ISRU Soil Water Extraction: Thermal challenges

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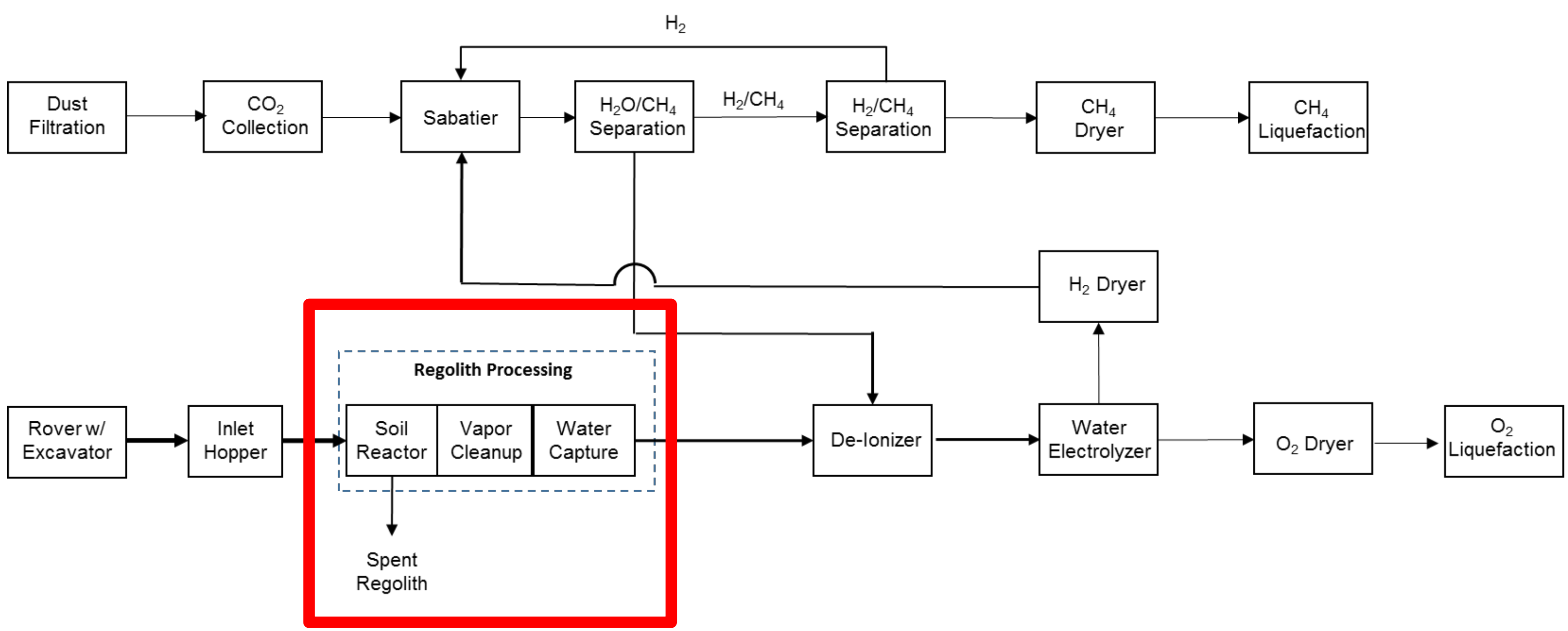
Soil Water Extraction in an ISRU system

- Water extraction from the Mars surface enables production of fuel (Methane) for ascent propulsion
  - Electrolysis of water provides hydrogen, which is used with atmospheric CO_2 in a Sabatier reactor to produce Methane.

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

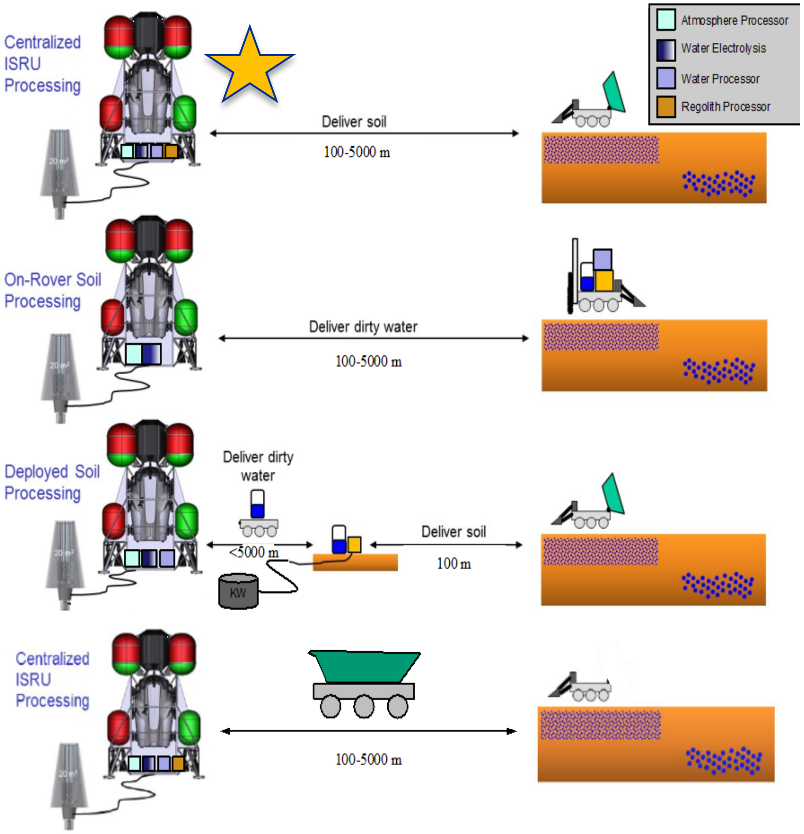
Soil: $2H_2O \rightarrow 2H_2 + O_2$

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



Boundary conditions

- The baseline architecture is to use hydrated surface material in a centralized ISRU processing system
  - Soil processing (water extraction) is centralized with the full ISRU plant
  - Rovers delivers fresh regolith and removes spent regolith from the ISRU plant
  - All water extraction (heating) takes place at the ISRU plant and is fed directly to downstream systems
  - Leverages power system of larger plant
    - Other options require mobile or deployed power systems
    - Potential to use heat recuperation from power systems (e.g. waste heat from Kilopower units)
- Regolith enters soil reactor at ambient conditions
- Water is extracted via vaporization
- Water vapor must then be captured (condensed) before it enters electrolysis unit
  - Contaminant removal may happen in vapor phase



Top level production requirements

- These requirements are based on the 2016 Evolvable Mars Campaign. The current ISRU Technology Project has slightly different timeline/production rate requirements
  - The EMC results (most recent system model) are shown to provide context for thermal discussion, but **please contact us for the most recent numbers.**
- Propellant mass based on the Mars Ascent Vehicle (MAV) study:
  - Polsgrove, T. et al. (2015), AIAA2015-4416
- MAV engines operate at mixture ratios (oxygen:methane) between 3:1 and 3.5:1, whereas the Sabatier reactor produces at a 4:1 ratio. Therefore:
  - Methane production is the driving requirement
  - Excess Oxygen will be produced
- **Production rate based on a mission timeline of 480 days (16 months)**
  - ISRU system arrives one launch opportunity ahead of humans
  - MAV must be fully fueled before human departure from earth

26 month launch opportunity

– 9 month transit time

– 1 month margin

16 months

		Total mass needed	Rate at 480days continuous operation
Requirement:	CH_4	6978 kg	0.61 kg/hr
Reactants needed to meet requirement:	H_2O	15701 kg (785,050 kg 2% soil)	1.36 kg/hr (68.2 kg/hr soil@2%)
	CO_2	19190 kg	1.67 kg/hr
Results in:	O_2	27912 kg total (22728 kg propellant, 5184 kg leftover)	2.43 kg/hr

Water Resources

	Deposit Type			
Essential Attribute	A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
Depth to top of deposit (stripping ratio)	3 m	0 m	0 m	0 m
geometry, size	bulk	bulk	bulk	bulk
Mechanical character of overburden	sand	NA	NA	NA
Concentration and state of water-bearing phase within the minable volume				
–Phase 1	90% ice	40% gypsum[1]	40% smectite[2]	23.5% basaltic glass[3]
–Phase 2	--	3.0% allophane[4]	3.0% allophane[4]	3.0% allophane[4]
–Phase 3	--	3.0% akaganeite[5]	3.0% akaganeite[5]	3.0% akaganeite[5]
–Phase 4	--	3.0% smectite[2]	3.0% akaganeite[5]	3.0% bassanite[6]
–Phase 5	--	--	--	3.0% smectite[2]
Geotechnical properties				
–large-scale properties ("minability"), e.g. competence, hardness	competent--hard	sand--easy	sand--easy	sand--easy
–fine-scale properties ("processability") , e.g. competence, mineralogy	no crushing needed	no crushing needed	no crushing needed	no crushing needed
The nature and scale of heterogeneity	variation in impurities	±30% in concentration	±30% in concentration	±30% in concentration
Distance to power source	1 km	1 km	1 km	100 m
Distance to processing plant	1 km	1 km	1 km	100 m
Amenability of the terrain for transportation	flat terrain	flat terrain	flat terrain	flat terrain
Presence/absence of deleterious impurities	dissolved salts	none	none	perchlorate?
First order power requirements	TBD	TBD	TBD	TBD

1. ~20 wt% water, 100-150°C
2. ~4 wt% water, 300°C
3. ~1 wt% water, >500°C
4. ~20 wt% water, 90°C
5. ~12 wt% water, 250°C
6. ~6 wt% water, 150°C

The M-WIP (Mars Water ISRU Planning) study was lead by SMD/Mars Program office and involved academy and industry members to identify impacts of Mars resources and their location, and the data still needed to best define them.

- The MWIP team report is posted: http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx

Hydrated Surface Material: Baseline options

% of bulk Regolith	mineral	water content %	Dehydration temperature, C	%water contribution to bulk	Heat of Dehydration, kJ/kg	Cp, kJ/kg*K
	D Garden Regolith			1.50%		
23.50%	Basaltic Glass (pyroxene?)	1%	500	0.24%	200.00	0.7
3%	Allophane	20%	90	0.60%	409.00	0.7
3%	Akaganeite	12%	250	0.36%	131.34	0.5
3%	Bassanite	6%	150	0.18%	686.19	0.82
3%	Smectite	4%	300	0.12%	152.94	1
64.50%	Bulk unhydrate	0%	0	0.00%	0.00	0.5
	B Mineral Rich- Gypsum			9.08%		
40.00%	Gypsum	20.00%	150	8.00%	568.58	1.09
0.00%	Basaltic Glass (pyroxene?)	1%	500	0.00%	200.00	0.7
3.00%	Allophane	20%	90	0.60%	409.00	0.7
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51.00%	Bulk unhydrate	0%	0	0.00%	0.00	0.5
	C Mineral Rich - Smectite			2.74%		
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51.00%	Bulk unhydrate	0%	0	0.00%	0.00	0.5
	Ice			90.00%		
90.00%	Ice	100.00%	100	90.00%	334.00	2
10.00%	Bulk unhydrate	0%	0%	0%	0	1

These minerals are based on the MWIP reference cases, but actual material will vary.

The heat of dehydration and Cp numbers are estimates based on mineral property references/

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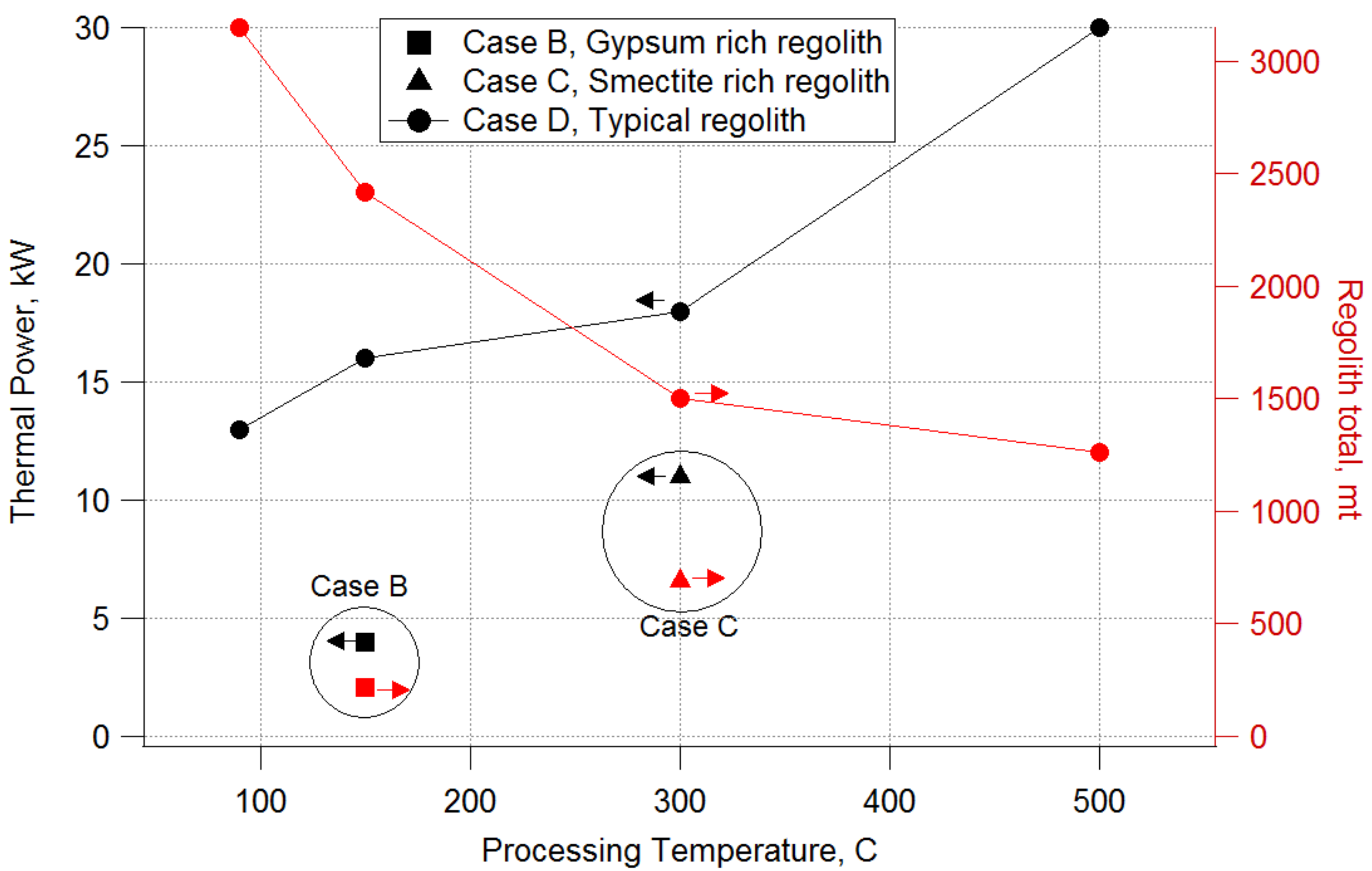
Target regolith processing temperature for each reference material

Water Resources: Trades

- For a full scale ISRU system, the below graph shows
  - Total thermal power needed to heat regolith to produce 1.36 kg H_2O/hr for each regolith type
  - Total regolith needed to be processed to meet production rate goals

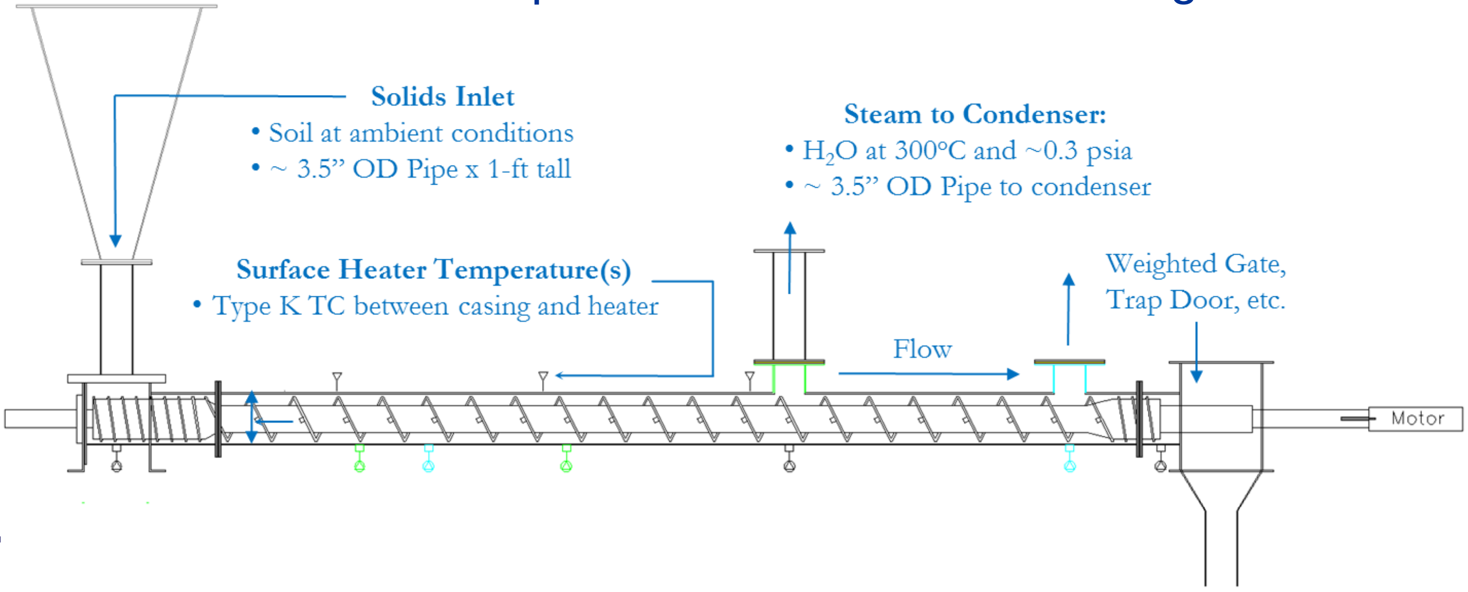


Soil Processing Element Technologies

- The current ISRU technology project focuses on four water extraction concepts for Mars.
  - Hydrated mineral resources
    - Auger Dryer
    - Microwave
    - Open air
  - Subsurface Ice
    - Rodriquez Well (“Rodwell”)
- The following slides overview each technology and discuss potential thermal considerations
  - Thermal consideration listed are at the component/subsystem level
  - Larger system thermal management considerations must be addressed at a higher level.

Auger Dryer

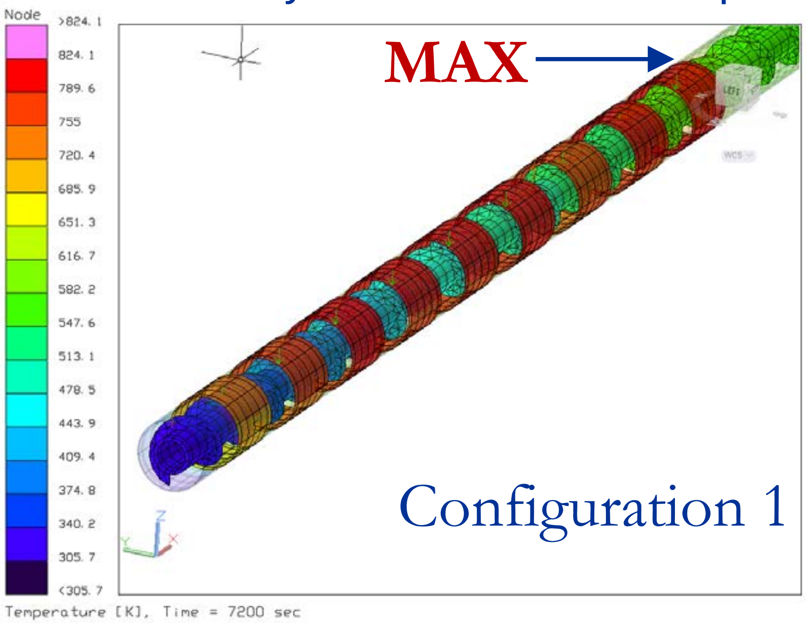
- Background:
  - Granular material is continuously conveyed through a closed, heated auger assembly. The varying pitch of the auger flutes, along with a regolith head in the hopper, seal the system so that the evolved water vapor is pressure fed to the condenser.
  - Based on terrestrial design for granular material dryers in pharmaceutical, agriculture, food industries, etc
  - Concept baselined in the 2016 EMC campaign ISRU system model study. Terrestrial system equations were modified and incorporated into model for scaling.



Plug seal example by Conveyor Engineering & Manufacturing

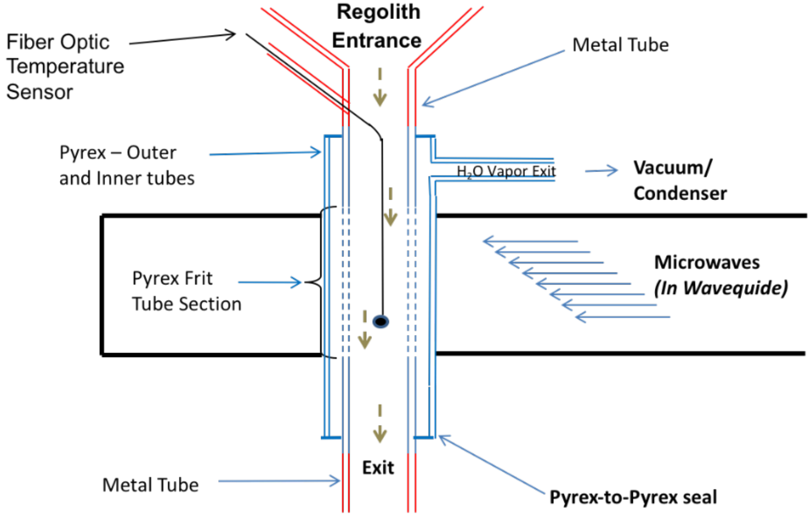
Auger Dryer: Thermal considerations

- Walls of the auger conveyor are heated: heat configuration is "outside-in"
  - Greater risk of heat loss to environment.
- Residence time at reaction temperature is not yet characterized for a given resource
  - Auger heated length may change or higher end temperature may be required to compensate
- Vapor pressure drives water vapor out of auger shaft, into water capture subsystem
  - Valves and seals must be temperature tolerant or isolated: Including rotating seals for auger motor
  - A soil column is to be used as the pressure seal at hopper side, eliminating valves and enabling continuous soil feed
- Soil exits system at reaction temperature. This heat is lost (no recuperation)



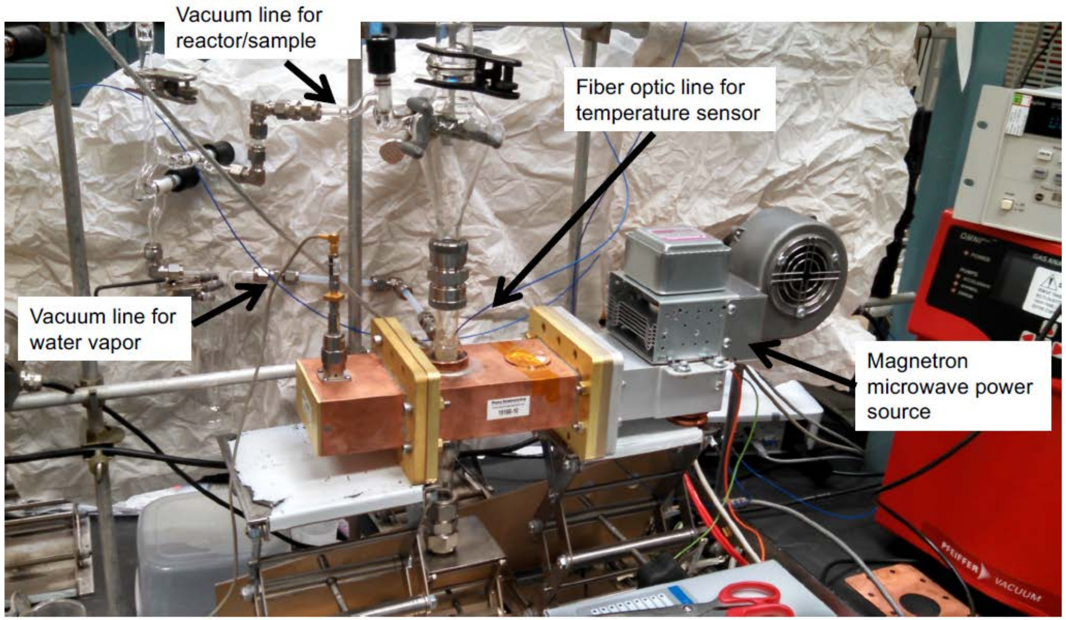
Microwave

- Background:
  - Granular material is fed into a resonant cavity where the water is released via microwave radiation. A porous Pyrex vessel is used to facilitate water release and collection such that a continuous feed of regolith can be processed.
  - Earlier efforts using microwave heating of lunar simulants for reactor and construction purposes
  - Internal R&D funds in 2017 to look at Mars application using various hydrated minerals was the direct predecessor to this work



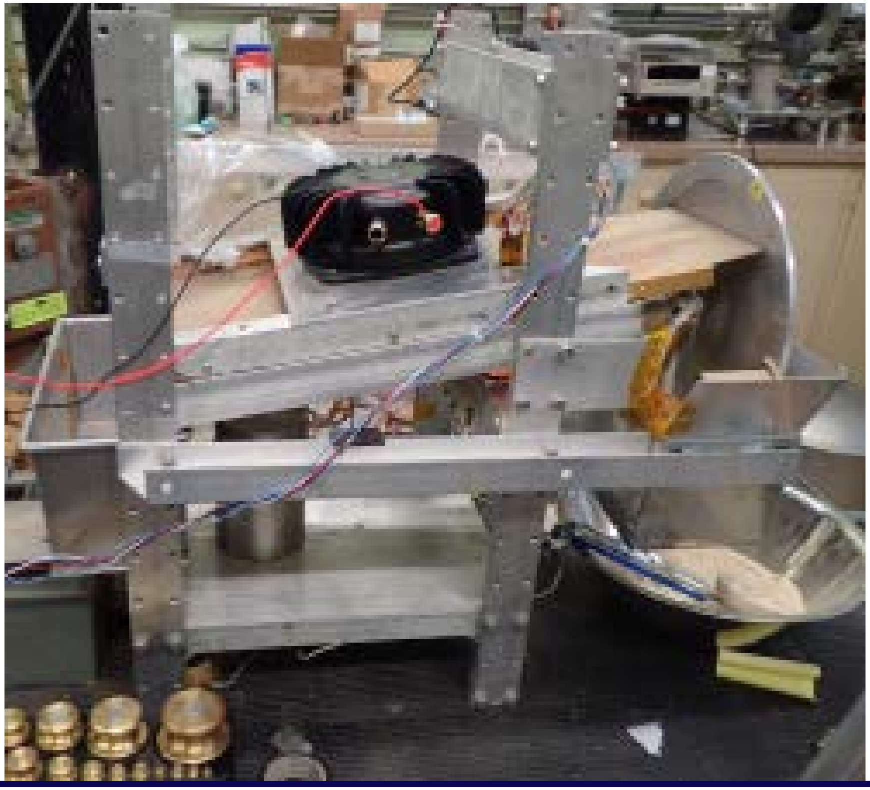
Microwave: Thermal Considerations

- The microwave reactor design focusses almost all the input power to uniformly heat the regolith
- Microwave power sources are ≥ 70% efficient
  - Recuperation of waste heat from other systems (e.g. power) cannot be used for soil water extraction
- Residence time at reaction temperature is not yet characterized
- Regolith exits reactor at full temperature
- Continuous soil feed is planned, with cold trap to condense water vapor coming though porous Pyrex tube



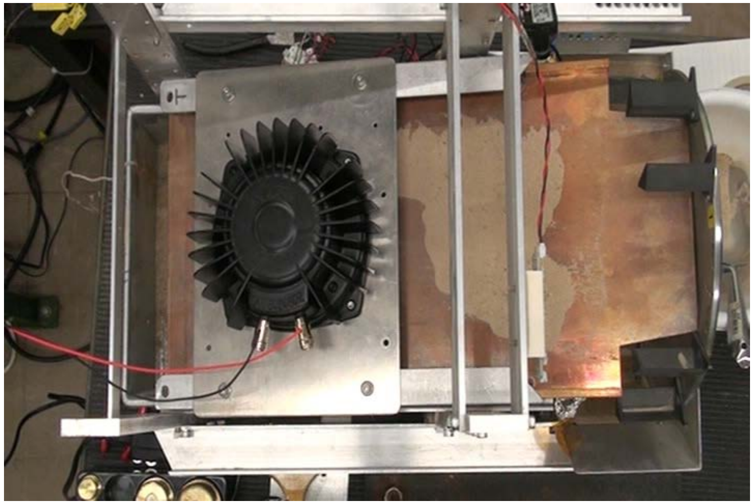
Open Air Processor

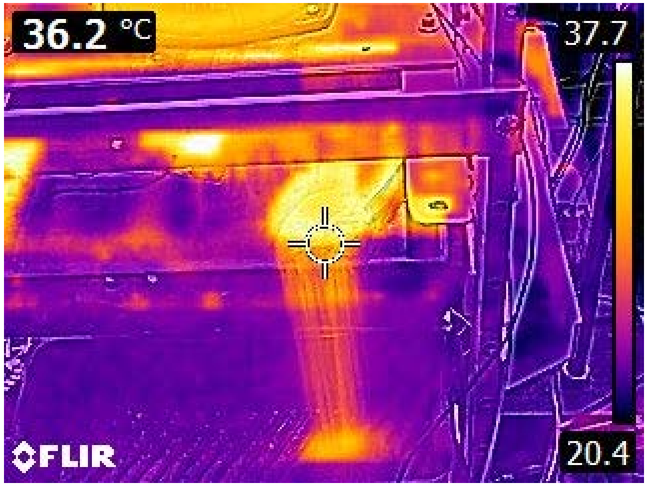
- Background
  - A bucket wheel is used to retrieve granular material from a hopper, or from the surface itself, and dump it onto a inclined heated tray. Atmospheric gas is blown over the tray (duct not shown) to sweep water vapor into the condenser. Vibration conveys material down the heated tray.
  - Internal R&D award in 2016 to examine proof of concepts
    - Roto-tiller concept in 2016, Bucket wheel concept in 2017
    - All proof-of-concept hardware tested at Mars environmental conditions (pressure, gas, simulant)
  - Concepts to avoid need for high temperature, dust tolerant seals



Open Air Processor: Thermal considerations

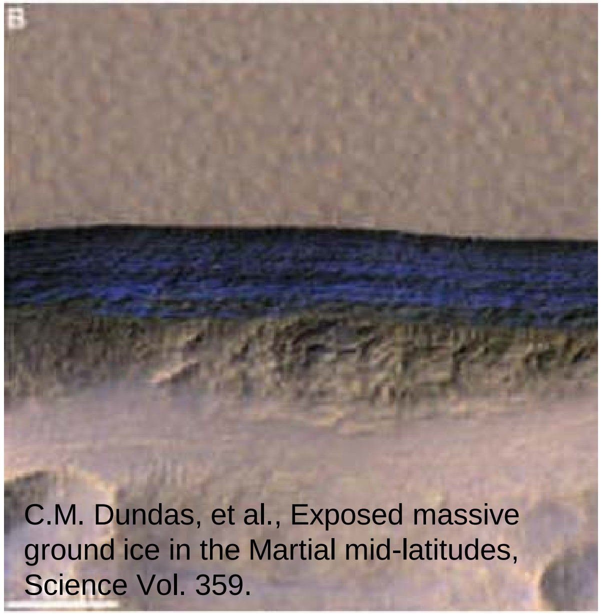
- The sweep gas past the heated tray will:
  - Cool the heated tray, convection coefficient unknown
  - Fresh Mars gas will be at ambient temperature to sweep heated water vapor into the capture system. There may be condensation issues.
- Heat losses from the heated tray surface reduce heating efficiency, though flow ducting atop the tray will provide some heat feedback
- Continuous feed of cold regolith will create thermal gradient on tray
- Difficult to characterize soil temperature, and residence time for water release is unknown
- Distribution of soil over tray is variable and difficult to characterize, making it difficult to model heat transfer into soil and heating efficiency of tray
  - Initial tests indicate that the bulk soil reaches steady state temperature within first ~15cm of the tray



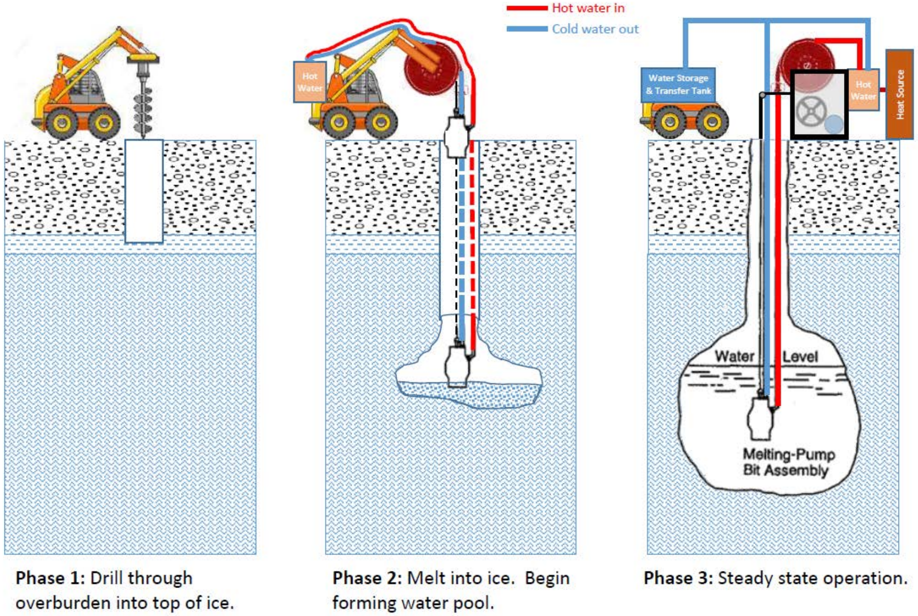


Ice mining: Rodwell concept

- Background:
  - This terrestrial concept is currently in use at Antarctic field stations. The ice sheet is accessed via a borehole and a heat probe is used to melt and maintain a liquid ‘well’ within the ice. Water is pumped out of the well for use.
  - Rodwells are in use terrestrially (Antarctic field stations) for water generation from subsurface ice sheets.
    - Subsurface Glaciers have been identified on Mars, as shallow as 1m deep (Dundas, 2018)

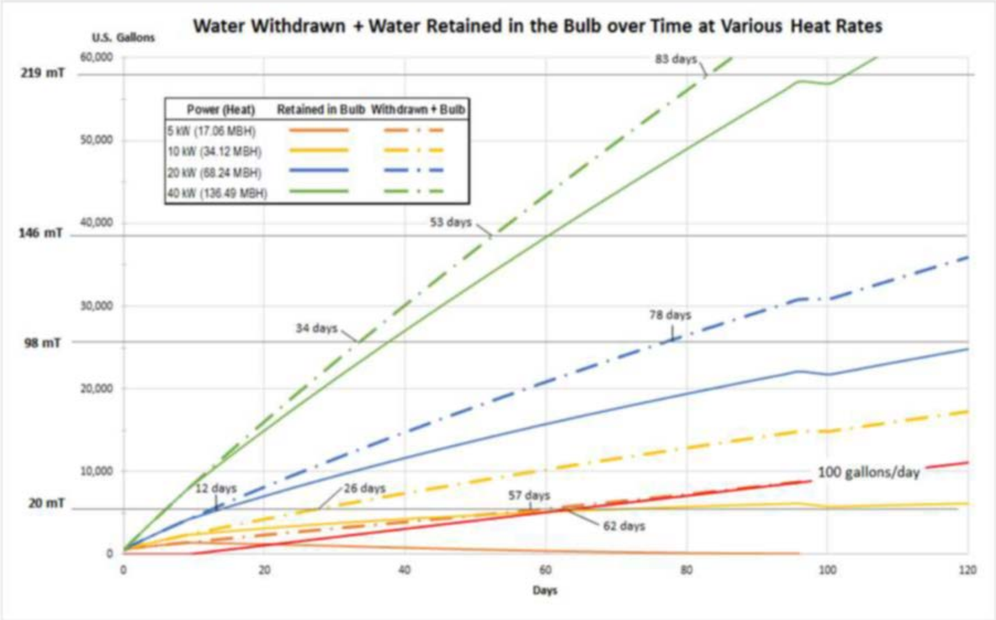


C.M. Dundas, et al., Exposed massive ground ice in the Martial mid-latitudes, Science Vol. 359.



Rodwell: Thermal Considerations

- CRREL (Cold Regions Research and Engineering Laboratory) has generated a numeric model for Rodwell design. This model has been leveraged to develop a ISRU Mars Rodwell system to:
    - Estimate mass & power for Mars relevant hardware
    - Examine Concept of Operations of Rodwell for various operating conditions (production rates, location, etc)
    - Initial trade study results to be published at AIAA Space 2018.
- The key thermal consideration is to balance the heat input into the well with the amount of water being withdrawn.
    - – Too little heat with high removal rate will result in collapse of the well
- The Mars ambient conditions encompass the triple point of water, which may impact ability to maintain liquid in well. Tests will take place in FY19 to determine the model parameters need to account for this.



Note: assumes -80° C ice

Summary

- Water extraction from regolith requires significant energy input; heating efficiency is key to system power balance
  - Regolith has low thermal conductivity
  - Recuperated heat from either reacted regolith or other systems merits examination, but must be done at the system model level (not component level)
- Water capture system may require significant reduction in temperature of the water vapor (e.g. condenser)
- Unknown parameters for modeling include:
  - Residence time for water release
  - Convection/conduction coefficients (sweep gas and/or flowing soil)
  - Heat of dehydration for Mars hydrates

Backup

Heat rejection for ISRU system

Subsystem	Component	Input power, W	Heat reject, W	Temperature of Cold head	Heat rejection Temperature	Notes
Excavation	Rover battery recharger	608	608			Assumes 8hr recharge of 5 Rassor batteries at a time (fully discharged batteries)
Regolith Processing	Size Sorter/hopper	300	300			
	Drier conveyor	108	108			
	Drier heater	17743	0			Heat Rejection acounted for in the Water Condensor, and remaining heat is disposed of w/spent regolith
	Vapor cleanup	90	0			Heat into the fluid to maintain phase
	Condenser	0	1675	305K (20K < H2O saturate vapor temp 325K)	303 K (30C)	Passive condenser, no active cooling so no input power
Atmospheric Processor	CO2 freezer valves, blower	273	273			
	CO2 cyrocooler input power	1597	1597			
	CO2 Cyrocooler Lift	337	337	150 K	303 K (30C)	
	Sabatier	0	0			One time startup power 360W, self sustaining exothermic
	Sabatier Condenser	0	1117	303 K (30C)	303 K (30C)	Passive condenser, no active cooling so no input power
PEM Electrolysis	PEM Stack power	16974	5809			Endothermic reaction. Heat rejection is Joule heating due to over potential of PEM cells to improve efficiency
	Pumps	214	214			
	De-Ionizer	20	20			
Gas Driers	Gas Driers	30	0			Heat into the fluid to maintain phase
Methane Liquefaction	Cryocooler Input power	1680	1680			
	Cryocooler Lift	297	297	109 K	303 K (30C)	
Oxygen Liquefaction	Cryocooler Input power	2640	2640			
	Cryocooler Lift	168	168	84 K	303 K (30C)	
SUM		43079	16843			