Current NASA Plans For *Mars In Situ* Resource Utilization

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Presentation to Center for the Utilization of Biological Engineering in Space (CUBES)

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Presentation Overview

- What is In Situ Resource Utilization (ISRU) and Why Incorporate it into Missions?
- Available Resources
- Mission Requirements and ISRU Economics
- Challenges and Risks for ISRU Incorporation into Missions
- Concept of Operation on Mars
- Current State of the Art (SOA)
- ISRU Development & Missions

What is ISRU and Why Use It in Missions?

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

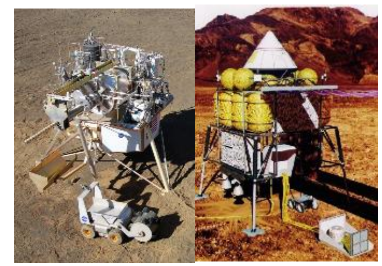
Resource Assessment (Prospecting)

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

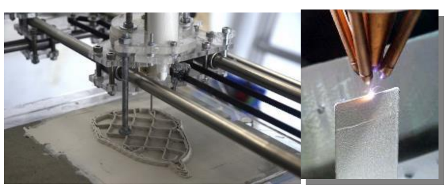
Resource Processing/ Consumable Production



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



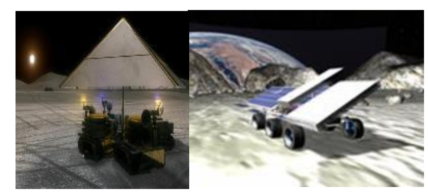
Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

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.

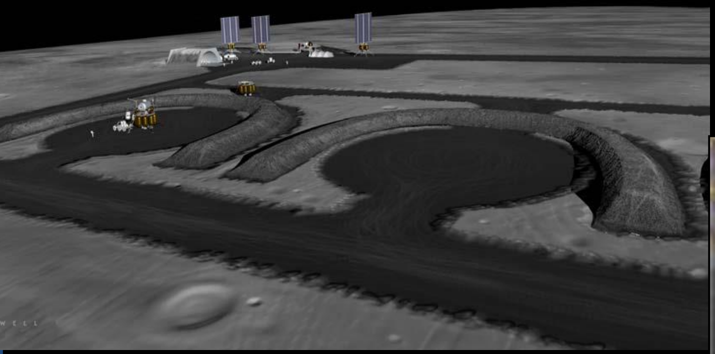
- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

Lunar ISRU Mission Capability Concepts

Resource Prospecting – Looking for Polar Ice

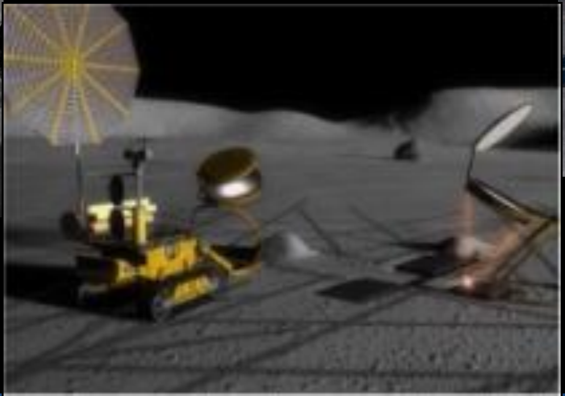
Excavation & Regolith Processing for O_2 Production

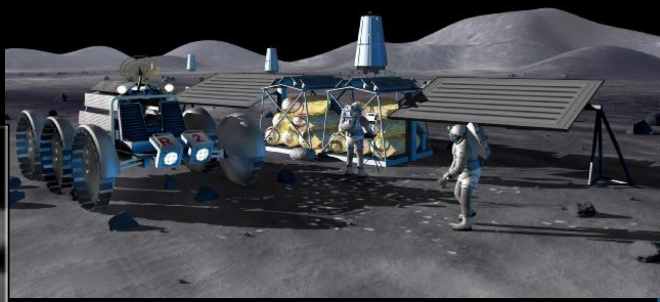
Carbothermal Processing with Recycled Lander Assets



Landing Pads, Berm, and Road Construction

Thermal Energy Storage Construction





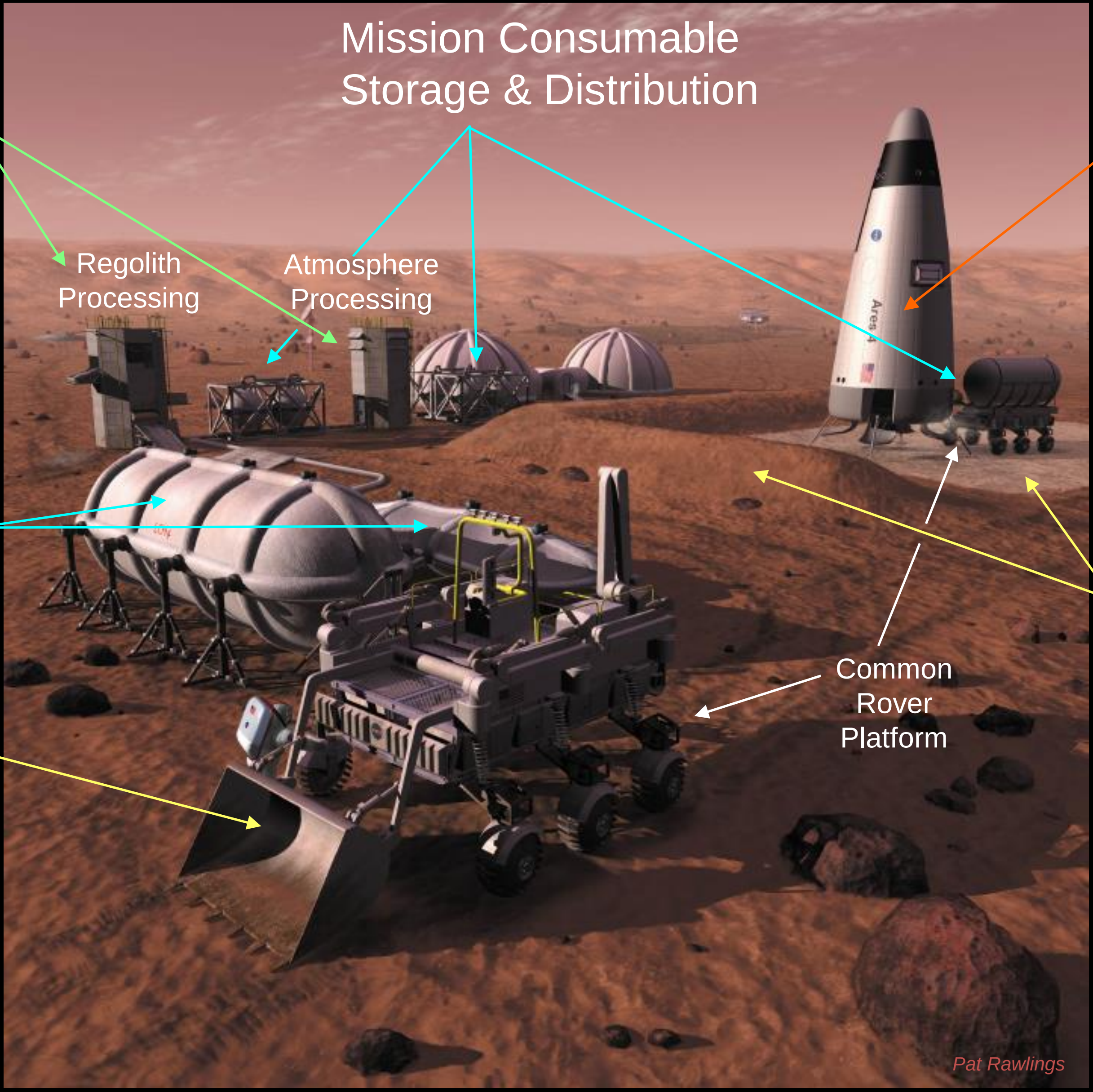
Consumable Depots for Crew & Power

Mars ISRU Mission Capability Concepts

Resource Processing Plants

Collapsible/ Inflatable Cryogenic Tanks

Multi-use Construction/ Excavator: resources, berms, nuclear power plant placement, etc.



Reusable lander/ascent vehicle or surface hopper fueled with in-situ propellants

Landing pad & plume exhaust berm

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)

Potential 'Solutions' Provided by Incorporation of ISRU

Increase Sustainability/Decreases Life Cycle Costs

- Reduce launch mass and/or number of launchers required
- Reuse landers and transportation elements can provide significant cost savings
- Growth in capabilities in life support, habitats, powers, etc.
- Enables path for commercial involvement and investment

Increase Mission Performance and Capabilities

- Longer stays, increased EVA, or increased 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
- Decreased logistics and spares brought from Earth

Reduce Mission and Crew Risks

- Minimizes/eliminates life support consumable delivery from Earth
- Increases crew radiation protection over Earth delivered options
- Can relax critical requirements in other system performance
- Minimizes/eliminates ascent propellant boiloff leakage issues
- Minimizes/eliminates landing plume debris damage – Civil engineering and construction

Increases Science

- Greater surface 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 eliminating consumable delivery

Supports Multiple Destinations

- Surface soil processing operations associated with ISRU applicable to Moon and Mars
- ISRU subsystems and technologies are applicable to multiple destinations and other applications
- Resource assessment for water/ice and minerals common to Moon, Mars, and NEOs

Pros & Cons of Human Exploration with ISRU

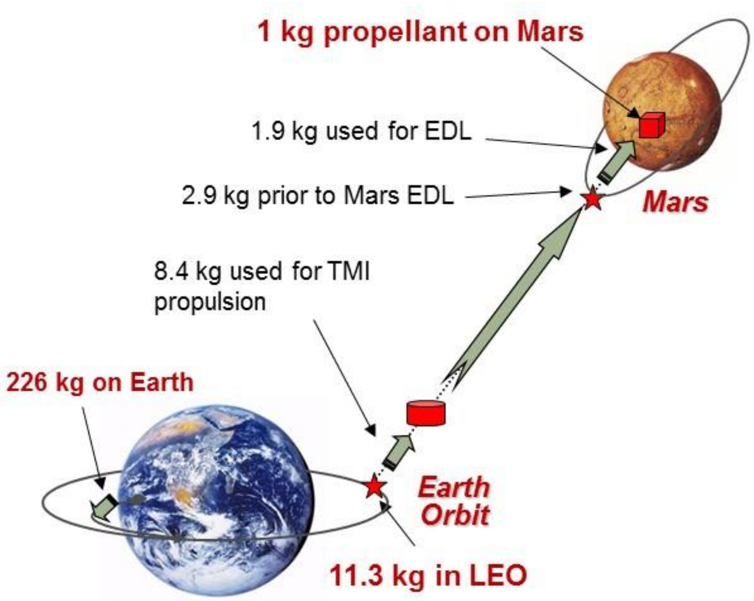
Pros	Cons
Enables Reusability & Flexibility	Higher initial risk
Increased delivered payloads/reduced consumables from Earth	Higher upfront costs
Interdependence – common hardware, interfaces, and standards	Interdependence - common failure modes across multiple subsystems
Long-term growth/reduced life cycle costs	Does not benefit short trips/stays
Linked objectives w/ Science; increased Science rationale and capabilities	Concern about impacting lunar environment and Mars search for life for science
Supports Commercial involvement/reduced costs	International agreement/Legal issues
Multi-Destination	Lunar/Mars must consider from start
Public Outreach & Interest. Not repeating Apollo	
Technology Spin-In and Spin-off	

Leverage (Gear) Ratios using ISRU

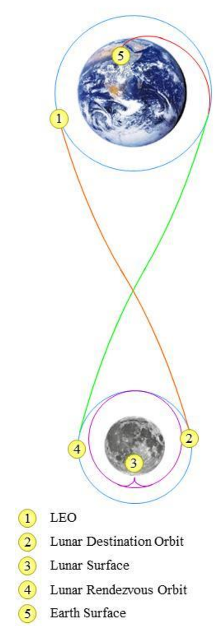
Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

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
- **Phobos mission**
  - Trash to O_2/CH_4 — 1000+ kg of propellant



Estimates based on Aerocapture at Mars

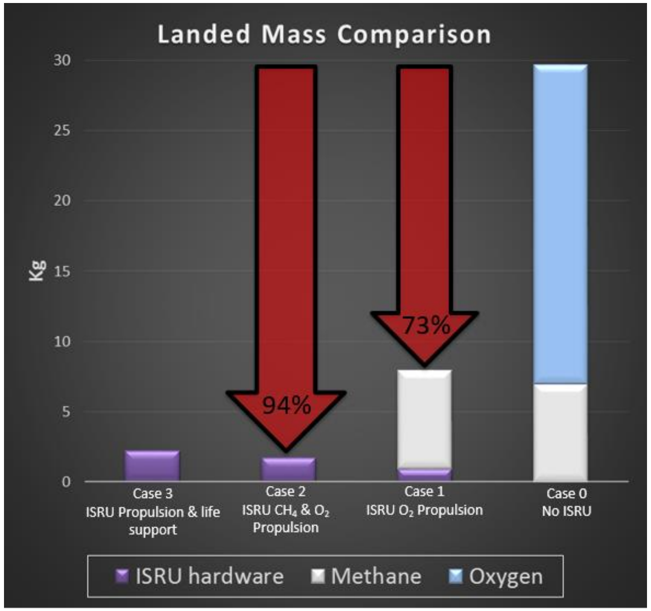


A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g.,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

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

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Available Resources

What are Space Resources?

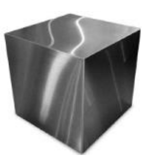
- **'Resources'**
  - Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, alloys, etc.
  - Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.

- **Energy**
  - Thermal Energy Storage Using Modified Regolith
    - Thermal conductivity of unmodified lunar regolith is very low (~1 mW/m-K); good insulator.
  - Permanent/Near-Permanent Sunlight
    - Stable thermal control & power/energy generation and storage
  - Permanent/Near-Permanent Darkness
    - Thermal cold sink for cryo fluid storage & scientific instruments

- **Environment**
  - Vacuum
  - Micro/Reduced Gravity
  - Large Thermal Gradients
  - Atmosphere Drag

- **Location**
  - Stable Locations/'Real Estate':
    - Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth
    - Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.

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

Lunar Resource Overview

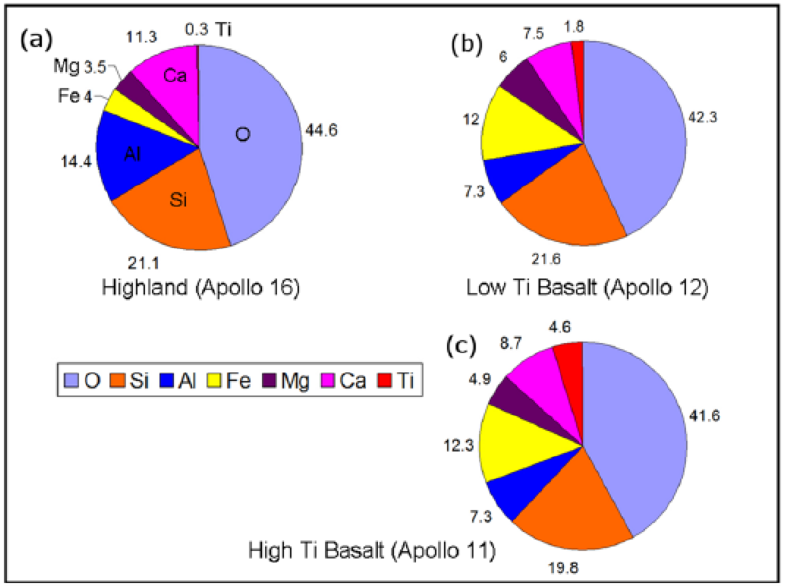


Figure 3. Example chemical compositions of lunar soils: (a) lunar highland minerals (Apollo 16); (b) low-Ti basalts (Apollo 12); and (c) high-Ti basalts (Apollo 11). Based on data collated by Stoeser et al. (2010), and reprinted from *Planetary and Space Science*, Vol. 74, Schwandt C, Hamilton JA, Fray DJ and Crawford IA, 'The production of oxygen and metal from lunar regolith' 49-56, Copyright (2012), with permission from Elsevier.

Table 1. Average concentrations of solar wind implanted volatiles in the lunar regolith (Fegley and Swindle 1993), where the quoted errors reflect the range (± one standard deviation) of values found at different sampling locations. The corresponding average masses contained within 1 m^3 of regolith (assuming a bulk density of 1660 kg m^{-3}; Carrier et al., 1991) are also given.

Volatile	Concentration ppm (μg/g)	Average mass per m^3 of regolith (g)
H	46 ± 16	76
^{3}He	0.0042 ± 0.0034	0.007
^{4}He	14.0 ± 11.3	23
C	124 ± 45	206
N	81 ± 37	135
F	70 ± 47	116
Cl	30 ± 20	50

In addition to the volatiles listed in Table 1, lunar soils contain small quantities (typically ≤ 1 μg/g) of the solar wind derived noble gasses Ne and Ar (and much smaller quantities of Kr and Xe). Perhaps more interesting from a resource perspective, they also contain a significant quantity of sulphur (715±216 μg/g; Fegley and Swindle 1993), mostly derived from the mineral troilite (FeS), and this would probably also be released by any process which extracts the other volatile elements.

From "Lunar Resources: A Review" by Ian Crawford,2015

		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Pr	ppm	13	---	7	9.2
Nd	ppm	63	40	39	41.5
Sm	ppm	21	14	13	7.05
Eu	ppm	2.2	1.9	1.7	2
Gd	ppm	27	20	15	6.2

Rare Earth Elements

		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Ag	ppb	1.5	18	9	75
Cd	ppb	10	100	50	150
In	ppb	3	5	<10	25
Te	ppb	16	72	---	1
Se	ppm	0.7	1.6	0.8	0.05

Vapor Mobilized Elements

From Bob Wegeng/PNNL

Lunar Polar Volatiles
(Observed at LCROSS Site)

					Instrument			
	Column Density (# m^{-2})	Relative to H2O(g) (NIR spec only)	Concentration (%)	Long-term Vacuum Stability Temp (K)	UV/Vis	NIR	LAMP	M3
CO	1.7e13±1.5e11		5.7	15			x	
H_2O(g)	5.1(1.4)E19	1	5.50	106		x		
H_2	5.8e13±1.0e11		1.39	10			x	
H_2S	8.5(0.9)E18	0.1675	0.92	47	x	x		
Ca	3.3e12±1.3e10		0.79				x	
Hg	5.0e11±2.9e8		0.48	135			x	
NH_3	3.1(1.5)E18	0.0603	0.33	63		x		
Mg	1.3e12±5.3e9		0.19				x	
SO_2	1.6(0.4)E18	0.0319	0.18	58		x		
C_2H_4	1.6(1.7)E18	0.0312	0.17	~50		x		
CO_2	1.1(1.0)E18	0.0217	0.12	50	x	x		
CH_3OH	7.8(42)E17	0.0155	0.09	86		x		
CH_4	3.3(3.0)E17	0.0065	0.04	19		x		
OH	1.7(0.4)E16	0.0003	0.002	>300 K if adsorbed	x	x		x
H_2O (adsorb)			0.001-0.002					x
Na		1-2 kg		197	x			
CS					x			
CN					x			
NHCN					x			
NH					x			
NH_2					x			

Volatiles comprise possibly 15% (or more) of LCROSS impact site regolith

*Chart courtesy of Tony Colaprete

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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 Magnetite Laterites	Jarosite Triolite 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 Aluminosilicates	Plagioclase 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

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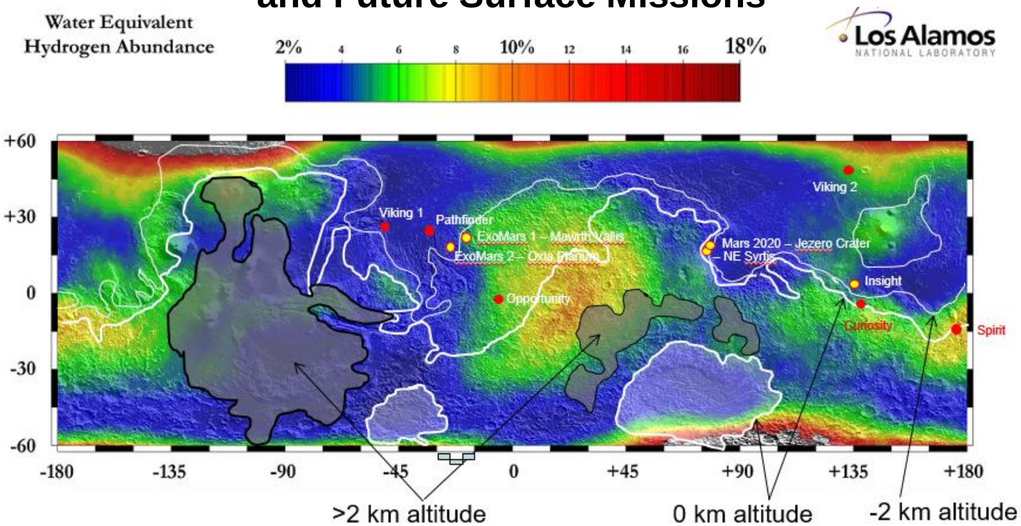
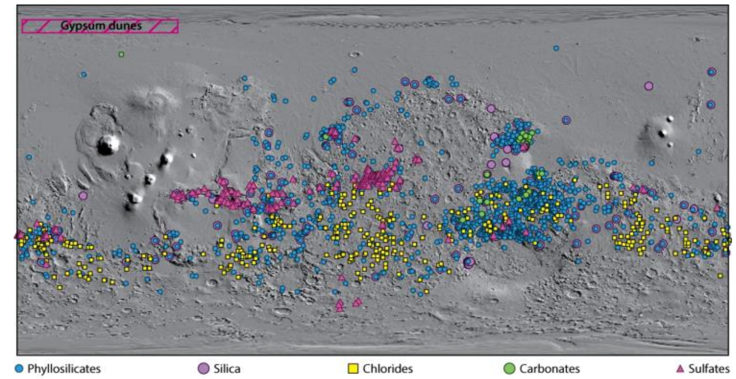
Mars Water Form & Distribution

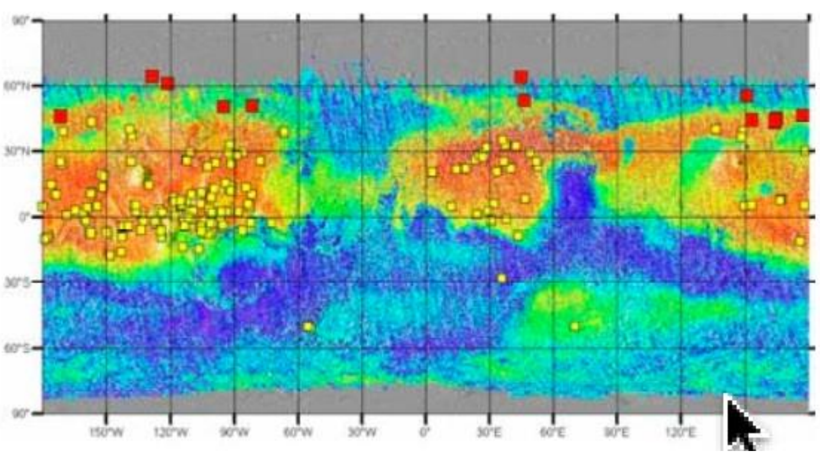
Water Abundance and Altitude with Past, Present, and Future Surface Missions



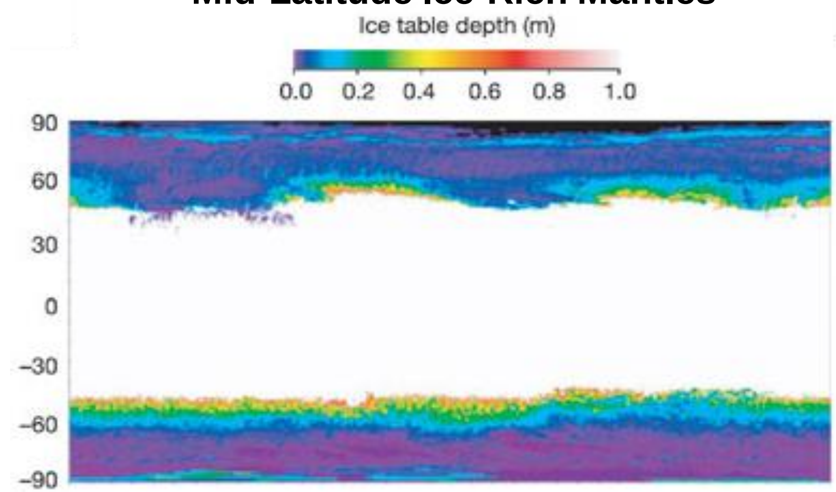
Map of aqueous mineral detections



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



Mid-Latitude Ice-Rich Mantles



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)

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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

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

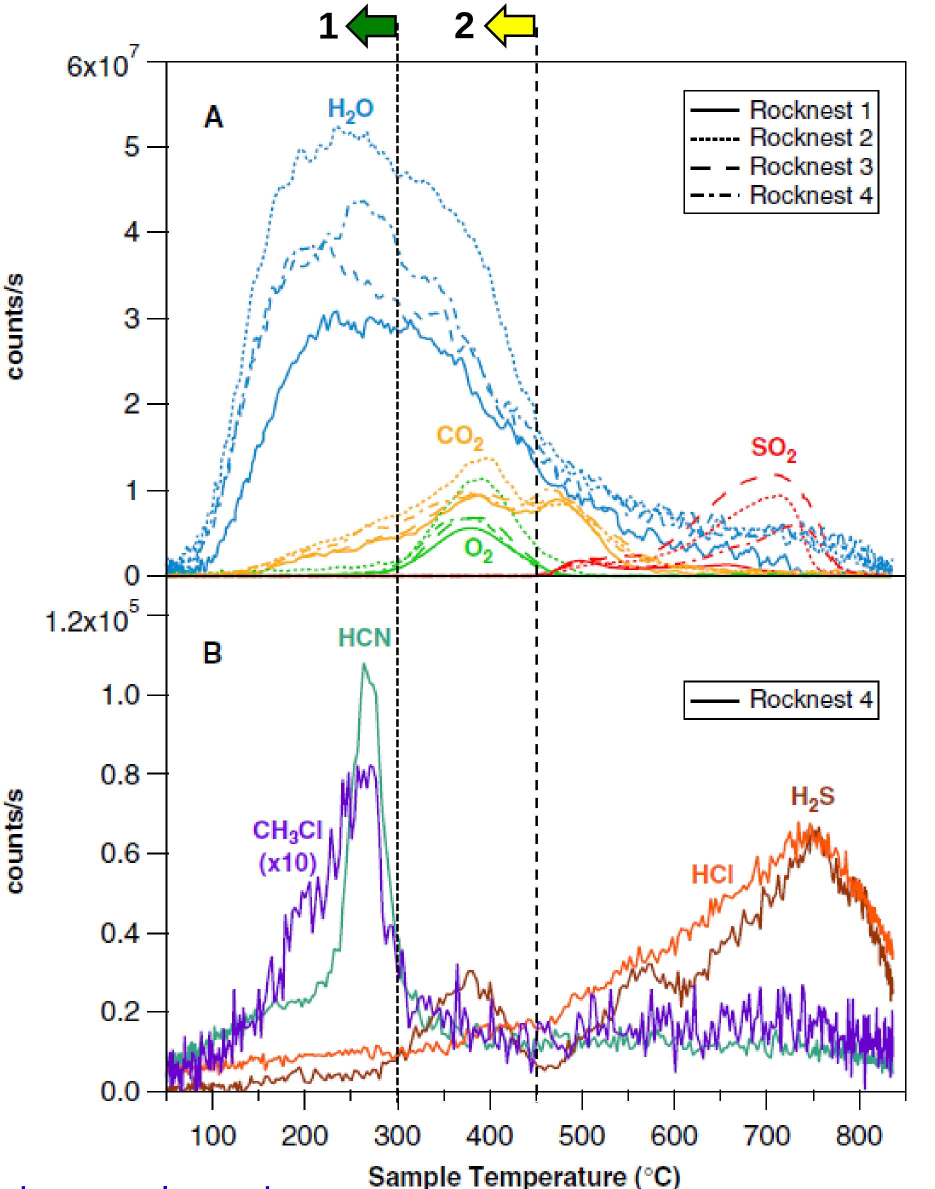
Region 2: <300 C
- >80% of the water released
- CO_2 and O_2 released from decomposition of perchlorates
- Some release of HCl or H_2S but before significant amounts are release

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

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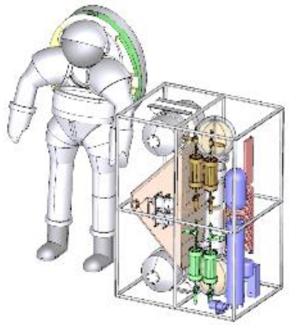
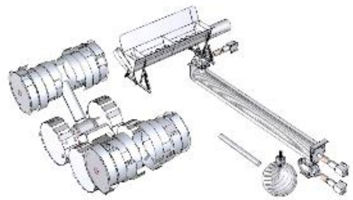
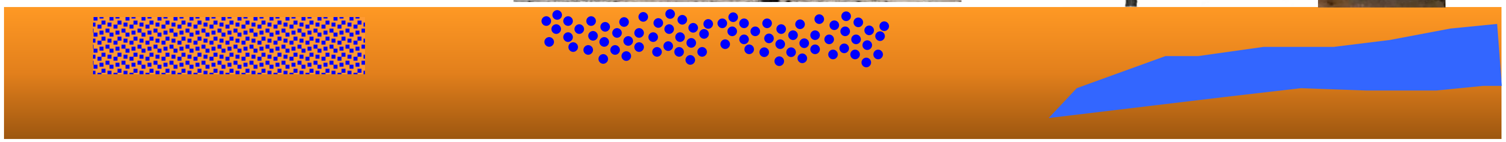
Mars Atmosphere & Water Resource Attributes

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
- Atm. 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 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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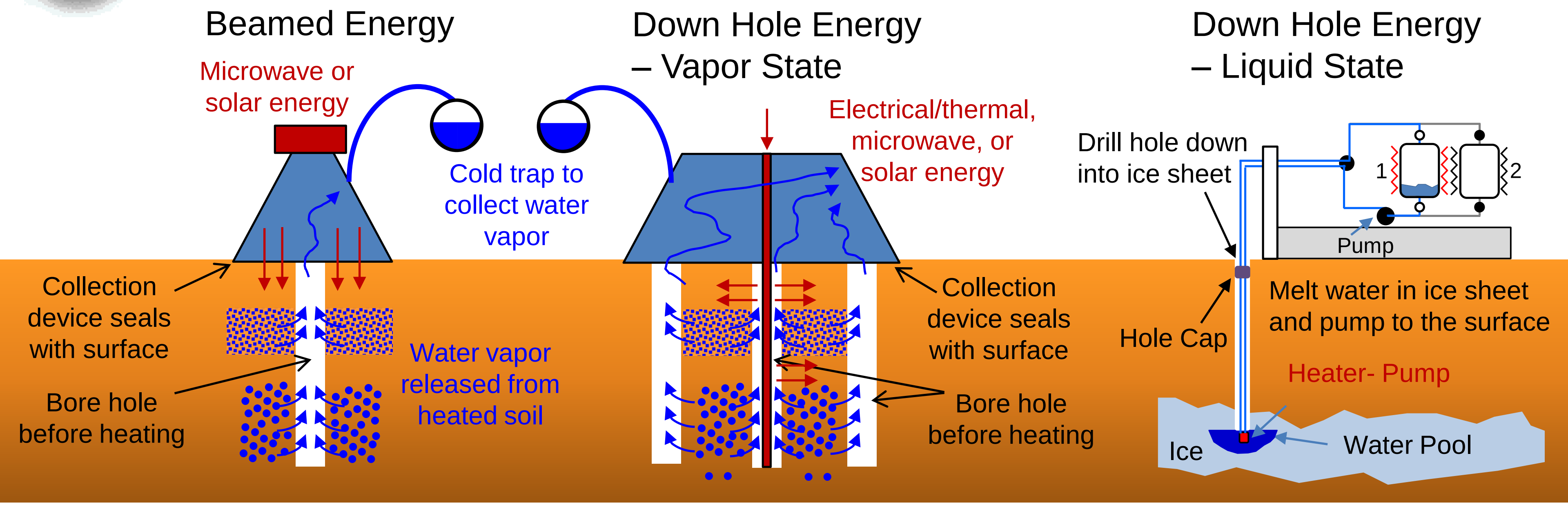
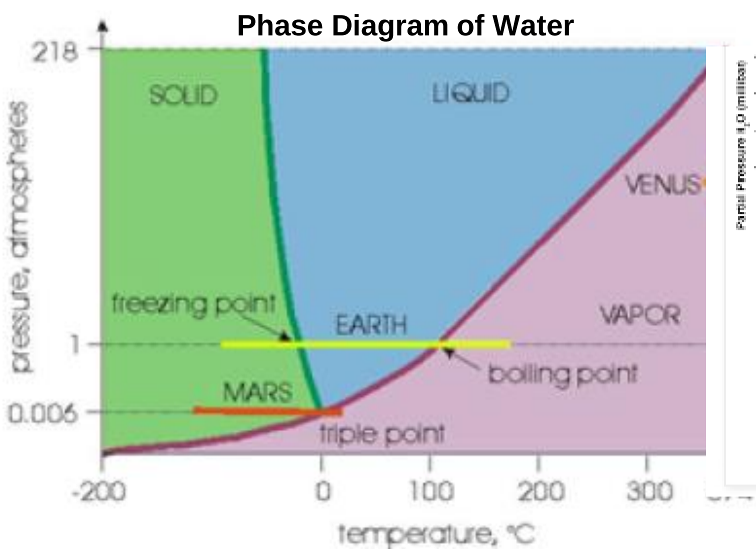
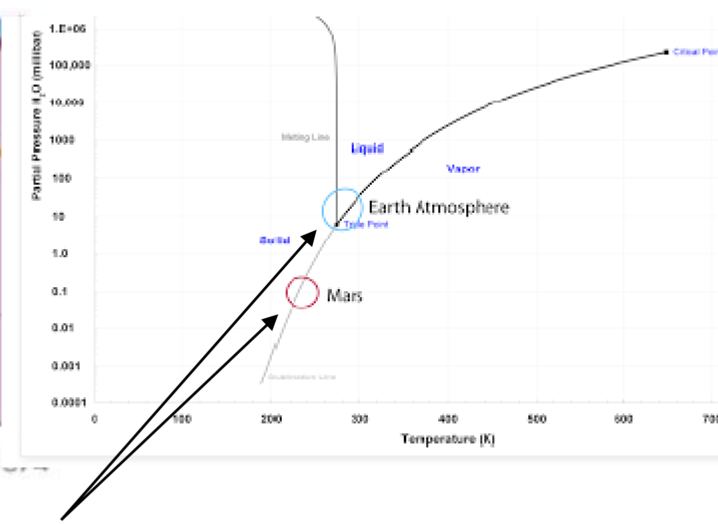
In Situ Water Extraction from Mars Soils



- Energy heats soil so that water converts to vapor (may transition thru liquid phase)
- Release of water helps further heat conduction into soil
- Water vapor follows 'path of least resistance' to bore hole
  - Vapor may also re-condense away from heat in colder soil
- Water vapor collected in cold trap in liquid/solid form
- Process may take hours





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

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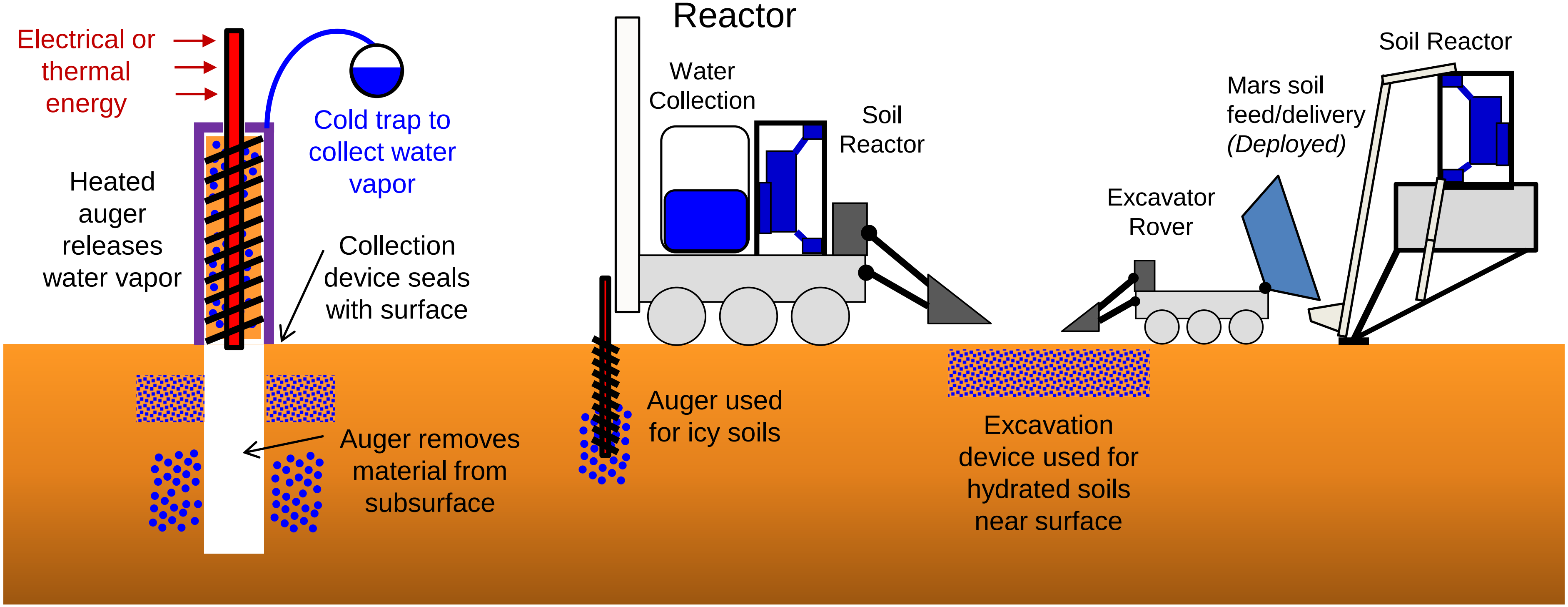
Water Extraction via Excavation & Processing Reactor

On Rover

Near Surface

Separate Soil Reactor

Excavation & Delivery to Stationary Reactor



- Soil is removed from subsurface
- Soil is heated via thermal to remove water vapor; can be higher temperature than *in situ* heating

- Soil is removed from surface/subsurface and transferred to soil reactor
- Soil is heated via thermal, microwave, and/or gas convection to remove water vapor at higher temperatures and pressures than for *in situ* heating

- Water vapor is condensed and stored
- Soil is dumped back onto surface after processing

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Mission Requirements & ISRU Economics

ISRU Produced Consumables for Mars Missions*

Capability Description	Capability Goal	Description/Basis	Refs.
Human Mission			
Oxygen production			
Total mass, kg	25,000	22,985 kg for ascent propulsion; 1906 kg for life support	Ref. 9, chart 30 Ref. 10, pg 5, Table I
Time for production, days	480	ISRU plant arrives October, yr 2 Crew departs Earth March, yr 4 (510 days after ISRU plant arrives) Crew arrives Mars September, yr 4 (182 days after departing Earth) Crew departs Mars February, yr 6 (510 days after arriving Mars)	Ref. 8, page 52, fig. 6-3
Daily operation, hrs	24	nuclear surface power	Ref. 8
Production rate, kg/hr			
Oxygen	2.2	for propulsion and life support; 2.0 kg/hr for propulsion only	
Methane	0.57	oxygen-to-fuel mixture ratio = 3.5:1	
Operational life, days	1200	Time from start of ISRU plant operation to departure of crew (510 + 182 + 510 days)	
Cycle life, #	40	Assumed average one shut-down per month for diagnostics	
Mars Direct Sample Return			
Oxygen production			
Total mass, kg	1525	average value from multiple references; returned sample between 1 - 30 kg; ascent vehicle 1, 2, or 2.5 stages; parking orbit or direct return	Refs. 14 - 18
Time for production, days	460	Typical stay time for conjunction-class mission less 10% contingency	
Daily operation, hrs	8	solar power	
Production rate, kg/hr			
Oxygen	0.41		
Methane	0.12	oxygen-to-fuel mixture ratio = 3.5:1	
Operational life, days	510	Production time plus 10% contingency	
Cycle life, #	510	Solar power results in daily cycle	

Possible Early Demo at 1/3 to 1/5th Scale

Sample Size, kg	Total Propellant, kg	Engine Mixture Ratio, O/F	Total O_2, kg	Total CH_4, kg	Notes	Ref.
5	1382	3.5	1075	307	2 1/2 stages to Mars parking orbit, then TEI	14
1	3330	3.4	2573	757	Single-stage ascent direct to Earth	
5	2801	4.0	2241	560	Ascent to 200 km parking orbit, then TEI	15
0.5	277	3.5	215	62	2 stage direct to Earth; employed extremely light sample return capsule of only 6 kg	16
25 - 30	2450	4	1960	490	single stage to Mars parking orbit, then TEI	17
0.5	1420	3	1065	355	ISRU first stage delivers Earth Return Vehicle (storable propellant) to near Mars escape	18
		Average:	1522	422		

*Tables obtained from Linne, Diane, Sanders, Gerald, and Taminger, Karen, "Capability and Technology Performance Goals for the Next Step in Affordable Human Exploration of Space", AIAA SciTech, Jan. 2015, Orlando, FL

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

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 ISRU Plant/Component Sizing & Design Requirements (1 of 3)

Items Affecting Decisions/Calculations on ISRU System/Component Sizing and Design

1. Amount of propellant/consumable needed
2. Time allowed for production
3. Failure tolerance for mission success and crew life
4. Approach to certifying ISRU system for human mission
5. Margin added to production capabilities and estimates of mass, power, and volume
6. External environment specifications
7. Soil, mineral, and water content properties (for excavation, water extraction, and mobility)

Note:

- Decisions for 1, 2, and 5 determine total average production rate
- Decisions for 3, 4, 6, and 7 determine component size/production rate

1. Amount of propellant/consumable needed
   a) Ascent propellant based on last design (Polsgrove AIAA 2015)
   b) Ascent propellant and life support consumables before crew decision (addition from Mars Water Rich Arch. Study)
2. Time allowed for production (Earth days; 24 hrs/day based on Earth mission calendar)
   – 540 days: This corresponds with times identified by the EMC as boundaries: (420 for SEP/Chem. & 540 for Hybrid) and with Mars DRA 3.0/5.0 for Conjunction-class missions with Hohmann transfer trajectories.
   – Do not worry about whether duration decision is based on crew leaving Earth or descending.
3. Failure Tolerance: Specify Failure Tolerance for Human Mission:
   – 1 Fault tolerance for mission success (making mission critical product. In this case ascent propellants)
   – 2 Fault tolerance for crew life/survival; catastrophic failure after crew arrival
     - Note: requirement could impact design of ISRU plant used for MAV filling if operations continue for other purpose after crew lands (cat. failure causes loss of MAV) or for other ISRU hardware operating near crew.
4. Approach To Certify for Human Mission.
   – Assume 3 of same modules for human flight mission;
     - Each module is zero fault tolerant
     - Can loose 1 module and still meet mission production rate; i.e. each module is 50% of human production rate.
   – Assume Pathfinder Mission is 1 module but with added active components to achieve 1 fault tolerance for mission success

Mars ISRU Plant/Component Sizing & Design Requirements (2 of 3)

6. 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 a 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

Mars ISRU Plant/Component Sizing & Design Requirements (3 of 3)

Component/Subsystem Production Size Range for Development

Based on approach selected

		O2 Only	O2	CH4
	Amount (kg)	22728	27912	6978
Human	Prod. For Min Time (kg/hr)	2.82	3.47	0.87
	Prod. For Max Time (kg/hr)	2.18	2.68	0.67
Precursor	Prod. For Min Time (kg/hr)	1.41	1.73	0.43
	Prod. For Max Time (kg/hr)	1.09	1.34	0.33

2.2 kg/hr O_2 for O_2 Only and 2.7 kg/hr O_2 for O_2/CH_4

		Days	
	Total Time	420	540
Criteria #5	Time for Setup/Failures	14	14
Criteria #5	Time for Failure Recovery (5%)	16.8	21.7
Criteria #5	Time for Dust Storms (6%)	20.1	26.1
Criteria #5	Reserve Time (10%)	33.6	43.5
	Prod Time	**335.5**	**434.7**
	Delta (Total - Prod Time)	84.5	105.3

Based on Separate discussions on mission trajectories, 540 days was selected

Note: the production rate for the human Mars mission calculated above based on criteria #1, #2, and #5 is an average assuming a constant and continuous process. Component/subsystem developers can size components to a different production rated based on the following as long as an average production rate is maintained over the production duration.

- Batch operation production variation (vs continuous)
- Day/night production variation (due to temperature, pressure, and/or sunlight)
- Seasonal production variation (due to temperature, pressure, and/or sunlight)
- Power source (continuous vs cyclic)

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

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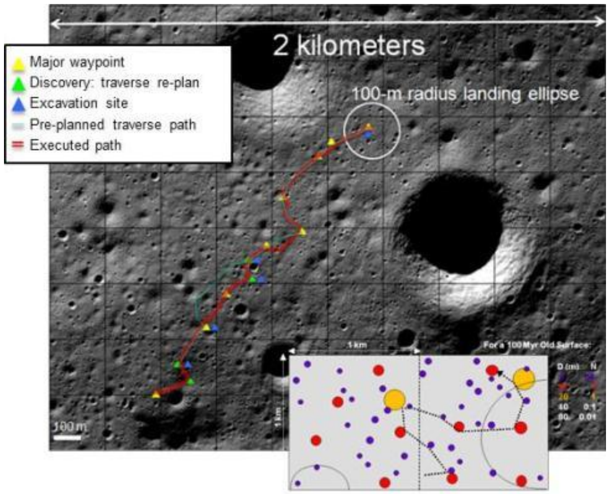
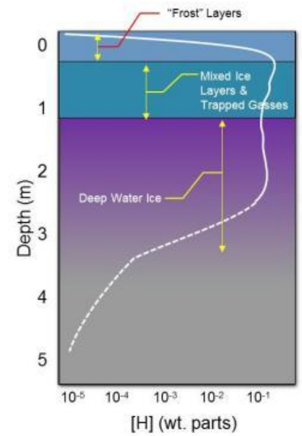
Economics of ISRU for Space Applications (2)

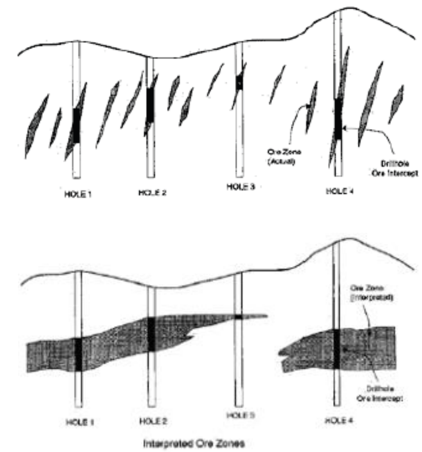
Need to Evaluate Local Region (1 to 5 km)



Need to Determine Vertical Profile



Need to Determine Distribution



Need to assess What is needed, How much is needed, How often 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)

Evaluation Criteria for ISRU Insertion

When Evaluating ISRU Concepts, you need to evaluate the following:

- 'Launch mass saved' or 'Additional mass to surface'
- Process and operation complexity
- Process scalability
- Ability to operate without human presence
- System power, mass & volume
- Mass of product/service vs Mass of ISRU "system"
- Amount of infrastructure and ease of delivery/deployment required before products are delivered for use
- Logistical support needs
  - Reactant/reagent losses and replacement brought from Earth
  - Hardware replacement. Reliability - Mean-time between failure

It's not about being able to do ISRU.
It's not about having the most efficient ISRU system.

It is about achieving the benefits of ISRU for a reasonable cost, mass, and risk.

Challenges and Risks for ISRU Development and Incorporation into Missions

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.

Location to Reduce/Eliminate ISRU Challenges/Risks

		Earth	Orbital	Surface
R1	What resources exist at the site that can be used?	S	S	**P**
R2	What are the uncertainties associated with these resources?	S	S	**P**
R3	How to address planetary protection requirements?	P		V
T1	Is it technically feasible to collect, extract, & process resources?	P		V
T2	How to achieve long duration, autonomous operation?	P		V
T3	How to achieve high reliability/minimal maintenace?	P		V
O1	How to operate in extreme environments?	S		**P**
O2	How to operate in low/micro gravity?	S		**P**
I1	How other systems designed to incorporate ISRU products?	P		V
I2	How to optimize at the architectural level with ISRU?	P		V
I3	How to manage the interfaces/interactions with other systems?	P		V

P = Primary; V = Validation, S = Support

- Most challenges and risks to ISRU development and incorporation can be eliminated through design and testing under Earth analog or environmental chamber testing at the component, subsystem, and system level
- Critical challenges/risks associated with fully understanding the extraterrestrial resource (form, concentrations, contaminants, etc.) and ISRU system operation under actual environmental conditions for extended periods of time can only be performed on the extraterrestrial surface
- ISRU precursors/demonstrations are extremely beneficial for validation of Earth-based testing and analysis

Approach to Reduce/Eliminate Resource & Site Risks

- **Analyze Exist Data**
  - Perform analysis of orbital and surface instrument data sets to provide the most effective screening to define discrete, evaluatable, prioritized prospects

- **Improved Understanding of Soil/Water-Based Resources – What is needed?**
  - **Purpose**
    - Determine resource availability, geologic context, depth, distribution, and homogeneity, and applicability to other locations on Mars
    - To support mining operations and infrastructure emplacement (terrain, environment, wind, sun)
  - **Sequence of knowledge/analyses needed**
    - Global understanding of resources/terrain to select landing sites
    - Higher resolution data for regions of interest (ROI) for landing
    - 1 meter or less resolution of terrain and <100 m resolution of resources in locations within ROI for landing site selection and preliminary infrastructure layout plans
    - <5 m resolution of resources to select mining sites of interest
    - <1 m mapping of terrain, surface/subsurface features and resources with ground truth verification of resources (and contaminants) at statistically relevant intervals to plan and perform mining operations and finalize mining hardware designs

    Orbital/ Aerial (first four items)

    Aerial/ Surface (last two items)
  - **Different ISRU phasing strategies can influence scope and timing of resource assessment**
    - Strategy 1: Start with lowest risk resource (hydrated mineral at surface) near initial infrastructure before or during 1st crewed mission. Perform resource evaluation and ISRU risk reduction demos on larger quantity/higher concentration resources as time goes on with crew present
    - Strategy 2: Identify the resource type of primary interest. Locate and perform ISRU risk reduction demos on that resource before crew arrives

Approach to Reduce/Eliminate ISRU Technical & Operational Risks

- Before a crewed mission will incorporate ISRU into a mission critical role, risk reduction activities need to be performed on ISRU resource extraction, processing, and storage systems to ensure products are available

THINGS WE CAN LEARN ON EARTH

- Earth-based environmental chamber and analog site testing can be utilized to reduce the risk of:
  - Feasibility of operations including traverse distance, repeatability, mass and power of hardware and infrastructure
  - Environmental compatibility
  - General understanding of hardware life, maintenance, and life/wear factors of concern

- Because Mars environments, minerals/contaminants, terrain, etc. can not be perfectly simulated, certain aspects may need to be demonstrated on Mars to completely retire risk before use in human missions
  - Impact of dust on filters, catalysts/processors, valves, thermal management, and long-term mechanical operations
  - Impact of lower gravity on excavation/drilling, extraterrestrial material flow/movement, separation processes, thermal convection, etc.
  - Impact of resource physical attributes on wear and energy of excavation/extraction and processing
  - Impact of variation in mineral form and contaminants on extraction and processing

THINGS WE NEED TO LEARN ON MARS

Earth-based Activities to Reduce/Eliminate ISRU Development and Incorporation Risks

- **Technology Development**
  - Atmosphere Collection & Processing Technologies
  - Resource Prospecting Instruments (Surface & Subsurface)
  - Regolith Excavation for Mars Mineral Resources
    - Granular and rock material mining (surface and pit mining)
  - Water/Ice Extraction for Mars Ice Resources
    - Borehole and subsurface mining
  - Oxygen/Fuel Liquefaction, Long-term Storage, and Transfer

Downselect as resource knowledge, landing site, and mission plans are refined

- **ISRU System Development: Develop end-to-end ISRU systems to perform the following:**
  - Determination of most important trade-off factors
  - Demonstrate feasibility of operations including traverse distance, repeatability, mass and power of hardware and infrastructure
  - Demonstrate environmental compatibility in Mars environmental chambers
  - Develop general understanding of hardware life, maintenance, and life/wear factors of concern

- **Mission Operation Development:** Develop and demonstrate Concepts of Operation for Mars ISRU. Use Analog sites for:
  - Deployment and Infrastructure Needs (ie. power, communication, and local navigation)
  - Operations with Autonomy/Limited Earth communication
  - Long duration testing for full mission operation duration (wear, reliability, repeatability, operational life)

- **Architecture and Surface Integration:** Develop and demonstrate Concepts of Operation for how ISRU will interface and interact with other surface elements.
  - Integrate other surface elements required for ISRU operation (comm., power, etc.)
  - Demonstrate ISRU product transfer and usage by other surface elements

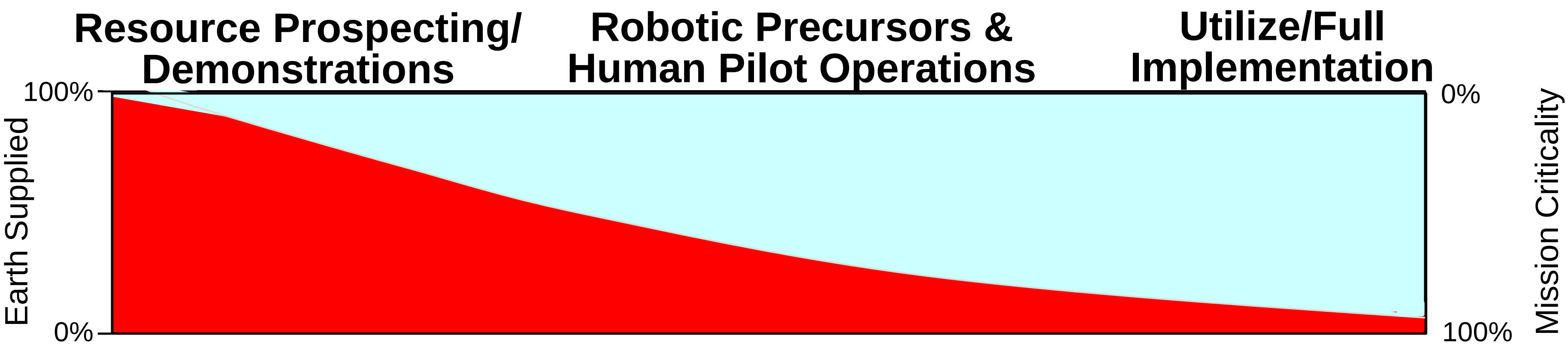
Mars-based Activities to Reduce/Eliminate ISRU Development and Incorporation Risks

- **Primary location for Evaluating Impacts of Resources and Environment on ISRU Hardware and Operations**
  - Impact of dust on filters, catalysts/processors, valves, thermal management, and long-term mechanical operations
  - Impact of lower gravity on excavation/drilling, extraterrestrial material flow/movement, separation processes, thermal convection, etc.
  - Impact of resource physical attributes on wear and energy of excavation/extraction and processing
  - Impact of variation in mineral form and contaminants on extraction and processing

- **Validation of Earth-based Risk Reduction**
  - Demonstrate long-term autonomous operations with limited communications and local navigation
  - Perform operations and product utilization at scales and durations relevant to human missions including traverse distances, number of trips, etc.
  - Demonstrate failure recovery and mitigation approaches
  - Demonstrate integration of ISRU systems with relevant human mission surface and transportation elements
  - Demonstrate use of ISRU products in relevant human mission applications

Phased Approach to ISRU Architecture Incorporation

Current approach is to utilize phased approach to incorporate ISRU with minimum risk to mission success



Purpose

- Characterize local material/resources; evaluate terrain, geology, lighting, etc.
- Demonstrate critical technologies, functions, and operations
- Verify critical engineering design factors & environmental impacts
- Address unknowns or Earth based testing limitations (simulants, micro/low-g, contaminants, etc.)

Purpose

- Enhance or extend capabilities/reduce mission risk
- Verify production rate, reliability, and long-term operations
- Verify integration with other surface assets
- Verity use of ISRU products

Purpose

- Enhance or enable new mission capabilities
- Reduce mission risk
- Increase payload & science capabilities

Examples

- **Curiosity Rover**
- **Resource Prospector**
- **Mars 2020**

- **Mars Surface Pathfinder**
- **Lunar Human Short Stay**

- **Mars DRA 5.0**
- **Evolvable Mars Campaign**
- **Lunar Outpost**
- **Commercial Space**

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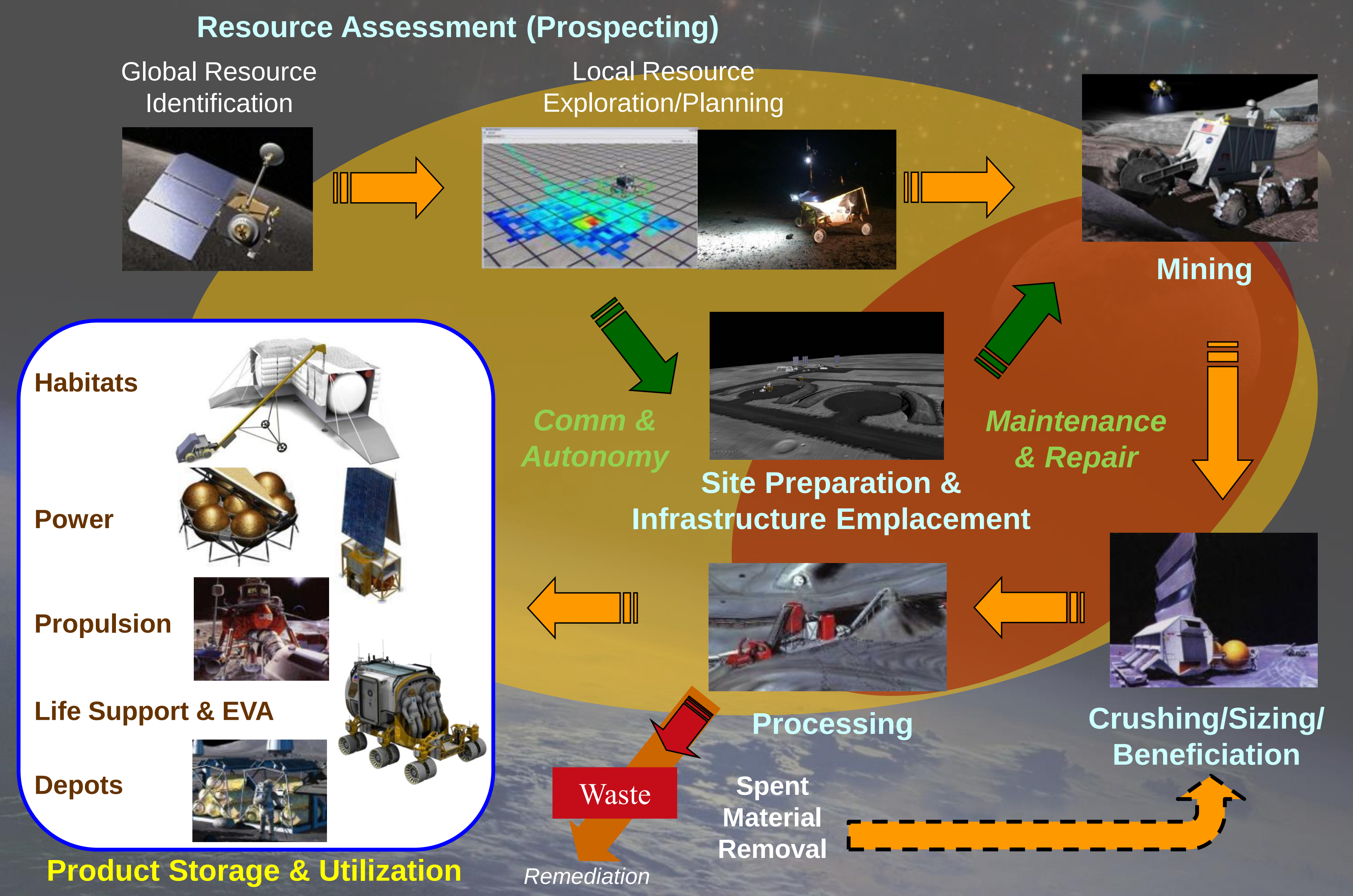
Concept of Operation on Mars

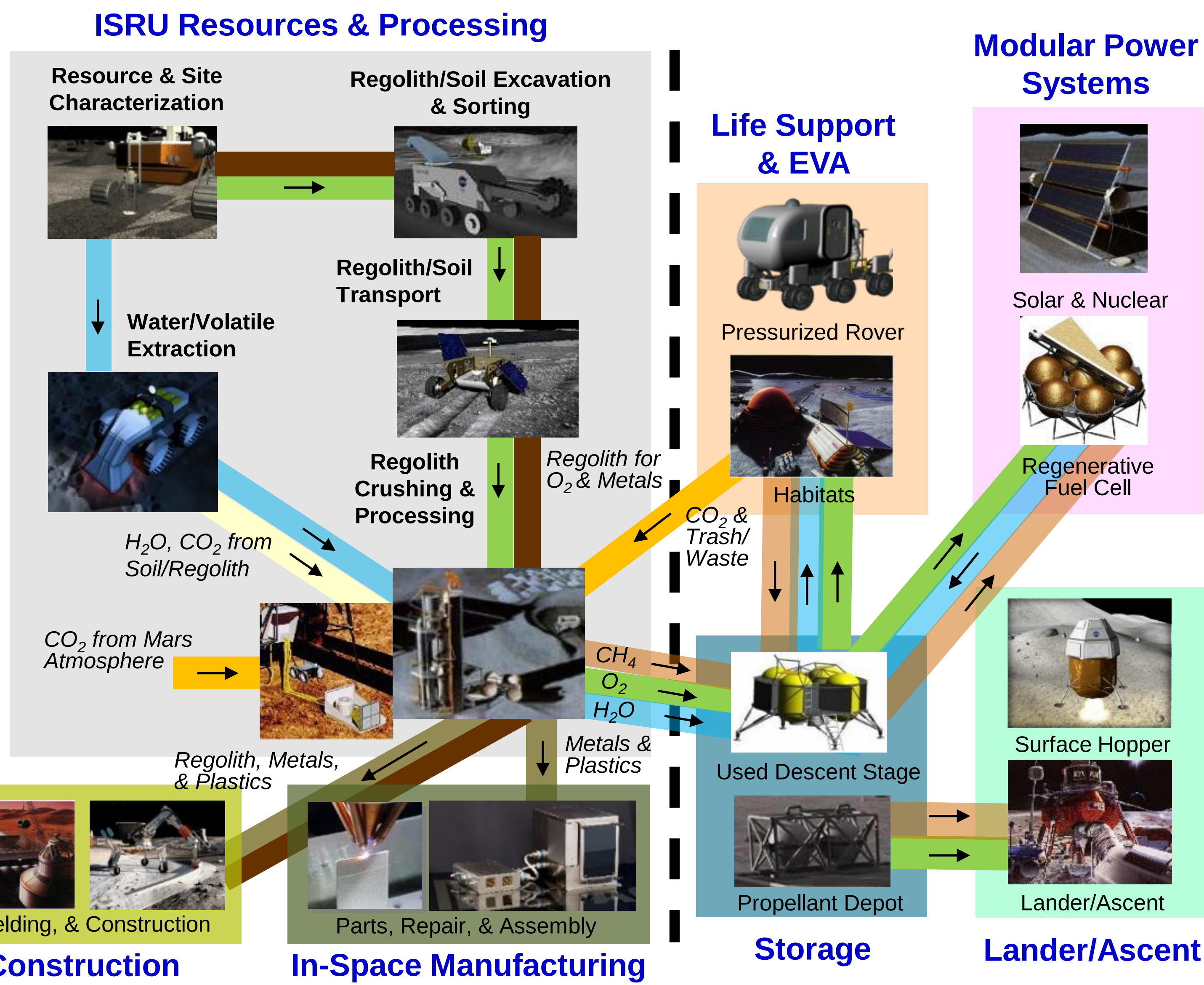
Space 'Mining' Cycle: *Prospect to Product*



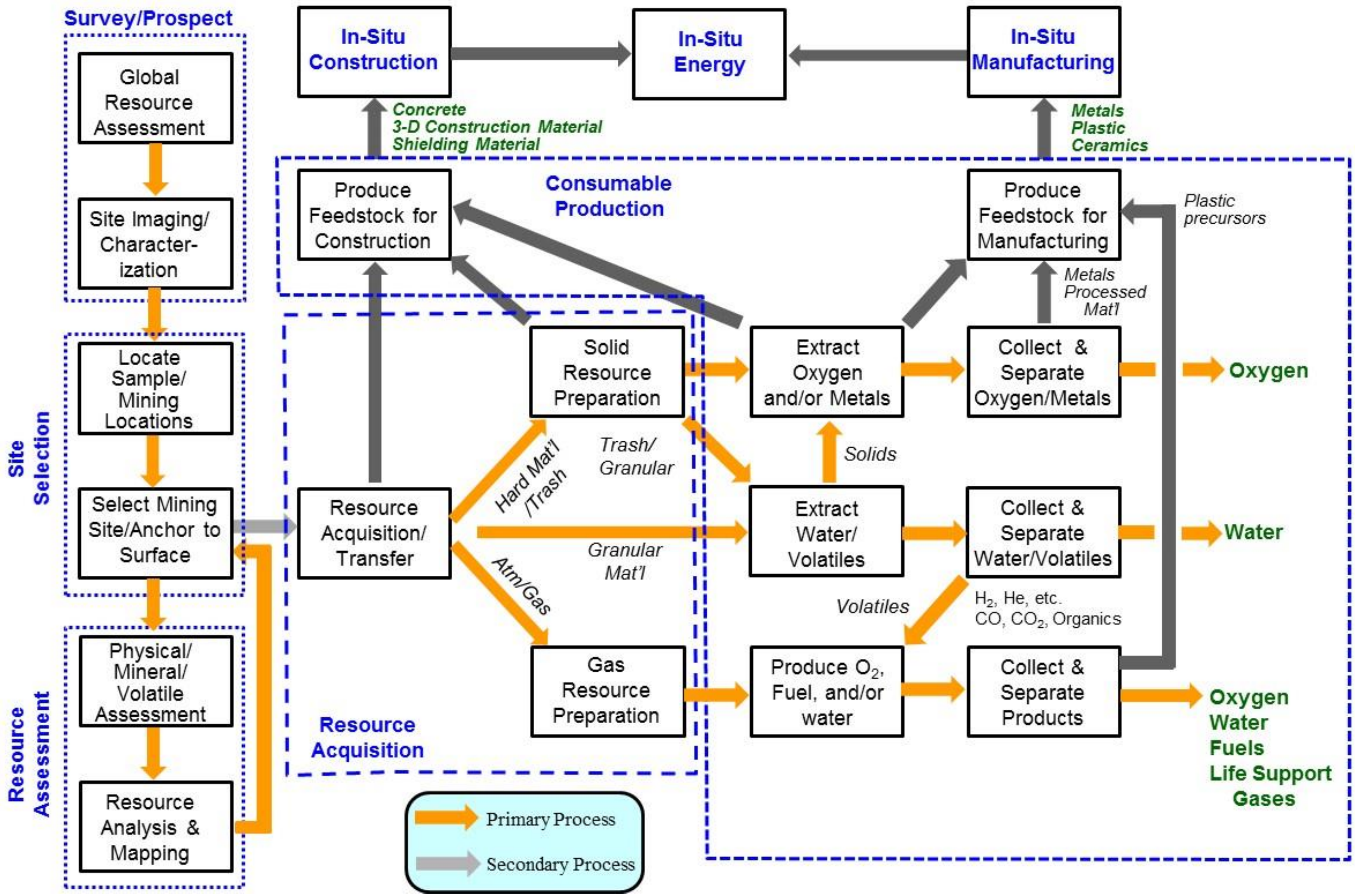
ISRU Integrated with Exploration Elements
(Mission Consumables)

ISRU Functions & Elements
- Resource Prospecting/ Mapping
- Excavation
- Regolith Transport
- Regolith Processing for:
  - Water/Volatiles
  - Oxygen
  - Metals
- Atmosphere Collection
- Carbon Dioxide/Water Processing
- Manufacturing
- Civil Engineering & Construction

Support Functions & Elements
- Power Generation & Storage
- O_2, H_2, and CH_4 Storage and Transfer

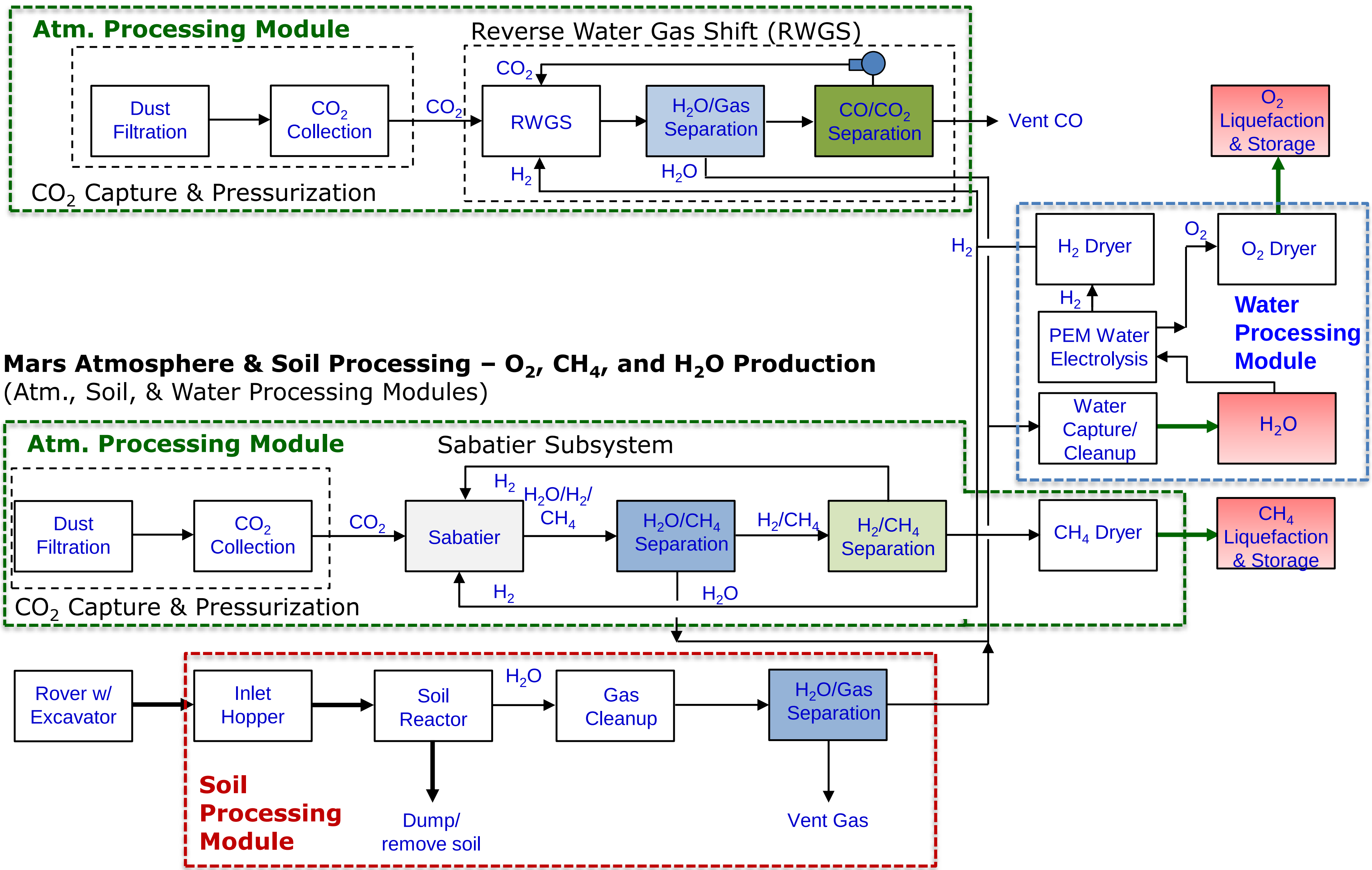


ISRU Capability-Function Flow Chart



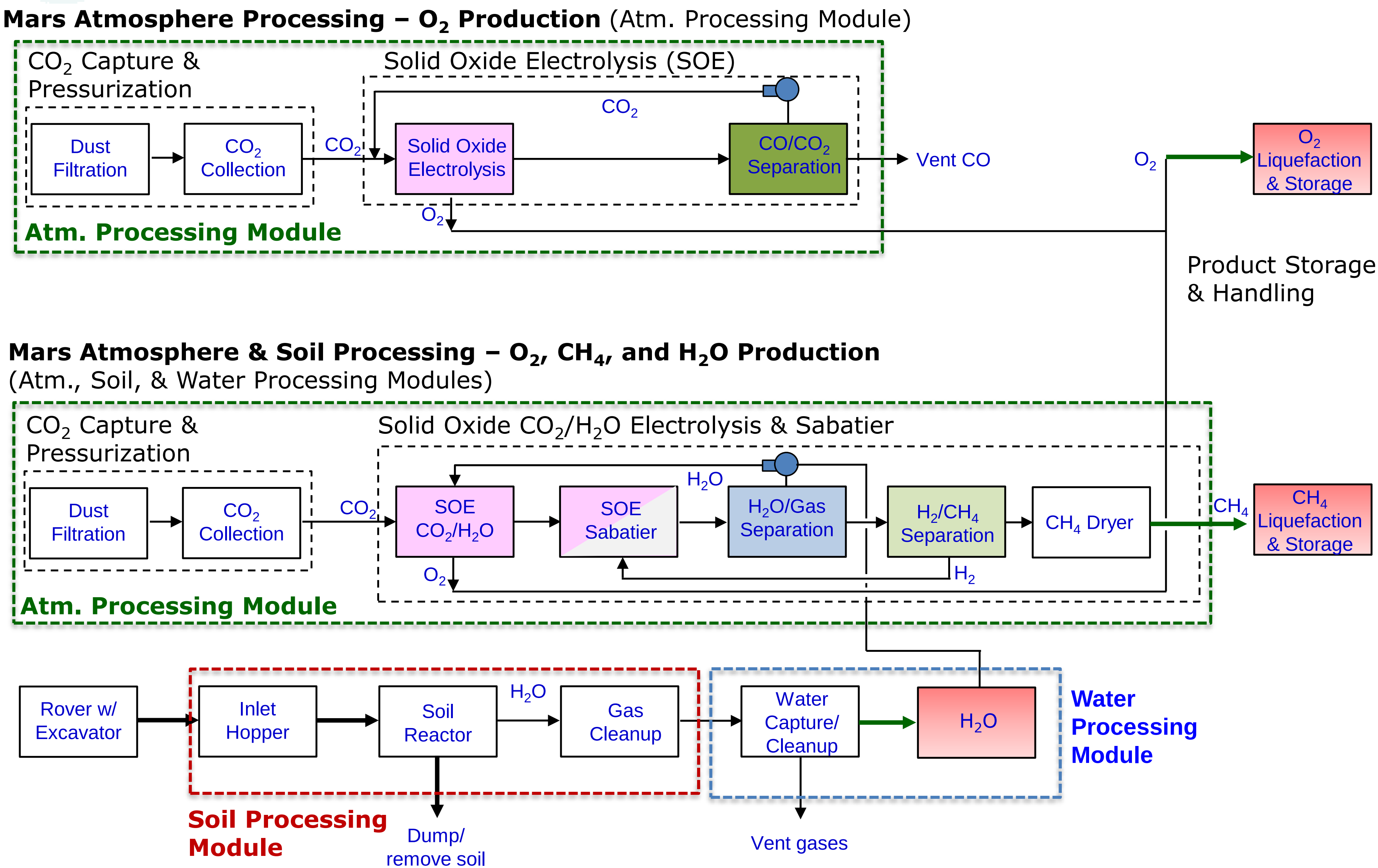
Mars Consumable ISRU: PEM-Based Electrolysis

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



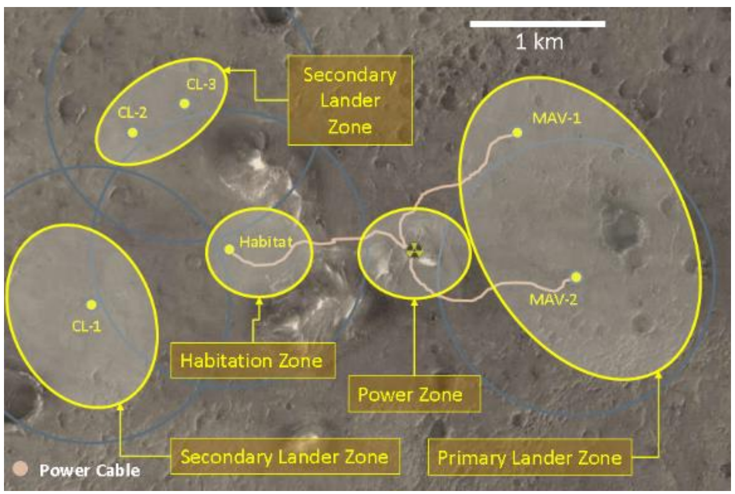
ISRU Products, Operations, and Resources Grow As Mission Needs and Infrastructure Grow

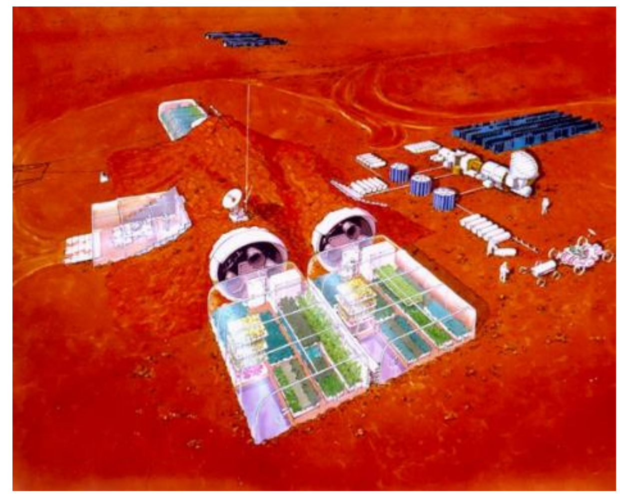
Initial Conditions:

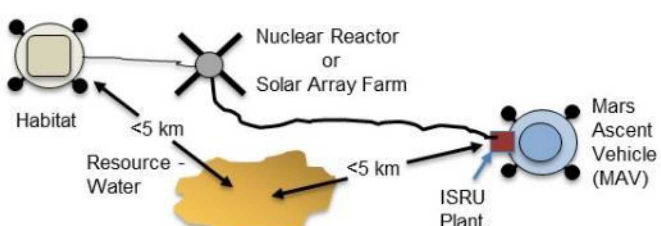
- Hardware delivered by multiple landers before crew arrives; Multiple landing zones
- Elements offloaded, moved, deployed, and connected together remotely
- 12-18 month stay for crew of 4 to 6; Gaps of time between missions where crew is not present
- Each mission delivers extra hardware & logistics

Ultimate Goal

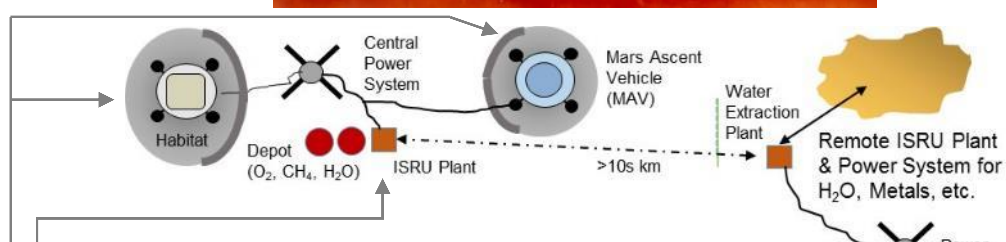
- Consolidated and integrated infrastructure
- Indefinite stay with larger crews
- Roam (and mine) anywhere within 200 km diameter Exploration Zone
- Earth independence; *In situ* ability to grow infrastructure: power, habitation, food, parts, etc.







- **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**

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Human Mars Surface Mission Overview (1)

- **Evolvable Mars Campaign Decisions to be used**
  - Crew of 4 to the surface; crew arrives in monolithic habitat on first mission; arrives with cargo on subsequent missions
  - Lander payload capacity = 20 to 22 ton payload
  - Power provided by 4 nuclear fission reactors with 10 KWe each on first lander (5^{th} unit as spare)
    - Nuclear reactors are redeployable
    - Power cables used to attach to nuclear reactors are provided on each subsequent lander
  - Habitat environment: 14.7 psia at 21% O_2 (Trades: 10.2 psia at 26.5% O_2; 8.2 psia at 34% O_2)
  - Closed loop consumable rates: 3.46 kg/person/sol + 97.57 kg/person

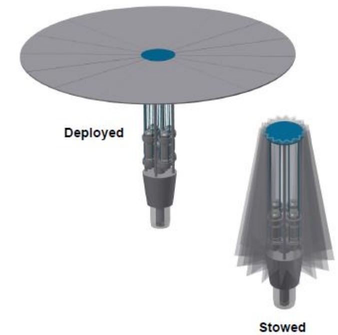
- **Landing Sequence for 1st Crewed Mission** (based on input from EMC)
  - Lander 1 – Nuclear reactors, Rovers
  - Lander 2 – Mars Ascent Vehicle (MAV) and ISRU hardware
  - Lander 3 – Cargo/Logistics
  - Lander 4 – Habitat and Crew (not allowed to land until after MAV is completely filled)

- **Infrastructure Layout for 1^{st} Crewed Mission** (based on input from EMC)
  - Landers have 100 m or less landing accuracy from desired point of landing
  - Lander spacing assumes no civil engineering or plume debris mitigation operations have been performed. Therefore, minimum spacing between landers (without natural terrain shielding) is 1 km from active lander to already landed assets.
  - Habitat should be central with all delivered elements

Human Mars Surface Mission Overview (2)

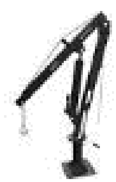
- **Infrastructure Available for ISRU Deployment and Operations**
  - Nuclear power is primarily aimed at ISRU operations
    - Keep alive/support power is required for habitat and other assets
    - Solar arrays and power storage still an option under consideration
  - A nuclear reactor can be deployed with ISRU water extraction hardware to a location away from the MAV/ISRU lander
  - Assets for lander payload unloading and transport for infrastructure emplacement can be used for ISRU operations until the crew arrives. Assets may include:
    - Asset 1: Mars Surface Transporter (6000 kg payload cap.)
      - Options are Chassis and/or ATHLETE
    - Asset 2: Transportable Off-loading Crane
    - Asset 3: Power cables – TBD length (~1 km assumed)
    - Asset 4: Robotic Assistant for Maintenance
    - Asset 5: Site Evaluation/Science rover

Nuclear Reactor



Mars Ascent Vehicle

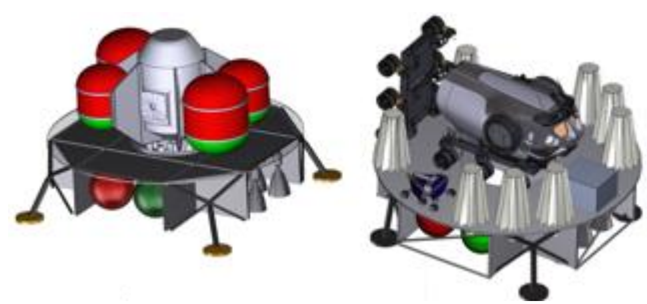
Asset 1



Asset 2

Asset 3

Mars Lander



Asset 4

Asset 5

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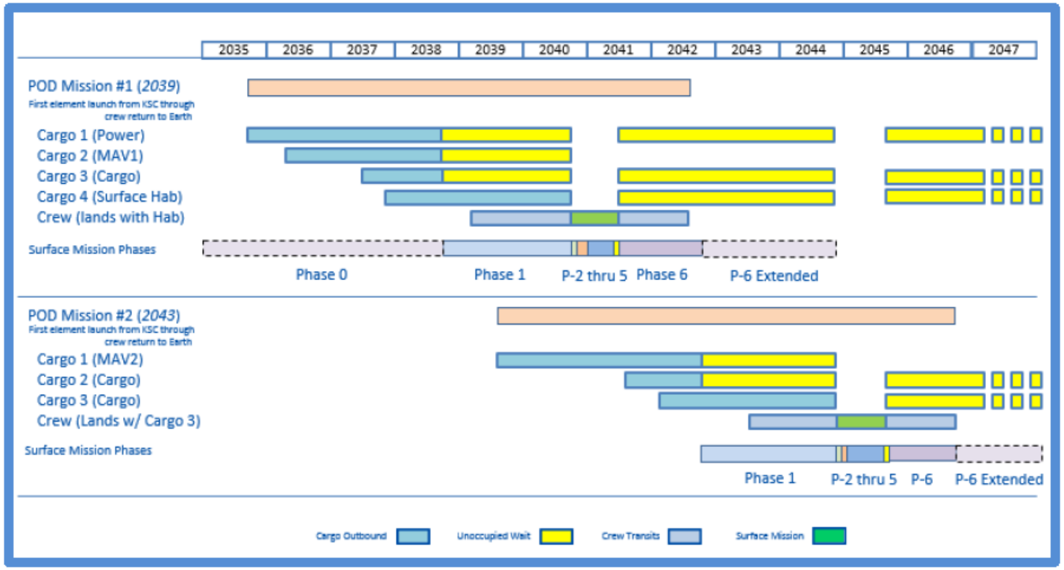
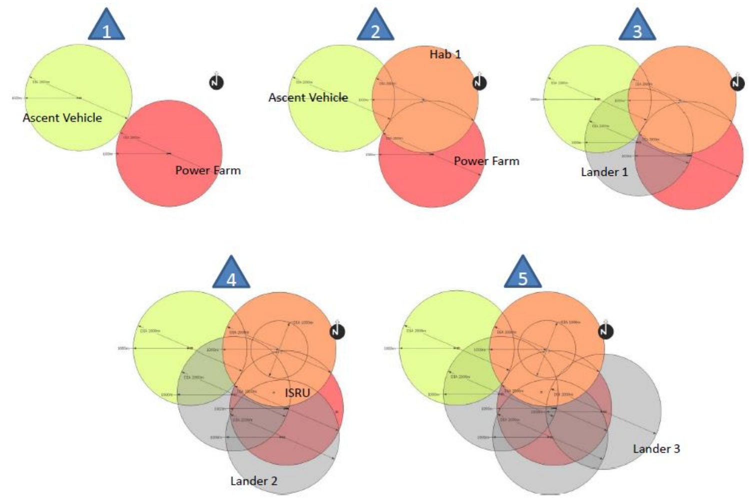
Human Mars Surface Exploration Sequence - First 1 to 3 missions (Notional - EMC based Information)





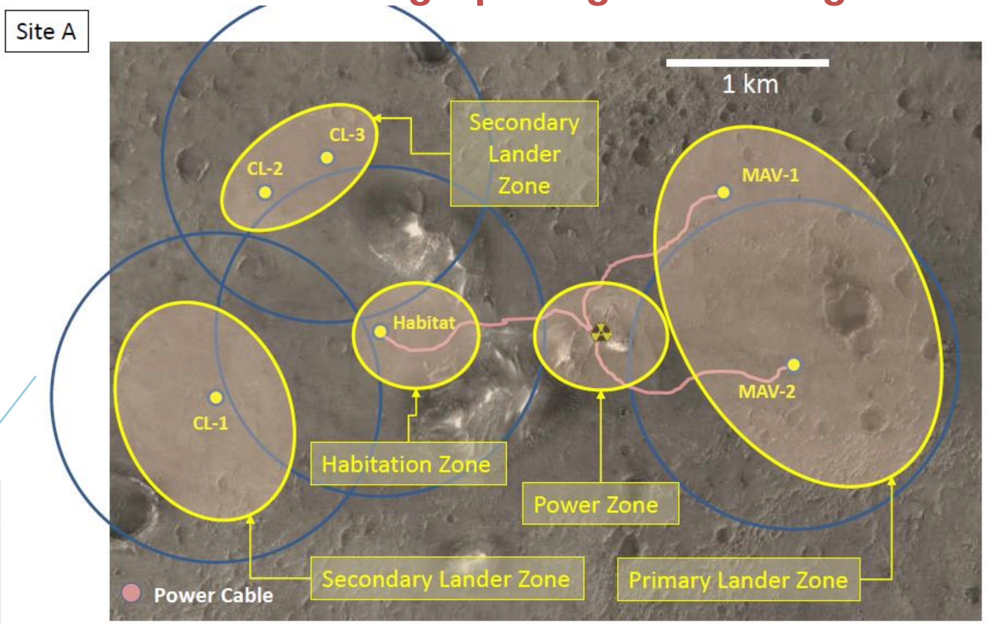
	Landers	1	2	3	4	5	6	7	8	9	10
	Crew				1			2			3
	Time on the Surface				*210 sols*			*357 sols*			*550 sols*
Point of Departure (POD)	Crew to the Surface										
	Mars Ascent Vehicle										
	ISRU										
	Fission Power										
	Power Distribution Systems										
	Robotics										
	Habitation / Logistics										
	EVA										
	Mobility										
	Science										

Point of Departure (POD)			MISSION 1				DAYS
		Landers	Lander 1	Lander 2	Lander 3	Lander 4 - Crew 1	210
		Mass In Cargo Container(s) (kg)	*2,883.03*	*-*	*5,084.14*	*4,165.04*	*12,132.21*
		Total Lander Mass (kg)	**19,989**	**20,000**	**19,996**	**19,971**	**75,658**
Crew	Crew	400				400	400
ISRU	Atmospheric Production Plant w/O2	1,677		1,677			1,677
	LOX Tanker (tankage and transfer equip)	600					-
	CH4 Tanker (tankage and transfer equip)	600					-
Power	Kilopower Fission Power System	6,176	6,176				6,176
	Power Distribution System	800	800				800
	Power cable (1 km length) + spool or box	70	140	70	70	70	350
Robotics	Special Regions Rover	500	500				500
	Crew Support Robotic Rovers	500	500				500
	Offloading Equipment (Hoist)	600	1,200				1,200
Habitation	Mars Surface Habitat - Monolithic	19,336			4,000	15,336	19,336
	Mars Surface Habitat - Split Habitat	10,129 kg +11,600 kg					
	Small Mars Surface Logistics Module - Single Hatch (4,480 kg capacity)	2,560					
	Small Mars Surface Logistics Module - Dual Hatch (3,500 kg capacity)	2,600	2,600		5,200		7,800
	Large Mars Surface Logistics Module (8,260 kg capacity)	3,130					-
	Descent Module	3,000					-
	MAV Access Tunnel	237		237			237
	Consumables for up to N sols	3.461 kg/person/sol + 97.57 kg	1,633.592		27.688	1,636.240	3,297.520
	Spares and Other Logistics	2.946 kg/sol + 2112.9 kg	1,085.910		1,056.450	589.200	2,731.560
	Maintenance	depends on mission (see calculator)	146.230				146.230
EVA	EVA + PLSS	692.8				692.8	692.8
	LEA	104				104	104
	EVA spares	4 crew: 1.73 kg/sol + 796.8 kg	17.30			1,142.80	1,160.10
Mobility	Mars Surface Transporter (Chariot, Athlete)	1,890	1,890		1,890		3,780
	Mars Surface Unpressurized Rover	300	300		300		600
	Mars Surface Pressurized Rover	6,452			6,452		6,452
	Spares and logistics	-					-
Science	Allocated Payload	1,000			1,000		1,000
	Reconfigurable Surface Science Facility	3,000	3,000				3,000
Transportation	Mars Ascent Vehicle (total wet mass)	MAV + tunnel +ISRU + cable = 20,000		18,016.30			18,016
		Unallocated Mass (kg)	**11**	**-**	**4**	**29**	**44**
		Number of Small, Dual-Hatch Logistics Modules:	**1**	**0**	**2**	**0**	**3**

Human Mars Landing Site Overview

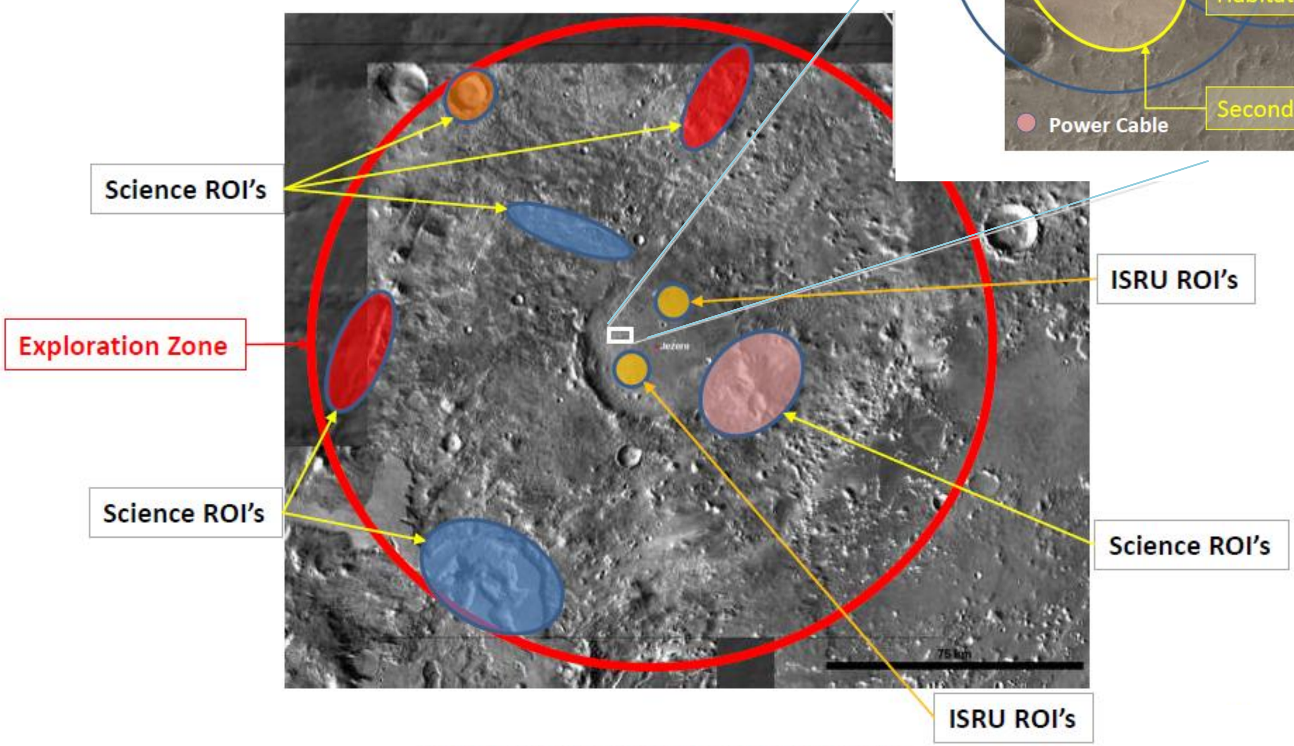
- Landing Site selected is near the center of an Exploration Zone of 200 km in diameter
  - First 3 missions will be focused on establishing support infrastructures for subsequent longer range exploration
  - Diameter based on expected capabilities of crewed pressurized rover extended excursions
  - 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)



Mars ISRU Concept of Operation (1)
Production of O_2 and CH_4 for MAV

- **Pre Human Mars Mission Landing**
  - Perform analysis of landing site using orbital data to preselect landing site locations
  - Perform analysis of landing site using orbital data to identify locations or prime interest for water resource extraction
  - Select landing locations and select sequence in which prime water resource locations will be evaluated; pre-plan traverses

- **Operating Approach for 1st Human Mars Surface Mission**
  - ISRU systems are deployed before crew arrives at Mars; no crew oversight or control
  - Communication time delay between Earth and Mars prohibits real-time control by Earth control centers; Data/operating parameters and decision are relayed back to Earth based on communication architecture (continuous vs batch data dumps)
  - Chemical Plant and Rover/Water Extraction System Operations are initiated by Earth but performed 'autonomously' through preplanned sequences with TBD levels of failure detection and failure recovery.
    - Preplanned stopping points or key operations may be incorporated into preplanned sequences for initiation or validation by control personnel on Earth
    - If failure or operating parameters exceed TBD failure recovery capabilities, the system will perform safe shutdown, relay data back to Earth, and await Earth control recovery

- **Lander 1 lands:**
  - Post landing safeing of propulsion systems
  - Deploy and activate the communication system
  - Verify and test of payload unloading system (Asset 2)
  - Unload Fission Surface Power System (FSPS) mobility system
  - Unload Site Evaluation/Science (SES) rover (Asset 5)

Mars ISRU Concept of Operation (2)
Production of O_2 and CH_4 for MAV

- **Lander 1 lands (Cont.):**
  - Charge FSPS mobility system (Asset 1)
  - Scout for potential FSPS sites with SES rover and make final selection (~1 sol)
  - Move, deploy, and start up FSPS, including cable runs (Asset 1, 2 & 3)
    - FSPS deployment and operation is a required activity
  - **Scout pre-identified sites for water resources and select site for processing (TBD sols)**
    - Start with highest priority site and work down in priority
    - Ops 2-1 Granular or Hard Hydrated Soils: Instruments include: TBD (cone penetrometer, microscopic imager, X-Ray Fluorescence, Neutron Spec/Gamma-Ray Spec, VIS/IR, ??)
    - Ops 2-2 Subsurface Ice: TBD (cone penetrometer, Ground Penetrating Radar, Neutron Spec/Gamma-Ray Spec, X-Ray Fluorescence, VIS/IR, ??)

- **Lander 2 lands:**

  Note: ISRU Chemical plant outlet already connected to MAV propellant tanks
  - Perform propulsion safing and communication system activation like Lander 1.
  - Deploy lander radiator
  - Attach cable on Lander 2 to nuclear reactors
  - Unload ISRU soil excavation and processing hardware from lander
    - Ops 2-1 Granular or Hard Hydrated Soils: Deploy soil excavation and transport unit(s) from Lander 1 or 2; soil processor for water extraction is on MAV Lander 2.
    - Ops 2-2 Subsurface Ice: Deploy drill, Rodwell unit, and 2 mobile water tanks from Lander 1 and/or 2; water delivered to ISRU Chemical Plant on MAV Lander

Mars ISRU Concept of Operation (3)
Production of O_2 and CH_4 for MAV

- **Deploy and Set-up ISRU Soil Excavation/Processing Assets:**
  - Transport ISRU soil excavation and processing hardware to selected resource site/area
  - Ops 2-1: Self-deploy soil excavation and transport unit(s); Units recharged at MAV lander
  - Ops 2-2: Use Asset 1 and 2 to deploy drill, Rodwell unit, 2 mobile water tank, and single FSPS nuclear reactor to site
    - Deploy Drill/Rodwell unit radiator
    - Attach cable from FSPS nuclear reactor to Drill/Rodwell unit
    - Attach 1 mobile water tank to Rodwell unit.

- **Start ISRU Operations:**
  - Checkout/verify hardware operation on MAV lander:
  - Checkout/verify deployed soil excavation/processing hardware
  - Begin Water Extraction Operations
  - Begin ISRU Chemical Plant operations to fill MAV O_2 and CH_4 tanks

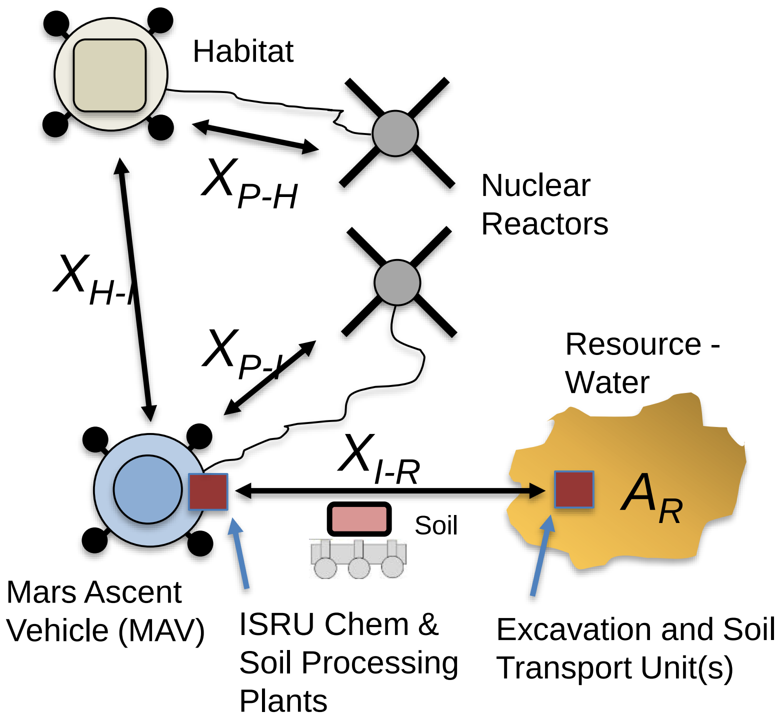
- **Post MAV Fill ISRU Operations (Options):**
  1. O_2 and CH_4 Maintenance and Failure recover (Requires low-power/rate operation mode)
  2. Fill Lander 3 descent tanks with O_2 and CH_4 for fuel cell power and/or life support backup
  3. Fill mobile Logistics Depot (new asset) with O_2, CH_4 and N_2.

- **Pre MAV Launch Operations:**
  - Isolate ISRU plant from MAV O_2 and CH_4 tanks
  - Disconnect feedline between ISRU plant and MAV O_2 and CH_4 tanks
  - Protect or remove ISRU plant hardware on Descent Module for future use or spare parts in subsequent missions

Mars ISRU Concept of Operation (4)

Production of O_2 and CH_4 for MAV

Option 2-1: O_2/CH_4 Production From Atmosphere & Hydrated Soils



X_{H-I} = >1 km

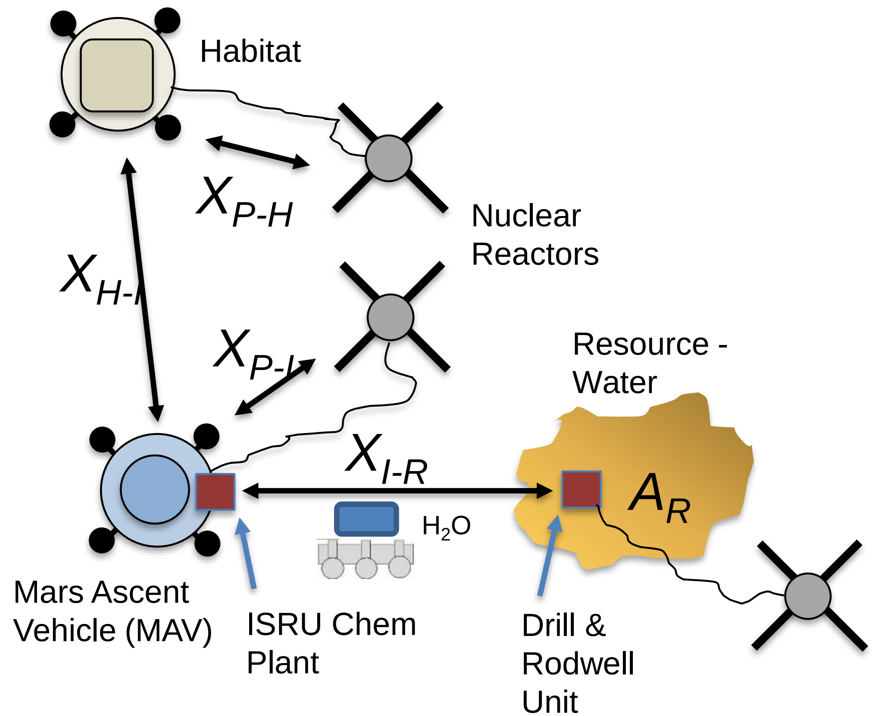
X_{P-I} = <1 km

X_{P-H} = <1 km

X_{I-R} = distance between ISRU Plant and Resource

A_R = Area of Resource

Option 2-2: O_2/CH_4 Production From Atmosphere & Subsurface Ice



X_{H-I} = >1 km

X_{P-I} = <1 km

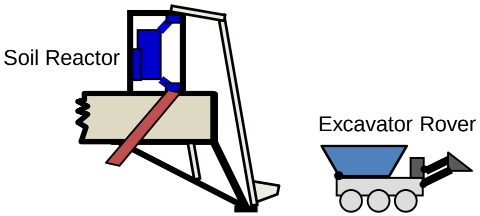
X_{P-H} = <1 km

X_{I-R} = distance between ISRU Plant and Resource

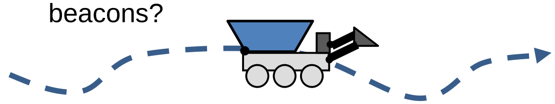
A_R = Area of Resource

Granular Hydrated Material Mining Operations

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

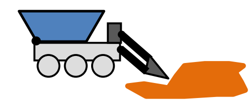


2. Excavator Rover Traverses to Excavation Site
   - Use route planned from Earth based on terrain/location map
   - Avoid obstacles and potentially other rovers during traverse
   - Autonomous operation; Use trail of beacons?

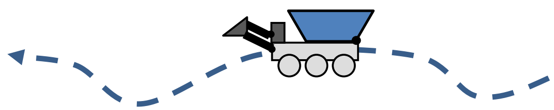


3. Excavator Rover Arrives at Excavation Site
   - Survey location to determine difference since last excavation to select excavation site (on-rover or LIDAR at site?)
   - Rover traverses to selected site

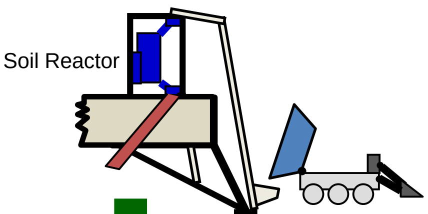
4. Excavator Rover Performs Excavation
   - Line up excavation device to exact point for excavation
   - Perform excavation; monitor forces on excavation device and wheel slippage to ensure proper excavation
   - Measure amount of soil excavated and loaded onto the rover



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?

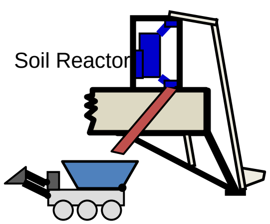


6. Excavator Rover Delivers Soil to Processor
   - Rover finds dumping soil bin
   - Rover lines up to dump soil
   - Rover dumps soil. Measure mass change to ensure soil has been delivered?

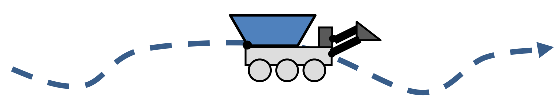


7a. Recharge Rover (if needed)
   - Rover finds charging port
   - Rover docks to charging port

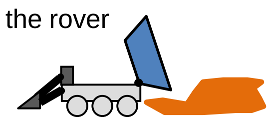
7b. Excavator Rover Receives Processed Soil
   - Rover finds dumping soil bin
   - Rover lines up to dump soil
   - Rover receives spent soil. Measure mass?



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?



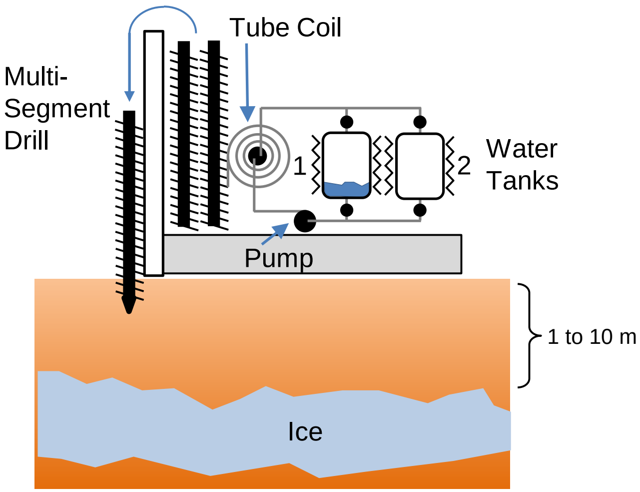
9. Excavator Rover Arrives at Dump Site
   - Survey location to determine difference since last dump to select dump site
   - Rover traverses to selected site
   - Line up dump device to exact point for dumping
   - Perform dumping
   - Measure amount of soil dumped from the rover



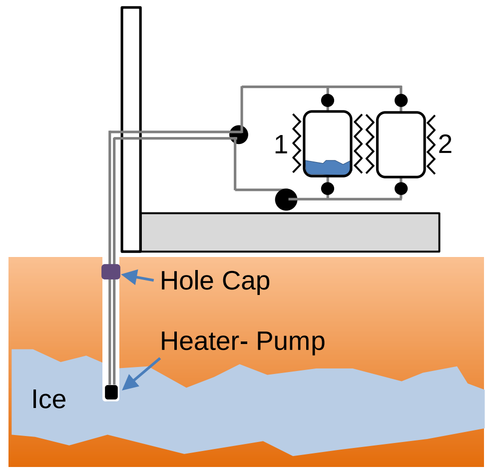
Return to Step 2

Subsurface Ice Mining Operations

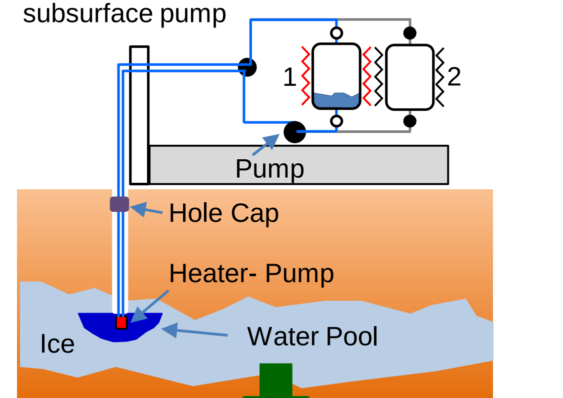
1. Drill through overburden into ice
   - Multi-segment drill from 1 to 10 m
   - Measure while drilling to evaluate when ice is met
   - Examine drill tailings or sensor on drill head for ice detection



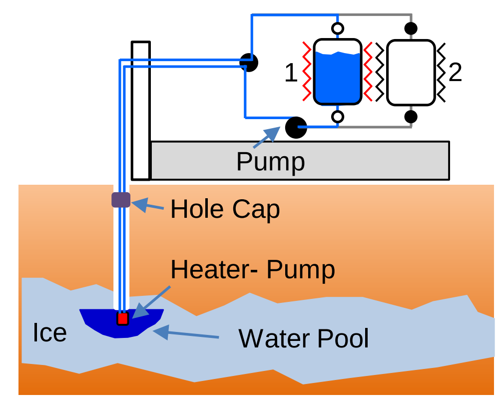
2. Establish tubing for water extraction
   - Lower tube with internal tubes for water flow down and up from Rodwell
   - End of tube includes downhole heater and water pump
   - Cap tube hole and tube (pneumatic) to seal chamber.



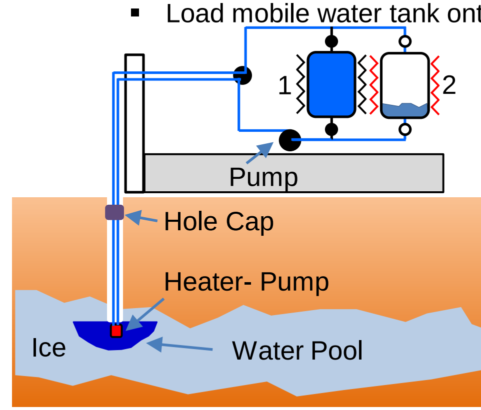
3. Begin water extraction from subsurface ice
   - Heat subsurface ice with downhole heater to begin subsurface water pool
   - Heat water from attached mobile water tank (precharged with amount to start ops) electrically or with thermal energy from FSPS
   - Begin flow of water from surface to subsurface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



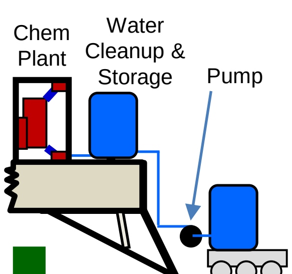
4. Continued water extraction
   - Continue extraction of water from subsurface pool into mobile water tank at balanced rate until



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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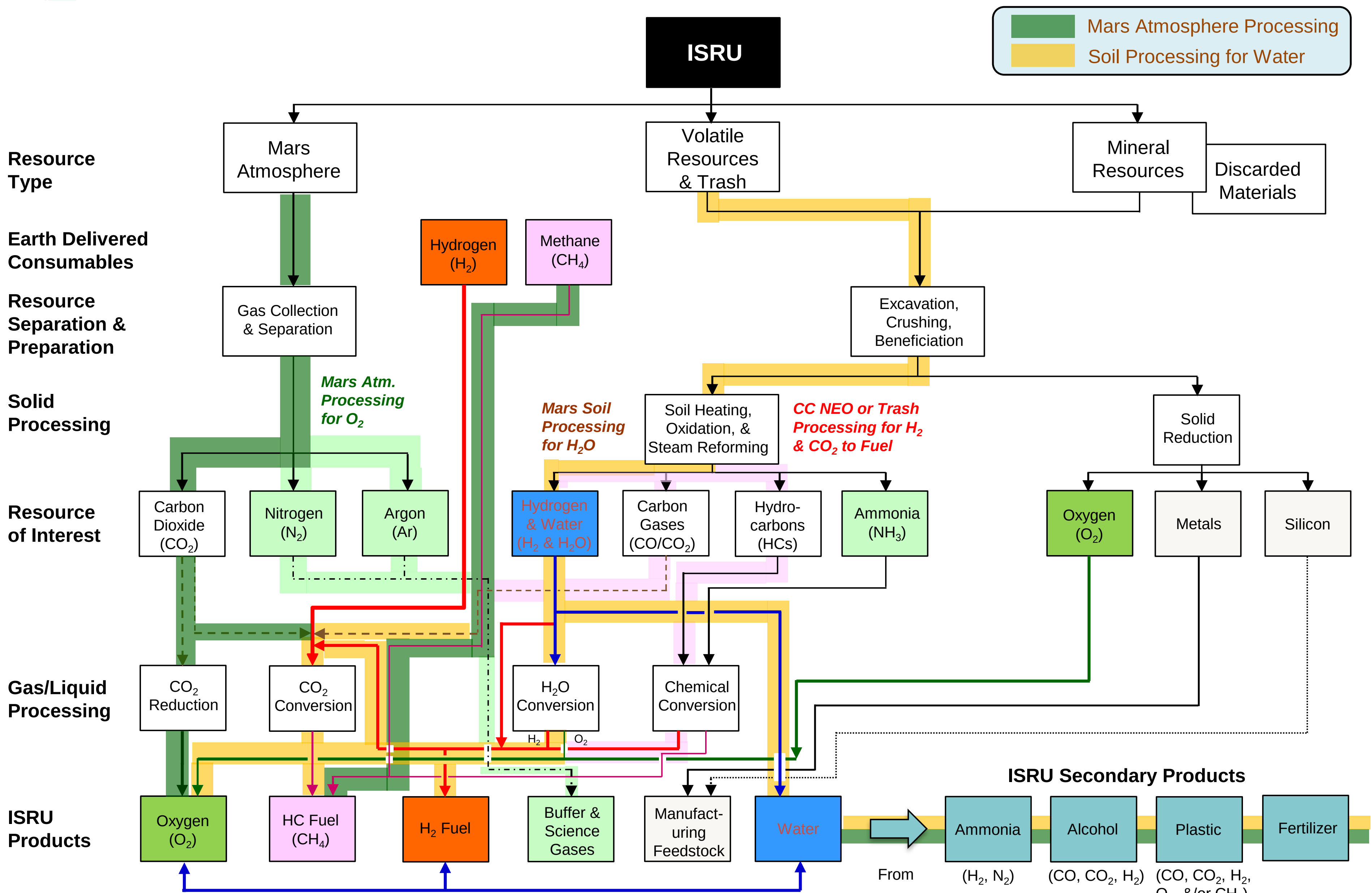
Current State of the Art for ISRU

ISRU Consumables Production Decision Tree



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The Chemistry of Mars ISRU

Oxygen (O_2) Production Only

Zirconia Solid Oxide CO_2 Electrolysis (SOE)

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

Reverse Water Gas Shift (RWGS)

$$CO_2 + H_2 \overset{400-650\,C}{\rightleftharpoons} CO + H_2O \quad \text{[catalyst]} \rightarrow H_2O \rightarrow \text{WE to } O_2$$

Bosch

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

Oxygen (O_2) & Methane (CH_4) Production

Sabatier Catalytic Reactor (SR)

$$CO_2 + 4\,H_2 \overset{200-300\,C}{\rightleftharpoons} CH_4 + 2\,H_2O \quad \text{[Ru catalyst]} \rightarrow H_2O, CH_4 \rightarrow \text{WE to } O_2$$

Methane Reformer

$$CO + 3\,H_2 \xrightarrow{250\,C} CH_4 + H_2O \quad \text{[Ni catalyst]} \rightarrow H_2O, CH_4 \rightarrow \text{WE to } O_2$$

Electrochemical Reduction

$$CO_2 + 2\,H_2O \rightarrow CH_4 + 2\,O_2 \quad \text{[Anode/Cathode]} \rightarrow O_2, CH_4$$

Other Hydrocarbon Fuel Production

Fischer-Tropsch (FT)

$$n\,CO + (2n+1)\,H_2 \xrightarrow{>150\,C} C_nH_{2n+2} + n\,H_2O \quad \text{[catalyst]} \rightarrow H_2O, C_nH_{2n+2} \rightarrow \text{WE to } O_2$$

Methanol

$$CO + 2\,H_2 \xrightarrow[50-100\,atm]{250\,C} CH_3OH \quad \text{[ZnO catalyst]} \rightarrow CH_3OH$$

$$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O \rightarrow H_2O, CH_3OH \rightarrow \text{WE to } O_2$$

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

Water Electrolysis (WE)

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

Steam Reforming

$$H_2O + CH_4 \rightarrow 3\,H_2 + CO \rightarrow 3\,H_2$$

Dry Reforming

$$CO_2 + CH_4 \rightarrow 2\,H_2 + 2\,CO \rightarrow 2\,H_2$$

2^{nd} Step

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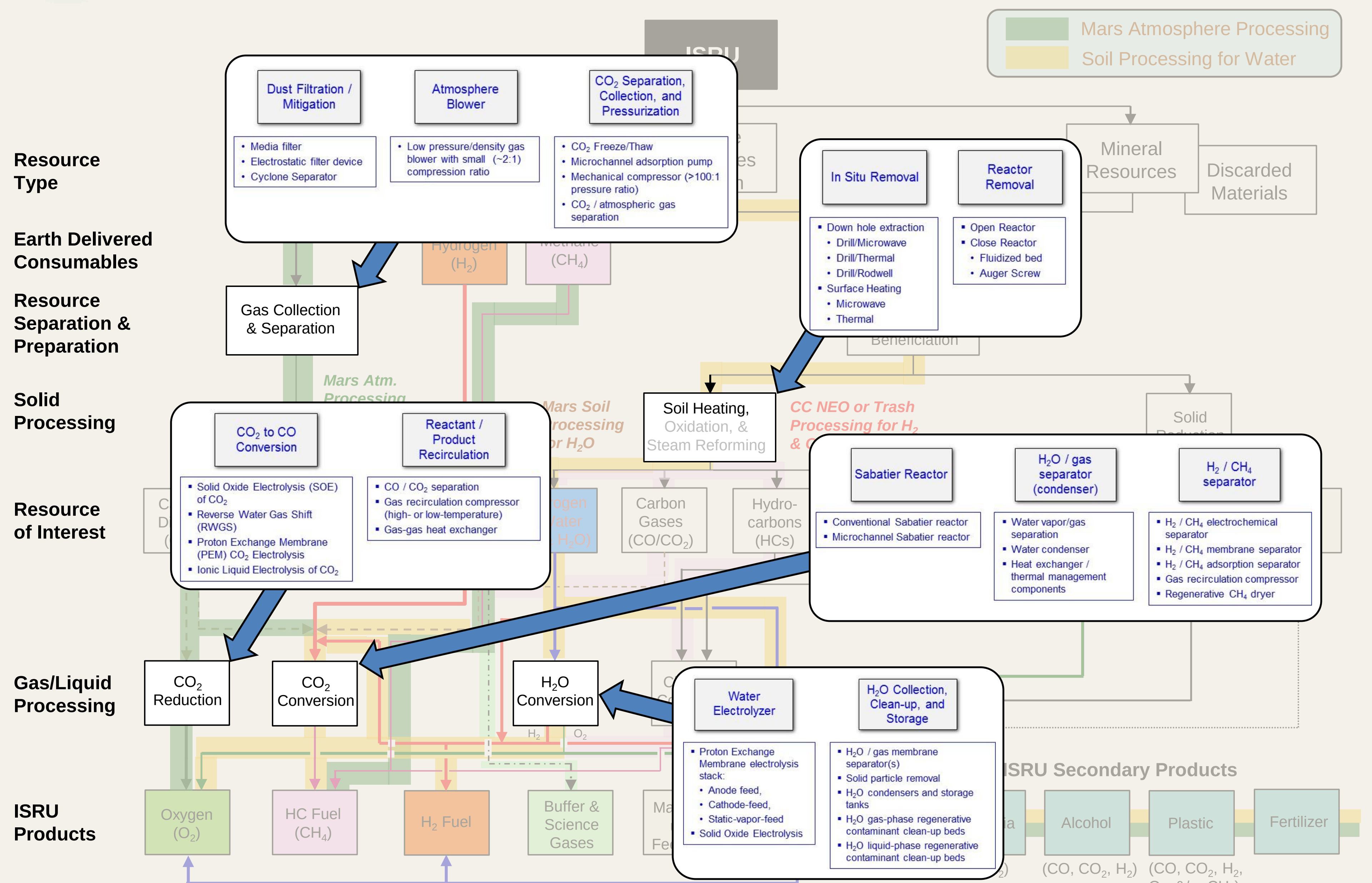
ISRU Consumables Production Decision Tree

Each Decision Has Technical Solution Options



Mars ISRU Propellant Production

Large Gap between Needs and Demonstrated

Needs

- **Propellant production for human mission ascent (Mars DRA 5.0)**
  - For O_2 only: 2.2 to 3.5 kg/hr O_2; 480 days or 300 days
  - For O_2/CH_4:
    - 0.55 to 0.88 kg/hr CH_4
    - 1.2 to 2.0 kg/hr H_2O; (41 to 66 kg/hr soil @ 3% H2O by mass)

- **Propellant production for Mars Sample Return**
  - 0.35 to 0.5 kg/hr O_2; 420 to 500 days (multiple studies)
  - 0.75 to 1.5 kg/hr O_2; 35 or 137 days (Mars Collaborative Study 4-2012)

- **Propellant production for Mars ISRU Demo**
  - 0.01 kg/hr O_2; 15 operations min. (MOXIE)
  - 0.00004 kg/hr O_2; 10 operations (MIP demo on Mars 2001 Surveyor)

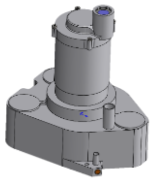
Demonstrated

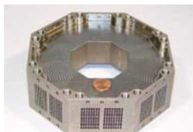
- **Mars ISRU Testbeds (late '90s early '00s):**
  - LMA/JSC Sabatier/Water Electrolysis: 0.02 kg/hr O_2; 0.01 kg/hr CH_4
  - KSC RWGS/Water Electrolysis 0.087 kg/hr O_2
  - Pioneer Astronautics (SWE & RWGS): 0.02 kg/hr O_2; 0.01 kg/hr CH_4
    (IMISPPS): 0.031 kg/hr O_2, 0.0088 kg/hr CH_4

- **Atmosphere Processing: MARCO POLO** (Individual subsystems)
  - CO_2 Collection: 0.088 kg/hr CO_2
  - CO_2 Processing: 0.066 kg/hr of O_2; 0.033 kg/hr of CH_4; 0.071 kg/hr of H_2O
  - Water Processing: 0.52 kg/hr H_2O; 0.46 kg/hr O_2

- **Soil Processing:**
  - Lunar H_2 Reduction - ROxygen Reactor: 5 to 10 kg/hr soil:
  - Lunar H_2 Reduction - PILOT Reactor: 4.5 to 6 kg/hr soil:
  - Mars Soil Auger - MISME: 0.18 to 0.2 kg/hr soil
  - Mars Soil Reactor-Pioneer Ast. Hot CO_2 4 kg/hr soil per batch

Past Mars ISRU Technology Development

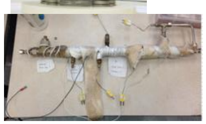






CO_2 Collection & Separation

- Mars dust filtration – filter, electrostatic, cyclone (GRC, KSC, JPL, SBIR)
- Mars atmosphere adsorption pump - Day/Night (LMA, JPL, ARC, JSC)
- Microchannel rapid-cycle adsorption pump (PNNL, SBIR)
- Mars atmosphere solidification (CO_2 freezing) pump (LM, SBIR, KSC)
- Mars atmosphere compressor (MOXIE/SBIR)
- Ionic liquids adsorption/electrochemistry (MSFC, SBIRs)




CO_2 Processing

- Solid Oxide CO_2 Electrolysis (NASA, Universities, Industry, SBIRs)
- Low pressure CO_2 Glow/Plasma Dissociation (Universities)
- Reverse Water Gas Shift (KSC, PNNL, SBIRs)
- Sabatier reactors (NASA, Industry, SBIRs)
- Bosch/Boudouard reactors – MSFC, KSC, Industry, Univ., SBIRs
- Methane reformer (JPL, SBIRs)
- Hydrocarbon fuel reactors - methanol, toluene, ethylene, etc. (SBIRs)
- Microchannel chemical reactors/heat exchangers (PNNL, SBIRs)
- ElectrolysisCo-Production O_2/Fuel – PEM and Ionic Liquids (MSFC/KSC, SBIRs)


Water Processing

- Water electrolysis/decomposition (NASA, Industry, SBIRs)
- PEM-High and Low Pressure & Solid Oxide (NASA, Industry, SBIRs)
- Water separation/collection – membrane & cooling (NASA, Industry)

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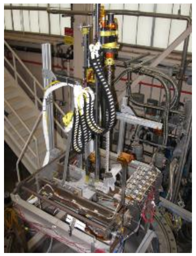
Past Mars-Relevant ISRU Technology Development

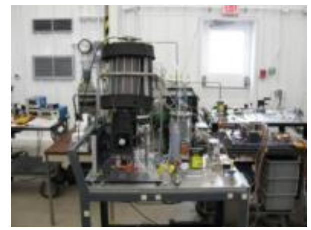
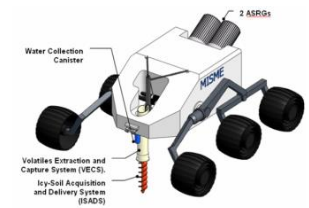




Soil Acquisition and Excavation

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

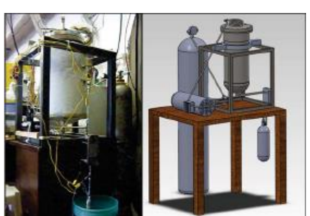





Soil Processing

- H_2 Reduction of regolith reactors (NASA, LMA)
- Microwave soil processing (MSFC, JPL, SBIR)
- Open and closed Mars soil processing reactors (JSC, GRC, SBIRs)
- Downhole soil processing (MSFC, SBIRs)
- Capture for lunar/Mars soil processing (NASA, SBIRs)
- Water cleanup for lunar/Mars soil processing (KSC, JSC, SBIRs)



Trash/Waste Processing into Gases/Water

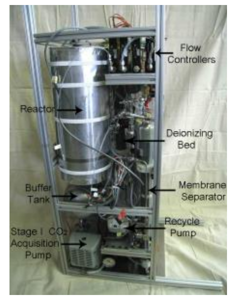
- Combustion, Pyrolysis, Oxidation/Steam Reforming (GRC, KSC, SBIRs)

Past Mars ISRU System Development

Mars Atmosphere Processing

- 1st Gen Sabatier/Water Electrolysis (SWE) breadboard under ambient & Mars environment testing in late '90s/early 00's (NASA, Lockheed Martin)
- 1st Generation Reverse Water Gas Shift with and w/o Fuel production (NASA, Pioneer Astronautics)

Sabatier/Water Electrolysis w/ CO_2 Absorption (LMA & JSC) *[Tested under simulate Mars surface conditions]*

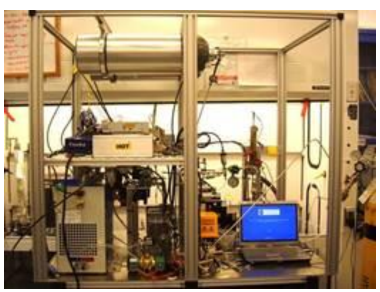


Combined Sabatier/ RWGS/Water Electrolysis (Pioneer Ast.)

CO_2 Electrolysis (GRC) *[Tested under conference conditions]*

Reverse Water Gas Shift/ Water Electrolysis (KSC & Pioneer Astrobotics)

- 2nd Gen MARCO POLO atmosphere processing (JSC, KSC)



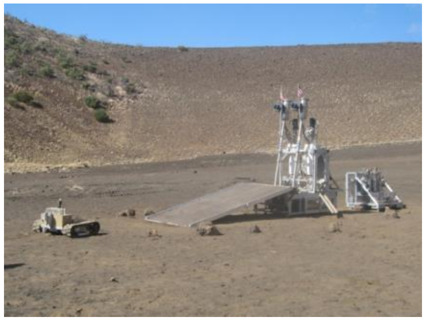
Atm Processing Module
0.088 kg/hr CO_2
0.033 kg/hr CH_4
0.071 kg/hr H_2O

Water Processing Module
0.52 kg/hr H_2O
0.46 kg/hr O_2
0.058 kg/hr H_2

Past Mars-Relevant ISRU System Development

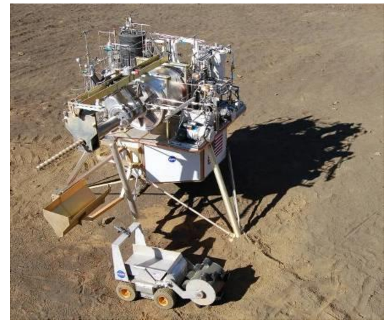
Lunar/Mars Soil Processing

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

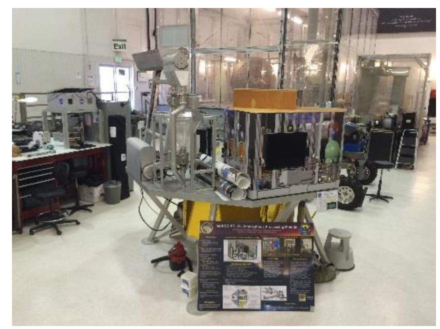


ROxygen H_2 Reduction
Water Electrolysis
Cratos Excavator

PILOT H_2 Reduction
Water Electrolysis
Bucketdrum Excavator



- 2nd Gen MARCO POLO soil processing system (JSC, KSC)



Soil Processing Module
10kg per batch; 5 kg/hr
0.15 kg/hr H_2O
(3% water by mass)

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ISRU Development & Missions

ISRU Related Development within NASA

ISRU

Resource Assessment/ Prospecting
- 1.1 Site Imaging/ Characterization
- 1.2 Physical Property Evaluation
- 1.3 Atmosphere/Gas Resource Evaluation
- 1.4 Mineral/Chemical Resource Evaluation
- 1.5 Volatile Resource Evaluation
- 1.6 Data Fusion, Analysis, Mapping & Monitoring

TRL 1-3 / TRL 4-6 / Flight Dev

Moon / Mars / NEAs

Resource Acquisition
- 2.1 In Situ Atmosphere/Gas Resources
- 2.2 Planetary Material Resources
- 2.3 Discarded Material/Trash Resources

TRL 1-3 / TRL 4-6 / Flight Dev

Mars / NEAs

Resource Processing/ Consumables
- 3.1 Extract/Produce Oxygen
- 3.2 Extract/Produce Fuel
- 3.3 Extract/Produce Water
- 3.4 Extract/Separate Gases for Life support/Science
- 3.5 Extract/Produce Manufacturing Feedstock
- 3.6 Extract/Produce Construction Feedstock
- 3.7 Extract/Produce Food Production Feedstock

TRL 1-3 / TRL 4-6 / Flight Dev

Moon / Mars

In Situ Construction
- 4.1 Area Clearing, Landing Pads, Roads
- 4.2 Excavation - Berms, Trenches, Burial
- 4.3 Structure/ Habitat Construction
- 4.4 Shielding Construction

TRL 1-3

Moon / Mars

Manufacturing with ISRU Feedstock
- 5.1 Manufacturing with *In Situ* Regolith/ Metal/Silicon
- 5.2 Manufacturing with *In Situ* derived Plastics
- 5.3 Manufacturing with *In Situ* Produced Ceramics
- 5.4 Manufacturing with Recovered/Recycled /Repurposed Materials

TRL 1-3 / TRL 4-6 / Flight Dev

Moon / Mars / ISS

In Situ Energy
- 6.1 Use of *In Situ* Material for Thermal Energy Storage
- 6.2 Use of *In Situ* Material for Electrical Energy Storage
- 6.3 *In Situ* Solar Array Production

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Where Does ISRU Work Reside in NASA?

NASA Headquarters

Human Exploration & Operations Mission Directorate

Advanced Exploration Systems Division

- ISRU Technology
- MOXIE
- Resource Prospector
- Lander Technology
- Logistics Reduction
- Synthetic Biology
- In-Space Manufacturing

- Autonomous Systems & Operations
- Modular Power Systems
- Life Support Systems
- Avionics and Software

MOXIE = Mars Oxygen ISRU Experiment

Space Technology Mission Directorate

STRG Office

- SBIR/STTR
- NSTRF/ECF/ESI
- STRI
- CIF

Game Changing Division

- ISRU
- MOXIE
- Advanced Manufacturing

- Robotics
- Power and Energy Storage
- Advanced Manufacturing

STRG = Space Technology Research Grants
SBIR = Small Business Innovation Research
STTR = Small Business Technology Transfer
NSTRF = NASA Space Technology Research Fellowships
ESC = Early Career Fellowship
ESI = Early Stage Initiative
CIF = Center Innovation Fund

Science Mission Directorate

- ROSES

Planetary Science Division

- Mars 2020

- PICASSO
- MatISSE
- SSERVI
- Orbital and surface missions

STRI = Space Technology Research Institute
ROSES = Research Opportunities in Space and Earth Sciences
PICASSO = Planetary Instrument Concepts for the Advancement of Solar System Observations
MatISSE = Maturation of Instruments for Solar System Exploration
SSERVI = Solar System Exploration Research Virtual Institute

Where Does ISRU-Related Work Reside in NASA?
- Projects/Programs, TRL, & Destination

TRL 1-3 · TRL 4-6 · Flight Dev · Moon · Mars · NEA · ISS

ISRU

- Resource Assessment/ Prospecting
- Resource Acquisition
- Resource Processing/ Consumables
- *In Situ* Construction
- Manufacturing with ISRU Feedstock
- *In Situ* Energy

Human Exploration and Operations Mission Directorate (HEOMD)

- Resource Prospector
- Cubesats

- ISRU Technology
- MOXIE

- ISRU Technology
- MOXIE
- Logistics Reduction
- Synthetic Biology

- Synthetic Biology

- In Space Manufacturing

Space Technology Mission Directorate (STMD)

- ISRU
- MOXIE
- SBIR/STTR
- NSTRF/ECF/ESI
- CIF
- STRI-CUBES

- ISRU
- MOXIE
- SBIR/STTR
- NSTRF/ECF/ESI
- CIF
- STRI-CUBES

- ACME
- SBIR/STTR
- 3D-Printed Habitat Challenge
- CIF
- STRI-CUBES

- CO_2-Li Battery

Science Mission Directorate

- ROSES
- SSERVI
- Surface Missions: Moon, Mars, NEAs

- ROSES

ISRU Capabilities Requires Information and Hardware from Other Projects

ISRU

- **Resource Assessment/ Prospecting**
- **Resource Acquisition**
- **Resource Processing/ Consumables**
- ***In Situ* Construction**
- **Manufacturing with ISRU Feedstock**
- ***In Situ* Energy**

Human Exploration and Operations Mission Directorate (HEOMD)

- Life Support Systems
- Life Support Systems
- Lander Technology

- Modular Power Systems
- Autonomous Systems & Operations
- Avionics and Software

Space Technology Mission Directorate (STMD)

- Propulsion (Cryo)
- Adv. Manufacturing Technology
- Lightweight Structures and Manufacturing

- Autonomy and Space Robotic Systems
- Solar Array with Storage

Science Mission Directorate

- Science Instruments & Data
- Sample Acquisition
- Resource Physical Data
- Resource Physical, Mineral, & Volatile Data
- Resource Physical & Mineral Data
- Resource Physical & Mineral Data

ISRU State-of-the-Art: Resource Acquisition, Processing, Consumables Production

- Significant work has been performed to demonstrate feasibility of ISRU concepts and develop components and technologies (TRL 1-4)
  - Mars atmosphere collection, separation, and processing into O_2 or O_2/CH_4
  - Lunar regolith excavation, beneficiation, and processing to extract O_2
  - Civil engineering/soil stabilization

- Some development & testing has been performed at the system level (TRL 4-6)
  - **Moon** (Lab, Analog sites)
    - Regolith and Environment Science & Oxygen and Lunar Volatiles Extraction (RESOLVE)
    - Precursor ISRU Lunar Oxygen Testbed (PILOT) and ROxygen
  - **Mars** (Lab, Environment)
    - Portable Mars Production Plant (early '90s),
    - Mars Sabatier/Water Electrolysis System (Mars environmental chamber in 2000)
    - Mars In-situ Propellant Precursor (MIP) (flight experiment for cancelled Mars 2001 mission)
    - Mars Oxygen ISRU Experiment (MOXIE) scheduled to fly on Mars 2020 mission

- However, **<u>significant work is needed to mature these technologies</u>**
  - Develop & test much closer to full-scale for human mission needs
  - Demonstrate much longer operational durations
  - Validate performance under relevant environmental conditions
  - Demonstrate integration and operation between the many components and subsystems that comprise an ISRU system
  - Realize synergy between ISRU and other exploration elements such as propulsion, life support, power, surface mobility, thermal management, etc.

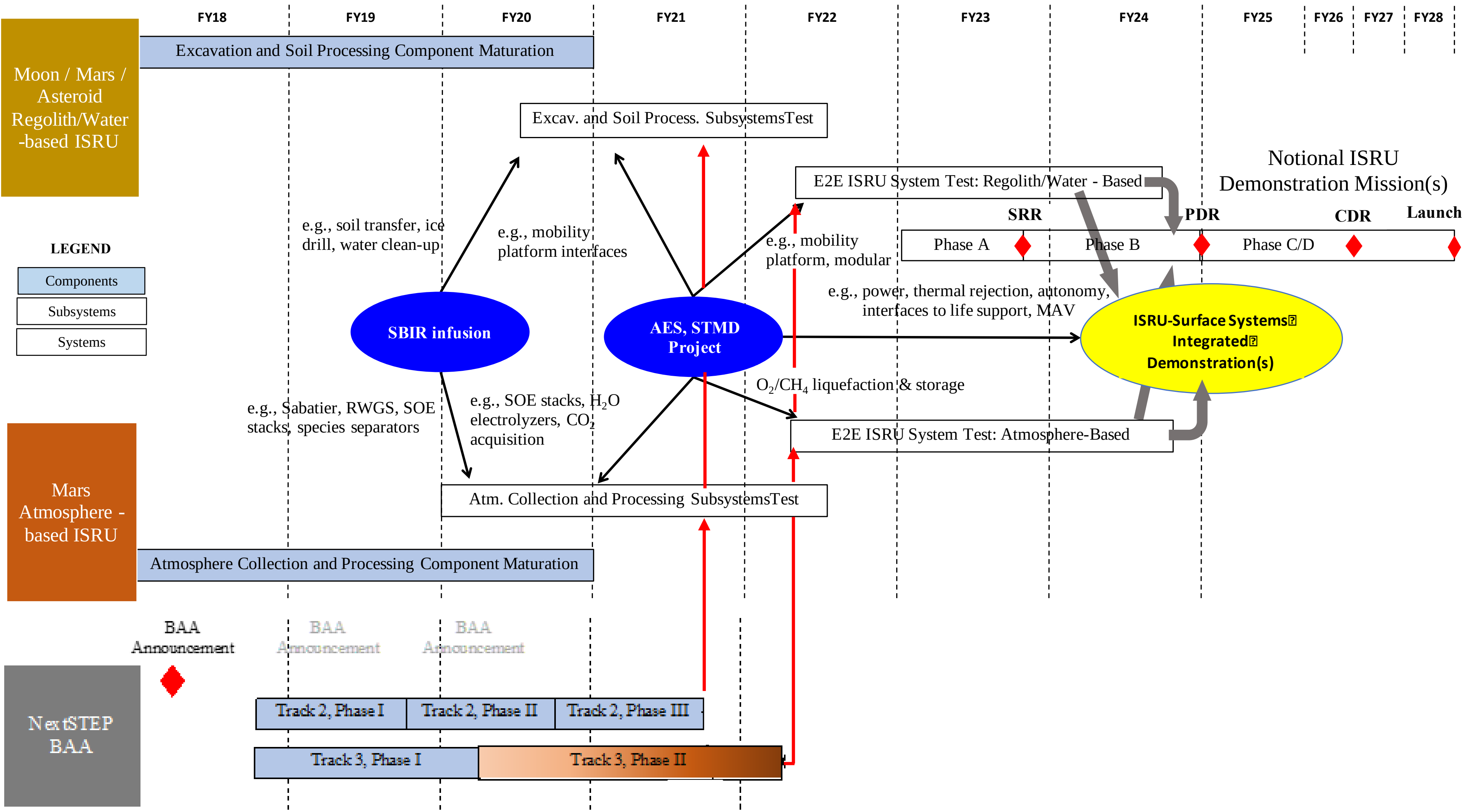
- **Scope: Develop the component, subsystem, and system technology to enable production of mission consumables from regolith and atmospheric resources at a variety of destinations**
  - Initial focus
    - Critical technology gap closure
    - Component development in relevant environment (TRL 5)
  - 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 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

ISRU Technology Project Schedule



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ISRU Product/Resource Processing Options Under Consideration

Oxygen/Fuel Production from Mars Atmosphere

Atmosphere Collection
- Dust Filtration
- Gas Separation (CO_2,N_2, Ar)
- Gas Pressurization (0.1 to >15 psia)
  - Pumps/Compressors
  - Cryogenic Separation
  - Adsorption

Chemical Processing
- CO_2 Reduction
  - Solid Oxide Electrolysis
  - Reverse Water Gas Shift
  - Ionic Liquid/PEM Electrolysis
- Fuel Production
  - Sabatier (CH_4)
  - Fischer Tropsch
  - Alcohols
  - Ethylene → Plastics
- Water Processing
  - Water Electrolysis (PEM vs SOE)
  - Water Cleanup/Deionization

Water/Volatile Extraction From Soils

Solid Extraction and Transport
- Granular Soil Excavation/Extraction →
  - Drills/Augers (1 to 3 m)
  - Load/Haul/Dump (LHD)
  - Bucket Wheels/Drums
- Consolidated Material Extraction & Preparation →
  - Drills/Augers
  - Percussive Blades
  - Ripper & LHD
  - Crushing & Sorting
- Material Transfer →
  - Augers
  - Pneumatic
  - Bucket ladders

Water/Volatile Extraction
- Hydrated soils
  - Open Reactor/Heating
  - Closed Fluidized Reactor
  - Auger Dryer
- Icy soils
  - Transport to Reactor
  - Downhole Enclosure
  - Downhole Heating & Removal

Oxygen Extraction from Minerals

Oxygen Extraction from Minerals
- Hydrogen Reduction of Iron Oxides
- Methane Reduction of Silicates
- Molten Oxide Reduction

Metal Extraction from Minerals

Metal Extraction from Minerals
- Molten Oxide Reduction
- Molten Salt Reduction
- Ionic Liquids/Acids
- Biological Extraction

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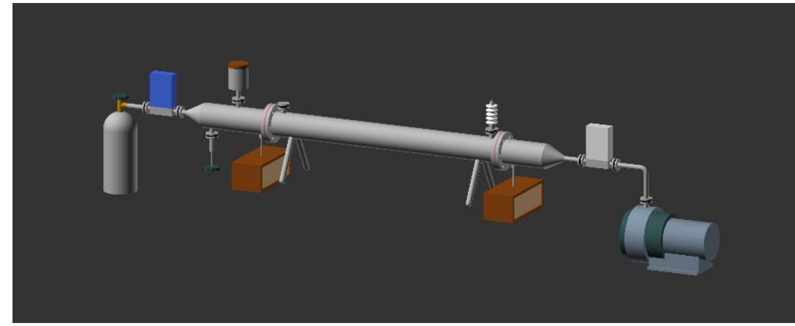
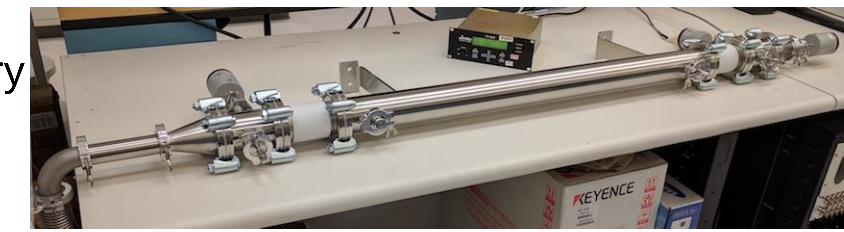
Resource Acquisition – Dust Filtration / Mitigation

- **Electrostatic precipitator (STMD)**
  - Assembling components for 2nd generation flow-through precipitator prototype
    - Can vary diameter with three interchangeable tubes (80, 100, 160 mm)
    - Will investigate varying inner electrode diameter (wires to rods) and different electrode materials
  - Physics-based model to optimize geometry
    - Modeling equations of motion of particles entering device
- **Media filter**
  - Physics-based model for scroll media filter
  - Use existing data for validation
    - Mars flow loop, MOXIE
  - Working with MOXIE team for filter analysis and dust loading measurement technique
  - Designing full-scale media filter component for fabrication and testing in FY18



Electrostatic Precipitator Design



Initial set-up of electrostatic precipitator in a flow-through test

Scroll filter designed for Space Station

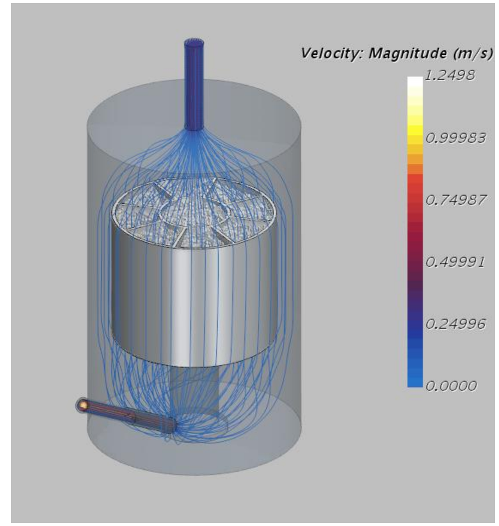
Resource Acquisition – CO_2 Compression

CO_2 Freezer Pump

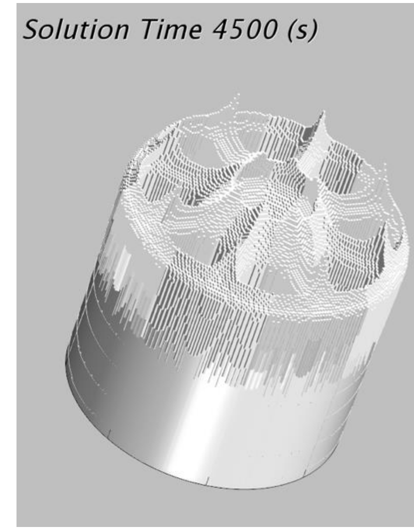
- **Analyzing different cold head designs**
  - Finite element modeling of flow and freezing
    - Compare to existing experimental data and iterate
  - Predicted CO_2 solid mass matches experimental results
- **Three 'ferris wheel' copper cold heads fabricated for testing**

Rapid Cycle Adsorption Pump

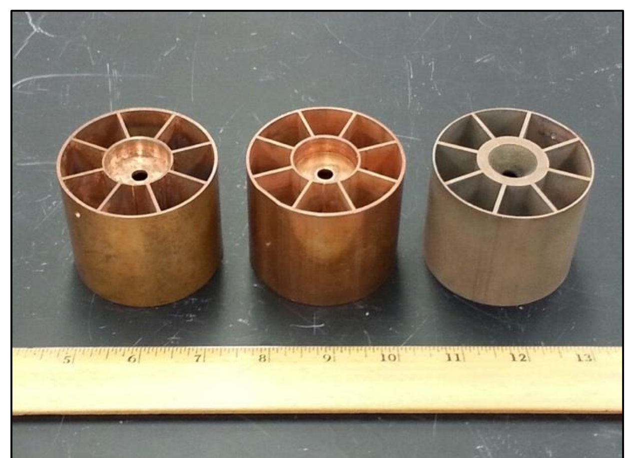
- **Developing Thermal Desktop / Sinda / Fluint model of microchannel rapid cycle sorption pump**
  - Sorbent (Zeolite 13X baseline) is contained in meso-channels
  - Fluid layers for rapid heating/cooling of adsorbent in microchannels
- **Addressing modeling / knowledge gaps to simulant Thermal-Swing Adsorption pump**
  - Toth and Langmuir 3-site isotherms coded into Sinda / Fluint
    - Adsorption rate, or kinetics, depend mostly on the isotherm
- **Design and analysis of realistic system for efficiently cycling temperature of adsorbent in 2 to 6 minute cycles**



Gas flow streamlines around cold head



CO_2 solid on cold head



Three 'ferris wheel' copper cold heads for testing; one on right is 3D printed out of GRCop-84

Resource Acquisition – Excavation

- **Excavation modeling**
  - Update lunar excavation models to include excavation of different resource types
    - Mars low-water-content loose surface regolith
    - Mars hydrated minerals
    - Icy soils at Moon and Mars
    - Deep ice deposits on Mars
  - Validate with existing data and new data when available
- **Excavator design and architecture**
  - Use models to evaluate proposed excavation concepts and generate new concepts for mission architecture
  - Design, build, and test new and existing excavator concepts and test in relevant environment

Centaur 2 w/ APEX positioning of Badger percussive bucket

Excavation force determination with soil surface 3D measurement using structured light stereography

RASSOR (Regolith Advanced Surface Systems Operations Robot) excavator delivering loose soils

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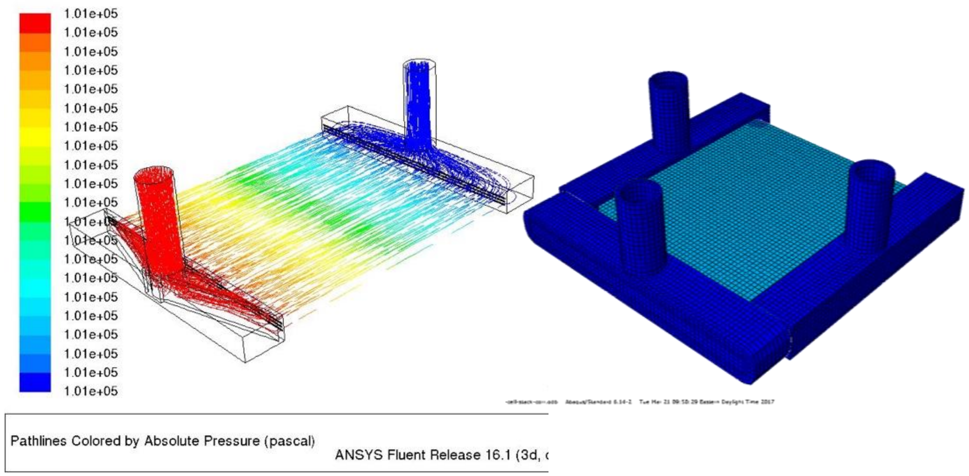
Resource Processing / Consumable Production

Solid Oxide Electrolysis (SOE) of CO_2

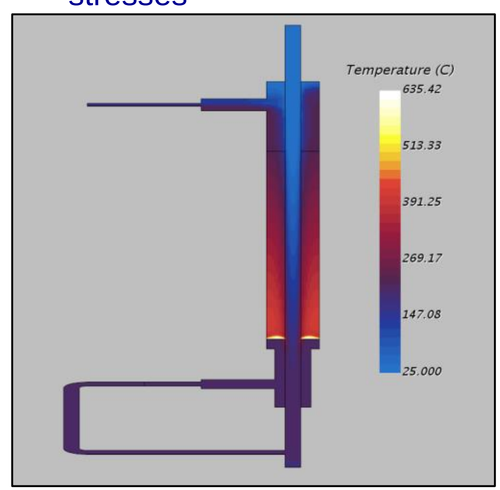
- **Baseline SOE stack and insulation model**
  - Gathering data for validation and improvements
  - Expanding and reformatting SOE physics-based performance model
  - Thermal insulation design model
- **GRC bi-supported cell fluid & mech. model**
  - Evaluate different manifold designs to improve gas distribution through stack
  - Identify stress points caused by thermal loads
  - Recommend design modifications to relieve critical stresses
  - Method will be applied to other SOE designs
- **SOE stack scaling limitations**
  - Use models to predict limits of active area per cell, # cells per stack

Sabatier Reactor for CH_4 Production

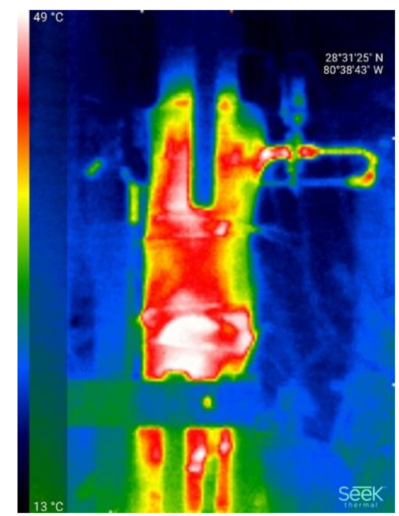
- **Sabatier reactor analytical model**
- **Reviewing state-of-the-art of conventional and microchannel reactor designs**
- **Catalyst pellets life investigation**
  - Analyze new and used catalyst pellets and identify nature of changes over time
  - Guide assessment of longevity/life challenges



Fluid and mechanical modeling of GRC bi-supported 3-cell stack. (left) pathlines colored by pressure; (right) mechanical stresses



Sabatier reactor thermal CFD model



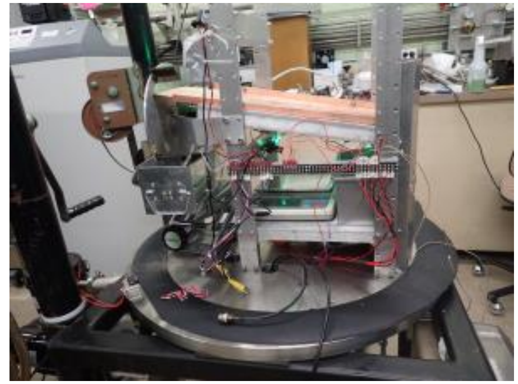
Thermal camera image of Sabatier reactor during operation.

Resource Processing / Consumable Production

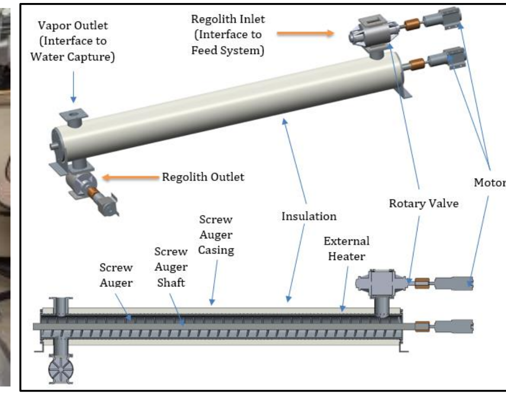
Open Reactor Concept
- **Open 'air' dryer concept testing completed at GRC**
  - Bucket wheel deposits soil on vibrating, heated plate
  - Fan blows Mars atmosphere over plate and sweeps liberated moisture into condenser
- **Tested with hydrated mineral, sodium tetraborate decahydrate (Borax), mixed in with GRC-3 simulant**
- **Physics-based model development**

Closed Reactor Concept
- **Auger-dryer concept based on terrestrial hardware**
  - Physics-based model to assess operation in Mars or lunar environment
- **Mars auger-dryer extraction hardware design**
  - Hardware to be tested in Mars environment chamber

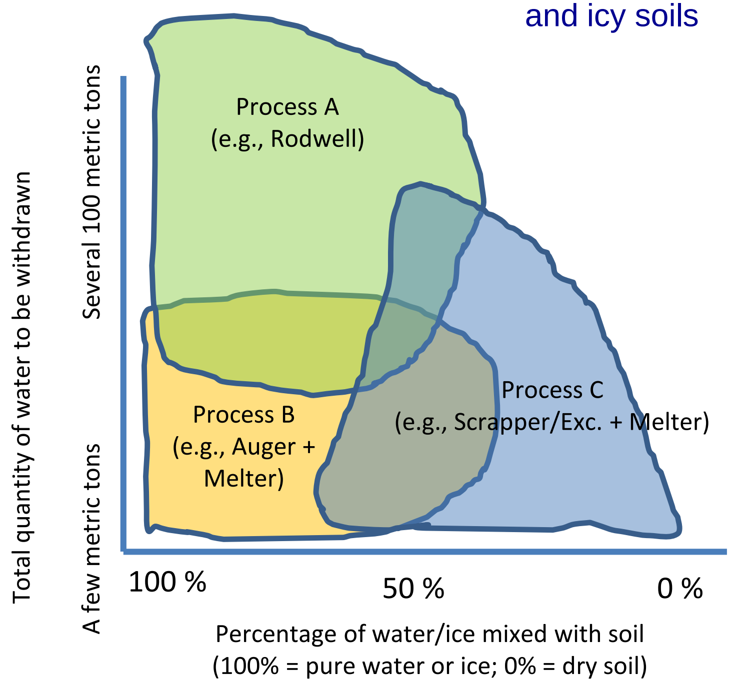
In-Situ Extraction Concepts
- **In-situ extraction modeling**
  - Extract the product at the resource location (process raw resource (ice) in place)
  - Working with analytical model developed for "Rodwell" on Earth to determine applicability to Mars (ice/soil mixtures, processing rates)



Open 'air' dryer at NASA GRC



Terrestrial auger soil dryer to be modeled for application to Mars and Lunar hydrated and icy soils



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In-Space Manufacturing (AES/GCD ISM Project)

- **In-Space Manufacturing & Repair Technologies**
  - What: Work with industry and academia to develop on-demand manufacturing and repair technologies for in-space applications.
    - Two polymer printers currently on ISS' Solicitation for 1st Gen. Multi-material 'FabLab' Rack capable of metallic and electronic manufacturing in-space released
  - ISRU relevance: These capabilities can use regolith and other in-situ materials for manufacturing & repair.
- **In-Space Recycling & Reuse**
  - What: Develop recycling capabilities to increase mission sustainability.
    - The Refabricator (integrated 3D Printer/Recycler) Tech. Demo. launching to ISS in early 2018.
  - ISRU relevance: In-situ materials and products can be recycled for reuse.
- **In-Space Manufacturing Design Database**
  - What: ISM is working with Exploration System Designers to develop the ISM database of parts/systems to be manufactured on spaceflight missions.
    - Includes material, verification, and design data. Information will be exported into Utilization Catalogue of parts for crew.
  - ISRU relevance: Database to include parts/systems manufactured using in-situ materials.

Additive Manufacturing Facility (AMF) on ISS developed via SBIRs with Made in Space, Inc.

ISS Refabricator (integrated 3D Printer/Recycler) developed via SBIRs with Tethers Unlimited, Inc.

CT Scan (right) of compression cylinder manufactured on ISS (left).

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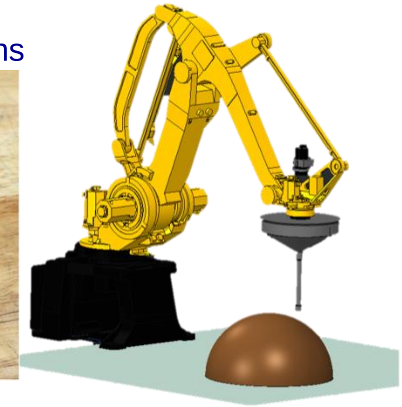
Additive Construction with Mobile Emplacement (ACME)
Automated Construction for Expeditionary Structures (ACES)

- **Additive Construction with Mobile Emplacement (ACME) (NASA STMD GCD)**
  - 2D and 3D printing on a large (structure) scale
    - Use in-situ resources as construction materials to help enable on-location surface exploration
  - Demonstrated fabrication of construction material using regolith simulant and multiple binders (polymers, cements)
  - Developing zero launch mass (ZLM) print head to extrude a mixture of regolith simulant and high density polyethylene through a heated nozzle
  - Use existing NASA GCD robots to position and follow tool paths with regolith print head end effector
- **Automated Construction for Expeditionary Structures (ACES) (U.S. Army Corps of Engineers)**
  - 3D print large structures to support deployment in remote areas
  - Dry Goods Delivery System provides continuous feedstock from in-situ materials
  - Liquid Goods Delivery System provides continuous flow of liquids/binders
  - Continuous Feedstock Mixing Delivery Subsystem combines all ‘ingredients’ and performs printing of structure

Standard 2-inch cube compression test specimens



ZLM print head demo illustration

3D print 32’ x 16’ x 8’ barracks with locally sourced concrete, within 48 hrs of deployment

Dry Goods Delivery System

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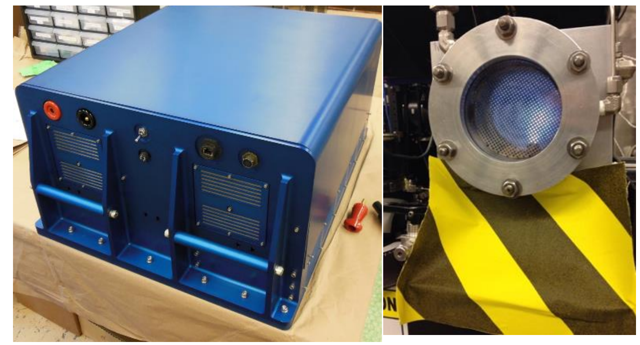
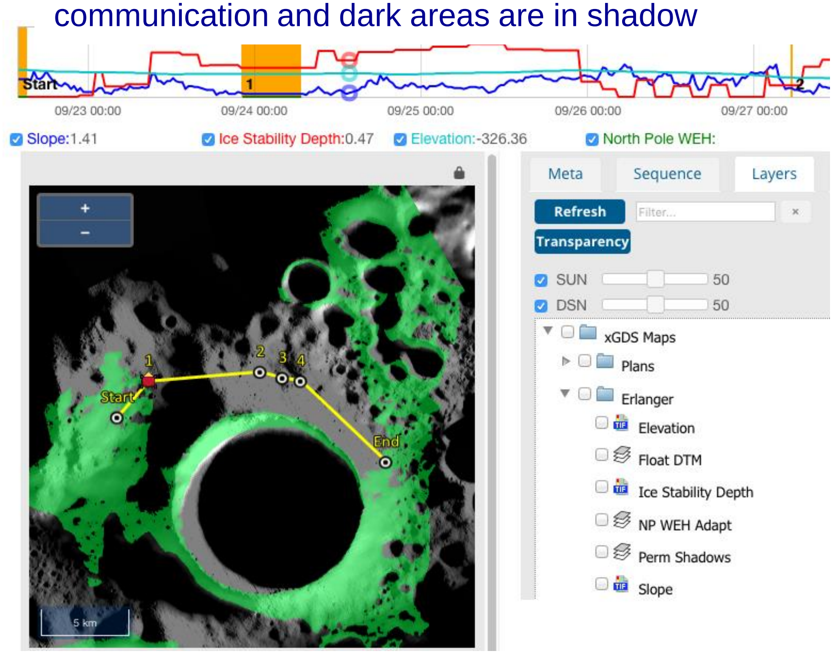
Autonomy (AES Autonomous Systems and Operations Project)

- **Autonomous Robotic Operations Planning**
  - What: Enhance existing tools for use during in-transit, orbital crewed missions
    - Fixed-based kinematics path-planning
  - ISRU relevance: Excavation and soil transport
- **Vehicle Systems Automation**
  - What: Integrate health management, scheduling and execution across vehicle systems
    - Ties together power and life support operations constraints
  - ISRU relevance: ISRU Sabatier and other components of processing plant
- **Robotic Mission Planning**
  - What: Mixed-initiative system that integrates traverse planning and activity planning
    - Planning with temporal, spatial, and spatial-temporal constraints
    - Managing duration uncertainty
  - ISRU relevance: excavation and soil transport

Vehicle Systems Automation: testing autonomy components integrated with flight software to operate hardware comparable to that needed for ISRU.



Robotic Mission Planning: Sunlight and communication layers in traverse planner; green areas have communication and dark areas are in shadow

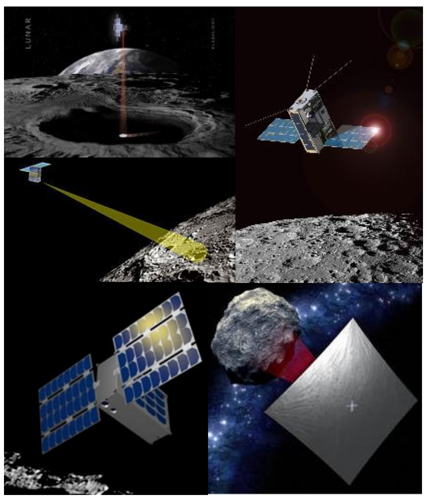


Current NASA ISRU Missions Under Development

Resource Prospector – RESOLVE Payload

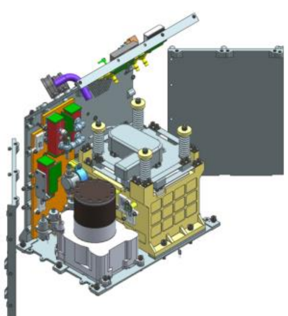
- Measure water (H_2O): Neutron spec, IR spec., GC/MS
- Measure volatiles – H_2, CO, CO_2, NH_3, CH_4, H_2S: GC/MS
- Possible mission in 2020

Cubesats (SLS EM-1 2018)



- Lunar Flashlight: Uses a Near IR laser and spectrometer to look into shadowed craters for volatiles
- Lunar IceCube: Carries the Broadband InfraRed Compact High Resolution Explorer Spectrometer (BIRCHES)

  LunaH-MAP: Carries two neutron spectrometers to produce maps of near-surface hydrogen (H)
- Skyfire: Uses spectroscopy and thermography for surface characterization
- NEA Scout: Uses a science-grade multispectral camera to learn about NEA rotation, regional morphology, regolith properties, spectral class



Mars 2020 ISRU Demo

- Make O_2 from Atm. CO_2: ~0.01 kg/hr O_2; 600 to 1000 W-hrs; 15 sols of operation
- Scroll Compressor and Solid Oxide Electrolysis technologies
- Payload on Mars 2020 rover

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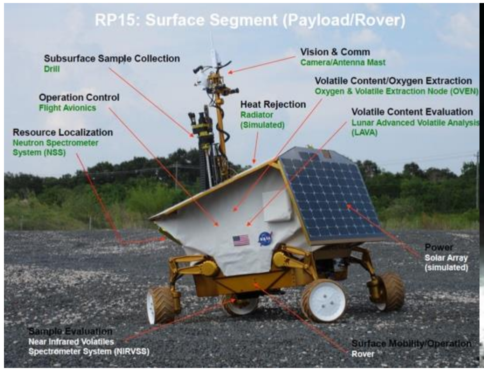
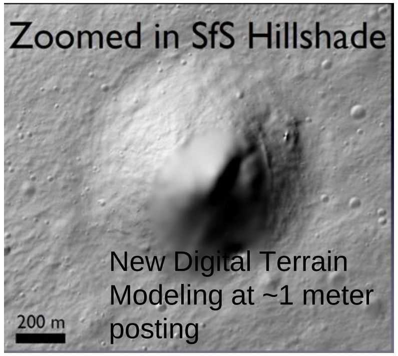
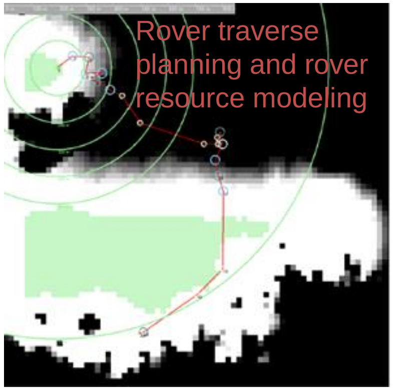
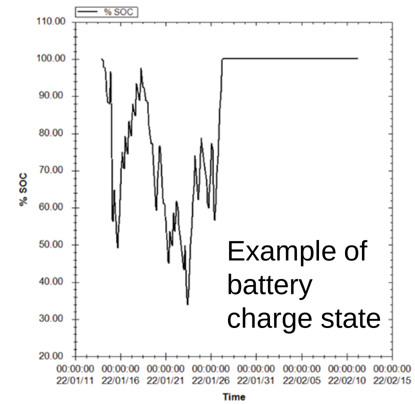
Resource Prospector

- **Resource Characterization**
  - What: Develop an instrument suite to locate and evaluate the physical, mineral, and volatile resources at the lunar poles
    - Neutron Spectrometer & Near Infrared (IR) to locate subsurface hydrogen/surface water
    - Near IR for mineral identification
    - Auger drill for sample removal down to 1 m
    - Oven with Gas Chromatograph/Mass Spectrometer to quantify volatiles present
  - ISRU relevance: Water/volatile resource characterization and subsurface material access/removal
- **Site Evaluation & Resource Mapping**
  - What: Develop and utilize new data products and tools for evaluating potential exploration sites for selection and overlay mission data to map terrain, environment, and resource information
    - e.g., New techniques applied to generate Digital Elevation Map (DEMs) at native scale of images (~1m/pxl)
  - ISRU relevance: Resource mapping and estimation with terrain and environment information is needed for extraction planning
- **Mission Planning and Operations**
  - What: Develop and utilize tools and procedures for planning mission operations and real time changes
    - Planning tools include detailed engineering models (e.g., power and data) of surface segment systems allows evaluation of designs
  - ISRU relevance: Allows for iterative engineering as a function of environment and hardware performance









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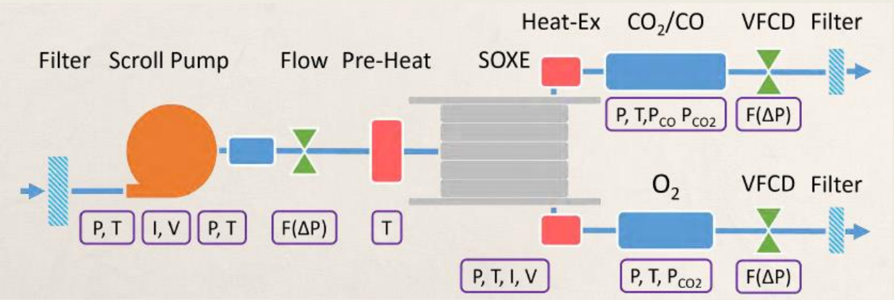
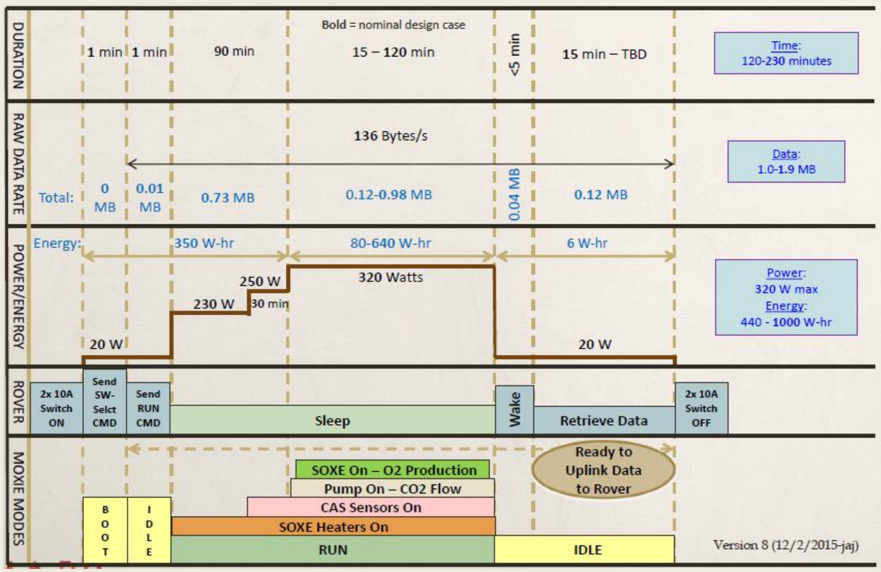
MOXIE

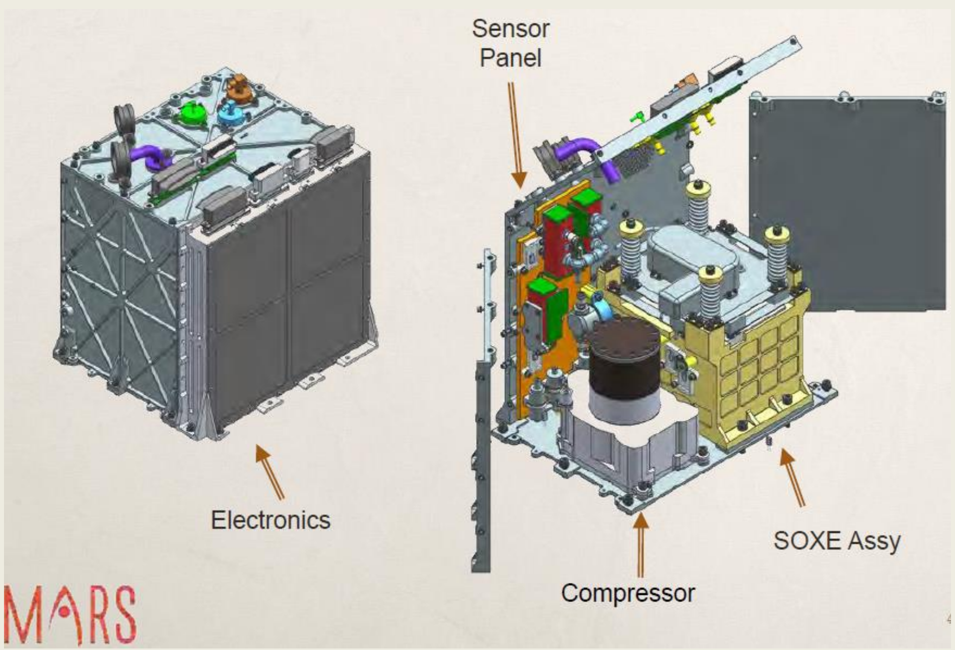
Requirement	Goal	Threshold
Oxygen Production Rate	8 g/hr at 5 Torr, 0°C.	6 g/hr at 5 Torr, 0°C.
Oxygen Purity	99.6%	98%
Number of Cycles	20	10



System Performance

- O_2 production – >1g/hr per cell (10 cells)
- Operational Cycle – >45 cycles w/ no failures
- O_2 purity – All recent stacks exceed 99.9%
- Limited by:
  - Inlet flow (pump capacity, gas density at landing site)
  - Available power (4A limit, equiv. to 12 g/hr)
  - SOXE capability (10 cells, 22.7 cm²/cell)





MARS