Mars In Situ Resource Utilization and the Importance of Water Resources

Presentation to
The Mars Ice Challenge
June 5, 2018

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Lead for ISRU System
Capability Leadership Team

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

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

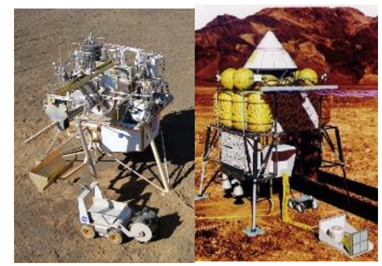
Resource Assessment (Prospecting)

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

Resource Acquisition

Atmosphere constituent collection, and material/volatile collection via drilling, excavation, transfer, and/or manipulation before Processing

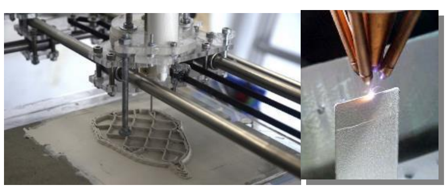
Resource Processing/ Consumable Production



Conversion of acquired resources into products with immediate use or as feedstock for construction & manufacturing

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

In Situ Manufacturing



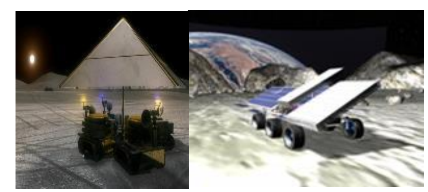
Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

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' 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

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Main *Natural* Space Resources of Interest

	Moon	Mars	Asteroids	Uses
Water	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	▪ 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 transmission

Similar Resources and Needs Exist at Multiple Locations

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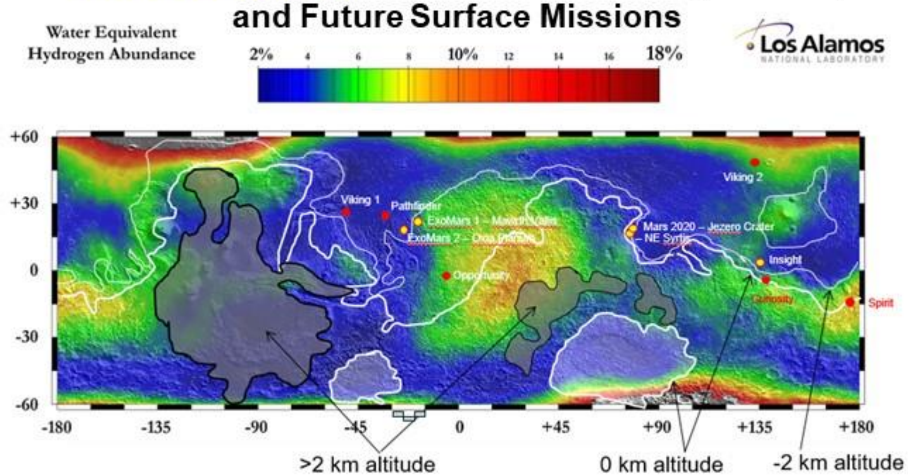
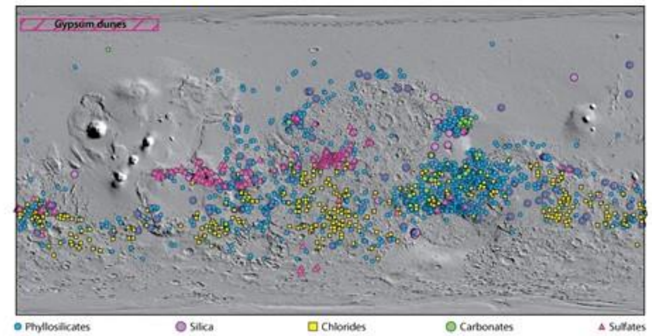
Similar Resources and Needs Exist at Multiple Locations

Selection of Water Resource Can Drive Landing Site Selection

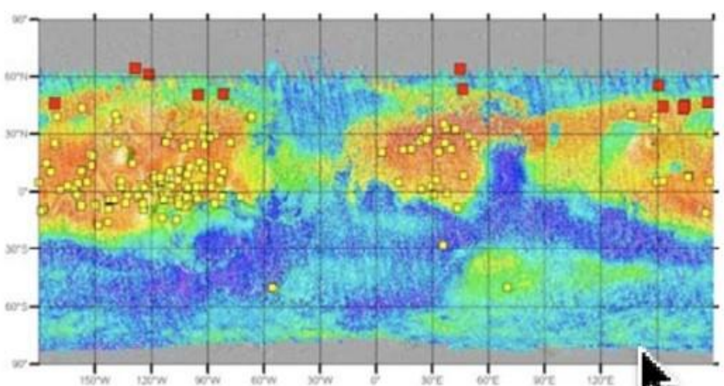
Water Abundance and Altitude with Past, Present, and Future Surface Missions



Map of aqueous mineral detections

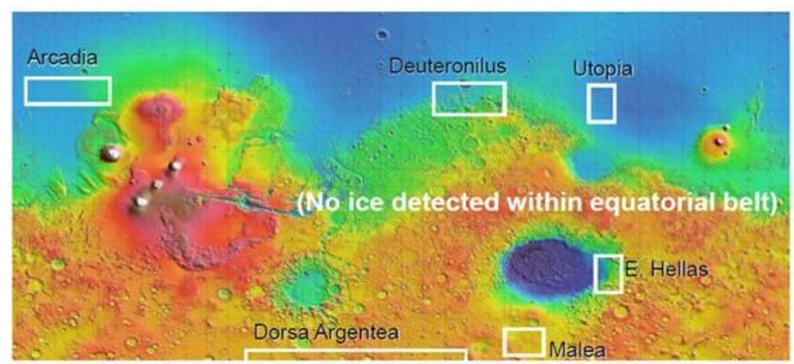


- Minerals formed in liquid water environments
- Phyllosilicates, sulfates, carbonates contain enhanced water content, to ~8%
- Exposed in areas without mid-latitude mantle



New Craters Confirm Shallow, Nearly Pure Ice

- Newly formed craters exposing water ice (red) are a subset of all new craters (yellow). Background color is TES dust index. (Adapted from Byrne et al. (2011) Science)



Summary map outlining areas of subsurface ice detections based on data from the MARSIS and SHARAD instruments. *Source: Special Regions SAG2, Rummel & Beaty et al., 2014.*

Radar Detection of Non-Polar Ice

Summary of What we Know About Water in "Hydrated Mineral Deposits"

Type of Deposit	General Description	How it has been Modeled Spectrally	Possible water content	Issues
Loose regolith	Powdered rock, salts, amorphous materials	Mix of plagioclase, olivine, pyroxene, npFeOx	4(2-5)% from spectral modeling and direct measurement	Easy to harvest; perchlorate salts may be common
Layered phyllosilicate	Stratified deposits rich in smectite	Mix of up to 50% smectite clays with primary igneous minerals (ol, px. Plag)	9-10% based on spectral modeling and assumed low hydration state of clays	Indurated and competent; more erodible than basalt
Crustal phyllosilicate	Smectite clays in basaltic groundmass	Mix of 5-10% smectite with weakly altered basalt	3-5% based on spectral modeling, examination by Opportunity	Fractured bedrock
Sulfate-bearing layered deposits	Dust + sand with variable content and type of sulfate cement	Mix of sulfate and hematite with Mix of plagioclase, olivine, pyroxene, npFeOx	6-14% from direct measurement of elemental abundances, hydration state from spectral models	Competent but easily erodible by wind; leaves little debris so must be fine-grained
Carbonate-bearing deposits	Olivine partly altered to carbonate	Mixture of olivine basalt and carbonate	7% based on spectral models	Probably very indurated bedrock
Hydrate silica-bearing deposits	Silica with range of hydration mixed w/ basalt	(Assumed: cement in basaltic sediment)	(5% based on assumed composition, could be up to)	Induration and purity probably highly variable

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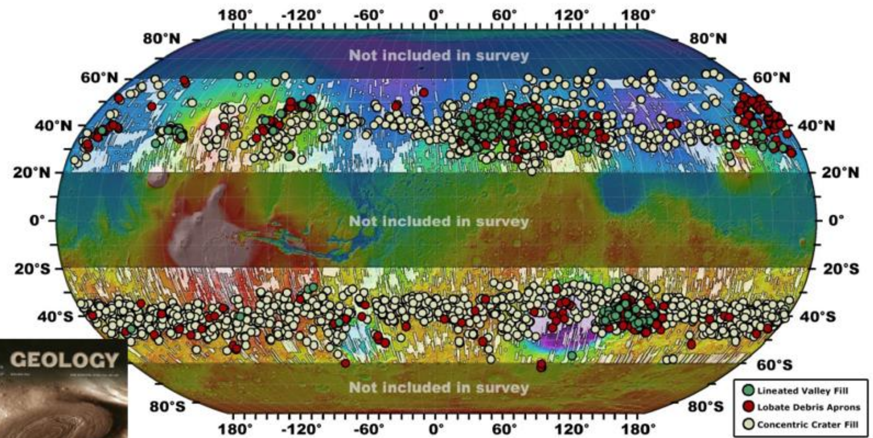
Mars Subsurface Ice

Map of Mars Glacial Features

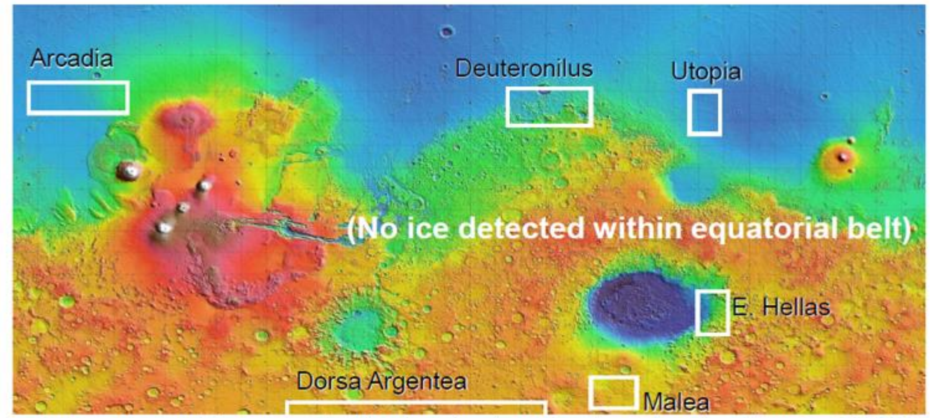


1/21/2016

- *With many features, no information about whether residual ice remains, or at what depth.*
- *Some lobate debris aprons do contain ice (next slides)*

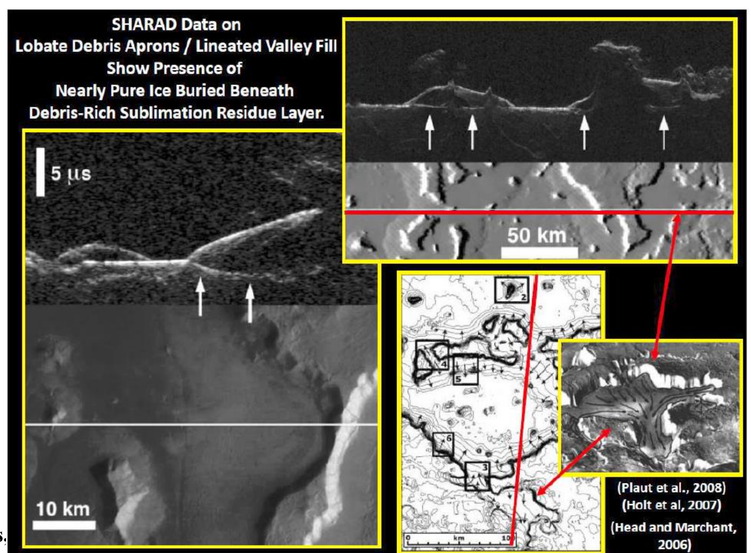
Map from Dickson et al., 2012

Radar Detection of Non-Polar Ice



Summary map outlining areas of subsurface ice detections based on data from the MARSIS and SHARAD instruments. *Source: Special Regions SAG2, Rummel & Beaty et al., 2014.*

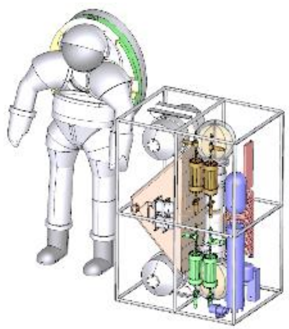
Ex, Radar Data for Glacier-Like Form Cross-Section



- Ice 100s of meters in thickness has been detected by the SHARAD radar instrument in several regions away from the poles (Plaut et al. 2009)
- Modeling estimates that these may contain 1.6 x 105 km3 or ~10x North American Great Lakes (Karlsson et al., 2015)

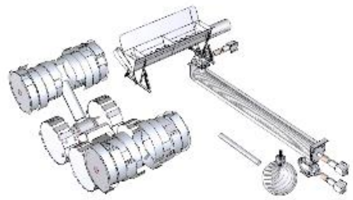
Mars Atmosphere & Water Resource Attributes

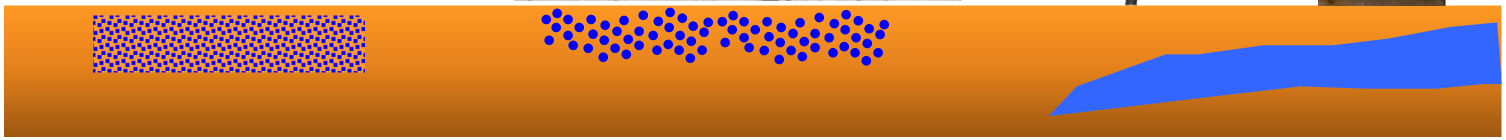
Atmosphere Processing



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

Granular Regolith Processing for Water





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/Sulfate Processing for Water

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**

Icy Regolith Processing for Water

Subsurface Ice
- **90%+ concentration**
- **Subsurface glacier or crater**: 1 to 3 m from surface possible
- **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

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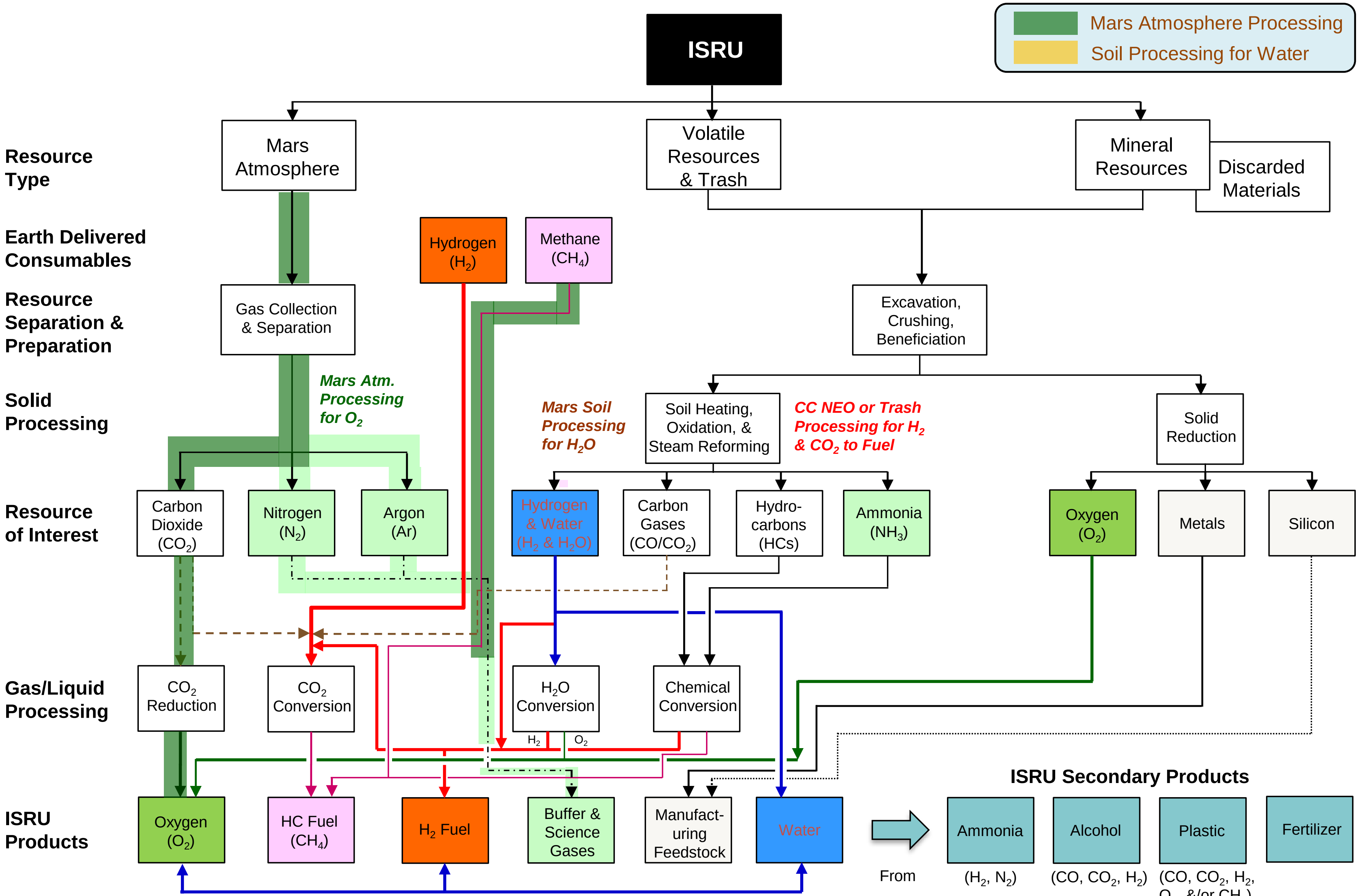
ISRU Consumables Production Decision Tree



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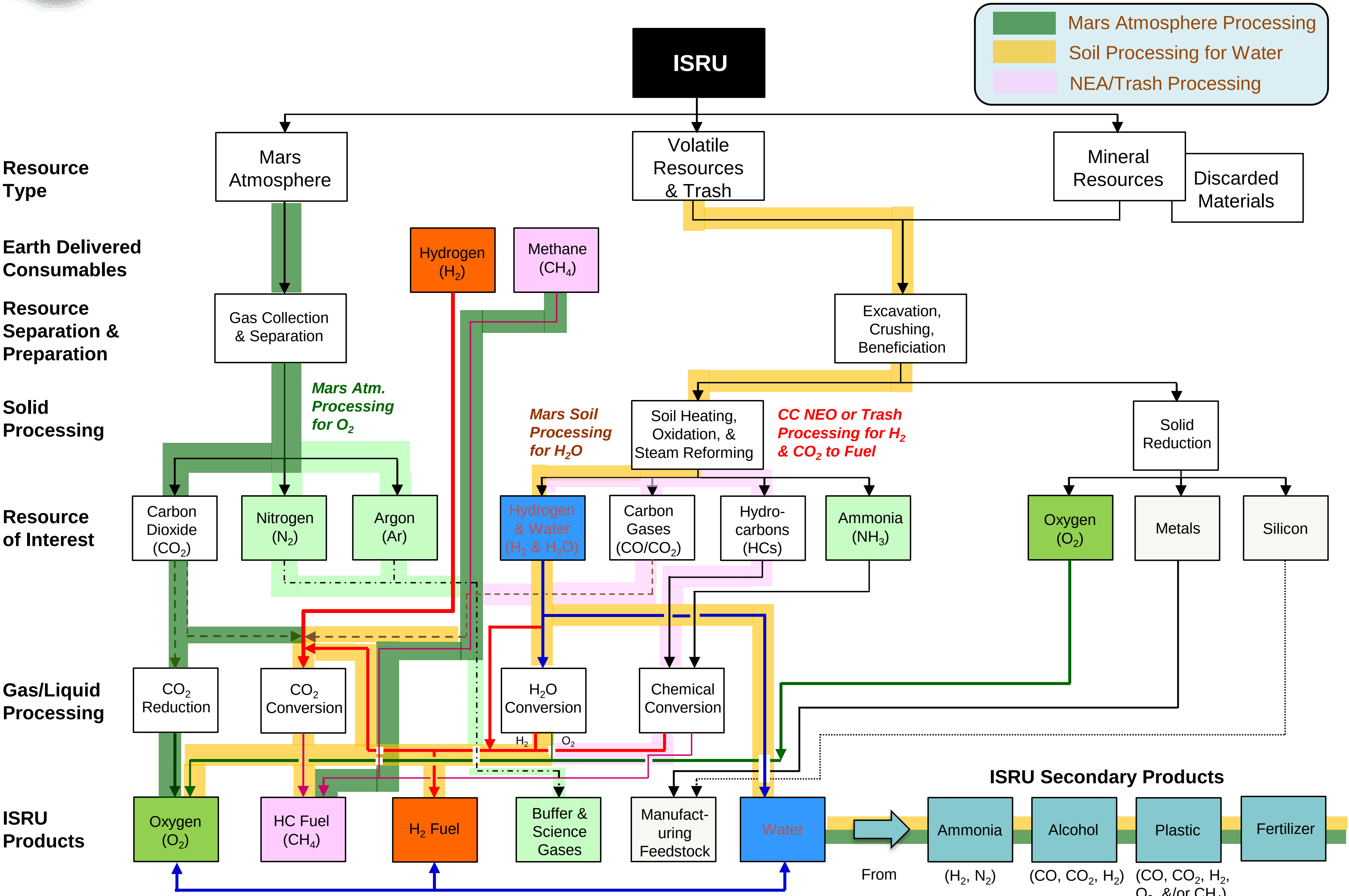

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Mars Consumable Production Requirements

The 2 Driving Requirements for ISRU are Amount Needed & Time Available

3.1 Amount Requirements (purpose, customer, amounts)

	NASA Reference Architectures				Mars ISRU Studies & Calculations				
	DRM 1.0	DRM 3.0	DRA 5.0	EMC ISRU	FC Powered Rover Study (14 day ops)	Hab. FC Power Backup (14.8 KW - 120 days)	Hercules Reusable Lander^	Mars Water Rich Study#	ISRU AES/STMD FY17
O_2 for Ascent Prop (kg)	83,500	30,333	22,985	22,728*			59,004	29,758	22,728*
O_2 for Life Support (kg)		4500	1906 (O_2 only)						See water
O_2 for FC Power					1000	21,000		30,276	TBD-SaWS
CH_4 for Ascent Prop. (kg)	23,200	8667	6250	6978*			17,102	8,748	6978*
CH_4 for FC Power					350	9,000		9,936	TBD-SaWS
N_2 for Life Support (kg)		3900	133						136^^
H_2O for Life Support/EVA (kg)		23,200	3192	3072 (EVA)**				24,379	4050 Closure/EVA#
H_2 Brought from Earth	5800	5420	399 (O_2 only)						0

Notes
*Mars Ascent Vehicle (Polsgrove AIAA 2015)
**FY16 EMC TIV Sep Briefing Task 11 ISRU
^Sustainable Human Presence on Mars Using ISRU and a Reusable Lander (Arney, Moses, et. al)
#A Water Rich Mars Surface Mission Scenario (978-1-5090-1613-6/17/$31.00 ©2017 IEEE)
^^Email from Dan Barta 7/31/17

[Green box] = Initial Requirements (~1.5 to2.2 kg/hr H_2O)
[Yellow box] = Horizon Goals (~7.5 kg/hr H_2O)

3.2 Time Requirements

- DRM 3.0/DRA 5.0): ISRU must complete production before crew leaves Earth
- EMC: ISRU must complete production before crew leaves Earth OR before crew descends to surface (depending on mission arch.)

	NASA Reference Architectures				Mars ISRU Studies & Calculations		
	DRM 3.0	DRA 5.0**	EMC ISRU	EMC GR&A***	FC Powered Rover Study (14 day ops)	Hercules Reusable Lander^	ISRU AES/STMD FY17
A. Time between ISRU Landing & Crew Leaving Earth (days)*	520	330				520	540
B. Contingency: Failures/dust storms (days)	40	30				40	See ISRU Tech Project Requirements 5-12-17
Production duration (= A – B)	480	300	480	>14 mo. min (420 days) for SEP-Chem. >18 mo. min (540 days) for Hybrid	30 (1 trip per month)	480 (1/op) 365 (1/yr) 183 (2/yr)	See ISRU Tech Project Requirements 5-12-17
ISRU Hardware Life: Days	▪ 480 min. ▪ Additional 240 days for life support consumables (between crew Earth departure & Mars arrival)	▪ 480 min. ▪ 1200 desired for additional operation through end of crew stay	▪ 480 min. ▪ Additional operation desired but not specified				540 min without maintanance
Operating Cycle Life			▪ 40^				40 nuc 540 max solar

Notes:
*Since launch dates/trajectories are based on the Earth calendar, mission durations are in Earth days (24 hrs) vs Mars sols. The amount of time also changes each opportunity due to variations in Mars eccentric orbit compared to Earth's
**Duration should have been similar to DRM 3.0. Unknown reason why the duration was reduced.
***Integration F2F Outbrief 6-9-2016v5.ppt
^Linne, et. al, "Capability and Technology Performance Goals for the Next Step in Affordable Human Exploration of Space", AIAA SciTech, Jan. 2015.

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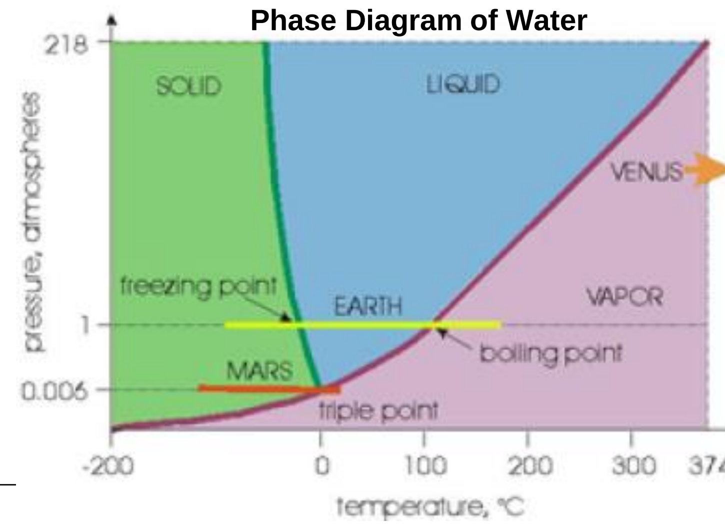
Mars External Environmental Specifications

External Environment Specifications: Consider day/night data for Summer and Winter Solstice at 3 landing site locations

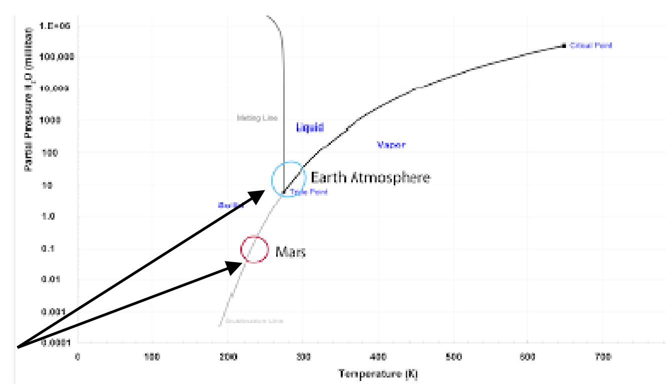
- Temperature
  - **For hydrated soil/minerals**. Use Viking 1 landing site data.
    Rationale. Mission data exists close to latitude of Jezero Crater (18.44 N) which is one of the preferred location the Mars 2020 landing site (2 of 3 selected landing sites are mid latitude)
  - **For subsurface icy soils**. Use Viking 2 landing site data.
    Rationale. Mission data exists close to latitude of 'near' subsurface ice detected by Mars orbiters

			Equator	Mid -Lat	Upper-Lat
			Curiosity	Viking 1	Viking 2
		MOLA: km	-4.4	-2.69	-3
		Lat: Deg	-4.5	22.48	47.97
N. Win	S. Sum	Day (C)	5	-52	-86
	Ls 270	Night (C)	-65	-95	-112
		Delta (C)	70	43	26
N. Sum	S. Win	Day (C)	-25	-25	-32
	Ls 90	Night (C)	-90	-89	-80
		Delta (C)	65	64	48



- Pressure:
  - Combine Curiosity and Viking 1 data for min/max. yearly pressures and daily pressure changes.
    Rationale. Both are reasonably close. Curiosity data for day/night changes is reasonably consistent throughout the year cycle. Viking 2 landing site pressure is higher so Viking 1 site is more 'worst case'.
    - Winter low: 690 Pa (i.e 690 to 790 Pa for daily day/night swing)
    - Summer High: 925 Pa (ie.925 to 825 Pa for daily day/night swing)
    - Daily day/night swing from lowest to highest: 100 Pa

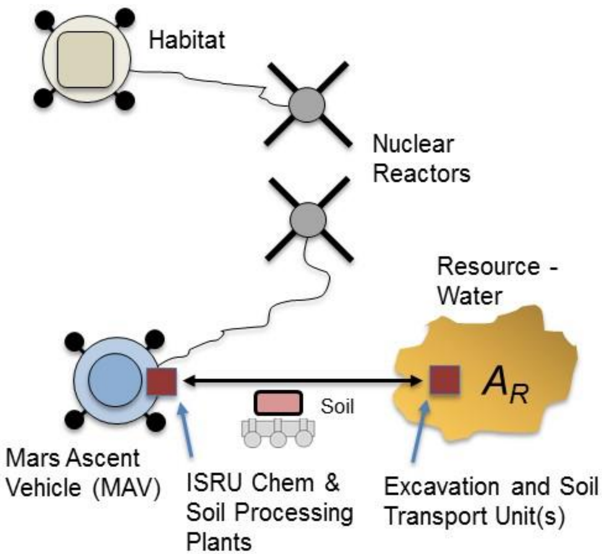
When we are dealing with an atmosphere, use the "partial pressure" of water vapor in the atmosphere to calculate the stability of water.



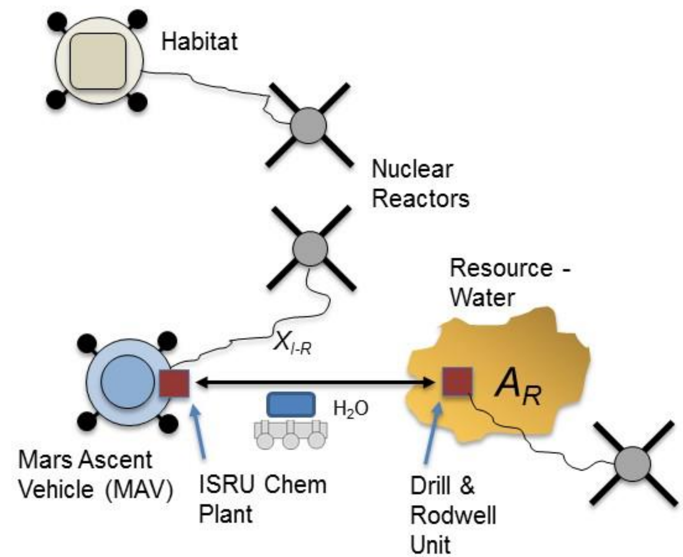
How Will Water be Mined on Mars?

Approach Selected will depend on:

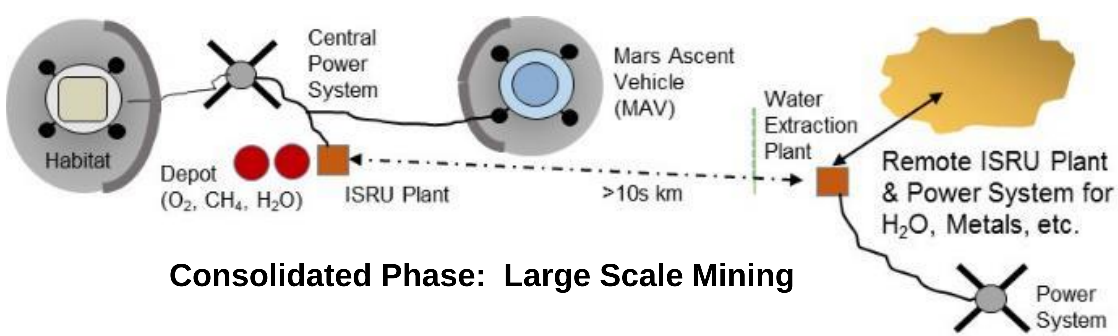
- Concentration of water resource
- Distance from ISRU and human support infrastructure
- How much is needed?
- Phase of human exploration of the Mars surface



Initial Phase: Low concentration Near ISRU/MAV



Initial Phase: High concentration Near ISRU/MAV



Consolidated Phase: Large Scale Mining

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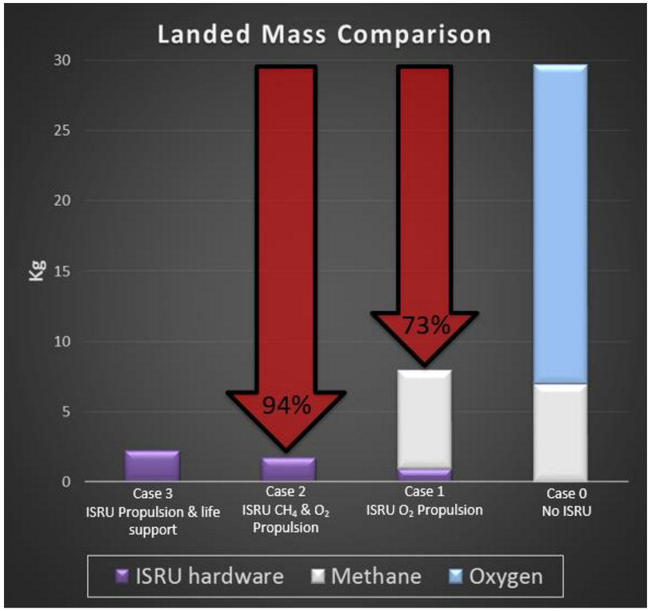
Example of Benefit of ISRU: Mars ISRU Study - Mass Result Comparison

	ISRU system Landed Mass Comparison (ISRU Hardware + Propellant from Earth)		
	The ISRU system leverages the power and radiator systems that are pre-positioned by the lander for human systems. So these are not explicitly part of the ISRU system.		
	ISRU Hardware Mass, mT	Total Mass, mT	Production Ratio: Propellant produced per kg of total mass
Case 3 ISRU propellants, & life support	2.2	2.2	13.5
Case 2 ISRU propellants, baseline regolith	1.7	1.7	17.7
Case 1 ISRU O_2 propellant	0.93	8.0 (1mt hardware + 7mt Methane)	2.9
Case 0 No ISRU	0	29.7 (23mt Oxygen + 7mt Methane)	na

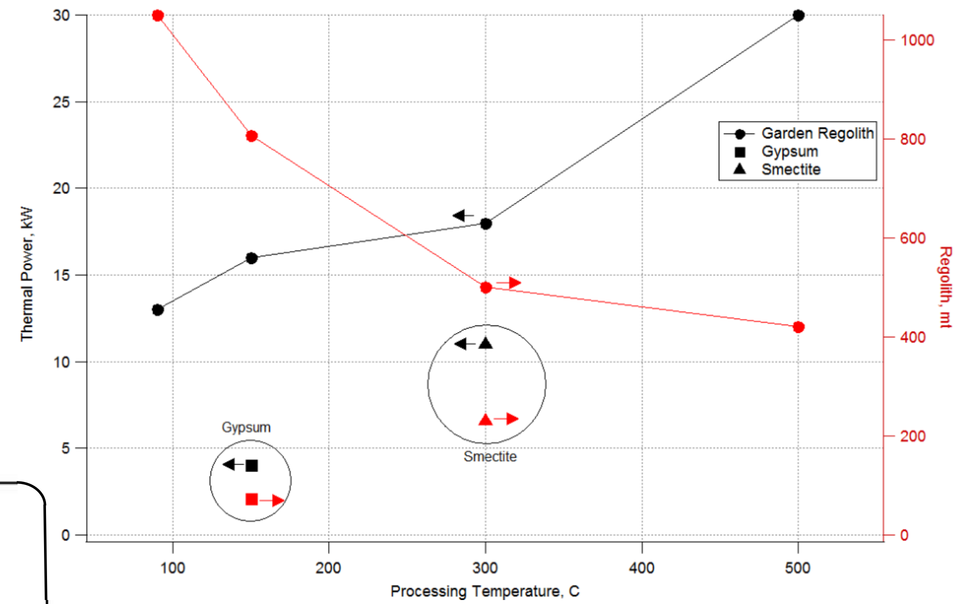
- **The addition of methane production increases ISRU mass 1 mT over the oxygen-only case assuing the lowest yield regolith**
- **Total mass considers ascent propellant mass transported from Earth. However producing that propellant in-situ will save additional mass not estimated:**
  - Propellant and hardware required to deliver hardware and ascent propellants from LEO
  - EDL systems to land the ascent propellant
- **Propellant production Ratio = Mass Propellant Produced / Hardware mass**
  - Full ISRU offers a 6x improvement over oxygen-only ISRU using the lowest yield regolith

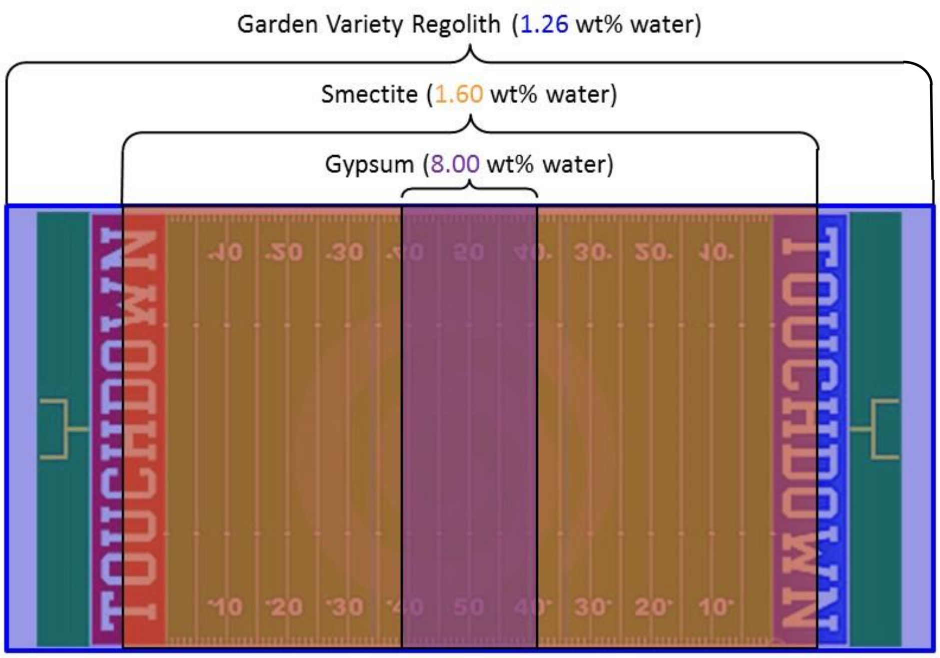


- **Mass savings in LEO is ~10 kg per 1 kg of propellant produced**
  - LEO Mass savings on the order of 300 mT with full ISRU system
  - Reduces cost and eliminates several heavy lift launch vehicles

Impact of Water Content in Regolith on Results

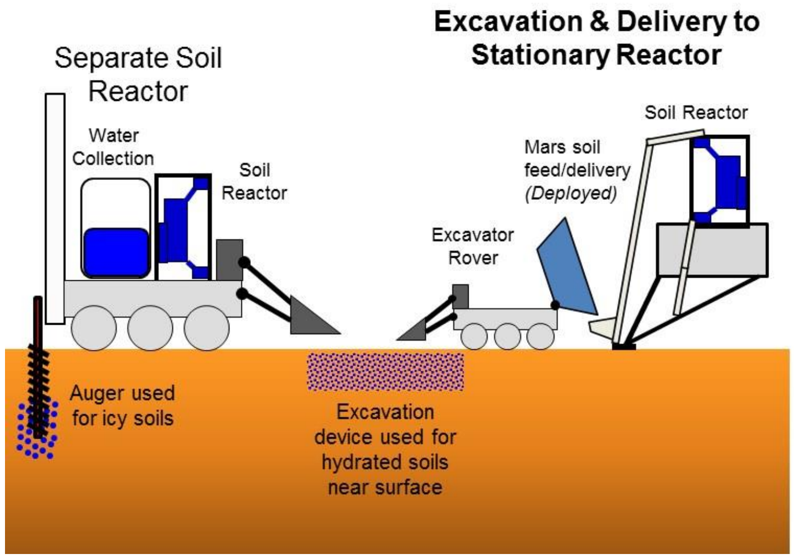
- **The real benefit of targeting higher weight percent water regolith is the power saving**
  - Less regolith to excavate and transport
  - Less regolith to heat
  - Heating at a lower temperature





Surface area required per mobile excavator with the following assumptions:
- 3 excavators used; Each excavator provides 40% of required water; Excavation depth = ~5cm (2.0 in)

Mars Hydrated Water Mining Process Options & Hardware



Soil Acquisition and Excavation

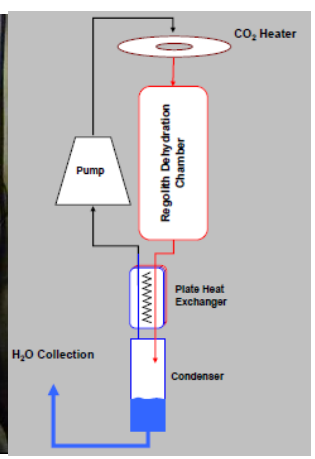
- Sample drills and augers (JPL, ARC, SBIRs)
- Scoops and buckets (GRC, KSC, JPL, Univ., SBIRs)
- Auger and pneumatic transfer (KSC, GRC, SBIRs)



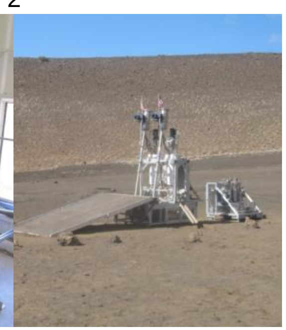



Lunar/Mars Soil Processing

Pioneer Astronautics Hot CO_2 Water Extraction from Soil

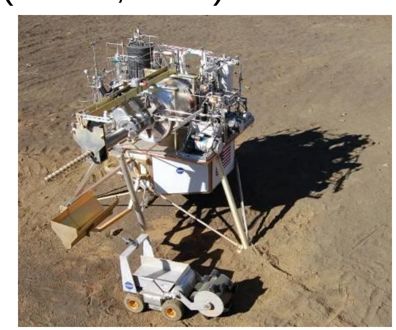



1st Gen H_2 Reduction from Regolith Systems (NASA, LMA)

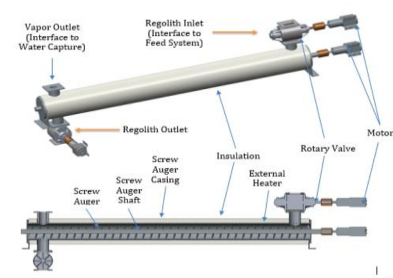
ROxygen H_2 Reduction
Water Electrolysis
Cratos Excavator

PILOT H_2 Reduction
Water Electrolysis
Bucketdrum Excavator



Concept for 'open-air' water extraction soil processor

Screw-conveyor dryer soil processor concept



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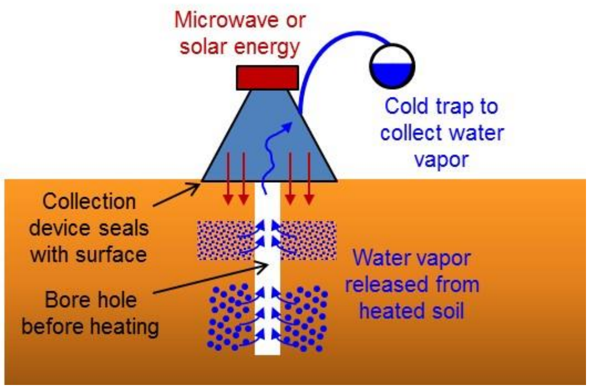
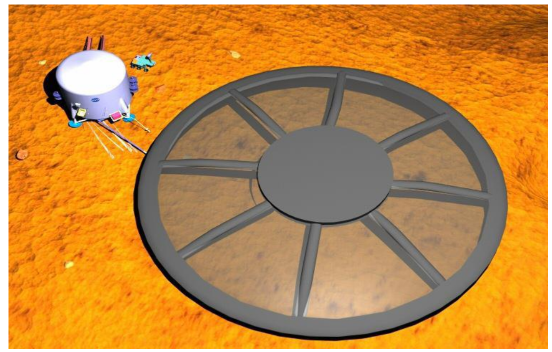
Mars Ice Mining Process Options & Hardware (1)

Beamed Energy

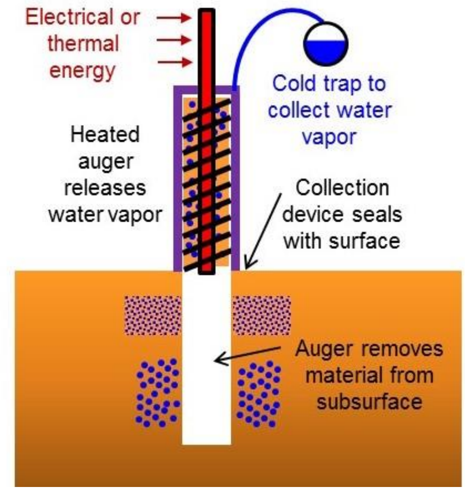


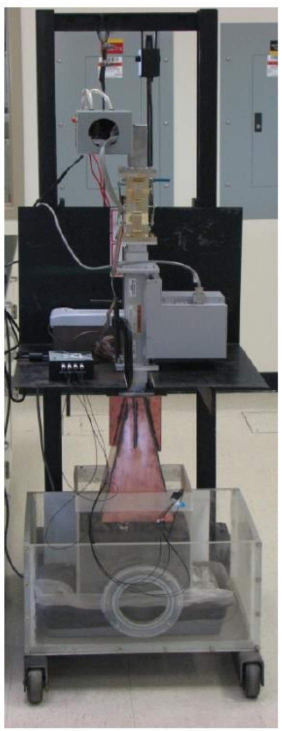
Solar Heating & Collection



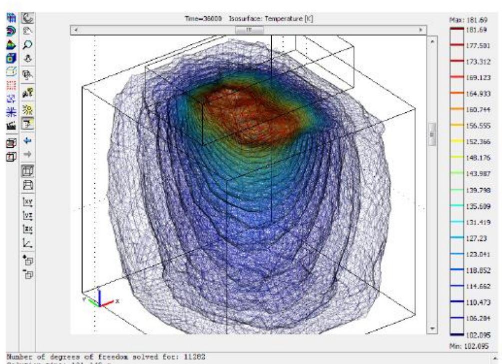
No or limited technical work

On Rover



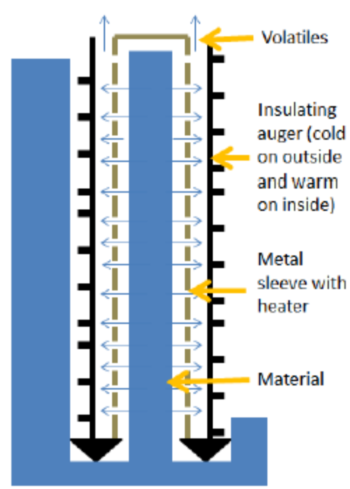


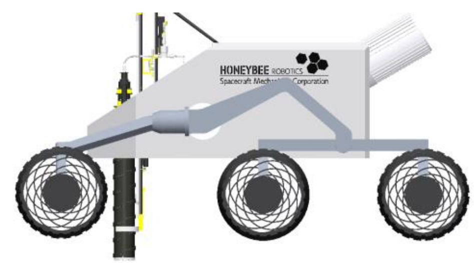
AIAA 2011-612, "**Microwave Processing of Planetary Surfaces for the Extraction of Volatiles**", Edwin C. Ethridge1



Honeybee Corer Concept (Near-Surface Ice)

Corer





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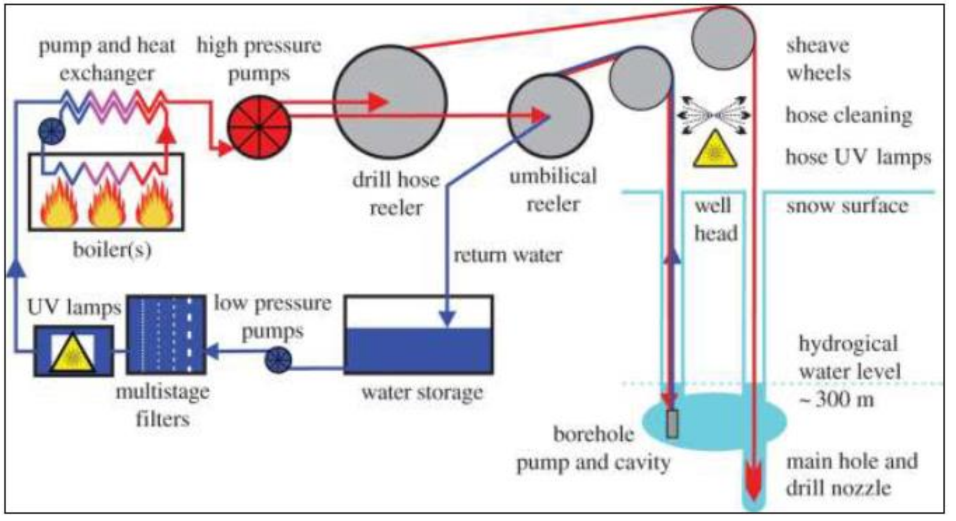
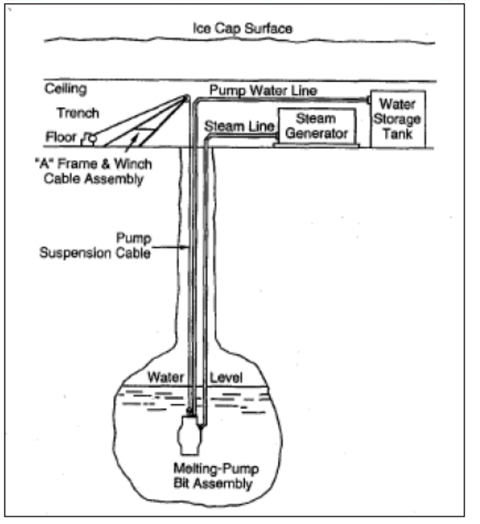
Mars Ice Mining Process Options & Hardware (2)

Rodwell Concept (Deep Ice)



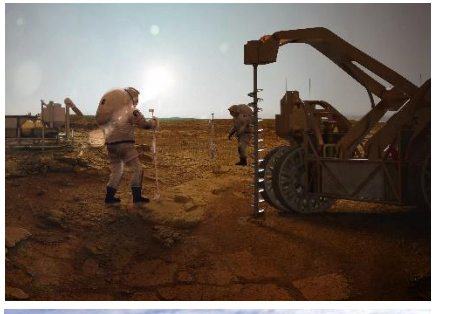


- Drilling Options
  - Mechanical drill
  - Electrothermal drill
  - Hot water drill
- Subsurface Ice Heating Options
  - Hot water pumped from surface
    - Thermal energy from Nuclear reactor
    - Electrical
  - Electric Heater

Honeybee Robotics Icebreaker 2m Drill

Mars Analog Research & Technology Experiment (MARTE) 10m Drill

NASA RASC-AL Mars Ice Challenge 2017

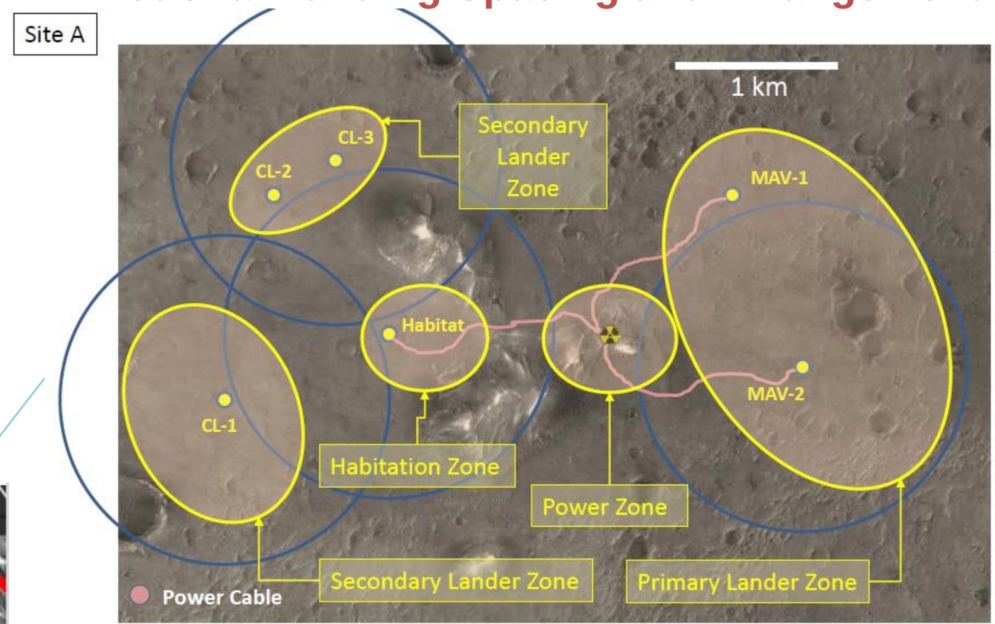


Terrestrial Experience

Human Mars Landing Site Overview

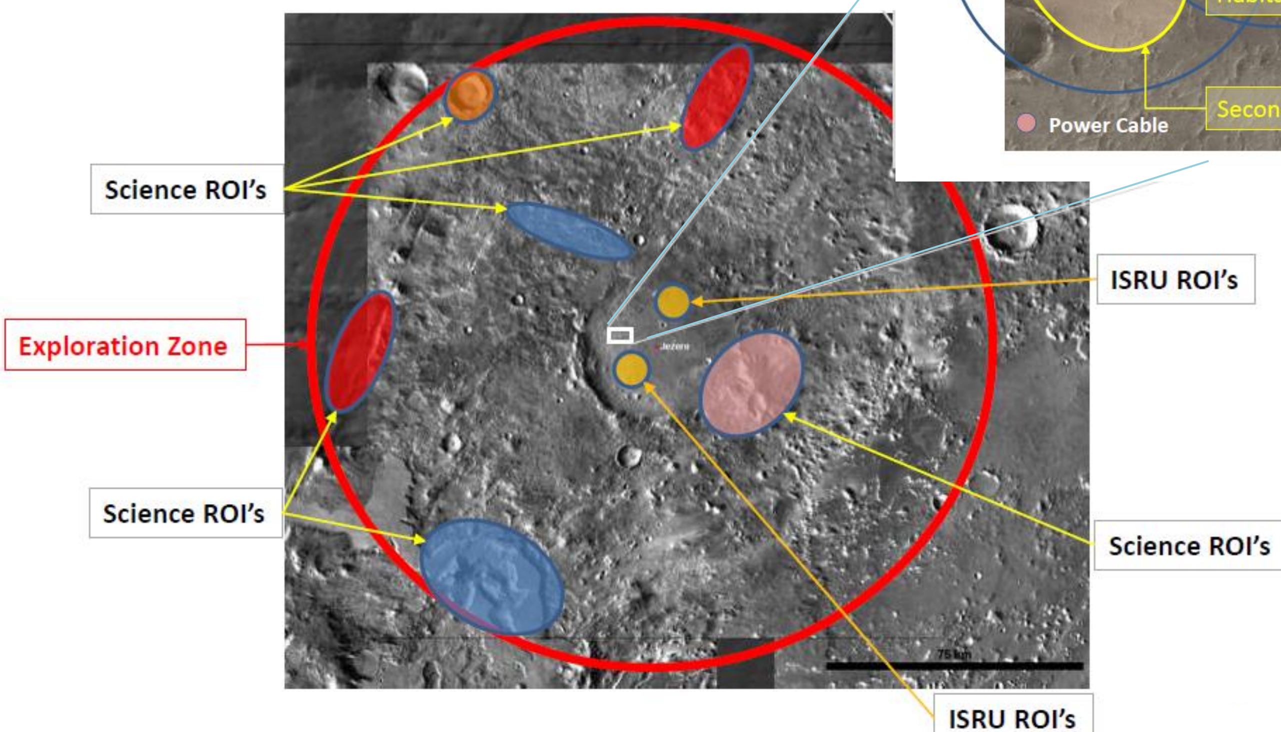
- Landing Site selected is near the center of an Exploration Zone of 200 km in diameter
  - First 3 missions will be focused on establishing support infrastructures for subsequent longer range exploration
  - Diameter based on expected capabilities of crewed pressurized rover extended excursions
  - EZ contains multiple sites of science and resource interests for ISRU (far ones for after initial 3 missions)

Notional Landing Spacing and Arrangement



(plume impingement *allowed* for any "dead" hardware)

Notional Exploration Zone (EZ)



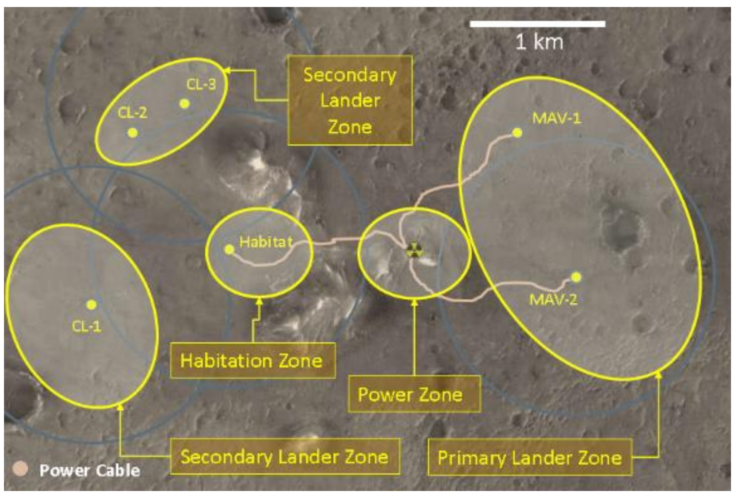
ISRU Products, Operations, and Resources Grow As Mission Needs and Infrastructure Grow

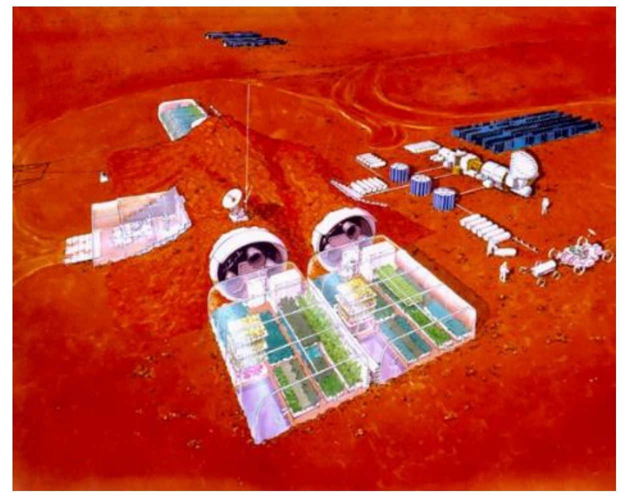
Initial Conditions:

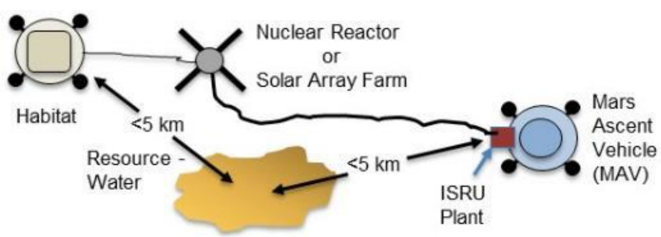
- Hardware delivered by multiple landers before crew arrives; Multiple landing zones
- Elements offloaded, moved, deployed, and connected together remotely
- 12-18 month stay for crew of 4 to 6; Gaps of time between missions where crew is not present
- Each mission delivers extra hardware & logistics

Ultimate Goal

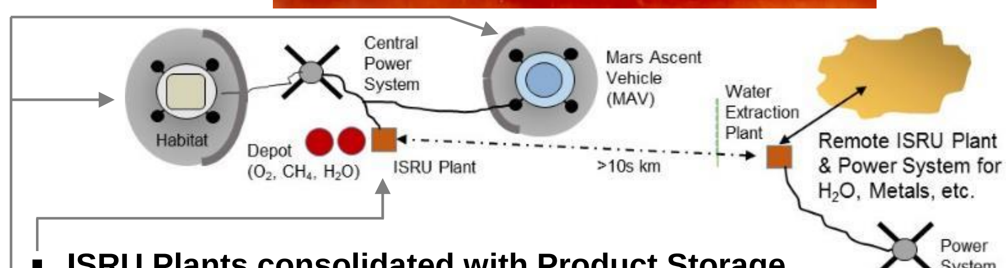
- Consolidated and integrated infrastructure
- Indefinite stay with larger crews
- Roam (and mine) anywhere within 200 km diameter Exploration Zone
- Earth independence; *In situ* ability to grow infrastructure: power, habitation, food, parts, etc.







- **ISRU hardware integrated with Landers**
- **'Easy' Resource very close to landing site/ Ascent vehicle**



- **ISRU Plants consolidated with Product Storage**
- **Civil Engineering and *In Situ* Construction operations**
- **Resources can now be farther from Habitat and Ascent Vehicle**
- **More/different resources needed for Earth independence**

Planetary Protection Concerns for ISRU and Search for Life

- **Forward contamination: Biological traces introduced to Mars**
- **Creation of special region: liquid water at 'comfortable' temperatures for long periods of time**
  - COSPAR defines Special Regions as "a region within which terrestrial organisms are likely to replicate"

Further Concerns for ISRU and Crewed Operations

- **Release of solids (dust grains) generated by excavation or drilling or reactor feeding spillover etc… after contact with machinery may be transported by winds and deposited somewhere else.**
- **Subsurface material attaches to spacesuit and goes into habitat through maintenance activities**
- **Release of gases/liquids through leakage, venting operations, or failure that could confuse search for life**

➢ **Note: ISRU processes considered for this presentation do not include biological or synthetic biology approaches**

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Backup

Mars Resources

Atmosphere

- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- Temperature: +35 °C to -125 °C
- Constituents: 95.32% Carbon Dioxide (CO_2); 2.7% Nitrogen (N_2); 1.6% Argon (Ar); 0.13% Oxygen (O_2); 0.08% Water (H_2O)

Resource	Potential Mineral Source	Reference
Water, Hydration/ Hydroxyl	Gypsum – ($CaSO_4.2H_2O$) Jarosite – ($KFe^{3+}{}_3(OH)_6(SO4)_2$) Opal & hydrated silica – ($SiO_2.nH_2O$) Phyllosilicates Other hydrated minerals (TBR)	Horgan, et al.(2009), Distribution of hydrated minerals in the north polar region of Mars, J. Geophys. Res., 114, E01005 Mustard et al.(2008), Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument, Nature 454, 305-309
Water, Ice	Icy soils Glacial deposits	Mellon & Feldman (2006) Dickson et al. (2012)
Iron*	Hematite, Jarosite Magnetite, Triolite Laterites, Ilmenite	Ming et al. (2006), Geochemical and mineralogical indicators for Aqueous processes in Columbia Hills of Gusev Crater, Mars" JGR 111, E02S12 Poulet et al. (2007), Martian surface mineralogy from OMEGA/Mex: Global mineral maps" JGR 112, E08S02
Aluminum*	Laterites, Plagioclase Aluminosilicates, Scapolite	
Magnesium*	Mg-sulfates, Mg-rich olivines, Forsterite	
Silicon	Pure amorphous silica Hydrated silica Phyllosilicates	Rice et al. (2010), "Silica-rich deposits and hydrated minerals at Gusev Crater, Mars: Vis-NIR spectral characterization and regional mapping" Icarus 205 (2010) 375–395
Titanium*	Ilmenite, Titanomagnetite	Ming et al. (2006), JGR 111, E02512

	Oxides (Wt%)													Elements (ppm)			
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3	Cl	SO_3	Ni	Zn	Br	Ge
MER Spirit – Laguna Soils, Panda Subclass	46.8	0.79	10.5	16.1	0.33	9.6	6.2	3	0.38	0.75	0.35	0.6	4.6	684	190	42	6
Rocknest Soil (Portage)	43.0	1.2	9.4	19.2	0.42	8.7	7.3	2.7	0.49	0.95	0.49	0.69	5.5	456	326	34	
Mojave Mars Simulant	49.4	1.09	17.1		0.17	6.1	10.5	3.3	0.48	0.17	0.05		0.1	118	71		0.07

ISRU Development and Implementation Challenges/Risks

Space Resource Challenges

R1 What resources exist at the site of exploration that can be used?

R2 What are the uncertainties associated with these resources?
Form, amount, distribution, contaminants, terrain

R3 How to address planetary protection requirements?
Forward contamination/sterilization, operating in a special region, creating a special region

ISRU Technical Challenges

T1 Is it technically feasible to collect, extract, and process the resource?
Energy, Life, Performance

T2 How to achieve long duration, autonomous operation and failure recovery?
No crew, non-continuous monitoring, time delay

T3 How to achieve high reliability and minimal maintenance requirements?
Thermal cycles, mechanisms/pumps, sensors/ calibration, wear

ISRU Operation Challenges

O1 How to operate in extreme environments?
Temperature, pressure/vacuum, dust, radiation

O2 How to operate in low gravity or micro-gravity environments?
Drill/excavation force vs mass, soil/liquid motion, thermal convection/radiation

ISRU Integration Challenges

I1 How are other systems designed to incorporate ISRU products?

I2 How to optimize at the architectural level rather than the system level?

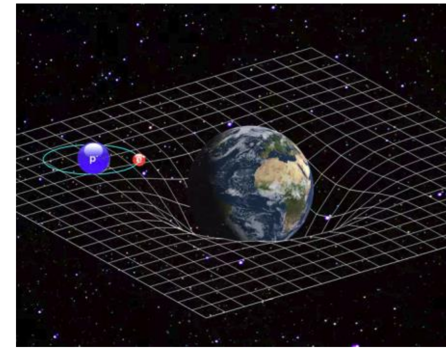
I3 How to manage the physical interfaces and interactions between ISRU and other systems?

Overcoming these challenges requires a multi-destination approach consisting of resource prospecting, process testing, and product utilization.

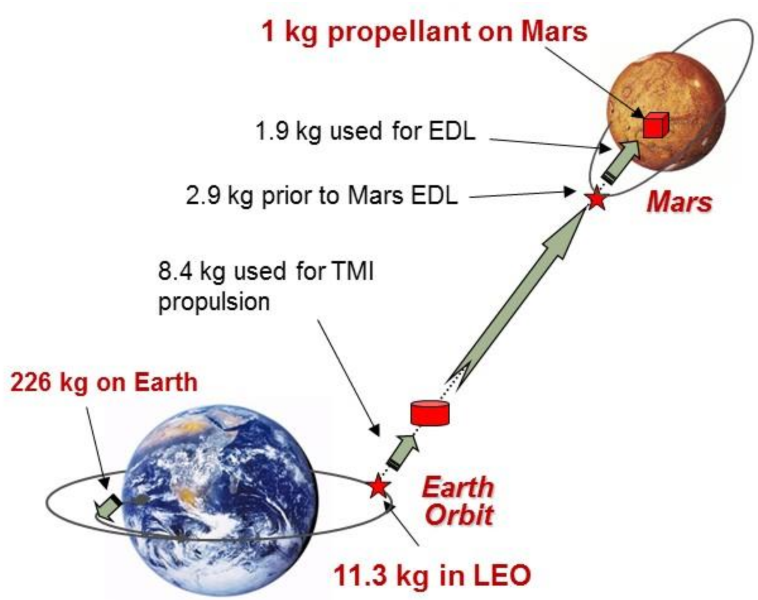
Leverage (Gear) Ratios using ISRU

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

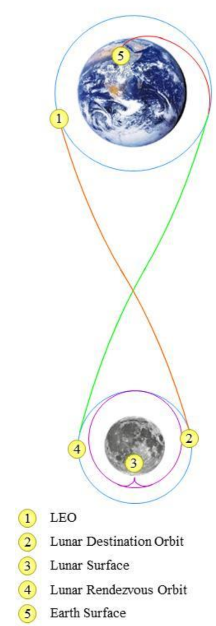
Potential 334.5 mT launch mass saved in LEO
= 3 to 5 SLS launches avoided per Mars Ascent



- **Mars mission**
  - Oxygen (O_2) only — 75% of ascent propellant mass: 20 to 23 mT
  - O_2/Methane (CH_4) — 100% of ascent propellant mass: 25.7 to 29.6 mT; Regeneration of rover fuel cell reactant mass
- **Phobos mission**
  - Trash to O_2/CH_4 — 1000+ kg of propellant



Estimates based on Aerocapture at Mars

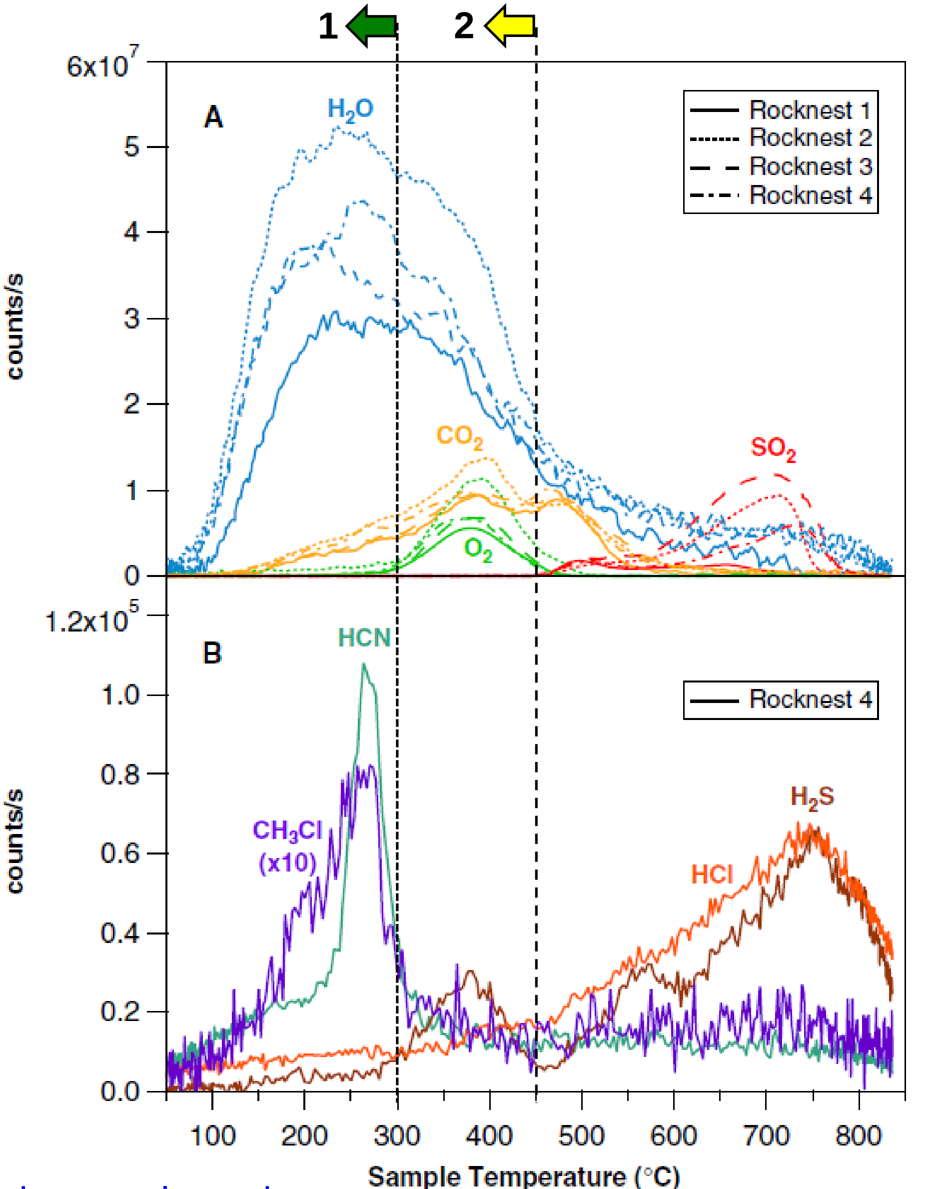


A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., 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

Water/Volatiles Released from Mars Soil
(SAM instrument: Rocknest sample)

Region 1: <300 C
- 40-50% of the water released
- Minimal release of HCl or H_2S

Region 2: <300 C
- >80% of the water released
- CO_2 and O_2 released from decomposition of perchlorates
- Some release of HCl or H_2S but before significant amounts are release



Predicted Volatile Release Based on Lab Experiments

CO_2 released by
1. Absorbed atmosphere <200C
2. Oxidation of organic material >200 C
3. Thermal decomposition of carbonates >450 C

O_2 released by
1. Dehydroxylation of clays <350 C
2. Decomposition of non-metal and metal oxides >500 C

CH_3Cl and CH_2Cl_2 released by
1. Decomposition of $Mg(ClO_4)_2$ percholrate >200C

Not all the water needs to or should be removed.
- Need to consider energy vs amount water and contaminants released

ISRU Influence on Mission Architectures

ISRU has greatest influence at the site of the resource/production

- **Transportation (propellant is the largest 'payload' mass from Earth)**
  - Crew ascent from Moon/Mars surface
    - O_2 only provides up to 80% of propellant mass
    - O_2/fuel – full asset reuse and surface hopping
  - Crew/Cargo ascent and descent from Moon/Mars surface – reusable
  - Supply orbital depots for in-space transportation
    - Cis-lunar (L1 to GEO or LEO)
    - Trans-Mars
- **Power (mission capabilities are defined by available power)**
  - Nighttime power storage/generation
    - Fuel cell reactants – increase amount and regeneration
    - Thermal storage
  - Mobile power – fuel cell reactants
  - Power generation: in situ solar arrays, 'geo'thermal energy
- **Infrastructure and Growth**
  - Landing pads and roads to minimize wear and damage
  - Structures and habitats
- **Crew Safety**
  - Radiation protection
  - Logistics shortfalls (life support consumables, spare parts)

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Economics of ISRU for Space Applications (1)

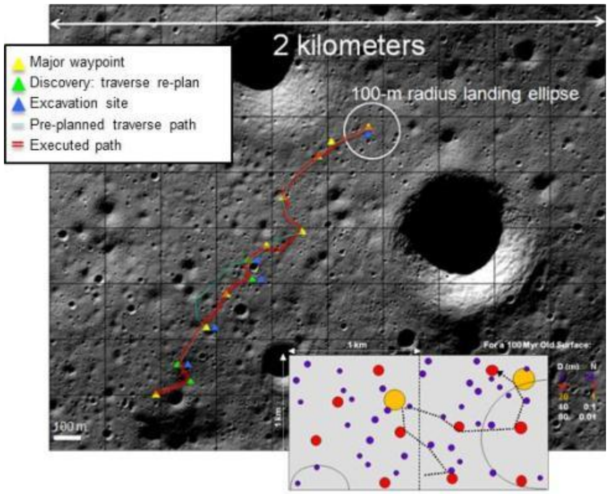
A 'Useful' Resource Depends on the Location, What is needed, How much is needed, How often it is needed, and How difficult is it to extract the resource

- **Location**
  - Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
  - Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.

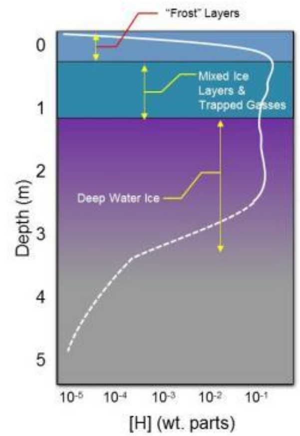
- **Resource extraction must be 'Economical'**
  - **Concentration and distribution of resource and infrastructure needed to extract and process the resource must allow for Return on Investment (ROI)** for:
    - Mass ROI - mass of equipment and unique infrastructure compared to bringing product and support equipment from Earth. Impacts number and size of launch vehicles from Earth
      - 1 kg delivered to the Moon or Mars surface = 7.5 to 11 kg launched into Low Earth Orbit
    - Cost ROI - cost of development and certification of equipment and unique infrastructure compared to elimination of launch costs or reuse of assets (ex. reusable vs single use landers)
    - Time ROI - time required to notice impact of using resource: extra exploration or science hardware, extended operations, newly enabled capabilities, etc.
    - Mission/Crew Safety ROI - increased safety of product compared to limitations of delivering product from Earth: launch mass limits, time gap between need and delivery, etc.
  - **Amount of product needed must justify investment in extraction and processing**
    - Requires long-term view of exploration and commercialization strategy to maximize benefits
    - Metric: mass/year product vs mass of Infrastructure
  - **Transportation of product to 'Market' (location of use) must be considered**
    - Use of product at extraction location most economical

Economics of ISRU for Space Applications (2)

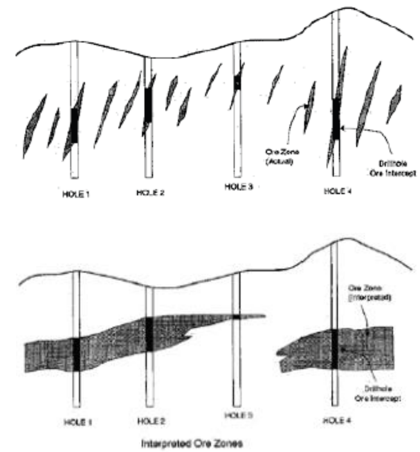
Need to Evaluate Local Region (1 to 5 km)



Need to Determine Vertical Profile



Need to Determine Distribution



Need to assess <u>What is needed</u>, <u>How much</u> is needed, <u>How often</u> it is needed

- **Resource Product Needs**

Location	Product	Amount (kg)	Need/Time	Use
Moon	O_2	1000	Per Year	Crew Breathing - Life Support Consumable Makeup
	O_2	3000 - 3500	2x Per Year	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to Low Lunar Orbit: Earth fuel
	O_2	~16000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L_1/L_2: Earth Fuel (4000 kg payload)
	O_2/H_2	~30,000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L_1/L_2 (4000 kg payload)
	H_2O	150,000	2x Per Year	Lunar Human Outpost & Reusable Transportation
	O_2/H_2	150,000	Per Year	Anount needed for Propellant Delivery to LDRO for Human Mars Mission
Mars	O_2/CH_4	22,728/6978	Per Use/1x 480 Days	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to High Mars Orbit
	O_2/CH_4	59,000/17,100	Per Use/1 or2x Per Yr	Reusable Ascent/Descent Propulsion - Surface to Mars Orbit
	H_2O	3,075	Surface/500 Days	Life Support System Closure
	H_2O	15,700	Per Use/1x 480 Days	Extracted H_2O to Make Non-Reusable Ascent Vehicle Propellant
	H_2O	38,300	Per Use/1 or2x Per Yr	Extracted H_2O to Make Reusable Ascent/Descent Vehicle Propellant

= Initial Requirement (orange box) = Horizon Goal (red box)

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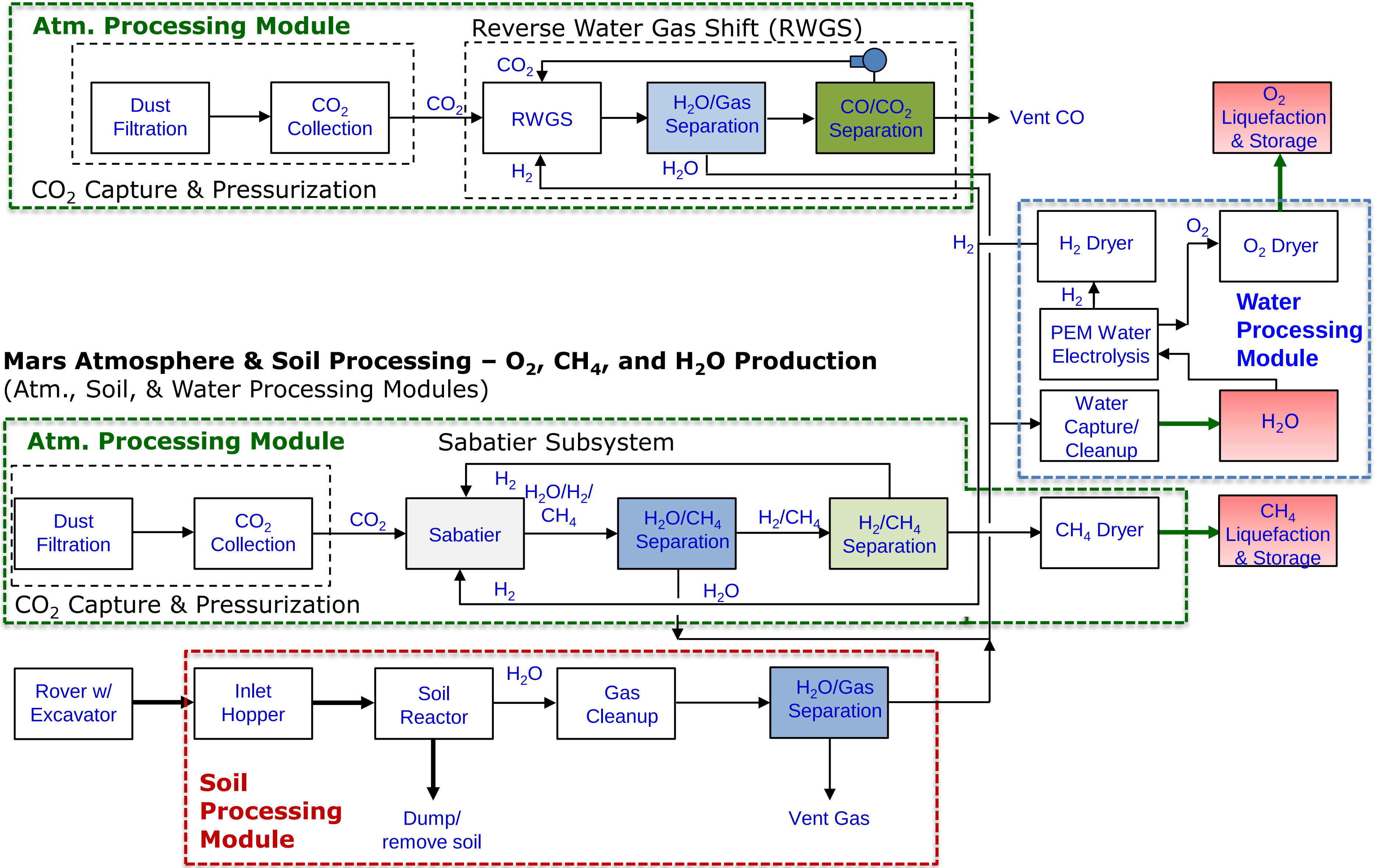
Mars Consumable ISRU: PEM-Based Electrolysis

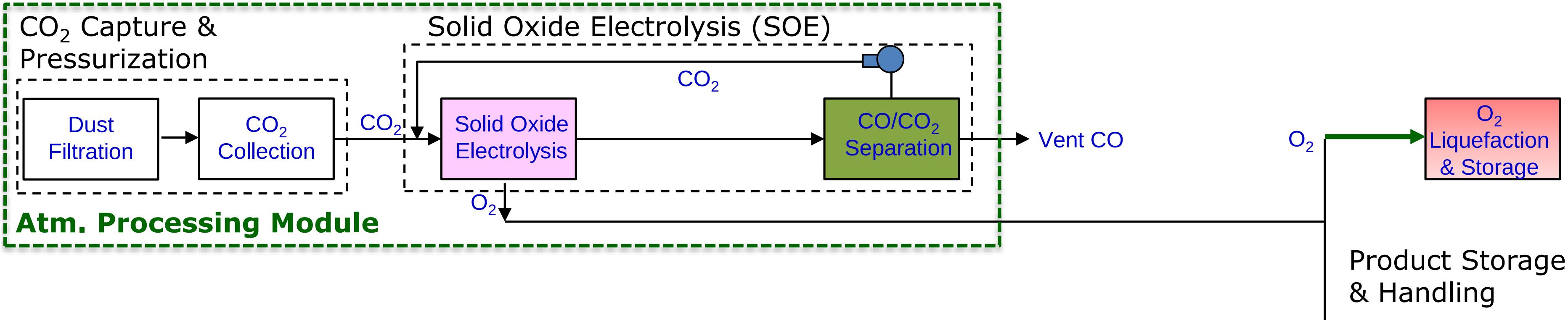
Mars Atmosphere Processing – O_2 Only Production (Atm. & Water Processing Modules)



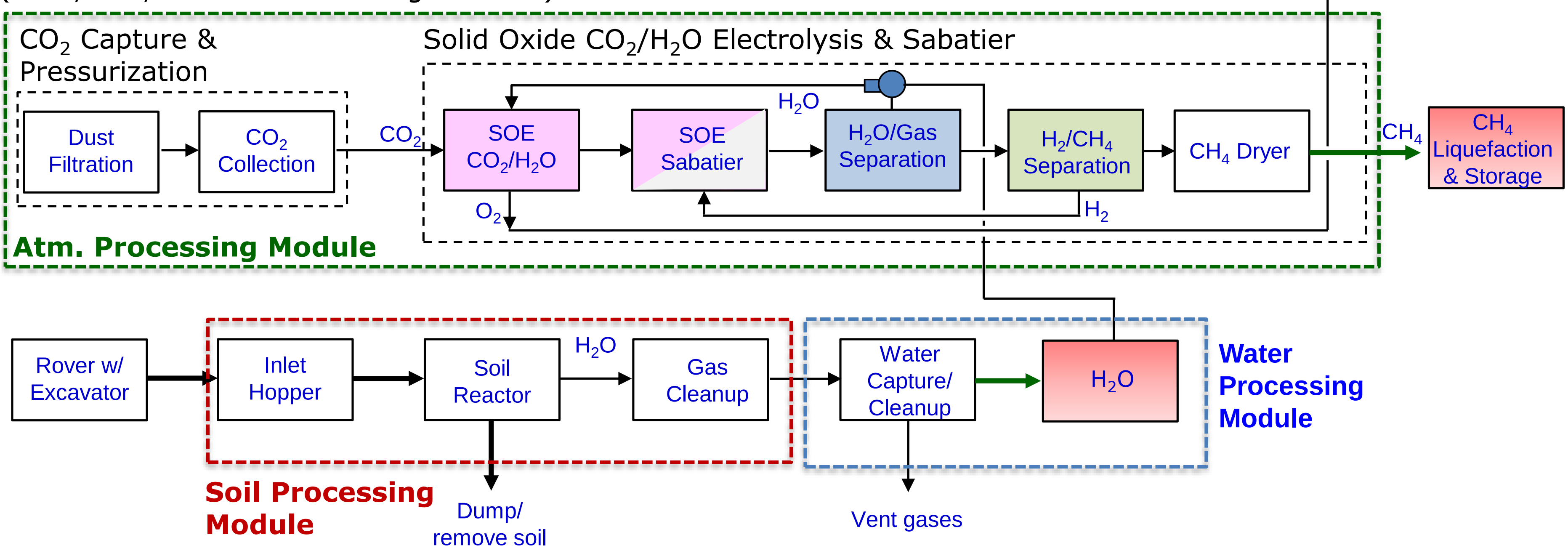
Mars Atmosphere & Soil Processing – O_2, CH_4, and H_2O Production
(Atm., Soil, & Water Processing Modules)

Mars Consumable ISRU: SOE-Based Electrolysis

Mars Atmosphere Processing – O_2 Production (Atm. Processing Module)

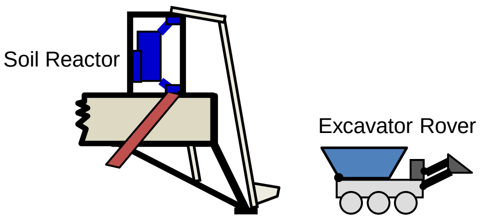


Mars Atmosphere & Soil Processing – O_2, CH_4, and H_2O Production
(Atm., Soil, & Water Processing Modules)

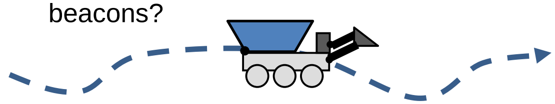


Granular Hydrated Material Mining Operations

1. Rover/Excavator Deploys from Lander
   - Unload rover
   - Activate rover

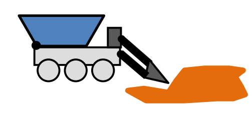


2. Excavator Rover Traverses to Excavation Site
   - Use route planned from Earth based on terrain/location map
   - Avoid obstacles and potentially other rovers during traverse
   - Autonomous operation; Use trail of beacons?

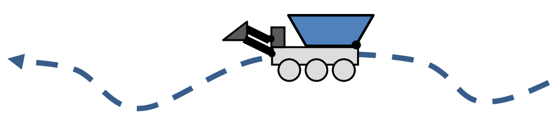


3. Excavator Rover Arrives at Excavation Site
   - Survey location to determine difference since last excavation to select excavation site (on-rover or LIDAR at site?)
   - Rover traverses to selected site

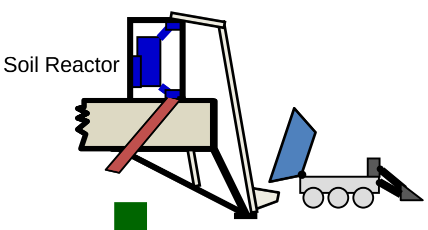
4. Excavator Rover Performs Excavation
   - Line up excavation device to exact point for excavation
   - Perform excavation; monitor forces on excavation device and wheel slippage to ensure proper excavation
   - Measure amount of soil excavated and loaded onto the rover



5. Excavator Rover Traverses back to Soil Processor
   - Use route planned from Earth based on terrain/location map
   - Avoid obstacles and potentially other rovers during traverse
   - Autonomous operation; Use trail of beacons?

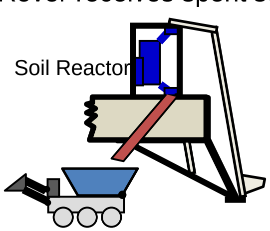


6. Excavator Rover Delivers Soil to Processor
   - Rover finds dumping soil bin
   - Rover lines up to dump soil
   - Rover dumps soil. Measure mass change to ensure soil has been delivered?

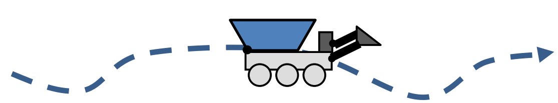


7a. Recharge Rover (if needed)
   - Rover finds charging port
   - Rover docks to charging port

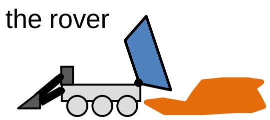
7b. Excavator Rover Receives Processed Soil
   - Rover finds dumping soil bin
   - Rover lines up to dump soil
   - Rover receives spent soil. Measure mass?



8. Excavator Rover Traverses to Dump Location
   - Use route planned from Earth based on terrain/location map
   - Avoid obstacles and potentially other rovers during traverse
   - Autonomous operation; Use trail of beacons?



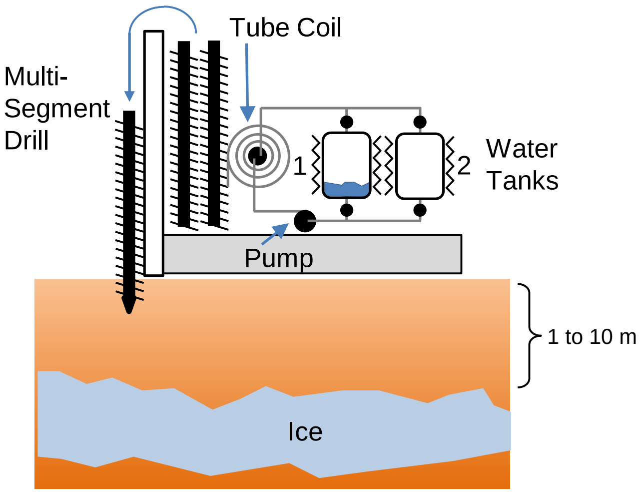
9. Excavator Rover Arrives at Dump Site
   - Survey location to determine difference since last dump to select dump site
   - Rover traverses to selected site
   - Line up dump device to exact point for dumping
   - Perform dumping
   - Measure amount of soil dumped from the rover



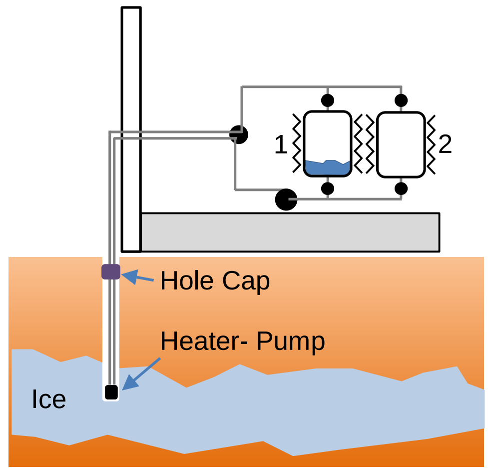
Return to Step 2

Subsurface Ice Mining Operations

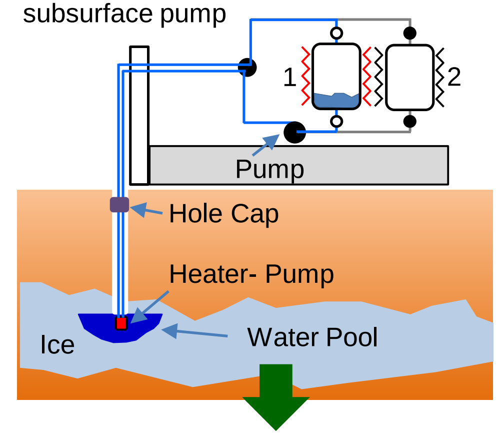
1. Drill through overburden into ice
   - Multi-segment drill from 1 to 10 m
   - Measure while drilling to evaluate when ice is met
   - Examine drill tailings or sensor on drill head for ice detection



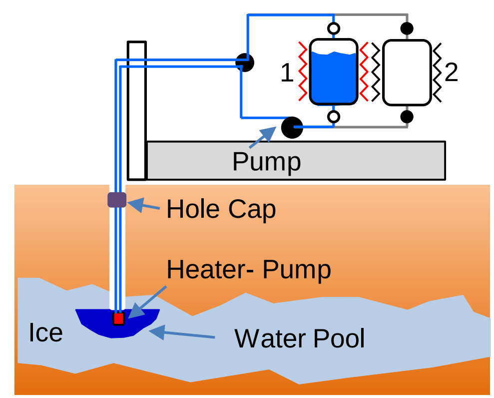
2. Establish tubing for water extraction
   - Lower tube with internal tubes for water flow down and up from Rodwell
   - End of tube includes downhole heater and water pump
   - Cap tube hole and tube (pneumatic) to seal chamber.



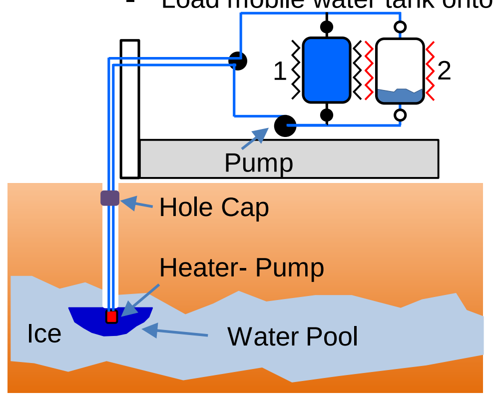
3. Begin water extraction from subsurface ice
   - Heat subsurface ice with downhole heater to begin subsurface water pool
   - Heat water from attached mobile water tank (precharged with amount to start ops) electrically or with thermal energy from FSPS
   - Begin flow of water from surface to subsurface to charge line with surface pump
   - Begin subsurface water extraction with subsurface pump



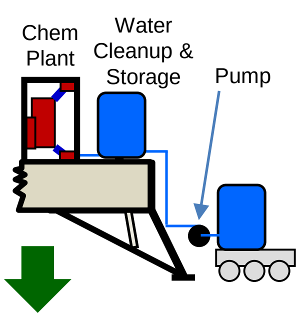
4. Continued water extraction
   - Continue extraction of water from subsurface pool into mobile water tank at balanced rate until



5. Remove mobile water tank for delivery
   - Attach and warm 2nd mobile water tank
   - Divert flow to 2nd mobile water tank
   - Detach 1st mobile water tank
   - Load mobile water tank onto Asset 1 or 2



6. Deliver Mobile Water tank to ISRU Chem Plant
   - Rover finds attachment point for water transfer
   - Rover lines up and connects mobile water tank
   - Transfer water to on-board water cleanup and storage tank



7. Return Mobile Water tank to Rodwell Unit

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The Chemistry of Mars ISRU

Oxygen (O_2) Production Only

Zirconia Solid Oxide CO_2 Electrolysis (SOE)
$2\ CO_2 \xrightarrow{900 - 1000\ C} 2\ CO + O_2$ [Pt catalyst] → O_2

Reverse Water Gas Shift (RWGS)
$CO_2 + H_2 \underset{}{\overset{400 - 650\ C}{\rightleftharpoons}} CO + H_2O$ [catalyst] → H_2O → WE to O_2

Bosch
$CO_2 + 2\ H_2 \xrightarrow{450 - 600\ C} C + 2\ H_2O$ [Ni, Ru, Fe, or Co catalyst] → H_2O → WE to O_2

Oxygen (O_2) & Methane (CH_4) Production

Sabatier Catalytic Reactor (SR)
$CO_2 + 4\ H_2 \overset{200 - 300\ C}{\rightleftharpoons} CH_4 + 2\ H_2O$ [Ru catalyst] → H_2O, CH_4 → WE to O_2

Methane Reformer
$CO + 3\ H_2 \xrightarrow{250\ C} CH_4 + H_2O$ [Ni catalyst] → H_2O, CH_4 → WE to O_2

Electrochemical Reduction
$CO_2 + 2\ H_2O \longrightarrow CH_4 + 2\ O_2$ [Anode/Cathode] → O_2, CH_4

Other Hydrocarbon Fuel Production

Fischer-Tropsch (FT)
$n\ CO + (2n+1)\ H_2 \xrightarrow{>150\ C} C_nH_{2n+2} + n\ H_2O$ [catalyst] → H_2O, C_nH_{2n+2} → WE to O_2

Methanol
$CO + 2\ H_2 \xrightarrow[50 - 100\ atm]{250\ C} CH_3OH$ [ZnO catalyst] → CH_3OH
$CO_2 + 3\ H_2 \longrightarrow CH_3OH + H_2O$ → H_2O, CH_3OH → WE to O_2

Oxygen (O_2) &/or Hydrogen (H_2) Production

Water Electrolysis (WE)
$2\ H_2O \longrightarrow 2\ H_2 + O_2$ → O_2, $2\ H_2$

Steam Reforming
$H_2O + CH_4 \longrightarrow 3\ H_2 + CO$ → $3\ H_2$

Dry Reforming
$CO_2 + CH_4 \longrightarrow 2\ H_2 + 2\ CO$ → $2\ H_2$

2^{nd} Step

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