ENGINEERING SENSITIVITIES TO ORE CHARACTERISTICS FOR WATER RESOURCES ON MARS AND IMPLICATIONS FOR RESOURCE EXPLORATION APPROACHES: M-WIP STUDY, PART 3.

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Introduction: In response to the Human Landing Site Selection Workshop (HLS2), held October 2015 (http://mars.nasa.gov/multimedia/webcasts/human-landing-site-selection-workshops/), at which a number of candidate Mars Exploration Zones were proposed, the Mars Water ISRU Planning (M-WIP) Study was undertaken. This study began with a survey of candidate resource classes (ores) proposed at the HLS2 workshop and developed candidate engineering approaches for the extraction of water from those ores. The different approaches for water extraction have differing sensitivities to several key physical characterists of the ore. These difference can have significant impact on the cost, complexity, mass and power requirement of the ISRU system. The current state of knowledge of these characteristics and strategies to extend this knowledge base were explored as part of the M-WIP study and are detailed herein.

Candidate Ores and Key Characteristics: The M-WIP Study focused on four cases of potential water sources available at potential future human landing sites on Mars: A) Subsurface Ice, B) Aqueous (or Hydrated) Minerals, C) Phyllosilicate (Clay) Mineral Deposits, and D) Regolith – representative of the typical materials present at almost any landing site that might be selected. For subsurface ice, two extraction strategies were considered: A1) "Open pit" surface mining, or A2) Subsurface ice extraction by drilling down through the overburden and melting/subliming the ice before recapturing the vapor via a cold trap at the surface. For cases B, C, and D, the mining operation involves collection of naturally available granular material at the surface, transportation to a central processing facility (co-located with a large power source) and heating the material to release water.

Relative Importance of Knowledge

ID	Characteristic	A1: Open Pit Ice	A2: Sub-surface Ice	B: Hydrated Sulfate	C: Clays	D: Rego-lith
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

Fig. 1. Relative importance of characteristics to different candidate ores.

Fig. 1 summarizes the relative importance of different characteristics for each of the ores considered. The subsurface ice cases (A1, A2) are sensitive to both the quantity (thickness) and quality (mechanical properties) of the overburden material, although the Subsurface ("down-hole") approach is less sensitive since only a "shaft" or "well" of material must be removed to enable access. For all ores except regolith (assumed to be present in proximity to the processing plant and energy source) transportation between the deposits and processing system are important – less so for Case A which transports only water than B or C which must transport the ore from which water must be extracted. All of the granular material strategies (B, C, D) are sensitive to the heterogeneity of the water concentration of the ore and other characteristics such as "processability" that influence the amount of ore that must be acquired, transported, and processed per unit of extracted water.

Finally, the processing systems for all ores are highly sensitive to the heterogeneity of the mechanical properties of the ore as it occurs naturally at Mars. This strongly drives the mass and energy required to initially aquire the material from its source environment, before any beneficial operations can be performed. Figure 2 illustrates a subset of cases to be considered. In the martian terrain on the left, granular materials with a mix of larger rocks are represented. Designing an acquisition system that can deal with this level of heterogeneity can be done, but will come at a cost (in mass, complexity, and likely efficiency) that could be avoided if not needed at a specific site. Similarly, on the right, glacial processes of formation and evolution on earth typically result in a degree of heterogeneity that may need to be factored into the design of future ISRU systems if similar conditions exist on Mars.

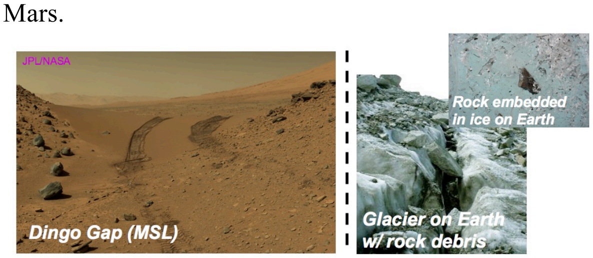

Fig. 2. Example: Scale of heterogeneity – mechanical consistency

Ability to Measure Key Ore Characteristics: Given these relative sensitivities of the ISRU engineering system to the ore characteristics, an evaluation of the strategies to refine existing knowledge or acquire new knowledge was undertaken. As shown in Fig. 3, for each of the cases considered, a ranking of the most sensitive characteristics was performed (based on expert opinion) and a feasibility assessment for measuring the characteristic was performed. More specifically, an evaluation of whether the characteristic in question could be feasibly measured from Mars orbit or if the measurement likely required an *in situ* "ground truth" measurement.

CASE	Most Important	2nd Most Important	3rd Most Important
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

Fig. 3. Means of acquiring most important information: Cells shaded in blue allow preliminary assessment from orbit. Cells in green require in situ data

Remote sensing from orbit is easiest for, but not limited to, surface characteristics measurable by passive detectors in either the optical or infrared bands, e.g. spectral mineralogy. Unfortunately, these data sets can only reveal the 2D extent of the deposits, not the depth, and have limited ability to make quantitative assessments of the concentrations of the minerals detected. Active sensing from orbit (e.g. radar or lower-frequency EM sounding) can be used to measure below the surface and, with appropriate selection of frequency and power levels, measure the thickness to ice deposits below any overburden that might be present. The ability to measure the mechanical properties of this overburden from orbit, however, may be limited and warrants further investigation.

An important consideration in this analysis is the fact that for orbital data sets, it is possible for a single "prospecting" orbital mission to collect data over the entire martian surface for all candidate landing sites. This contrasts with characteristics that can only be measured *in situ*, where each site effectively requires a dedicated mission per candidate site.

Implications and Proposed Approach: The data available to date from prior Mars missions suggest promising opportunities for future ISRU systems but falls short of the standard of "proven reserves" as used for typical earth-based mineral resource exploration.

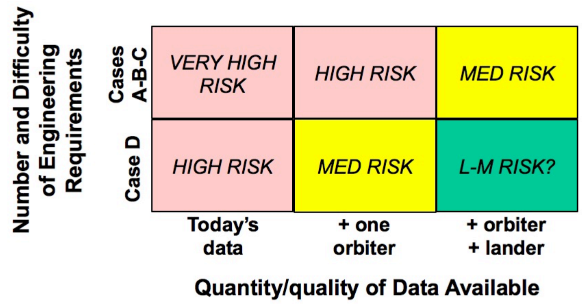

Fig. 4. Risk reduction effects with additional data

Fig. 4 illustrates the assessment of risk versus knowledge. For each ore considered in the M-WIP study, a set of assumptions were postulated about what kind of deposits might exist on Mars. Case D makes the fewest assumptions and is based on material which should be ubiquitous, but even so, is sensitive to local variation. The other approaches are even more sensitive.

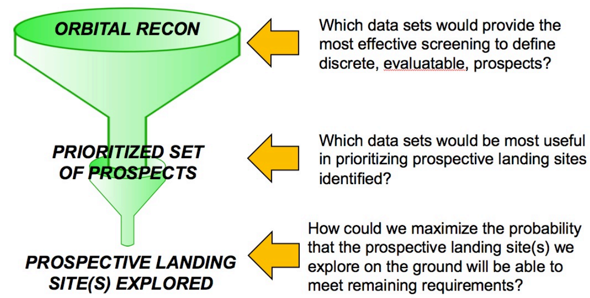

Fig. 5. Proposed exploration Strategy

Fig. 5 illustrates the proposed approach of using initial orbital reconnaissance of as much as possible of the Martian surface for the key characteristics described, followed by at least one *in situ* surface mission to provide *in situ* ground truth at that site before committing to a full scale ISRU production system supporting the future human exploration of Mars.