Novel Concepts for Extraction and Capture of Water from Martian Regolith

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Space Resources Roundtable (SRR)
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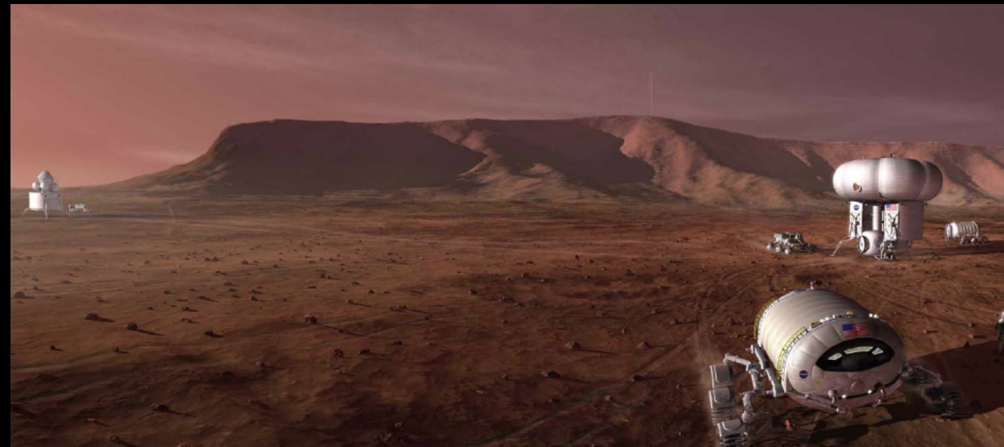
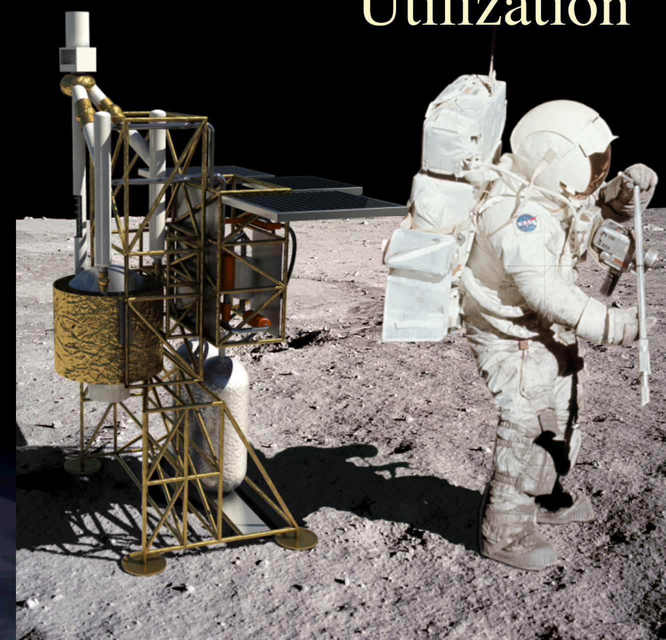
Living off the Land



In-Situ Resource Utilization



Bootstrapping Exploration

NASA Office of Chief Technologist
Technology Roadmaps
available at:
2015nasatechroadmaps.taurigroup.com

Public comments being accepted until June 10th

ISRU technology included in
Technology Area 7 – Human Exploration
Destination Systems

7.1 – In Situ Resource Utilization
7.1.2 – Resource Acquisition: Technology Candidates

TA	Technology Name	Description
7.1.2.5	Cutting Tools for Cold/Hard Regolith and/or Rock/Metal	Dig or drill down through hard or frozen regolith, rock, or metals to gather resource.
7.1.2.6	Long-Life or Self-Renewing/Repairing Cutting Edges	Cutting edges that can either be sharpened in place, preferably as part of natural use, or continually renewed by discarding used or dulled edge.
7.1.2.7	Discrete Element Method to Model Regolith	Lagrangian modeling of individual soil grains discretely using contact force and contact torque equations.
7.1.2.8	Eulerian Modeling of Regolith	Eulerian modeling of soil as a continuum using constitutive equations.
7.1.2.9	Pneumatic Excavation and Material Transport	Gather and transport unconsolidated regolith using pneumatics.
7.1.2.10	Auger Material Transport	Transfer and transport unconsolidated regolith.
7.1.2.11	Magnetic Material Transport	Transfer and transport unconsolidated regolith.
7.1.2.12	Regenerable/Scroll Media Filtration	Use filter media to remove dust from incoming gas stream; filter media are regenerable or can scroll to replace spent filter.
7.1.2.13	Cyclone Dust Separation	Use cyclones to remove dust from incoming gas stream.
7.1.2.14	Inertial Impactor Dust Separation	Use orifices and impaction plates or bands to collect particulate matter above a certain particle cut size; impaction plates or bands can be cleaned off by wipers or scrapers once loaded.
7.1.2.15	Electrostatic Separation	Use electrostatics to remove dust from incoming gas stream.
7.1.2.16	Electrostatic Beneficiation	Use electrostatics to separate regolith by particle sizes or by mineral content.
7.1.2.17	Magnetic Beneficiation	Use magnetism to separate regolith particles by mineral content.
7.1.2.18	Non-Clogging and/or Self-Cleaning Sieves	Process raw regolith through multiple sieves to obtain desired particle size range for processing.
7.1.2.19	Crushers/Grinders for Rock and Metal	Crush or grind large, hard resources to reduce to smaller particles.
7.1.2.20	Molten Metal Transport	Crucible, ladle, and bottle storage technologies for melting, storing, and transporting molten metal derived from ISRU and recycling sources.
7.1.2.21	Molten-to-Powder Metal Technologies	Gas atomizer for producing spherical powdered metal to convert molten metal to powdered feedstock for manufacturing.

Example Technology Candidate Snapshot

57 in 7.1 ISRU
155 total in TA07

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

7.1.2.5 Cutting Tools for Cold/Hard Regolith and/or Rock/Metal

TECHNOLOGY

Technology Description: Dig or drill down through hard/frozen regolith, rock, or metals to gather resources.

Technology Challenge: Ability to generate reaction force using other than mass offset. Longevity of bit, stem, shank, and other dynamically loaded materials in extreme temperatures (down to 40 K in lunar polar regions) – metal embrittlement occurs at these temperatures. Effective waste material removal during drilling (terrestrial deep digging typically uses large amounts of consumables such as water or compressed gas).

Technology State of the Art: Terrestrial mining, drilling, and deep digging equipment achieves deep depths and large rates of mass excavated, but relies on high-mass machines to provide reaction force and high power to penetrate hard materials.

Parameter, Value:	TRL
Terrestrial 'small' excavator mass: 10 to 20 kilogram vehicle mass per kilogram per hour excavation rate; Terrestrial peak power: ~ 0.07 kW power per kilogram per hour excavation rate; Depth: terrestrial depths down to 3,800 meters; Quantity: up to 200,000+ tonnes per day	3

Technology Performance Goal: Need to provide reaction force using means other than pure mass offset, especially on moon or asteroids where gravity is very low. Need to minimize power requirement.

Parameter, Value:	TRL
Mass: < 2 kilogram vehicle mass per kilogram per hour excavation rate; Power: < 0.007 kW per kilogram per hour excavation rate; Depth: 1 to 2 m; Quantity: 0.5 to 1 tonne per day	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solids resource acquisition.

Capability Description: Digging/drilling into cold, hard regolith and drilling in rock and metal ores.

Capability State of the Art: Phoenix Robotic Arm has scooped and trenched icy soils.

Parameter, Value:
Scoop chattered upon reaching icy soils as shallow as 2.5 - 3 centimeters. Trenched as deep as 18 centimeters in non-icy soil.

Capability Performance Goal: Need to acquire water resource from icy soils that are some depth below surface.

Parameter, Value:
Mars: Depth: > 3 centimeters below surface at polar locations;
Quantity rate: 400 kilogram of soil per day (at 8% water content) to > 1,000 kilograms of soil per day (at 3% water content).
Lunar: Depth: > 10 centimeters and as deep as 1 meter;
Quantity rate: 100 kilograms of soil per day (5% water content) to > 550 kilograms of soil per day (1% water content).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 -2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years

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ISRU Enabling Mars Human Exploration

Mars Design Reference Architecture 5.0

- Most recent 'official' Mars architecture
  - Nuclear thermal propulsion for in-space transportation
  - up to 40 tons landed mass
  - LOX/LCH_4 ascent propulsion
- Lists ISRU as *enabling* for robust human Mars missions
  - ~ 25,000 kg oxygen from atmosphere for ascent and life support
- "Atmospheric based ISRU processes less operationally complex than surface based"
  - "…limited concept evaluation to date and Mars surface water property and distribution uncertainty would not allow [Mars soil water processing] to be baselined at this time"

Mars DRA 5 Problem Statements

Challenge 1: Mars surface water property and distribution uncertainty

Challenge 2: Limited concept evaluation to date

Mars Surface Water Property and Distribution Uncertainty

- Orbital observations of Mars, such as Odyssey spacecraft, indicate 2 to 10 wt % water equivalent hydrogen in equatorial regions, and even higher for polar latitudes.
  - Detection : 50 cm depth
- Curiosity results indicate that 1.5 to 3 wt % is present in the surface fines (<150 um fraction) as hydrated minerals: likely amorphous component
  - This component is distributed across surface
- Phoenix results indicated icy soil below 5 cm
  - Accessible subsurface ice likely only available at high latitudes

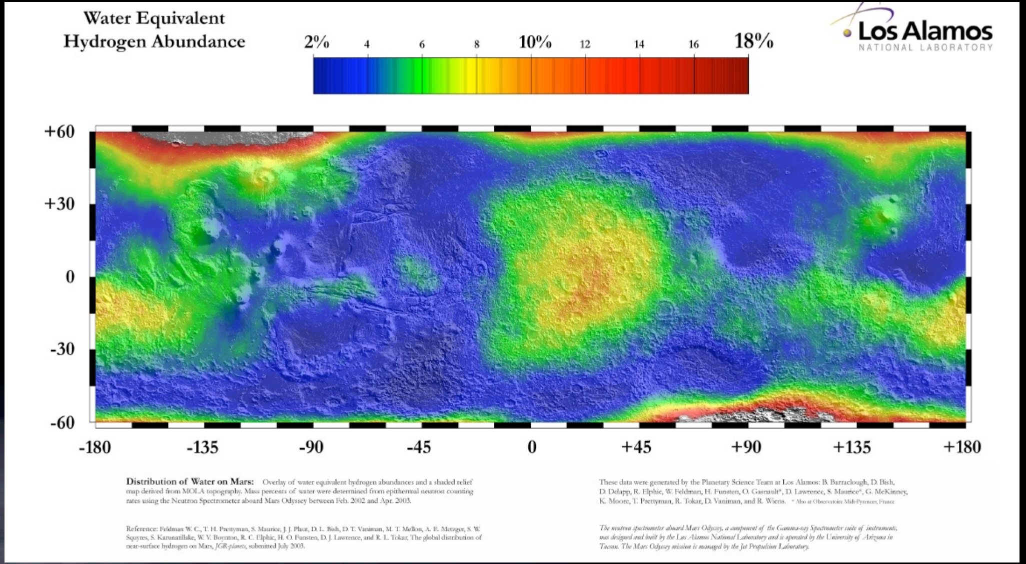


Figure orig. ref: Feldman, W.C., et. al., "The global distribution of near-surface hydrogen on Mars," JGR *planets*, Vol 109, Sept 2004.

Mars Surface Water Property and Distribution Uncertainty

- For near term ISRU prospects, exploration is focused on near - equatorial locations
  - ISRU of water resources targets the hydrates and not the more loosely bound water ice
- Curiosity SAM instrument indicates water release of hydrates occurs across broad peak centered at 300 °C

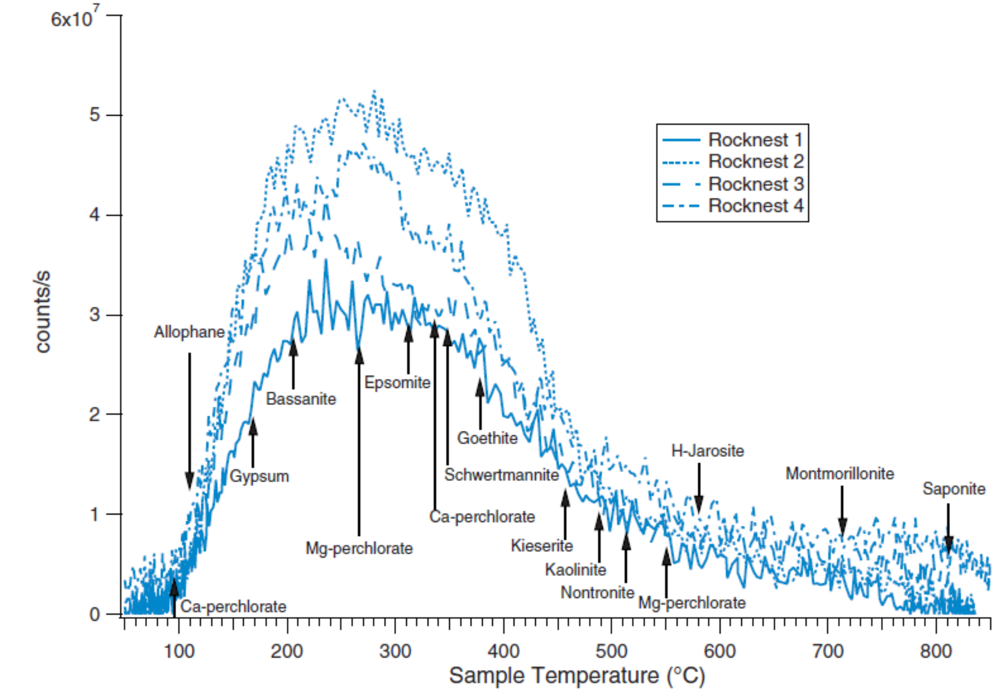


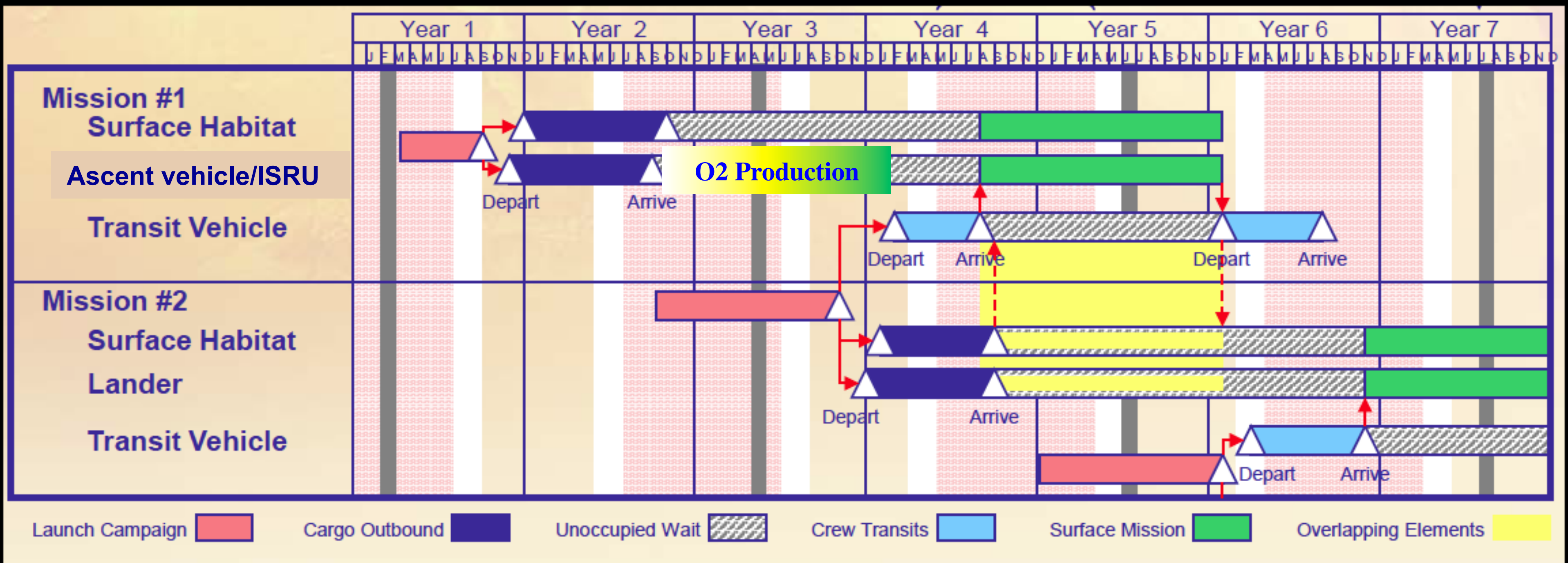
Fig. 2. Water release from Rocknest compared to laboratory measurements of mineral breakdown. Water release versus temperature for Rocknest <150-μm fraction measured by the SAM QMS. Arrows indicate temperatures of water-release peaks determined by laboratory analysis for select hydrous minerals phases under conditions similar to that in SAM (17).

Figure Ref: Leshin, L.A., et. al., "Volatile, Isotope, and Organic Analysis of Martian Fines with the Mars Curiosity Rover," Science, Vol 341, Sept. 2013.

Mars Capability Requirements

Mars DRA 5 – Human Exploration

- Ascent vehicle sent on first opportunity with production plant
  - Ascent vehicle must be fully loaded on Mars surface before crew is launched
  - Oxygen/methane engines at O/F = 3.5 (by mass)



Ref: Drake, B.G., "Human Exploration of Mars Design Reference Architecture 5.0, Executive Summary," Feb, 2009

Mars Missions – Human Exploration

Capability Description	Capability Goal	Description/Basis
Human Mission		
Oxygen production		
Total mass, kg	25,000	22,985 kg for ascent propulsion; 1906 kg for life support
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)
Daily operation, hrs	24	nuclear surface power
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

Ref: Linne, D.L., Sanders, G.B., and Taminger, K., "Capability and Technology Performance Goals for the Next Step in Affordable Human Exploration of Space," AIAA 2015-1650, Jan. 2015

Mars Missions – Robotic Sample Return

Capability Description	Capability Goal	Description/Basis
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
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

Ref: Linne, D.L., Sanders, G.B., and Taminger, K., "Capability and Technology Performance Goals for the Next Step in Affordable Human Exploration of Space," AIAA 2015-1650, Jan. 2015

Mars Processing Technology

Mars Atmosphere and Water Processing - Sabatier

- Sabatier reaction to make oxygen and methane from atmospheric CO_2 and soil water:
  - Conventional catalytic reactors at ~400 °C have shown up to 95% reduction of CO_2
  - O_2/CH_4 at O/F = 2, or add additional water for O/F = 4

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$
$$2H_2O \rightarrow 2H_2 + O_2$$
$$CO_2 + 2H_2 \rightarrow CH_4 + O_2$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$
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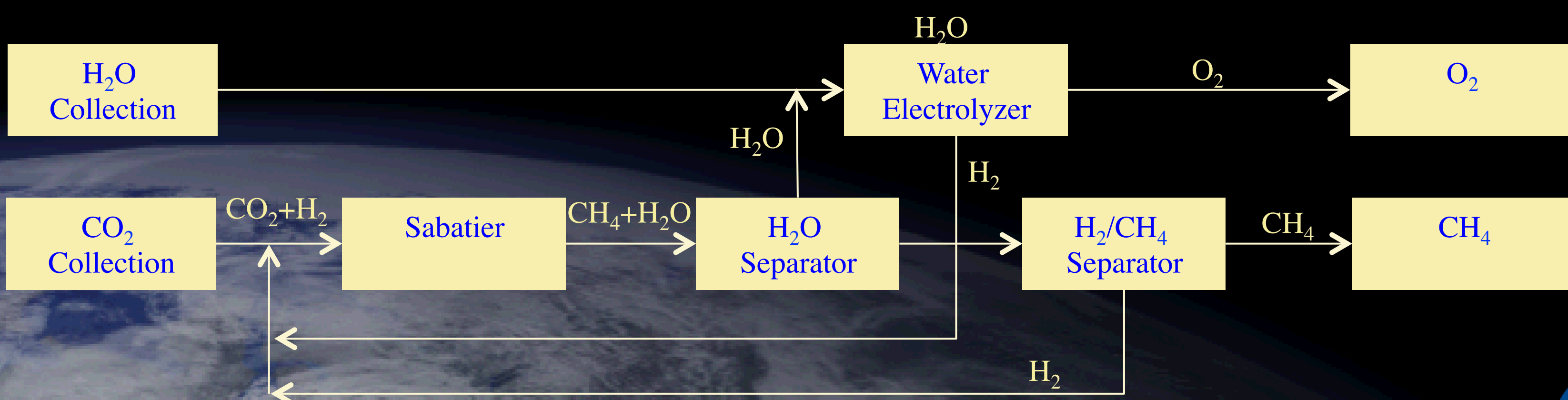
$$CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$$



Mars Atmosphere and Water Processing

	Human Mission		Robotic Sample Return	
all numbers in kg/hr	**OF = 2:1**	**OF = 4:1**	**OF = 2:1**	**OF = 4:1**
CO_2 into Sabatier reactor	3.2	1.6	0.66	0.33
H_2 into Sabatier reactor	0.30	0.15	0.06	0.03
H_2O out of reactor	2.48	1.24	0.51	0.25
CH_4 out of reactor	1.1	0.55	0.23	0.11
CO_2 out of reactor	0.16	0.08	0.033	0.016
H_2 out of reactor	0.029	0.139	0.006	0.029
additional H_2O into electrolyzer		1.24		0.25
H_2O electrolyzed	2.48	2.48	0.51	0.51
CO_2 from atmosphere	**3.2**	**1.6**	**0.66**	**0.33**
H_2O from soil		**1.24**		**0.25**
Soil processed (3% H_2O content)		41		8.3
Soil processed (8% H_2O content)		16		3.1

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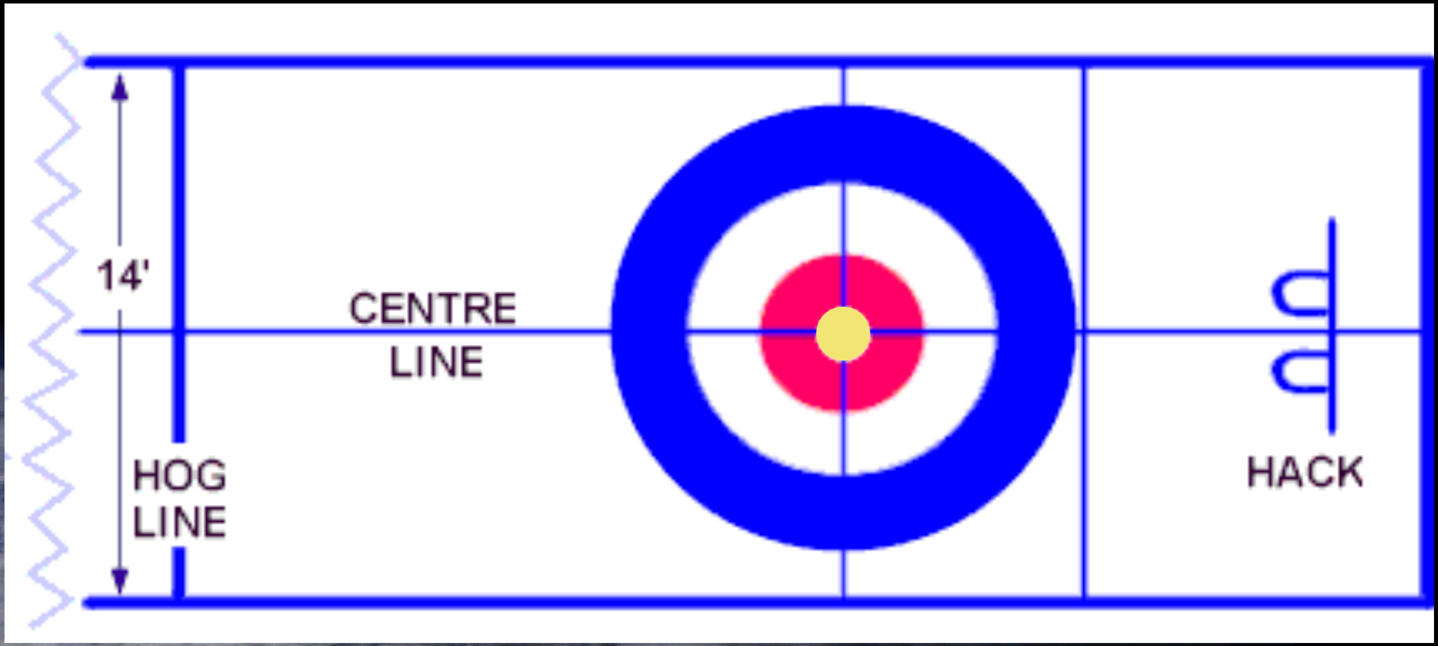
Mars Atmosphere and Water Processing

Mission	Water Content %	Regolith Acquisition Rate, kg/day	Excavation Depth, cm	Common area analogy (based on Curling Ice)
Robotic Sample Return	3 8	67 25	2 5	2 Red circles 5 Buttons
Human Mission	3 8	992 372	2 5	Hog line to Back line White Circle



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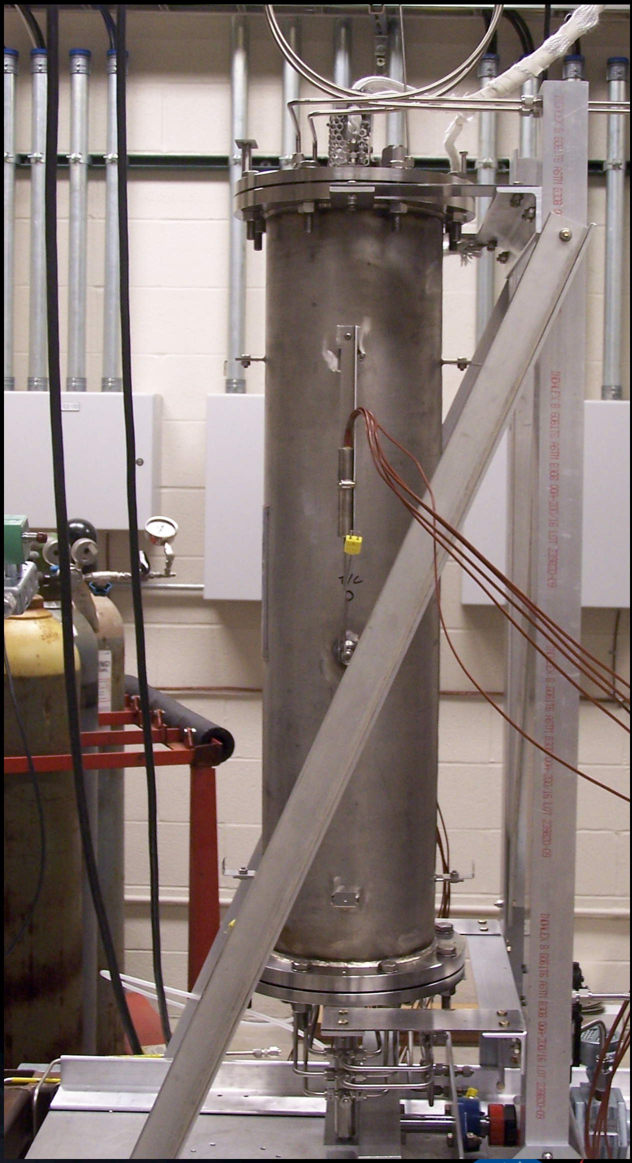
Challenge 2: "Limited concept evaluation to date"

"Limited Concept Evaluation to Date"

- Lunar regolith O_2 extraction processing experience
  - Lunar regolith is fluidized and heated to high temperatures with H_2 to produce H_2O from iron-bearing minerals
- Mars similarity concept:
  - soil placed in fluidized bed reactor
  - heated to moderate temperatures
  - inert gas flow used to fluidize the bed and help with water desorption

Mars Soil Reactor Modeled after Lunar Reactors - Challenges

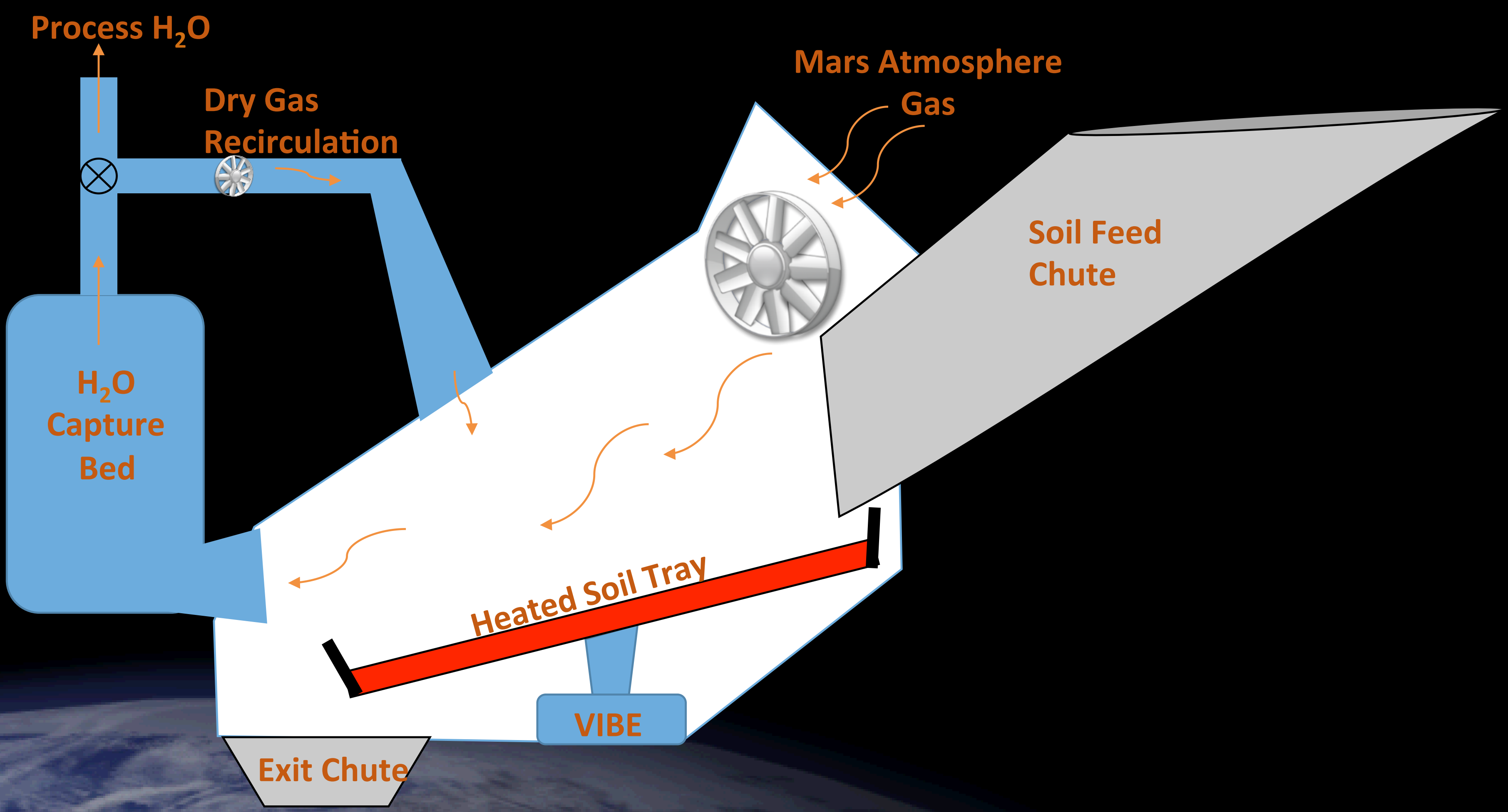
- High-temperature dusty seals
  - Biggest challenge of lunar ISRU reactors
  - More moderate temperatures required for water extraction still does not solve the dust challenge
- Working gas requires downstream separation and recycling to reduce consumables loss
- High aspect ratio reactor
  - Optimized for lunar fluidized bed process to minimize required gas flow
  - Different shape may be better for water extraction
- Batch process heating thermally inefficient



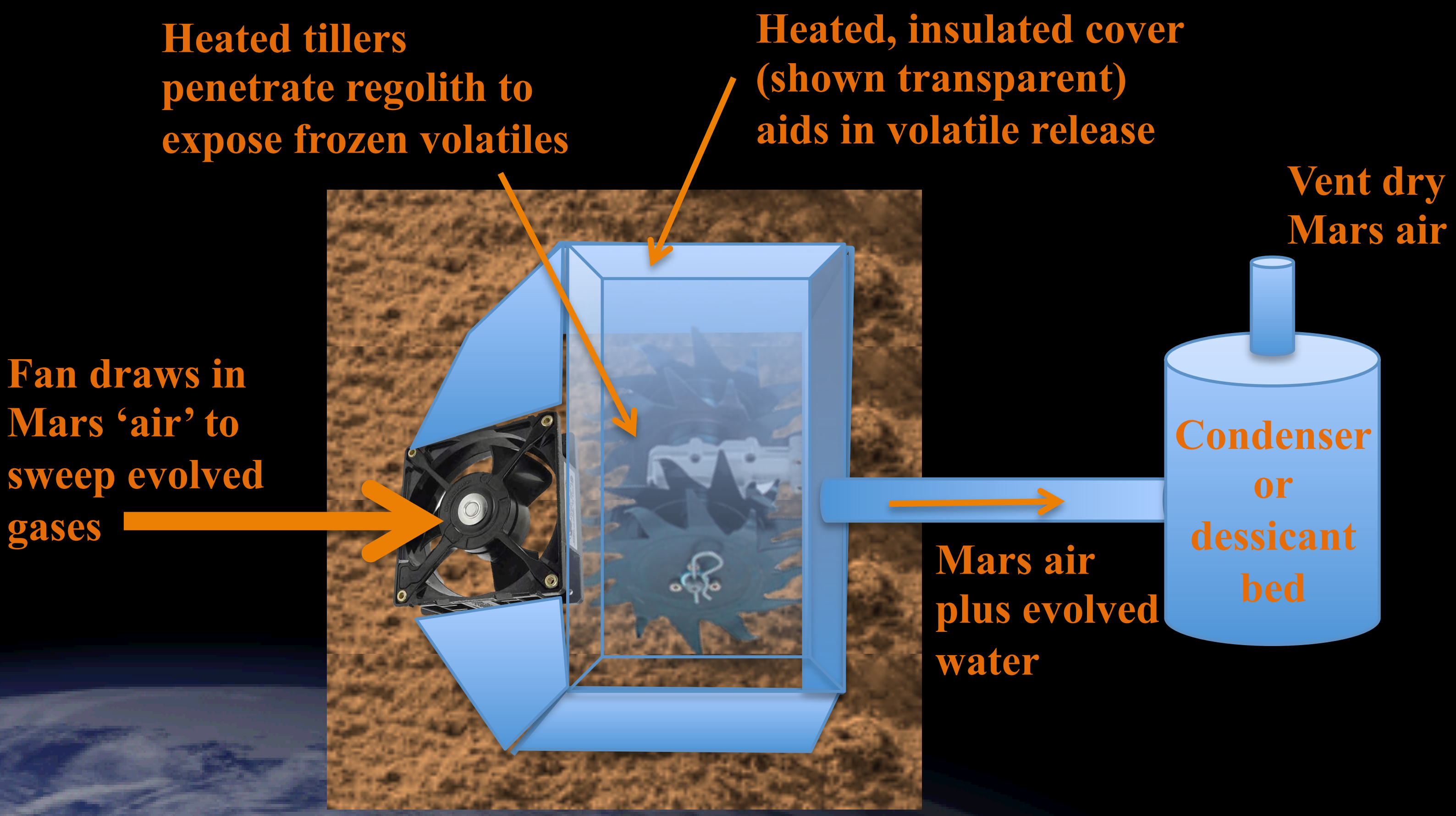
New Mars Soil Water Capture Concept

- Eliminate need for repeated sealing of hot, dusty seals
  - Accept that not all evolved water will be captured
- Use Mars air as working gas
  - Do not have to recover/recycle as the air is ‘free’
- Heat soil in small quantities/at granular level
  - Reduces residence time and increases thermal efficiency

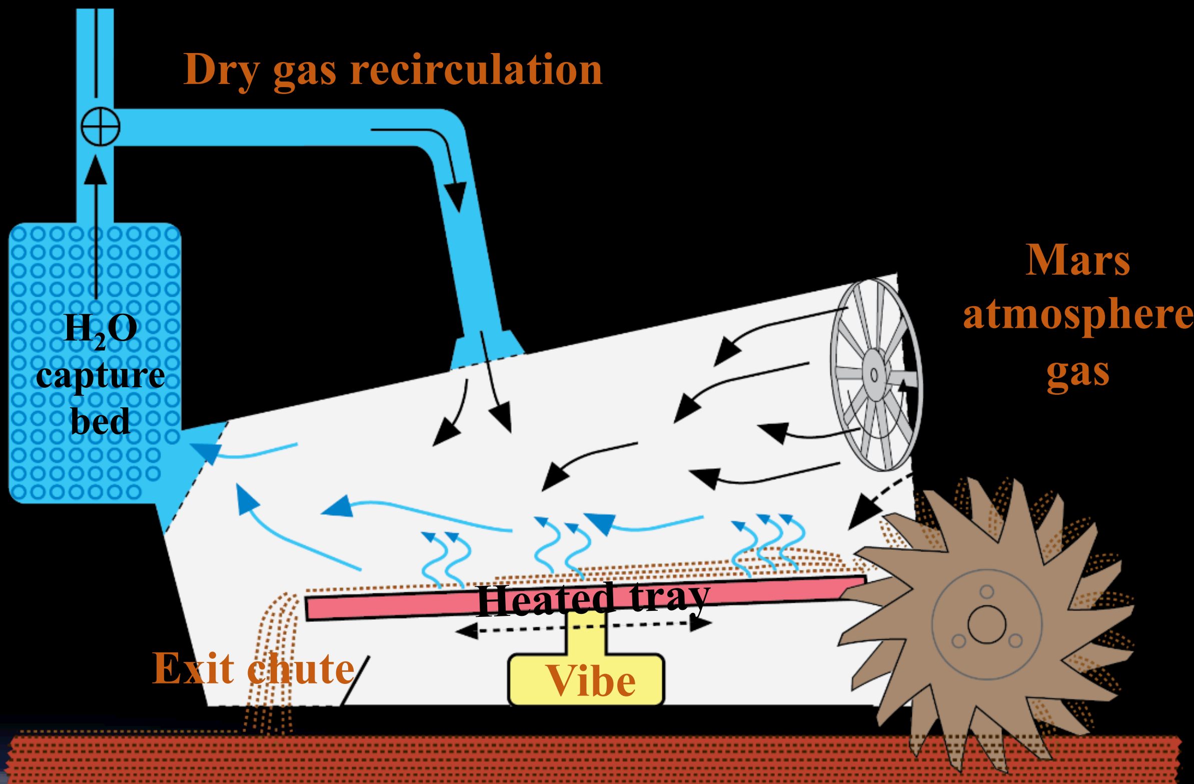
'Open Air' Mars Water Harvester Concept



'Open Air' Mars Water Harvester Concept II



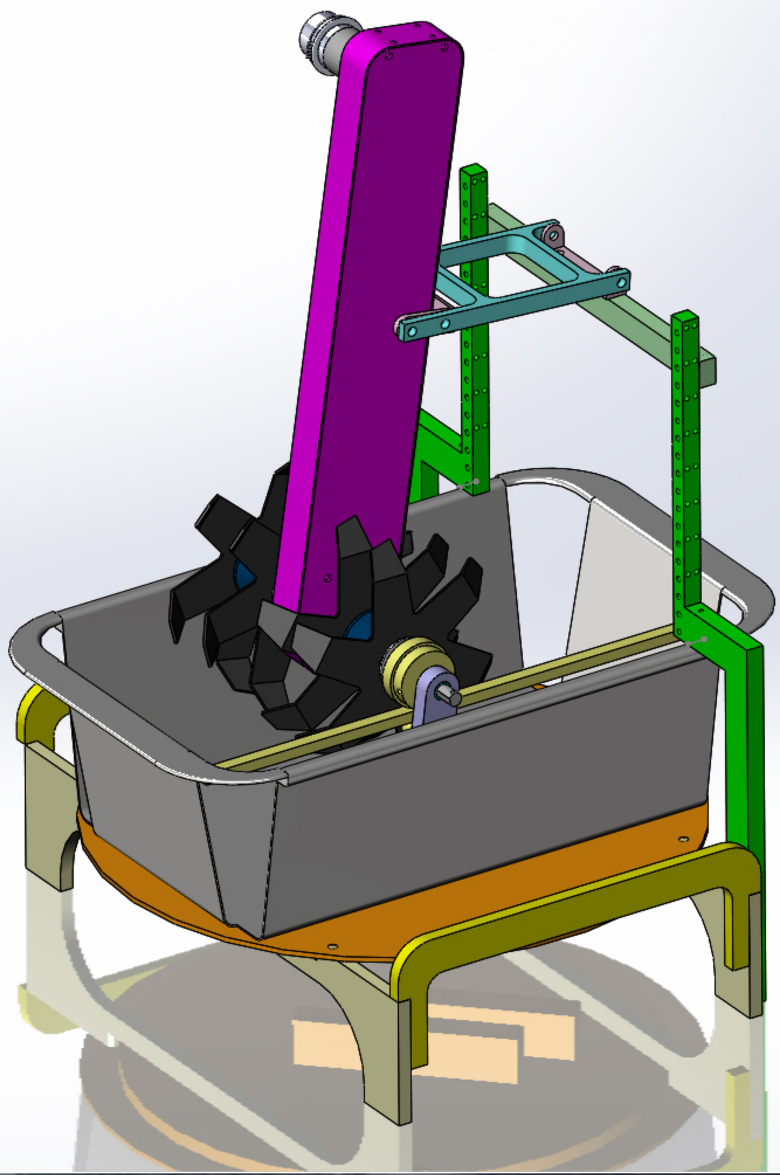
‘Open Air’ Mars Water Harvester Concept III



Mars Atmosphere Chemistry Simulator (MACS) Facility

- Mars pressure
  - 5 to 8 torr
- Mars gas mixture
  - ~96% CO_2, 2.5% N_2, 1.6% Ar
- Thermal shroud (not shown) for Mars temperature
  - -70 °C at night
  - ~ 0 °C daytime high

Mars Water Harvester Test Hardware



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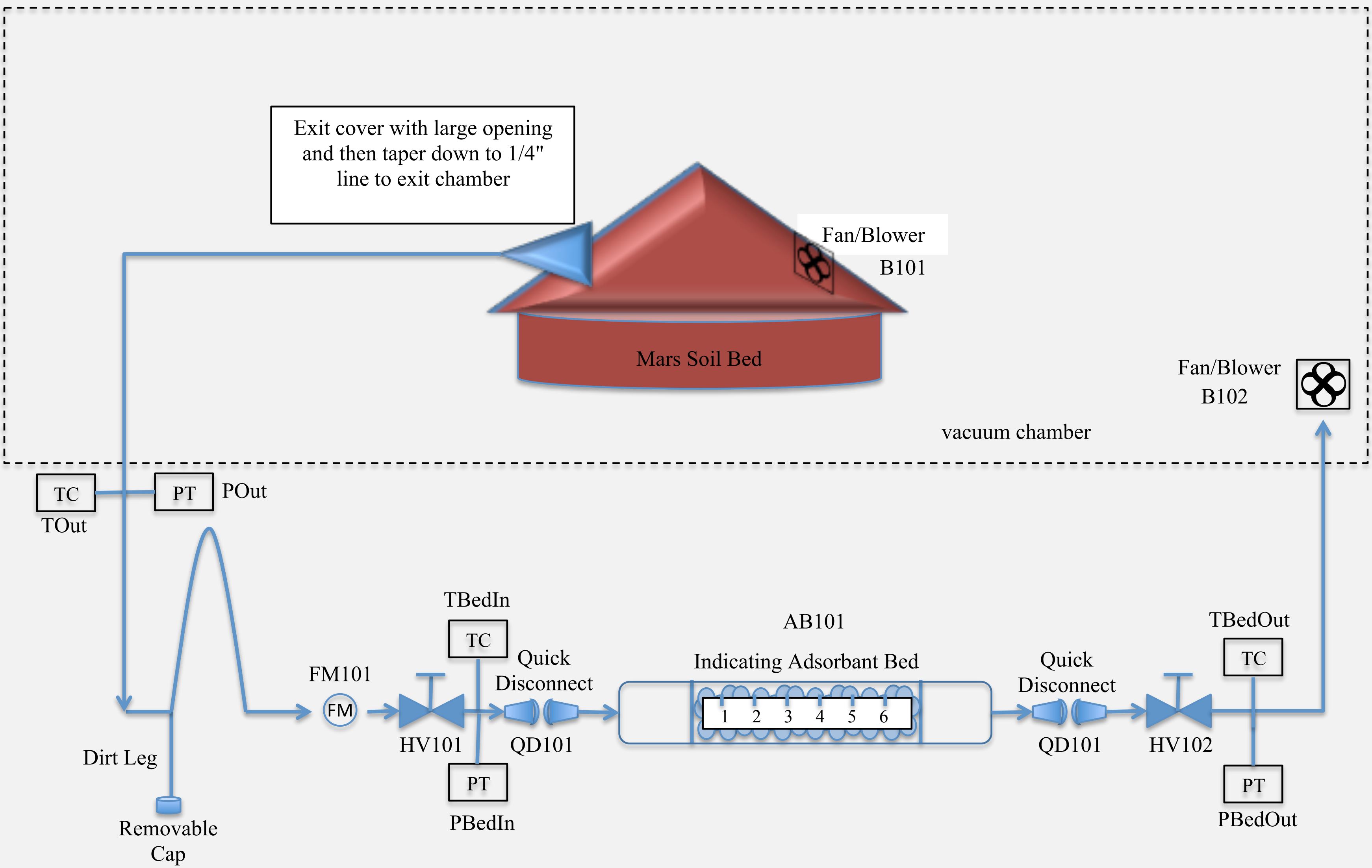
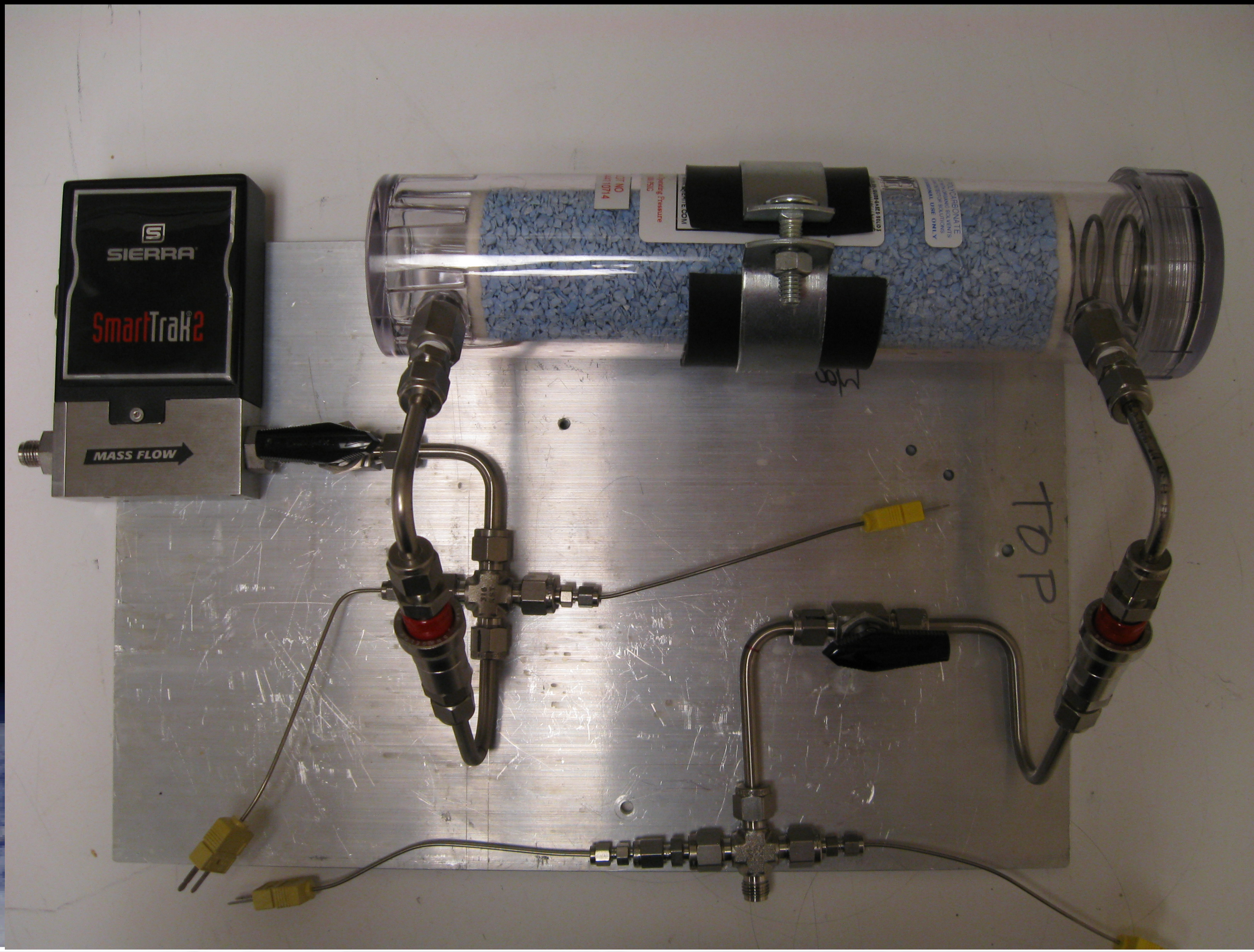


Mars Water Harvester Test Hardware



Summary

- NASA OCT Technology Roadmaps released for public comment
  - TA 7.1.2 includes technology snapshots on resource acquisition and beneficiation – comments being accepted through June 10th
- Most recent 'official' Mars Design Reference Mission included O_2 production from atmosphere in baseline
  - Soil water processing considered too uncertain and immature
- Near-equatorial regions contain 1.5 – 3 wt% water in surface fines
  - Soil excavation/processing rates of 25 – 70 kg/day for robotic mission and 375 – 1000 kg/day for human mission
- Now need to focus on soil processing concepts that are:
  - Low complexity/high reliability
  - Low mass
  - Thermally efficient

Questions?