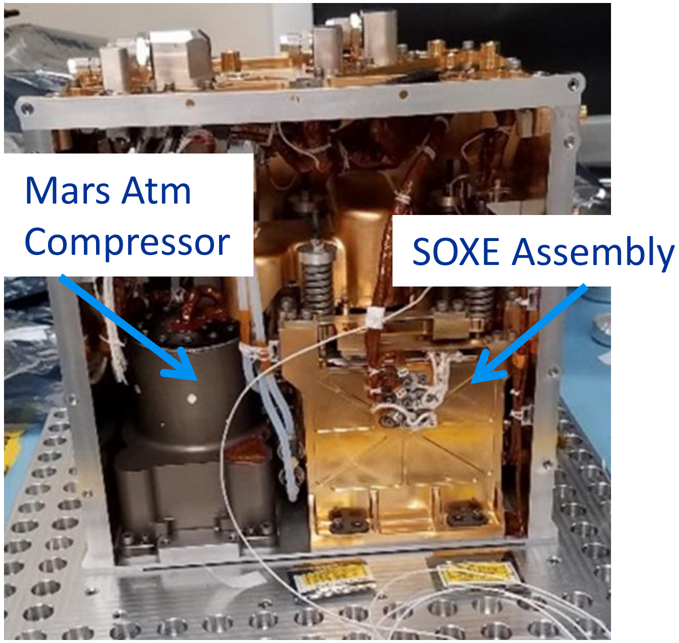




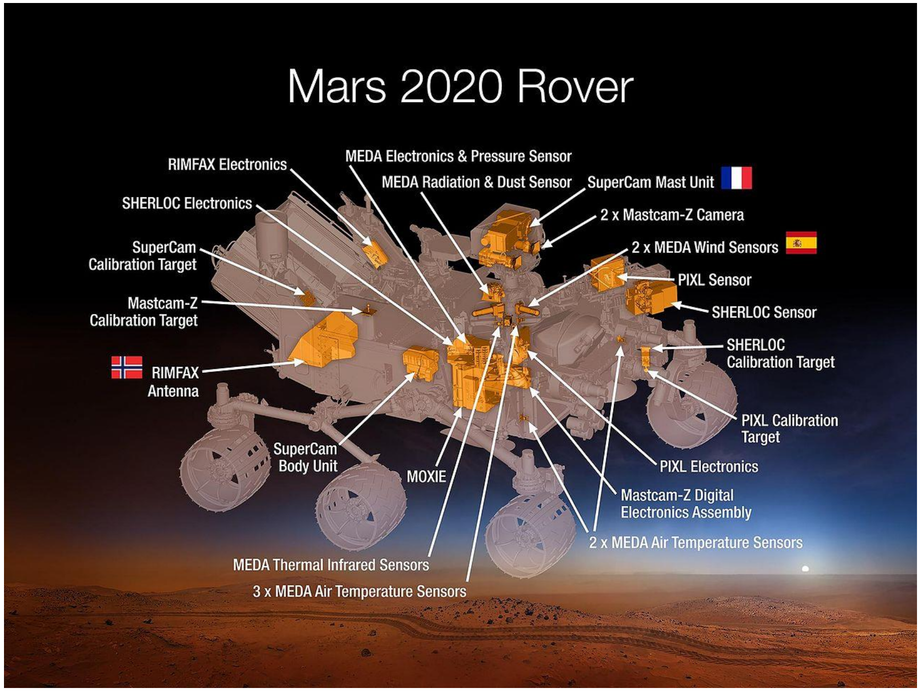
MOXIE (Mars Oxygen ISRU Experiment): Mars 2020

- In-Situ Demonstration of Mars ISRU technology
- Solid Oxide Electrolysis
  - Electrochemical conversion of atmospheric CO_2 to O_2
  - Approximately 1% scale: 12 g/hr (versus human mission scale)
- Lead by MIT. SOXE by Ceramatec, Inc. (now OxEon LLC)

SOXE stack before assembling in insulated box



MOXIE Assembly, 15 kg, ~11.5" X 10.25" X 12"



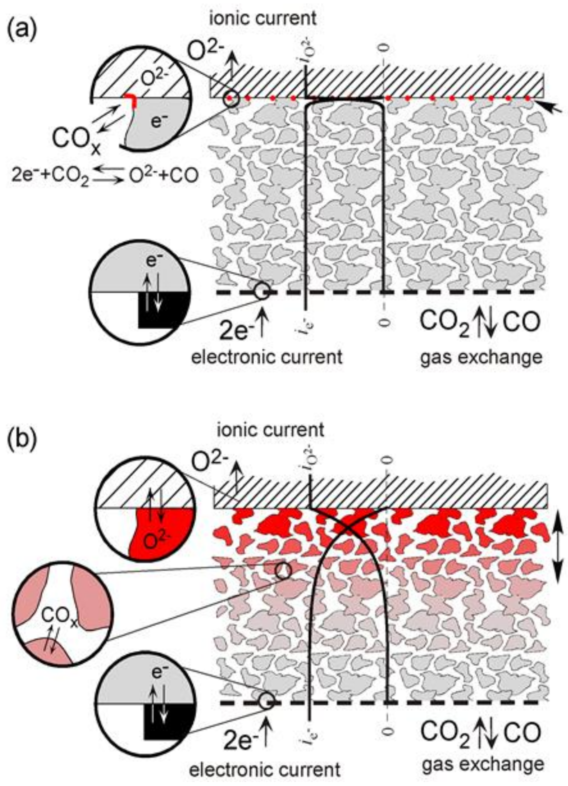
CO_2 Solid Oxide Electrolysis Technology Challenges

- Energy intensive process (ΔH_r = +293.0 kJ/mol compared to ΔH_r = +285.9 kJ/mol for H_2O)
- High temperature operation (800-900 C)
- Thermal cycling
  - CTE mis-match, thermal gradients due to poor thermal conductivity of ceramic layers.
  - Effects CONOPS (i.e. start-up time).
- Performance degradation
  - CO_2 reduction cathode degrades at high rate in dry CO_2 (redox stability, Ni coarsening, gas contaminants).
  - Anode (delamination of electrode layer under high current density, high ionic O^{2-} flux).
  - Carbon deposition (coking) at high CO/CO_2 gas ratios. (Limits CO_2 utilization/conversion).
- Structural integrity
  - Structural materials are brittle (ceramics).
  - Require metal-to-ceramic interfaces.
- Sealing
  - Sealing for long-term high temperature operation. Limited work in other technologies above 700 deg C.
  - Thermal cycling adds additional challenges, again due to CTE mis-match between sealing materials and sealing interfaces.
  - Tubular SOFC/SOE designs more tolerant [but not as mass or volumetrically compact as planar.]
- Packaging
  - High temperature thermal insulation, electrical heaters, gas connections, etc.

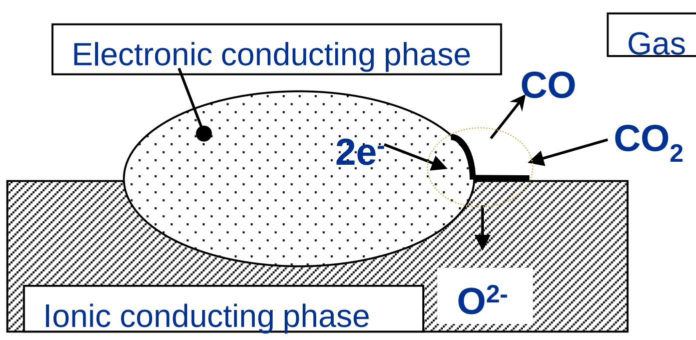
MOXIE development has solved thermal cycling, structural, and sealing issues for their specific design and requirements.

Brief description of CO_2 reduction electrochemistry

A qualitative illustration of (a) electronic-only conducting and (b) mixed-conducting porous electrode design. In (a), the three phase boundary (TPB) area is confined to the limited area where the electronic-only conducting electrode meets the ionic-conducting electrolyte. In (b), the TPB area is enhanced due to the mixed ionic-electronic conducting properties of the electrode; the reaction can occur over a larger extent of the internal surface area of the porous electrode, away from the electrode/electrolyte interface. The variation in shade of red color illustrates this variation in the CO_2 reduction reaction rate through the thickness of the electrode.

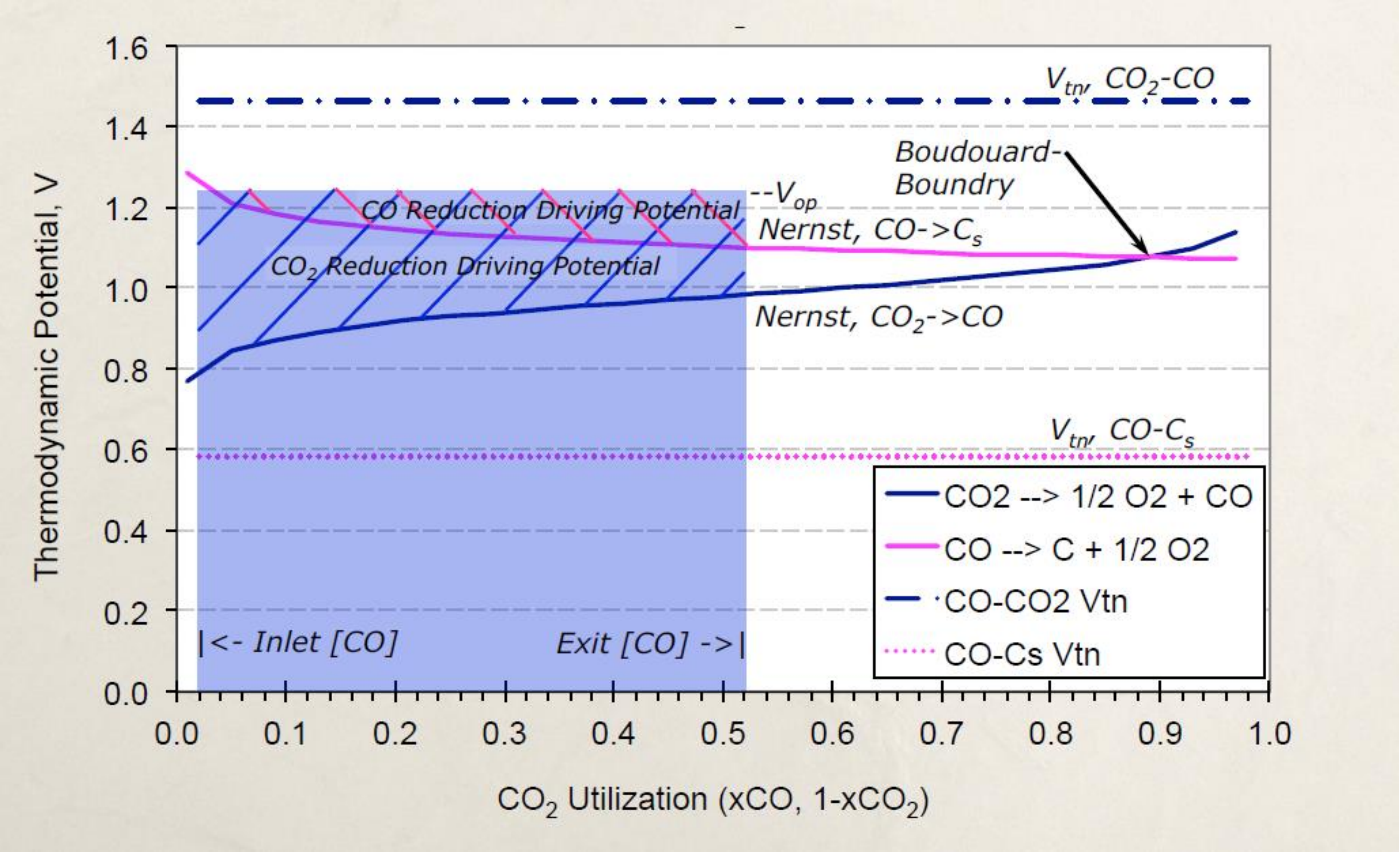


Triple-Phase Boundary (TPB)



CO_2 reduction: $CO_2 + 2e^- \leftrightarrow CO + O^{2-}$

Carbon deposition (coking) limit for CO_2 reduction



MOXIE team did extensive work characterizing this effect for their system.

Summary

- ISRU advantages include:
  - Enabling missions and architectures that were not possible otherwise
  - Significantly reducing mission cost and risk
  - Extending mission duration, reducing earth reliance
  - Can be leveraged at multiple destinations at a variety of scales (e.g. human, robotic sample return, robotic science exploration)
- ISRU primary challenges include:
  - Highly multi-disciplinary (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
  - Infrastructure: Long term operation that requires understanding and management of component life-cycles.
  - Requires autonomous operations on a level not yet achieved (mining/excavating, system operation, etc)
- ISRU technology challenges:
  - The technical development challenges for multiple technologies
  - CO_2 solid oxide electrolysis technology issues were highlighted here.

Acknowledgements

- NASA's Advanced Exploration Systems (AES) and Space Technology Mission Directorate (STMD) fund the ISRU Project.
- A thanks to Gerald Voecks (NASA JPL) for providing MOXIE experiment images and data.

BACKUP

CURRENT NASA ISRU ACTIVITIES

NASA ISRU Project

Scope: Develop and demonstrate, in ground demonstrations, the component, subsystem, and system technology to enable production of mission consumables from regolith and atmospheric resources at a variety of destinations

- Initial focus
  - Critical technology gap closure
  - Component development in relevant environment (TRL 5)
- Interim goals
  - ISRU subsystems tests in relevant environment (Subsystem TRL 6)
- End goals
  - End-to-end ISRU system tests in relevant environment (System TRL 6)
  - Integrated ISRU-Exploration elements demonstration in relevant environment

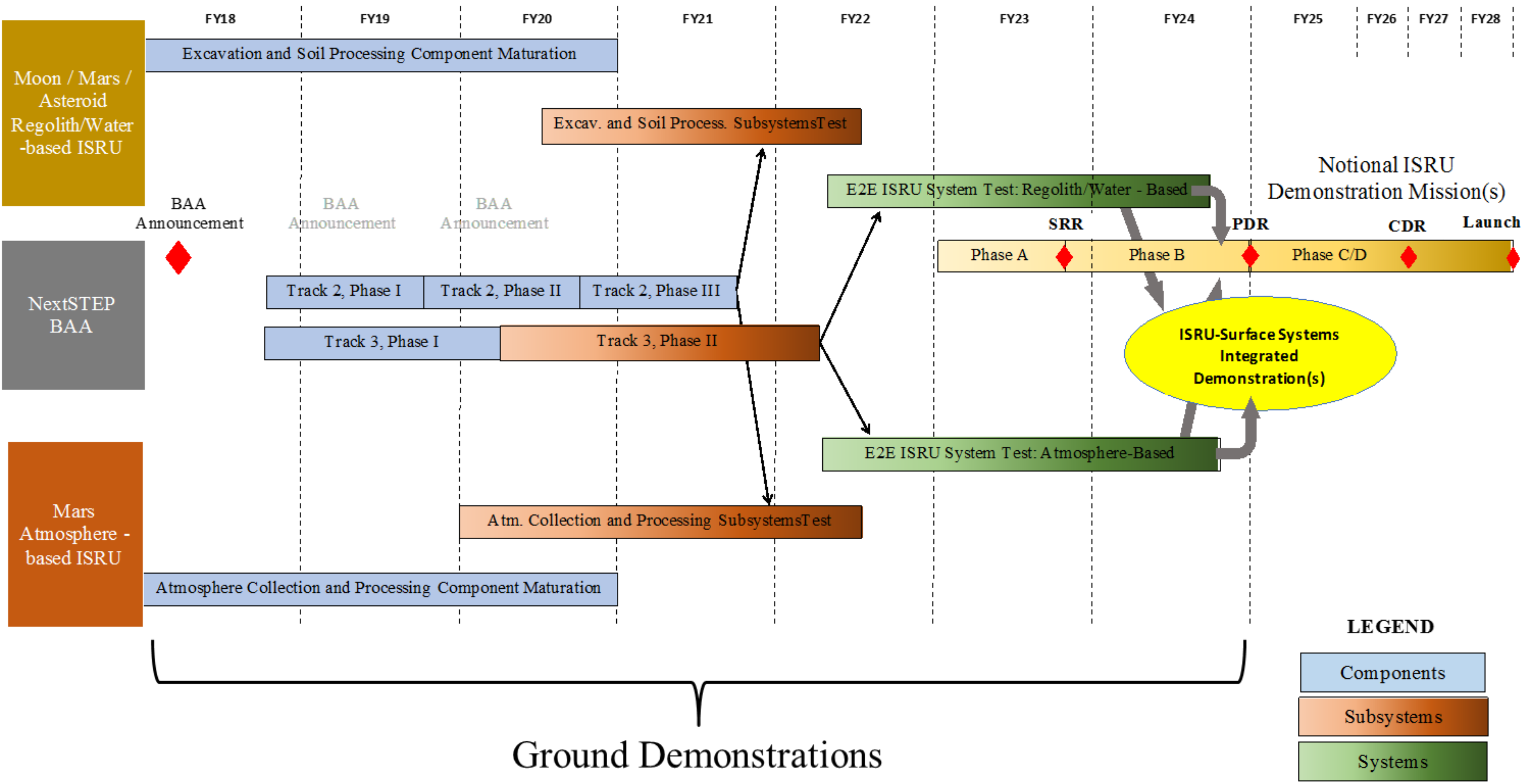
Overall Project Goals

System-level TRL 6 to support future flight demonstration missions

Provide Exploration Architecture Teams with validated, high-fidelity answers for mass, power, and volume of ISRU Systems

NASA ISRU Project

All dates are subject to evolving agency policy and funding priorities



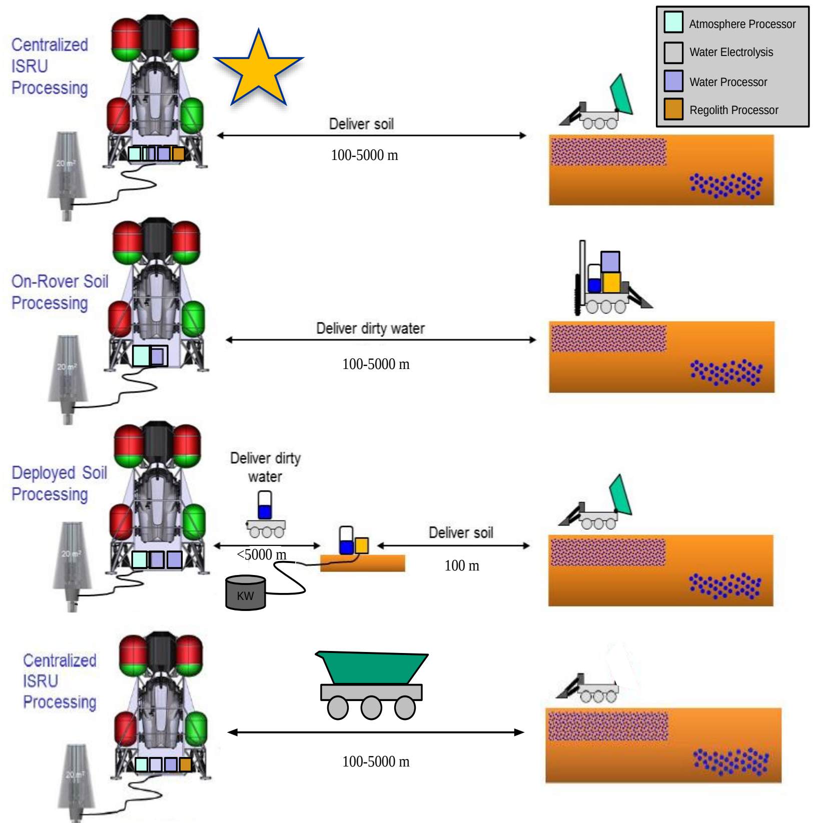
Assumptions

- Production Rate driver: *6978 kg of Methane needed + 0.5% margin*
  - Methane is the driver since excess oxygen will be produced using Sabatier process
- Time of ISRU production: *480 day operation, 24hr/day*

Phase-I Case Study

- Soil Water resource (baseline): *Water from surface regolith = hydrates*
  - Ubiquitous (location independent)
  - Available in surface material (subsurface excavation not required)
  - Lower resource yield is more of a worse case for water extraction system
- Processing: *Regolith is transported* and delivered to a centralized processing plant that is co-located with the Lander/MAV

Phase-II Case Study



- **Liquefaction:** *Takes place in the MAV tanks*. ISRU system only includes mass/power for crycoolers needed to liquefy. MAV responsible for tanks and zero boil-off systems
- **Power Source:** Not part of ISRU system**.** Assumes a fission reactor will be needed for human presence, ISRU will use reactor when humans are not present. (TBD- as power needs are identified)
- **Radiators:** Not part of ISRU system**.** ISRU will be packed on lander.

Lunar Resources & Products of Interest

LUNAR RESOURCES

MARE REGOLITH

Ilmenite - 15%

FeO•TiO_2	98.5%

Pyroxene - 50%

CaO•SiO_2	36.7%
MgO•SiO_2	29.2%
FeO•SiO_2	17.6%
Al_2O_3•SiO_2	9.6%
TiO_2•SiO_2	6.9%

Olivine - 15%

2MgO•SiO_2	56.6%
2FeO•SiO_2	42.7%

Anorthite - 20%

CaO•Al_2O_3•SiO_2	97.7%

VOLATILES (Solar Wind & Polar Ice/H_2)

Hydrogen (H_2)	50 - 150 ppm
Helium (He)	3 - 50 ppm
Helium-3 (^3He)	10^{-2} ppm
Carbon (C)	100 - 150 ppm
Polar Water (H_2O)/H_2	1 - 10%

→ Thermal Volatile Extraction

Hydrogen Reduction of Ilmenite/glass Process

Fluidized Bed Reactor

$2FeTiO_3 + 2H_2 \xrightarrow{900°C} 2H_2O + 2Fe + 2TiO_2$ → 2Fe

Water electrolysis

$O_2 + 2H_2 \xleftarrow{25°C} 2H_2O$ → O_2

Sulfuric Acid Reduction

Desolve/Digest Reactor

$2FeTiO_3 + 2H_2SO_4 \rightarrow 2H_2O + 2FeSO_4 + 2TiO_2$

Electrolysis bed

$O_2 + 2Fe + 2H_2SO_4 \leftarrow 2H_2O + 2FeSO_4$ → O_2, 2Fe

New: Ionic Liquids

$M_nO_m + 2_m[H^+] \rightarrow mH_2O + nM^{+m}$

Methane Reduction (Carbothermal) Process

Methane Reduction Furnace

$2FeTiO_3$, Fe_2SiO_4, $FeSiO_3$, Mg_2SiO_4, MgSiO, $CaSiO_3$ $+ 2CH_4 \xrightarrow{1625°C} 2CO + 4H_2 +$

- $2TiO_2$ + 2Fe → 2Fe
- 2FeO + Si
- FeO + Si
- 2MgO + Si
- MgO + Si
- CaO + Si

→ Si

Methane Reformer

$2H_2O + 2CH_4 \xleftarrow{250°C} 2CO + 6H_2$

Water electrolysis

$2H_2O \xrightarrow{25°C} 2H_2 + O_2$ → O_2

Molten Electrolysis

Molten Electrolysis Reactor

$2SiO_2 \rightarrow 2SiO + O_2$	→ O_2	
$2FeTiO_3 \rightarrow 2Fe + 2TiO_2 + O_2$	→ O_2, 2Fe	
$2FeO \rightarrow 2Fe + O_2$		

Vapor Pyrolysis Process

Pyrolysis Reactor/Condenser

$2SiO_2 \xrightarrow{>2000°C} 2SiO + O_2$	O_2
$2FeTiO_3 \xrightarrow{2500°C} 2Fe + 2TiO_2 + O_2$	O_2, 2Fe
$2FeO \xrightarrow{>2000°C} 2Fe + O_2$	
$2Al_2O_3 \xrightarrow{>2000°C} 4AlO + O_2$	O_2
$2Al_2O_3 \xrightarrow{>2000°C} 2AlO + 2Al + O_2$	O_2, 2Al
$2MgO \xrightarrow{>2000°C} 2Mg + O_2$	O_2
$2CaO \xrightarrow{>2000°C} 2Ca + O_2$	
$2CaAl_2Si_2O_8 \xrightarrow{2500°C} 2Ca + 4AlO + 4SiO + 4O_2$	$4O_2$, 2Ca
$2CaAl_2Si_2O_8 \xrightarrow{2500°C} 2Ca + 2AlO + 2Al + 4SiO + 5O_2$	$5O_2$, 2Al, 2Ca

NEXT Step BAA

Together, the 10 awarded proposals represent an excellent portfolio meeting important ISRU Project objectives for significant technical advancement and effective public-private partnerships, while filling critical gaps for both Moon and Mars destinations

Company	Short Title	Track
Blue Origin	Enhancing Lunar Exploration with ISRU Strategies	1
United Launch Alliance	ULA NextSTEP-2 ISRU Affordability Thresholds	1
University of Illinois	Integrated Architecture Trade Studies	1
UTAS 1	Trade Study, Water Electrolysis	1
Blazetech 1	Compact High Efficiency Self-Cleaning Dust Filter for Martian Air	2
Paragon 2	ISRU-derived Water Purification and Hydrogen Oxygen Production	2
Skyhaven 2	Hydrogen and Methane Separator for Martian ISRU Processing	2
Teledyne Energy Systems	Advanced Alkaline Electrolyzer to Support NASA ISRU Application	2
Honeybee Robotics	RedWater: Extraction of Water from Mars' Ice Deposits	3
Oxeon	Production of O2 & Fuels from In-Situ Resources on Mars	3

Some Backup information

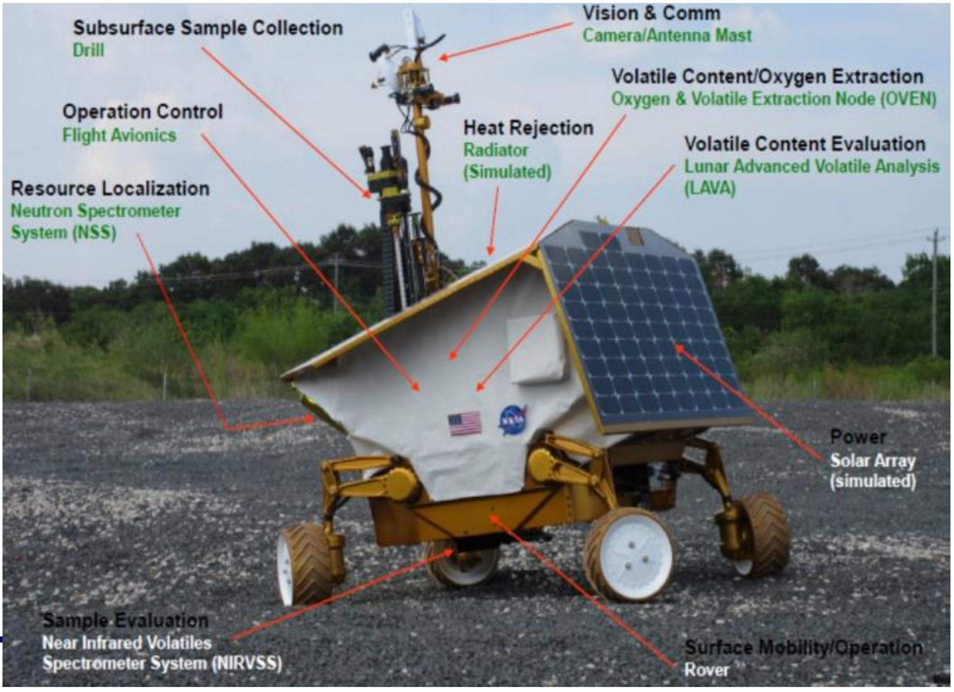
- Analog for Mars hydrated soil used in some of NASA's ground testing: Borax or sodium tetraborate pentahydrate, ($Na_2B_4O_7 \cdot 5H_2O$)
- Boiling points for propellants being considered for production via ISRU processes:
  - Hydrogen (H_2) BP: -253 °C (20 K)
  - Oxygen (O_2) BP: -183 °C (90 K)
  - Methane (CH_4) BP: -161.5 °C (111.5 K)
- Apollo Lunar Module (LM)
  - Launch mass: 33,500 pounds (15,200 kg)
  - Dry mass: 9,430 pounds (4,280 kg)

Resource Prospector (RP)

- Resource Characterization (Prospecting): Lunar Polar Water
  1. Locate surface and near-subsurface volatiles,
  2. Excavate and analyze samples of the volatile-bearing regolith
  3. Demonstrate the form, extractability and usefulness of the materials
- Rover based instrument suite including
  - Neutron Spectrometer and Near Infrared Spectrometer: surface water signatures
  - 1m sampling drill: Subsurface water distribution
  - Oven with Gas chromatograph/Mass Spectrometer: sample characterization
- Targeting South Pole
- 6-14 day mission
- Class D, Category 3

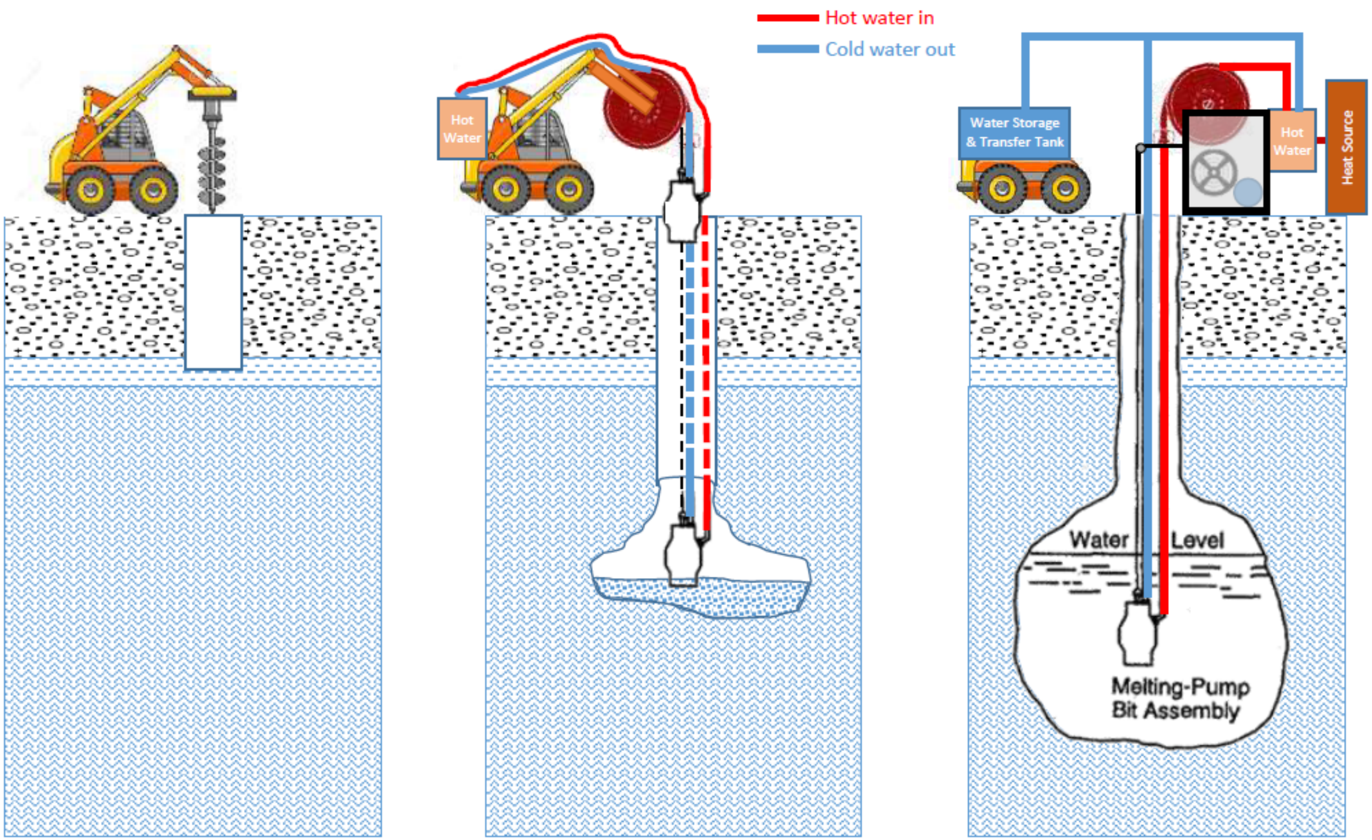
Status

- RP was canceled in May 2018 due to agency reorganization.
- Instrument development will continue separately
- Discussions for incorporation onto upcoming commercial lander opportunities (NASA CLPS program)



Subsurface Ice Mining: Rodwell

- Rodwells are in use terrestrially (Antarctic field stations) for water generation from subsurface ice sheets.
- CRREL (Cold Regions Research and Engineering Laboratory) has generated a numeric model for Rodwell design. This model has been leveraged to develop a ISRU Mars Rodwell system to:
  - Estimate mass & power for Mars relevant hardware
  - Examine Concept of Operations of Rodwell for various operating conditions (production rates, location, etc)
  - Initial trade study results to be published at AIAA Space 2018.



Phase 1: Drill through overburden into top of ice.

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

Phase 3: Steady state operation.

Shared Requirements and Hardware With *In Situ* Resource Utilization

	Requirements Impacted or Shared	Hardware Impacted or Shared
Propulsion	Type of propellant and/or pressurant	Propellant/pressurant storage tanks and valves
	Quantity and production rate of propellant/pressurant	Propellant/pressurant transfer
	Propellant storage (temperature/pressure)	Solar collectors/heat transfer
Life Support & EVA Systems	Type of life support consumables	Consumable storage tanks and valves
	Quantity and production rate of consumables	Water processing/electrolysis
	Waste products and trash type	Waste/trash processing
	Waste products and trash quantity	Carbon dioxide processing
	Consumable storage quality (temperature/ pressure)	Reactant/product seperation
		Consumable transfer
		Solar collectors/heat transfer
Habitat	Shielding and protection for crew and equipment	Structure and shielding concepts
	Inflation gas quantity and type	Thermal management
	Thermal management	
Surface Mobility	Mobility vehicle size	Mobility platforms for excavation and civil engineering
	Mobility vehicle terrain and environment compatibility	Actuators, motors, and control software
	Mobility power requirements	
Power	Daytime power amount (nominal & maximum)	Consumable storage tanks and valves
	Nighttime/eclipse power amount	Water processing/electrolysis
	Fuel cell reactant type	Propellant/pressurant transfer
	Quantity and production rate of fuel cell reactants	Reactant/product seperation
	Fuel cell reactant storage quality (temp/ pressure)	Solar collectors/heat transfer
Science	Sample mineral characterization and mapping	Science instruments
	Sample physical characterization and transfer	Subsurface samples access
	Sample volatile characterization	Test gases and reagents for science