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

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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.

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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.

Objectives of This Study (Tasks)

1. Prepare an initial description of hypothetical “reserves” (identified, usable resource deposits*) that may exist on Mars. Assume that these reserves are the output of an exploration program, and the input to an overall engineering system. Specify all relevant parameters.
2. Estimate the rough order-of-magnitude mass/power/complexity of the ISRU engineered system (mining/acquisition, extraction, transportation, processing and storage) needed to produce a given quantity of water from each of several categories of potential water “ore” deposits.
3. Prepare a sensitivity analysis of the major inter-relationships between geological attributes of the water deposits (Task #1 above), and the engineering attributes of the production and processing systems (Task #2 above), in order to propose preliminary minimum acceptable thresholds for “reserves”.
4. Prepare an initial description of the preliminary implications for exploration for the different reserves.

***** *The adjective "hypothetical" is assumed throughout these slides, modifying "reserves" from its legal meaning in terrestrial mining practice (see* **Slide #10***).*

Introduction to the Problem

Identify Resources on Mars, Establish **Reference** Cases

Engineering Analysis of **Selected Reference**** Cases

Explore Sensitivity of Engineering to Geology

Preliminary Exploration Implications

**Primary focus was on water-bearing surface materials for a variety of reasons - Availability of scientific & engineering data, initial survey of prior efforts, and others. *Engineering evaluation of mid-latitude subsurface ice at the same level of detail is a key next step.*

Key Antecedent #1: EMC (Evolvable Mars Campaign)

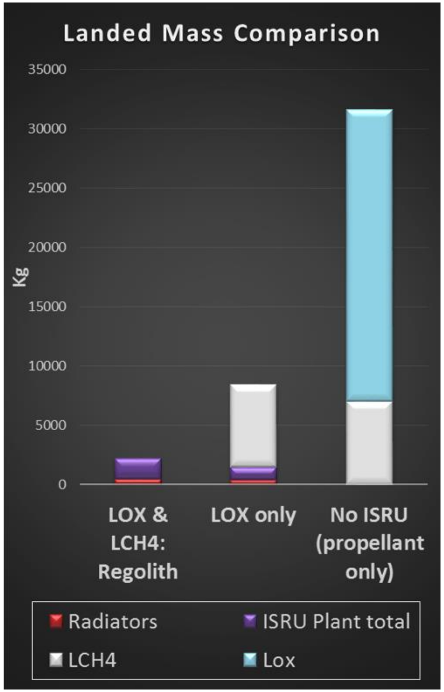
The Potential Benefit of Acquiring Local Water (1 of 2)

	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.

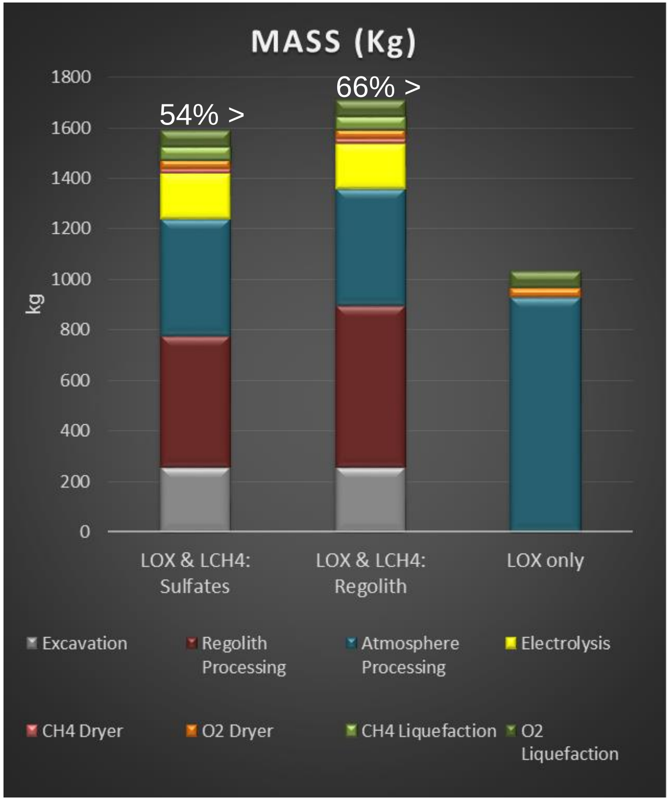
<u>For every kg of total ISRU system mass delivered to Mars:</u>

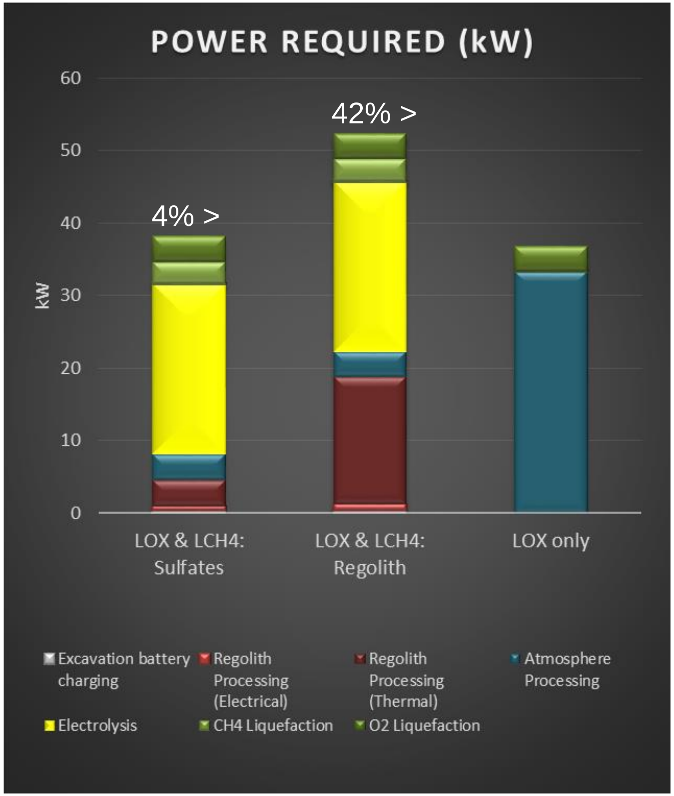
- A Lox/LCH_4 ISRU system can produce 20 kg of propellant
- A Lox-only ISRU system can produce 3 kg of propellant

Key Antecedent #1: EMC

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

- The graph below compares ISRU systems for two different water resources and an ISRU LOX-only (no water) system (which is the current architecture baseline).
  - The masses are for the ISRU hardware only. While the water processing system masses are ~60% greater than the LOX-only case, consider that the latter still requires 7mt of terrestrial Methane each trip
  - The benefit of a higher yield granular resource is a power savings. The power required for case B is comparable to the lox-only ISRU system.





Percentages on the graphs represent comparison to LOX-only ISRU

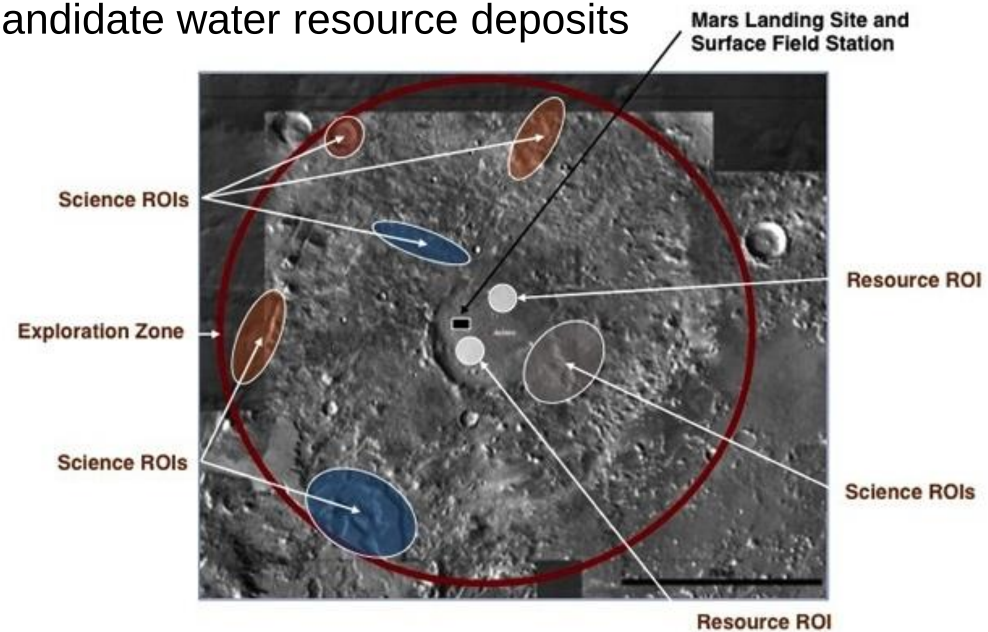
Key Antecedent #2: HLS^2

- 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



Possible configuration of an Exploration Zone. Note hypothetical "Resource ROIs" in gray.

Ground Rules and Assumptions

1. A single surface location on Mars will be visited and explored by multiple crews (source: EMC).
   - Implication: Site selection prior to any Mars missions must consider ISRU, even if ISRU is manifested later in the campaign.
2. The site is equatorward of 50° latitude (source: HLS^2).
3. The ISRU production window would be 480 days which would assume that the ISRU system would arrive one mission opportunity ahead of the first crew, and produce all propellant prior to crew launch.
   - 480days = 26 month launch window – 9 month transit time – 1 month margin
   - This production timeline, baselined from DRA 5.0, is assumed to apply to any ISRU produced resources (LOX-only or LOX/LCH_4).
   - This is a minimum production time since once the equipment is set up, there would be more time to produce propellant for subsequent crews.
4. The ISRU system will be co-located with the ascent vehicle/habitat such that all ISRU products can be delivered to and stored in the system that will use them.
   - No separate storage is currently planned, implying that the utilization systems (e.g. MAV, habitat) arrive with or before the ISRU system (as per DRA 5.0).
   - Excavation equipment delivers raw material to the ISRU system, where processing takes place. (Current baseline – subject to future trades).
5. A nominal quantity of 16 metric tons of water per crew is assumed to meet the requirements of a fully fueled MAV and oxygen for crew life support.
6. Planetary protection constraints not considered at this time (see **Slide #86**).

The Exploration-Production Flow:

Introduction

“Reserves” are the fundamental interface between exploration and production (see **Slide #12**).

<u>Some critical questions</u>

1. How exactly would production interact with reserves?
2. Can we identify thresholds, above or below which the proposed production system would not be viable?
3. How would exploration discover and define reserves?

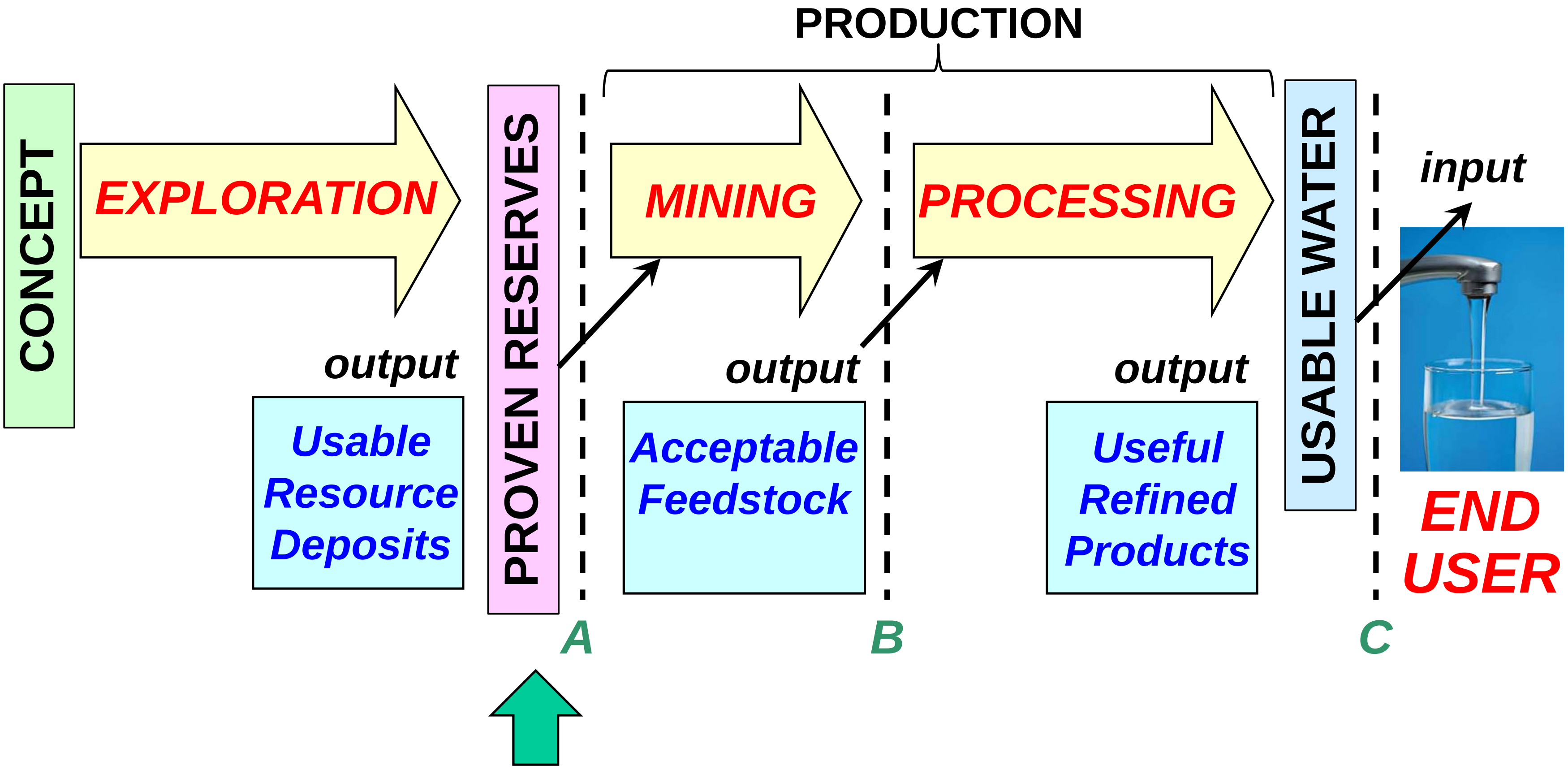
Confidence: The Concept of Reserves

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%**

Definition of Reserves

- **Reserve** is the raw material in-place, not yet extracted and processed but **proven** to be feasible to extract and process. **Proven** means the risk that the material is not present as modeled, or is not extractable, or is not processable, is sufficiently low (see practical definitions on **Slide #10**).
- Reserves are the output of the exploration process and the input to the production process (see **Slide #12**).
- On Earth, reserves are proven using a feasibility study that meets a set of industry standards, generally including a pilot program; and the risk is expressed in financial terms, for example the interest rate on a bank loan one could get using the 'reserve' as collateral.
- For Mars ISRU water, a future study team will need to define the set of NASA and mining industry standards that a feasibility study must meet. NASA will define the acceptable level of risk.

The Exploration-Production Flow



PRODUCTION

CONCEPT

EXPLORATION

output

Usable Resource Deposits

PROVEN RESERVES

A

MINING

output

Acceptable Feedstock

B

PROCESSING

output

Useful Refined Products

USABLE WATER

input

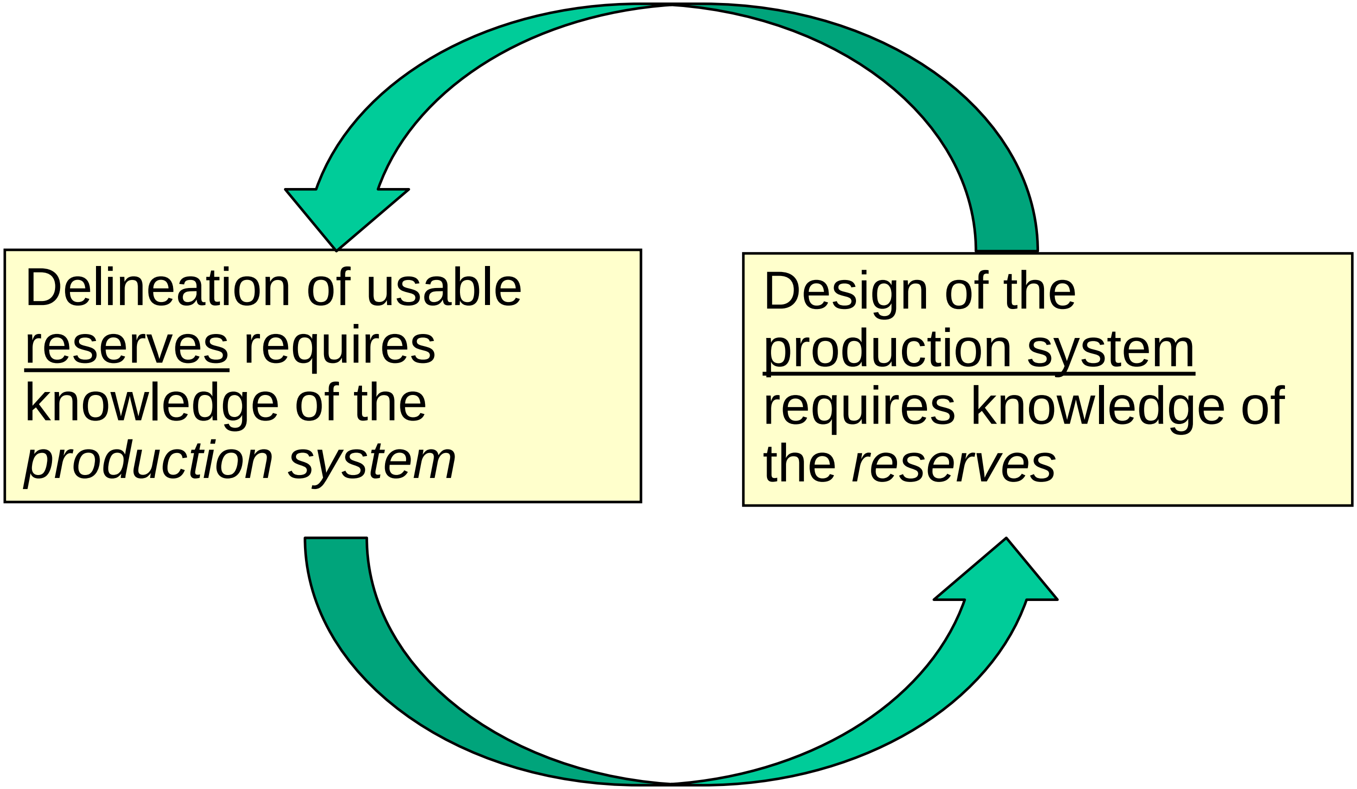
END USER

C

"Reserves" are the essential interface between "exploration" and "production"

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

A Chicken-Egg Issue



Delineation of usable reserves requires knowledge of the *production system*

Design of the production system requires knowledge of the *reserves*

Because of this chicken-egg relationship, both exploration and engineering need to advance together.

From Beaty et al. (2016)

Exploration Risk

(Risk of Failing to Make an Acceptable Discovery)

Ease of Engineering Requirements

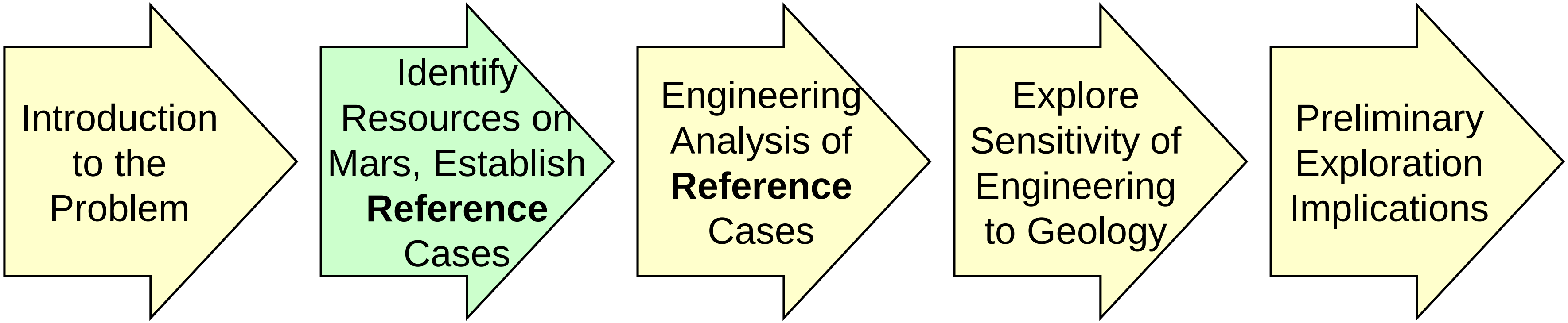
	H	M	L
L	*MED RISK*	*HIGH RISK*	*VERY HIGH RISK*
M	*LOW RISK*	*MED RISK*	*HIGH RISK*
H	*LOW RISK*	*LOW RISK*	*MED RISK*

Quantity/quality of Data the Explorationists are Able to Work with

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

Task #1

Prepare an initial description of hypothetical “reserves” that may exist on Mars



Introduction to the Problem

Identify Resources on Mars, Establish **Reference** Cases

Engineering Analysis of **Reference** Cases

Explore Sensitivity of Engineering to Geology

Preliminary Exploration Implications

Introduction: Reference Cases

1. Since both sides of the “reserves” interface are incompletely defined (see **Slides #11-13**), the best way to proceed is by defining a set of reference cases, and using them to evaluate the relationships between “discoverability” and “producibility”.
2. The reference cases are all hypothetical—the question we are asking is “if discovered, would these be useful”?
   - The hypothetical cases are based on our current incomplete knowledge of Mars: We perceive there to be reasonable potential that deposits as good as these exist (but discovering and defining them would take work!).
3. Once we understand the thresholds differentiating viable from non-viable, and the parameters that most matter for optimizing the engineered system, the priorities for a logical exploration program can be defined.

Definition of Reference Reserve Cases

Four reference cases were chosen to represent the output of HLS[2] (See **Slide #7**)

	Deposit Type			
Essential Attribute	A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
Depth to top of deposit (stripping ratio)	variable (1-10m)	0 m	0 m	0 m
Deposit 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% bassanite[6]	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
Not Considered				
Planetary Protection implications	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

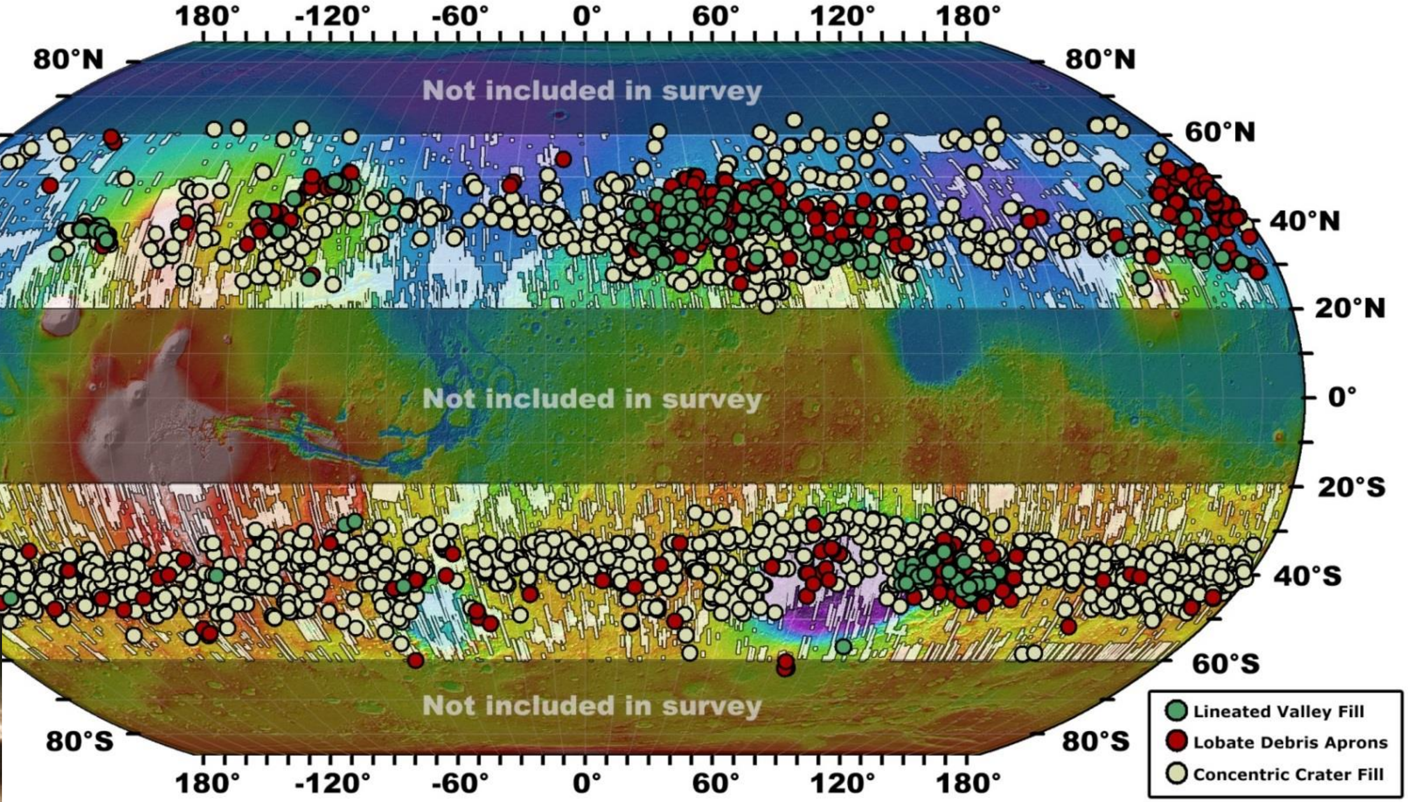
Note: Planetary Protection implications are addressed on **Slide #86**

Reference Reserves Notes

1. Assume Case A consists of glacial ice underlying a sublimation lag, but is divided into A1: an ice deposit mined by open pit methods, and A2: an ice deposit mined by down-hole heating/recovery methods. The thickness of this lag is in the 1-10 m range limited by SHARAD measurements (See **Slide #20**.) Future data sets and instruments can improve this precision.
2. For Cases B and C, assume that in a location where bedrock containing high concentrations of these minerals exists, locations can be found where weathering has disaggregated the rock into granular material.
3. The 4 wt% water noted for smectite in Cases B, C and D is the average wt% water in a combination of Na- and Ca- forms; the average water content may be higher for some other types of phyllosilicates (see **Slide #22**).
4. The source data from Case D is explained in detail on **Slides #23-25**. Note that the “water” is inferred to be contained in three phases, two of which dehydrate at 100C, and one of which dehydrates at >500C. We make the assumption (to be reviewed) that material of this quality can be found at most/all candidate landing sites without exploration. Since this material occurs “everywhere”, transportation demands would be minimized.
5. Whether deposits better than these reference cases can be discovered and defined is left as an exploration question (see **Slide #62**).

Basis for Case A

Map of Mars Glacial Features



Inside:
Rise, of a Weak Crust, in Britain, p. 371
and Fall, of a Strong Mantle, in Italy, p. 375
The Varnished Truth about a Wet Desert, p. 403

With many of these glacier-related geomorphic features, we have no information about whether residual ice remains, and if so, at what depth. Note that some lobate debris aprons have been confirmed to contain ice by radar investigations.

From Dickson et al., 2012; discussion with Jim Head acknowledged

Glacial Deposits on Mars: More Detail

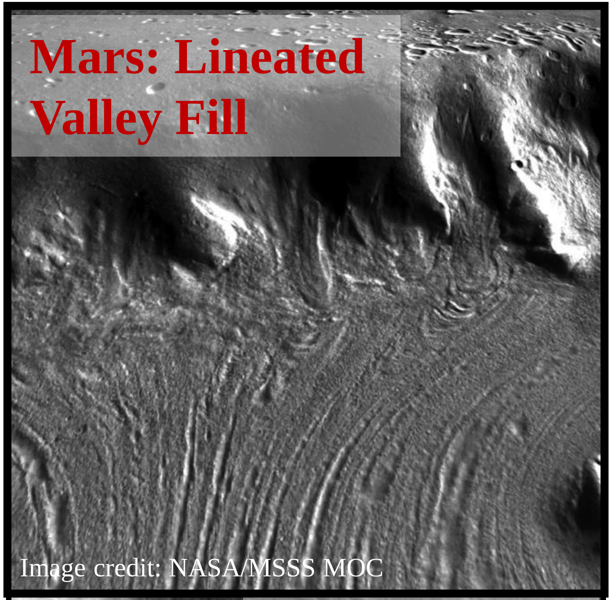


Image credit: NASA/MSSS MOC

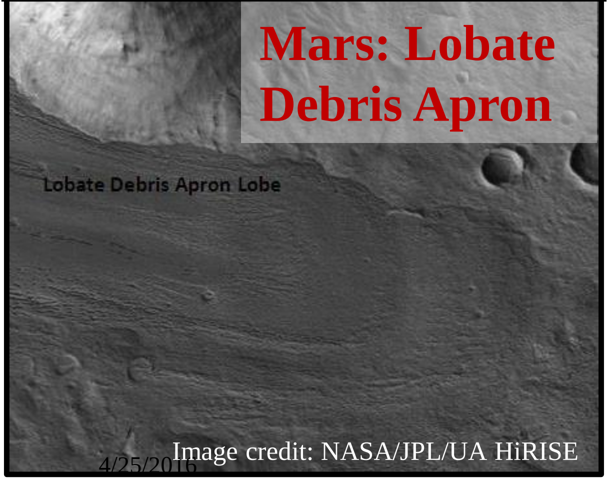
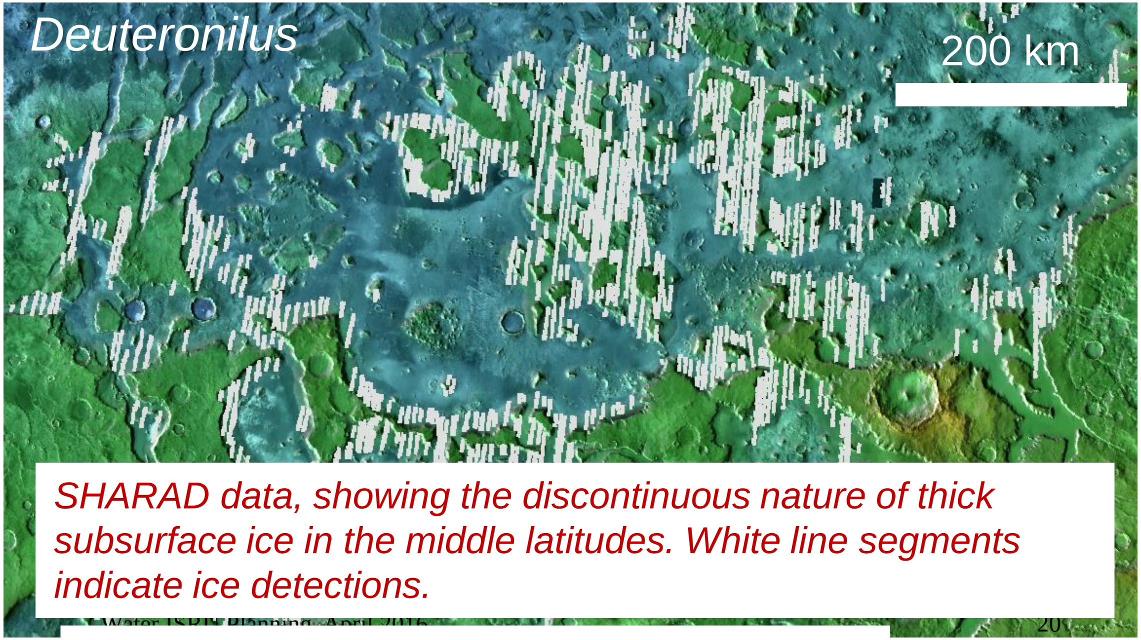


Image credit: NASA/JPL/UA HiRISE

- Mars glaciers are covered with a combination of sublimation till (the residue left as a result of ice sublimation) and rubble from nearby exposed outcrops.
- SHARAD data show a single, discrete surface echo over glaciers, implying that the thickness of the protective debris/dust cover is on order of the SHARAD vertical resolution (~10m) or less.
  - Could be between 1-10 m thick
- Glacial ice is 100s of meters thick.



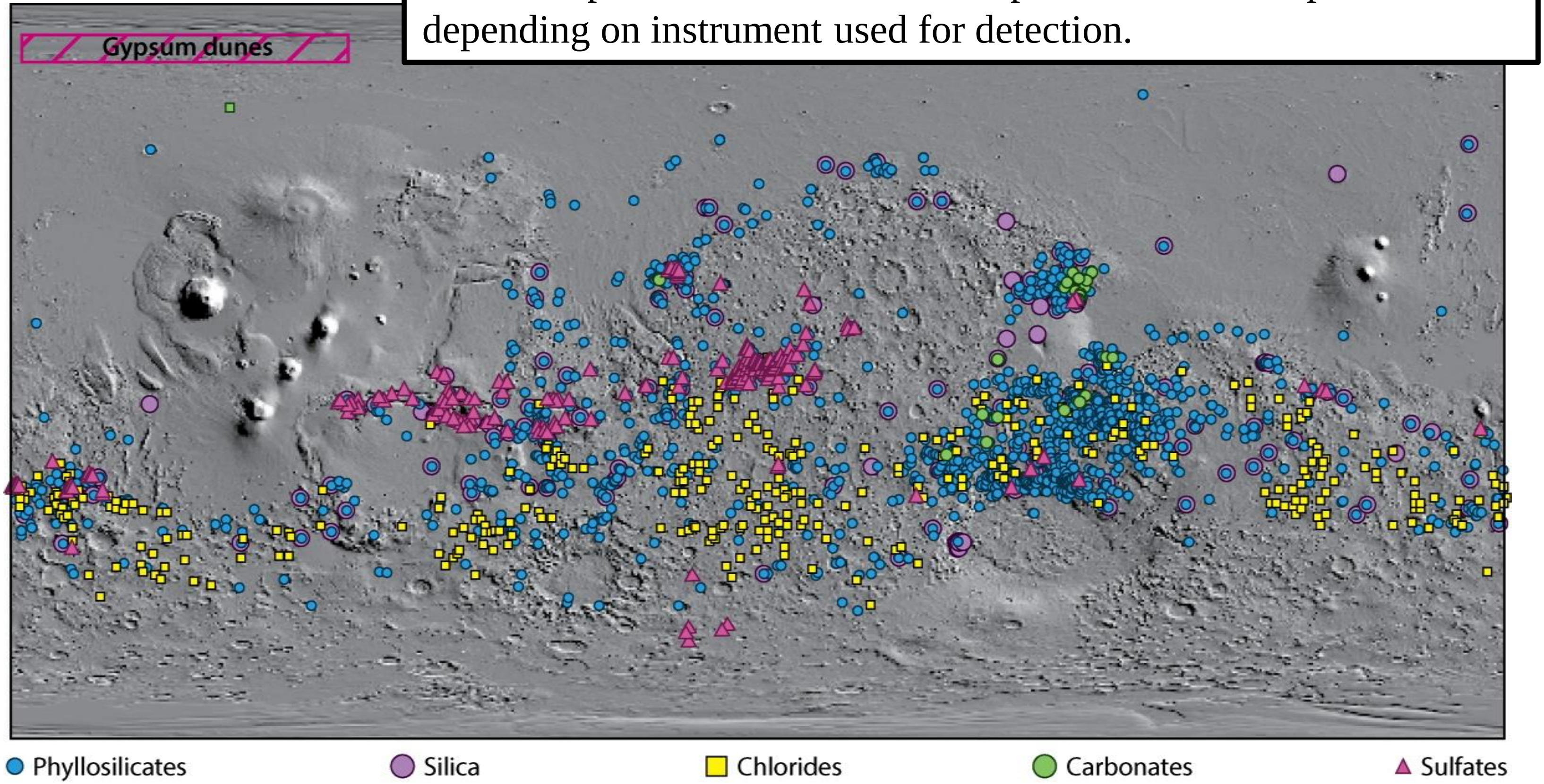
SHARAD data, showing the discontinuous nature of thick subsurface ice in the middle latitudes. White line segments indicate ice detections.

Rummel et al. (2014) and Plaut (2016, Pers. Comm.)

Basis for Cases B, C

Map of aqueous mineral detections

Note: footprint size is from 3x6km spots to 18-2000m/pixel depending on instrument used for detection.



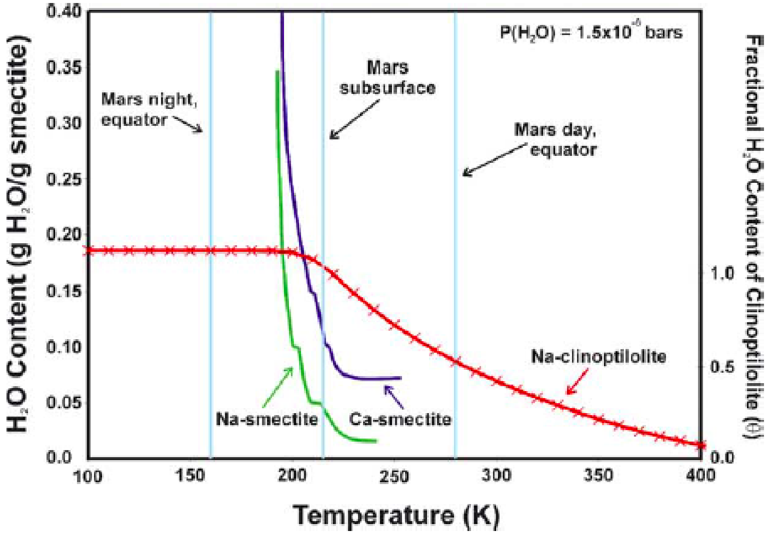
A master compilation of all mineral detections for Mars. Of relevance to this study are the phyllosilicate and sulfate detections.

From Ehlmann and Edwards (2014)

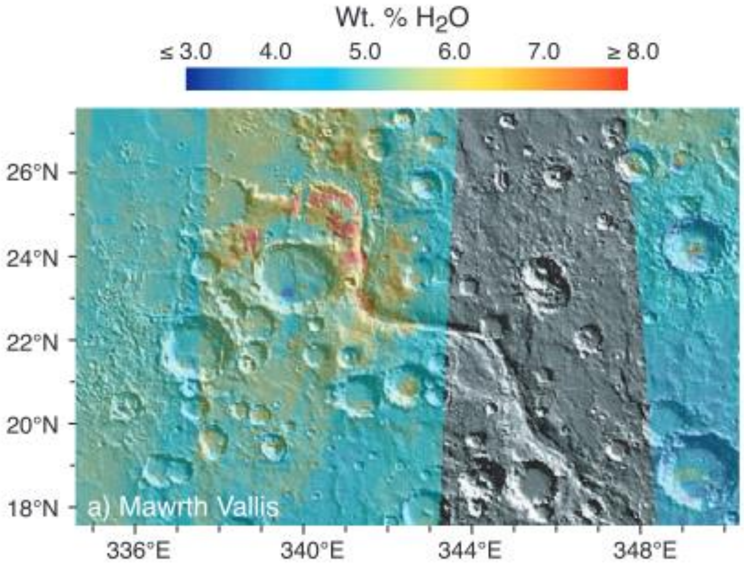
Basis for Case C

Phyllosilicate Water Content

- For the purpose of this analysis, we assume a deposit consisting of smectite with an average of 4 wt% water content – note that this is lower than would be expected for terrestrial samples. It is also possible that phyllosilicate deposits with higher water contents could be identified.



Equilibrium hydration state of Na- and Ca-smectites (left axis) and of Na-clinoptilolite (right axis) as a function of T at a P (H_2O) of 1.5x10^{-6} bars. Note that at Mars surface conditions, Na-smectite has ~2 wt% water, and Ca-smectite has ~7 wt% water.



Modeled hydration maps for phyllosilicates in the Mawrth Vallis region. These regions exhibit water contents 2–3 times higher than surrounding terrains with similar albedo values, approaching values of 6–9 wt.% H_2O.

From Bish et al (2003) (left), Milliken et al (2007) (right), and discussion with Dave Bish and Ron Peterson

Basis for Case D (1 of 3)

Introduction to the Martian Regolith

- The broadest definition of “regolith”, as it is used in a planetary sense, is: “The entire layer or mantle of fragmental and loose, incoherent, or unconsolidated rock material, of whatever origin (residual or transported) that nearly everywhere forms the surface, and that overlies more coherent bedrock.” As such, this term as applied to Mars encompasses “soil”, dunes, talus, ejecta, rubble, airfall dust, etc.

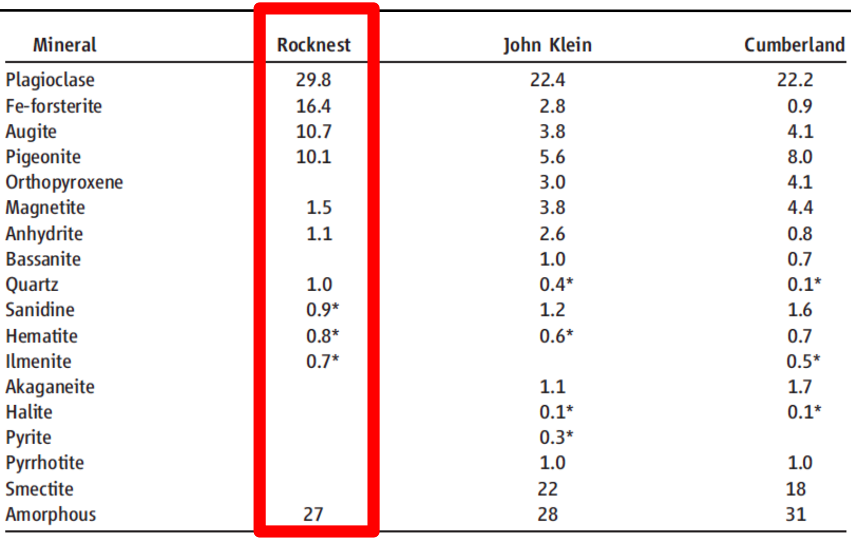
JPL/NASA

Although regolith, in the strictest sense, is present essentially everywhere on Mars, it is not all equally amenable to ISRU operations. Note significant differences in mechanical properties.

Basis for Case D (2 of 3)

What is the Regolith Made of? (Data from MSL)

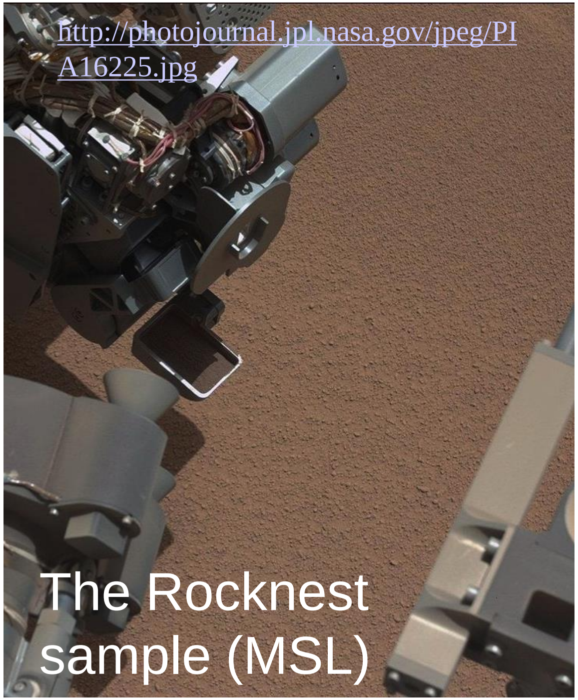
- Mineralogy and total weight percent water used for reference Case D are based on data from MSL instruments: CheMin, SAM, and DAN.
- Case D mineralogy was based primarily on Rocknest, with additional minor components from John Klein and Cumberland to match the 1.5 wt% water indicated by the more conservative DAN results.



Mineral	Rocknest	John Klein	Cumberland
Plagioclase	29.8	22.4	22.2
Fe-forsterite	16.4	2.8	0.9
Augite	10.7	3.8	4.1
Pigeonite	10.1	5.6	8.0
Orthopyroxene		3.0	4.1
Magnetite	1.5	3.8	4.4
Anhydrite	1.1	2.6	0.8
Bassanite		1.0	0.7
Quartz	1.0	0.4*	0.1*
Sanidine	0.9*	1.2	1.6
Hematite	0.8*	0.6*	0.7
Ilmenite	0.7*		0.5*
Akaganeite		1.1	1.7
Halite		0.1*	0.1*
Pyrite		0.3*	
Pyrrhotite		1.0	1.0
Smectite		22	18
Amorphous	27	28	31

Crystalline and amorphous components (wt%) of the John Klein and Cumberland drill powders, compared with the Rocknest scooped eolian deposit. From plagioclase to pyrrhotite the estimated errors are ~6% of the amount shown for abundances of >20%, ~15% for abundances of 10 to 20%, ~25% for abundances of 2 to 10%, and ~50% for abundances of <2% but above detection limit. Phases marked with an asterisk are at or near detection limit. Relative 2σ errors are ~50% of the amount shown for smectite and ~60% for the amorphous component. [*Data primarily from CheMin, with smectite information from SAM.*]

From Vaniman et al. (2014)



http://photojournal.jpl.nasa.gov/jpeg/PIA16225.jpg

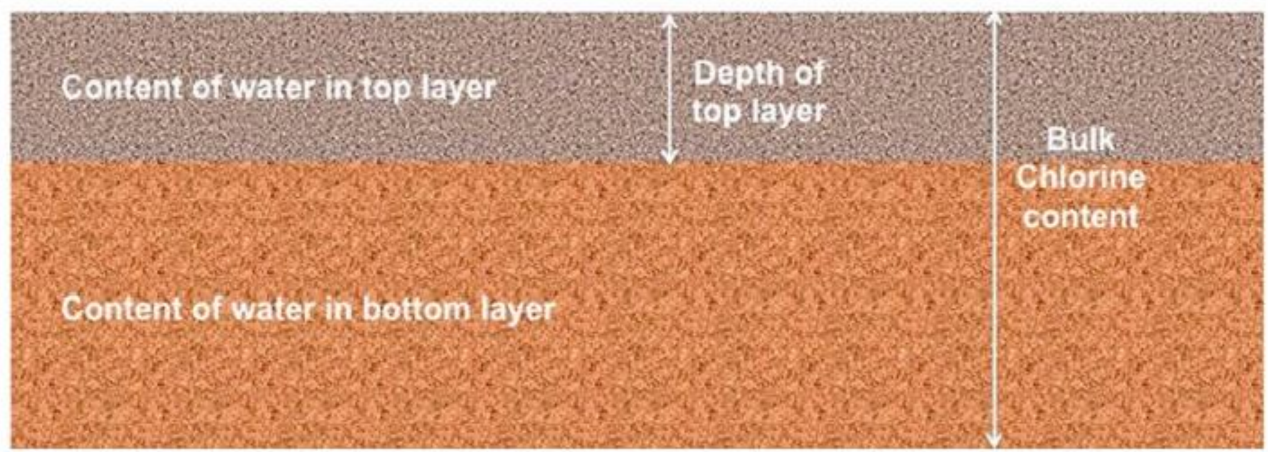
The Rocknest sample (MSL)

This material was analyzed in detail by MSL.

Basis for Case D (3 of 3)

DAN Measurements of Water Equivalent Hydrogen

- DAN measures total hydrogen over a footprint 3m wide and down to a depth of ~60 cm.
- Data from DAN are best modeled by a 2-layer structure
  - Upper layer has less H (average 1.5-1.7% WEH) than the lower layer (average 2.2-3.3% WEH).
  - Local anomalies as high as 6% WEH were measured in the first 361 martian sols; in later sols contents up to 10% WEH were measured.



Data from MSL's DAN instrument are best modelled using a two-layer subsurface structure. The top layer ranges between 10-30 cm thick. Water concentrations are in table below.

Note that the DAN instrument detects H, not water. The H could be present in hydrous minerals or as OH—it is almost certainly not present as liquid water. The "water-equivalent hydrogen" or WEH measured by DAN, is used to calculated the potential amount of "water" present using the models.

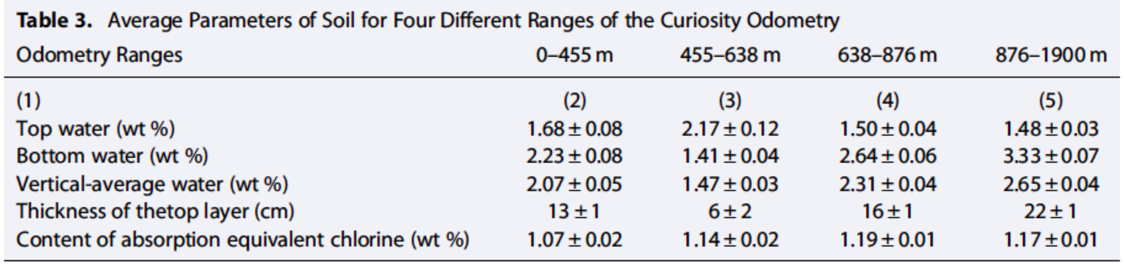


Table 3. Average Parameters of Soil for Four Different Ranges of the Curiosity Odometry

Odometry Ranges	0–455 m	455–638 m	638–876 m	876–1900 m
(1)	(2)	(3)	(4)	(5)
Top water (wt %)	1.68 ± 0.08	2.17 ± 0.12	1.50 ± 0.04	1.48 ± 0.03
Bottom water (wt %)	2.23 ± 0.08	1.41 ± 0.04	2.64 ± 0.06	3.33 ± 0.07
Vertical-average water (wt %)	2.07 ± 0.05	1.47 ± 0.03	2.31 ± 0.04	2.65 ± 0.04
Thickness of thetop layer (cm)	13 ± 1	6 ± 2	16 ± 1	22 ± 1
Content of absorption equivalent chlorine (wt %)	1.07 ± 0.02	1.14 ± 0.02	1.19 ± 0.01	1.17 ± 0.01

From Litvak et al. (2014) (top) and Mitrofanov et al. (2014) (bottom).

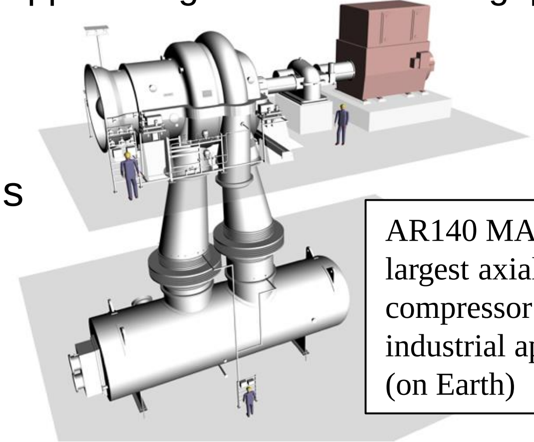
Other Options Considered and Ruled Out: Extraction of Water from the Atmosphere

Some general facts and calculations:

1. At Mars surface pressure = ~6 mbar; atm density averages ~0.020 kg/m^3, water ~210 ppm = 0.0042 g(water)/m^3
2. 1 kg water is contained in 250,000 m^3 of atmosphere
3. To produce 5 mt water per yr, 0.57 kg would have to be produced per hour, which means 2400 m^3 (~1 Olympic sized swimming pool) of atmosphere would have to be handled per minute, assuming 100% recovery. This is equivalent to 84,000 CFM.
4. Martian atmosphere is at 1% of the pressure of the inlet pressure for compressors on Earth, thus an additional compression factor of 10^2 would have to be applied to get the same throughput.

→ We have not seen a credible method proposed for separating the water from an airstream of this scale, so we cannot estimate recovery efficiency.

→ The air-handling system implied by these calculations would be on the same order of magnitude as the largest air compressors known on Earth: ~600,000 CFM, requiring 65 megawatts to run, and roughly 5x5x10m in size.



AR140 MAN1 – the largest axial flow compressor for use in industrial applications (on Earth)

<u>CONCLUSION</u>: The mass, power, volume, and mechanical complexity of the system needed for this approach are far outside of what is practical for deployment to Mars.

Other Options Considered and Ruled Out: RSL, Permafrost, High Latitude Ice

Recurring Slope Lineae (RSL)

- Only occur on steep slopes – very difficult for mining/transport operations.
- By definition, RSL are transient (seasonal). If liquid water is present, it may be only temporary.
- Hydrated minerals likely present, but are not necessarily more concentrated than in our other cases.

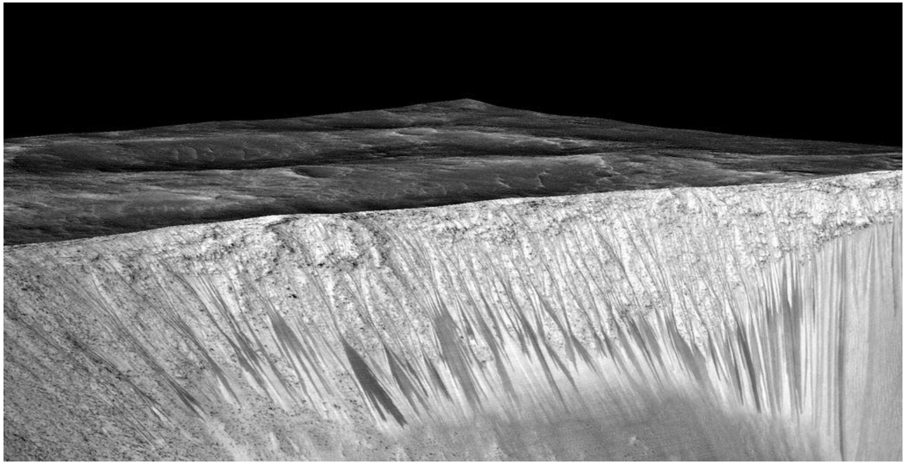


Image of a set of RSL (dark streaks) on a crater wall. Image credit JPL/NASA/Univ. Arizona

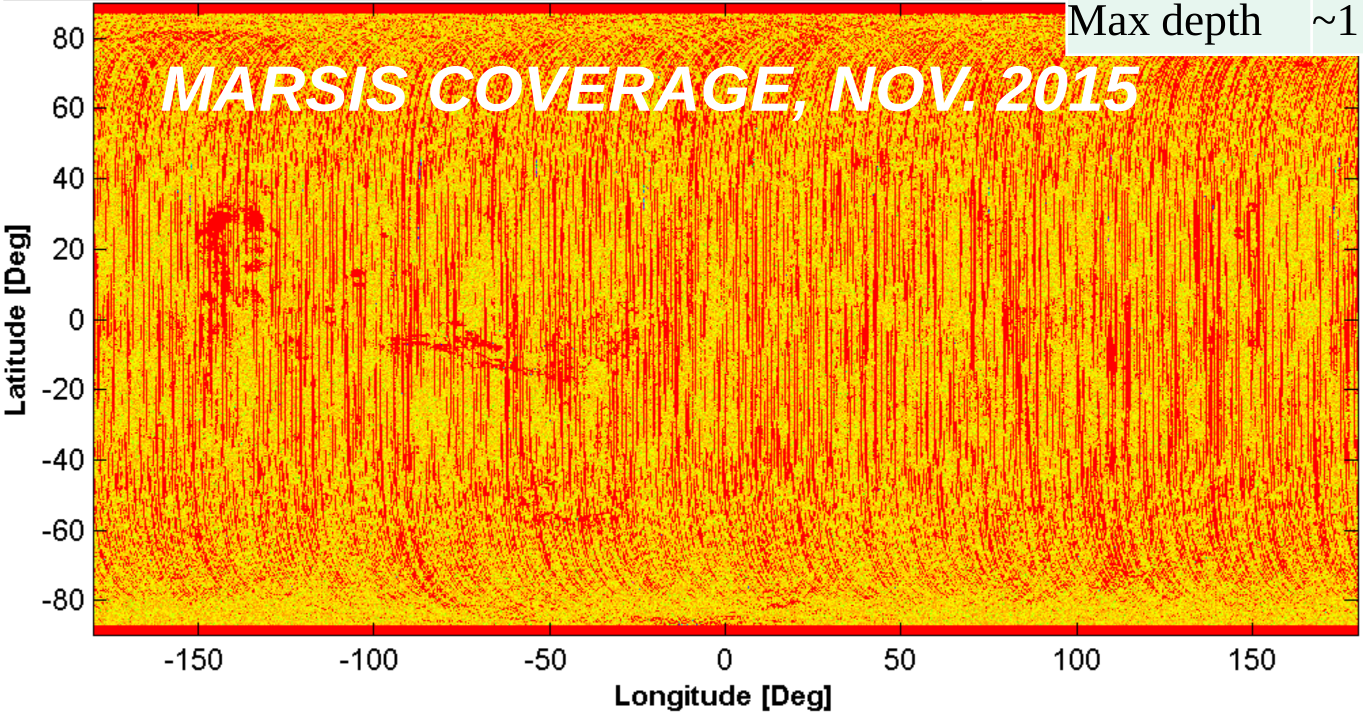
Permafrost: Although this exists (at high latitudes) on Mars, permafrost represents the existence of ice in the pore space of rock or soil, which is a low-grade variant of Case A (glacial ice). Since this will be less productive than glacial ice, we evaluate the latter here.

High Latitude Ice: Although large deposits of ice exist on Mars above 60° latitude, these exceed the latitudes set by our ground rules and assumptions (see **Slide #8**).

Other Options Considered and Ruled Out: Deep Groundwater (1 of 2)

- MARSIS and SHARAD (radars) would be able to detect Mars groundwater (liquid water or brine in Mars bedrock) if it were present within the depths cited.
- ***<u>No such groundwater has been detected</u>***.

	MARSIS	SHARAD
Coverage	~69%	~31%
Spatial res.	~10 km	~0.5 km
Depth res.	~100 m	~10 m
Max depth	~1 km	~ 300 m

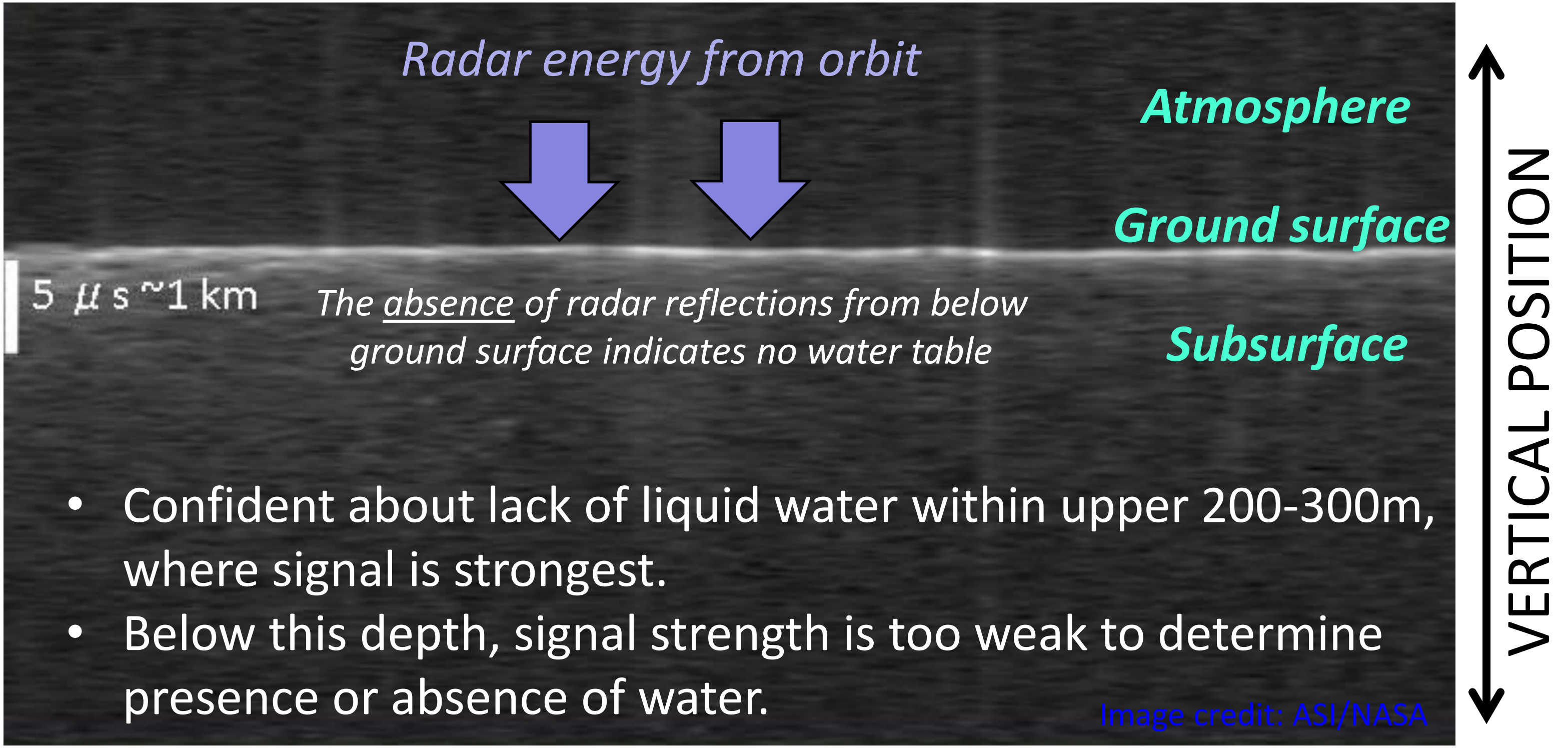


Map of Mars showing MARSIS data coverage as of Nov. 2015.

- *Yellow: Survey completed and no water detected (evidence of absence).*
- *Red: No data or SNR too low (absence of evidence)*

Contribution from Jeff Plaut; discussion with Rich Zurek, Serina Diniega

Other Options Considered and Ruled Out: Deep Groundwater (2 of 2)



The *absence* of radar reflections from below ground surface indicates no water table

- Confident about lack of liquid water within upper 200-300m, where signal is strongest.
- Below this depth, signal strength is too weak to determine presence or absence of water.

Image credit: ASI/NASA

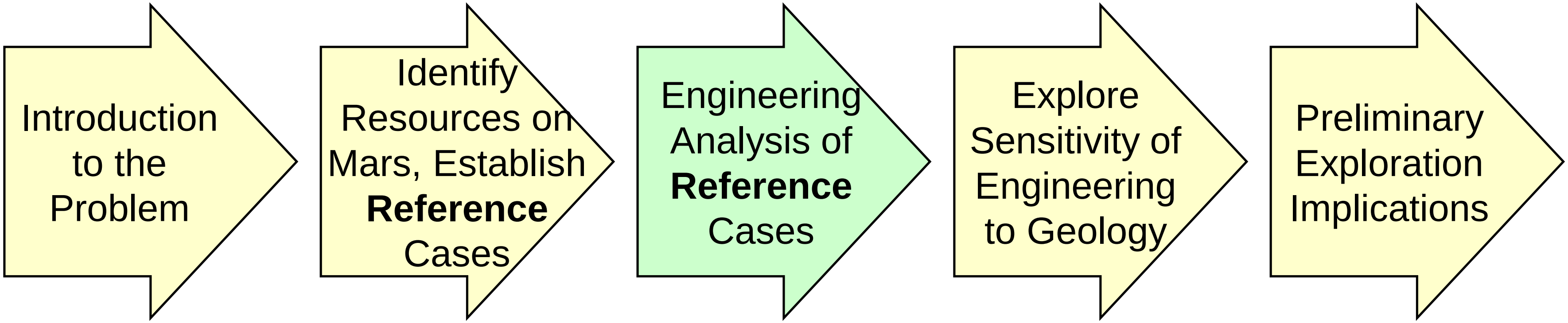
MARSIS 5-MHz, radargram of the Athabasca region of Mars (4-7N, 149E). Images are taken along the track of the orbiter, using radar to detect subsurface features like water, which would show up as a reflective surface.

- Given the absence of detections, and the fact that the coverage map is rapidly filling in → *unlikely that there is groundwater at a depth shallower than ~200-300 m anywhere on the planet.*

Contributions from Jeff Plaut; Rummel et al. 2014

Task #2

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



Introduction to the Problem

Identify Resources on Mars, Establish **Reference** Cases

Engineering Analysis of **Reference** Cases

Explore Sensitivity of Engineering to Geology

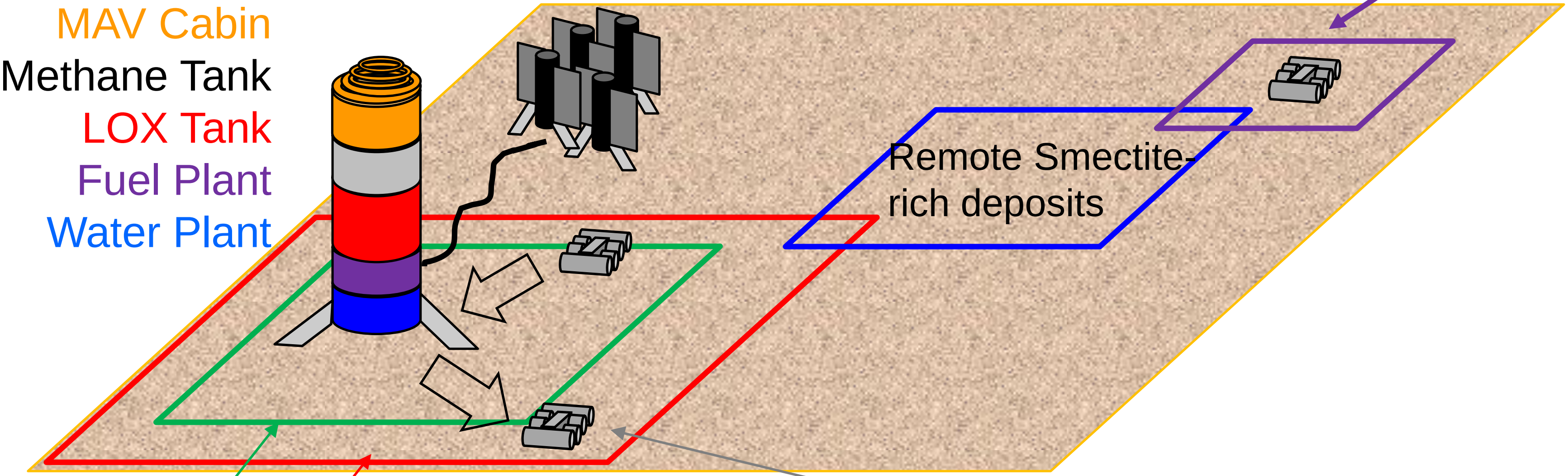
Preliminary Exploration Implications

Introduction to the Engineering Analysis

- **A NOTE ABOUT UNEQUAL DATA**. Although both granular materials (Cases B-C-D) and ice cases (Cases A1 & A2) are considered in this section, more prior work has been done on the former which enabled analysis in greater detail at this time. We would like to see further analysis of the latter to bring these to comparable levels of understanding.
- In addition to the overall Ground rules and Assumptions (**Slide #8**):
  - Infrastructure assets would be pre-deployed ahead of crew mission: Power systems (10's of kW), Mars Ascent Vehicle (unfueled), ISRU processing plants, off-earth mining excavation equipment (rovers).
  - 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)

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

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

Remote Smectite-rich deposits

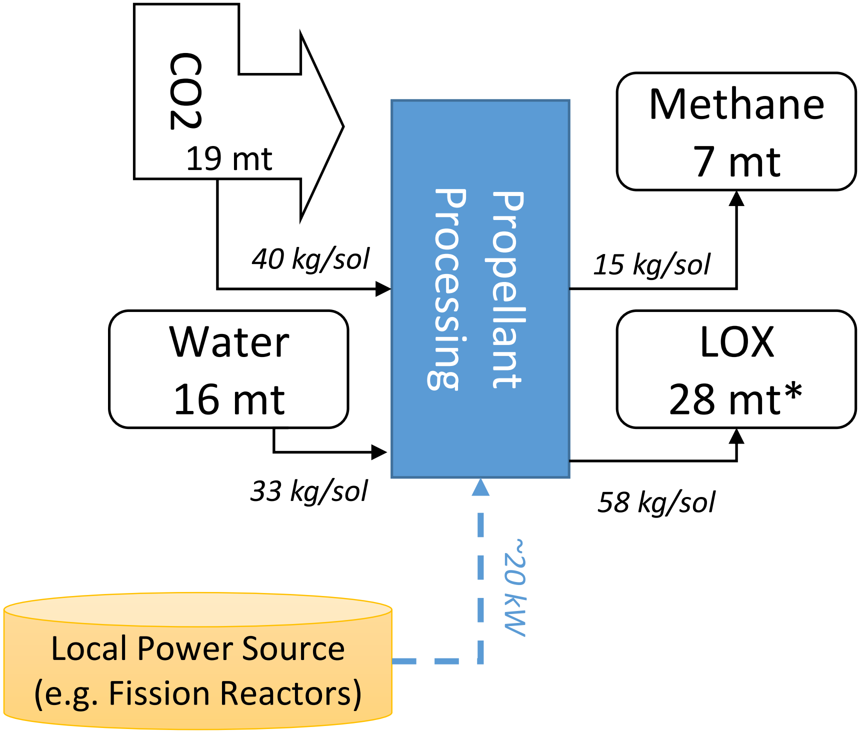
Local regolith fields
(larger or smaller depending on
Processing temperature)

Excavators deliver ore,
Remove spent tailings

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



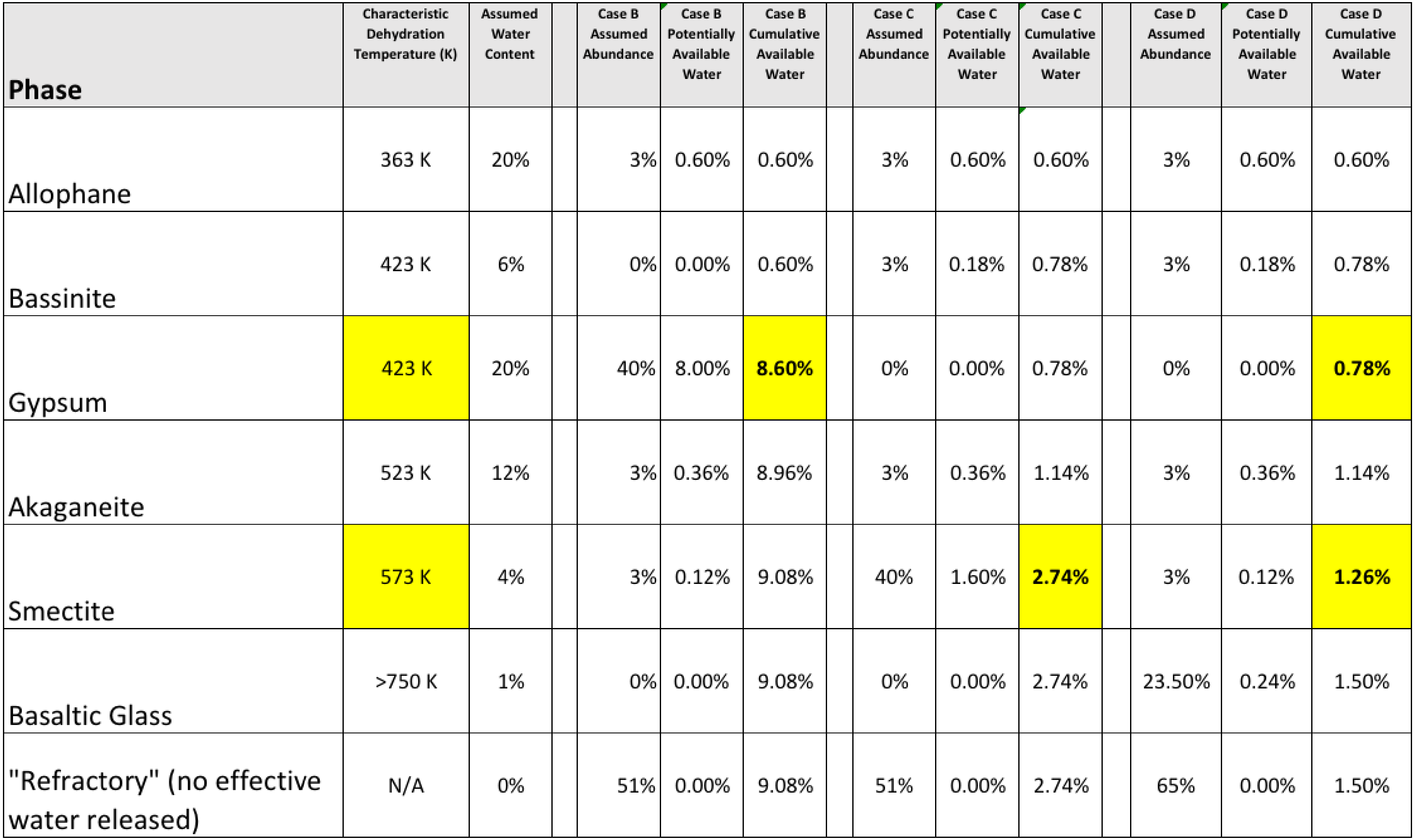
**Note: only 23 mt required for MAV propellant. Balance available for crew or other uses*

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 Smectite-rich Typical Martian Regolith



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%

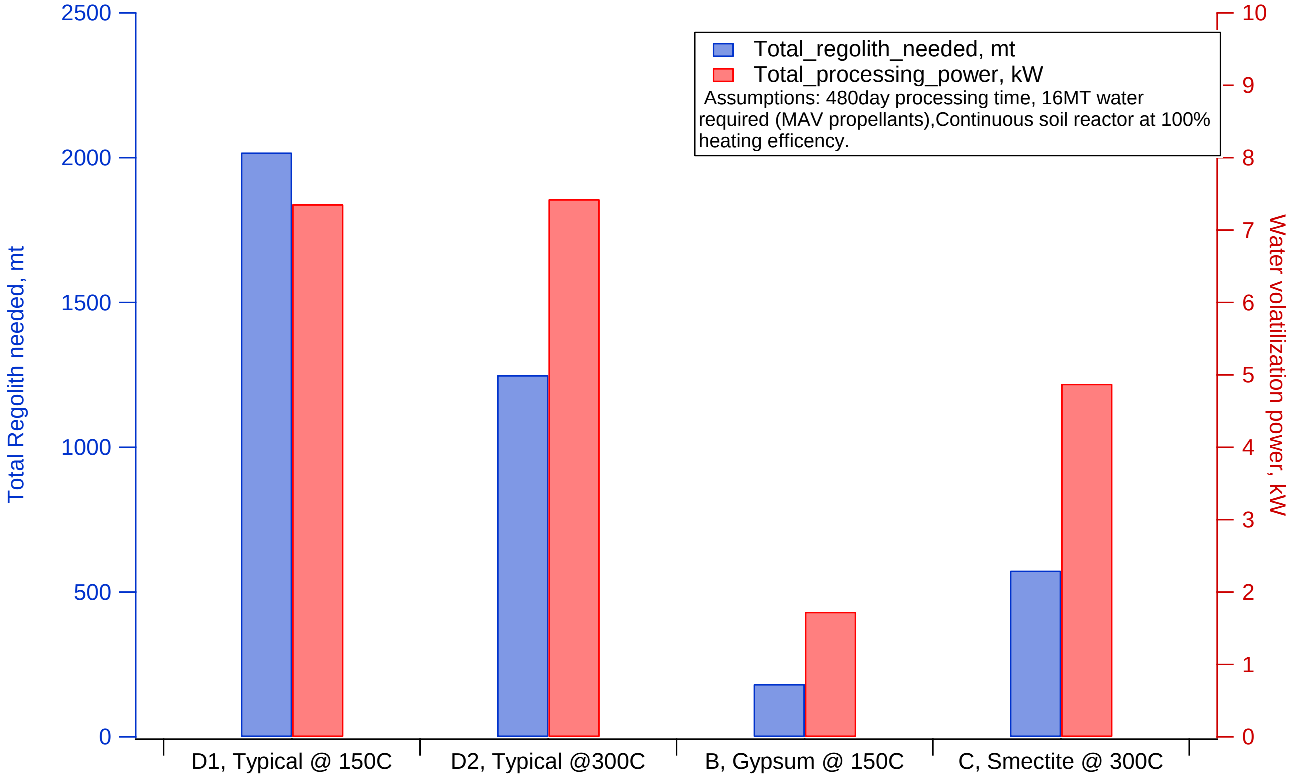
Energy Calculation Method

- 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



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

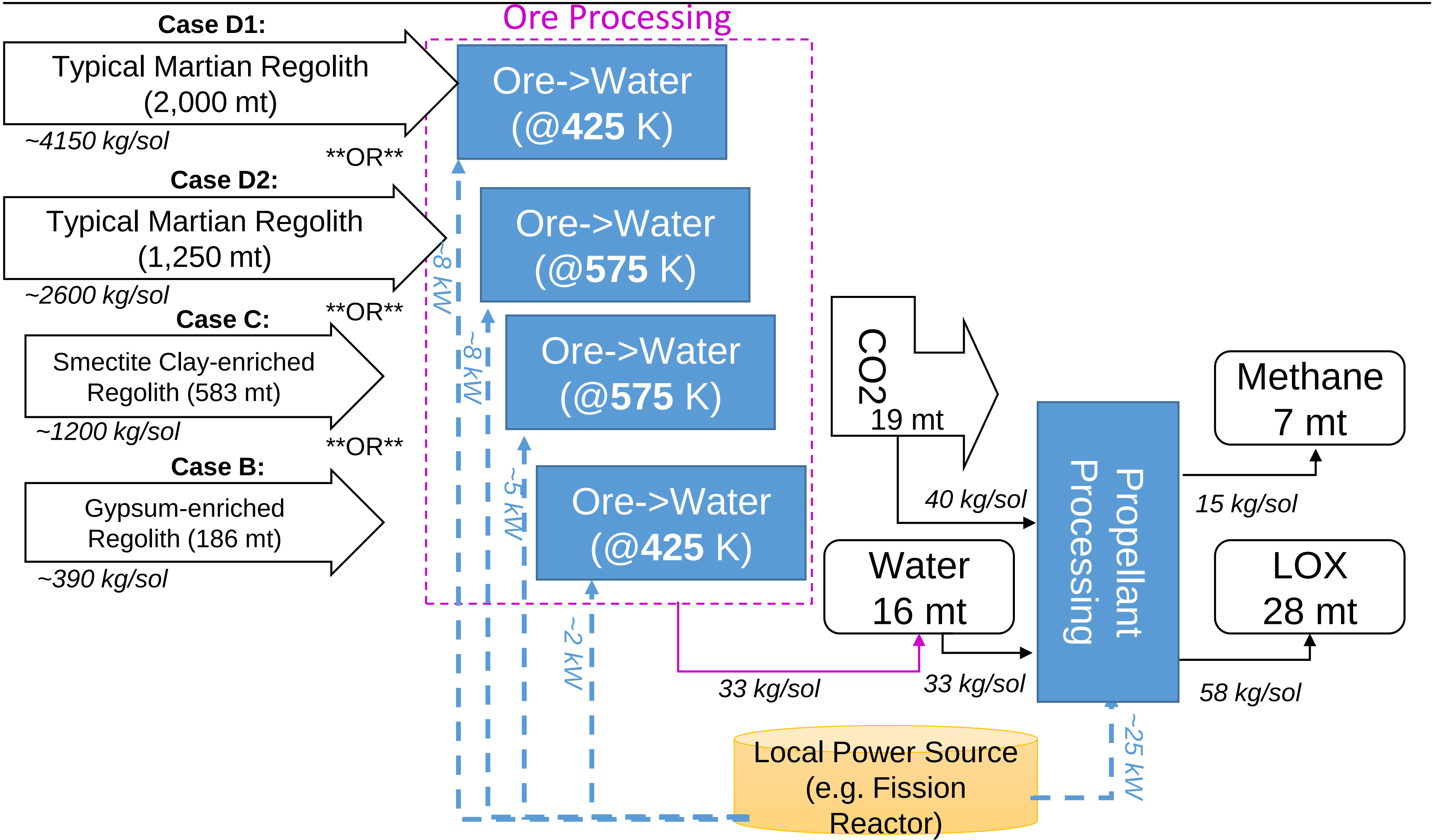
RASSOR Key Characteristics

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.

Key Characteristics Assumed:

- 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]

End-to-end Process Flow



Case D1:

Typical Martian Regolith (2,000 mt)

~4150 kg/sol

OR

Case D2:

Typical Martian Regolith (1,250 mt)

~2600 kg/sol

OR

Case C:

Smectite Clay-enriched Regolith (583 mt)

~1200 kg/sol

OR

Case B:

Gypsum-enriched Regolith (186 mt)

~390 kg/sol

Ore Processing

Ore->Water (@**425** K)

Ore->Water (@**575** K)

Ore->Water (@**575** K)

Ore->Water (@**425** K)

~8 kW

~8 kW

~5 kW

~2 kW

33 kg/sol

Water 16 mt

33 kg/sol

CO_2 19 mt

40 kg/sol

Propellant Processing

15 kg/sol

Methane 7 mt

LOX 28 mt

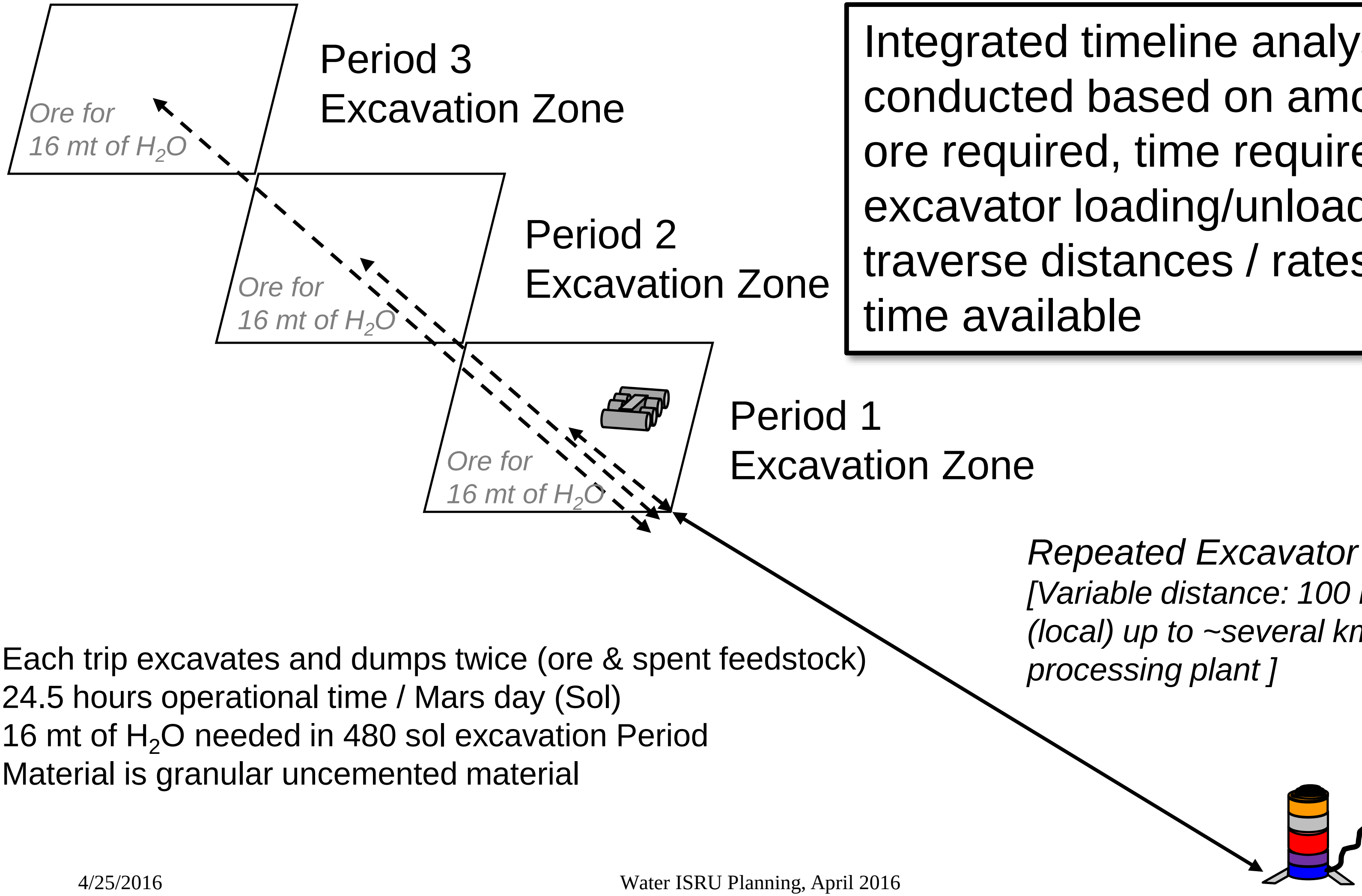
58 kg/sol

Local Power Source (e.g. Fission Reactor)

~25 kW

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



Period 3
Excavation Zone

Ore for
16 mt of H_2O

Period 2
Excavation Zone

Ore for
16 mt of H_2O

Period 1
Excavation Zone

Ore for
16 mt of H_2O

Repeated Excavator Trips
[Variable distance: 100 m (local) up to ~several km from processing plant]

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

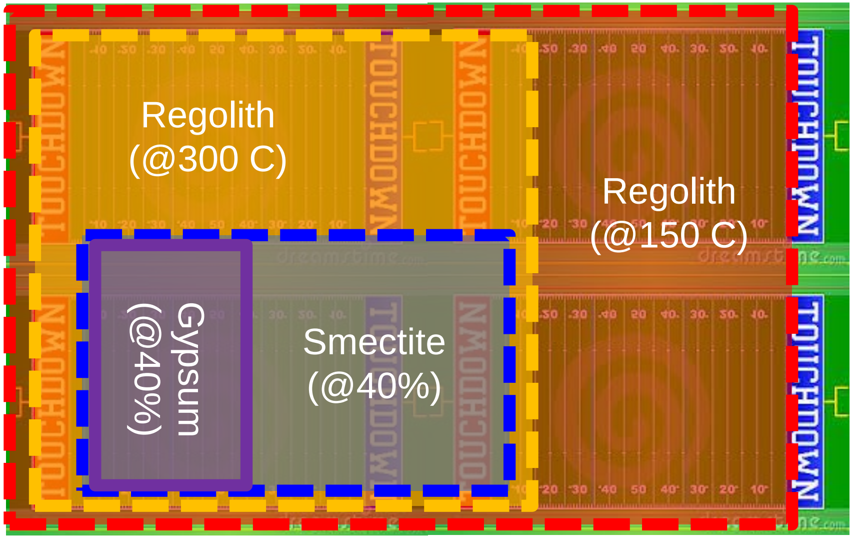
Summary of Excavation/Travel Analysis

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 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)

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@300	1,269,841	635	12,698	2.4
Regolith@150	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).

Granular Mineral Deposits:

Engineering Summary (1 of 2)

1. Although regolith (in some form) is present almost everywhere on Mars, it is not yet known how common are deposits that meet all of the specifications to be classifiable as minable “reserves” (this is an exploration question).
2. It would be ideal if the mine could be established in the immediate vicinity of the lander, allowing for short-range excavators which could leverage power, processing and storage at the lander site. Transportation distance would be a major driver in these scenarios.
3. Regolith is comparatively low grade (~1.5% WEH), and it consists of multiple diverse components that release their water at a variety of 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. However, it is unknown how either of these would compare to a specific regolith deposit.

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**), and this may imply larger transportation distances for the rovers (a significant negative consequence) or may control the base location (giving less freedom in the layout of the human exploration zone). However, the higher yield of high-grade deposits would reduce batch sizes, and total volume of raw material to be moved—a significant advantage in mass and power. 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)”

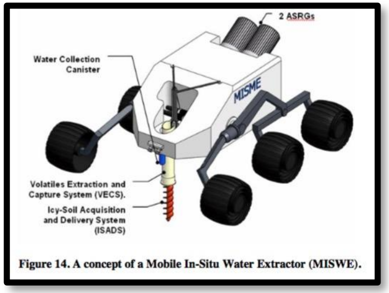
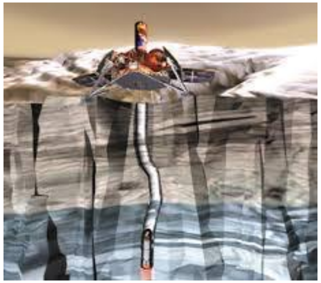


Figure 14. A concept of a Mobile In-Situ Water Extractor (MISWE).

“Cryobot” for Science Exploration (earlier concept)

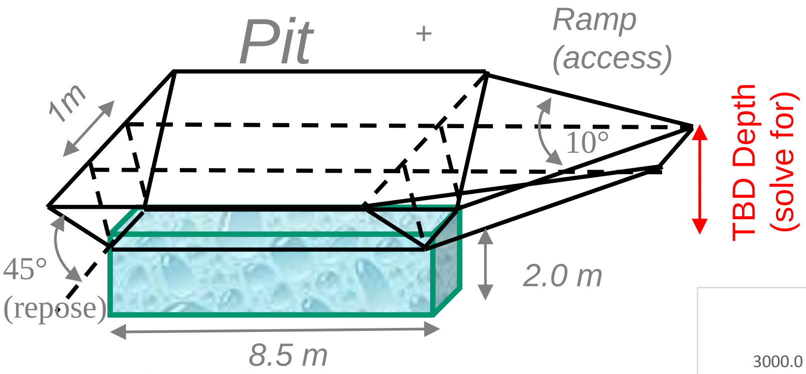


Credit: K. Zacny, Honeybee Robotics

Credit: NASAJPL (1999)

Overburden removal for an Open Pit Over Ice

Overburden:



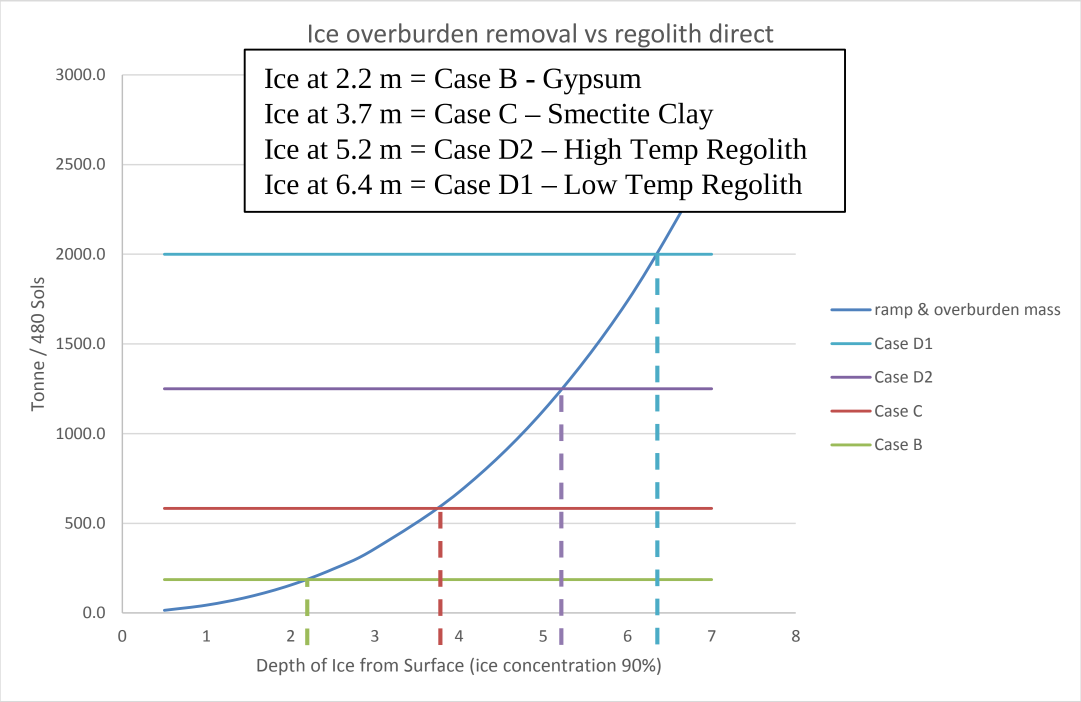
Subsurface Ice:

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.*

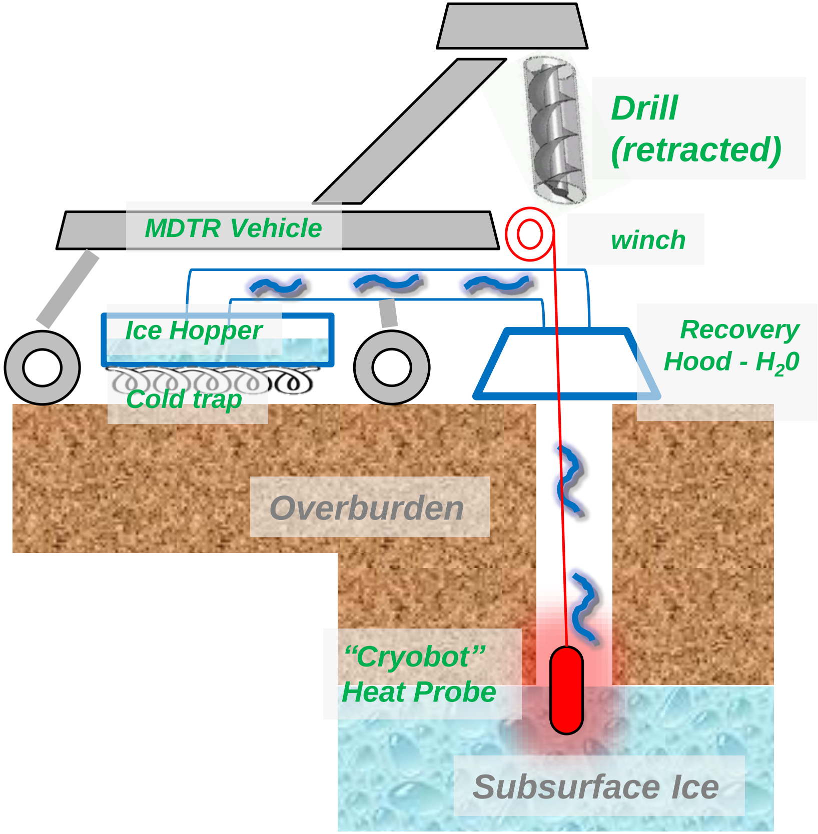
- Analysis conducted to compare mass/volume of overburden to be removed for subsurface ice (to enable surface mining of ice)
- Q: At what ice depth does overburden mass/volume exceed mass/volume required for other granular cases (B-C-D)?


Ice overburden removal vs regolith direct

Ice at 2.2 m = Case B - Gypsum
Ice at 3.7 m = Case C – Smectite Clay
Ice at 5.2 m = Case D2 – High Temp Regolith
Ice at 6.4 m = Case D1 – Low Temp Regolith

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.



Schematic illustration of a possible down-hole water recovery system.

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

Subsurface Ice Deposits:

Engineering Summary

1. Accessing subsurface ice deposits using a small open pit would require significant removal of overburden. The mass to be moved would go up geometrically with depth to ice, and 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. Methods to collect volatiles in-situ (e.g. down-hole processing) are potentially attractive, but are low TRL and may have complications due to the creation of an underground void.
5. Because the raw material would have a 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. In addition, the 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.

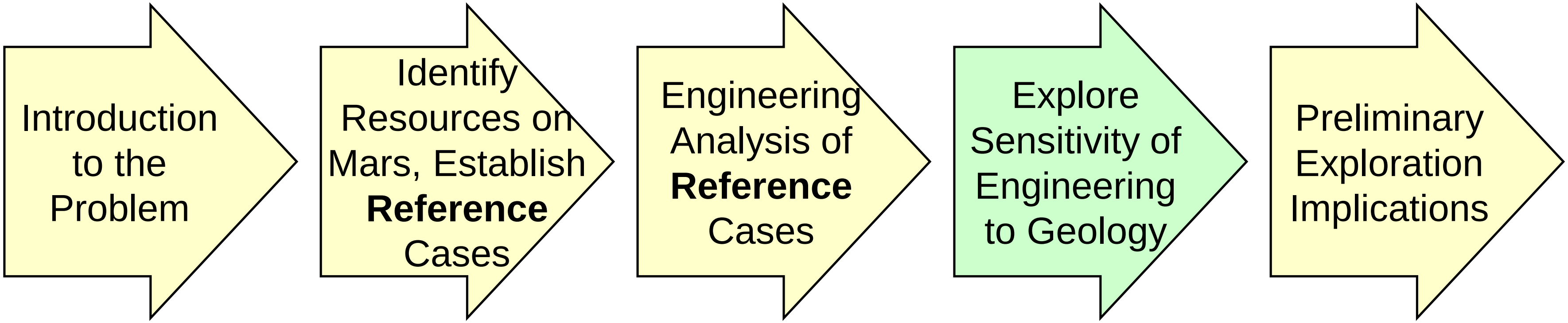
Blasting and Crushing

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.

Task #3

Prepare a sensitivity analysis of the major dependencies between the engineered systems and known or potential geological variation



Introduction to the Problem

Identify Resources on Mars, Establish **Reference** Cases

Engineering Analysis of **Reference** Cases

Explore Sensitivity of Engineering to Geology

Preliminary Exploration Implications

Dependencies of Engineering on Natural Geological Variation

- Several attributes of the natural geological variation of the deposits represented by the reference cases (**Slide #17**) have the potential to exert a significant influence on the engineering architecture. Choosing and optimizing a specific engineering design is therefore dependent on knowledge of these properties. The following appear to be of greatest importance:
    1. Geometry, size, location, accessibility of the ore deposit
    2. Chemical properties (“processability”) of the ore deposit
    3. Nature and scale of ore heterogeneity: mechanical consistency
    4. Nature and scale of ore heterogeneity: water concentration
    5. Thickness of overburden
    6. Mechanical properties of overburden
    7. Distance between the deposit and the processing plant
- Evaluating these dependencies in more than a qualitative way is deferred to future studies.

Geometry, Size of the Ore Deposit

1. Knowledge of the specific geometry and size of the deposit is deemed to be associated with significantly less risk for Cases A, D.
    a) For glacial ice (Case A), the natural scale of glaciers is far larger (see **Slide #20**) than the minimum required production of 16 mt (**Slide #8**). The chance of discovering a glacial ice deposit that would yield less than 16 mt is effectively non-existent.
    b) For martian regolith (Case D), the assumed properties may be generic enough that if appropriate regolith is present at all, it will be in a quantity >>>16 mt.
2. For Cases B and C, the deposits represent more highly concentrated occurrences. Until we understand better the specific processes that have created these hypothesized concentrations, we have poor ability to predict the form and the amount of material present in a minable configuration.

Nature and Scale of Ore Heterogeneity—Mechanical Consistency (1 of 2)

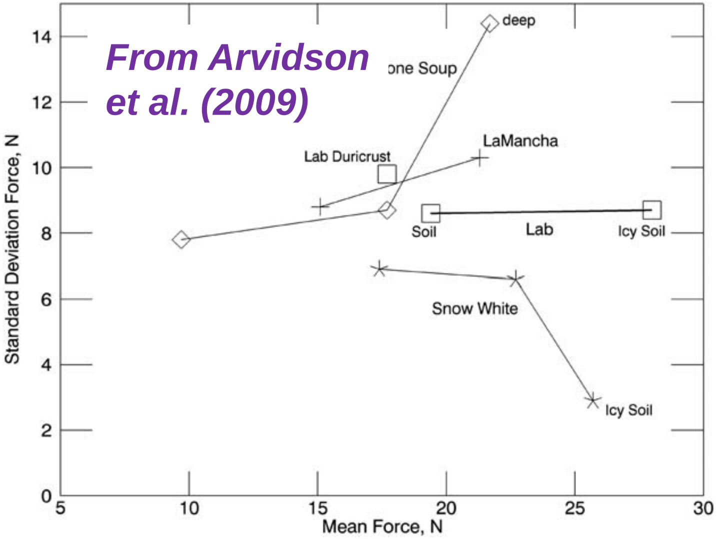
Given the kinds of mining and processing systems described in Task #2, several aspects related to the mechanical consistency of the ore have the potential to cause difficulties that would reduce the efficiency of the water production system:

- Cases B-C-D: Many kinds of granular material deposits consist of uneven particle size distributions that include significant amounts of smaller and larger sizes than the process-optimum.
  - The abundance, and variation in size, of rocks is an issue that can be dealt with by the choice/development of mining method. The presence of even a few very large boulders would sanitize a portion of the deposit, but a well-designed excavation sequence in space and time would minimize this impact.
  - Over-sized material (rocks) wedging in hardware and clogging the process flow would reduce water production rate and shorten equipment life.
  - Under-sized material (fines) lost during excavation and transport could reduce water production rate to a degree depending on the process used.

Note significant variation in mechanical properties of the regolith across this image.

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 efficiency.



From Arvidson et al. (2009)

The ice at the PHX landing site was found to be very hard.

Rock embedded in ice on Earth

Glacier on Earth w/ rock debris

Dealing with glacial ice may require a strategy to deal with associated rocks.

Thickness and Mechanical Properties of Overburden

1. Case A1 involves the removal of overburden to create a small open pit (**Slide #46**). Thus, the quantity and mechanical properties of the material to be moved make a very important difference in the viability of this deposit type. This material could be referred to as a “sublimation lag deposit”, and such materials can be notoriously heterogeneous with respect to properties like particle size distribution (mixed or cemented ice, rock and sand), shape, and composition.
2. For Case A2, the amount of overburden to be moved or drilled through is significantly smaller than for A1, but the concept is completely dependent on creating an opening through which the glacial ice can be accessed (**Slide #47**). This may induce ground stability complications (both hole and cavity) that may or may not be amenable to engineering control.
3. For Cases B-C-D, it is assumed for now that no overburden needs to be moved.

Note: **Slide #18** has more notes on the reserve reference cases.

Distance Between Mine and Plant

1. In Case D, the mass of the material to be moved is the largest (see **Slides #42-44**), so this scenario has the greatest sensitivity to travel distance from the mine to the processing plant. Fortunately, these deposits appear to be the most widespread, so the opportunity to choose sites that are close enough to each other may exist. With distances > 100-200 m, this case quickly becomes unfavorable.
2. The ore deposits in Cases B and C are expected to be more localized, and “rarer” (see **Slide #72**), but since the grade is higher (and thus less ore mass is required), more distance could be justified.
3. For Cases A1 and A2, only water in the form of ice or liquid would need to be transported. This would significantly reduce the transportation challenge. However, since it may be undesirable to place other necessary facilities (Hab, MAV, power plant, etc.) with foundations above glacial ice, and this ice is likely to form in areas with significant topography, this may increase distance, though this may not be an issue due to the reduced volume mined.

Cases D and C might be optimized with a larger excavator than has been considered in this study. However, this would come with a penalty in mass for a larger excavator.

Traversability

- Traversability for mining requires nearly-identical trips to be made many times (the variation arises within the mining area, which constantly changes configuration). For mines on Earth, haul-road design is limited to very small variations for economic reasons. We need to design a transportation system that can reliably and quickly travel almost the same route over and over on auto pilot.
- Loose regolith can cause loss of traction. Excavation and transport will loosen the regolith in concentrated areas, causing potential trafficability issues. Must design roads, vehicles, or mining method to address this issue.
- Note however, that since the assumption is that regolith is everywhere, this is more an engineering problem than an exploration problem.

Other Dependencies of Engineering on Geology

1. Ore deposit chemical properties – the complexity and energy requirements for the production system are much higher for Case D, and moderately higher for Cases B and C, than for Cases A1 or A2 (due to diversity of both mineralogical and mechanical properties).
2. Ore deposit water concentration – since Case D involves processing significant amounts of material, a deposit where the grade is abnormally low could be a very high risk to the mission. This is important for Case B and C as well, but less so.

Additional factor affecting engineering conclusions, but not assessed:

- Impurities – certain types of impurities potentially present in any of the cases could be damaging to the processing system or generate unwelcome byproducts.

Dependency of Engineering Conclusions on Variations in Geology

Relative Importance of Knowledge

Row #	Characteristic	A1: Ice (Open Pit)	A2: Ice (Subsurface)	B: Hydrated Sulfate	C: Clays	D: Regolith
1	Geometry, size of the minable ore deposit	L	L	M	M	L
2	Chemical properties (“processability”) of the ore deposit	L	L	M	M	H
3	Nature and scale of ore heterogeneity: mechanical consistency	H	H	H	H	H
4	Nature and scale of ore heterogeneity: water concentration	L	L	M	M	M
5	Thickness of overburden	H	M	n/a	n/a	n/a
6	Mechanical properties of overburden	H	M	n/a	n/a	n/a
7	Distance between the deposit and the processing plant	M	M	H	H	L

Task #4

Some Preliminary Implications for Resource Exploration

- Introduction to the Problem
- Identify Resources on Mars, Establish **Reference** Cases
- Engineering Analysis of **Reference** Cases
- Explore Sensitivity of Engineering to Geology
- Preliminary Exploration Implications

Overview of Mineral Exploration

Typical Earth-based exploration process and applications to Mars ISRU

1. Develop a concept: What commodity do you want to look for? What deposit type(s) & appropriate geology? What is the political infrastructure? Decide where to go and do basic reconnaissance in those areas.
   - For Mars: Looking for water and have identified four potential deposit types. Geographic determination comes from the engineering requirement to stay <50° latitude (rather than political infrastructure). Existing missions are doing basic reconnaissance.
2. Identify places worth a closer look, and stake claims or negotiate leases. Do initial exploration such as soil samples, systematic rock chip samples, geophysical surveys, geological inference. Out of 1000 places where you do this, maybe 100 will look promising enough to start doing expensive work.
   - For Mars: This step will need to be done entirely from orbit, as only after a down-select would we be willing to send landed missions. Initial exploration would be high-resolution orbital spectroscopy augmented by historical and structural implications of topography and geophysics.

Overview of Mineral Exploration

3. Develop drill targets and test them, modeling the results and doing several rounds of follow up. Do initial metallurgical work. Out of 100 prospects that looked good enough to drill, perhaps a dozen will look promising enough to continue to development work.
   - For Mars: This will be done by robotic tools such as RASSOR. By working smart, could we shortcut the numbers of how many tests are required to find prospects worth advancing, or is it possible that the uniqueness of location would over-ride the possibility of shortcuts?
4. Produce a detailed ore body model and begin engineering plans. Continue metallurgical testing and begin baseline environmental monitoring. Produce a Preliminary Economic Assessment. Of a dozen properties undergoing this, perhaps 3 or 4 will have a positive assessment and advance to the next stage.
   - For Mars: The equivalent of metallurgical testing might be determining the recovery rate of potable or feedstock-quality water. The equivalent of Economic Assessment might be study of energy necessary. Can we work smarter here?
5. Perform final engineering and bankable feasibility studies. Open up the ore body with a preliminary pit, decline, or shaft and begin bulk sampling and test mining. One deposit from a thousand may survive to become profitable!

Do Deposits as Good or Better than the Reference Cases Exist on Mars?

- The analysis in Sections #2-3 of this report is based on the set of hypothetical reference deposits described in **Slide #17**. The question we have been asking to this point is if deposits at least as good as these could be discovered and characterized, would any of them be good enough to justify an ISRU operation?
- We do not know (yet) whether or not deposits of at least this quality actually exist on Mars in a minable configuration and in a location that is accessible to human explorers.
- We also have only partial information related to the consequence of making a discovery that is significantly better or worse than the reference cases.
- Some crucial exploration-related questions related to **Slide #61**:
  - How could this knowledge be generated?
  - How much risk associated with incomplete knowledge is acceptable?
  - What is the most expeditious path to making the discovery needed?

What Would it Take to Get to Reserves?

1. One implication of “reserves” (see **Slides #10-11**) is that the in-place raw material is known to be present (at a certain confidence level) in the form that the extraction and processing engineered systems can be reliably designed.
2. Although all of the knowledge specified on **Slide #61** matters for establishing this confidence, on Earth we have learned from experience that:
    1. In cost-constrained exploration programs, it is common that not all of the data desired can be afforded.
    2. Some information related to exploration questions is more useful for decision-making than other information.
    3. Not all information related to exploration questions is equally expensive.

FINDING #5. In order to optimize an exploration program, it is very important to prioritize information needs, costs, and decisional value.

Information of Highest Priority to Engineering

The information of highest priority to determining engineering viability (**Slide #61**). Are these the parameters of greatest usefulness in exploration screening?

CASE	#1	#2	#3
A1 (Ice+open pit)	Thickness of overburden	Mechanical properties of overburden	Mechanical consistency of ore deposit
A2 (Ice+subsurface)	Mechanical consistency of ore deposit	*Thickness of overburden*	*Mechanical properties of overburden*
B (hydrated sulfate)	2D geometry/size of ore deposit	Mechanical consistency of ore deposit	Distance to processing plant
C (clay)	2D geometry/size of ore deposit	Mechanical consistency of ore deposit	Distance to processing plant
D (regolith)	Water concentration of ore deposit	Mechanical consistency of ore deposit	Chemical properties of ore deposit

Information in cells shaded in blue are those for which preliminary assessments can be made from orbit, those in green require data collected in situ. For Case A2 only parameter #1 was ranked high priority, parameters #2 and #3 (in italics) were ranked medium priority.

The Importance of Scale

- An aspect of **Slide #61** that needs more consideration is the minimum required scale for each of the categories of knowledge described.
- For all of these, the scale of our need to know is different in the vertical and horizontal dimensions—these need to be considered separately.
- For horizontal scale, mining operations can be sensitive to variations (concentrations, rock properties) on the scale of centimeters. Measurements at this scale cannot be done with passive spectral imaging from orbit, and Opportunity and Curiosity have shown that it can be hard to find minerals detected in CRISM footprints (best resolution 18m/pxl) as they are sequestered in the fine structure of the surface in high concentration but over limited areal extent.
- The NEX-SAG report has pointed out that getting finer spatial resolution coverage will help, but this would probably not be available at equally good resolution everywhere on Mars.
- For vertical scale, the capability of measurement from orbit is different for the different cases, and the sensitivity of the mining operations would be different for the different cases – depending highly on access.

The Importance of Subsurface Knowledge

- For Case A, the depth to top of ice is perhaps the single most important piece of information needed (see **Slide #67**). This could be generated to within some level of precision using an orbital SAR (see NEX-SAG, 2015).
- For the mineral-based cases (B-C-D), we have the limitation that most aqueous mineral detections are in the short-wave IR (e.g., OMEGA, CRISM) looking at reflected sunlight, which probes only microns deep. This is equally true of orbital- vs. lander-mounted instruments. Estimates of the depth of these deposits below that can only be done using the principles of geologic inference, and modeling how hydrated these deposits are at depth could be supplemented by additional simulant testing or field work in similar deposits.
- Determining whether the mechanical consistency of the material to be moved (overburden in Case A; ore in cases B-C-D) is within acceptable bounds is hard to measure directly. Some geological processes associated with the creation/deposition of granular materials are associated with size sorting. These processes need to be understood, and models developed for how/when they were active on Mars. This can give us models for size distribution that could have predictive value. Key remaining issues are the priority and methods for testing these models.

This is a 2-step (at least) Exploration Problem

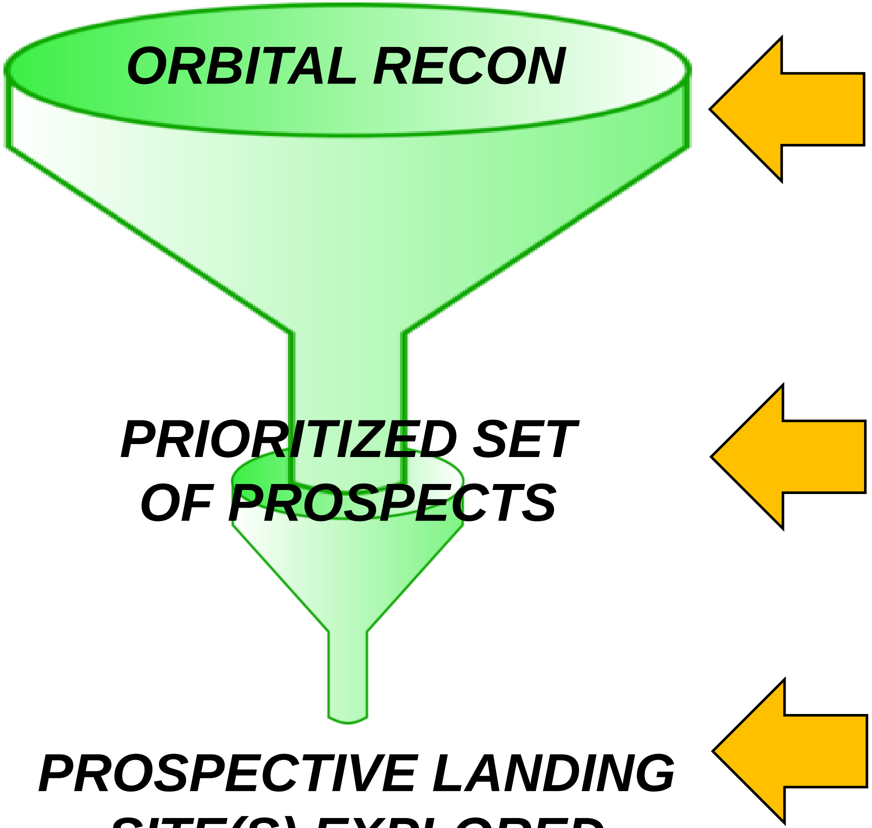
FINDING #6. Using orbital data alone it is not possible to collect the data necessary to achieve "proven reserves" for any of Cases A-B-C. Some of the required data are not observable at all from an orbiter, and others cannot be observed at an appropriate spatial scale.

- The best we will be able to do from orbit is to identify places of enhanced potential, or maybe "possible reserves" (see **Slide #10**).

FINDING #7. All of the parameters listed on **Slide #61** can be measured from a properly-equipped rover, as long as it is sent to the right place.

- There is a time factor that matters. When is the earliest that we can get data from the second mission and when is it needed in order to influence mission architecture?

The Importance of Decisional Support



ORBITAL RECON

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

PRIORITIZED SET OF PROSPECTS

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

PROSPECTIVE LANDING SITE(S) EXPLORED

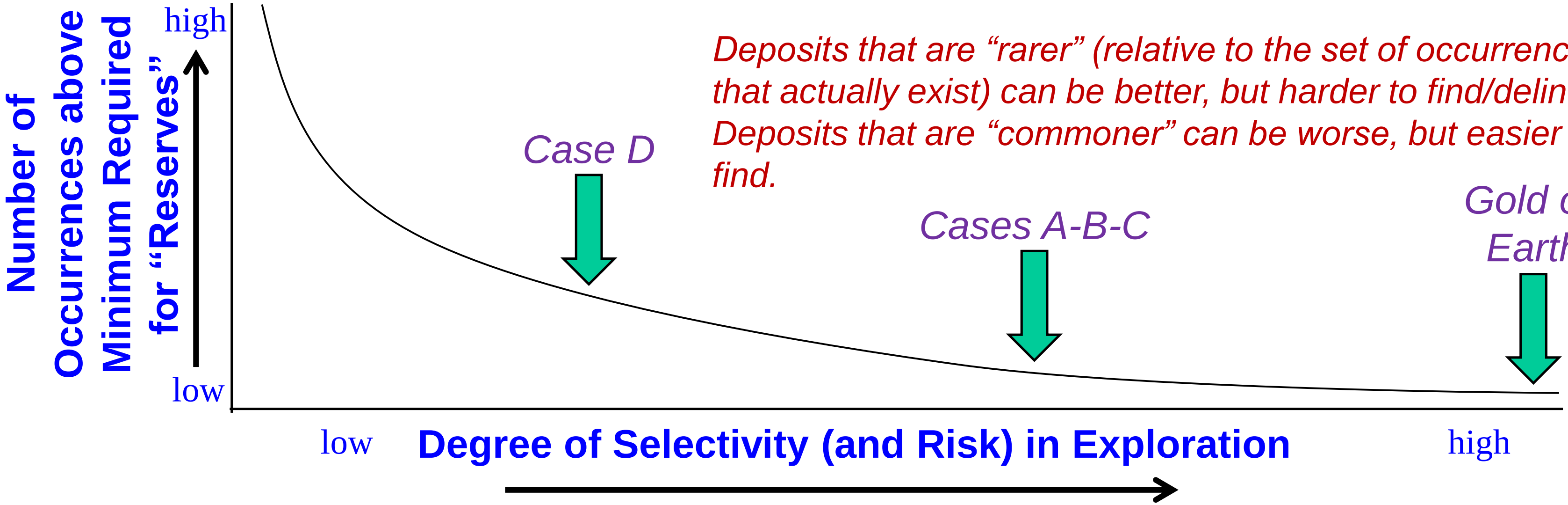
How could we maximize the probability that the prospective landing site(s) we explore on the ground will be able to meet remaining requirements?

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**.

Exploration Risk (1 of 3)

What is the exploration risk (= the risk of failing to make an acceptable discovery)?

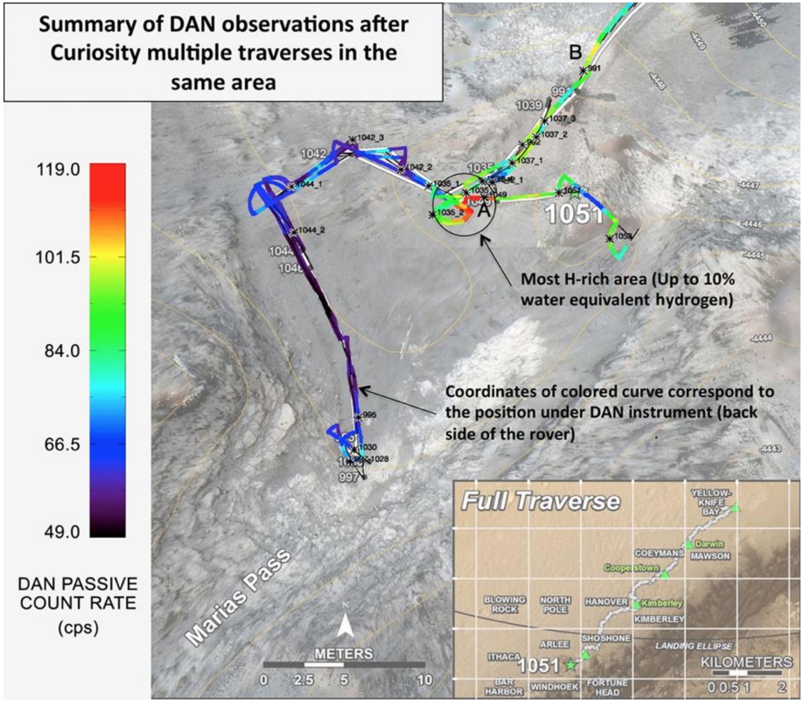
- We don't know how rare, within the available geologic provinces, ore deposits that meet/exceed minimum engineering specifications would be. The exploration risk would depend on the engineering tolerances and the natural geologic variation. The rarer the occurrence, the harder the exploration problem.
- For all of our reference ore deposit cases, potential deposits will have a dispersion about a mean, with some instances being better than average, and others being worse than average.



Deposits that are "rarer" (relative to the set of occurrences that actually exist) can be better, but harder to find/delineate. Deposits that are "commoner" can be worse, but easier to find.

Exploration Risk (2 of 3): Case D - Regolith

- We have data for the water content of the regolith, at a scale relevant to mining, for <u>ONE</u> place on Mars: Gale Crater (and this has been used to define Case D; 1.5% WEH).
- What is the risk that at some geologically similar alternate site, the values are less than minimum acceptable values? How can this risk be estimated?
  - Modeled values from DAN go as low as 1.02 +/- 0.04% WEH (data from Sol 59)
- Would continued data collection from DAN in addition to the data from FREND (on ExoMars-TGO – spatial resolution up to 30-40m) help to understand this risk?



Summary of DAN observations after Curiosity multiple traverses in the same area

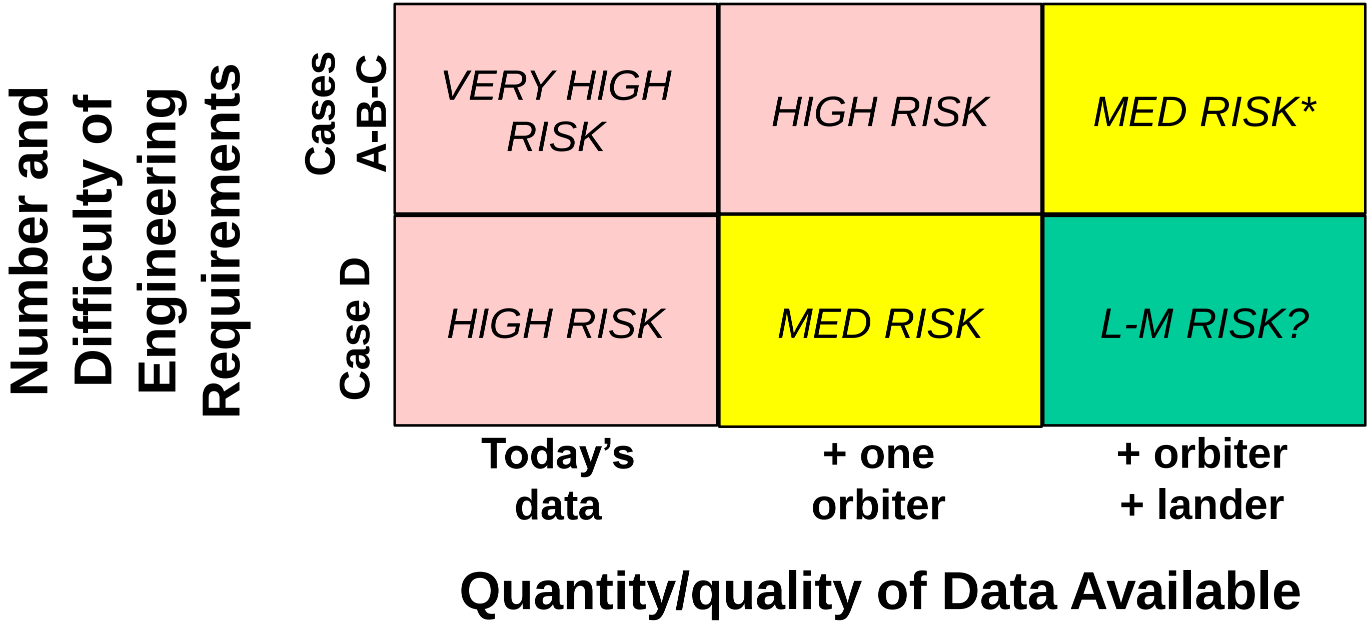
Most H-rich area (Up to 10% water equivalent hydrogen)

Coordinates of colored curve correspond to the position under DAN instrument (back side of the rover)

Unusually H-rich area of Mars' surface detected by DAN, showing data through Sol 1051 – note that color coding is by passive count rate, and that this is correlated to WEH by measuring the time after PNG pulse – WEH is calculated from a model, and is not directly equivalent to hydration state (JPL Press Release, August 19, 2015)

Exploration Risk (3 of 3)

(= Risk of Failing to Identify Necessary Reserves)



Number and Difficulty of Engineering Requirements

	Today's data	+ one orbiter	+ orbiter + lander
Cases A-B-C	*VERY HIGH RISK*	*HIGH RISK*	*MED RISK**
Case D	*HIGH RISK*	*MED RISK*	*L-M RISK?*

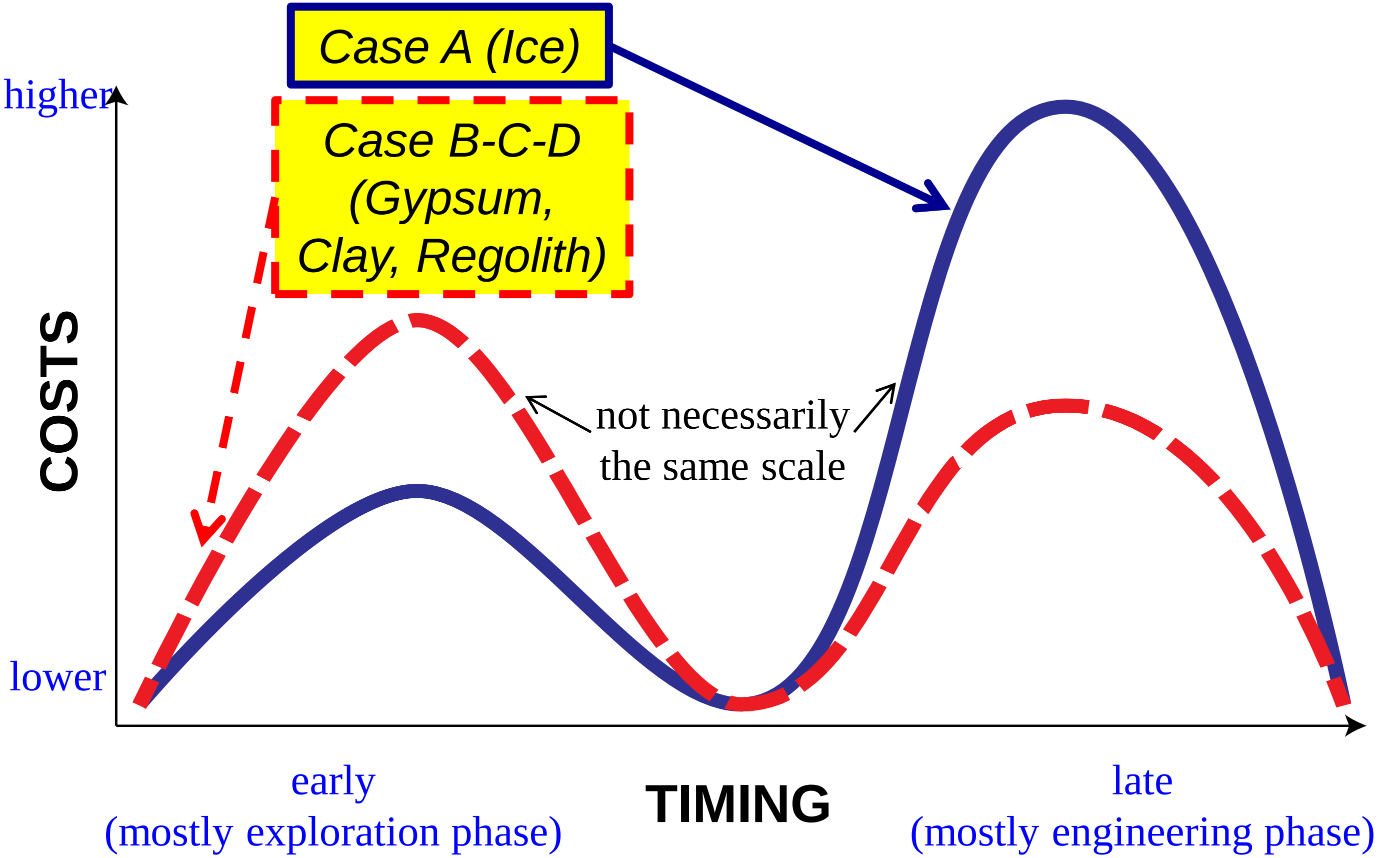
Quantity/quality of Data Available

*could be lower if you hit paydirt with first lander

Assuming that reserves are present without sufficient exploration is a high-risk strategy. This risk can be reduced by acquiring data (this is a classic problem in the exploration community on Earth.

FINDING #8. We can buy down risk by means of purchasing data. However, the risk cannot be taken to zero (Q: how much residual risk is acceptable?).

When Would Investment Be Made?



Comparison of the phasing of investments. Experience from Earth-based exploration-mining projects is that early exploration-related investments pay off many-fold in later engineering related investments.

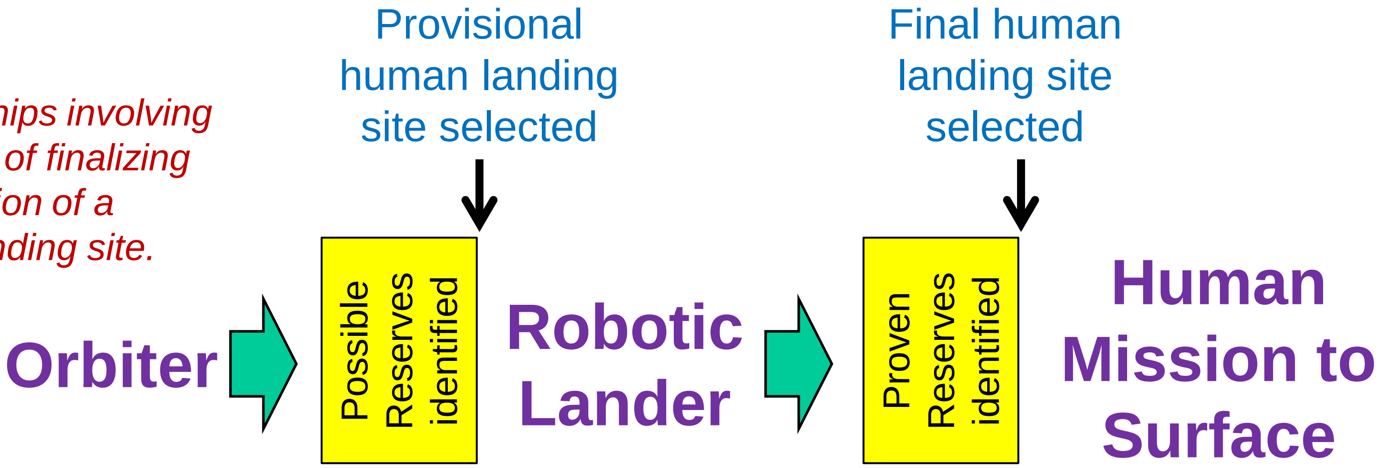
An Alternative Risk-balancing Strategy

Since Case D (typical martian regolith) is postulated to be applicable at almost any location on Mars, these ores could be assumed to exist in conjunction with each of our other deposit types (Type A, B or C). This allows for the following variant that draws the astronauts into the exploration process (after arrival):

Set up the initial engineering system sized so as to make use of Case D (low grade deposits), but keep the option open of shifting later to Cases A, B or C (higher grade deposits) for the long term once validated. This would also provide reserves if Cases A, B or C could be found. Drawbacks: 1) Cannot know in advance if this is feasible 2) Requires oversizing for worst case in several dimensions (greater # of excavators, larger throughput, higher processing temperatures / power levels) 3) Processing has to be compatible.

Some Timing Considerations, and Landing Site Selection

- As discussed on **Slide #70**, it is impossible to achieve proven water reserves, for any of the resource types considered, with one exploration orbiter. At least one lander is also required.
- That lander would need a landing site. It would be highly advantageous if that site were the actual human landing site. However, if knowledge of proven water reserves is a prerequisite to selecting the human landing site, it may not be possible to choose the latter to within reasonable risk standards until after an exploration lander mission has been completed.
- This suggests the following decisional logic:



Relationships involving the timing of finalizing the selection of a human landing site.

Conclusions

Conclusions (1 of 2)

- ISRU would significantly reduce the total overall mass which needs to be sent to Mars. The baseline assumption would be that we are only producing LOX using atmospheric ISRU. However, for a relatively small increase in the initial mass of ISRU equipment sent to Mars, CH_4 could also be produced, dramatically increasing propellant produced by a factor of 6 per kg of total ISRU system mass.
- There is reasonable potential to produce mission-significant quantities water on Mars, using systems that may be compatible with the architecture of a human mission, from at least 4 potential resource types (ice, polyhydrated sulfate concentrations, phyllosilicate concentrations, regolith).
- Mining subsurface glacial ice by open pit methods would have multiple challenges. It would be particularly sensitive to the thickness of the overburden, and to the mechanical properties of the ore. For all but the shallowest glacial ice deposits (2-6m), this approach would require 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 but is the 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 to other surface mining approaches, because the grade would be so low. For this reason, it would be especially sensitive to transportation distance, and to heterogeneity in grade, but offers the more 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 reference case (not including the down-hole case). The viability would be 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.

Conclusions (2 of 2)

- The phyllosilicate reference case (Case C) is significantly inferior to the polyhydrated sulfate case, and only somewhat better than typical martian regolith. 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.
- The establishment of "reserves" in any of the four cases evaluated in this study would require a). Refinement of the production method, b). An exploration program.
- 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.
- It is not possible to collect the data necessary to achieve "reserves" using orbital data alone. This is a 2-step (at least) exploration problem, involving both an orbiter and a follow-up landed mission.
- Due to the engineering importance of mineral deposit properties that are not measureable from orbit, a significant portion of exploration risk could be reduced by a robotic surface mission sufficiently earlier than the planned human landing that its findings could be incorporated in mining method/technology design and development.
- Several attributes of the natural geological variation of the deposits represented by the reference cases have the potential to exert a significant influence on the basic viability of candidate sites, as well as the engineering architecture. Choosing and optimizing a specific engineering design is therefore dependent on knowledge of these properties. The exploration missions should be designed to focus on acquiring these data.
- Two general factors that will be important in establishing "reserves" are scale and subsurface knowledge. These need more discussion.

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.

Some Identified Areas for Follow-up Work (2 of 6)

Technology Development

4. Technology concepts should be matured for potentially competitive methods of heating/subliming ice from depth with cold-trap recovery at the surface, or excavation without a cold trap, through drill-holes that are less sensitive to depth of deposits than open pit ice mining.
5. The trade between dedicated prospecting rovers, excavators, regolith processing on vehicles, and/or regolith/product transport vehicles should be determined based on a number of factors. (We may still want to have a common rover chassis/bus with different “specialized” attachments vs. completely different rover chassis.)
6. Given the lower temperature/energy requirements, systems such as a plutonium RTG-powered (~2 kW thermal, ~100-150 W electrical) “field retort” where ore could be processed into water at the mine location and only water/ice transported back to the fuel processing plant co-located with the MAV/reactors should be considered for optimization, in conjunction with “specialized” rovers for gypsum (and potentially smectite). Also, smaller, modular portable fission reactors (10 kW or less) might be advantageous in this scenario.
7. Establish the feasible working lifetimes (processing cycles, haul trips, etc.) of potential technologies (specialized or generic rovers, retorts, etc).

Some Identified Areas for Follow-up Work (3 of 6)

Advanced Mission Planning

8. Continue refinement of engineering parameters for resource reference cases A, B, C, and D. Continue working trade studies on distance and resource parameters with HAT ISRU team. Dive more into icy soil evaluation as a function of depth from 1 to 3 meters.
9. Gain a better understanding of the effect of surface properties and terrain on mining method concepts. Use this to identify better terrestrial 'feedstock' for creating simulants that represent these 4 resource types for upcoming ISRU development activities.
10. Study the effects of over- and under-sized material on excavation forces, durability of equipment and processing systems, and efficiency of excavation and processing methods. Develop mitigation approaches.
11. Continue to examine the impact of the power architecture on mining method and hardware sizing.
12. Integrate mass/cost estimation approaches: Overall economics of these and other (subsurface ice) will depend not only on mass / cost estimates for the systems described by this analysis, but also estimates of the alternatives, such as:
    a. Mass / complexity of flight excavators, flight ore processing reactors, flight water → fuel processing systems.
    b. Analysis of the development and launch/transportation costs (and reliability) and of how these systems trade against either:
        - directly transporting the required propellants from earth (without water processing) or
        - transporting water (or other hydrogen source) from earth for manufacturing propellant using native carbon/CO_2

Some Identified Areas for Follow-up Work (4 of 6)

Improved Understanding of Mars

13. Assess the potential of various martian geologic provinces to contain deposits of categories A, B, or C that meet or exceed the hypothetical driving specifications used in this analysis. Are our hypotheticals overly rare (making the exploration problem too hard) or overly low grade (making the engineering problem unnecessarily difficult)?
14. Analyze how effectively we can use the principles of geologic inference to model variation with depth, since this cannot easily be directly measured. Can this be studied via Earth analogs?
15. Identify local characteristics of deposits: How homogeneous are the deposits over different scales (across surface, x-y, or in depth, z)? Presence of impurities or larger “rocks” in the deposit that would reduce efficiency of either excavation or water extraction?
16. Gain better understanding of the concentration-frequency distribution of water in the regolith, including the on-going operation of the DAN instrument, and better understanding of the mineral phases that the water is stored in, including more measurements of regolith from the SAM instrument. This is a key input for estimating the risk that sites other than Gale Crater have lower values of water than Case D (regolith) and for bounding the variability in similar locations.
17. Once exposed, the ice deposit would be unstable w.r.t. sublimation. We need a better understanding of the rate of this process, including its practical significance to water production methods and the need for mitigation strategies.

Some Identified Areas for Follow-up Work (5 of 6)

Refinement of Exploration Strategy

18. Produce a better definition of the degree of confidence implied by the term “reserves” (for Mars), and especially, more widespread agreement on risk tolerance (both probability and effect) in this context.
19. Define the set of standards that a “reserve” feasibility study must meet for Mars water production.
20. Have more discussion of the risks, and possible risk mitigation strategies, associated with down-selecting to the landing site for a possible landed exploration mission. What are the essential data sets, and spectral and spatial resolution, needed to support this decision? **Slide #71** needs to be followed up with an analysis of the possible or proposed steps or missions to accomplish each step.
21. Create a better analysis of which data sets would provide the most effective screening to define discrete, evaluatable, prioritized, prospects.
    a. Evaluate the potential value to the exploration flow of the FREND data set from TGO.
    b. Evaluate the potential value to the exploration flow of the data that could be produced from various candidate instruments on NASA’s NeMO mission.
22. Incorporate the principal conclusions of this analysis into the workshop series associated with identifying and prioritizing candidate human landing sites (HLS^2).

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

Other

23. Have additional discussions of planetary protection concerns.

Note:

- The concept of producing water on Mars would raise a number of questions if evaluated against the Planetary Protection policy of 2016.
  - Would any of the approaches to extracting ice create an ‘induced special region’?
  - Would the establishment of reservoirs of water inside the various engineered systems create microbial habitats that would be an issue?
- However, the key is the relationship of these ISRU issues to the future PP policy that would be in place at the time the human missions happen—that policy has not yet been written.

Appendix

Affiliations

M-WIP Committee Members

Name		Affiliation
Abbud-Madrid	Angel	Colorado School of Mines
Beaty	Dave	Mars Program Office, Jet Propulsion Laboratory - California Institute of Technology
Boucher	Dale	Deltion Innovations Ltd.
Bussey	Ben	NASA - Headquarters
Davis	Richard	NASA - Headquarters
Gertsch	Leslie	Missouri University of Science and Technology
Hays	Lindsay	Mars Program Office, Jet Propulsion Laboratory - California Institute of Technology
Kleinhenz	Julie	NASA - Glenn Research Center
Meyer	Michael	NASA - Headquarters
Moats	Michael	Missouri University of Science and Technology
Mueller	Rob	NASA - Kennedy Space Center
Paz	Aaron	NASA - Johnson Space Center
Suzuki	Nantel	NASA - Headquarters
van Susante	Paul	Michigan Technological University
Whetsel	Charles	Mars Program Office, Jet Propulsion Laboratory - California Institute of Technology
Zbinden	Elizabeth	Geological Society of Nevada

Reviewers

Name		Affiliation
Hoffman	Steven	NASA - Johnson Space Center
Parrish	Joseph	Mars Program Office, Jet Propulsion Laboratory - California Institute of Technology
Sanders	Gerald	NASA - Johnson Space Center
Zurek	Richard	Mars Program Office, Jet Propulsion Laboratory - California Institute of Technology

Acronyms & Definitions

- CheMin – Chemistry and Mineralogy Instrument (instrument on the 2011 MSL rover)
- CRISM - Compact Reconnaissance Imaging Spectrometer for Mars (instrument on the 2005 MRO orbiter)
- DAN – Dynamic Albedo of Neutrons (instrument on the 2011 MSL rover)
- DRA – Design Reference Architecture
- EDL – Entry, Descent and Landing
- EMC – Evolvable Mars Campaign
- FREND - Fine Resolution Epithermal Neutron Detector (instrument on the 2016 ExoMars-TGO orbiter)
- HAT – Human Architecture Team
- HLS^2 – Human Landing Site Selection
- ISRU – In Situ Resource Utilization
- LCH_4 – Liquid Methane
- LOX – Liquid Oxygen
- MARSIS - Mars Advanced Radar for Subsurface and Ionosphere Sounding (instrument on the 2003 Mars Express orbiter)
- MAV – Mars Ascent Vehicle
- MRO – Mars Reconnaissance Orbiter
- MSL – Mars Science Laboratory
- NEX-SAG – Next Orbiter Science Analysis Group
- PP – Planetary Protection
- RASSOR – Regolith Advanced Surface Systems Operations Robot
- ROI – Region of Interest
- RSL – Recurring Slope Lineae
- SAM – Sample Analysis at Mars (instrument on the 2011 MSL rover)
- SHARAD – Shallow Subsurface Radar (instrument on the 2005 MRO orbiter)
- TGO – ExoMars Trace Gas Orbiter
- TRL – Technology Readiness Level
- WEH – Water Equivalent Hydrogen

Definitions (terms as used in the context of this study)

- Exploration: As applied to resource deposits, the set of activities that result in the discovery and delineation of reserves.
- Feedstock: The output of one industrial process that is input to another.
- Mining method: The spatial (layout) and temporal (scheduling) sequence of mining activities.
- Resource: (1) Any useful raw material (2) A natural concentration or enrichment of water-bearing material that has the potential to become a proven reserve.
- Processing: Activities related to extracting, refining, and purifying the water from mined ore.
- Production: The combined activities of mining + processing for which the output is a commodity.

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