Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study

April 11, 2016

Angel Abbud-Madrid, David Beaty, Dale Boucher, Ben Bussey, Richard Davis, Leslie Gertsch, Lindsay Hays, Julie Kleinhenz, Michael Meyer, Michael Moats, Robert Mueller, Aaron Paz, Nantel Suzuki, Paul van Susante, Charles Whetsel, Elizabeth Zbinden

(affiliations in Appendix)

This "first-order" analysis of questions about supply-side planning related to potential water resource deposits on Mars was jointly requested by NASA-SMD and NASA-HEOMD in Jan. 2016.

Recommended Bibliographic Citation:

Abbud-Madrid, A., D.W. Beaty, D. Boucher, B. Bussey, R. Davis, L. Gertsch, L.E. Hays, J. Kleinhenz, M.A. Meyer, M. Moats, R.P. Mueller, A. Paz, N. Suzuki, P. van Susante, C. Whetsel, E.A. Zbinden, 2016, Report of the Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study; 90 p, posted April, 2016 at http://mepag.nasa.gov/reports.cfm.

Executive Summary (1 of 2)

This scoping analysis is intended to provide guidance regarding a number of complex and inter-related issues involving the potential use of Martian water resources, and for which follow-up action by a number of different entities would be beneficial.

- Objectives: 1). Formulate descriptions of hypothetical reserves on Mars, 2). Estimate the rough order-of-magnitude of the engineered system needed to produce each of the reference cases, 3). Prepare a first draft analysis of the sensitivity of the production system to the known or potential geological variation, 4). Prepare an initial description of the preliminary implications for exploration.
- Reference cases: Four reference cases have been defined: Case A – glacial ice; Case B – a natural concentration of poly-hydrated sulfate minerals; Case C – a natural concentration of phyllosilicate minerals; Case D – regolith with average composition as observed from in situ missions.
- The ice case (Case A) appears to have certain advantages relative to granular materials (e.g. less sensitive to transport distance), but also some disadvantages (e.g. the need to deal with overburden). More study of the ice case is needed to put it on the same footing as the granular materials cases (B-C-D).
- Of the granular materials cases (B-C-D), Case B would involve moving the lowest mass of raw material, AND would have lower power requirements. Using regolith (Case D) would require moving more mass (because it is lower grade), and would require more power to extract. Case C is intermediate.

Executive Summary (2 of 2)

- Whether any of these cases is above minimum thresholds for a potential future human mission depends on the resource envelope for that mission, as well as its architecture and priorities—none of which has yet been determined.
- The different cases have different sensitivity to known or potential natural geologic variation. The granular materials cases (B-C-D) are most sensitive to the nature/scale of the mechanical heterogeneity of the ore deposit, and the distance between the mine and the processing plant. The ice case (A) is most sensitive to the thickness and properties of the overburden.
- We do not have enough orbital or ground data to be able to determine if deposits as good or better than the reference cases exist at Mars. Exploration is needed at several different scales.
- The details of the logic imply that this is a 2-step exploration problem—there needs to be an orbital reconnaissance mission followed by at least one landed exploration mission. The details of how these missions are optimized is left to future study teams.
  - This is needed to pick the landing site, whether or not we would be doing ISRU right away.
- Follow-up work is needed in multiple areas, including technology development for ice and granular mining cases, advance mission planning (including in both the human and the robotic arenas), improving our understanding of Mars, the geology, nature and mechanical properties of representative deposits, and in refining our exploration strategy from orbit and on the surface.

Key Antecedent #1: EMC (Evolvable Mars Campaign)

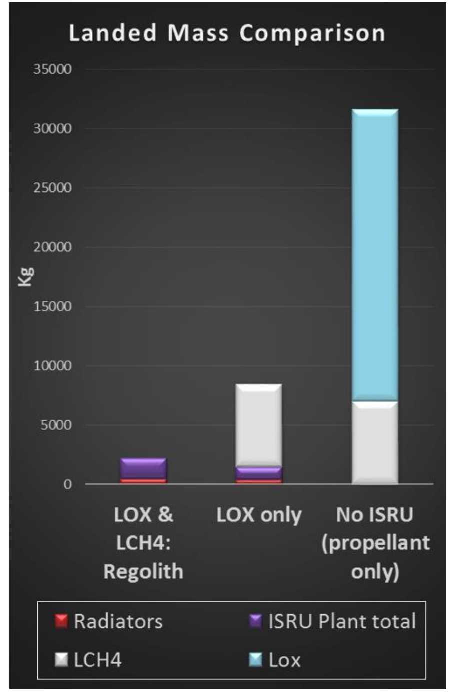
The Potential Benefit of Acquiring Local Water (1 of 2)

	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.	
	Total Mass, mt	Ratio: Propellant produced per kg of landed mass
ISRU for LOX & LCH_4: Sulfates	1.6	22.1
ISRU for LOX & LCH_4: Regolith	1.7	20.5
ISRU for LOX only (no water)	8.0 (1mt hardware + 7mt Methane)	3.1
Propellant only (no ISRU)	31.6 (24mt Oxygen + 7mt Methane)	na

These comparisons consider ISRU end-to-end systems encompassing excavation, resource processing and propellant production, cleanup, and liquefaction.

For the LOX-only ISRU case, methane would have to be delivered to Mars from Earth.

These calculations only account for the mass of the propellant that is needed in the MAV. They do not account for the additional propellant mass which would be required to deliver that MAV propellant to Mars from LEO. Thus the advantage of a combined ISRU LOX/Methane production system would be greater than indicated.



Harnessing even the lowest yield Mars regolith water resource for ISRU would offer a 6x improvement over an LOX-only ISRU in the terms of the mass of propellant generated for each kg of total ISRU system mass.

For every kg of total ISRU system mass delivered to Mars:

- A Lox/LCH_4 ISRU system can produce 20 kg of propellant
- A Lox-only ISRU system can produce 3 kg of propellant

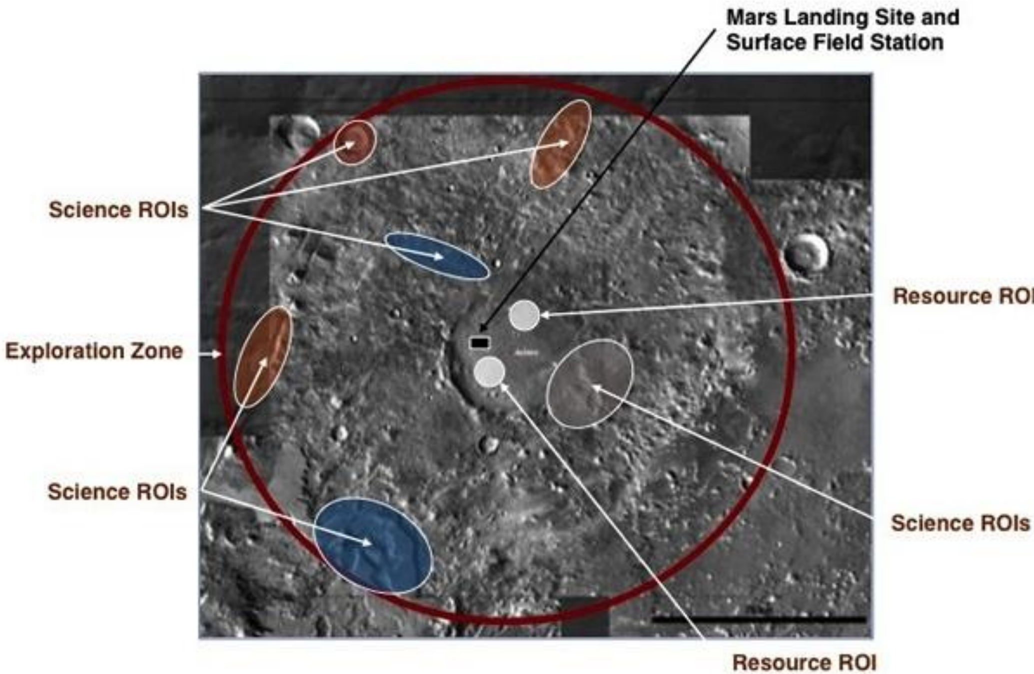
Key Antecedent #2: HLS^2

- Human Landing Site Selection (HLS^2): October 2015 workshop on Mars Exploration Zones.
- In addition to science regions of interest, all site proposers were asked to identify one or more candidate water resource deposits within their Exploration Zone that have the potential to produce 5 metric tons of water per year.
- 47 candidate sites proposed by the world's leading experts in ISRU and Mars geology. The four most common candidate water resource deposits proposed include (not in priority order):

1. ***Mid-latitude ice***
2. ***Concentrations of poly-hydrated sulfate minerals***
3. ***Concentrations of phyllosilicate minerals***
4. ***Regolith.***

See also ICE-WG (2015; Hoffman and Mueller, co-chairs)

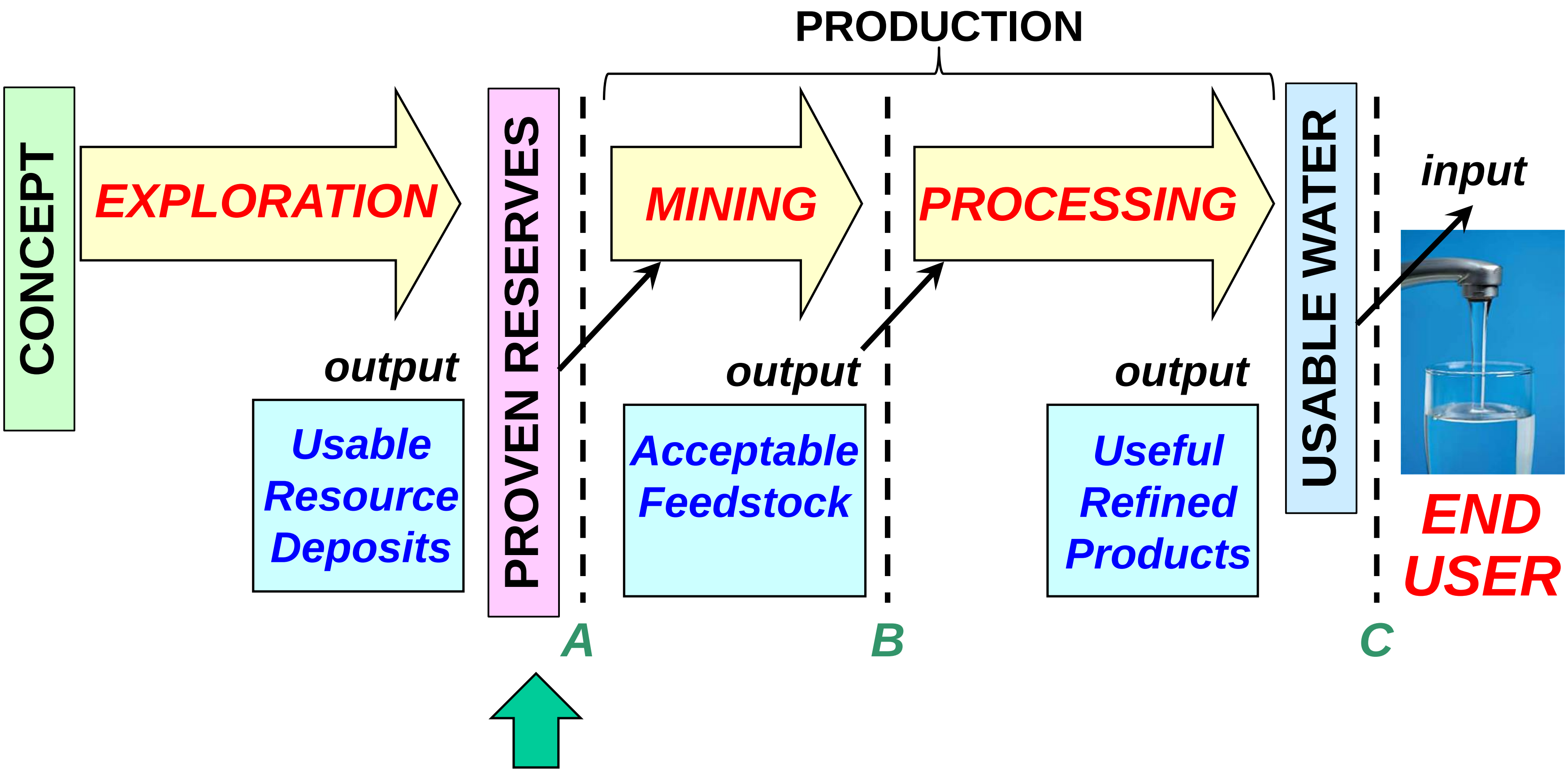
http://www.nasa.gov/journeytomars/mars-exploration-zones



Confidence: The Concept of Reserves

Reserve Classification	Earth Application	Mars ISRU Application	Confidence
Proven	Use as collateral for a bank loan	Astronaut lives can depend on it	99%
	MAKE COMMITMENTS		
Probable	*SPECIFIC DEFINITIONS EXIST*	*UNDEFINED*	90%
Possible		*UNDEFINED*	50%
Potential	*THE EXPLORATION ARENA*		<50%

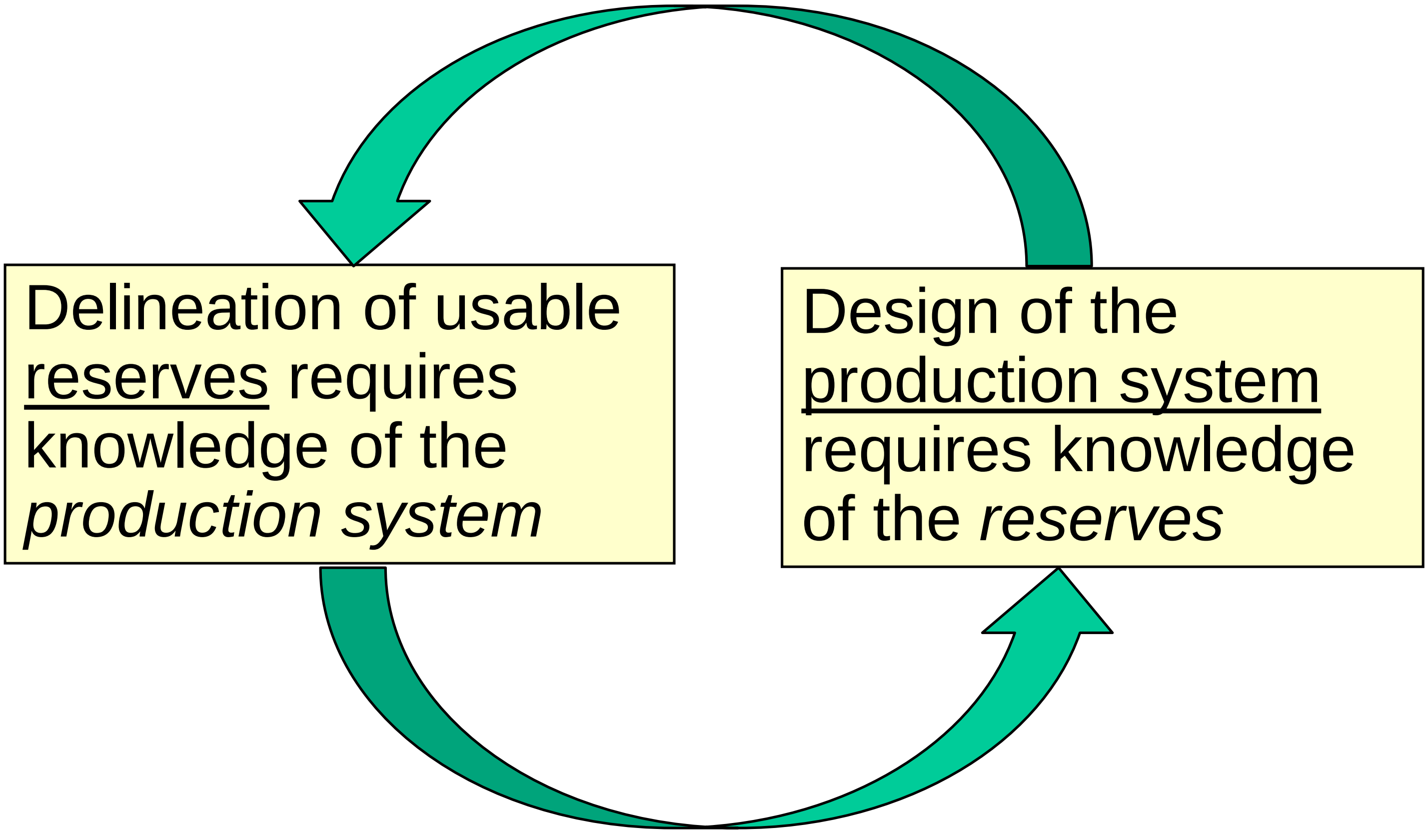
The Exploration-Production Flow



The essential interface between "exploration" and "production"

From Beaty et al. (2016), discussion with the Geological Society of Nevada acknowledged

A Chicken-Egg Issue



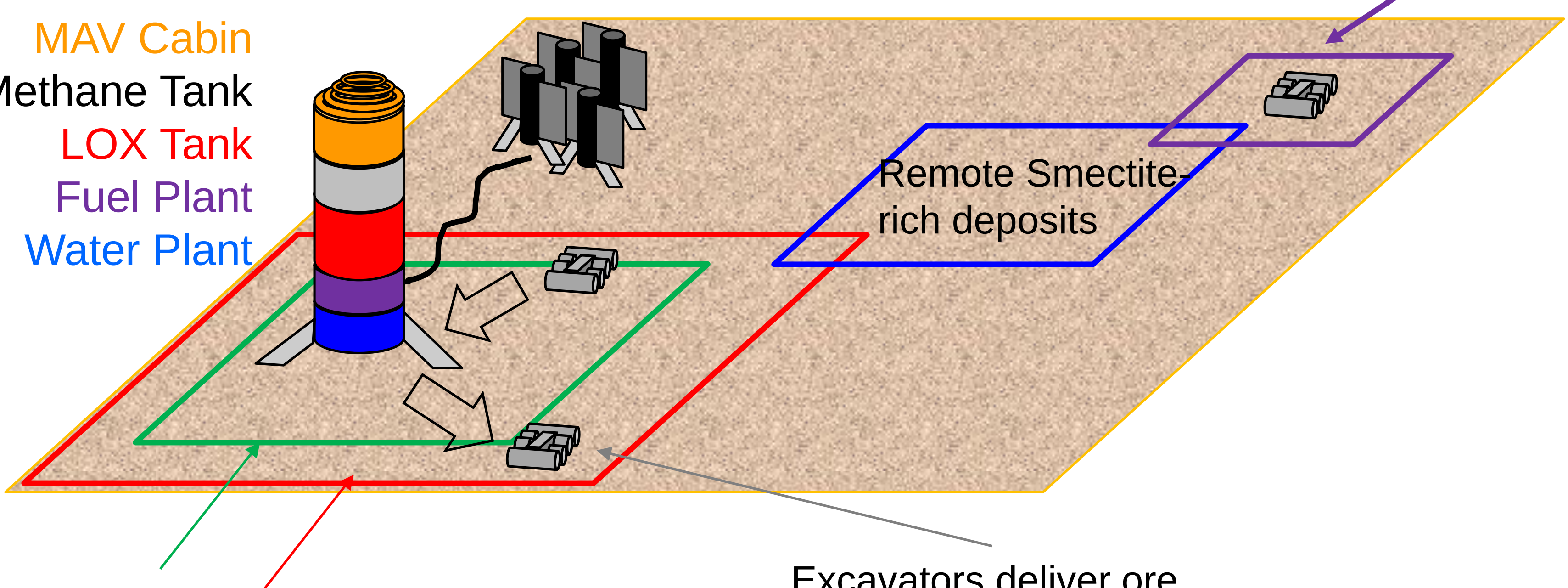
From Beaty et al. (2016)

Granular Materials Cases:
Pre-deployed ISRU "Enterprise"

Power Source
(e.g. 4x 10 kW fission reactors)

Remote Gypsum-rich
deposits

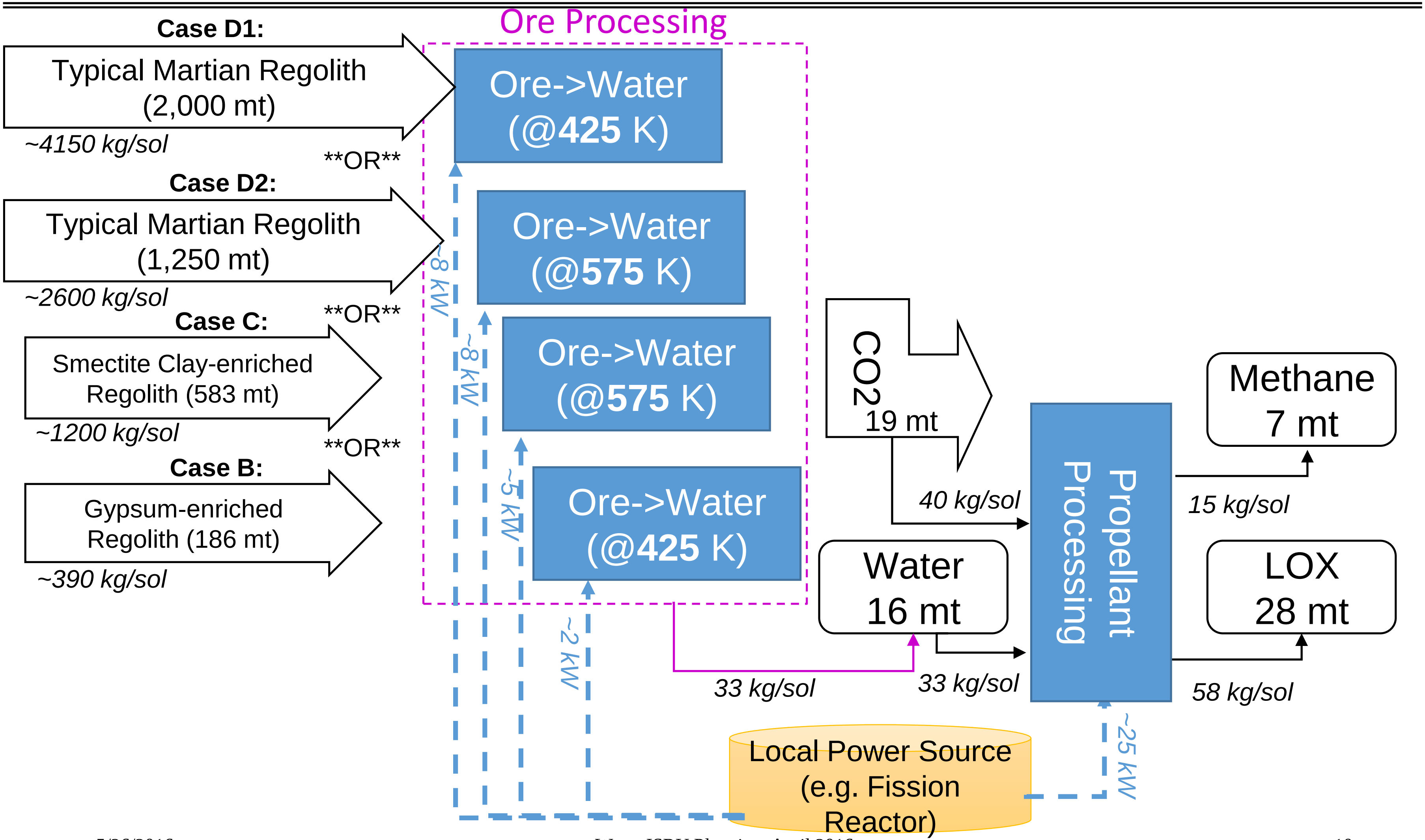
MAV Cabin
Methane Tank
LOX Tank
Fuel Plant
Water Plant



Local regolith fields
(larger or smaller depending on
Processing temperature)

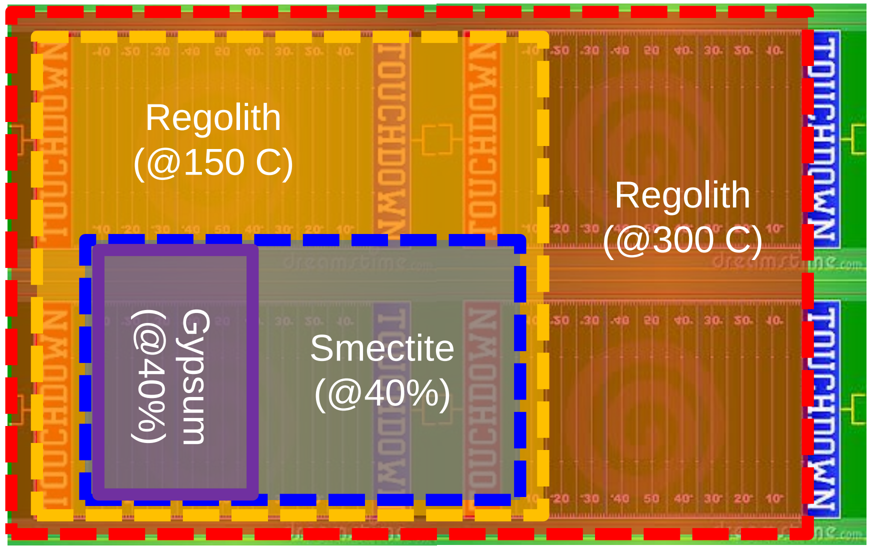
Excavators deliver ore,
Remove spent tailings

End-to-end Process Flow



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:

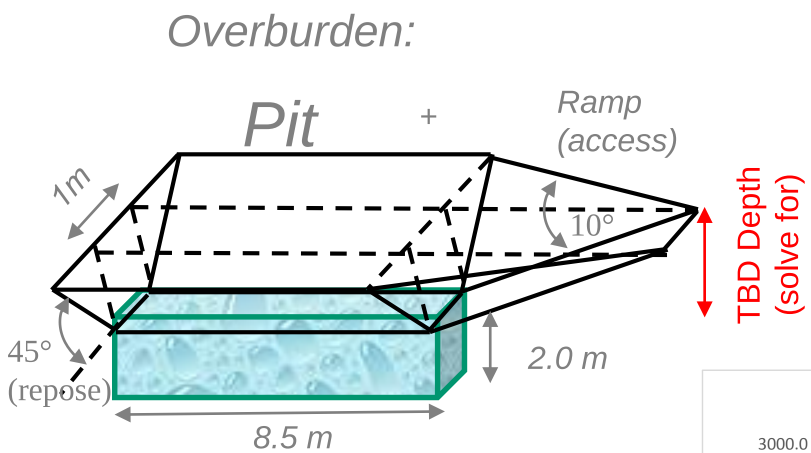
- These areal estimates presume an erosional deposits configuration that is broad but relatively thin (homogenous on at least ~5 cm scale)
- Actual depth could be greater or lesser depending on nature of deposits and vehicle design. Also, for deeper deposits, option exists to excavate multiple shallow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

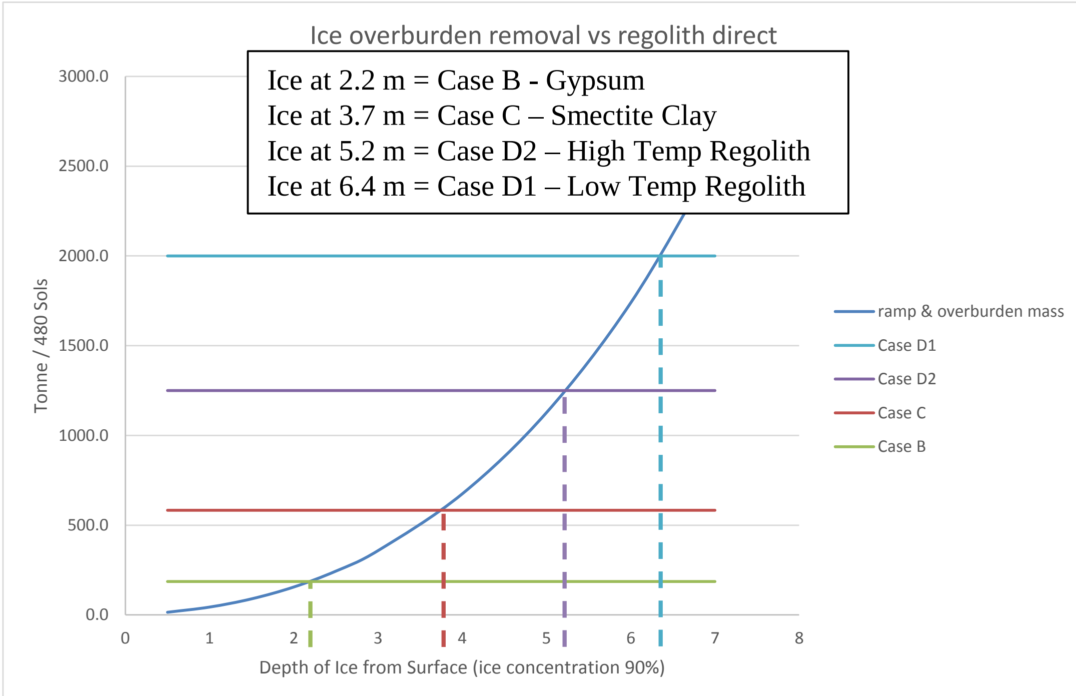
Overburden removal for an Open Pit Over Ice



- Analysis conducted to compare mass/volume of overburden to be removed for 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:

$17.4m^3$ 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.*

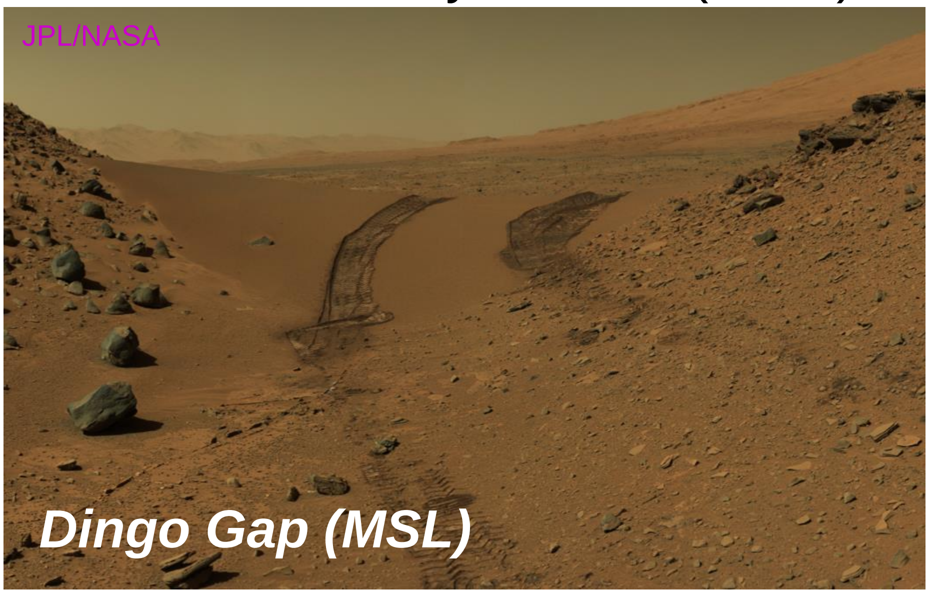
Summary of Key Factors

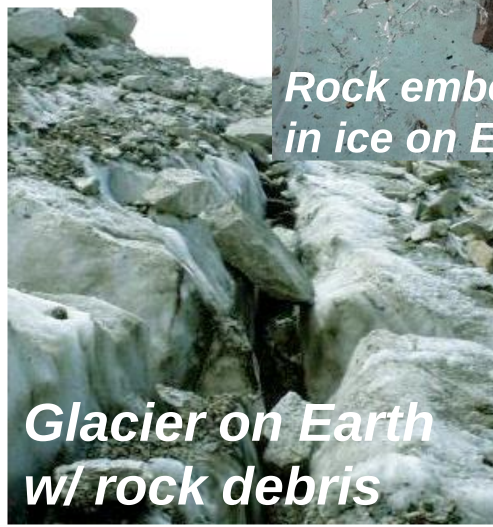
Deposit	Strategy	Landing Proximity	Excavation/ Extraction Approach	Ore/Tailings Mass per Mission	Transport to Refinery/Retort	Refinery / Retort	Transport to Fuel Plant	Fuel Processing	Total Power Estimate[1] (Summary)
Regolith	Surface Mining, Central Processing (higher temp, lower mass)	Land on	Batch 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.

Nature and Scale of Ore Heterogeneity—Mechanical Consistency (2 of 2)

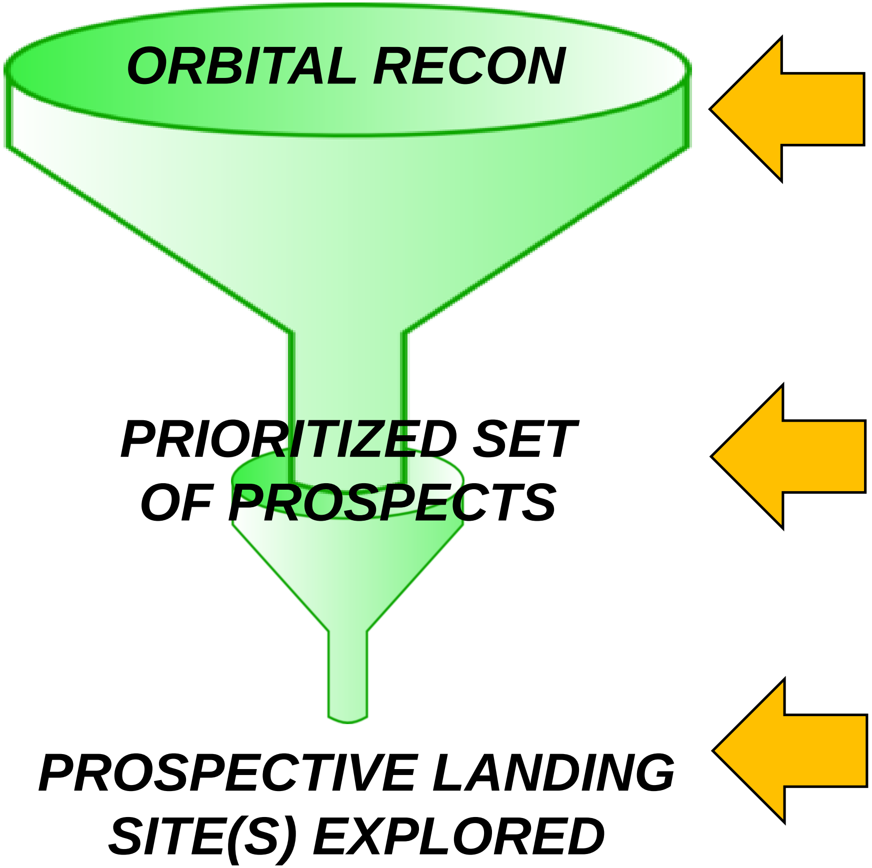
- <u>Case A:</u> Glaciers are well-known for having entrained rocks/gravel/sand. In our definition of Case A, we assumed 90% ice, and 10% entrained other material. That proportion can vary widely in natural glaciers, as can the size of these rocks. The choice/development of mining method will determine the effect of entrained refractory material (rocks) on the process e





In both of these examples, note significant variation in mechanical consistency.

The Importance of Decisional Support



Which data sets would provide the most effective screening to define discrete, evaluatable, prospects?

Which data sets would be most useful in prioritizing prospective landing sites identified?

How could we maximize the probability that the prospective landing site(s) we explore on the ground will be able to meet remaining requirements?

Note: Creating a list of possible or proposed steps or missions to accomplish each step is an important piece of follow-up work, captured in #20 on **Slide #85**.

Some Identified Areas for Follow-up Work (1 of 6)

This scoping analysis is intended to provided guidance regarding a number of complex and inter-related issues, and for which follow-up action by a number of different entities would be beneficial.

General

1. We encourage broader community discussion of these water ISRU issues at open conferences, such as the Space Resources Roundtable and the ASCE Earth and Space Conference, especially those that support the publication of referenceable documents.
2. We encourage the continued development of engineering concepts and geological data for both of the primary pathways identified: ice, and hydrated minerals. It is too early to attempt to prune either of these two branches of the trade space.
   a. We currently have better data for the granular "regolith" and "mineral" cases (Cases B-C-D) than the ice cases (A1 & A2), and we really need to improve our understanding of the latter to bring them to an equal level of detail and understanding.
3. The possible or proposed steps or missions to accomplish each stage along the decisional support pathway should be identified, from orbital recon to prioritized set of prospects to prospective landing site(s) so that these missions can get appropriate emphasis.