ENGINEERING ANALYSIS OF CANDIDATE ORE CASES FOR ISRU WATER PRODUCTION ON MARS:

THE M-WIP STUDY, PART 2

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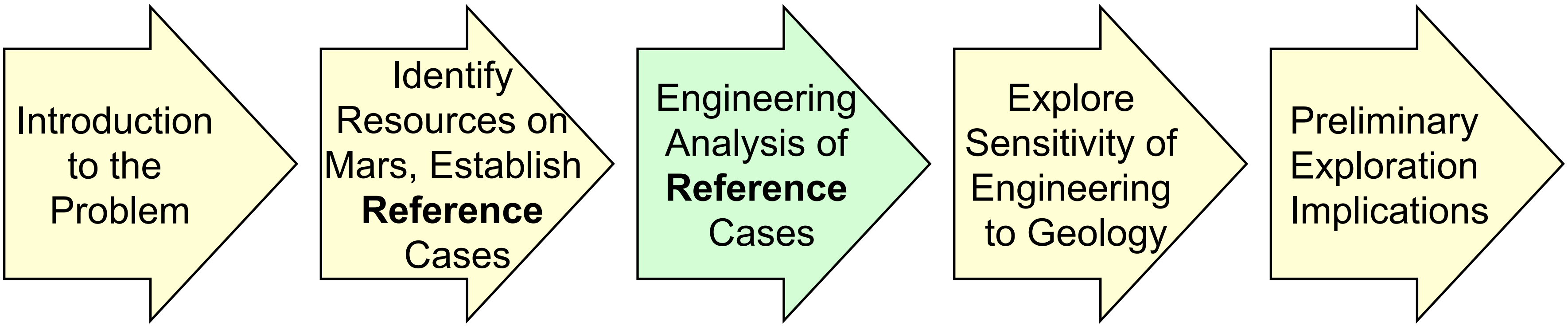
For further information, see the full M-WIP report: http://mepag.nasa.gov/reports.cfm.

Task #2

Estimate the basic engineering attributes of the potential production and processing ISRU systems



Introduction to the Engineering Analysis

- **A NOTE ABOUT UNEQUAL CURRENT ENGINEERING DATA**.

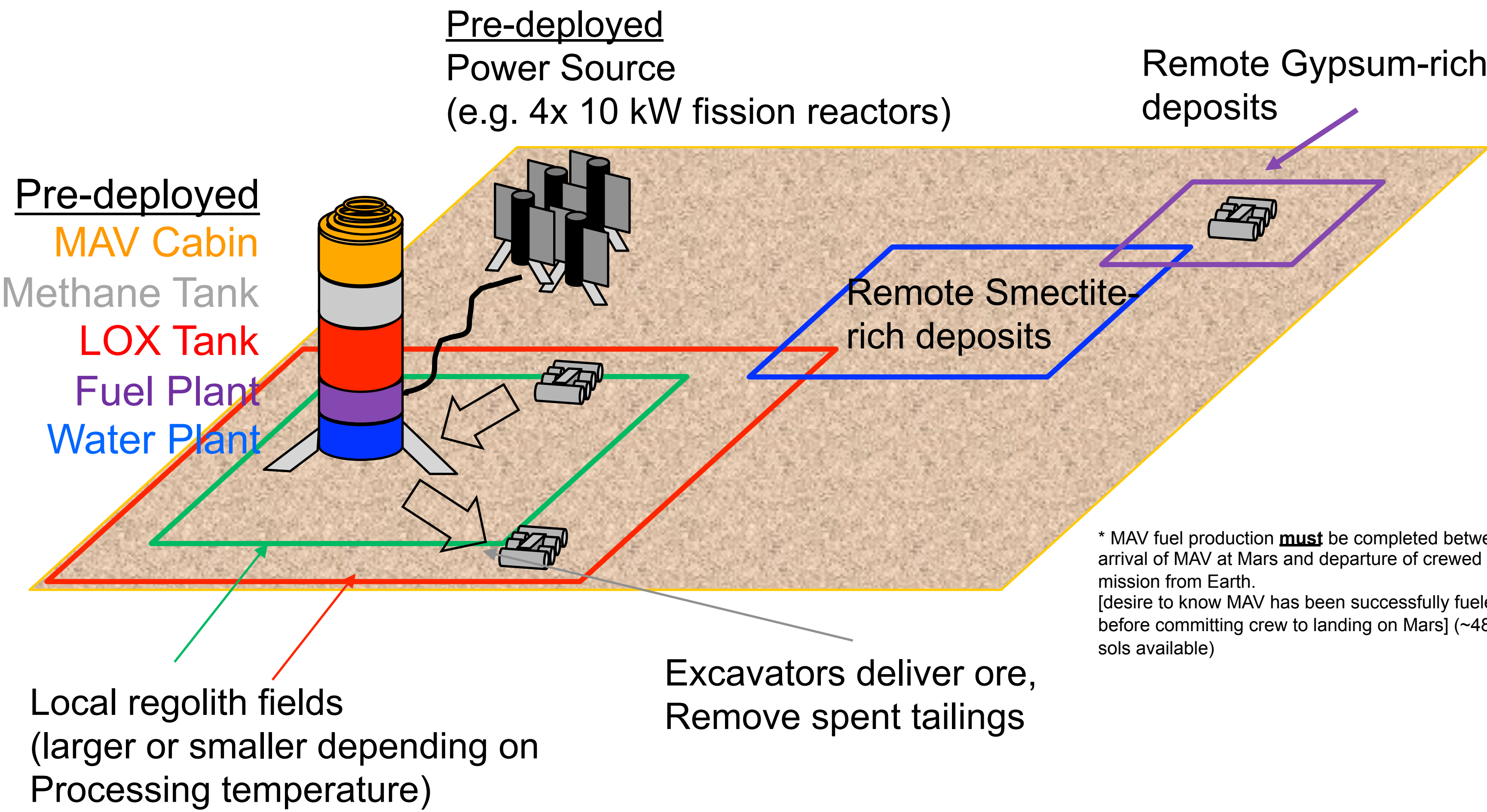
Two main cases

- **Granular materials** (Cases B-C-D) – more technology development has been done

- **Ice cases** (Cases A1 & A2) – less technology development has been done

**Note: "mt" used for metric ton throughout (1,000 kg)*

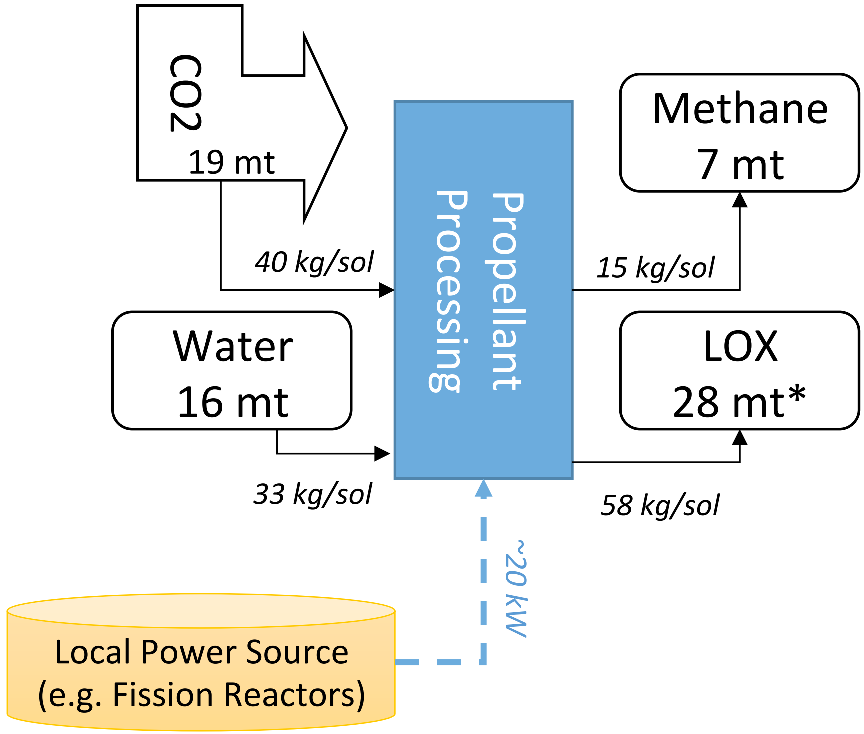
Granular Materials Cases:
Pre-deployed ISRU ”Enterprise”



* MAV fuel production **must** be completed between arrival of MAV at Mars and departure of crewed mission from Earth.
[desire to know MAV has been successfully fueled before committing crew to landing on Mars] (~480 sols available)

Fuel Processing

- To generate MAV propellants, total of 16 mt of water would need to be delivered/processed in 480 sols available (33 kg/sol)
- Combines with 19 mt of atmospheric CO_2 to generate Methane & LOX



**Note: only 23 mt required for MAV propellant. Balance available for crew or other uses*

Ore Temperature Processing Choice

- Water available from various feedstocks is a function of the temperature at which ore is processed.
- For hypothesized deposits, processing temperatures would be selected where “most” of water is extracted at lowest reasonable temperature / power points.
- For typical martian regolith, two scenarios considered, based on two dominant mineral phases (see following).
  - Hypothesis: Lower temperature processing may require more feedstock, but might result in less power required.
  - [Note: Upon analysis, this hypothesis was subsequently proven false – processing greater mass of ore in same amount of time resulted in roughly equivalent power required.]
  - **Additionally, regolith processing temperatures above 450 C may release corrosive contaminants which may be harmful to equipment for diminishing returns of water.**

Water Abundances by Feedstock/Temperature

Gypsum-rich (B) Smectite-rich (C) Typical Martian Regolith (D)

Phase	Characteristic Dehydration Temperature (K)	Assumed Water Content	Case B Assumed Abundance	Case B Potentially Available Water	Case B Cumulative Available Water	Case C Assumed Abundance	Case C Potentially Available Water	Case C Cumulative Available Water	Case D Assumed Abundance	Case D Potentially Available Water	Case D Cumulative Available Water
Allophane	363 K	20%	3%	0.60%	0.60%	3%	0.60%	0.60%	3%	0.60%	0.60%
Bassinite	423 K	6%	0%	0.00%	0.60%	3%	0.18%	0.78%	3%	0.18%	0.78%
Gypsum	423 K	20%	40%	8.00%	**8.60%**	0%	0.00%	0.78%	0%	0.00%	**0.78%**
Akaganeite	523 K	12%	3%	0.36%	8.96%	3%	0.36%	1.14%	3%	0.36%	1.14%
Smectite	573 K	4%	3%	0.12%	9.08%	40%	1.60%	**2.74%**	3%	0.12%	**1.26%**
Basaltic Glass	>750 K	1%	0%	0.00%	9.08%	0%	0.00%	2.74%	23.50%	0.24%	1.50%
"Refractory" (no effective water released)	N/A	0%	51%	0.00%	9.08%	51%	0.00%	2.74%	65%	0.00%	1.50%

Sorted by increasing release temperature

Energy Calculation Method

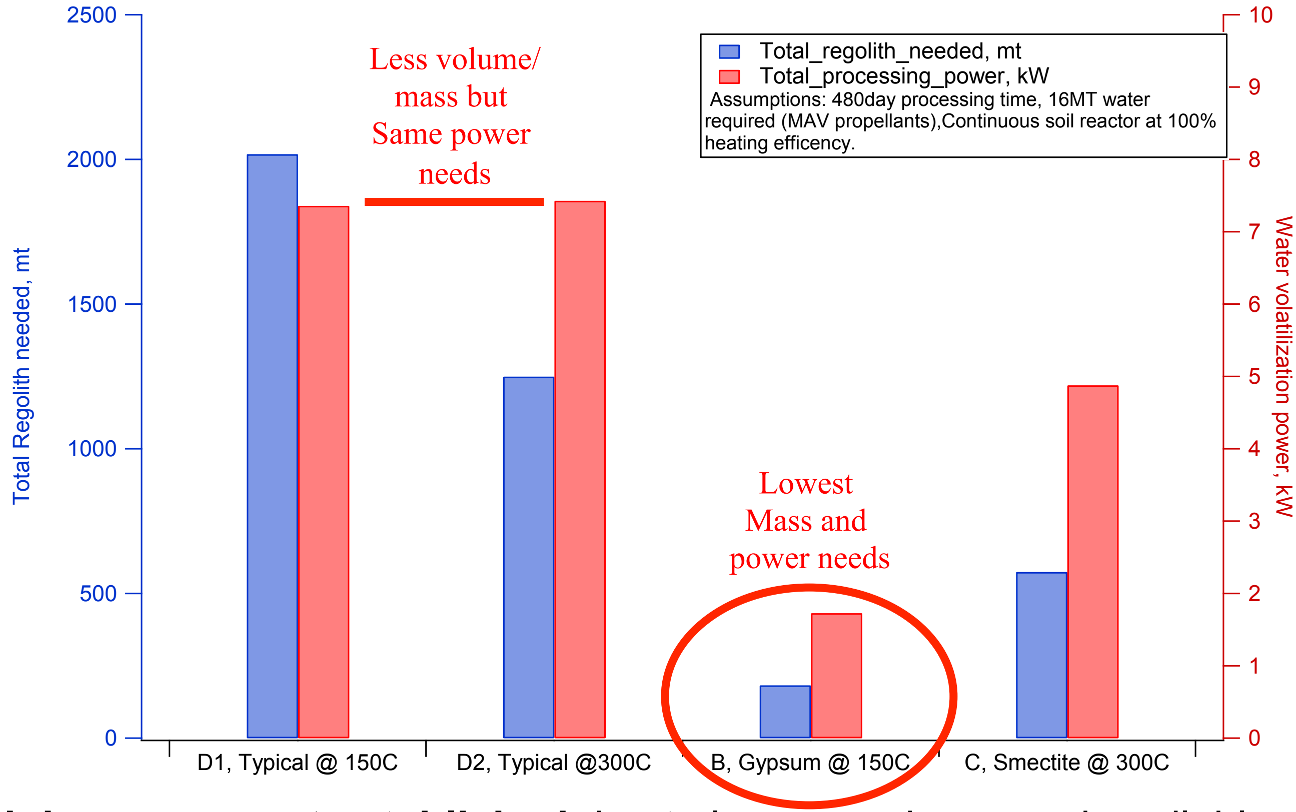
- Feedstock definition (specifically, water availability per processing temperature) used to determined mass of each type of ore needed to achieve water production target.
  - Assumed 75% efficiency of water removal from ore.
- Calculated heat necessary to raise ore temperature to dehydration temperature and added heat of dehydration.

$$\Delta H = m\ c_p\ \Delta T + \Delta H_{dehydration}$$

* Current analysis assumes heat loss to calcination reactor is negligible compared to heat required to raise ore temperature (i.e. thin walled, well-insulated) [Assumption may need to be revisited in future work].

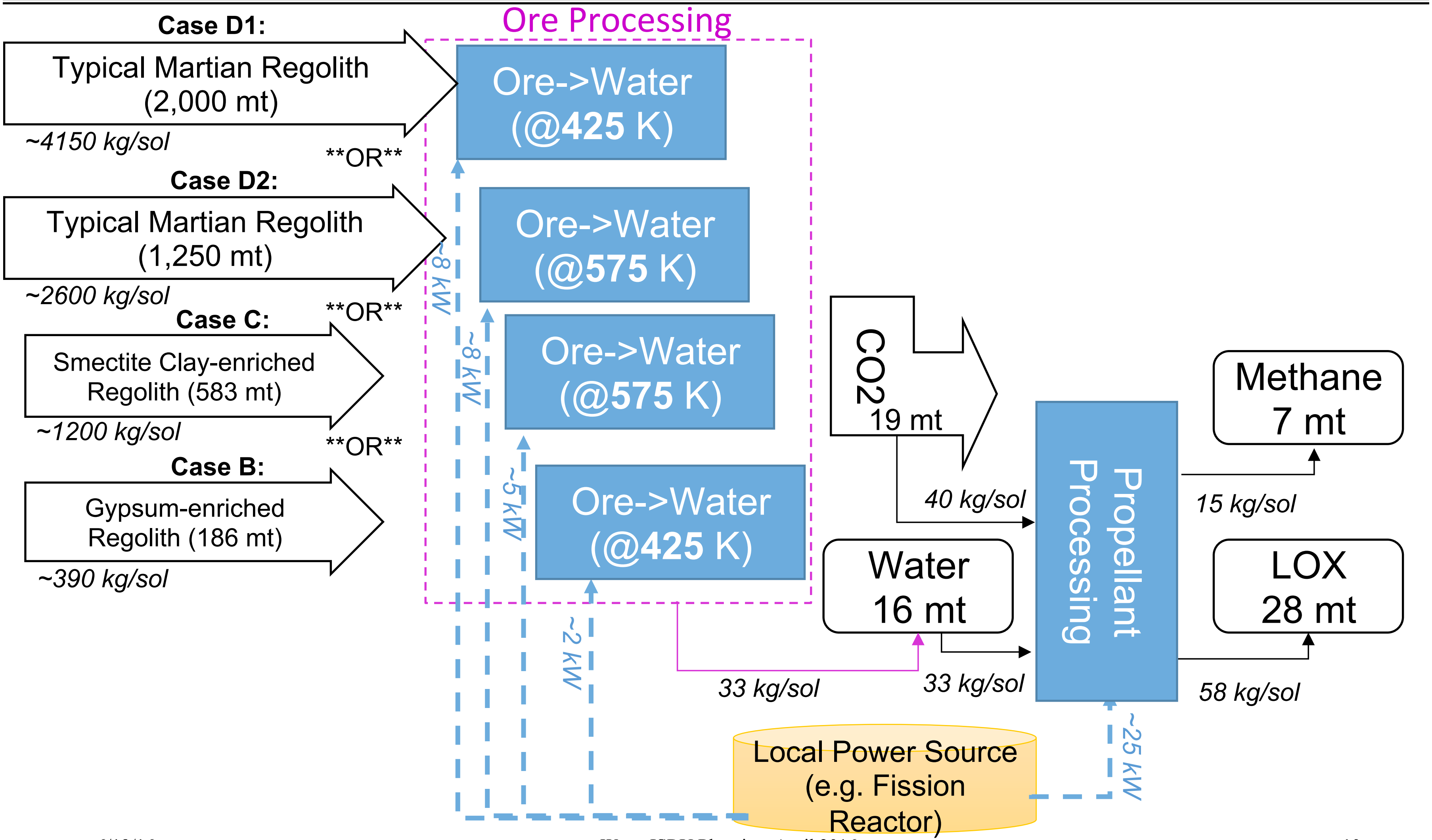
- Power Required = ΔH / time
  - Calculated for both continuous processing and “batch-mode” – essentially same power required with either calculation.
  - Batch mode assumed two hours to heat up each batch of ore.

Key Characteristics by Feedstock



- **Ice mining power not established** due to less experience and available data (Case A)
- Granular gypsum deposits would have the lowest mass AND power requirements.
- Typical martian regolith processed at low temperatures doesn't result in lower power (due to production rates) AND requires more mass -> NO ADVANTAGE

End-to-end Process Flow Options



RASSOR Key Characteristics

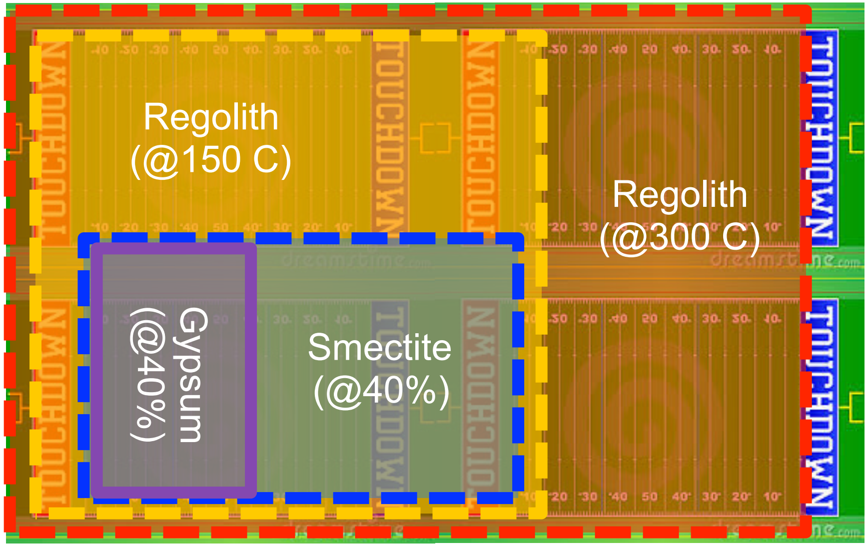
Baseline hardware design of NASA KSC-developed RASSOR Prototype Excavator - key characteristics of this reference model have been used for preliminary sizing analysis. For additional information about this prototype, contact Rob Mueller.

<u>Key Characteristics Assumed:</u>

- Excavator capacity: 2 x 40 kg drums of granular material
- Traverse speed: 25 cm/s
- Battery powered – recharge in proximity to power source
- Duty Cycle / Recharge: 60% on-duty, 40% off-duty [Battery powered – recharge at plant site]

Area Required (at 5 cm depth*)

	Mass (kg)	Volume (@ 2t/m^3)	Area (at 0.05 m depth)	Football Fields (@ 5400 m^2)
Gypsum	186,047	93	1,860	0.3
Smectite	583,942	292	5,839	1.1
Regolith@150	1,269,841	635	12,698	2.4
Regolith@300	2,051,282	1,026	20,513	3.8



Caveats:

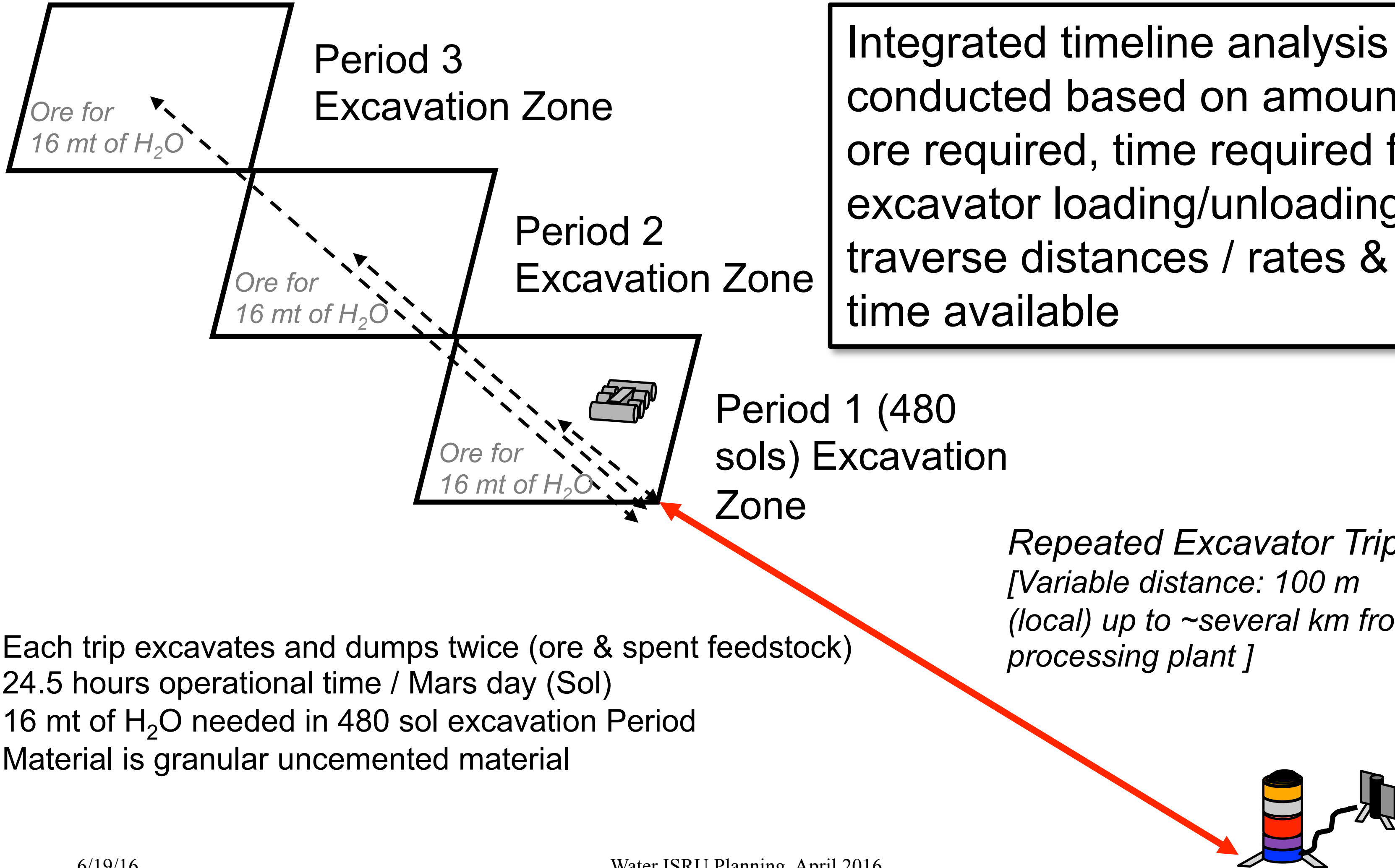
- These areal estimates presume an erosional deposits configuration that is broad but relatively thin (homogenous on at least ~5 cm scale)
- Actual depth could be greater or lesser depending on nature of deposits and vehicle design. Also, for deeper deposits, option exists to excavate multiple shallow layers with repeated trips to same site.

Bulk Density Heuristics Used for Analysis:
0% porosity minerals ("rocks"): ~ 2.7-3.3 g/cc (3 +/- 10%)
35% porosity "undisturbed" granular deposits: ~ 1.8-2.2 g/cc (2 +/- 10%)
50% porosity "disturbed" (extracted) granular material: ~1.35-1.65 (1.5 +/- 10%)

c.f. Water = 1.0 g/cc, terrestrial sand= ~1.6 g/cc

*5 cm excavation depth assumed based on RASSOR demonstrated capability to date (originally designed for lunar scenario).

Intro to Excavation/Travel Analysis



Integrated timeline analysis conducted based on amount of ore required, time required for excavator loading/unloading, traverse distances / rates & time available

Each trip excavates and dumps twice (ore & spent feedstock)
24.5 hours operational time / Mars day (Sol)
16 mt of H_2O needed in 480 sol excavation Period
Material is granular uncemented material

Summary of Excavation/Travel Analysis

Case	Mass of Ore Required (metric tons)	# RASSOR-class loads (@80 kg/load)	Distance from Ore to Plant, typical	# RASSOR – class Excavators used (@ 60% On-Duty)	Duration Required (sols, <480 available)
D1 – Regolith @425K	~2,050 mt	>25,000	~100 m	**3** excavators	382 sols
D2 – Regolith @ 575K	~1,270 mt	>15,800	~100 m	**2** excavators	350 sols
C – Smectite (proximity)	~580 mt	>7,000	~100 m	**1** excavator	318 sols
B - Gypsum	~185 mt	>2,000	**~100 m**	**1** excavator	88 sols
B - Gypsum	(same)	(same)	**~1,200 m**	**1** excavator	480 sols
B - Gypsum	(same)	(same)	**~3,000 m**	**2** excavators	453 sols

- Multiple excavators would be required for typical martian regolith cases (three for D1/two for D2)
- D1 / D2 assumed to be feasible at "any" location (i.e. transportation always ~100m)
- Single excavator could handle hydrated minerals (case B and C) in local proximity
- Smectite would be feasible <100m from lander (318 sols), distances >100m would require >1 excavator
- Pair of rovers could handle gypsum at distances of up to 3 km (same as D2 in local proximity to plant)

Granular Mineral Deposits:
Engineering Summary (1 of 2)

1. Regolith exists almost everywhere on Mars, but how common are deposits that are classifiable as minable "reserves" is not known (this is an exploration question).
2. Mining closer to the lander would leverage power, processing and storage at the lander site. Transportation distance is a major driver for mass, energy and time.
3. Regolith is low grade (~1.5% WEH), and it consists of multiple diverse components that release their water at various temperatures. Recovering some water would be possible at relatively low-T, but recovering all of the water would require high-T (with the possibility of additional released contaminants).
4. Polyhydrated sulfate deposits would have BOTH a lower decomposition temperature, AND a higher water content, than clay mineral deposits.

FINDING #1. The more demanding the requirements for defining "reserves", the higher the quantity/quality of data needed to make a minimally acceptable discovery.

FINDING #2. Three different types of granular mineral water deposits (Cases B, C and D) may have similar implications for acquisition, but favorability from the point of view of extraction is (accumulations of poly-hydrated sulfate minerals, clay accumulations, and typical martian regolith with ~1.5% WEH).

Granular Mineral Deposits:
Engineering Summary (2 of 2)

5. Higher grade mineral deposits are likely to be sparsely distributed (see **Slide #72**)
   - May imply larger transportation distances for the rovers (negative)
   - May control the base location (constraining the layout of the exploration zone – potential negative).
   - The higher yield of high-grade deposits would reduce batch sizes, and total volume of raw material to be moved (positive)
   - The trade-off between these needs to be evaluated in more detail.

FINDING #3. A key trade-off between regolith and higher-grade mineral deposits: The latter are likely to be locally distributed (and thus may be associated with larger transportation distances), and the former would require moving and heating larger masses of raw material.

Engineering Notes on Case A

- Although Case A (buried glacial ice deposits) may represent the most concentrated source of water, work during this study was hampered by the relatively low amount of recent engineering research conducted in this area.
  - Recent emphasis has been on near-surface approaches more applicable on Moon or in northern permafrost regions on Mars (>50° from equator)
- Candidate Strategies for deeper ice (>1m) include:
  - **Surface mining of ice**: Remove overburden, extract solid ice [Preliminary Analysis Conducted herein] or
  - **In Situ Recovery**: Drill through overburden, melt/dissolve ice at depth and recover/separate at surface [Not analyzed in this study– **See Slide #82**]

Near-Surface "Mobile In Situ Water Extraction (MISWE)"

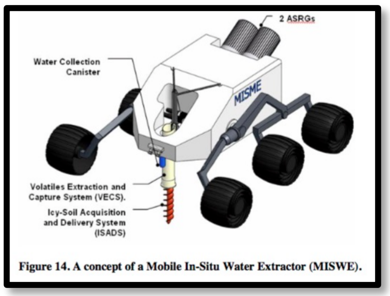


Figure 14. A concept of a Mobile In-Situ Water Extractor (MISWE).

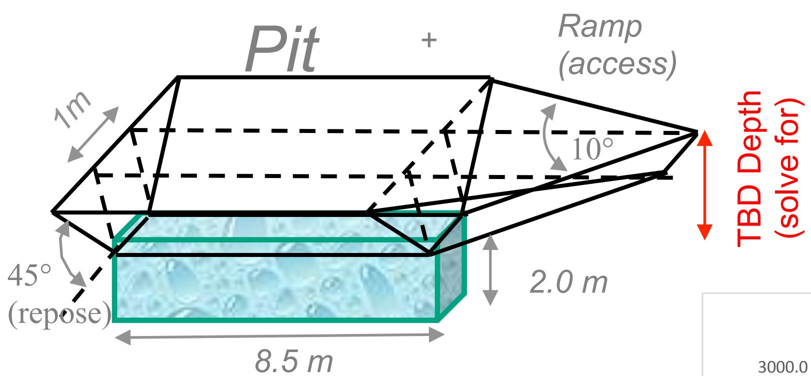
Credit: K. Zacny, Honeybee Robotics

"Cryobot" for Science Exploration (earlier concept)

Credit: NASAJPL (1999)

Overburden removal for an Open Pit Over Ice

Overburden:



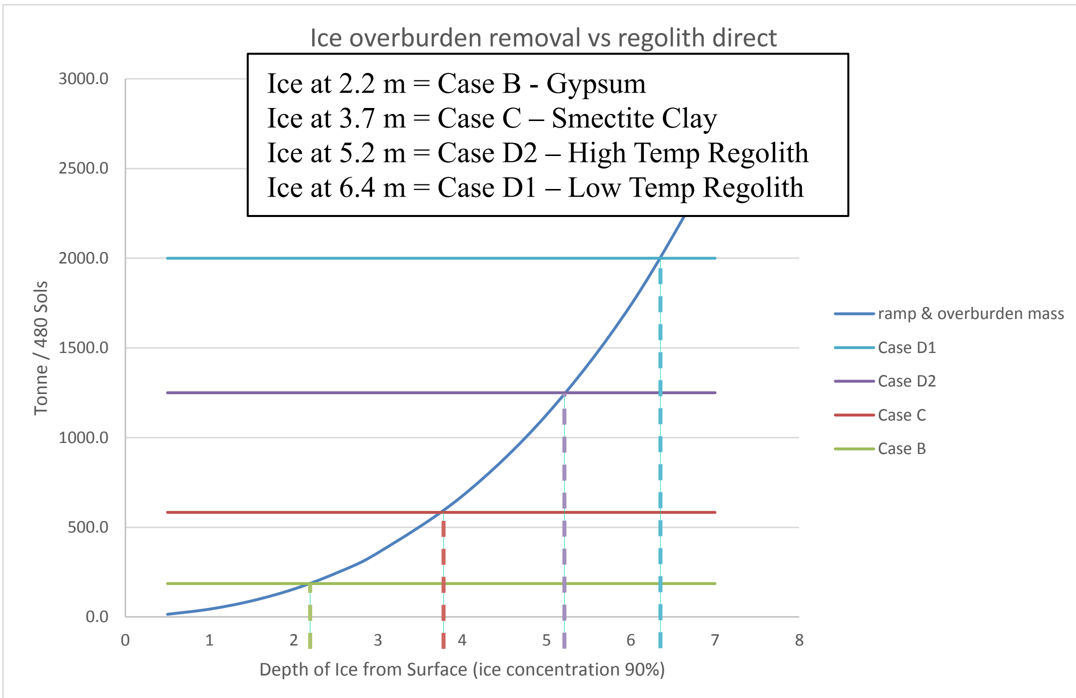
Subsurface Ice:

17.4m³ required for 16t water
= 8.5m (l) X 1m (w) x 2.0m (d)
(width based on notional excavator geometry)

Notes/Caveats:

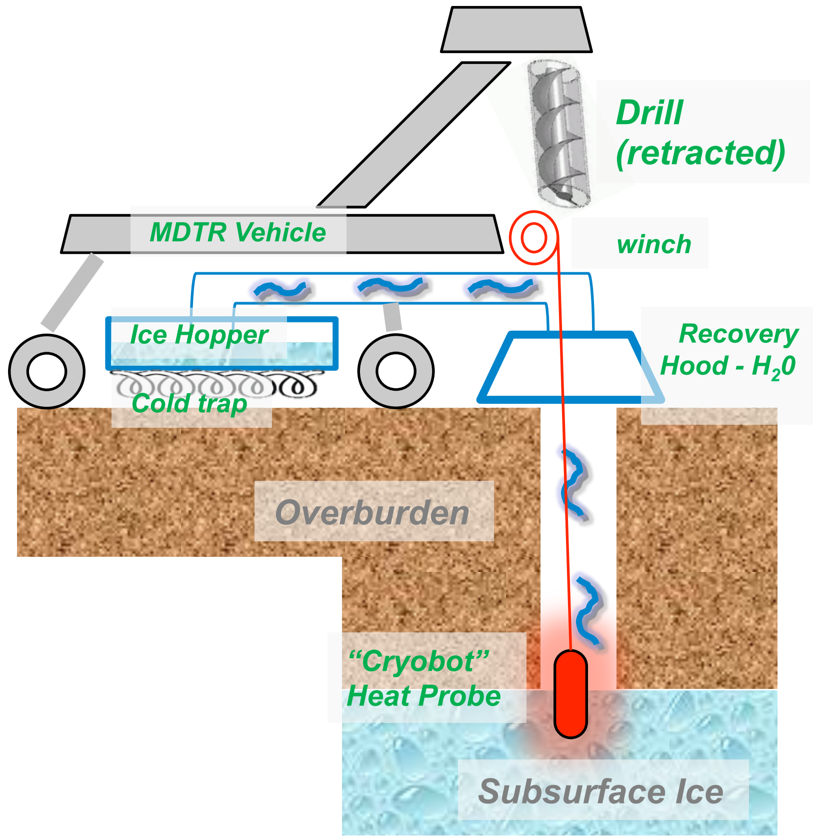
- *Does not take into account the potentially more difficult excavation of ice-regolith mixtures.*
- *Overburden removal disturbs the thermal equilibrium which may lead to ice subliming away over time.*

- Analysis conducted to compare mass/volume of overburden to be removed to reach subsurface ice (to enable surface mining of ice)
- Q: At what ice depth does overburden mass/volume exceed mass/volume required for other granular cases (B-C-D)?



Subsurface Ice – A 2nd Possible Concept of Operations

- A) Initial landed assets arrive (MAV, ISRU Plant, Power Source) including rover carrying drilling + cryobot equipment (Mobile Drilling/Transport Rig = **MDTR**)
- B) MDTR traverses to the buried ice deposit
- C) MDTR drills through the overburden (may or may not need to “case the hole” while drilling)
  - “Cryobot” heat probe may either be part of drilling operation, or lowered down the shaft after ice is reached
- D) Once ice layer is reached, cryobot is heated, ice melts/sublimes – cold-trapped in “hood” over “hopper” onboard rover at surface
- E) Once MDTR hopper is filled with ice, rover returns to MAV/Fuel plant. Hopper full of ice is re-melted & processed.
- F) MDTR returns to buried ice deposits for as many round trips as necessary.



Full implications of drilling + melting not examined for this study – see Follow-Up Work **Slide #82**

Subsurface Ice Deposits:
Engineering Summary

1. Open pit ice mining would require significant removal of overburden.
   - The mass to be moved would go up geometrically with depth to ice
   - the break-even point appears to be not more than a depth of burial of 2-3 m.
2. The mechanical acquisition of hard ice could be difficult
   - especially if there are entrained rocks/sand.
   - Higher excavation energy may be required than for granular materials.
3. Once exposed, the ice deposit would be unstable.
   - The rate of this process has not been modeled, so we don't know yet if this has a practical significance.
4. Downhole extraction methods potentially attractive, but low TRL
   - may have complications due to the creation of an underground void.
5. Higher concentration of water than any of the mineral-based possibilities
   - the mass to be transported would be lower and thus transportation distances could be larger.
   - processing could probably be operated with higher yield, lower power, fewer batches/cycles.

FINDING #4. Significant engineering challenges may be associated with mining buried glacial ice. If these challenges could be resolved, the subsurface ice cases (A1 & A2) would involve less mass and energy for transportation and processing compared to any of the mineral cases (B-C-D).

Key Factors in Comparing Cases

- Summary Table Generated to Compare Cases (see following)
- For each case (row), the following attributes are characterized:
  - **Type of Ore Considered** (Gypsum-rich (Case B), Smectite-rich (Case C), Typical Martian Regolith (Case D))
  - **Excavation/Extraction Strategy**– What is the equipment needed to removed the ore or overburden from its original location? For typical martian regolith: Processed at low temperature or high?
  - **Ore processing temperature & power** – What are the specs for the processing systems for the method selected?
  - **Transport to processing plant** – What must be transported to a processing location, and how far? Can the plant potentially be located at the site of the resource?
  - **Ore/tailings mass per mission** – How much mass of the given ore is needed for each human mission? How to dispose of equivalent mass of spent tailings?
  - **Transport to fuel plant** – What is the equipment needed to transport the raw ore to a fuel location?
  - **Fuel processing** – what power is needed for converting water + atmospheric CO_2 into LOX/ Methane?

Summary of Key Factors

Deposit	Strategy	Landing Proximity	Excavation/ Extraction Approach	Ore/Tailings Mass per Mission	Transport to Refinery/ Retort	Refinery / Retort	Transport to Fuel Plant	Fuel Processing	Total Power Estimate[1] (Summary)
Regolith	Surface Mining, Central Processing (higher temp, lower mass)	Land on	Batch Excavation Rovers	~1,300 tons (@1.25%)	Not Required /Minimal	300 C / Continuous or Batch (8 kW)	Not required	Common (~20 kW)	~28 kW[1]
Regolith	Surface Mining, Central Processing (lower temp, higher mass)	Land on	Batch Excavation Rovers	~2,000 tons (@0.75%)	Not Required /Minimal	150 C / Continuous or Batch (8 kW)	Not required	Common (~20 kW)	~28 kW[1]
Clays	Surface Mining, Central Processing	~several km from base	Batch Excavation Rovers	~600 tons (@3%)	Ore Transport Rover (~600 tons)	300 C / Continuous or Batch (5 kW)	Not required	Common (~20 kW)	~25 kW[1]
Hydrated Sulfates	Surface Mining, Central Processing	~several km from base	Batch Excavation Rovers	~200 tons (@9%)	Ore Transport Rover (~200 tons)	150 C / Continuous or Batch (2 kW)	Not required	Common (~20 kW)	~22 kW[1]
[FUTURE WORK]: Subsurface Ice	Surface Mining	~several km from base	Prohibitive beyond TBD meters?	Not required	Not required	Not required	Ice Transport Rover (16 tons)	Common (~20 kW)	TBD (field) + ~20 kW
[FUTURE WORK]: Subsurface Ice	Down-hole heat probe + In Situ Recovery	~several km from base	Drill / Kerf only, Downhole "Cryobot" heat probe	Not required	Not required	Subsurface heating, Gas-phase Recovery with cold trap (TBD kW)	Ice Transport Rover (16 tons)	Common (~20 kW)	TBD (field) + ~20 kW

[1] Total power does not include power to load and transport feedstock on a transporter. Power for feedstock extraction are idealized power levels without efficiency losses. If efficiency losses are added in difference between options will likely be greater and potentially, significantly greater.

Blasting and Crushing

1. Comminution (blasting, crushing, and grinding) is used on a wide variety of rock ores on Earth. These technologies color how we think about "production" (see **Slide #12**). Should we think about their specific application to water production at Mars?
2. For water-bearing minerals on Mars (Cases B-C-D), natural long-term weathering processes may have resulted in materials in granular form in suitable concentrations. If these deposits can be found, blasting will not be needed.
3. Crushing and grinding typically are used to raise the recovery efficiency in the processing plant. For Mars, we are assuming a recovery method consisting simply of heating/vapor capture. For materials under consideration in this study, grain size has less effect on water recovery than traditional experience on terrestrial ores.
4. Blasting, crushing, and grinding are complex processes – they require significant mass, power, and equipment with many moving parts (and by inference, high maintenance and low reliability).

CONCLUSION: For these reasons, we assume that comminution is neither necessary nor effective as a part of the Mars water production scenario. We encourage this assumption be challenged by future study teams.

Conclusions

Conclusions (1 of 2)

- Mining subsurface glacial ice by open pit methods would have multiple challenges
  - thickness of the overburden,
  - mechanical properties of the ore.
  - For all but the shallowest glacial ice deposits (2-6m) requires processing larger amounts of material than surface mining of hydrated minerals or typical martian regolith.
- “Down-hole” or “In Situ Recovery” of subsurface glacial ice by sublimation/recondensation (Case A2) appears to be the most promising approach to subsurface ice access
  - least mature technology.
  - This study was not capable of performing direct comparison with the other cases at this time.
- Producing water from typical martian regolith would require both collecting the most “dirt” and the greatest processing energy compared
  - Especially sensitive to transportation distance, and to heterogeneity in grade
  - most flexibility in terms of landing site options and still offers a favorable system mass trades.
- A deposit of poly-hydrated sulfate (Case B) minerals appears to be the most advantageous granular reference case
  - particularly sensitive to the distance from the deposit to the other infrastructure (e.g. power, extraction plant).
  - This might be minimized by strategies that involve specialized classes of rovers (excavators vs. transporters) and/or field processing of the ore into water/ice for transport (subject to movable power/heat sources such as smaller movable reactors or RTGs).
  - Surface granular material excavation technologies are at relatively high TRLs.
- The phyllosilicate reference case (Case C) is significantly inferior to polyhydrated sulfate (Case B), and only somewhat better than typical martian regolith (Case D).
  - In order for this deposit type to be competitive, we may need either a deposit of a mineral that has more water than smectite, and/or a higher smectite concentration than in the reference case.
  - We do not yet know whether deposits as good or better than the reference cases used in this study, and in a minable configuration, exist on Mars.