National Aeronautics and Space Administration

Extraction of Volatiles from Regolith or Soil on Mars, the Moon, and Asteroids

**Presented at the Joint
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Water Extraction from Regolith/Soil

- **NASA's Advanced Exploration Systems ISRU Technology Project is evaluating concepts to extract water from all resource types**
- **Near-term objectives:**
  - Produce high-fidelity mass, power, and volume estimates for mining and processing systems
  - Identify critical challenges for development focus
  - Begin demonstration of component and subsystem technologies in relevant environment
- **Several processor types:**
  - Closed processors
    - either partially or completely sealed during processing
  - Open 'air' processors
    - operates at Mars ambient conditions
  - In-situ processors
    - Extract product directly without excavation of 'raw' resource

Resource types

- **Extraction and processing hardware will be dependent on type of resource targeted**

	Deposit Type				
Essential Attribute	**Bright Soils**	**Clay**	**Poly-hydrated Sulfate**	**Icy Soil**	**Ice**
Anticipated water content at temp. (%)	1 - 2	1 - 7	6 - 14	10 - 50	> 90
Temperature for water release as vapor (°C)	~ 300	~ 300	150 - 300	0 - 100 (dependent on operating pressure)	
Depth to top of deposit (m)	0	0	0	0.03 - 10 +	5 - 10
Geotechnical properties of resource ("minability")	sand - easy	mudstone - med	easy to hard (not well known)	cemented - hard	hard
Mechanical character of overburden	NA	NA	NA	same	see icy soil

Refs:

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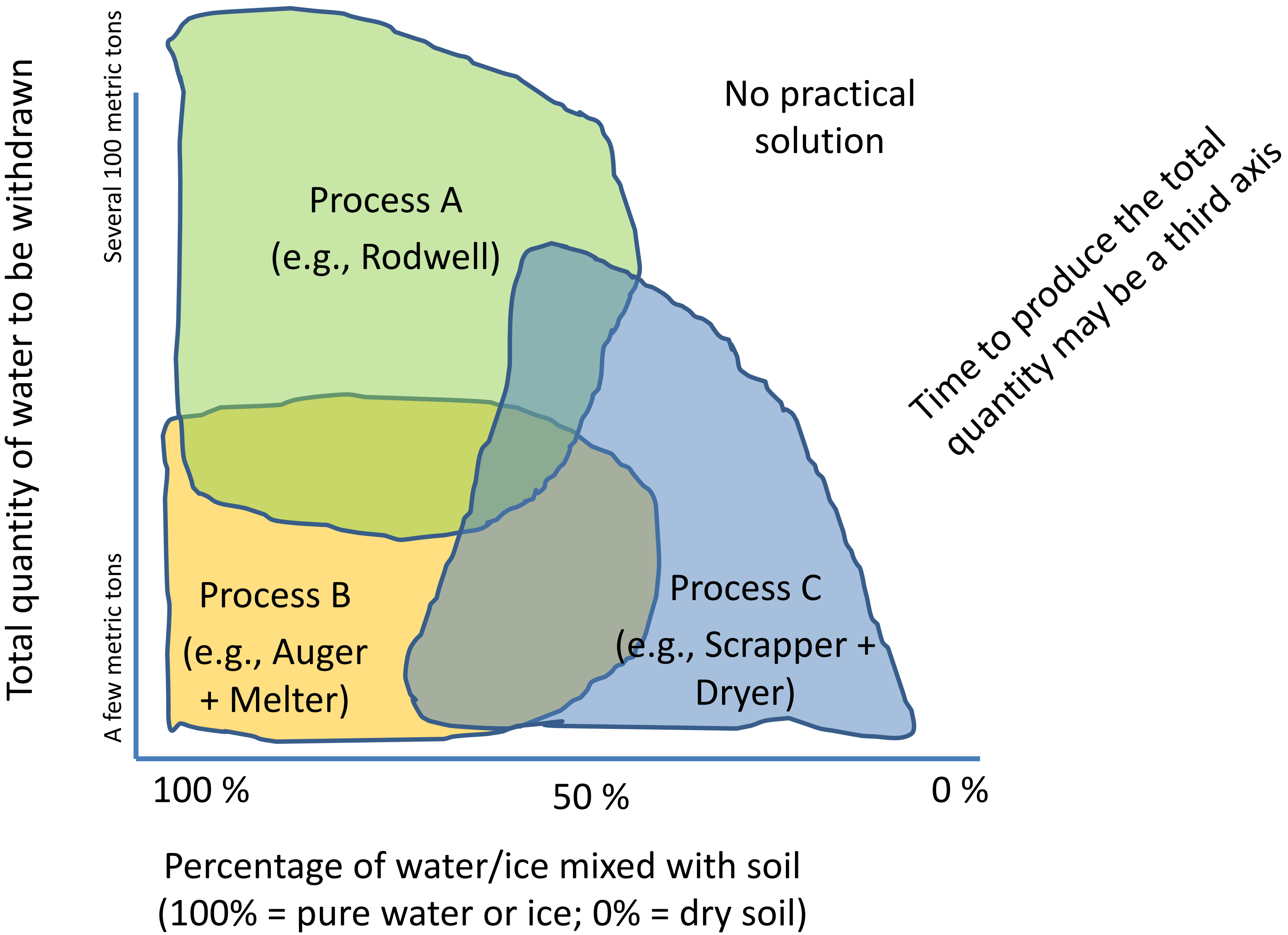
Murchie, S. L., J. F. Mustard, B. L. Ehlmann, R. E. Milliken, J. L. Bishop, N. K. McKeown, E. Z. Noe Dobrea, et al. "A Synthesis of Martian Aqueous Mineralogy after 1 Mars Year of Observations from the Mars Reconnaissance Orbiter." Journal of Geophysical Res. 114 (Sept. 22, 2009). doi:10.1029/2009JE003342.

Audouard, J., F. Poulet, M. Vincendon, R. E. Milliken, D. Jouglet, J.-P. Bibring, B. Gondet, and Y. Langevin. "Water in the Martian Regolith from OMEGA/Mars Express." Journal of Geophysical Research: Planets 119, no. 8 (August 1, 2014): 2014JE004649. doi:10.1002/2014JE004649.

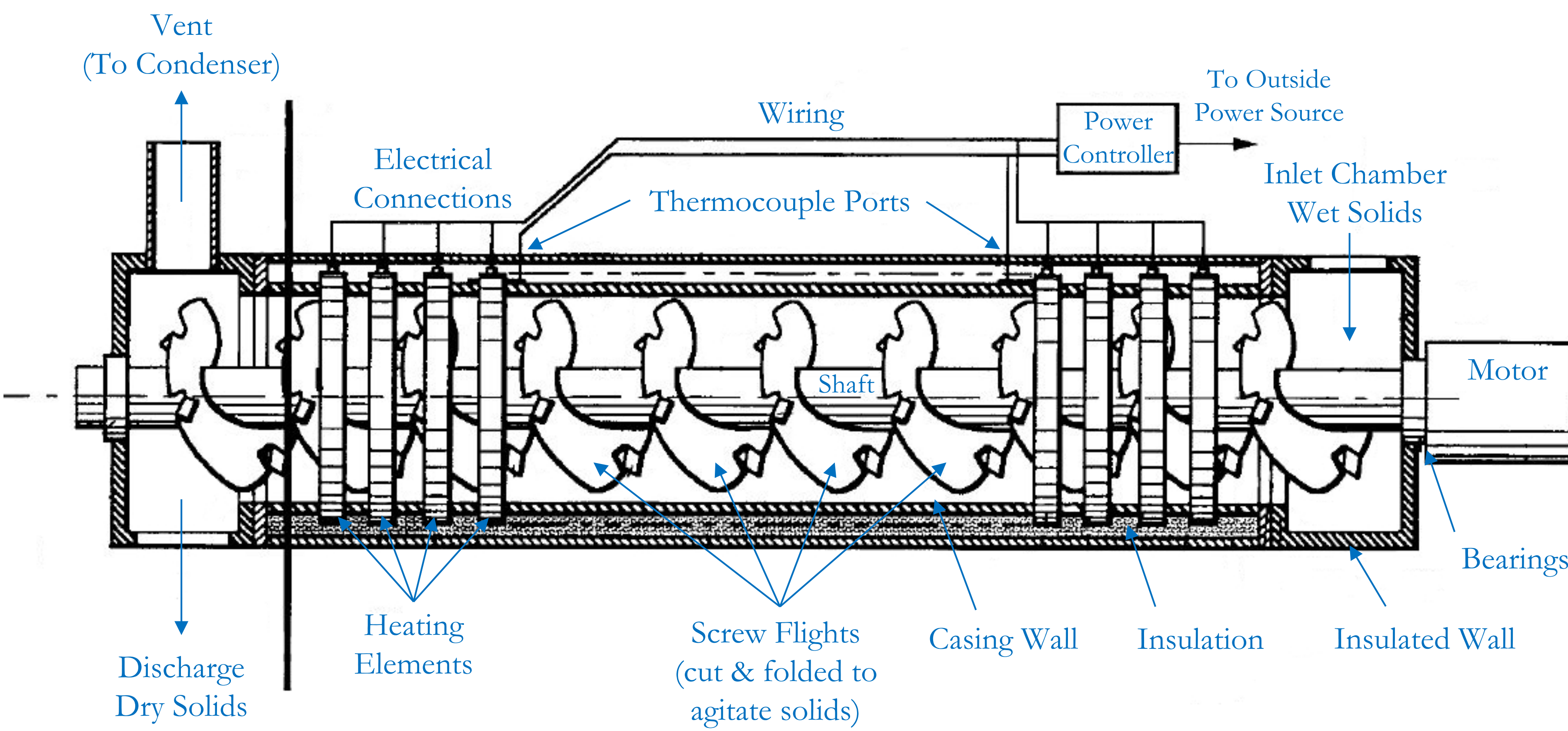
Processor Selection Dependent on Several Factors



Closed Processors

Screw Conveyor Drive Processor Concept

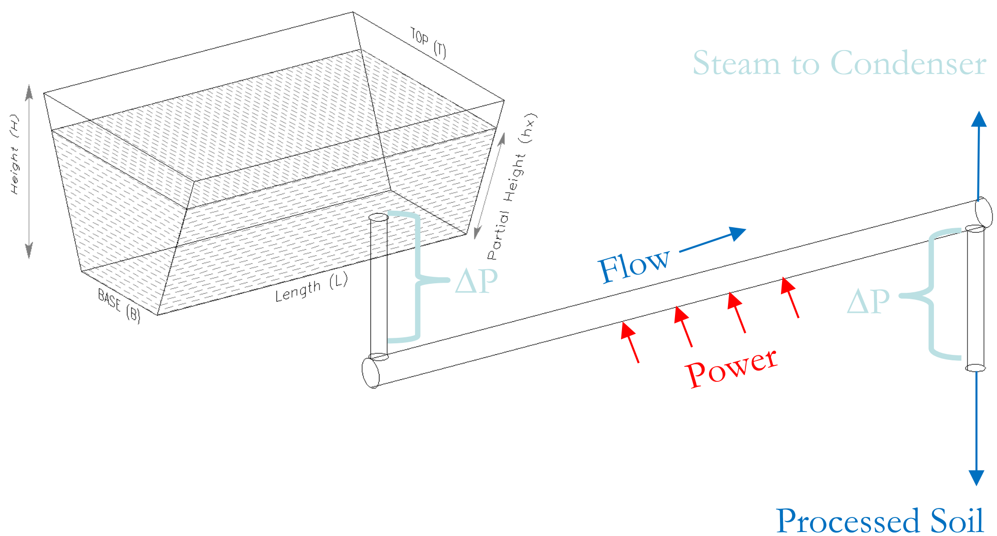
- OBJECTIVE:
  Develop Screw Conveyor Dryer (SCD) sized to provide Mars Ascent Vehicle (MAV) propellant requirements by capturing water vapor formed during the drying of soil
- Based on terrestrial SCD technology of minerals and ores

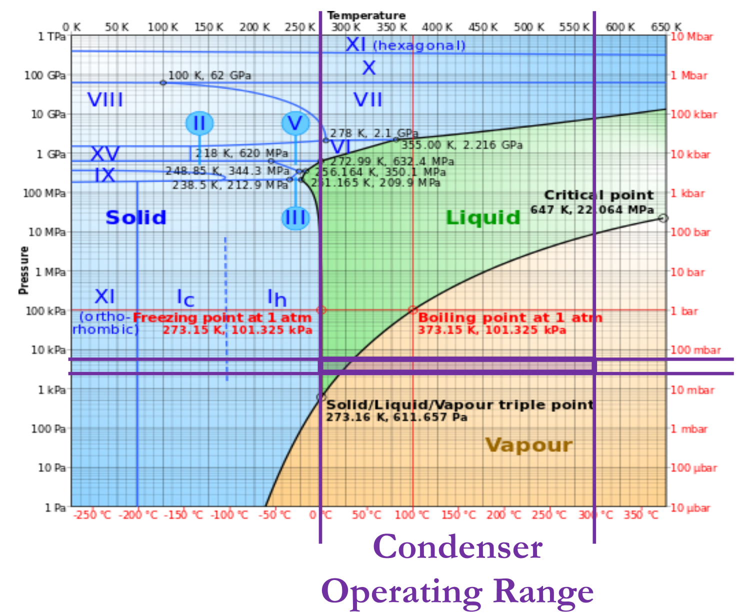


Drawing modified from: United States Patent #5531034 "Horizontal Dryer Having a Screw Conveyor and Ring Electrical Heating Elements", July 2, 1996.

Screw Conveyor Drive Processor Concept

- Design features:
  - Open to Martian environment to reduce system complexity
    - Rover can continuously add soil to hopper
    - Pressure maintained in SCD / Condenser by height differential (ΔP) of soil in hopper
    - Avoids isolation valves into/out of SCD to build pressure (complex controls, additional mass, cycles)
  - Elimination of CO_2 sweep gas reduces dust particles in water condensate
  - Condenser sized to liquefy water vapor at Martian atmospheric conditions





Screw Conveyor Drive Processor Concept

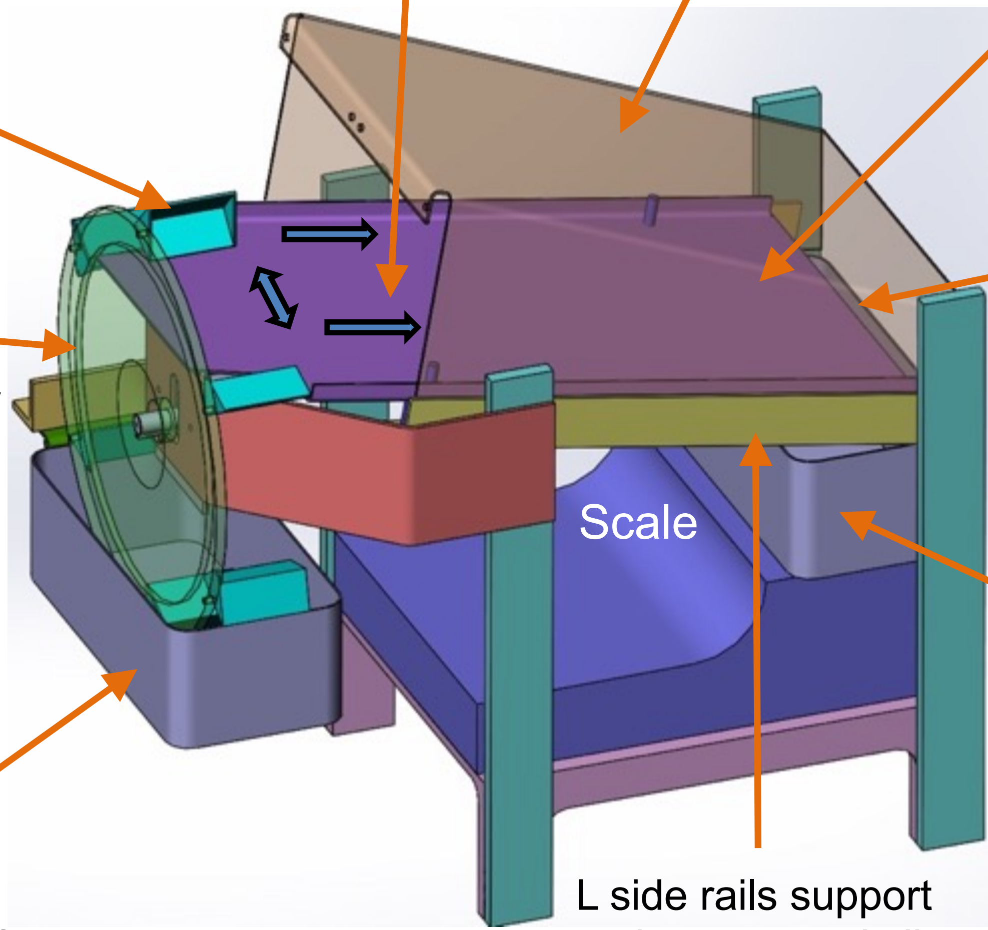
- Model developed to evaluate key design parameters:
  - Geometry: conveyor diameter, screw diameter, shaft diameter, flight spacing and pitch
  - Operational: screw speed vs screw length (residence time)
  - Thermal: heat flux, heat transfer to soil
- Testing to demonstrate feasibility and performance:
  - Phase I: Polycarbonate casing with no heaters
    - Determine how to feed soil into/out of SCD (soil seal to create ΔP)
    - Test various outlet configurations (latch valve, spring, angled plate, etc.)
    - Examine mixing, clogging, channeling, bridging, and dust effects based on RPM settings
    - Determine transient time as function of screw shaft rotation
    - Examine two screw pitch configurations
  - Phase II: Add heating elements, insulation, and condenser
    - Examine methods to heat soil based on energy input
    - Compare uniform versus non-uniform temperature profiles
    - Determine H_2O yield as function of residence time and temperature
    - Examine high temperature soil effect on seals, bearings, etc.
  - Phase III: Thermal vacuum chamber testing (relevant environment)

Open Processors

Open ‘Air’ Processing Concept

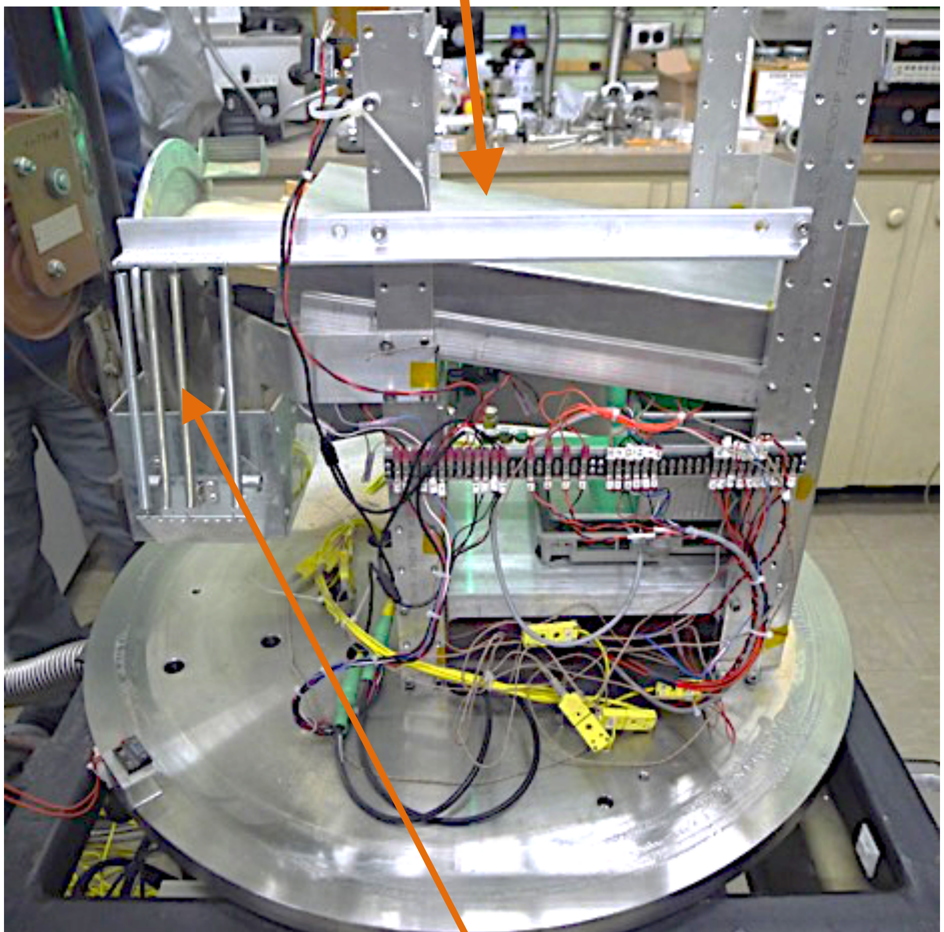
- **Excavate, extract volatiles, and dispose of soil in continuous process**
  - Deposit thin layers of soil on vibrating, heated plate
  - Fans blow Mars ‘air’ over plate and sweep liberated moisture into condenser
  - Dried soil falls off end of plate back to ground
- **Key benefits:**
  - Eliminates need for repeated sealing with hot, dusty seals
  - Eliminates granular/soil valves
  - Uses Mars air as working gas
    - Do not have to recover/recycle as the air is ‘free’
  - Efficient and continuous heating / water extraction
    - Direct heating of thin layers of soil
- **Key challenges:**
  - Must heat soil to release temperature before end of plate
  - Capture efficiency – amount of released water captured in condenser
    - Accept that not all evolved water will be captured

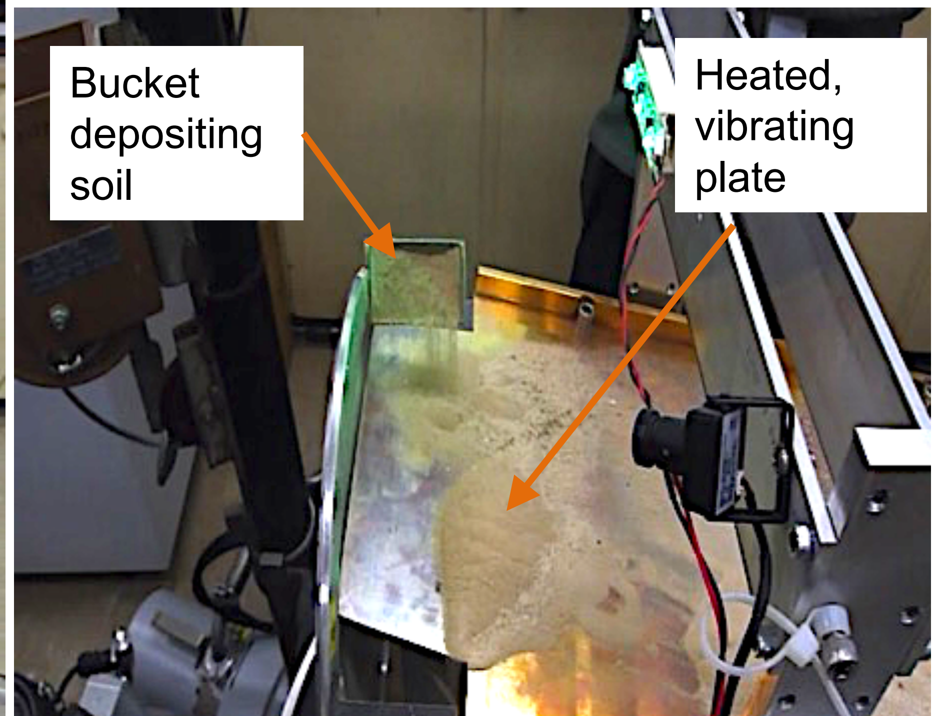
Solid Works Model of Open Reactor Design



Open ‘Air’ Processing Concept

Shroud

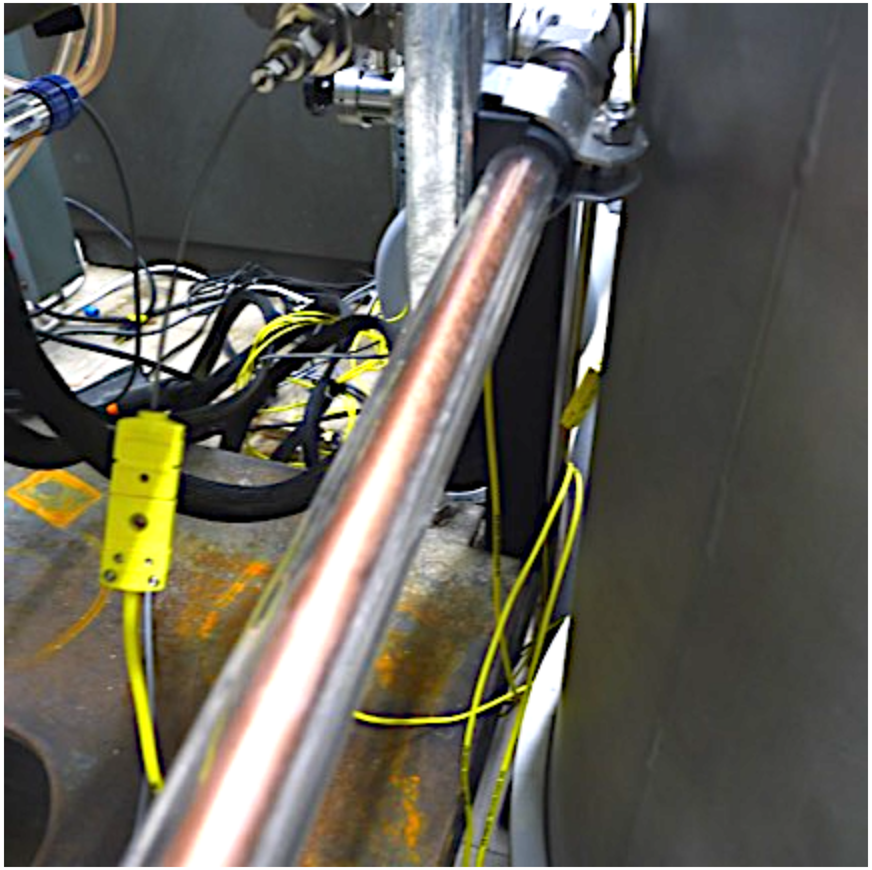




Tension springs keeps regolith in source bin in contact with bucket wheel assembly

External Condenser

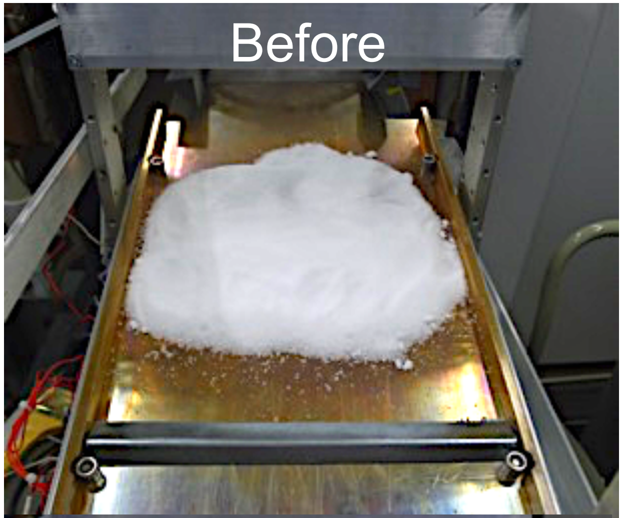
- **Condensing tube with cooled copper center tube**
  - External refrigeration cools captured vapor to 0 $^{\circ}$C to condense
  - Mounted with 10° tilt to flow condensate into collection tube
- **Vertical collection tube with scale to measure collected water in real time**



Soil Transport Test at 4 RPM

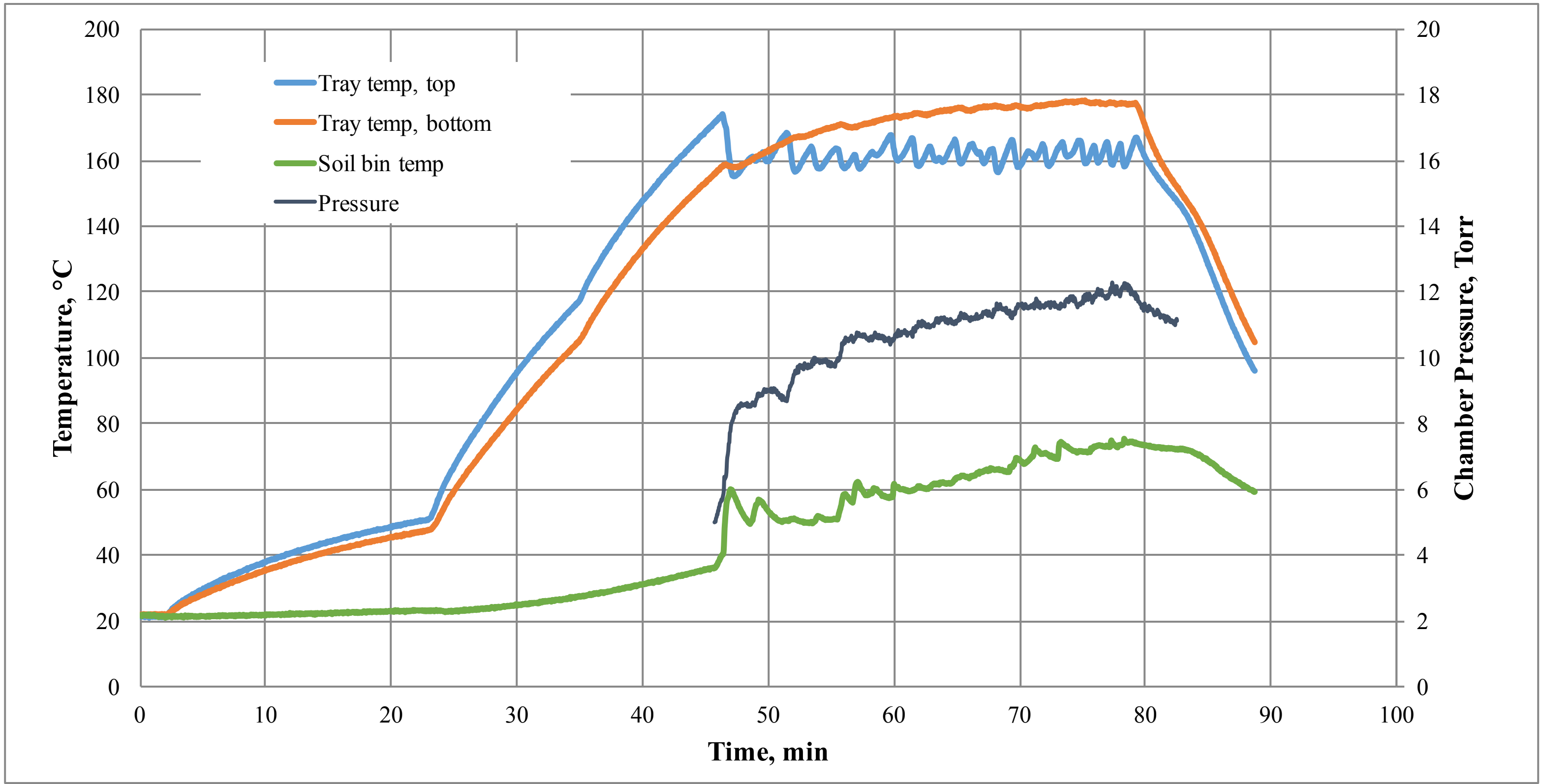
Hydrated Simulant

- **Borax decahydrate (BDH) added to GRC-3 simulant for a total extractable water content of 3% by mass**
- **$Na_2B_4O_7 \cdot 10H_2O$**
  - Eight water molecules exist as crystal water and can be released at temperatures between 59 and 150 ˚C
  - Remaining two water molecules can only be removed by molecular decomposition
- **Heated 200 gm of BDH to 150 ˚C**
  - Final mass = 180 gm (20 gm H2O released)
  - Captured ~13.5 gm H2O
  - Capture efficiency ~67.5%
- **Dehydrated Borax has increased surface area and decreased bulk density – i.e., it 'puffs up'**



Hydrated Mineral in Soil Test

- **200 gm Borax decahydrate added to 2000 gm GRC-3**
  - About 3.4 % extractable water (assuming 8 of 10 H2O molecules)
- **Soil dumped onto heated tilt tray with tray vibrated in pulse-mode to increase residence time ensuring soil is heated to target temperature**
  - Tray temperature drops as each bucket of cold soil is dropped
  - Chamber pressure jumps with each bucket indicating volatile release



Preliminary Results of Open Air Soil Processor

- **Four tests processed 440 – 500 gm of simulant doped with Borax decahydrate**
  - Average water capture of 8.3 gm in ~ 30 minutes (16.5 gm/hr) (about 1/50th full scale rate)
- **Pulse-mode used to increase residence time as tilt tray length limited by chamber size**
  - Early tests showed soil moved too quickly across tilt tray in vacuum and did not reach desired temperature

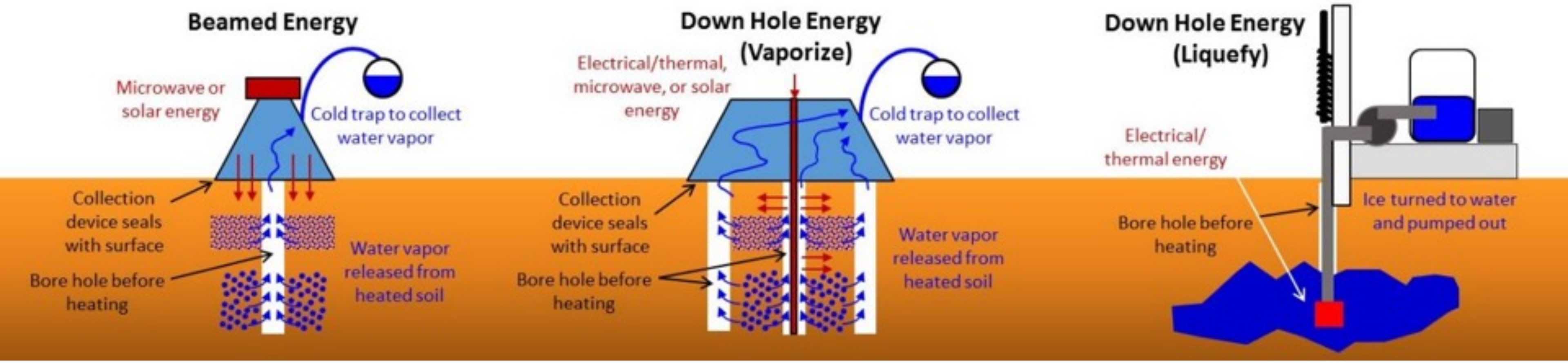
Test	Soil Processed (gm)	Extractable Water (gm)	Water Captured (gm)	Capture Efficiency (%)	Tray Temp, Ave (°C)
1	446	15.3	7	46	151
2	488	16.8	9	54	161
3	444	15.3	9	59	162
4	497	17.1	8	47	161
Average	469	16.1	8.3	51	159

PRELIMINARY RESULTS

In Situ Processors

In-situ Processors

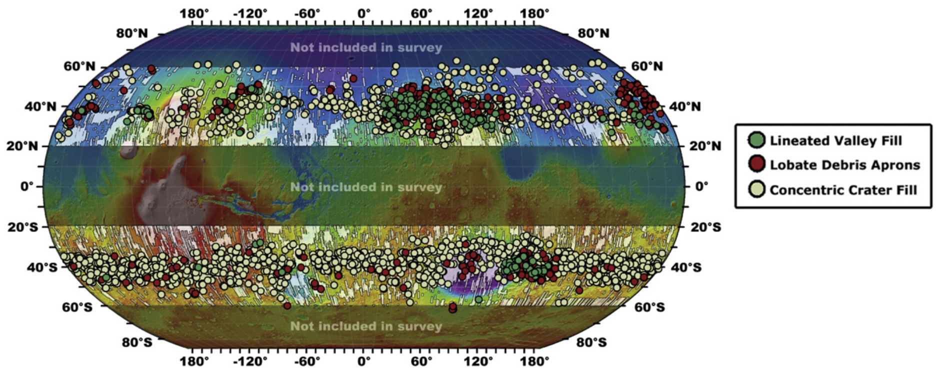
- **Extract product directly without excavating raw resource**
- **Several concepts have been proposed**

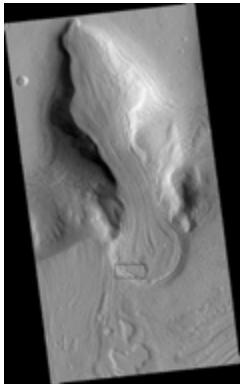


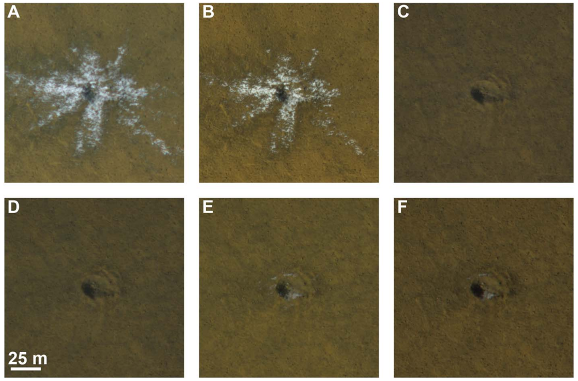
In-Situ Processors: Current Status and Future Work

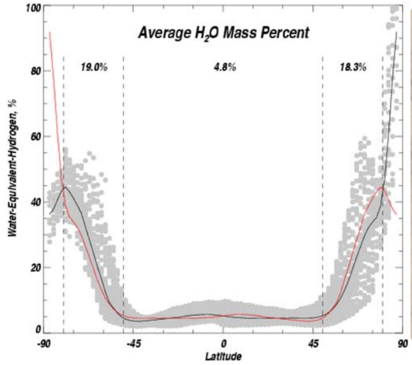
- **At least one relevant terrestrial example of in-situ processing (the Rodriguez Well) with substantial operational history and associated technology**
  - Both concept of operations and basic technology appear adaptable for Mars missions
  - Current focus of in-situ processor model development to estimate mass and power/heat needed for this concept; other concepts are part of future work
- **Parameters driving system performance**
  - Depth of overburden covering/protecting ice deposit
  - Total quantity of water extracted
  - Rate at which water is extracted
- **Challenges and uncertainties**
  - Subsurface profile and properties of overburden layer and ice body (e.g., proportion and properties of intermixed soils or other impurities).
  - Can the Rodwell concept operate at Mars ambient pressure? Or is pressurization needed?
  - Maintaining subsurface water pool requires continuous monitoring and adjustment of this recirculating water system. Remote operations procedures need refinement/customization
- **Future work**
  - Current simulation based on terrestrial applications; some parameters are empirical. Environmental chamber testing may be required to determine equivalent Martian parameters
  - If simulation results continue to look favorable, adapting and testing terrestrial systems under Martian conditions will be next step

Martian Water Sources









To date *Mars Express MARSIS and Mars Reconnaissance Orbiter (MRO) SHARAD radars* ***have failed to detect any indications of liquid groundwater within 200-300 m of the surface anywhere on Mars [Clifford, et. al. 2010]***

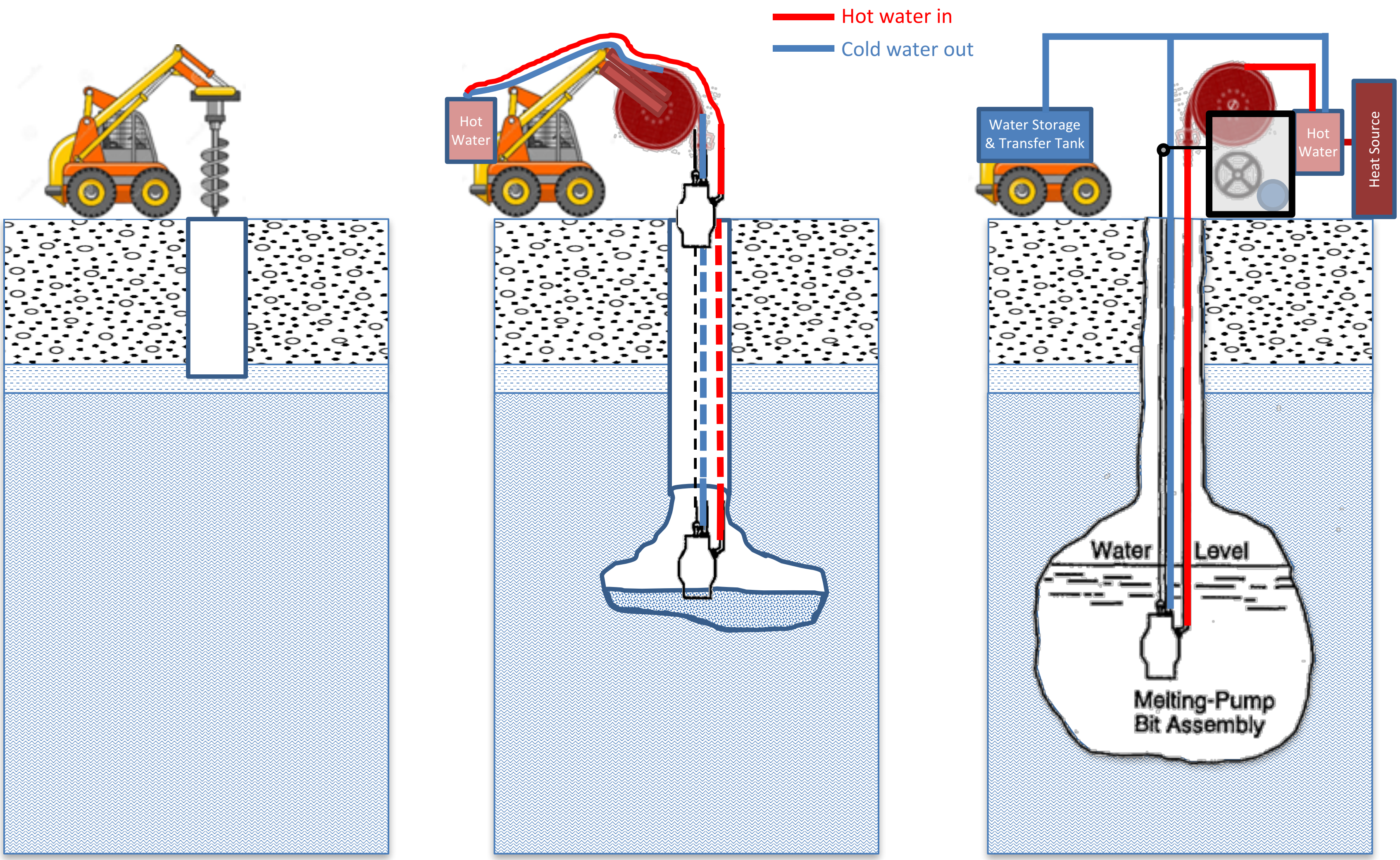
However:

- Martian geological features suggest evidence **for large-scale *mid-latitude* glaciation** ("ice ages"), potentially driven by changes in obliquity of planetary rotation axis
- MRO SHARAD radar took soundings of "lobate debris aprons" (LDAs) in southern and northern regions
- Radar properties completely consistent with **massive water ice (100s of m thick, >90% pure) covered by relatively thin (0.5 - 10 m) debris layer** [Holt, et. al. 2008]

- Fresh impacts detected by MRO HiRISE imager actually ***show*** **excavated, clean ice** (~1% regolith content), verified by CRISM spectrometer
- Majority of craters showing ice in mid-latitudes correspond to the suspected glaciers (LDAs), estimated **excavation ~2 m**

- Mars Odyssey gamma ray/neutron spectrometer confirmed previous predictions of extensive ground ice within *one meter* of surface
  - Poleward of 50° N and S
  - Concentration highly variable ~20-90%
  - Cryosphere estimated to be 5-15 km thick [Clifford, et. al. 2010]
- Predictions and orbital measurements confirmed by Phoenix Lander (68°N)
  - Ice excavated at 2-6 cm, up to 99% pure

Subsurface Water Well Development: Rodwell Approach

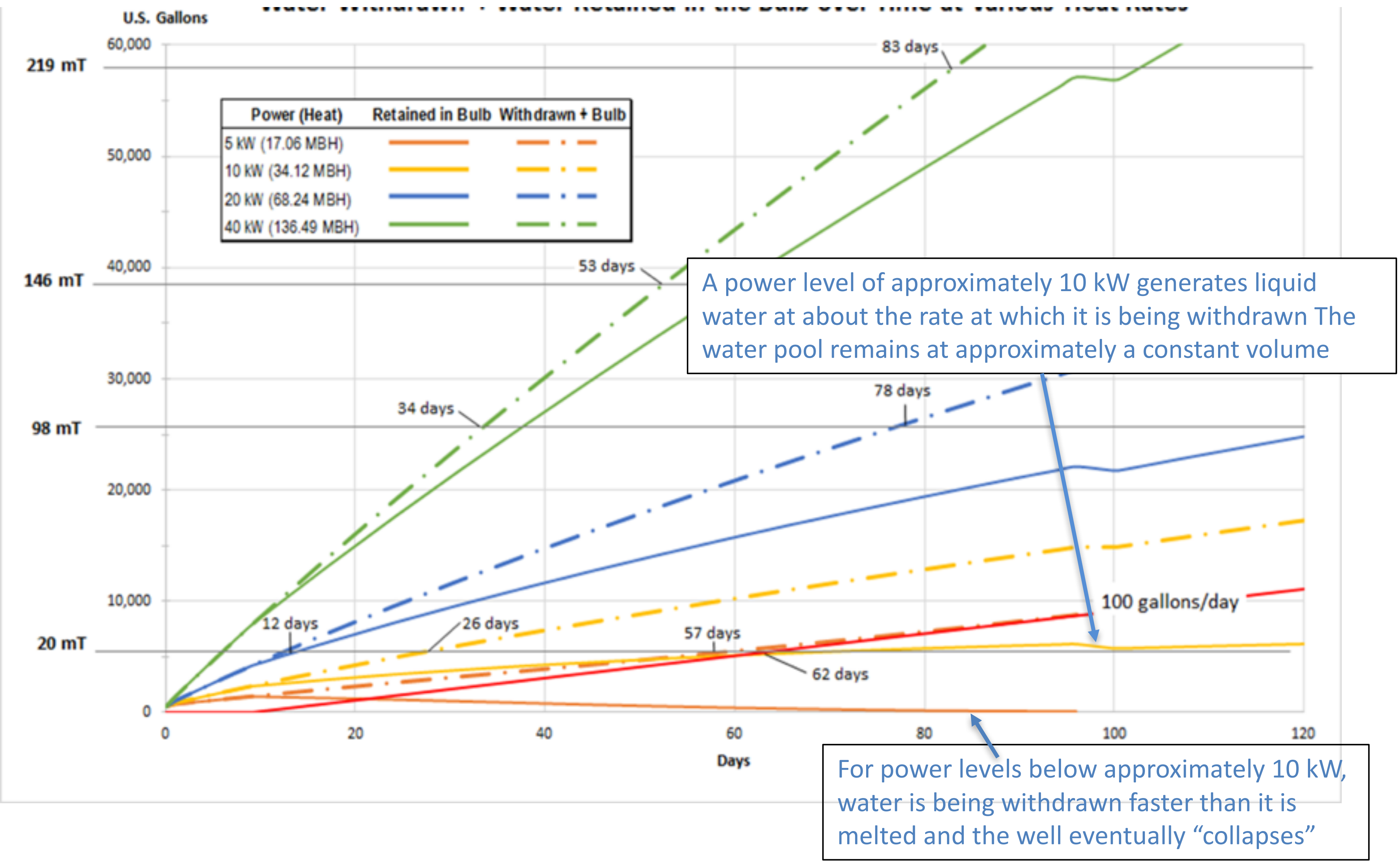


Phase 1: Drill through overburden into top of ice.

Phase 2: Melt into ice. Begin forming water pool.

Phase 3: Steady state operation.

Example: Time Needed to Withdraw Water at 100 gal/day



Ref: Hoffman, Stephen J., Alida Andrews, B. Kent Joosten, and Kevin Watson, "A Water Rich Mars Surface Mission Scenario," 2017 IEEE Aerospace Conference, Big Sky MT, March 5-12, 2017.

Water Extraction from Regolith/Soil - Summary

- **Several concepts for extracting water from icy soils on the moon and Mars are being evaluated both analytically and experimentally**
- **Auger-dryer based on terrestrial dryers**
  - No sweep gas needed
  - Requirement to trap evolved gases in low pressure environment requires analysis and testing to determine feasibility and performance
- **Open air dryer**
  - Trade system complexity vs capture efficiency
    - Preliminary data indicates ~ 50 % capture of water from sodium borate mixed in with simple soil simulant
- **Deep ice mining**
  - Evaluating Rodwell concept in more detail to understand operation in Mars environment

Ultimate choice of processing hardware will be dependent on resource type, quantity of water required, and time for processing

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