



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)?



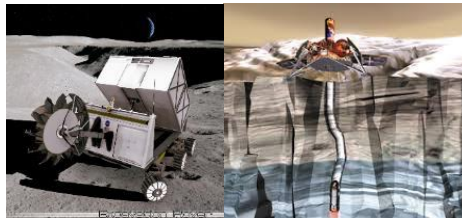
ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

Resource Assessment (Prospecting)



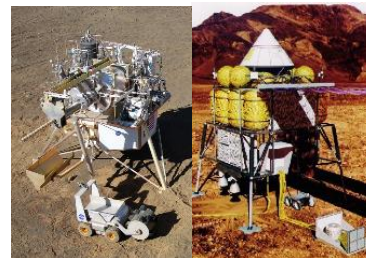
Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition



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

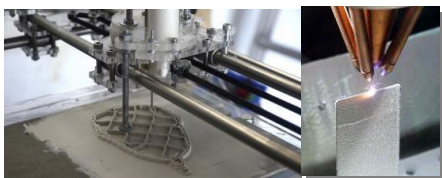
Resource Processing/ Consumable Production



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

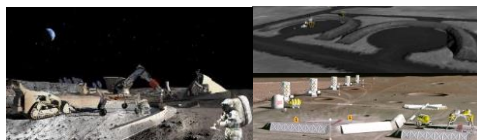
➤ Propellants, life support gases, fuel cell reactants, etc.

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.

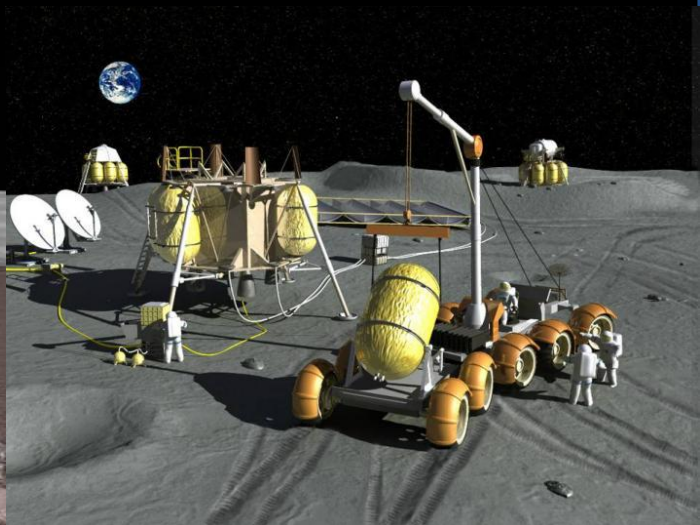
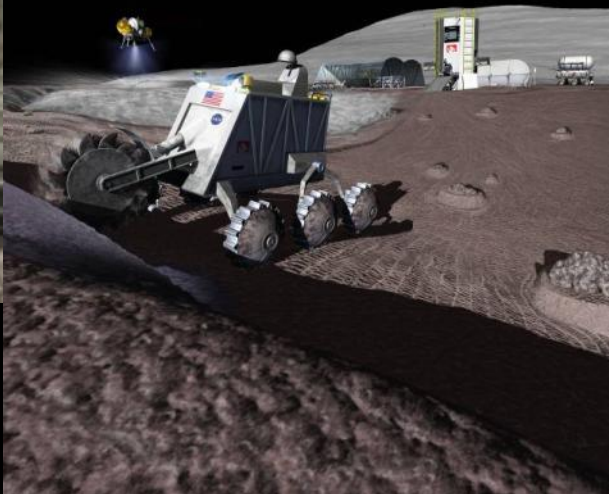
- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

Lunar ISRU Mission Capability Concepts

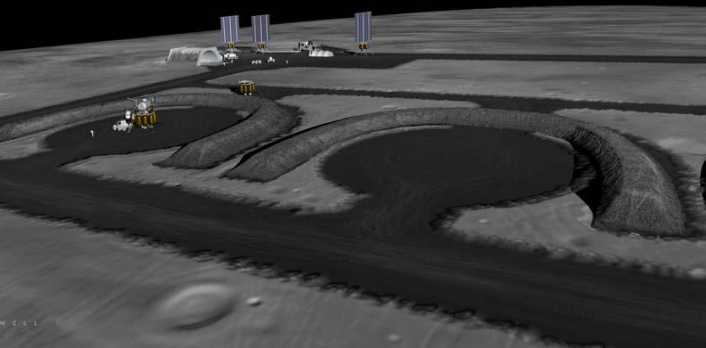


**Resource Prospecting –
Looking for Polar Ice**

**Excavation & Regolith
Processing for O₂
Production**

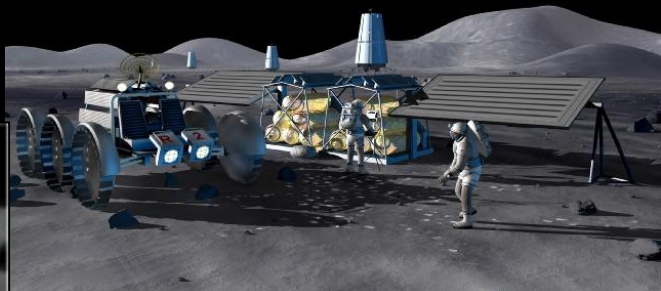
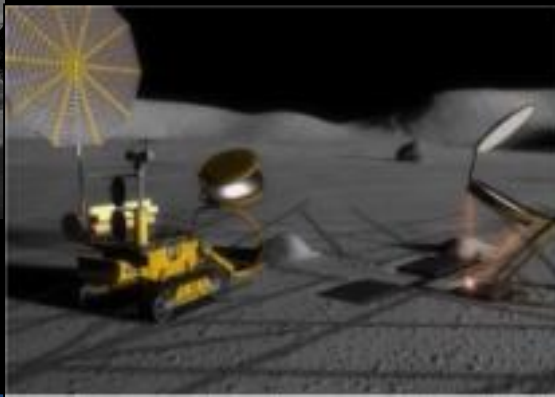


**Carbothermal Processing
with Recycled Lander Assets**



**Landing Pads, Berm, and
Road Construction**

**Thermal Energy Storage
Construction**



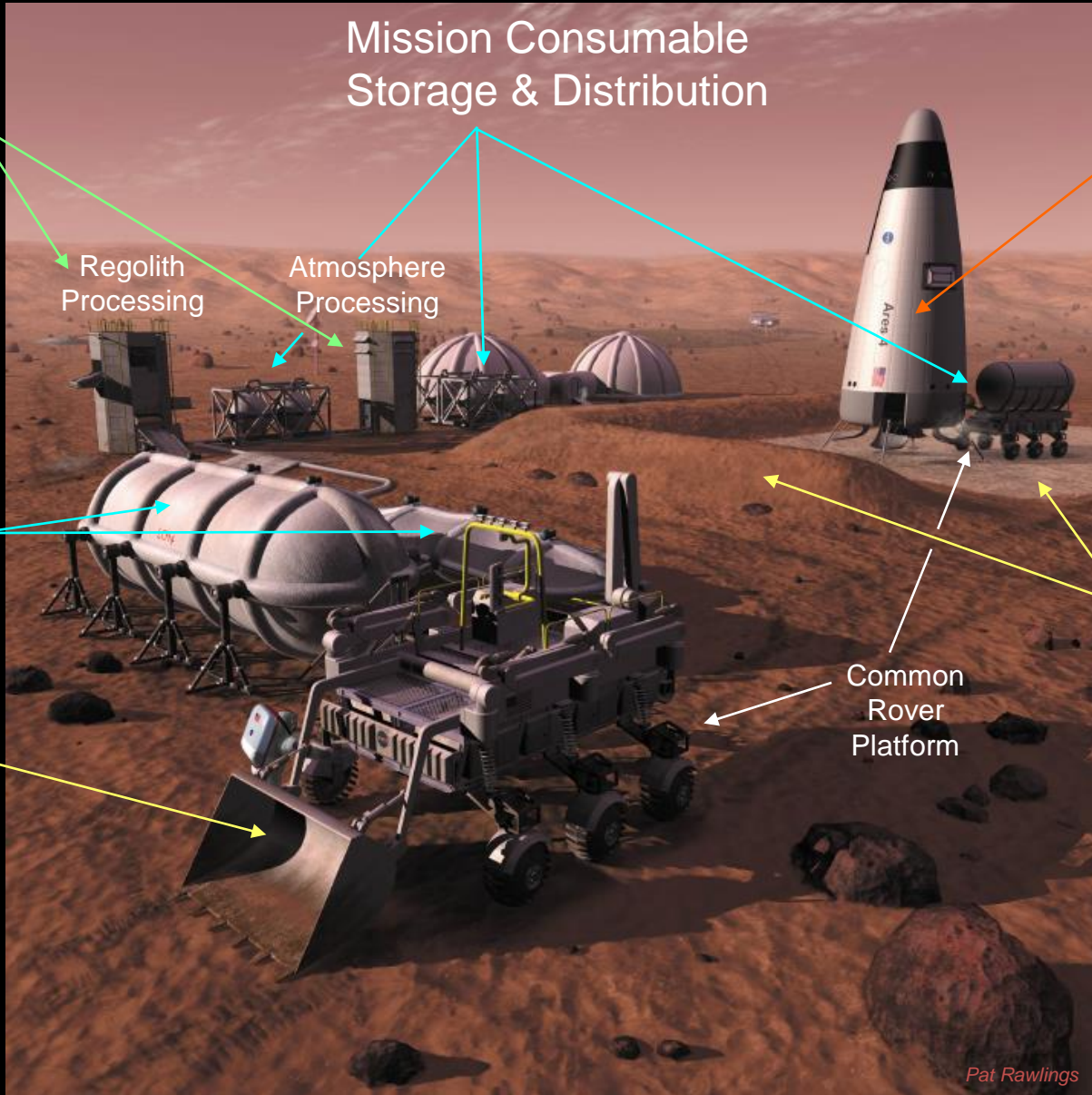
**Consumable Depots for
Crew & Power**

Mars ISRU Mission Capability Concepts

Resource Processing Plants

Collapsible/Inflatable Cryogenic Tanks

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



Mission Consumable Storage & Distribution

Regolith Processing

Atmosphere Processing

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

Landing pad & plume exhaust berm

Common Rover Platform

Pat Rawlings



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
 - O₂ only provides up to 80% of propellant mass
 - O₂/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**

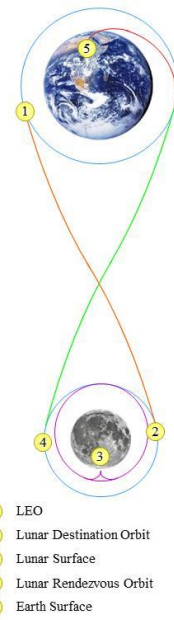
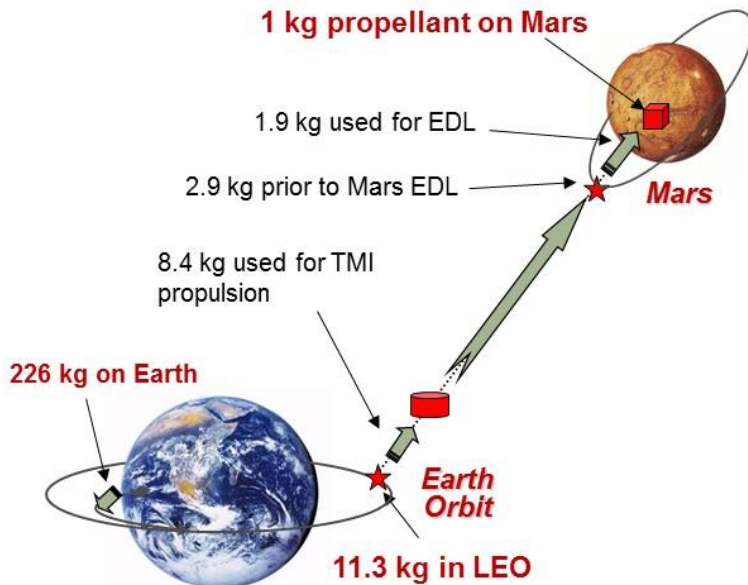
- Oxygen only
- Methane + Oxygen

75% of ascent propellant mass; 20 to 23 mT
 100% of ascent propellant mass: 25.7 to 29.6 mT
 Regeneration of rover fuel cell reactant mass

▪ **Phobos mission**

- Trash to O₂/CH₄

1000+ kg of propellant



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

Estimates based on Aerocapture at Mars



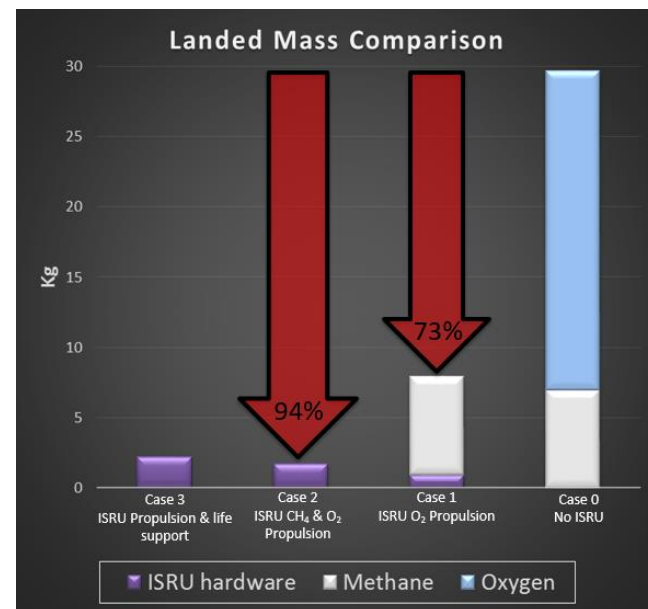
Example of Benefit of ISRU: Mars ISRU Study - Mass Result Comparison



	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 assuming 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





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

Water



Icy Regolith in Permanently Shadowed Regions (PSR)

Solar wind hydrogen with Oxygen

Oxygen



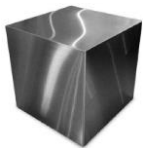
Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite

Carbon



- CO, CO₂, and HC's in PSR
- Solar Wind from Sun (~50 ppm)

Metals



Minerals in Lunar Regolith

- Iron/Ti: Ilmenite
- Silicon: Pyroxene, Olivine, Anorthite
- Magnesium: Mg-rich Silicates
- Al: Anorthitic Plagioclase



Mars

Hydrated Soils/Minerals: Gypsum, Jarosite, Phyllosilicates, Polyhydrated Sulfates

Subsurface Icy Soils in Mid-latitudes to Poles

Carbon Dioxide in the atmosphere (~96%)

Carbon Dioxide in the atmosphere (~96%)

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



Asteroids

Subsurface Regolith on C-type Carbonaceous Chondrites

Minerals in Regolith on S-type Ordinary and Enstatite Chondrites

Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites

Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids

Uses

- Drinking, radiation shielding, plant growth, cleaning & washing
- Making Oxygen and Hydrogen
- Breathing
- Oxidizer for Propulsion and Power
- Fuel Production for Propulsion and Power
- Plastic and Petrochemical Production
- *In situ* fabrication of parts
- Electrical power transmission

Similar Resources and Needs Exist at Multiple Locations



Lunar Resource Overview

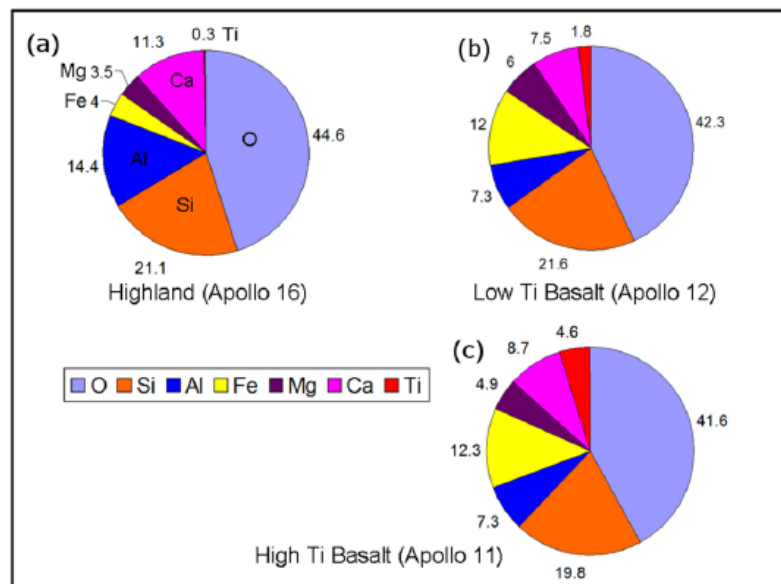


Figure 3. Example chemical compositions of lunar soils: (a) lunar highland minerals (Apollo 16); (b) low-Ti basalts (Apollo 12); and (c) high-Ti basalts (Apollo 11). Based on data collated by Stoesser et al. (2010), and reprinted from *Planetary and Space Science*, Vol. 74, Schwandt C, Hamilton JA, Fray 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 (\pm one standard deviation) of values found at different sampling locations. The corresponding average masses contained within 1 m³ of regolith (assuming a bulk density of 1660 kg m⁻³; Carrier et al., 1991) are also given.

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

In addition to the volatiles listed in Table 1, lunar soils contain small quantities (typically $\leq 1 \mu\text{g/g}$) of the solar wind derived noble gases 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 \pm 216 $\mu\text{g/g}$; 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

From Bob Wegeng/PNNL

		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



Lunar Polar Volatiles (Observed at LCROSS Site)



	Column Density (# m ⁻²)	Relative to H ₂ O(g) (NIR spec only)	Concentration (%)	Long-term Vacuum Stability Temp (K)	Instrument			
					UV/Vis	NIR	LAMP	M3
CO	1.7e13±1.5e11		5.7	15			x	
H ₂ O(g)	5.1(1.4)E19	1	5.50	106		x		
H ₂	5.8e13±1.0e11		1.39	10			x	
H ₂ S	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 ₂ H 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 ₃ OH	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 ₂ O (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



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 (CO₂); 2.7% Nitrogen (N₂); 1.6% Argon (Ar); 0.13% Oxygen (O₂); 0.08% Water (H₂O)

Resource	Potential Mineral Source		Reference
Water, Hydration/ Hydroxyl	Gypsum – (CaSO ₄ ·2H ₂ O) Jarosite – (KFe ³⁺ ₃ (OH) ₆ (SO ₄) ₂) Opal & hydrated silica – (SiO ₂ ·nH ₂ O) 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 ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cr ₂ O 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

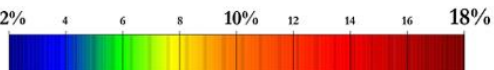


Mars Water Form & Distribution

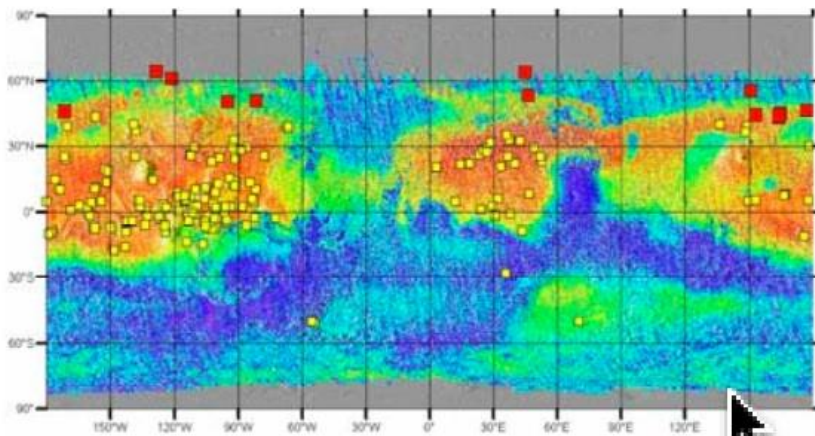
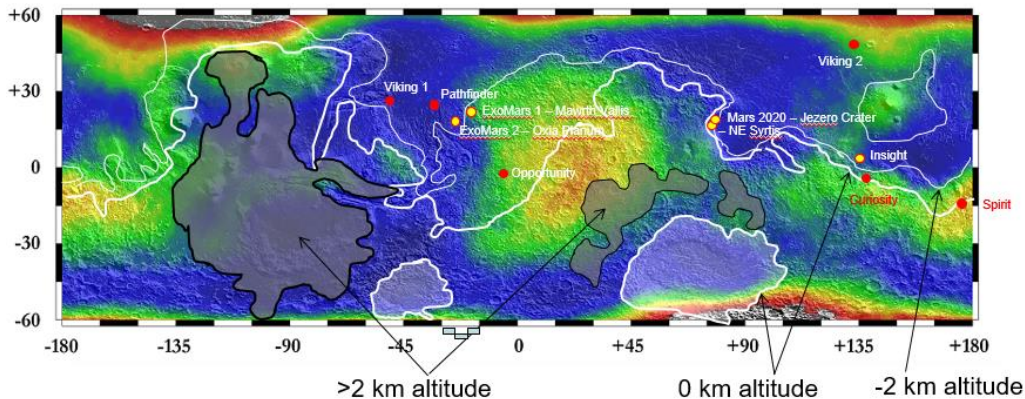


Water Abundance and Altitude with Past, Present, and Future Surface Missions

Water Equivalent Hydrogen Abundance



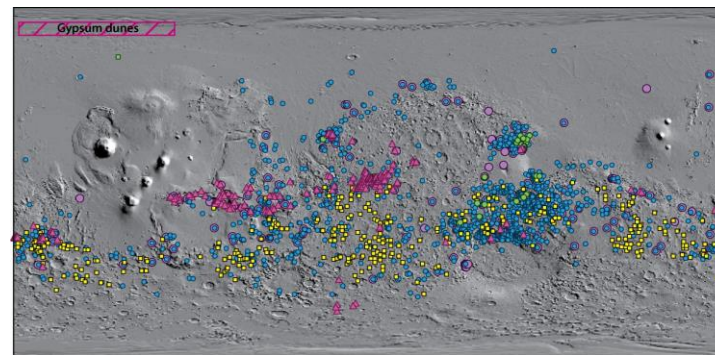
Los Alamos NATIONAL LABORATORY



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)

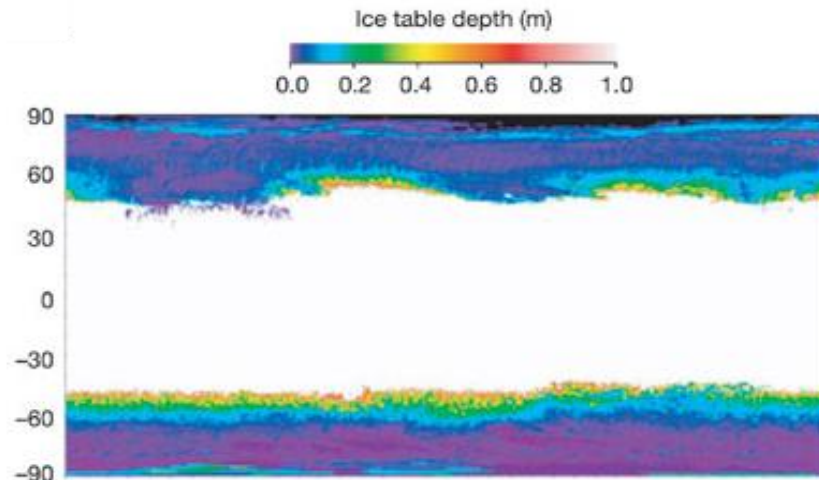
Map of aqueous mineral detections



Phyllosilicates Silica Chlorides Carbonates Sulfates

- 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





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 H₂S

Region 2: <300 C

- >80% of the water released
- CO₂ and O₂ released from decomposition of perchlorates
- Some release of HCl or H₂S but before significant amounts are release

Predicted Volatile Release Based on Lab Experiments

CO₂ released by

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

O₂ released by

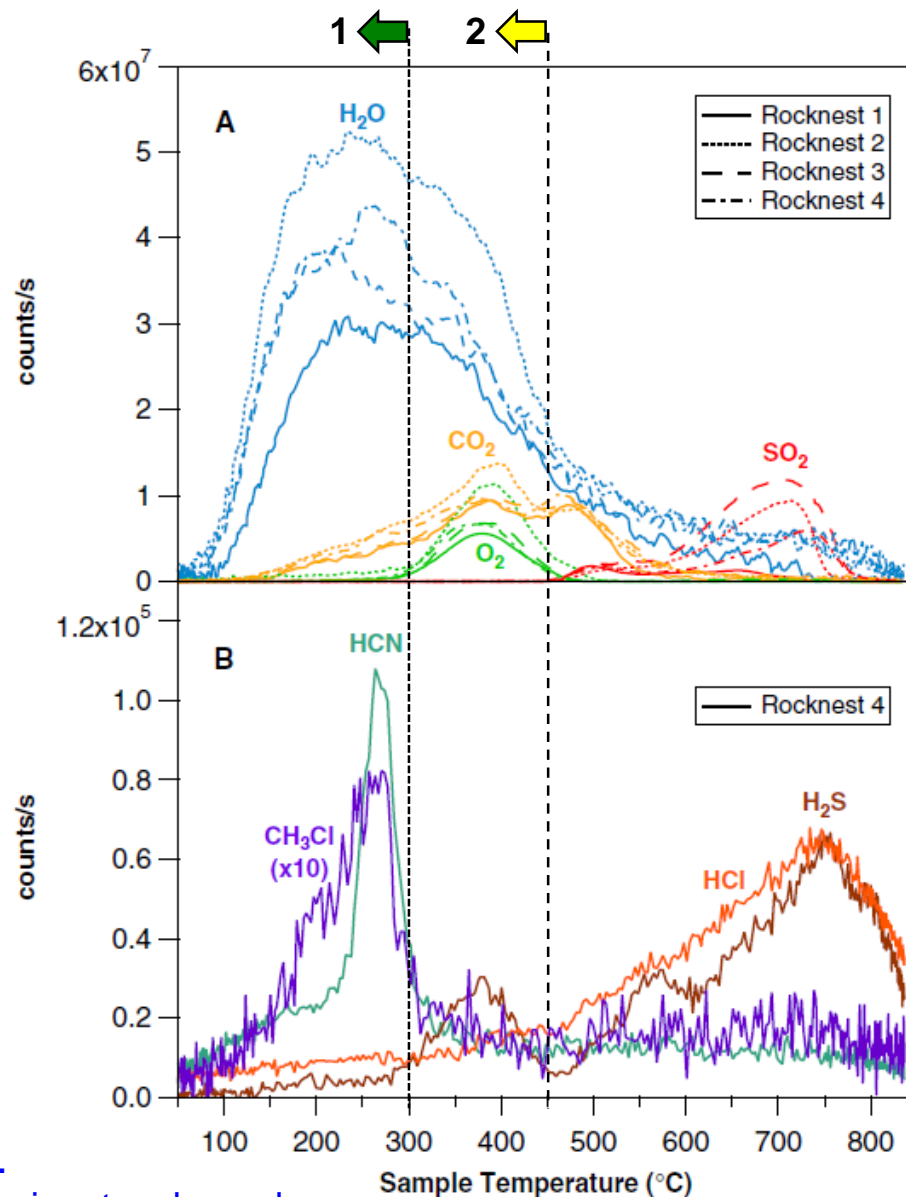
1. Dehydroxylation of clays <350 C
2. Decomposition of non-metal and metal oxides >500 C

CH₃Cl and CH₂Cl₂ released by

1. Decomposition of Mg(ClO₄)₂ perchlorate >200C

Not all the water needs to or should be removed.

- Need to consider energy vs amount water and contaminants released

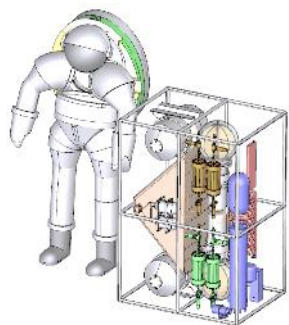




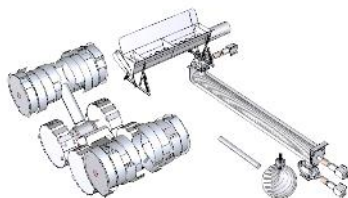
Mars Atmosphere & Water Resource Attributes



Atmosphere Processing



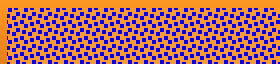
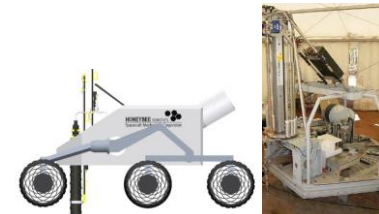
Granular Regolith Processing for Water



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





In Situ Water Extraction from Mars Soils



Beamed Energy

Microwave or solar energy

Cold trap to collect water vapor

Water vapor released from heated soil

Collection device seals with surface
Bore hole before heating

Down Hole Energy – Vapor State

Electrical/thermal, microwave, or solar energy

Collection device seals with surface
Bore hole before heating

Down Hole Energy – Liquid State

Drill hole down into ice sheet

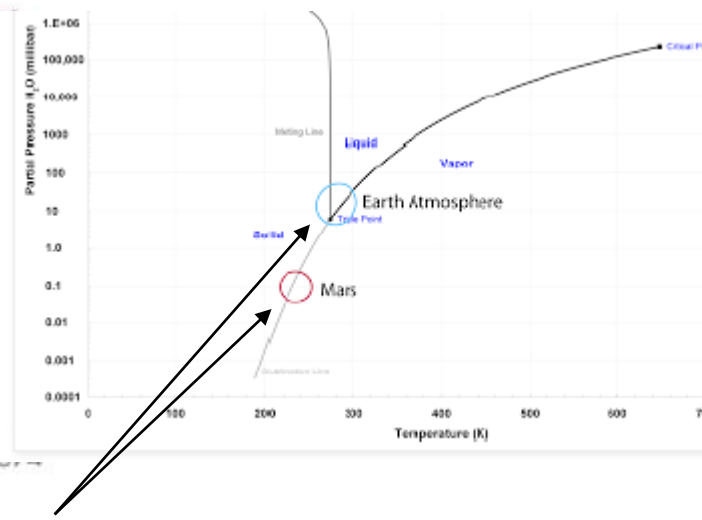
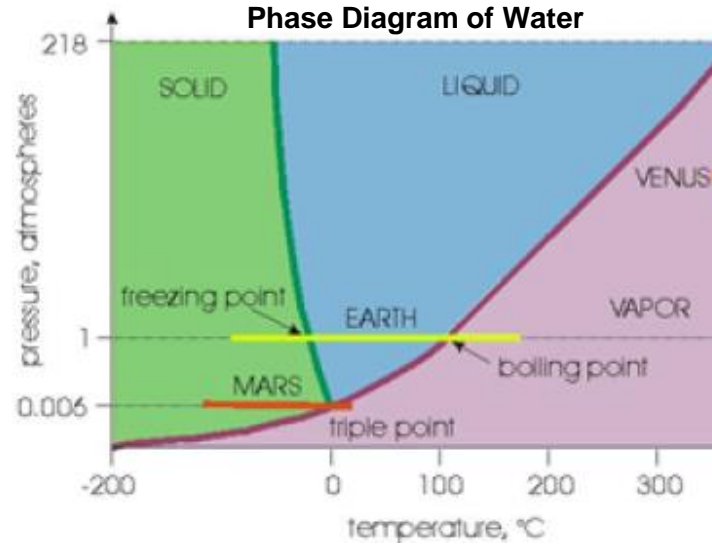
Hole Cap

Melt water in ice sheet and pump to the surface

Heater- Pump

Ice Water Pool

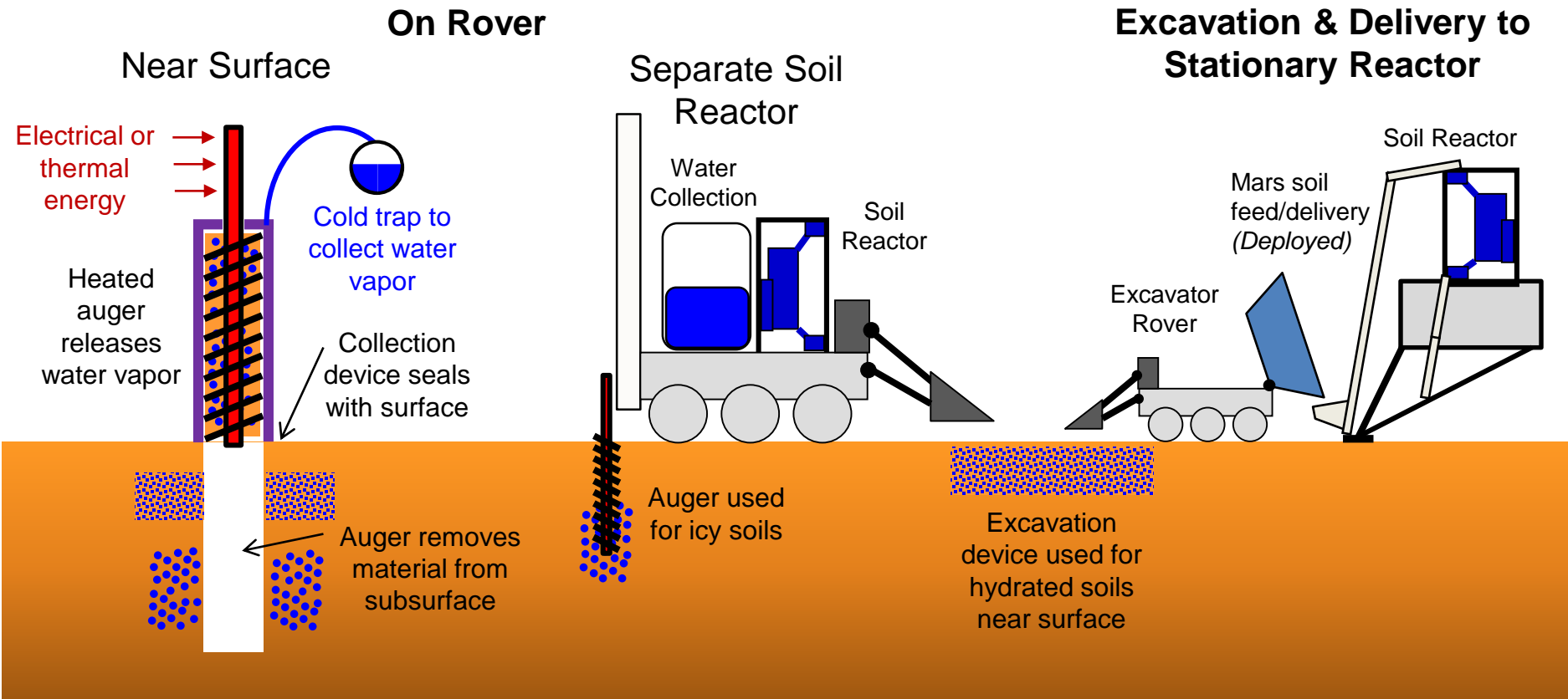
- Energy heats soil so that water converts to vapor (may transition thru liquid phase)
- Release of water helps further heat conduction into soil
- Water vapor follows 'path of least resistance' to bore hole
 - Vapor may also re-condense away from heat in colder soil
- Water vapor collected in cold trap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



Water Extraction via Excavation & Processing Reactor



- Soil is removed from subsurface
- Soil is heated via thermal to remove water vapor; can be higher temperature than *in situ* heating
- Water vapor is condensed and stored
- Soil is dumped back onto surface after processing
- 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



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

*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

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		



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 ^a	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 ₂ O 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

^aSustainable 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

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.

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 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 ^a	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	<ul style="list-style-type: none"> 480 min. Additional 240 days for life support consumables (between crew Earth departure & Mars arrival) 	<ul style="list-style-type: none"> 480 min. 1200 desired for additional operation through end of crew stay 	<ul style="list-style-type: none"> 480 min. Additional operation desired but not specified 				540 min without maintenance.
Operating Cycle Life			40.				40 nuc. 540 max solar



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 lose 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 Ls 270	Day (C)	5	-52	-86
		Night (C)	-65	-95	-112
		Delta (C)	70	43	26
N. Sum	S. Win Ls 90	Day (C)	-25	-25	-32
		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 O₂ for O₂ Only and
2.7 kg/hr O₂ for O₂/CH₄

		Days	
Total Time		420	540
Criteria #5	Time for Setup/Failures	14	14
	Time for Failure Recovery (5%)	16.8	21.7
	Time for Dust Storms (6%)	20.1	26.1
	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

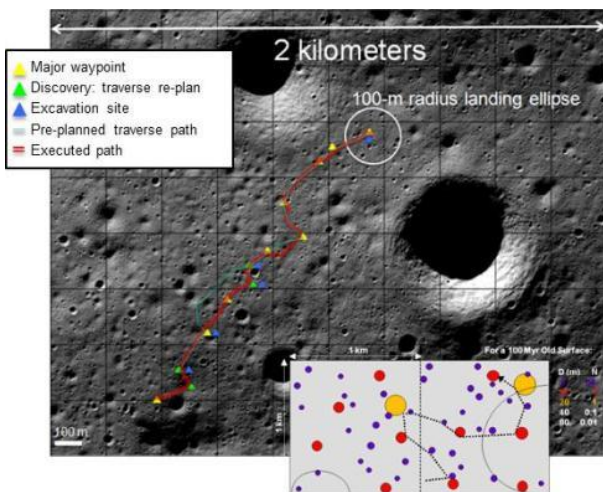




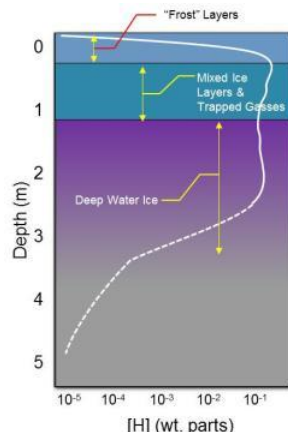
Economics of ISRU for Space Applications (2)



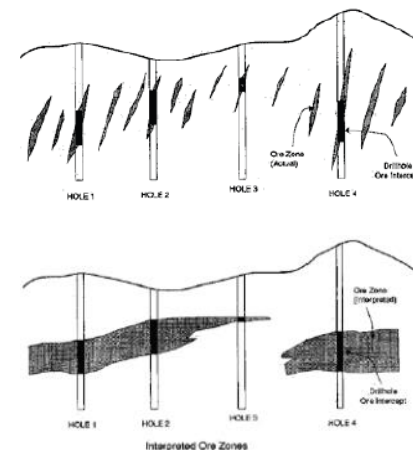
Need to Evaluate Local Region (1 to 5 km)



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 ₂ O	150,000	2x Per Year	Lunar Human Outpost & Reusable Transportation
	O ₂ /H ₂	150,000	Per Year	Amount 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 or 2x Per Yr	Reusable Ascent/Descent Propulsion - Surface to Mars Orbit
	H ₂ O	3,075	Surface/500 Days	Life Support System Closure
	H ₂ O	15,700	Per Use/1x 480 Days	Extracted H ₂ O to Make Non-Reusable Ascent Vehicle Propellant
	H ₂ O	38,300	Per Use/1 or 2x Per Yr	Extracted H ₂ O to Make Reusable Ascent/Descent Vehicle Propellant

 = Initial Requirement = Horizon Goal



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 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 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 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 maintenance?	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

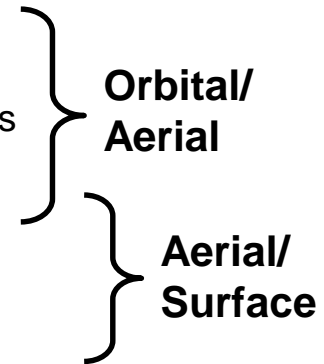
- Most challenges and risks to ISRU development and incorporation can be eliminated through design and testing under Earth analog or environmental chamber testing at the component, subsystem, and system level
- Critical challenges/risks associated with fully understanding the extraterrestrial resource (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
- **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

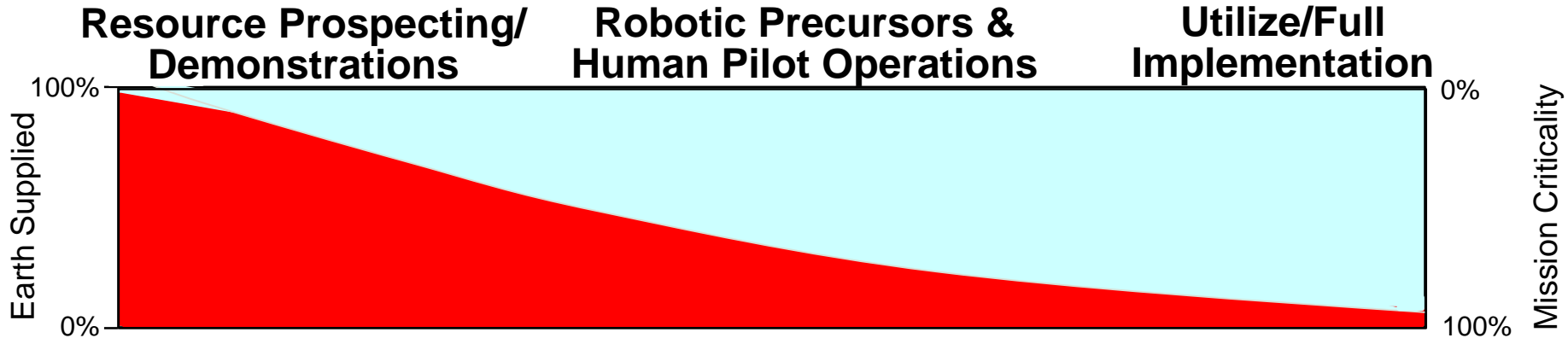
- **Validation of Earth-based Risk Reduction**
 - Demonstrate long-term autonomous operations with limited communications and local navigation
 - Perform operations and product utilization at scales and durations relevant to human missions including traverse distances, number of trips, etc.
 - Demonstrate 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
- Verify 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



Concept of Operation on Mars

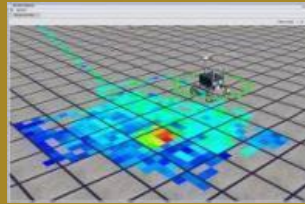
Space 'Mining' Cycle: *Prospect to Product*

Resource Assessment (Prospecting)

Global Resource Identification



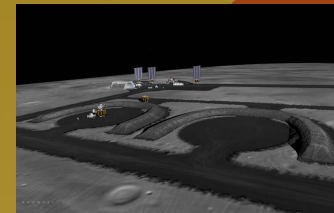
Local Resource Exploration/Planning



Mining



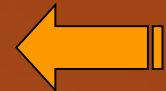
Crushing/Sizing/
Beneficiation



Site Preparation &
Infrastructure Emplacement



Processing



Spent
Material
Removal



Waste

Remediation



Habitats



Power




Propulsion



Life Support & EVA



Depots



Product Storage & Utilization



ISRU Integrated with Exploration Elements (Mission Consumables)



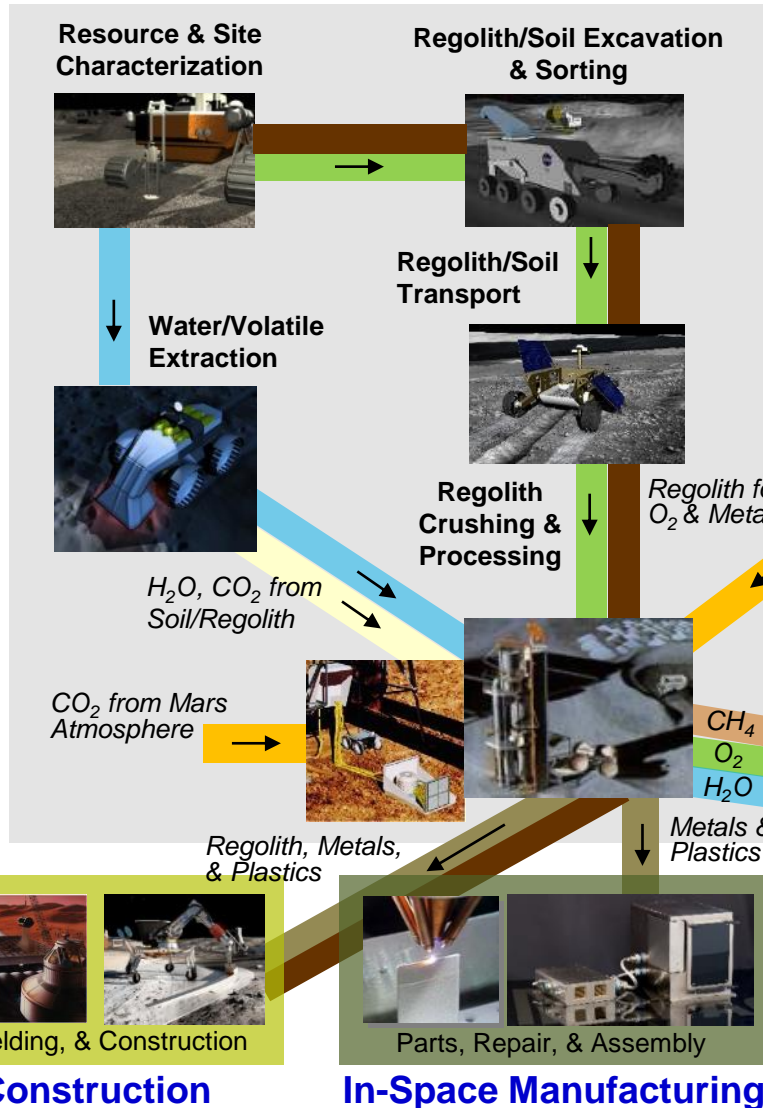
ISRU Functions & Elements

- 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
- O₂, H₂, and CH₄ Storage and Transfer

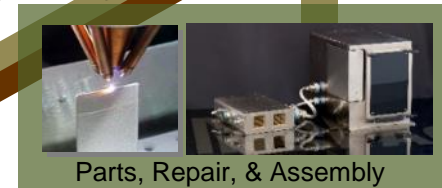
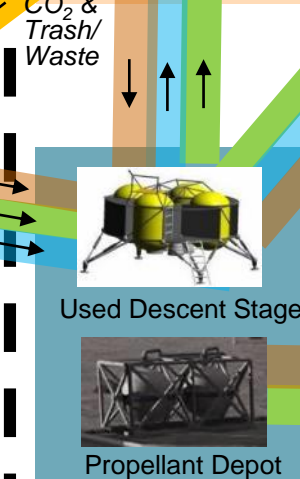
ISRU Resources & Processing



Life Support & EVA



Modular Power Systems



In-Space Construction

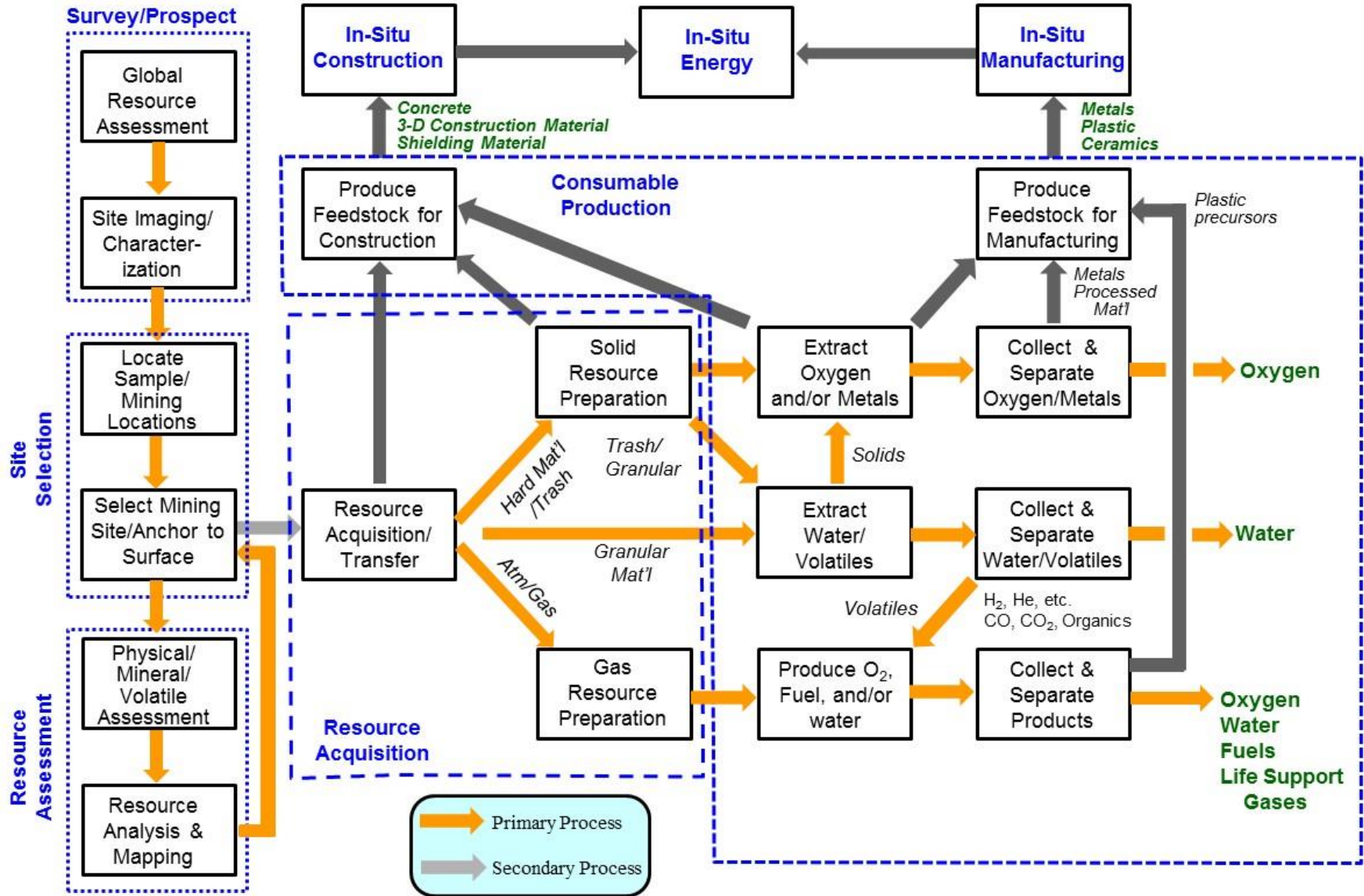
In-Space Manufacturing

Storage

Lander/Ascent



ISRU Capability-Function Flow Chart

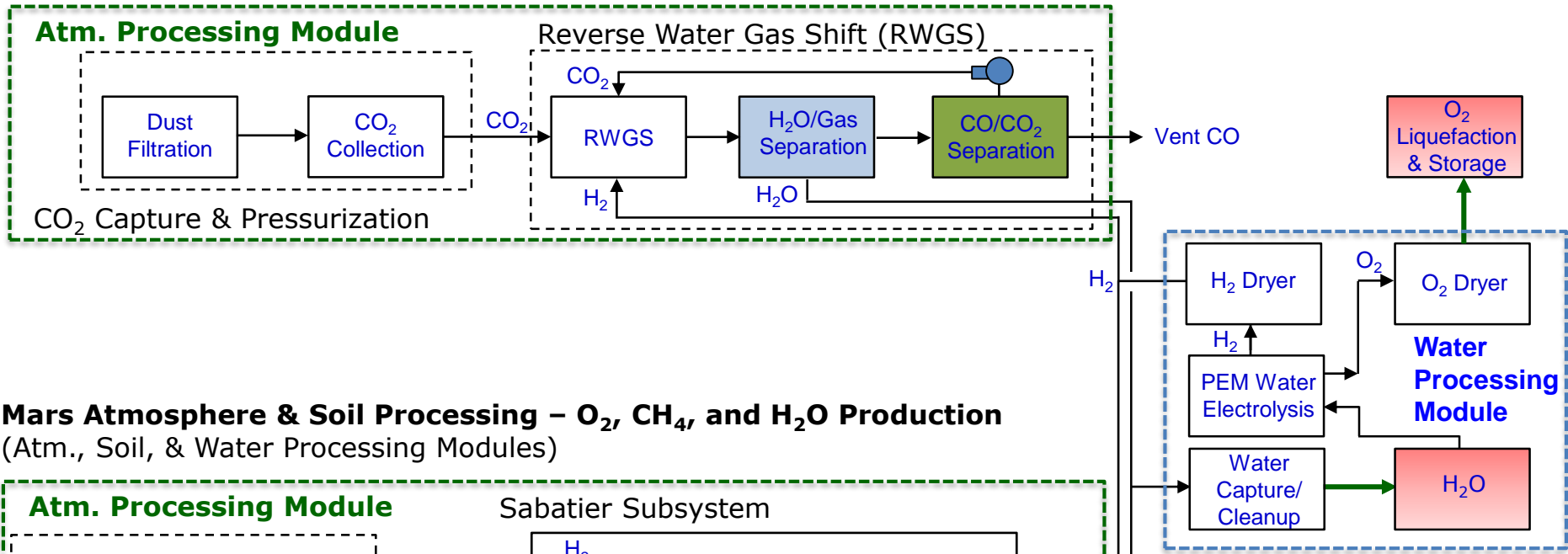




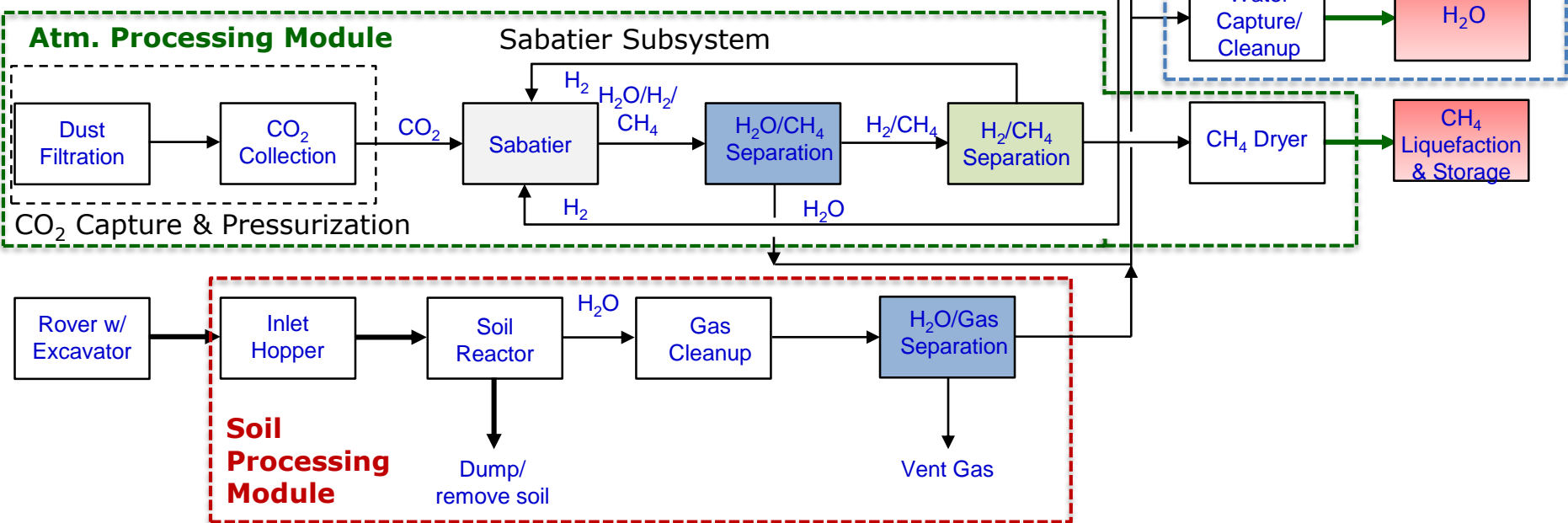
Mars Consumable ISRU: PEM-Based Electrolysis



Mars Atmosphere Processing – O₂ Only Production (Atm. & Water Processing Modules)



Mars Atmosphere & Soil Processing – O₂, CH₄, and H₂O Production (Atm., Soil, & Water Processing Modules)

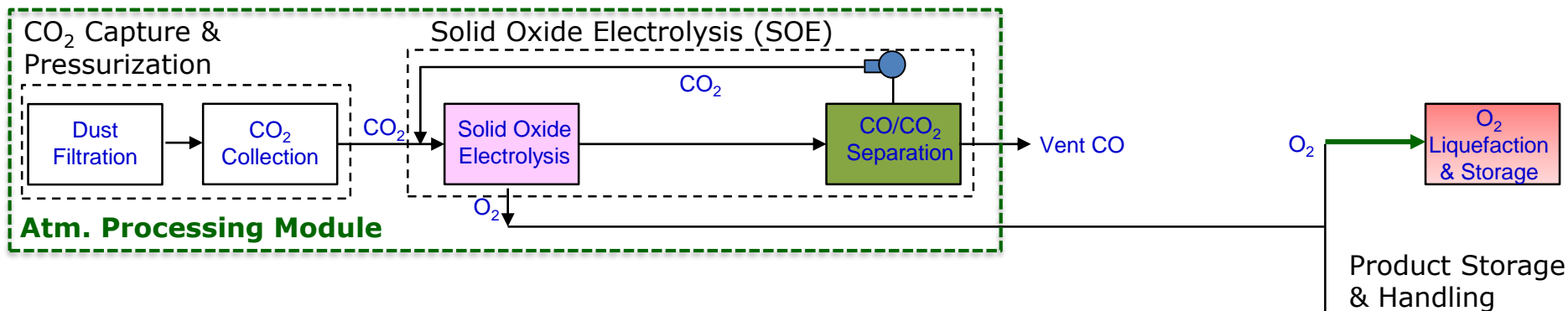




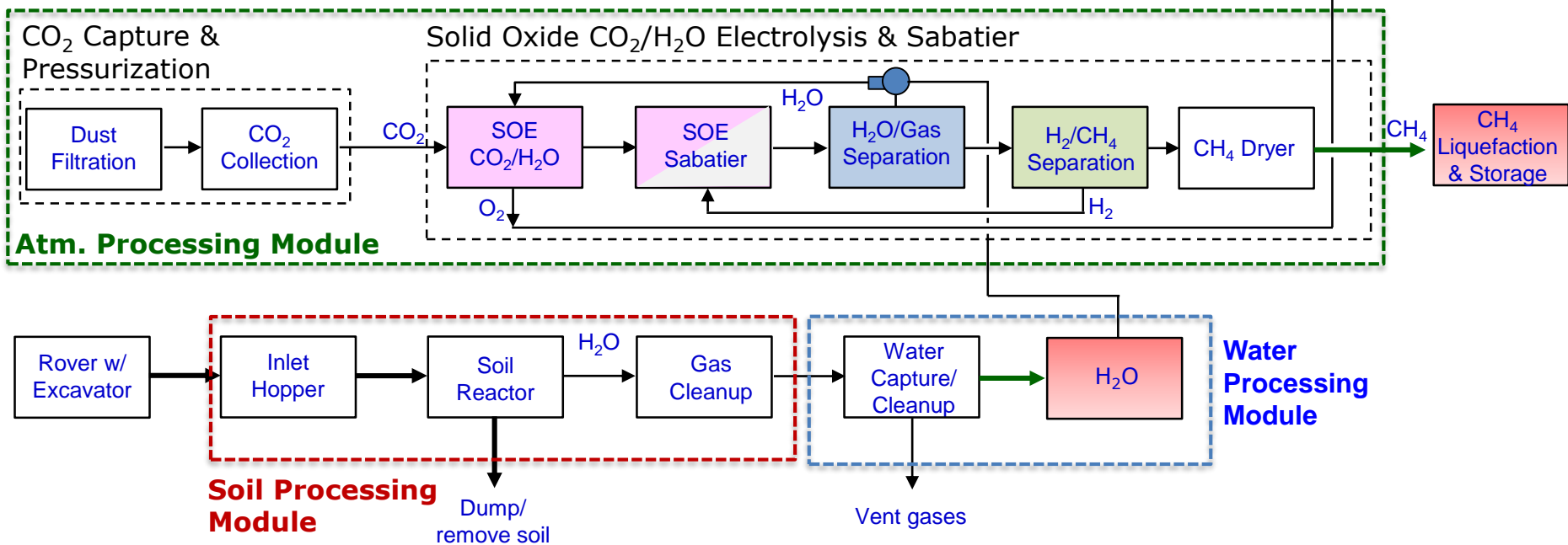
Mars Consumable ISRU: SOE-Based Electrolysis



Mars Atmosphere Processing – O₂ Production (Atm. Processing Module)



Mars Atmosphere & Soil Processing – O₂, CH₄, and H₂O Production (Atm., Soil, & Water Processing Modules)





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

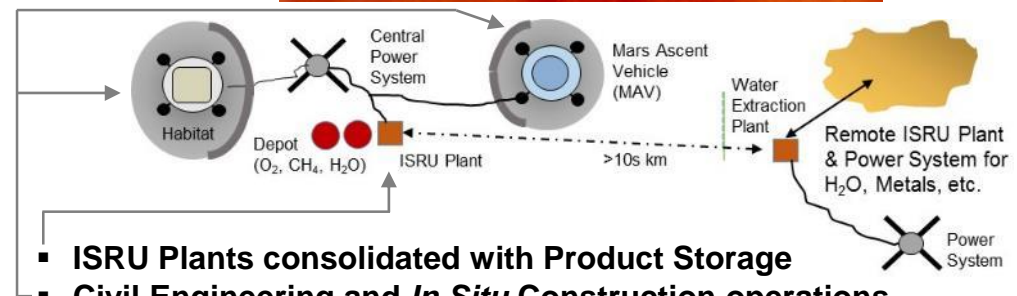
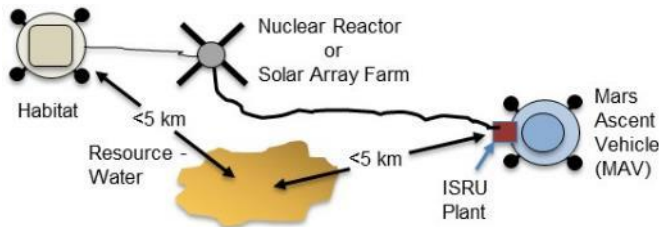
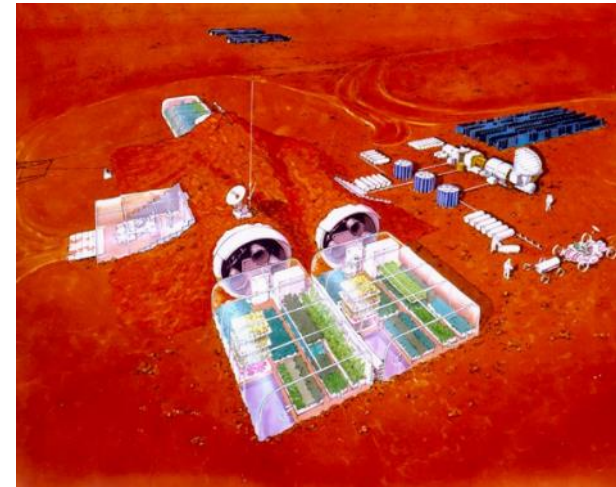
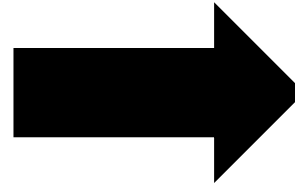
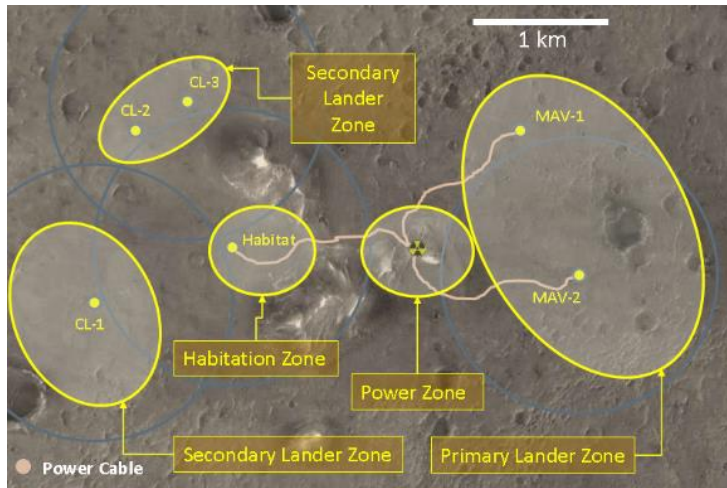


Initial Conditions:

Ultimate Goal

- 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

- 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



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 (5th 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% O₂ (Trades: 10.2 psia at 26.5% O₂; 8.2 psia at 34% O₂)
- 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 1st 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

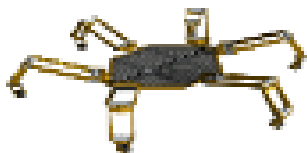
- Nuclear power is primarily aimed at ISRU operations
 - Keep alive/support power is required for habitat and other assets
 - Solar arrays and power storage still an option under consideration
- A nuclear reactor can be deployed with ISRU water extraction hardware to a location away from the MAV/ISRU 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



Asset 1



Asset 2



Asset 3

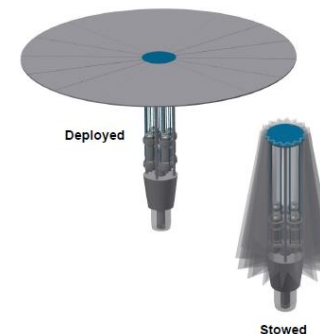


Asset 4



Asset 5

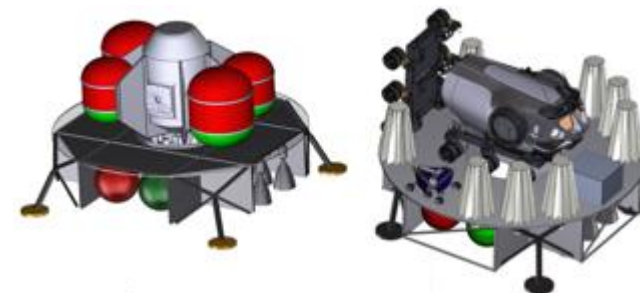
Nuclear Reactor



Mars Ascent Vehicle

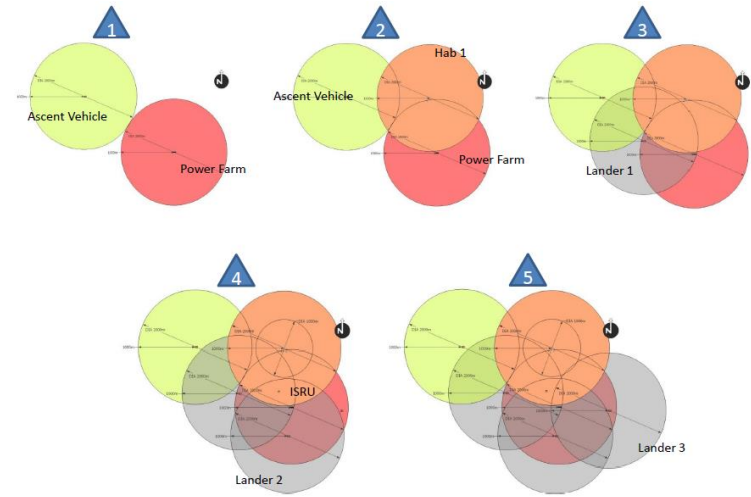
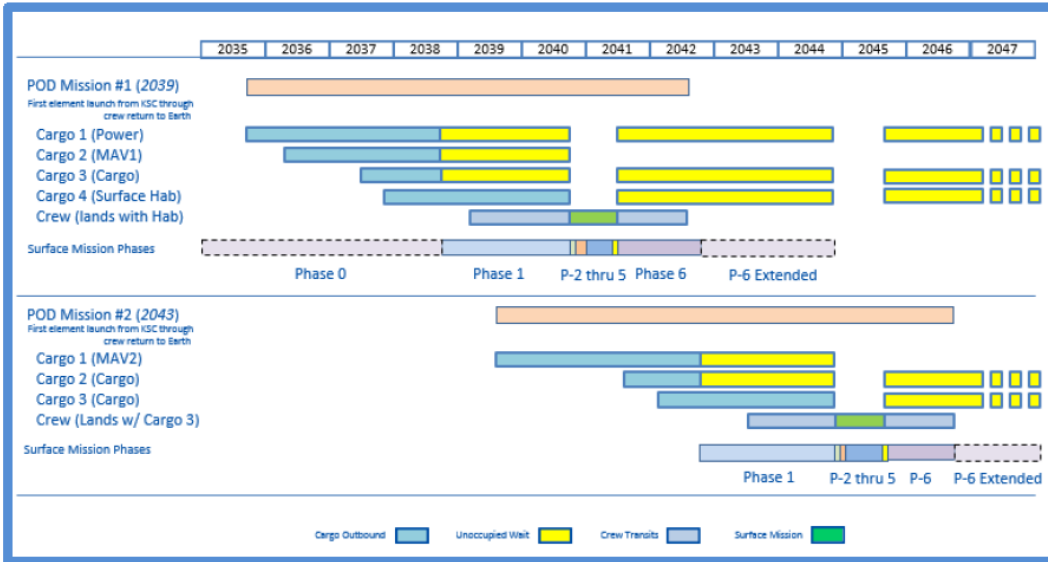


Mars Lander





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



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



Point of Departure (POD)		MISSION 1				DAYS
		Landers			Lander 4 Crew 1	210
		Lander 1	Lander 2	Lander 3	4,165.04	17,132.17
Mass in Cargo Containers (kg)		2,883.03	5,084.14	4,165.04	4,165.04	17,132.17
Total Lander Mass (kg)		19,989	20,000	19,996	15,971	75,658
Crew	Crew	400			400	400
ISRU	Atmospheric Production Plant w/02	1,677		1,677		1,677
	LOX Tanker (tankage and transfer equip)	600				600
	CH4 Tanker (tankage and transfer equip)	600				600
	Kilopower Fission Power System	6,176	6,176			6,176
Power	Power Distribution System	800				800
	Power cable (1 km length) + spool or box	70	140	70	70	350
	Special Regions Rover	500	500			500
Robotics	Crew Support Robotic Rovers	500				500
	Offloading Equipment (Hoist)	600	1,200			1,200
Habitation	Mars Surface Habitat - Monolithic	19,316		4,000	15,316	19,316
	Mars Surface Habitat - Split Habitat	10,129 kg				10,129
	Small Mars Surface Logistics Module - Single Hatch (4,480 kg capacity)	2,560				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				3,130
	Descent Module	3,000				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
	Spare and Other Logistics	2,846 kg/sol + 212.9 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	
Mobility	EVA spares	4 crew: 1.73 kg/sol + 796.8 kg	17.30		1,142.90	1,160.19
	Mars Surface Transporter (Chariot, Athlete)	1,890	1,890	1,890		3,780
	Mars Surface Unpressurized Rover	300				300
Science	Mars Surface Pressurized Rover	6,452			6,452	6,452
	Spare and Logistics	1,000				1,000
Transportation	Allocated Payload	3,000				3,000
	Reconfigurable Surface Science Facility	3,000				3,000
MAV + tunnel + ISRU + cable = 20,000			18,016.30			18,016.30
Unallocated Mass (kg)		11	-	4	29	44
Number of Small, Dual-Hatch Logistics Modules:		1	0	2	0	3

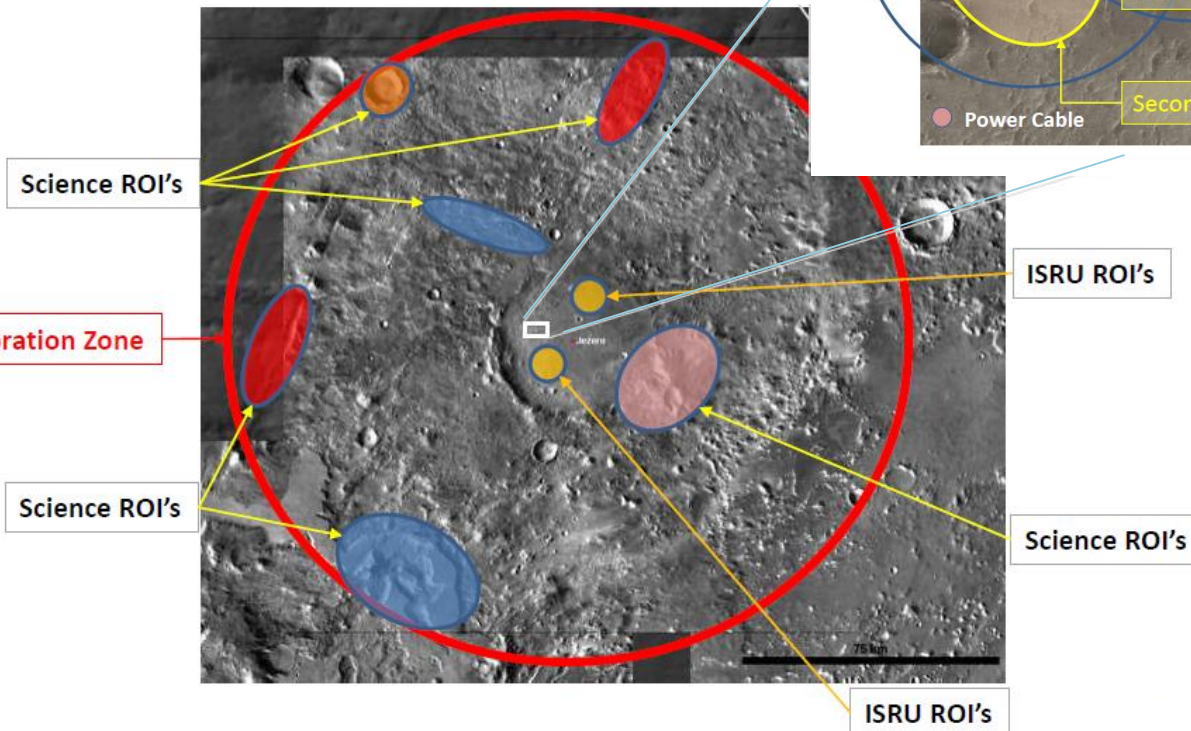


Human Mars Landing Site Overview

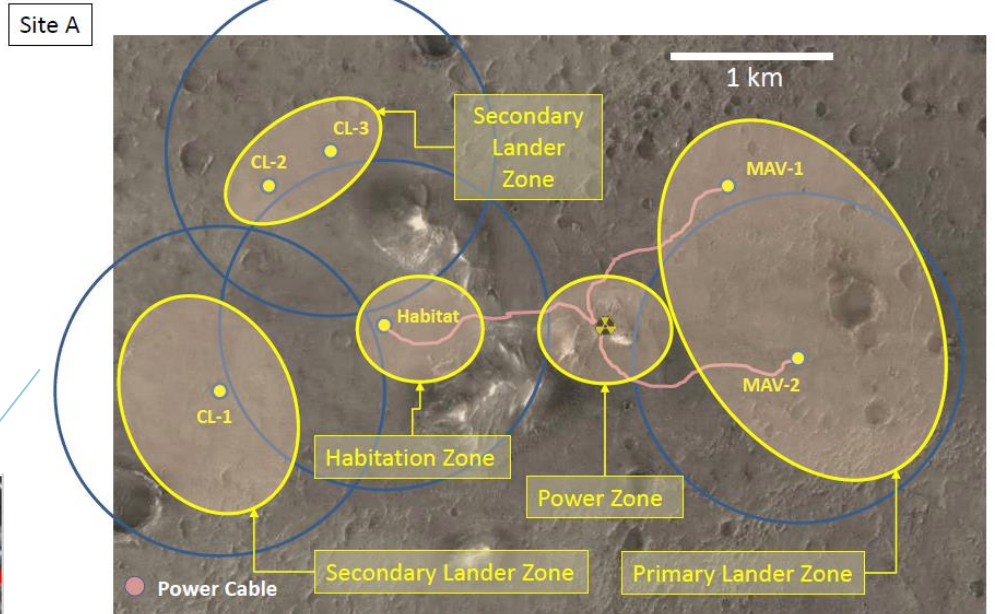


- Landing Site selected is near the center of an Exploration Zone of 200 km in diameter
 - First 3 missions will be focused on establishing support infrastructures for subsequent longer range exploration
 - Diameter based on expected capabilities of crewed pressurized rover extended excursions
 - EZ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

Notional Exploration Zone (EZ)



Notional Landing Spacing and Arrangement



(plume impingement allowed for any "dead" hardware)



Mars ISRU Concept of Operation (1)

Production of O₂ and CH₄ 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 O₂ and CH₄ 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 O₂ and CH₄ 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 O₂ and CH₄ tanks

▪ **Post MAV Fill ISRU Operations (Options):**

1. O₂ and CH₄ Maintenance and Failure recover (Requires low-power/rate operation mode)
2. Fill Lander 3 descent tanks with O₂ and CH₄ for fuel cell power and/or life support backup
3. Fill mobile Logistics Depot (new asset) with O₂, CH₄ and N₂.

▪ **Pre MAV Launch Operations:**

- Isolate ISRU plant from MAV O₂ and CH₄ tanks
- Disconnect feedline between ISRU plant and MAV O₂ and CH₄ tanks
- Protect or remove ISRU plant hardware on Descent Module for future use or spare parts in subsequent missions

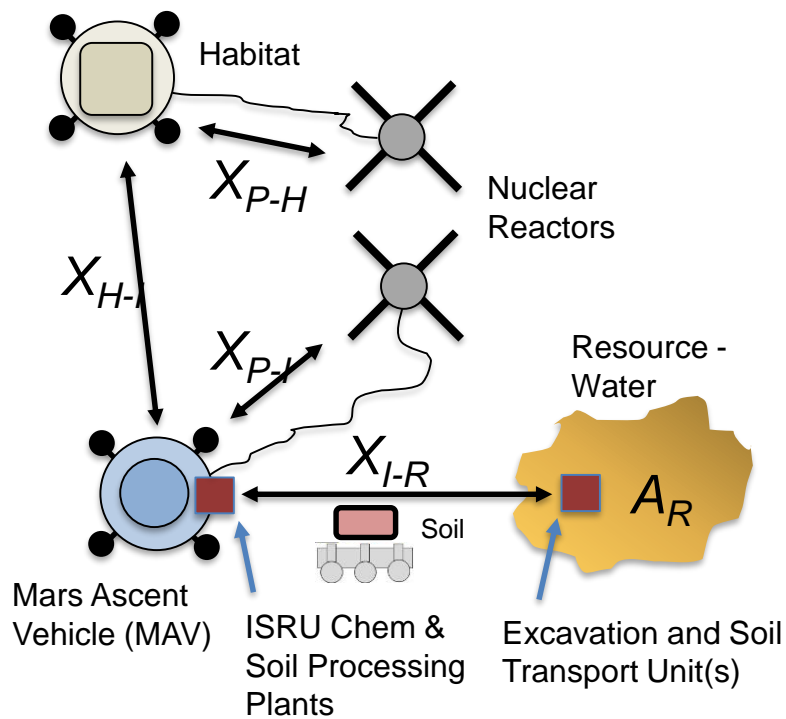


Mars ISRU Concept of Operation (4)

Production of O₂ and CH₄ for MAV



Option 2-1: O₂/CH₄ Production From Atmosphere & Hydrated Soils



$$X_{H-I} = >1 \text{ km}$$

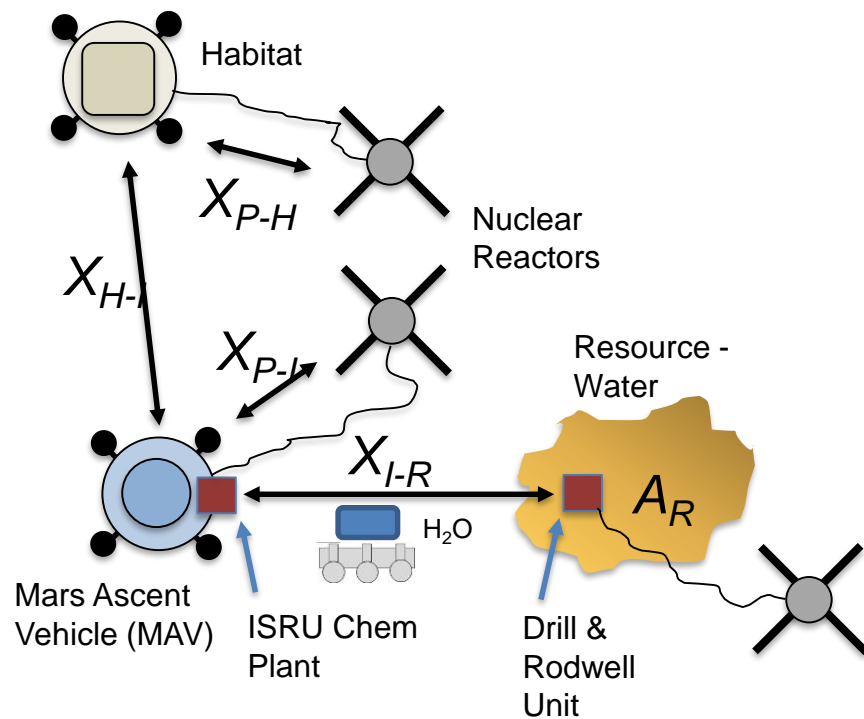
$$X_{P-I} = <1 \text{ km}$$

$$X_{P-H} = <1 \text{ km}$$

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

$$A_R = \text{Area of Resource}$$

Option 2-2: O₂/CH₄ Production From Atmosphere & Subsurface Ice



$$X_{H-I} = >1 \text{ km}$$

$$X_{P-I} = <1 \text{ km}$$

$$X_{P-H} = <1 \text{ km}$$

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

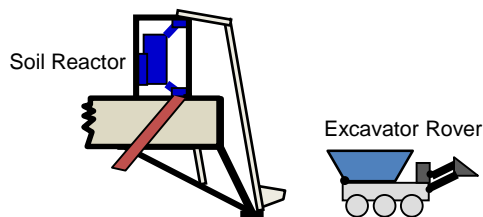
$$A_R = \text{Area of Resource}$$



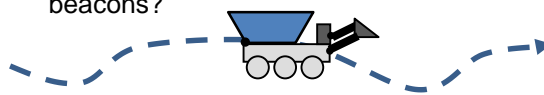
Granular Hydrated Material Mining Operations



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



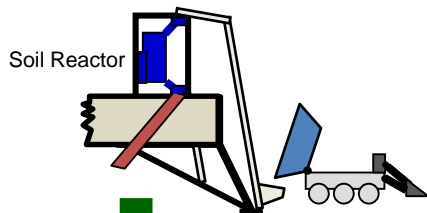
2. Excavator Rover Traverses to Excavation Site
 - Use route planned from Earth based on terrain/location map
 - Avoid obstacles and potentially other rovers during traverse
 - Autonomous operation; Use trail of beacons?



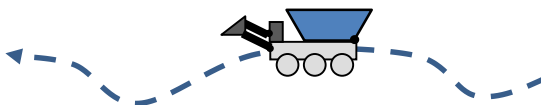
3. Excavator Rover Arrives at Excavation Site
 - Survey location to determine difference since last excavation to select excavation site (on-rover or LIDAR at site?)
 - Rover traverses to selected site



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?



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?

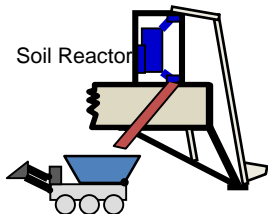


4. Excavator Rover Performs Excavation
 - Line up excavation device to exact point for excavation
 - Perform excavation; monitor forces on excavation device and wheel slippage to ensure proper excavation
 - Measure amount of soil excavated and loaded onto the rover



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

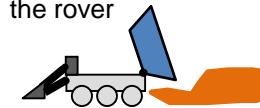
- 7b. Excavator Rover Receives Processed Soil
 - Rover finds dumping soil bin
 - Rover lines up to dump soil
 - Rover receives spent soil. Measure mass?



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



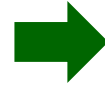
Subsurface Ice Mining Operations



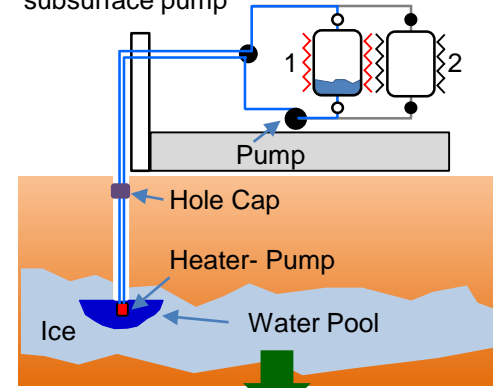
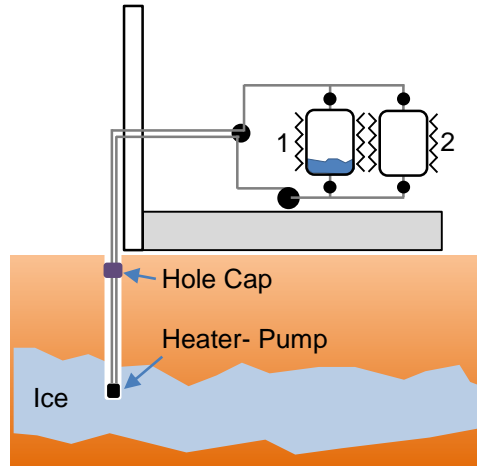
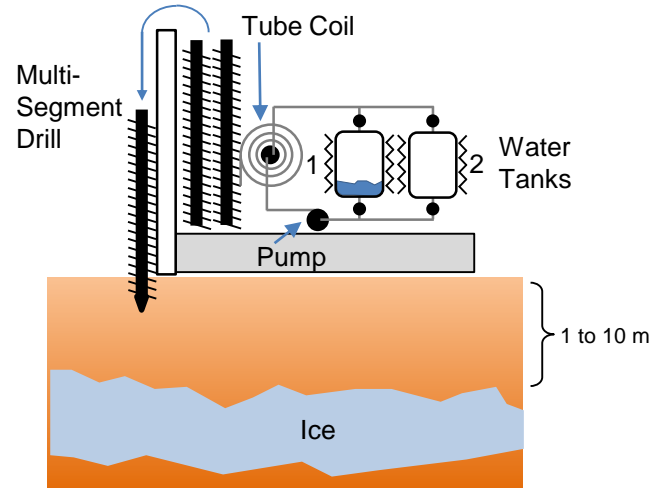
1. Drill through overburden into ice
 - Multi-segment drill from 1 to 10 m
 - Measure while drilling to evaluate when ice is met
 - Examine drill tailings or sensor on drill head for ice detection



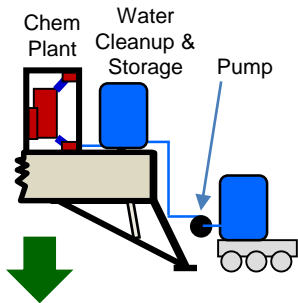
2. Establish tubing for water extraction
 - Lower tube with internal tubes for water flow down and up from Rodwell
 - End of tube includes downhole heater and water pump
 - Cap tube hole and tube (pneumatic) to seal chamber.



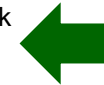
3. Begin water extraction from subsurface ice
 - Heat subsurface ice with downhole heater to begin subsurface water pool
 - Heat water from attached mobile water tank (precharged with amount to start ops) electrically or with thermal energy from FSPS
 - Begin flow of water from surface to subsurface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



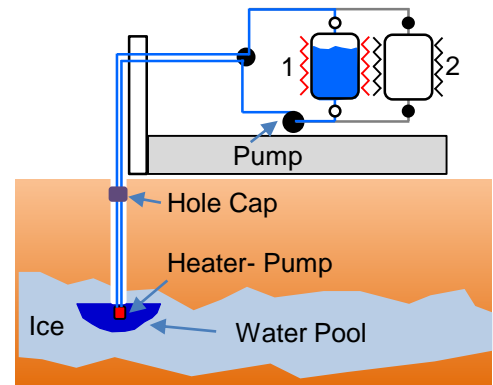
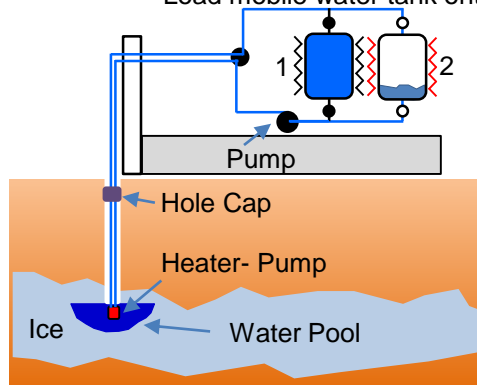
6. Deliver Mobile Water tank to ISRU Chem Plant
 - Rover finds attachment point for water transfer
 - Rover lines up and connects mobile water tank
 - Transfer water to on-board water cleanup and storage tank



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



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



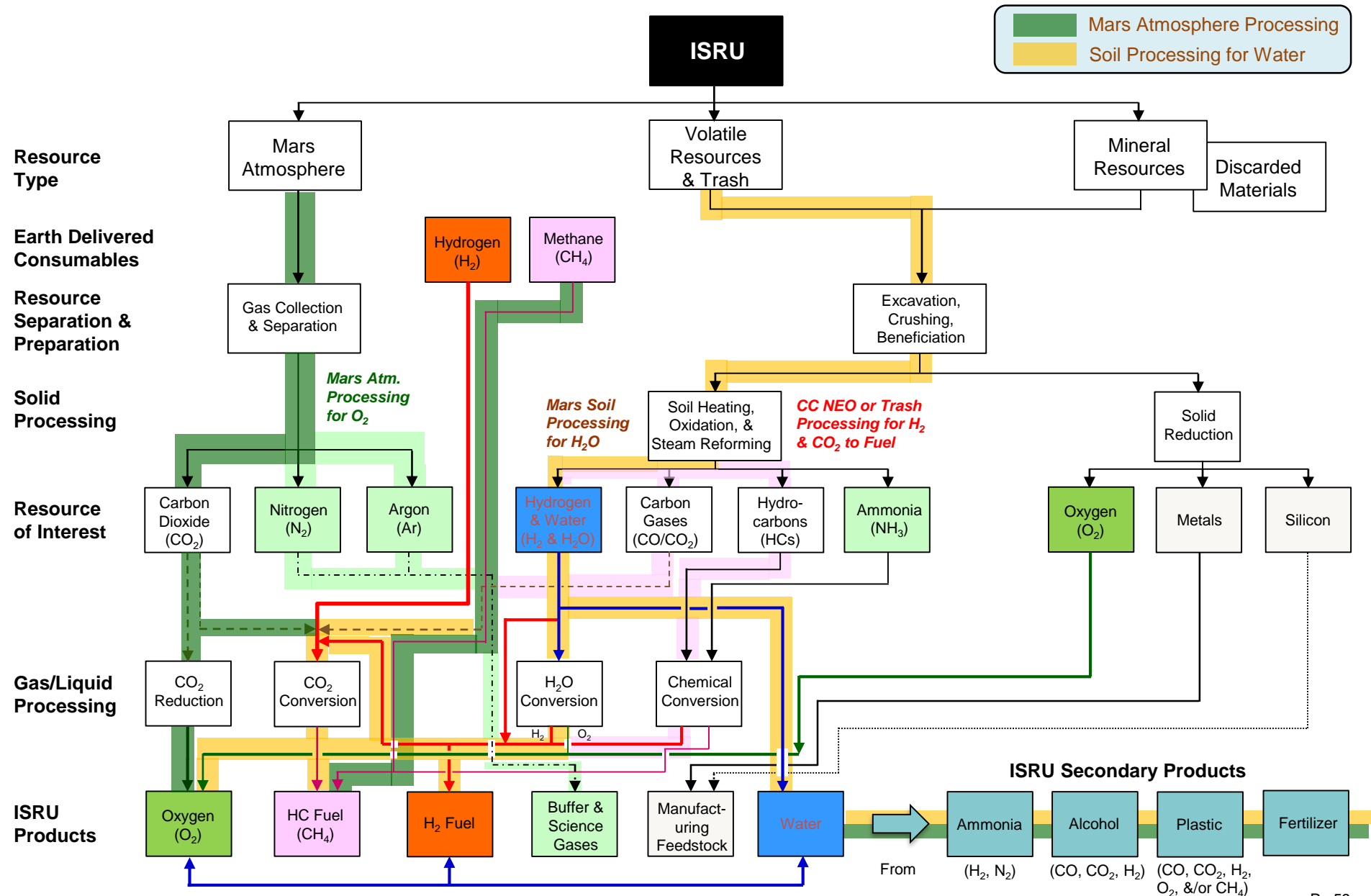
7. Return Mobile Water tank to Rodwell Unit



Current State of the Art for ISRU



ISRU Consumables Production Decision Tree

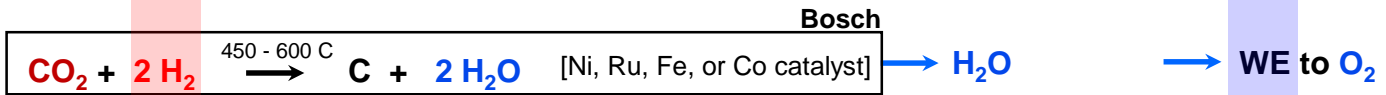
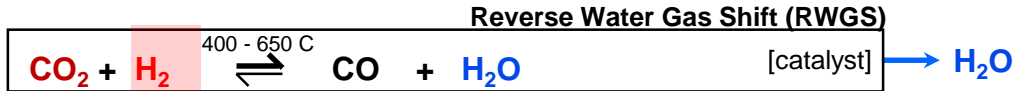
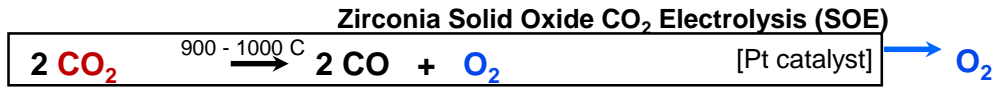




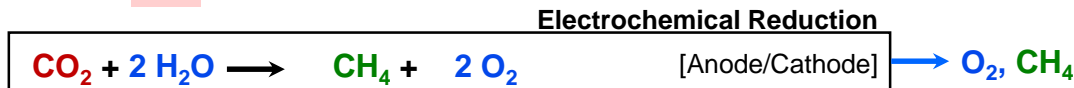
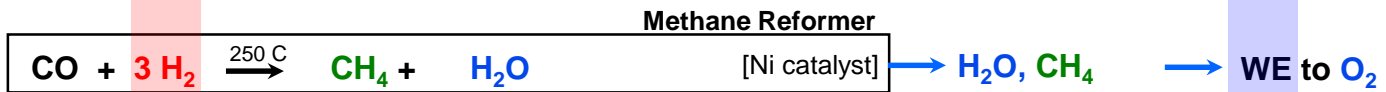
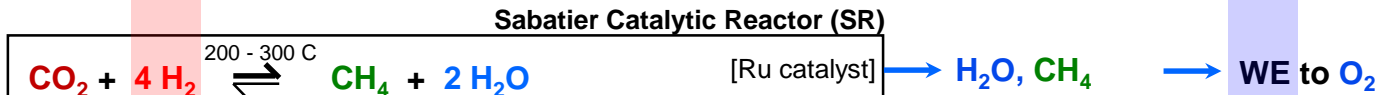
The Chemistry of Mars ISRU



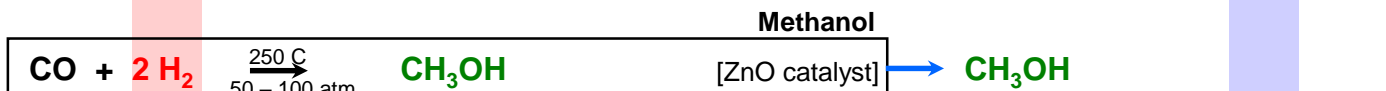
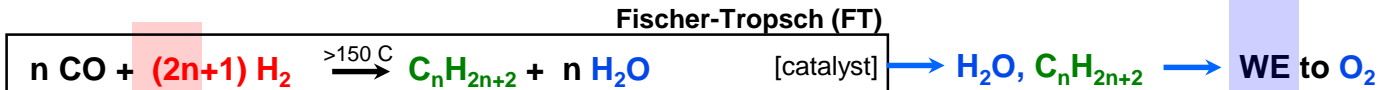
Oxygen (O₂)
Production Only



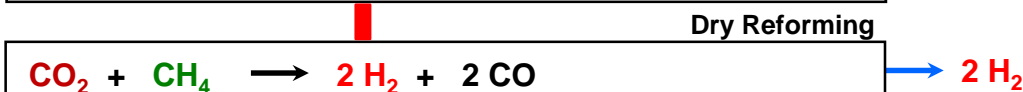
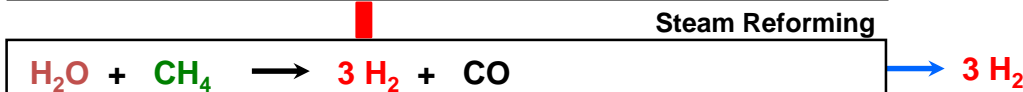
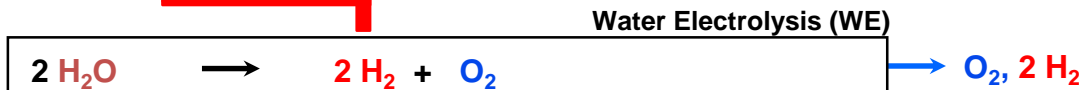
Oxygen (O₂) &
Methane (CH₄)
Production



Other
Hydrocarbon
Fuel Production



Oxygen (O₂) &/or
Hydrogen (H₂)
Production



2nd Step

→ WE to O₂

→ WE to O₂

→ WE to O₂

→ WE to O₂

→ WE to O₂

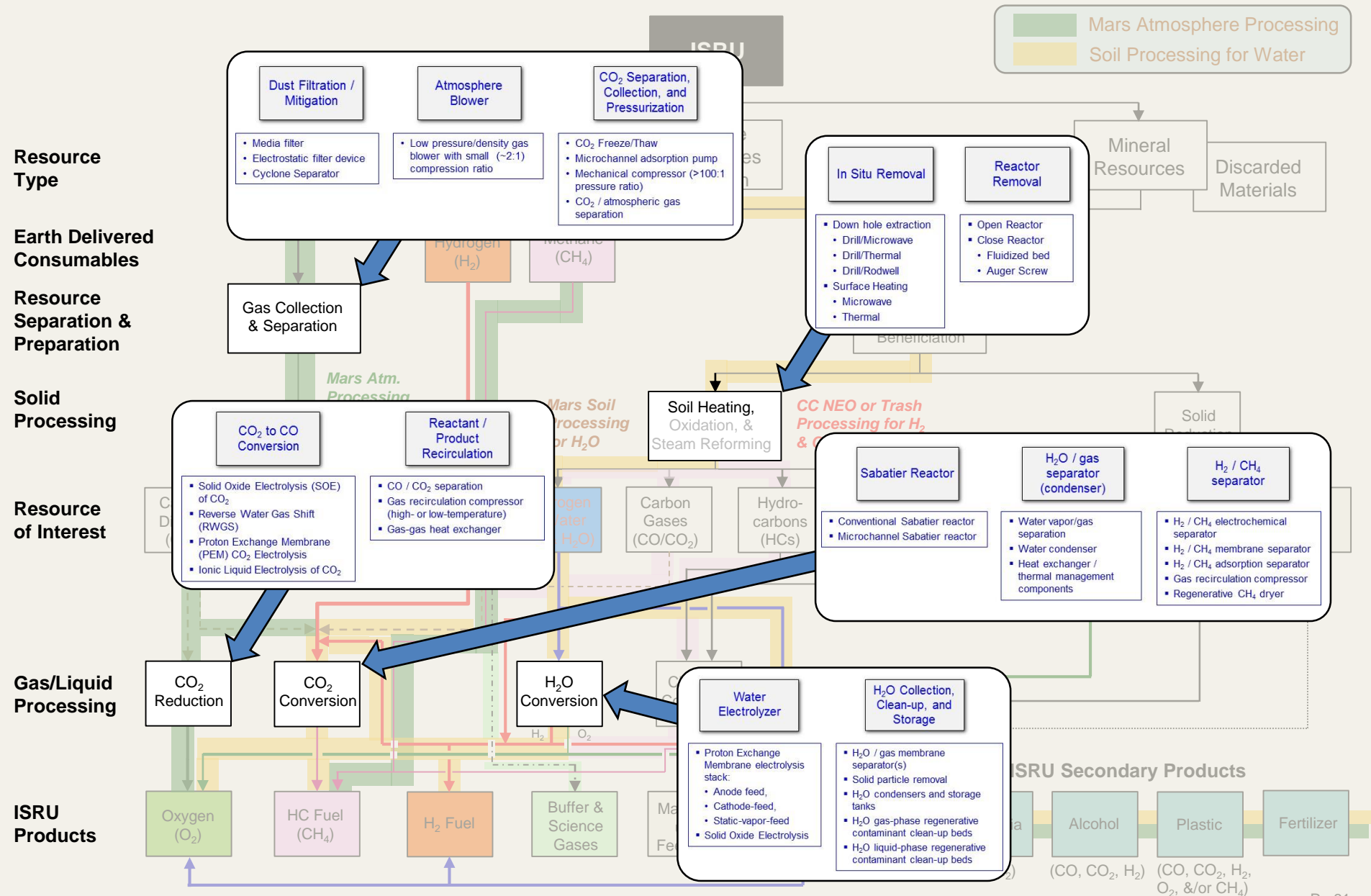
→ WE to O₂

→ WE to O₂



ISRU Consumables Production Decision Tree

Each Decision Has Technical Solution Options





Mars ISRU Propellant Production



Needs

- **Propellant production for human mission ascent (Mars DRA 5.0)**
 - For O₂ only: 2.2 to 3.5 kg/hr O₂; 480 days or 300 days
 - For O₂/CH₄:
 - 0.55 to 0.88 kg/hr CH₄
 - 1.2 to 2.0 kg/hr H₂O; (41 to 66 kg/hr soil @ 3% H₂O by mass)
- **Propellant production for Mars Sample Return**
 - 0.35 to 0.5 kg/hr O₂; 420 to 500 days (multiple studies)
 - 0.75 to 1.5 kg/hr O₂; 35 or 137 days (Mars Collaborative Study 4-2012)
- **Propellant production for Mars ISRU Demo**
 - 0.01 kg/hr O₂; 15 operations min. (MOXIE)
 - 0.00004 kg/hr O₂; 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 O₂; 0.01 kg/hr CH₄
 - KSC RWGS/Water Electrolysis: 0.087 kg/hr O₂
 - Pioneer Astronautics (SWE & RWGS): 0.02 kg/hr O₂; 0.01 kg/hr CH₄
(IMISPPS): 0.031 kg/hr O₂, 0.0088 kg/hr CH₄
- **Atmosphere Processing: MARCO POLO (Individual subsystems)**
 - CO₂ Collection: 0.088 kg/hr CO₂
 - CO₂ Processing: 0.066 kg/hr of O₂; 0.033 kg/hr of CH₄; 0.071 kg/hr of H₂O
 - Water Processing: 0.52 kg/hr H₂O; 0.46 kg/hr O₂
- **Soil Processing:**
 - Lunar H₂ Reduction - ROxygen Reactor: 5 to 10 kg/hr soil:
 - Lunar H₂ 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 CO₂ 4 kg/hr soil per batch



Large Gap between Needs and Demonstrated



Past Mars ISRU Technology Development

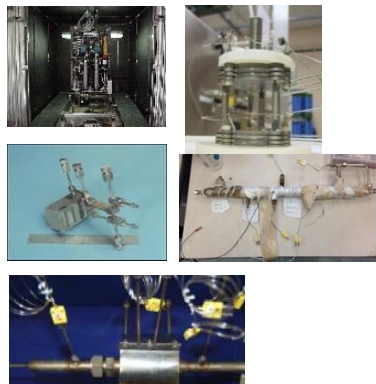


CO₂ Collection & Separation

- 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 (CO₂ freezing) pump (LM, SBIR, KSC)
- Mars atmosphere compressor (MOXIE/SBIR)
- Ionic liquids adsorption/electrochemistry (MSFC, SBIRs)

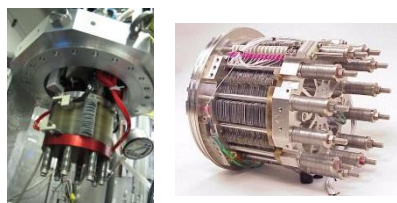
CO₂ Processing

- Solid Oxide CO₂ Electrolysis (NASA, Universities, Industry, SBIRs)
- Low pressure CO₂ 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 O₂/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)



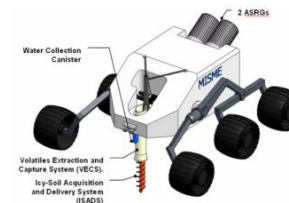


Past Mars-Relevant ISRU Technology Development



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)



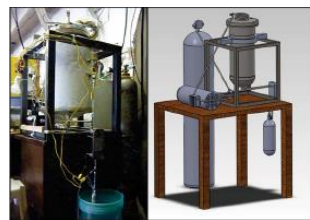
Soil Processing

- H₂ 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



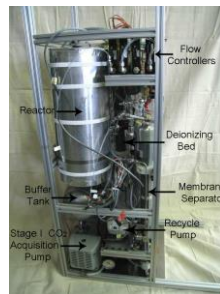
Mars Atmosphere Processing

- 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/ CO₂ Absorption (LMA & JSC)
[Tested under simulate Mars surface conditions]

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

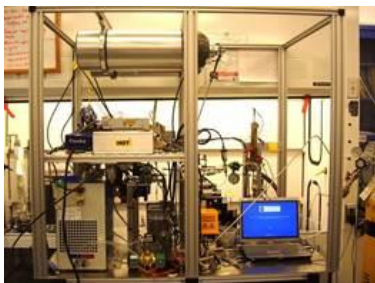


CO₂ Electrolysis (GRC)
[Tested under conference conditions]

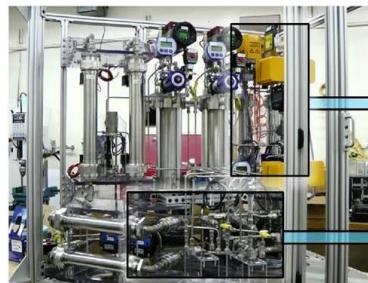
Reverse Water Gas Shift/
 Water Electrolysis
 (KSC & Pioneer Astrobotics)



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



Atm Processing Module
 0.088 kg/hr CO₂
 0.033 kg/hr CH₄
 0.071 kg/hr H₂O



Water Processing Module
 0.52 kg/hr H₂O
 0.46 kg/hr O₂
 0.058 kg/hr H₂

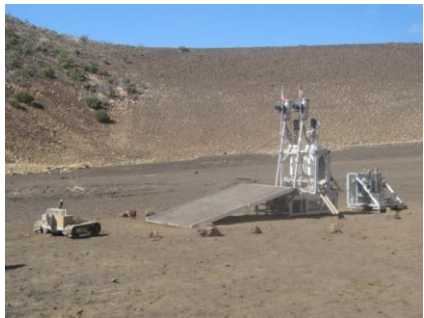


Past Mars-Relevant ISRU System Development



Lunar/Mars Soil Processing

- 1st Gen H₂ Reduction from Regolith Systems (NASA, LMA)

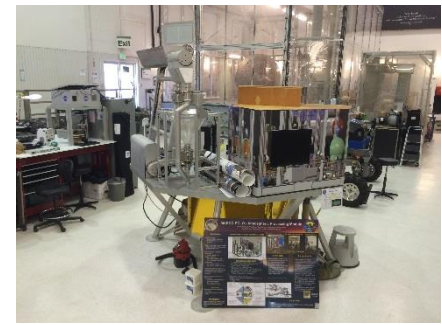


ROxygen H₂ Reduction
Water Electrolysis
Cratos Excavator



PILOT H₂ 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 H₂O
(3% water by mass)



ISRU Development & Missions



ISRU Related Development within NASA



ISRU

Resource Assessment/ Prospecting

Resource Acquisition

Resource Processing/ Consumables

In Situ Construction

Manufacturing with ISRU Feedstock

In Situ Energy

- 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

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

- 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

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

- 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

- 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

TRL 1-3

TRL 4-6

Flight Dev

Moon

Mars

NEAs

TRL 1-3

TRL 4-6

Flight Dev

Mars

NEAs

TRL 1-3

TRL 4-6

Flight Dev

Moon

Mars

TRL 1-3

Moon

Mars

TRL 1-3

TRL 4-6

Flight Dev

Moon

Mars

ISS



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

Science Mission Directorate

- ROSES

Planetary Science Division

- Mars 2020

- PICASSO
- MatISSE
- SSERVI
- Orbital and surface missions

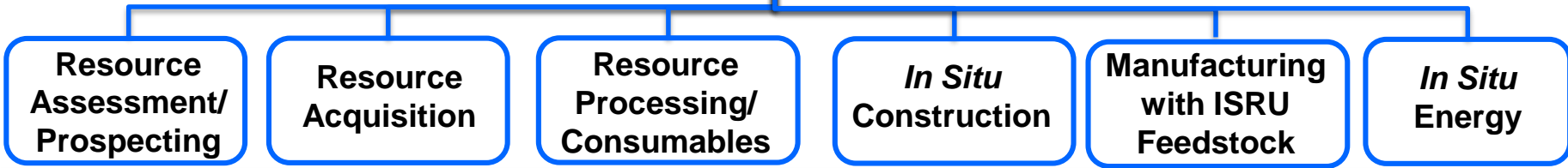
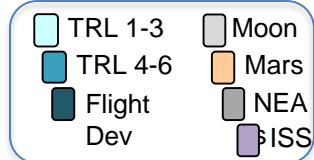
STRG = Space Technology Research Grants
 SBIR = Small Business Innovation Research
 STTR = Small Business Technology Transfer
 NSTRF = NASA Space Technology Research Fellowships
 ECF = Early Career Fellowship
 ESI = Early Stage Initiative
 CIF = Center Innovation Fund

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

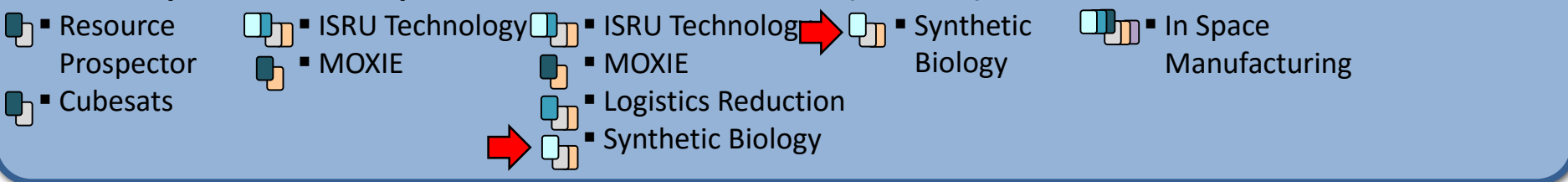


Where Does ISRU-Related Work Reside in NASA?

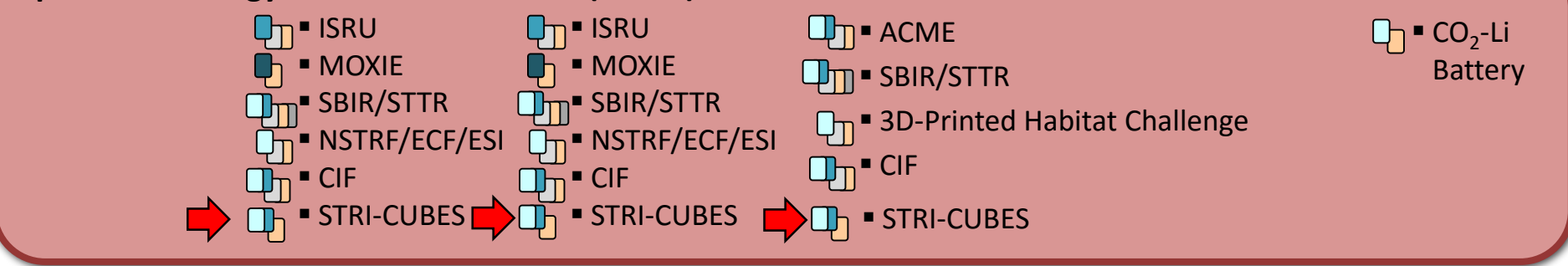
- Projects/Programs, TRL, & Destination



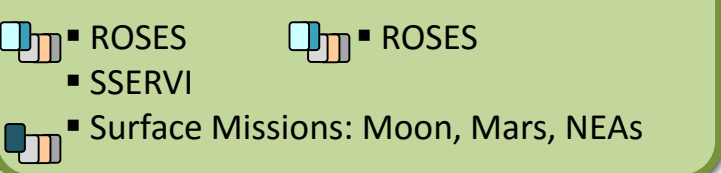
Human Exploration and Operations Mission Directorate (HEOMD)



Space Technology Mission Directorate (STMD)



Science Mission Directorate





ISRU Capabilities Requires Information and Hardware from Other Projects



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)

- Autonomy and Space Robotic Systems
- Solar Array with Storage

- Adv. Manufacturing Technology
- Lightweight Structures and Manufacturing

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, **significant work is needed to mature these technologies**
 - 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.



NASA ISRU Technology Project

Adv. Exploration System/Space Technology Mission Directorate (AES/STMD)



- **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

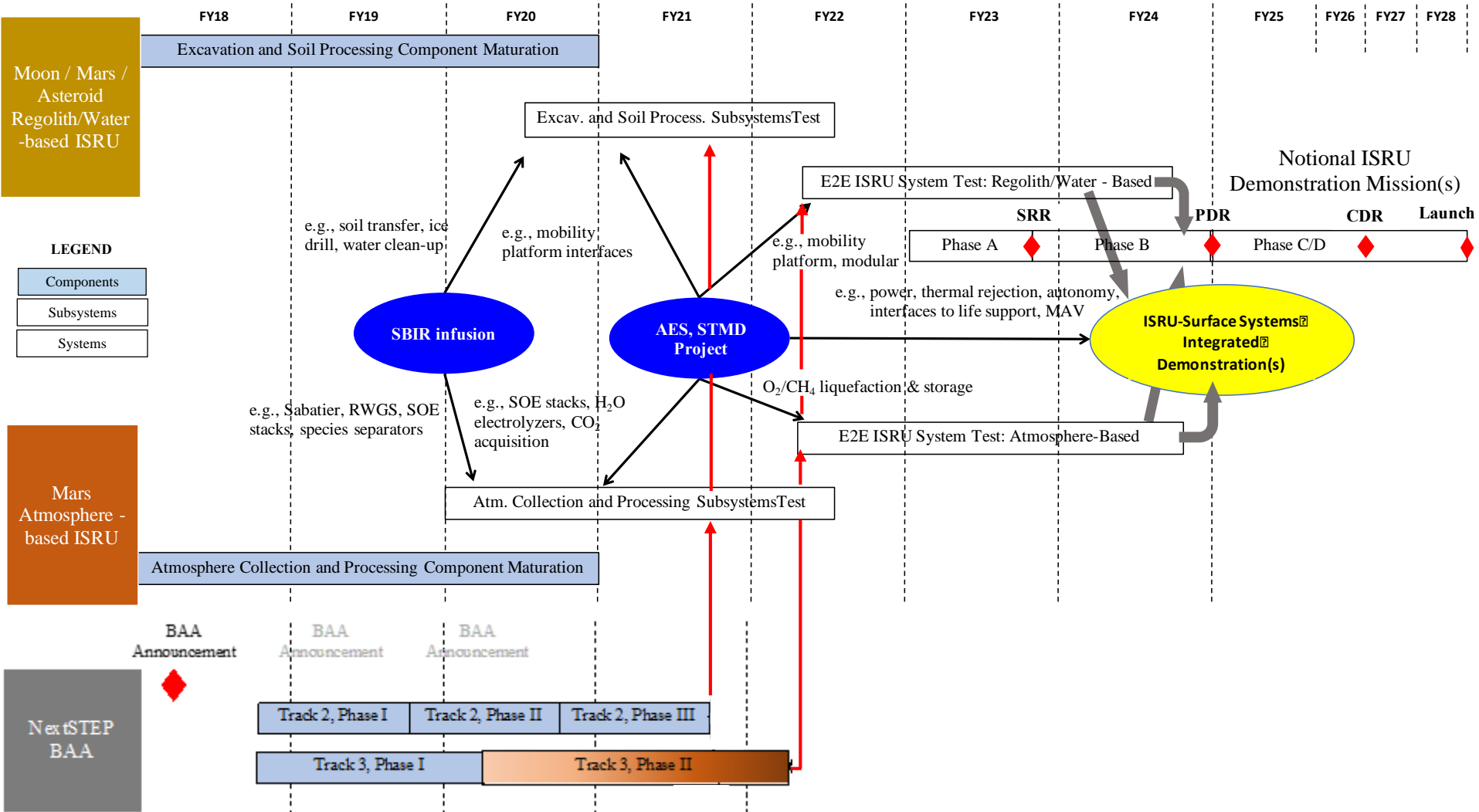
Overall Goals

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





ISRU Product/Resource Processing Options Under Consideration



Oxygen/Fuel Production from Mars Atmosphere

Water/Volatile Extraction From Soils

Oxygen Extraction from Minerals

Metal Extraction from Minerals

Atmosphere Collection

- Dust Filtration
- Gas Separation (CO₂, N₂, Ar)
- Gas Pressurization (0.1 to >15 psia)
 - Pumps/Compressors
 - Cryogenic Separation
 - Adsorption

Chemical Processing

- CO₂ Reduction
 - Solid Oxide Electrolysis
 - Reverse Water Gas Shift
 - Ionic Liquid/PEM Electrolysis
- Fuel Production
 - Sabatier (CH₄)
 - Fischer Tropsch
 - Alcohols
 - Ethylene → Plastics
- Water Processing
 - Water Electrolysis (PEM vs SOE)
 - Water Cleanup/Deionization

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

- Hydrogen Reduction of Iron Oxides
- Methane Reduction of Silicates
- Molten Oxide Reduction

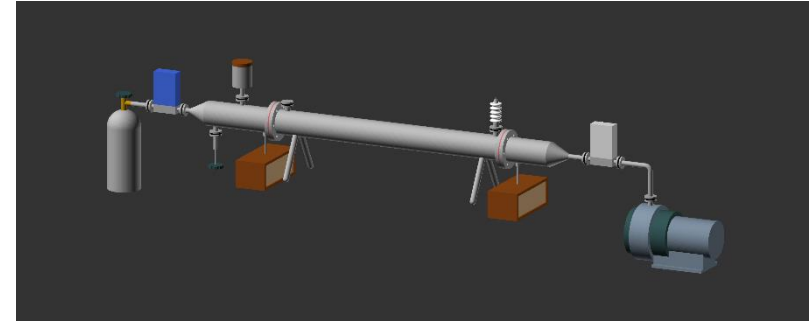
Metal Extraction from Minerals

- Molten Oxide Reduction
- Molten Salt Reduction
- Ionic Liquids/Acids
- Biological Extraction



- **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 – CO₂ Compression

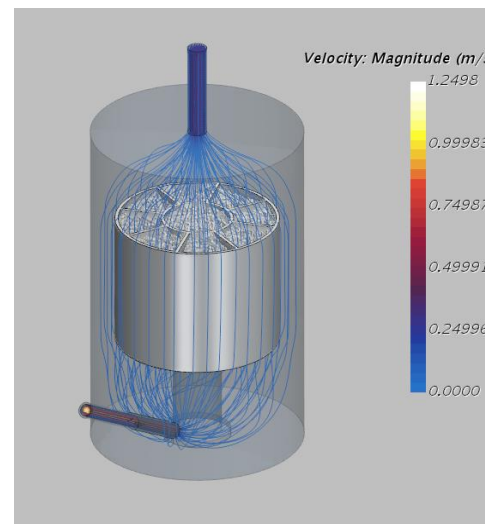


CO₂ Freezer Pump

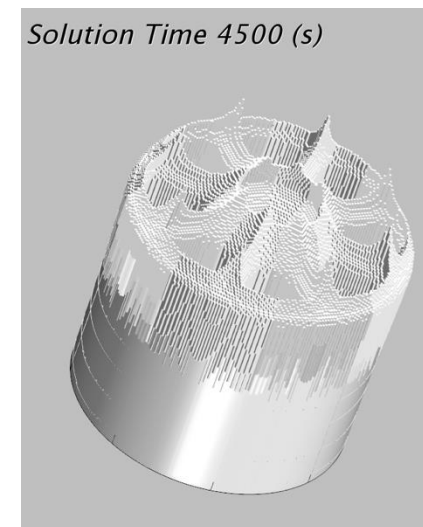
- **Analyzing different cold head designs**
 - Finite element modeling of flow and freezing
 - Compare to existing experimental data and iterate
 - Predicted CO₂ solid mass matches experimental results
- **Three ‘ferris wheel’ copper cold heads fabricated for testing**

Rapid Cycle Adsorption Pump

- **Developing Thermal Desktop / Sinda / Fluent 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 / Fluent
 - 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



CO₂ solid on cold head



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



- **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



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



Centaur 2 w/ APEX positioning of Badger percussive bucket



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



Solid Oxide Electrolysis (SOE) of CO₂

■ 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

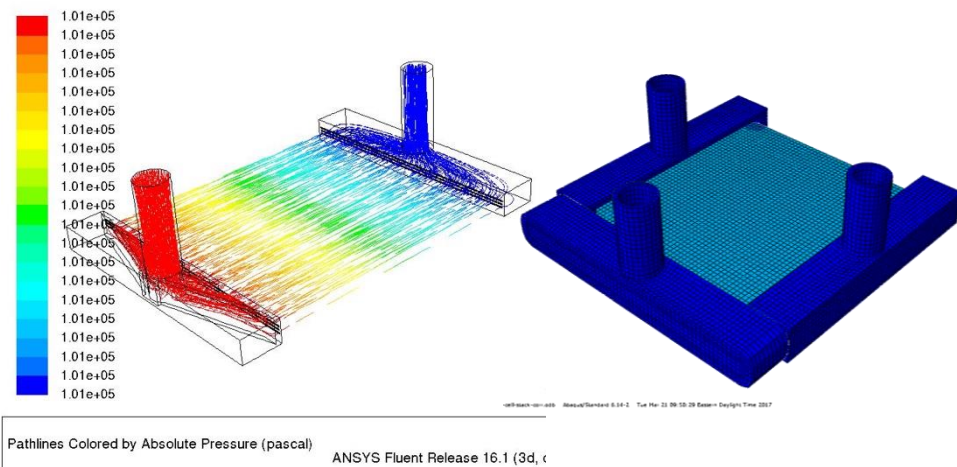
• SOE stack scaling limitations

- Use models to predict limits of active area per cell, # cells per stack

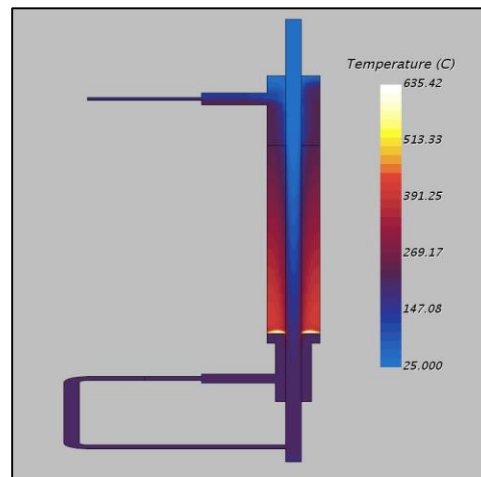
Sabatier Reactor for CH₄ Production

- Sabatier reactor analytical model
- Reviewing state-of-the-art of conventional and microchannel reactor designs
- Catalyst pellets life investigation

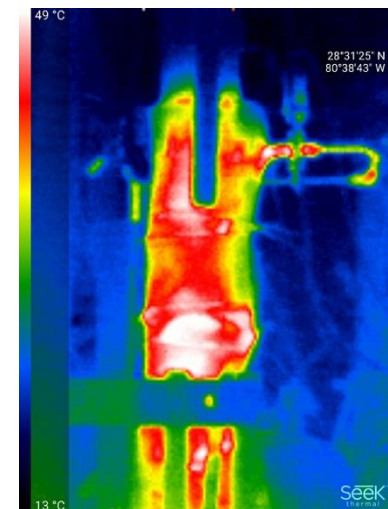
- Analyze new and used catalyst pellets and identify nature of changes over time
- Guide assessment of longevity/life challenges



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.

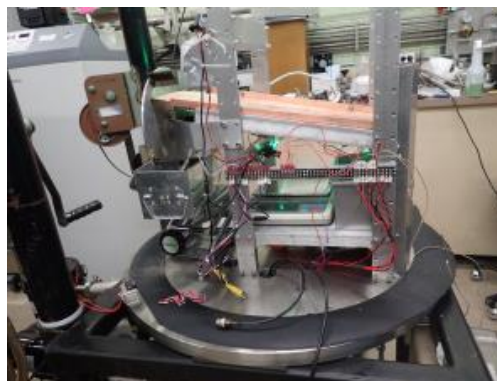


Resource Processing / Consumable Production

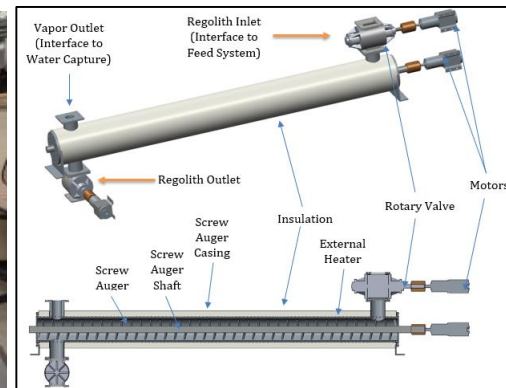


Open Reactor Concept

- **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**



Open 'air' dryer at NASA GRC



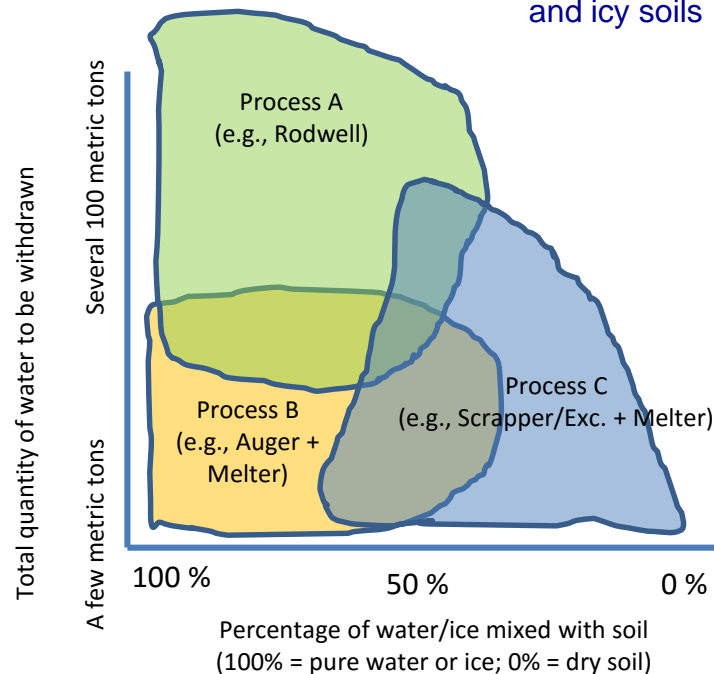
Terrestrial auger soil dryer to be modeled for application to Mars and Lunar hydrated and icy soils

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)





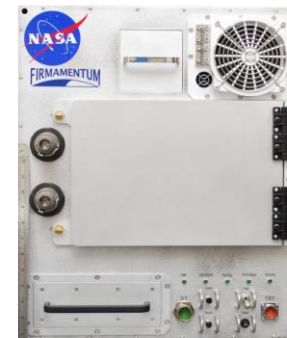
In-Space Manufacturing (AES/GCD ISM Project)



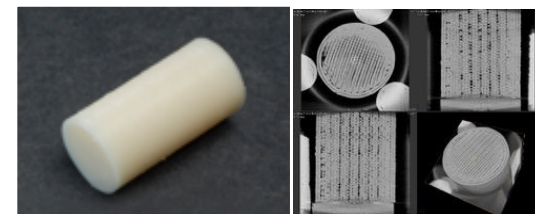
- **In-Space Manufacturing & Repair Technologies**
 - What: Work with industry and academia to develop on-demand manufacturing and repair technologies for in-space applications.
 - Two polymer printers currently on ISS' Solicitation for 1st Gen. Multi-material 'FabLab' Rack capable of metallic and electronic 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).

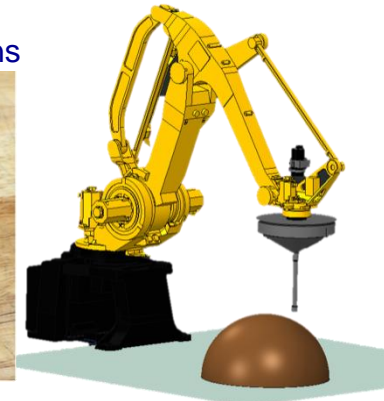


Additive Construction with Mobile Emplacement (ACME) Automated Construction for Expeditionary Structures (ACES)



- **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

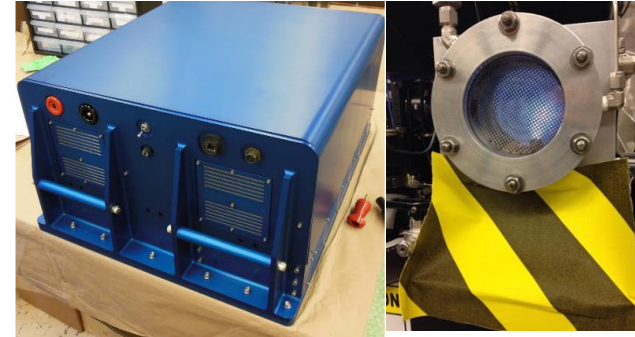


Autonomy (AES Autonomous Systems and Operations Project)

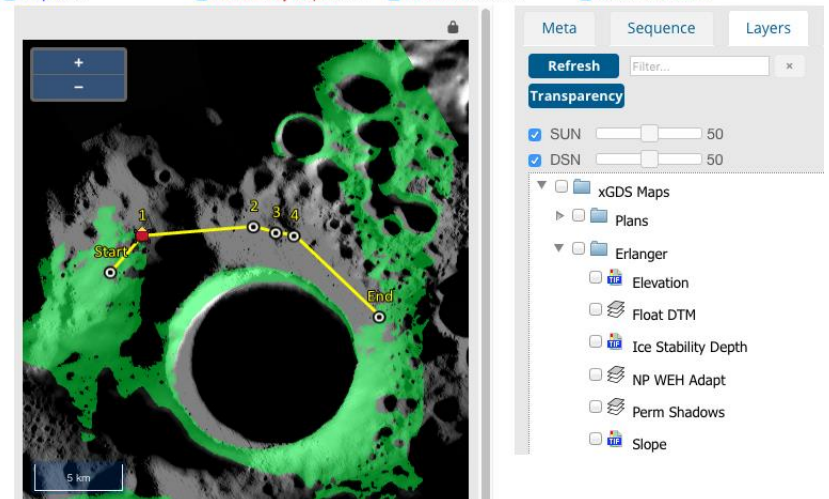


- **Autonomous Robotic Operations Planning**
 - What: Enhance existing tools for use during in-transit, orbital crewed missions
 - Fixed-based kinematics path-planning
 - ISRU relevance: Excavation and soil transport
- **Vehicle Systems Automation**
 - What: Integrate health management, scheduling and 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

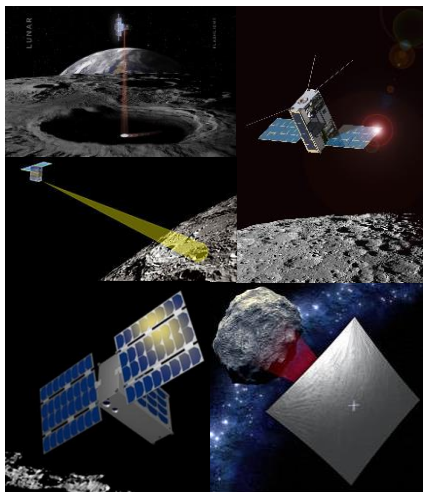


Resource Prospector – RESOLVE Payload

- 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

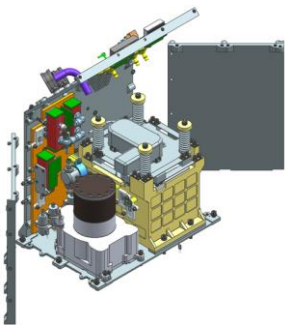
Cubesats (SLS EM-1 2018)

- 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





Resource Prospector



Resource Characterization

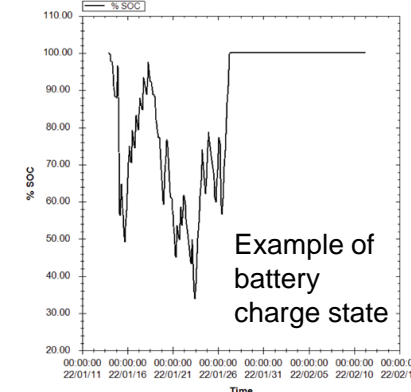
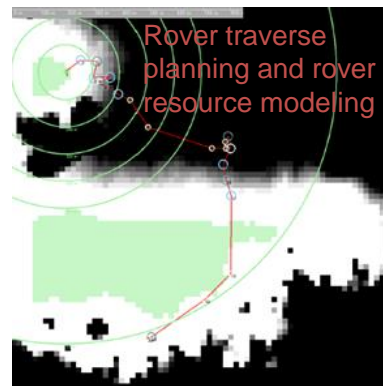
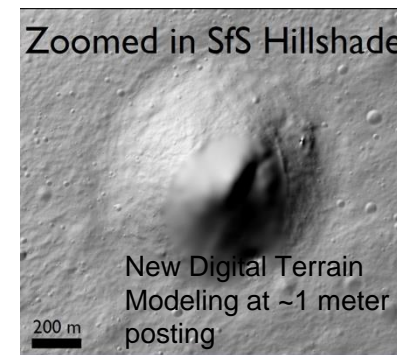
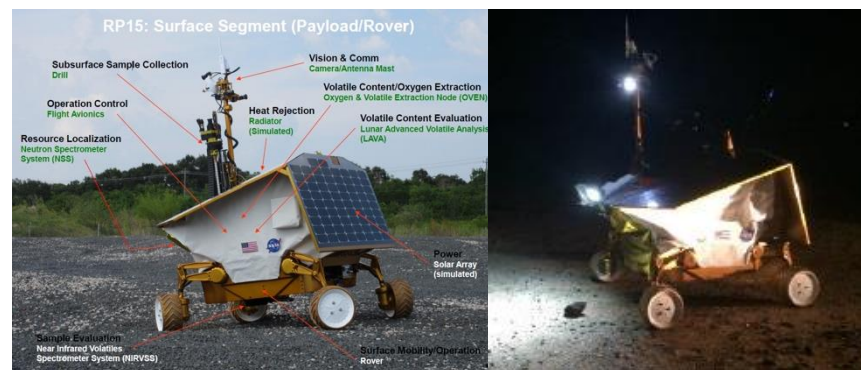
- What: Develop an instrument suite to locate and evaluate the physical, mineral, and volatile resources at the lunar poles
 - Neutron Spectrometer & Near Infrared (IR) to locate subsurface hydrogen/surface water
 - Near IR for mineral identification
 - Auger drill for sample removal down to 1 m
 - Oven 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





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

- O₂ production – >1g/hr per cell (10 cells)
- Operational Cycle – >45 cycles w/ no failures
- O₂ 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)

