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A Water Rich Mars Surface Mission Scenario

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Abstract — **In an on-going effort to make human Mars missions more affordable and sustainable, NASA continues to investigate the innovative leveraging of technological advances in conjunction with the use of accessible Martian resources directly applicable to these missions. One of the resources with the broadest utility for human missions is water. Many past studies of human Mars missions assumed a complete lack of water derivable from local sources. However, recent advances in our understanding of the Martian environment provides growing evidence that Mars may be more "water rich" than previously suspected. This is based on data indicating that substantial quantities of water are mixed with surface regolith, bound in minerals located at or near the surface, and buried in large glacier-like forms.**

This paper describes an assessment of what could be done in a "water rich" human Mars mission scenario. A description of what is meant by "water rich" in this context is provided, including a quantification of the water that would be used by crews in this scenario. The different types of potential feedstock that could be used to generate these quantities of water are described, drawing on the most recently available assessments of data being returned from Mars. This paper specifically focuses on sources that appear to be buried quantities of water ice. (An assessment of other potential feedstock materials is documented in another paper.) Technologies and processes currently used in terrestrial Polar Regions are reviewed. One process with a long history of use on Earth and with potential application on Mars – the Rodriguez Well – is described and results of an analysis simulating the performance of such a well on Mars are presented. These results indicate that a Rodriguez Well capable of producing the quantities of water identified for a "water rich" human mission are within the capabilities assumed to be available on the Martian surface, as envisioned in other comparable Evolvable Mars Campaign assessments. The paper concludes by capturing additional findings and describing additional simulations and tests that should be conducted to better characterize the performance of the identified terrestrial technologies for accessing subsurface ice, as well as the Rodriguez Well, under Mars environmental conditions.

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1. INTRODUCTION

For many years NASA has investigated alternative human Mars missions, examining different mission objectives, trajectories, vehicles, and technologies. At the highest levels, decisions regarding the timing and objectives for a human mission to Mars continue to evolve, while at the more specialized levels, relevant technologies and discoveries about Mars continue to advance. This results in an on-going series of assessments collected together into reference missions or architecture options that provide meaningful characterizations to assist those making decisions regarding timing, objectives, and technologies. One area of continuing interest among these decision-makers is the innovative leveraging of technological advances in conjunction with the use of accessible Martian resources to make human missions more affordable and sustainable.

Recent Mars robotic missions have yielded data that points to an age when liquid water flowed on the surface for substantial periods of time [1]. Were this water still available, it would substantially change the approach to human missions on the surface. But Mars' geologic record clearly shows that the planet lost its surface liquid water a very long time ago, and, in any case, there is certainly none present today. There are large amounts of ice currently located in the polar ice caps, and liquid water is presumed by many to be present in the deep subsurface, but these are inaccessible for use by human crews. However, there is growing evidence that Mars may be more "water rich" than previously suspected, based on data indicating that substantial quantities of water are mixed with surface regolith, bound in minerals located at or near the surface, and buried in large glacier-like forms [2]. All of these potential sources of water have been identified in areas and in forms that are likely to be accessible to human crews.

Studies carried out as part of NASA's Evolvable Mars Campaign effort examined the impacts of a "water rich" human Mars mission scenario. For this assessment, those elements of a human Mars mission that would most benefit from the largely unconstrained availability of water were identified and the "typical" quantities of water that would be used by crews under this scenario were estimated. Sources of feedstock material from which water could be extracted were then identified based on the most recent available data for the surface of Mars. These feedstock materials tended to fall into two broad categories: regolith/minerals and ices. Two separate assessments were carried out for each of these feedstock types. This paper discusses the assessment of ice as

a feedstock. A separate paper [3] discusses the results from the assessment of regolith/minerals as a feedstock.

Before discussing possible methods of acquiring ice on Mars and turning it into usable water for human crews, this paper will first describe the "water rich" scenario for human missions and the implications for quantities of water needed to support the crews. This is followed by a summary of current knowledge of water feedstock material, including both regolith/mineral sources and ice sources. The remainder of the paper will focus on water ice as the feedstock material and methods for deriving liquid water from this ice for use by the crews. Technologies currently in use in the Polar Regions of Earth could be applied directly to, or at least point to, a system for use on Mars. One particular terrestrial approach for generating and storing liquid water in the Polar Regions – the Rodriguez Well – is reviewed and results from a quantitative analysis are compared with the previously described needs of the "water rich" human mission scenario.

The paper concludes with findings and observations regarding approaches for generating water from ice on Mars along with suggestions for next steps to better understand the implications of following any of the approaches or uses of the technologies described.

2. Water Rich Mission Scenario

To estimate the water requirements for a "typical" crewed Mars surface mission, we use the characteristics of NASA's recent "Evolvable Mars Campaign" studies [4]. In these, each surface mission consists of a crew of four on the Martian surface for about 500 days utilizing a central habitation module for crew living/working activities, spacesuits and pressurized rovers for remote exploration, and a single ascent vehicle for return to an orbiting interplanetary vehicle. For each of these functional elements, we investigate the maximum use of Martian resources, including water, to reduce the amount of supplies required to be transported from Earth. We do not attempt to perform conceptual designs of the processing equipment and associated power systems here; instead, we simply use likely processing chemistry to estimate the water required in order to inform resource requirements.

Ascent Propellant

Many previous studies have examined the use of Martian resources for ascent vehicle propellant production [5, 6]. One of the most effective propellant combinations is methane and oxygen, but previous uncertainties in the availability of easily extractable Martian water has limited the concepts to production of oxygen only (extracted from the carbon dioxide in the Martian atmosphere) or, at best, the importation of terrestrial hydrogen for use in a combination of water electrolysis and Sabatier processes. Such a process, modified

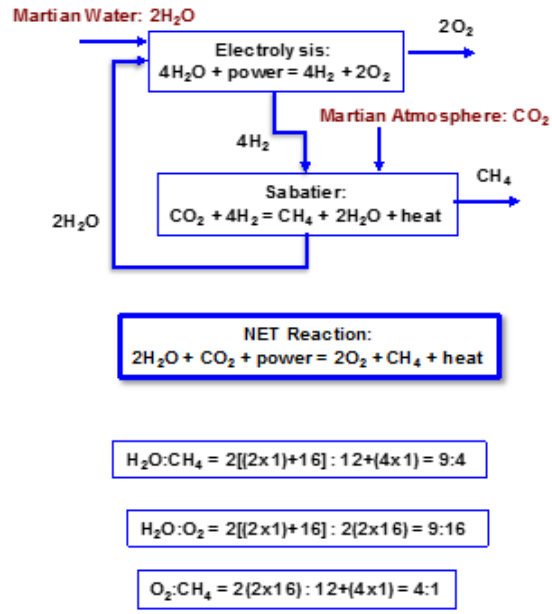

Figure 1. Assumed Resource Production Process

for the utilization of Martian water, is shown in Figure 1, along with the water-to-product mass ratios. Note that only Martian resources are required for process feedstock.

Extensive Mars Ascent Vehicle (MAV) design studies were performed as part of the Evolvable Mars Campaign analysis [7]. Typically, to maximize the benefit of in-situ produced propellant, the transportation architecture will be biased toward the highest Mars orbit practical for the MAV-to-interplanetary vehicle rendezvous. Such a vehicle concept is depicted in Figure 2 [8].

The total propellant load required is 38,506 kg at an oxidizer-to-fuel (OF) ratio of 3.4. Given the water-to-product mass ratios from Figure 1, this will require 19,683 kg (~5,210 gallons) of Martian water (and 24,059 kg of Martian CO_2). Since the Sabatier/water electrolysis process produces oxygen and methane in a 4:1 ratio, 5,235 kg of excess oxygen will be produced.

Life Support

Traditional Mars surface habitation systems assume closed-loop (recyclable) water and oxygen systems for crew life support. While greatly reducing the import mass requirements for these commodities, the resulting systems are complex and, as experience on the International Space Station has indicated, prone to frequent repair and maintenance. In addition, the power and mass of these systems limit water usage to rather basic levels (e.g., no showers, laundry, etc.).

Subsystem	Mass (kg)	
	MDM Payload	Mars Liftoff
Crew Cabin	**3,427**	**4,122**
Structures	881	881
Power	377	377
Avionics	407	407
Thermal	542	542
ECLS	502	502
Cargo	422	1,117
Non-Prop. Fluids	295	295
1st Stage	**9,913**	**31,432**
Dry Mass	3,605	3,605
LO_2	0	21,519
LCH_4	6,308	6,308
2nd Stage	**5,006**	**13,246**
Dry Mass	2,566	2,566
LO_2	0	8,239
LCH_4	2,440	2,440
TOTALS	**18,345**	**48,799**

Figure 2. Mars Ascent Vehicle Conceptual Design

With the availability of Martian water, the strategy for life support could change in several ways.

1. It could be advantageous to reduce the water and oxygen recycling levels to increase reliability or reduce system development costs, using in situ Martian water to make up the differences.
2. Systems could "temporarily" rely on Martian water to allow for repair and maintenance of closed-loop systems.
3. Life support could rely completely on Martian water for life support water and oxygen, thereby eliminating both development cost and mass of closed-loop systems.

It should be stressed that open-loop water systems introduce the issue of cleanup or sequestration of waste water before reintroduction into the Martian environment. Sequestration could be possible by storage of waste water containers in used logistics modules, for example. However, if high waste water cleanliness levels are necessary, advantages of open-loop systems may be less apparent. This will need to be addressed as part of the overall human Mars mission in the context of planetary protection.

Water resupply requirements for closed-loop, "restrained" open-loop, and "robust" open-loop scenarios for a four-crew 500-day surface mission are shown in Table 1 [9]. The relatively low closed-loop water makeup requirements are due to the intrinsic water content in the crew's food supply, and the closed-loop oxygen makeup is delivered in the form of water which is subsequently electrolyzed for oxygen. The open-loop requirements illustrate one case with the same usage level as the closed-loop and a second case with a substantially higher level due to the addition of a laundry system.

It can be seen that for the "restrained" open-loop case, the 500-day water requirement is 9,519 kg (~2,520 gallons), or about half of that required for propellant production. The addition of the laundry more than doubles that amount. In any case, the life-support water needs are "in kind" with those of the MAV.

Finally, it should be pointed out that the excess oxygen resulting from the propellant production exceeds the crew's metabolic oxygen requirement, so it is not bookkept in Table 1.

Table 1. Life Support Water Supply Requirement (4 Crew for 500 Days)

	Closed-Loop H_2O, O_2	Open-Loop H_2O, O_2	Open-Loop + Laundry
H_2O Closed-Loop Makeup	970	0	0
O_2 Closed-Loop Makeup	2,480	0	0
Laundry	0	0	14,660
EVA	0	3,072	3,072
Food Rehydration	0	1,070	1,070
Medical	0	107	107
Drink	0	4,280	4,280
Flush	0	134	134
Hygiene	0	856	856
TOTAL	**3,450 kg (~913 gallons)**	**9,519 kg (~2,520 gallons)**	**24,379 kg (~6,549 gallons)**

Radiation Protection

Outside of the Earth's magnetosphere, there are generally two types of radiation that can impact crews' health – Solar Particle Events (SPEs) and Galactic Cosmic Radiation (GCR). On the Martian surface, the SPEs are greatly attenuated (approximately an order of magnitude) by the atmosphere. GCR is also somewhat attenuated. However, interaction between GCR ions and the atmospheric molecules result in a pion and electromagnetic cascade ("π/EM cascade"). In addition, collision between GCR ions and the Martian soil creates a neutron field ("albedo neutrons"). Both of these GCR effects contribute to the total exposure experienced by a crewmember on the Martian surface. The effectiveness of using Martian water as a shield was investigated.

Models have been developed [10] to account for GCR effects including four-π radiation transport methodology ("HZETRN-π/EM") through an atmospheric density/ composition model, a regolith model and a shielding material model using the International Commission on Radiological Protection (ICRP) Publication 60 quality factor to compute the GCR dose equivalent. A human phantom model is used to compute dose equivalence at radiosensitive tissue targets and weighted (ICRP 103) to compute effective dose. Shielding effectiveness has been computed for aluminum and polyethylene, and as polyethylene characteristics are nearly identical to water, we use that model here.

Figure 3 illustrates the effects of various factors in reducing the GCR effective dose on the Martian surface. As can be seen, by far the greatest reductions are due to the planetary blockage of half the sky and atmospheric attenuation (but still taking into account π/EM cascade and albedo neutrons). The additive effect of a water shield, however, is disappointingly small. Even very large quantities of water shielding only reduce effective dose by around 20%. This is caused by GCR-induced neutron production and emission *in the shielding material itself*.

Nevertheless, for study purposes we assumed 20 g/cm^2 of water shielding – equivalent to a 20 cm thick water shell – around a Mars surface habitat. Such a shell would provide about 15% effective dose reduction. Assuming the habitat is a 7 m diameter cylinder that is 6.5 m tall (typical of conceptual habitat designs), this shell would be the equivalent of 43,000 kg (~11,382 gallons) of water.

Such a water shell could be combined with the water quantities previously calculated for a robust open-loop life support scenario. The radiation shield could represent a life-support water "buffer" or storage supply for such an open loop system. If configured correctly, this buffer would provide the additional benefit of (albeit limited) radiation shielding.

Mobility Power

For extended surface mobility and exploration exceeding the time limits imposed by spacesuits, pressurized, multi-crewmember rovers are often envisioned. Power sources for these concepts are always problematic, however, especially in multi-day traverse scenarios. Battery weights are prohibitive without recharge and solar arrays consistent with recharge power levels are inconsistent with roving vehicles. Alternative concepts involving small nuclear power sources may be technically viable, but have significant cost implications.

Hydrogen-oxygen fuel cells have also been proposed as a power source [11], but the volumetric and cryogenic challenges of liquid hydrogen, along with the regeneration

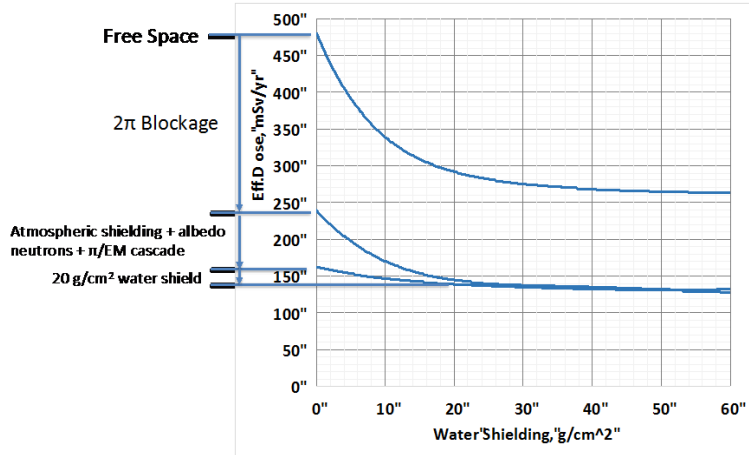

Figure 3. GCR Water Shielding Effectiveness

challenges of liquid hydrogen and the regeneration necessity with no Martian hydrogen source, have made this choice unattractive. However, Martian water combined with methane reformer technology may offer a better answer.

Solid oxide fuel cells can utilize methane and oxygen to produce electrical power for rover drive motors and for life support. The hydrogen-oxygen fuel cell produces water, which is fed into a steam reformer to generate hydrogen from methane (produced, in turn, from Martian water and carbon dioxide), which is fed into the fuel cell. The reaction is illustrated in Figure 4. Note that the oxygen and methane are consumed in a 3:1 mass ratio, indicating that if the reactants are produced from the Sabatier/electrolysis process, excess oxygen will once again result (just as in MAV propellant production). In addition, water in excess of that required by the steam reformer is produced from the fuel cells, and is available for crew metabolic needs, either as potable water or as oxygen via electrolysis.

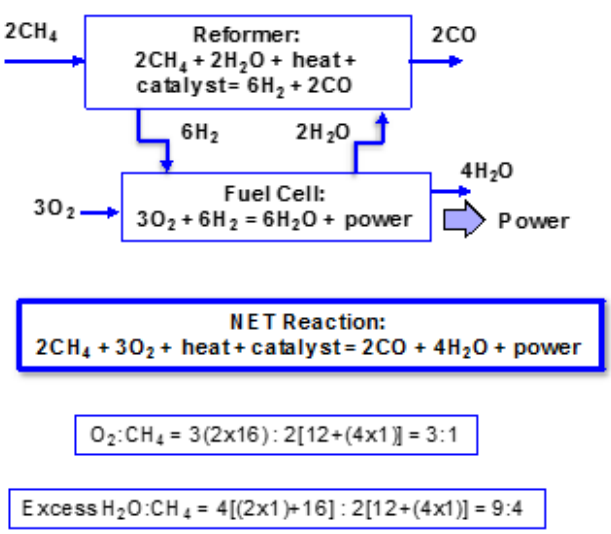

Figure 4. Methane Oxygen Fuel Cell Chemistry

To characterize performance, we postulate rover and surface excursion parameters [12] shown in Table 2 (1 sol = 1 Martian day, 24.65 hrs). As can be seen, the fuel cells will produce 621 kg (~164 gallons) of water in excess of that required by the methane reformer, more than enough to supply the crew's potable water requirement (estimated at 100 kg for a crew of two). To extrapolate this excursion over the duration of a 500-day surface mission, we assume that for every excursion, two rovers will explore in tandem to maintain mutual rescue capability in case of malfunction, and that such an excursion is performed every 28 sols, resulting in 18 excursions per mission. This equates to a total requirement of 9,936 kg of methane and 30,276 kg of oxygen. Again, assuming Sabatier/electrolysis methane-oxygen production, this will require 22,396 kg (~5,928 gallons) of Martian water – similar in magnitude to the MAV propellant requirement.

Table 2. Surface Excursion Characteristics

Trip Duration	14 sols
No. of Days Driving	9 sols
Crew	2
Rover Drive Time/Sol	9 hours
Total Energy Needed	1,564 kW-hrs
Total O_2 Needed	841 kg
Total CH_4 Needed	276 kg
Excess H_2O Produced	621 kg (~164 gallons)

Summary of Surface Mission Water Requirements

By totaling the MAV, "robust" open-loop life-support, and mobility requirements, we can estimate total "per mission"

Table 3. Products and Required Feedstock (per Mission)

	O_2	CH_4	H_2O	Martian H_2O Required
MAV	29,758	8748	N/A	19,683
Life Support	N/A	N/A	24,379	24,379
Mobility	30,276	9936	N/A	22,936
Total	**60,034 kg (~15,891 gallons)**	**18,684 kg (~4,946 gallons)**	**24,379 kg (~6,453 gallons)**	**66,998 kg (~17,735 gallons)**

water extraction requirements, shown in Table 3, assuming Martian water (and carbon dioxide) are the sole feedstock for the products. Such a summation can aid in developing water extraction and processing concepts and the associated power requirements. It should be pointed out that little effort has been made in optimizing or integrating these needs.

For example, while surface roving excursions are taking place, habitat consumables requirements will be reduced. It has, however, been pointed out that habitat oxygen needs can be met with excess MAV oxygen production, rover life support consumables can be produced with fuel cell excess water production, and a life support water buffer can produce modest radiation protection.

Assuming a continuing series of human excursions to the Martian surface, the cadence of these missions will dictate the necessary commodity production rates and hence the water extraction rates. The "Evolvable Mars Campaign" was predicated on a Mars surface mission on alternating Earth-Mars synodic periods, implying a mission every 50 months. Combined with the per-mission requirements of Table 3, this implies production and water extraction rates shown in Table 4.

Table 4. Commodity Production and Martian Water Extraction Rates

O_2 Production	14,141 kg/yr
CH_4 Production	4,486 kg/yr
H_2O Production	5,853 kg/yr
Martian H_2O Required	**16,086 kg/yr (~4,258 gallons/yr)**

3. WATER SOURCES ON MARS

As robotic missions continue to explore Mars from orbit and from the surface, the understanding of past and current sources of water is evolving. For utilization during human surface missions, the desire would be for water (or water ice) to be relatively concentrated, relatively accessible and in regions consistent with exploration objectives. The potential Mars water "inventory" can be divided into roughly six categories [13].

Polar Surface Water Ice

We know of very large deposits of relatively pure water ice on the surface of Mars. Both the north and south Martian poles have permanent caps of water ice at latitudes greater than 80° which are covered by CO_2 ice during the respective winters. The CO_2 fully sublimes at the North Pole during the summer, revealing a permanent cap of 90-100% pure H_2O 100 km in diameter and 3 km thick. The south pole CO_2 deposits never fully sublime, leaving around 8 m of CO_2 ice covering most of the permanent cap, the size of which is not well known.

These regions, however, are not generally considered favorable for long duration human exploration due to long periods of seasonal darkness during the winter and the dynamic, low visibility conditions due to subliming CO_2 in the summer.

Atmospheric Water Vapor

The average water content of the Martian atmosphere is quite low at around 300 ppm, equating to 1 kg of water per 170,000 cubic meters of atmosphere. However, because the atmosphere is so thin, relative humidity can be quite high, reaching near saturation levels. While direct collection does not appear attractive (e.g., through condensation), the Martian water vapor may interact with other water sources, as described below.

Water Sequestered in Minerals

The Mars Reconnaissance Orbiter's (MRO) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) and Mars Express' Infrared Mineralogical Mapping Spectrometer (OMEGA) have detected minerals that presumably formed in ancient Martian aqueous environments [14]. These hydrous minerals are localized (around 3% of the Martian surface) but widespread, consisting mostly of phyllosilicates (clay minerals), chlorites and sulfates. As mixtures of these minerals exist, water content may vary considerably from around 2-9% by weight. While soil excavation and transport would be necessary to harvest the water bound in these minerals, such engineering studies have been performed [15].

Groundwater

"Recent" presence of Martian groundwater (<10 million years ago) has been inferred by outflow channel formations observed from orbit (Figure 5). It had been assumed that subsurface liquid water in the form of aquifers was located below a thin cryosphere and had "burst through" occasionally to form these features.

Much more recently, dark, narrow (0.5 to 5.0 m) markings have been observed on steep (25° to 45°) slopes. MRO High Resolution Imaging Science Experiment (HiRISE) images show incremental growth during warm seasons and fading during cold seasons [16]. These "Recurring Slope Lineae"

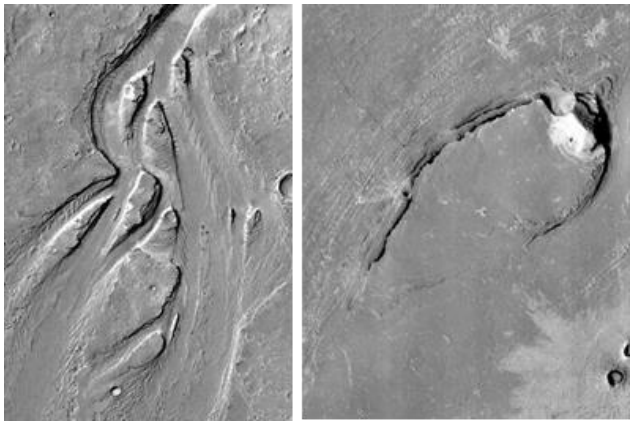

Figure 5. Athabasca Valles, Images Courtesy NASA/JPL/Malin Space Science Systems

(Figure 6) have been interpreted as intermittent flows of briny liquid water and this was confirmed by the MRO CRISM spectrometer in 2015. However, the water source was unclear, and some interpreted this as more evidence of aquifers exposed by these slopes.

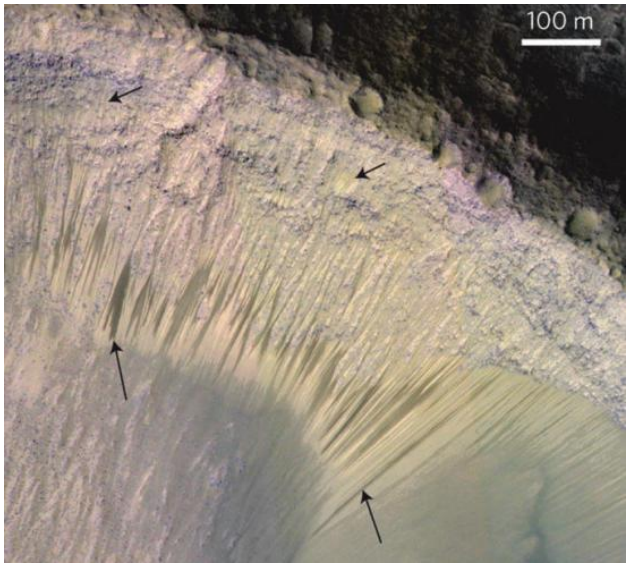

Figure 6. Recurring Slope Lineae [16]. Image credit NASA/JPL/University of Arizona

The Mars Express Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) and the MRO Shallow Subsurface Radar (SHARD) instruments were designed to specifically detect such subsurface liquid water. However, to date MARSIS and SHARAD have *failed to detect any indication of liquid water within 200-300 m of the surface anywhere on Mars* [17]. It may be that the formations depicted in Figure 5 are older than initially thought, and the groundwater is gone or is locked up in the subsurface cryosphere, and the flooding was caused by infrequent localized crustal heating and cryosphere melting. As for the RSL, atmospheric water vapor may be the "feedstock" for absorption by salty minerals (perchlorates and other hygroscopic salts), resulting in temporary muddy flows. In any event, the prospects of easily accessible subsurface *liquid* water appear unlikely.

Shallow Sequestered Water Ice

Certain Martian geological features suggest evidence for large-scale mid-latitude glaciation, potentially driven by changes in the obliquity of Mars' rotation axis. These Lobate Debris Aprons (LDAs), Lineated Valley Fills (LVFs) and Concentric Crater Fills (CCFs) [18] all bear similarity to terrestrial glaciation features (Figure 7) and are widely distributed in the Martian mid-latitudes (Figure 8).

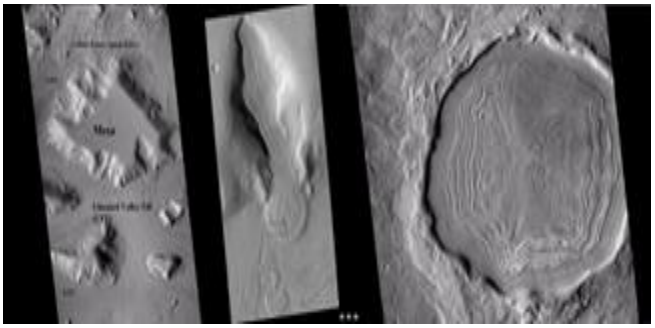

Figure 7. LDA, LVF and CCF Martian Glaciation Features (MRO Context Camera)

The MRO SHARAD radar took soundings of LDAs in both the northern and southern mid-latitudes and obtained results completely consistent with *massive layers (100s of meters thick) of relatively pure (>90%) water ice covered by a relatively thin (0.5 to 10 m) debris layer* [19].

As a further line of evidence, fresh impact craters in these suspected glacial regions detected by the MRO HiRISE imager [20] actually *show* excavated, clean ice, verified by the CRISM spectrometer (<1% regolith content). The excavated material has been observed to sublime away over several months' time in subsequent images (Figure 9). The excavation depths are estimated to be less than two meters.

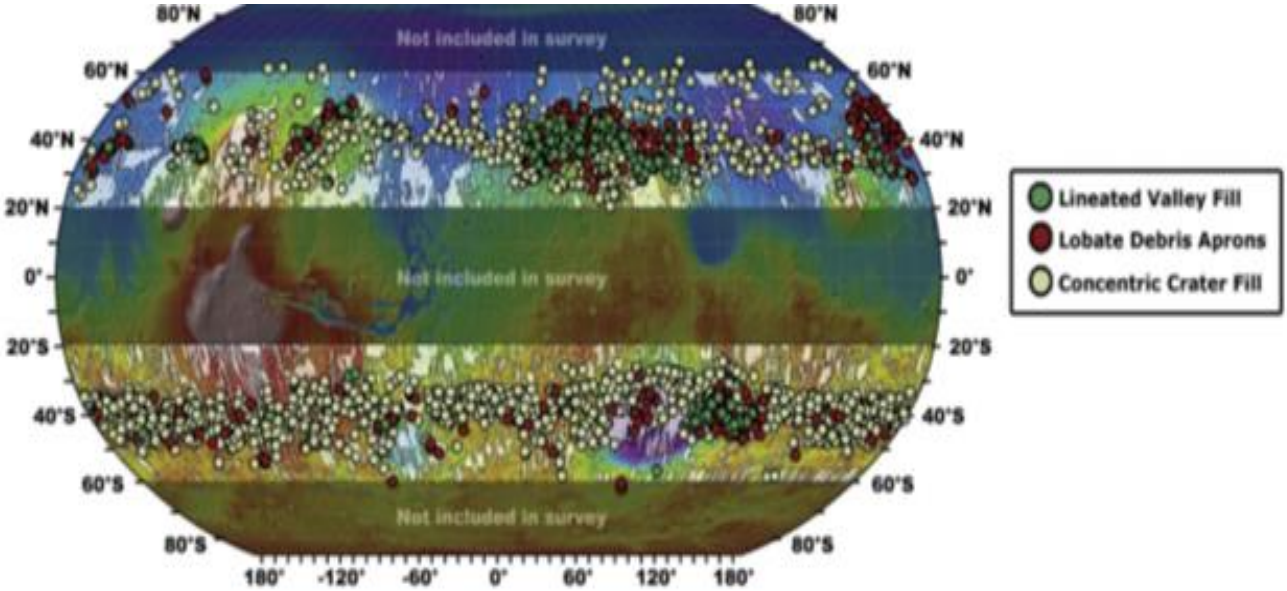

Figure 8. Global Distribution of LDA, LVF and CCF Features [18]

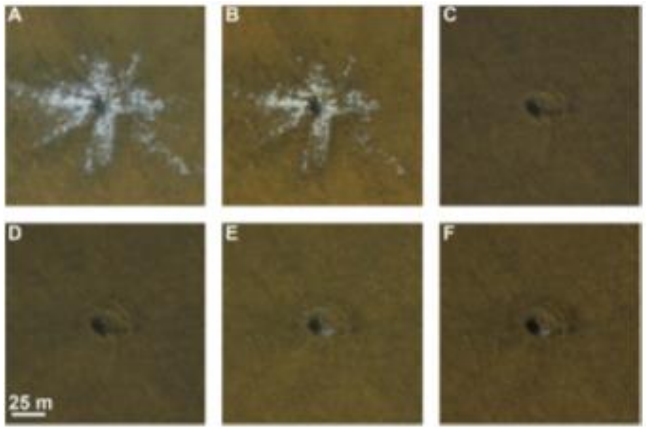

Figure 9. Impact Crater Ice Excavation and Sublimation [16]

Subsurface Cryosphere

The Mars Odyssey gamma ray/neutron spectrometer has confirmed previous predictions of extensive ground ice within *one meter* of the Martian surface poleward of 50° north and south latitude with a concentration of 20-90% [21] and an estimated thickness of 5-15 *kilometers* [17]. These measurements and predictions were confirmed by the Phoenix Lander (landing site 68° N latitude) which excavated 99% pure ice only 2-6 *centimeters* from the surface (Figure 10).

Water Sources for Human Exploration

Of the water sources listed, the most promising seem to be the massive ice deposits in the mid-latitudes (Figure 8) associated with the glacial LDA, LVF and CCF features and nearly everywhere poleward of 50° latitude. The regolith overburden seems to be less than two meters and the underlying ice relatively pure. If these regions correspond to exploration priorities for human Mars missions, the investigation of techniques to extract this water ice should be a high priority.

Figure 10. Ice Excavated by Phoenix Lander, Image NASA/JPL/University of Arizona, Texas A&M University

4. ACCESSING AND EXTRACTING SUBSURFACE ICE

The previous section describes several promising feedstocks that could be used to generate significant quantities of water on Mars. To understand the implications for a human mission, however, requires a more detailed assessment of processes and the associated systems or technologies that are necessary to gather this feedstock material and process it into usable water. Two recent studies have been carried out to examine alternative processes and technologies for these varied feedstocks. One study – the Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study [15] – examined primarily those feedstocks associated with solid materials such as regolith or specific minerals identified at a number of locations on the Martian surface. Results from this study are described in a separate conference paper [3]. The other major feedstock type – substantial deposits of essentially pure water ice – is the focus of the assessment described in this paper.

Evidence suggests that this water ice feedstock can be found in what are described as glacier-like features [18], sometimes differentiated into features called "lineated valley fill" (LVF) and "lobate debris aprons" (LDA). Examples of these features are illustrated in Figure 11. In addition to these visually distinctive features, radar data from the SHARAD and MARSIS instruments indicate a vertical profile that is typical of an essentially pure water ice deposit covered by some currently uncertain amount of solid debris material [19]. Based on the known performance of these radar instruments and other instruments designed to detect hydrogen (a surrogate for direct detection of water), the bounds on the thickness of this debris layer "… can be constrained as greater than 0.5 meters, based on the lack of a strong hydrogen signature in gamma ray and neutron data, and less than ~10 meters, based on the lack of a detection of a shallow soil-ice interface in SHARAD data" [22].

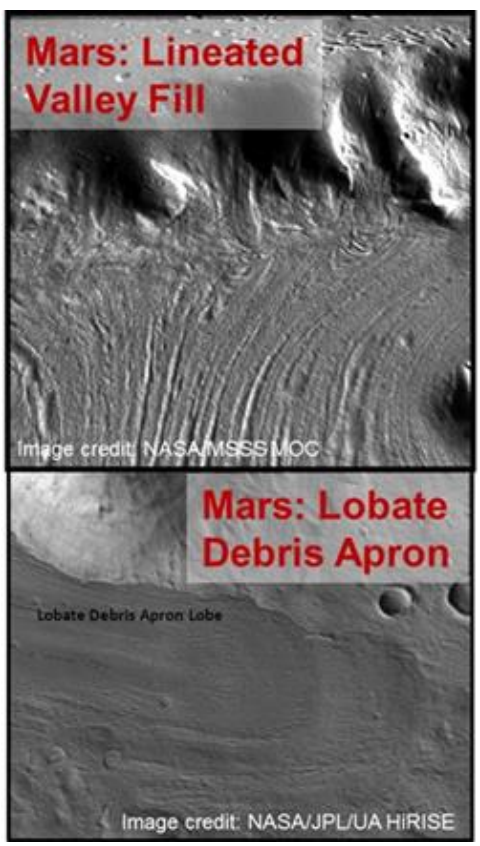

Figure 11. Examples of Lineated Valley Fill (LVF) and Lobate Debris Aprons (LDA)

These glacier-like features are thought to have at least three distinct layers: a debris/sublimation till layer, a firn layer, and a solid ice layer (Figure 12). The ***debris/sublimation till layer*** is likely to resemble terrestrial glacial till - an unsorted collection of rocks, cobbles, sand, and fine sedimentary material. The ***firn layer*** is a feature typically found on terrestrial glaciers and ice sheets - a layer of granulated snow and ice crystals that is gradually being compressed into solid ice. Because of the granular/porous nature of this layer, any liquid water in the layer (e.g., if formed in an attempt to remove it from this layer) will move to lower levels until a solid interface is encountered. Due to the lack of snowfall and the overlying debris layer it is thought that any firn on Mars will long ago have been compressed into solid ice (i.e., the firn layer has zero thickness). The ***ice layer*** is a solid layer of water ice. This layer is likely to contain debris, gathered as

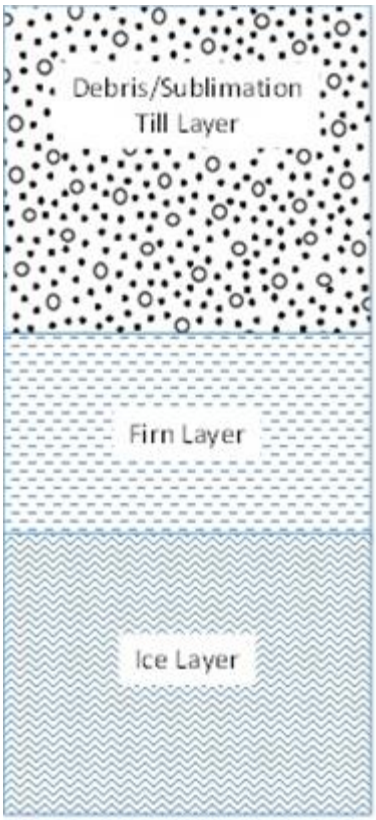

Figure 12. Layers of Martian Glacier-like Features

the body of ice was formed, as well as fractures of varying sizes, resulting from a variety of causes. Depending on the size of the fracture, these could be "self-healing" in the presence of liquid water. Based on data gathered by the orbiting radars mentioned previously, this ice layer could be 100's to 1000's of meters thick.

Two general approaches have been examined for reaching these buried deposits of ice: removing the debris layer to expose the ice for excavation, and drilling through the debris layer followed by extracting the ice or water by one of several methods. Current environmental conditions on the surface of Mars do not allow exposed water in a liquid or solid form to exist for long – sublimation will turn both of these forms of water into a vapor relatively quickly. This implies that excavating exposed ice will require either acceptance of the loss of some amount of ice to sublimation or some sort of covering to mitigate this effect during excavation. Because of the structural characteristics of the layers in the vertical profile described above, it is likely that any attempt to access the ice layer by means of some sort of drill (examples discussed below) will require that both the debris layer and the firn layer (if it exists) be penetrated and the resulting access hole lined by an impervious casing. This casing will be needed for several reasons: (1) to prevent any debris layer material from falling into and possibly sealing the access hole, (2) to prevent any of the liquid water being withdrawn from leaking into the two upper layers, and (3) to provide a means of maintaining some amount of elevated atmospheric pressure within the hole to prevent or minimize sublimation of the subsurface ice or water.

In addition to these issues, the M-WIP study found that the energy costs of removing even a modest thickness of debris to expose the ice layer quickly exceeded other options for generating water from other feedstock [15]. The M-WIP study made a cursory examination of drilling into the ice layer, but deferred any detailed assessment due to what the M-WIP study team felt was a lack of appropriate expertise. A second group – those supporting the work reported in this paper – made a more in-depth assessment of drilling through the debris and firn layers to reach the buried ice. The remainder of this section will describe the findings of this assessment.

As a starting point for assessing the viability of accessing and withdrawing water from these potential ice features on Mars, a review was made of technologies and systems used in terrestrial Polar Regions to access, gather, and then convert ice into water. Two approaches are typically used in these terrestrial Polar Regions to "mine" snow and ice for potable and utility water: (a) "harvesting" surface snow/ice by means of a front-end loader and using snow melters (typically using waste heat from diesel power generators) to make water, and (b) drilling into ice layers and creating a subsurface reservoir of water (Figure 13). As discussed above, snow or ice will not long exist on the surface under current Mars environmental conditions. However, the second option appears to be feasible for Martian applications because the

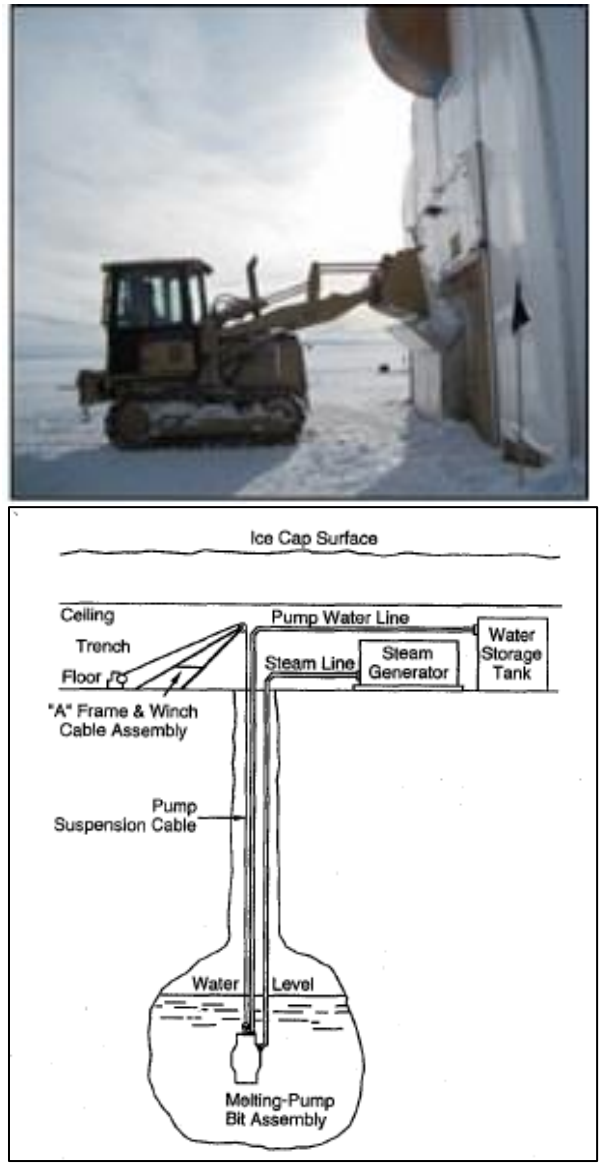

Figure 13. Two Approaches to Mining Snow and Ice for Water in the Earth's Polar Regions [23]

water remains protected from surface conditions. Subsurface water reservoirs were first designed and built by the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) in the early 1960s for several U.S. Army camps located in Greenland [24, 25]. These reservoirs are commonly referred to as Rodriguez wells, or Rodwells.

From the Schmitt and Rodriguez report [24]:

> "A Rodwell is developed by drilling a hole into snow or ice and then melting the ice in place using a heat source, typically recirculated hot water. The melt water then ponds when an impermeable strata in the snow or ice is reached or until refreezing melt water forms its own impermeable barrier. (This is necessary because melt water will not pond in the firn layer.) The melt water forms a cavity above the

impermeable layer and remains as a liquid pool so long as sufficient heat is added to overcome the heat lost to both the surrounding snow or ice and the atmosphere above the pool of water. After a sufficient reserve capacity of liquid water has been established in the well, pumping can begin to supply potable water to the surface. The size and shape of the ponding cavity depends on the relative rates of melting and water removal by pumping and upon the rate of heat application to the pool:

- With a large heat supply and small pumping rate the cavity can grow laterally rapidly.
- If the pool is over-pumped, the cavity tends to develop rapidly downward (rather than laterally) due to the high temperature of the reservoir water.
- The well will "collapse" (i.e., stop producing liquid water) if the rate of water extraction exceeds the rate of heat input necessary to maintain the liquid pool."

Some examples of Rodwell use over the years includes:

- Camp Fistclench (Greenland, 1957)
- Camp Century (Greenland, 1959 and 1960)
- Camp Tuto (Greenland, 1960)
- South Pole Station (Antarctica, 1972-73 and 1995-present)
- IceCube drilling operation at South Pole (2004 – 2011; seasonal only)

South Pole Station is currently using its *third* Rodwell, the first two having reached a depth at which it was no longer efficient to pump water to the surface.

To develop a Rodwell for the presumed Martian conditions described above (see Figure 12) will require drilling through the overburden layer and far enough into the ice layer so that the resulting cavity will not collapse due to the weight of the overburden. A cased hole through at least the overburden and possibly the upper ice layer will be required so that the cavity can be sealed and pressurized to some TBD level to minimize water sublimation. To assess this option, the following elements must be identified and characterized:

- A drill that can penetrate the overburden layer and emplace a casing;
- A drill that can penetrate the ice layer (may or may not be the same as the overburden drill);
- A concept to melt and recirculate water within the Rodwell "melt pool".

Three broad categories of drills were identified as candidates for the drilling steps just identified.

1. Mechanical drills: This type must be used for the overburden; it can be used for ice. Many designs have been put forward for both coring and drilling on robotic missions.
2. Electrothermal drills: This type can only be used for snow and ice. Many designs exist for both coring and drilling.
3. Hot water drills: This type can only be used for snow and ice. This technology is easily scalable to create larger diameter and/or deeper holes.

Mechanical Drills

A study of available mechanical drill options for future human missions was completed in 2013. Results from this study are documented in "Drilling System Study; Mars Design Reference Architecture 5.0" [26]. This study captured results from a drilling workshop for robotic missions, also completed in 2013 (Planetary Drilling and Sample Acquisition (PDSA) held at the NASA Goddard Space Flight Center in May, 2013).

An example drill representative of the type likely to be suitable for this Martian drilling application is the "Icebreaker" drill under development at the NASA Ames Research Center [27]. This drill has been tested in a representative analog environment: University Valley – a debris covered glacier in the Dry Valleys region of Antarctica (Figure 14). Some of the key characteristics of this drill include:

Figure 14. NASA Ames Research Center's "Icebreaker" Drill (Photo courtesy of B. Glass)

- Drill string diameter 2.54 cm

- Depth to ice varied 20-50 cm.
- Penetration rates of about 40-50 cm/hour, with <100N downward force
- Typical power draw of 50-80W (not counting avionics, communications, etc.).
- Max depth for University Valley test was about 1.4 m, limited by drill string length.

Many factors must be considered when choosing a specific drill design for the Martian drilling application. The previously mentioned studies and reports provide insight into capabilities developed for a variety of situations and facilitate these comparisons of mission needs with capabilities.

Electrothermal drills

Electrothermal drills use resistive heating to melt snow or ice. The most typical use of electrothermal drills in terrestrial applications is to create bore holes or to cut ice cores. These drills represent a relatively simple technology and hardware designs are easily scalable to appropriate diameters (Figure 15). Liquid water created during the drilling process must be pumped out or periodically lifted out (e.g., in a container) before it refreezes. Electrothermal drills are particularly useful in ice close to the pressure melting point (e.g., ice approximately above -10°C), where mechanical drills are at risk from melting and refreezing of the surrounding ice. Under conditions well below freezing, such as the interiors of terrestrial polar ice sheets (or ice conditions likely to be found on Mars), mechanical drills are typically used.

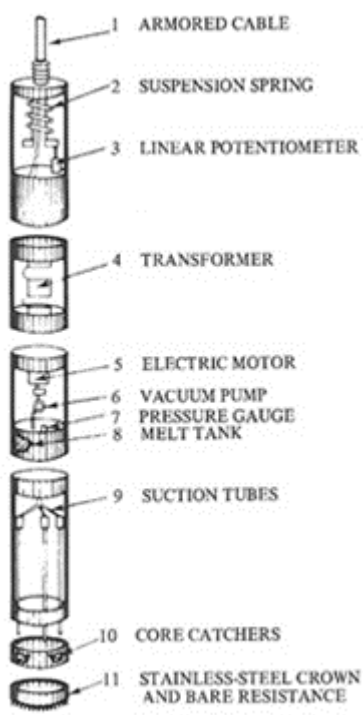

Figure 15. Electrothermal Drill [28]

A closely related drill uses a closed circuit of a hot fluid (typically water or glycol) instead of resistive heating to melt snow or ice. Figure 16 illustrates one possible configuration of this type of drill. This particular device was used to drill a large number of holes for the IceCube Neutrino Observatory at the South Pole [29] and is used to make bore holes instead of cores. It is capable of melting ice at much lower temperatures than the coring drill because its purpose is to simply melt water for removal rather than cutting a core that must be preserved in its solid form.

Figure 16. Hot Fluid Drill Used for the IceCube Neutrino Observatory [29]

Hot Water Drill

This is a relatively simple concept, using a jet of "hot" water to create a hole in snow, firn, or ice. "Hot" is a relative term – the water jet must be hot enough to melt the snow or ice and then stay liquid long enough to be pumped out of the hole. Some amount of "seed water" is needed to start the process, but then melt water is used to drill to depth. This system is scalable to meet the application need. Small devices are used to create holes approximately 2-4 cm in diameter with depths

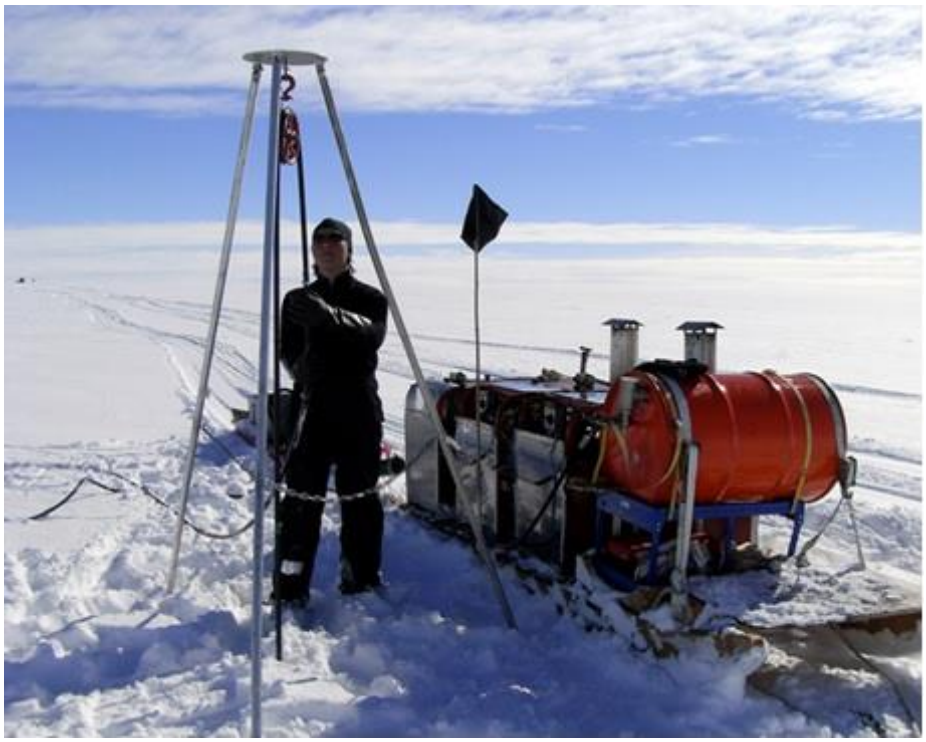

Figure 17. Hot Water Drill Developed by the National Science Foundation [30]

of 20-40 meters. It is frequently used for explosive "shots" used in seismic work (Figure 17) [30]. Large devices are used to create holes as large as approximately 60 cm in diameter with depths to several thousand meters (current deepest bore hole is 3000 m).

The device pictured in Figure 17 was developed by the National Science Foundation primarily for seismic shot holes, but they have also been used for access holes through a thin ice shelf. This device is relatively light weight (1000 kg when ready for use) so that it can be transported by helicopter or light aircraft. It can be operated rapidly: during one 3-month Antarctic season, this device drilled nearly 170 shot holes (25-30 meters depth) and completed four seismic transects.

A "clean hot water drilling" capability has been developed to meet scientific needs when drilling into sub-glacial lakes or other regions where life forms may exist [31]. This is important for Mars drilling applications in that the protocol used is comparable to what will be needed to meet planetary protection concerns (which are still under development).

To summarize the drilling options, there are three general classes of drills – mechanical, electrothermal, and hot water – all of which are in common use for drilling into terrestrial snow and ice. All of these options have specific implementations that have been (relatively easily) scaled to meet a variety of drilling needs. For applications at Mars:

- A mechanical drill is the only option able to drill through the overburden layer;
- If the firn layer is relatively thin (or non-existent), the mechanical drill could continue drilling into the ice to a sufficient depth where Rodwell operations can begin;
- If a thick firn layer or a highly fractured ice layer is encountered under the overburden, a hot water drill can be used to reach depths in the ice where Rodwell operations can begin.

Both of these last two statements indicate that a preliminary survey of the candidate drilling site using ground penetrating radar or test bore holes may be necessary. Electrothermal drills are unlikely to be useful given the anticipated ice temperatures. And finally, terrestrial ice drilling operations have already started to address concerns that are likely to be raised for planetary protection reasons on Mars.

The key elements of a system to access subsurface Martian ice could include several viable drill types to access both the presumed ice layer under a debris layer plus a Rodwell in which liquid water will be formed and pumped out for use. A specific analysis of the drill element of this system will depend on the type(s) of drills selected. This selection of drill type and analysis of the energy costs to create the access hole may depend in part on the details of the site at which it is used. However, once the access hole has been created, development of the Rodwell will likely be similar at any of

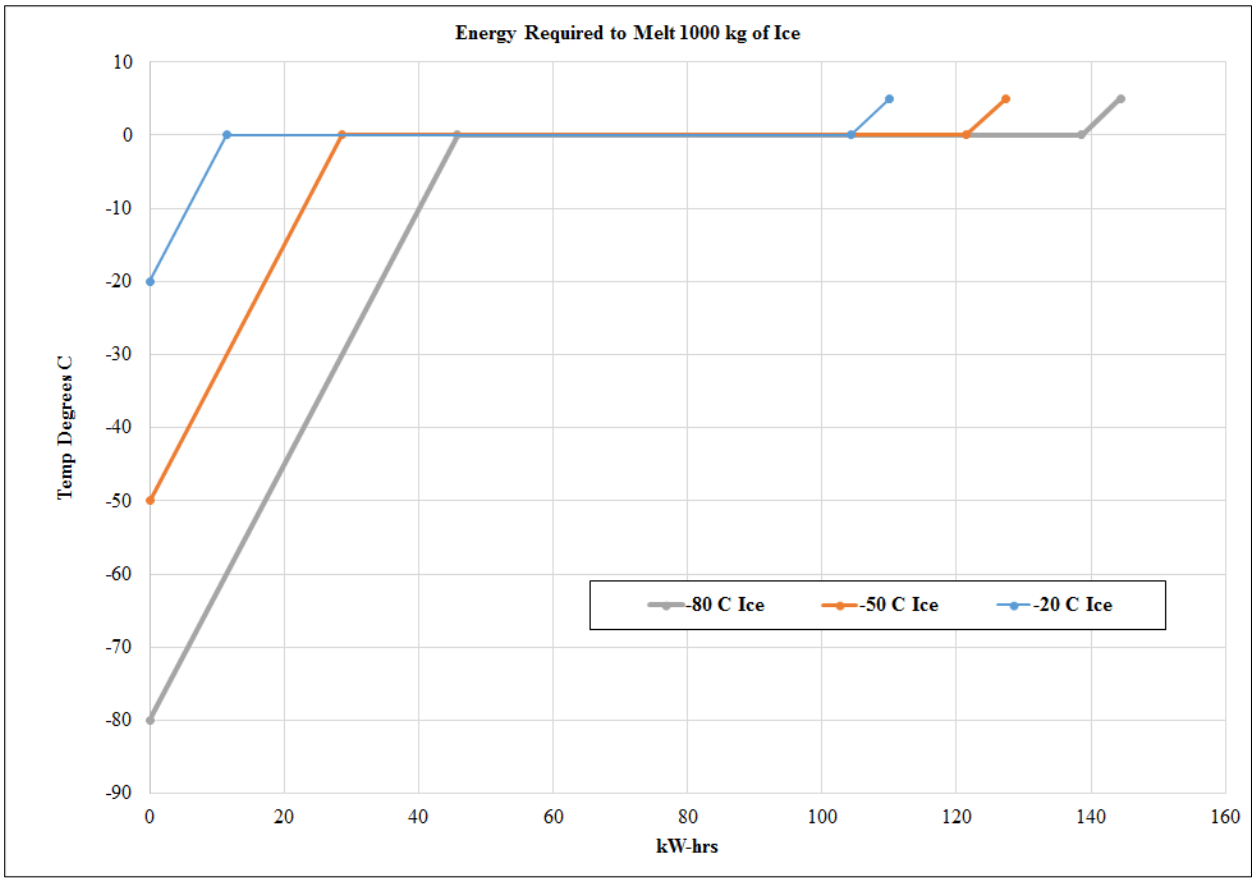

Figure 18. Energy Required to Melt 1000 kg of Ice

the sites selected. As this hole is being drilled it is very probable that the hole must be cased – to prevent debris from falling into the hole and to allow for some to-be-determined level of pressurization to mitigate sublimation of the water and ice in the developing subsurface cavity. The engineers at CRREL have developed computer simulations [23] to allow a preliminary analysis of initial development of a Rodwell as well as operation (i.e., withdrawing water at differing rates and total quantities) of that well.

A complete analysis of the multiple requirements for energy to "mine" water ice must include:

- The energy required to change ice to liquid water (adding sensible heat and latent heat; see Figure 18);
- Once melted, a method to keep water liquid until the desired quantity is pumped out (i.e., feed heat lost to surrounding ice and atmosphere in cavity); and
- An ability to pump liquid to the surface from a liquid water pool that is gradually sinking as water is withdrawn.

The CRREL simulation combines the effects of the first two; pump energy must be determined separately.

These simulation tools were applied to the situation as well as they are currently understood for mid-latitude glacier-like forms at Mars. As a reminder, the current NASA plan for human Mars missions envisions a crew of up to four people on the surface supported by up to 40 kW of electrical power. (There is likely to be additional thermal energy associated with power generation that could be used for this process, but the magnitude and accessibility of this thermal energy is uncertain until some decisions are made about the specific source of electrical power.) These parameters set some of the trade space boundaries for the analysis using the CRREL simulation tools. The discussion in Section 2 of this paper indicated the total amount of water likely needed for the "water rich" scenario(s) as well as the rate at which this water is needed/used:

- Mars Surface Crew (population of four crew without laundry): ~1.6 gallons/person/day (6.0 kg/person/day)
- Mars Surface Crew (population of four crew with laundry): ~3.5 gallons/person/day (13.3 kg/person/day)

Two other terrestrial examples can help to define an even more conservative estimate of water usage rate for this assessment of the Rodwell as a source of potable water:

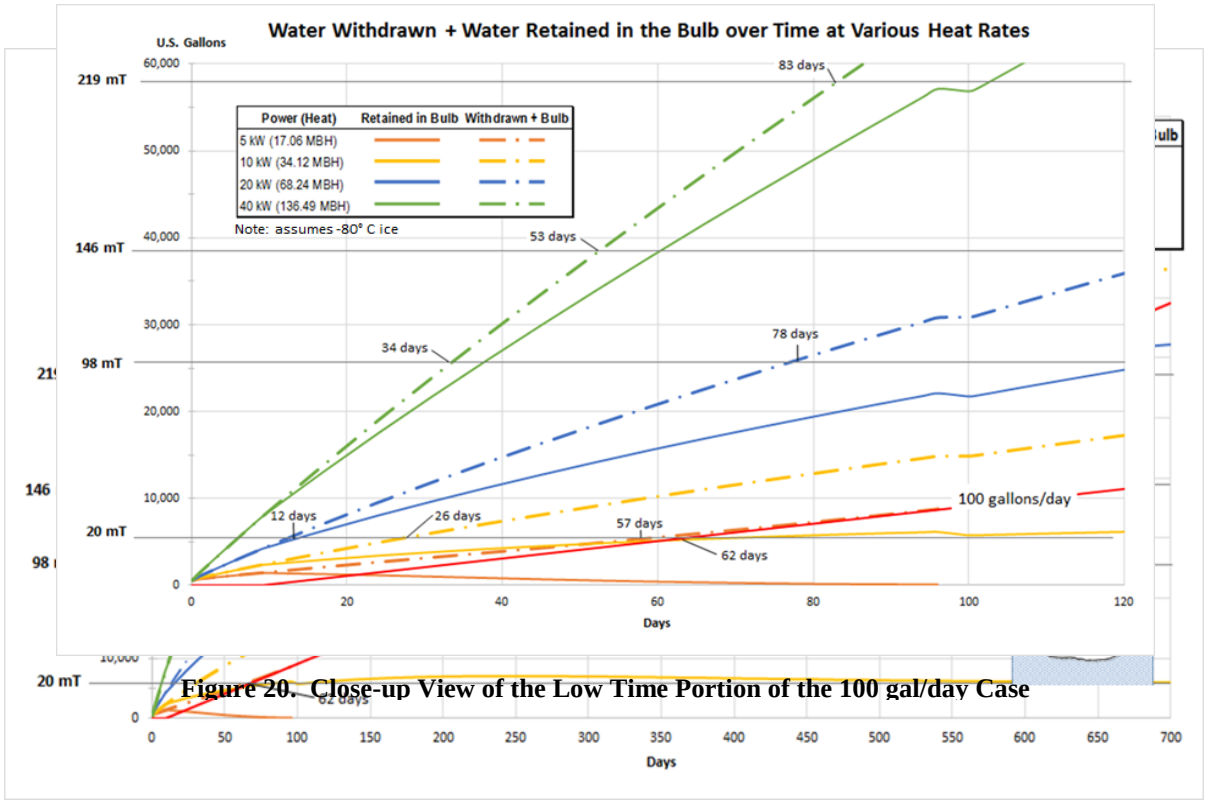

Figure 20. Close-up View of the Low Time Portion of the 100 gal/day Case

Figure 19. Water Withdrawn at 100 Gallons per Day

- NSF's Summit Station, Greenland (winter): ~18 gallons/person/day (68 kg/person/day) based on an average population of four people [32].
- "Typical" U.S. family of four: 100 gallons/person/day (379 kg/person/day). This is both indoor and outdoor usage; 70% indoor and 30% outdoor [33].

Using the 100 gal/person/day rate as a starting point for this assessment, the time evolution of a Martian Rodwell was analyzed using the CRREL simulation tool (modified to reflect current best understanding of Martian surface and subsurface conditions). Figure 19 shows the results of these simulations for a range of power used to form and maintain the subsurface water bulb. (Note: power needed to pump water out of this bulb will depend on the depth below the surface, but will be relatively small compared to the power levels indicated.)

The red diagonal line in Figure 19 indicates the amount of water withdrawn at 100 gallons per day. This diagonal line starts at day 9 of the simulation – the amount of time allowed for initial formation of the liquid water bulb. Horizontal lines indicate some of the key quantities of water described in Section 2. So the intersection of these two lines indicates the number of days needed to withdraw a given amount of water (for example: 53 days are needed to withdraw 20 mT [using 264 US gallons per metric tonne] plus the 9 days to form the bulb = 62 days). The dotted and solid curved lines are the results from the CRREL simulation for different power levels and the 100 gallon/day withdrawal rate. The dotted line indicates the total amount of ice that has been turned into liquid. The solid line indicates the amount of water that remains in the subsurface bulb, and the difference between the dotted and solid lines is the water withdrawn at the 100 gallon/day rate.

Figure 19 was created to show large quantities and durations. The production rates at the low end of the power levels in this simulation are not clearly visible at this scale. Figure 20 provides a close-up view of the lower end of both the quantity and time scale to provide a more clear view of the simulation results for these low power levels.

Some observations regarding the 100 gal/day withdrawal rate

For power levels above approximately 10 kW, liquid water is being created at a much faster rate than it is being withdrawn, resulting in very large subsurface water pools that will not be used (at least for the scenario described in Section 2). A power level of approximately 10 kW generates liquid water at about the rate at which it is being withdrawn. The water pool remains at approximately a constant volume. However, the water pool will gradually sink to lower levels, which will drive the amount of power needed to pump water from these deeper levels, and it will eventually reach a depth at which it will become unreasonable to pump water from these depths (this is the situation at South Pole Station); but it is likely to take quite some time to reach these depths. For power levels below approximately 10 kW, water is being withdrawn faster than it is being melted and the well eventually "collapses." At a power level of approximately 5 kW, the 20 mT projected

need for a single crew (as described in Section 2) could be withdrawn before the well "collapses", but little additional water would be made (this can best be seen in Figure 20).

The "collapse" of the well is a known outcome that can occur under certain conditions. Finding these conditions for the range of power likely available for Mars surface missions and for potential rates of withdrawal is important for understanding how the Rodwell performance varies over different usage scenarios. Figure 21 illustrates the general range of conditions where the Rodwell will be operable and where it is likely to collapse (the "kilopower" items mentioned refer to fission power systems, each copy of which would be sized for 10kW of electrical output, being considered for use on these Mars surface missions).

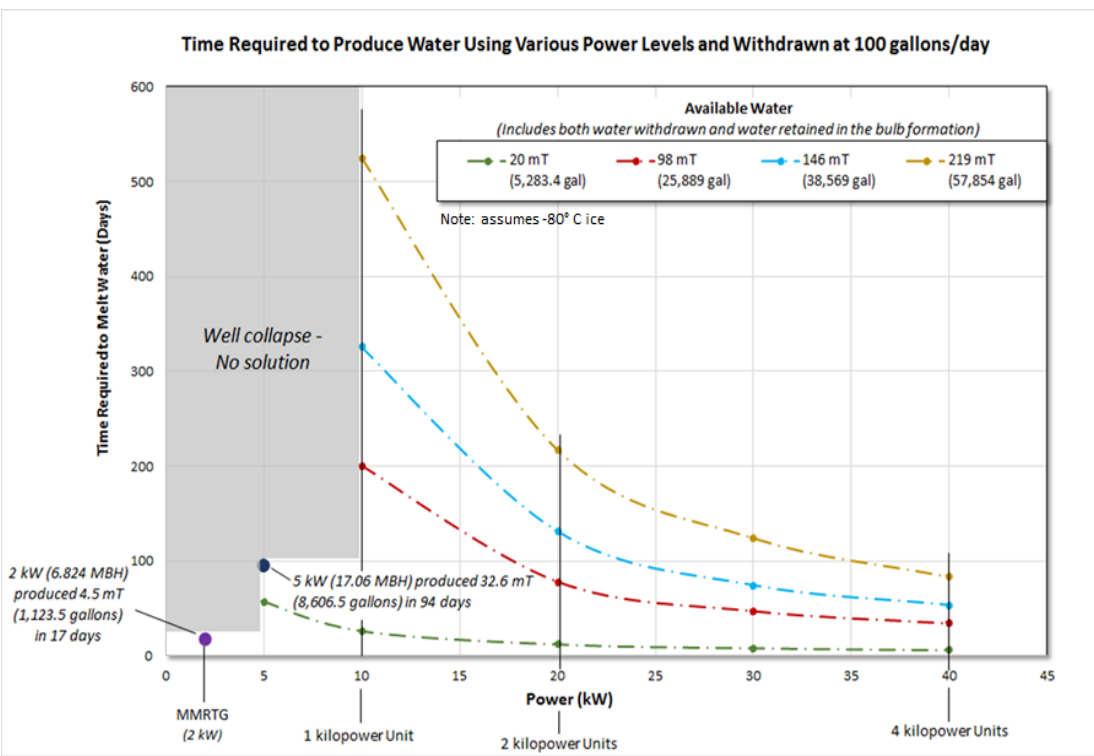

Figure 21. Impact of Power Input for a 100 gal/day Withdrawal Rate

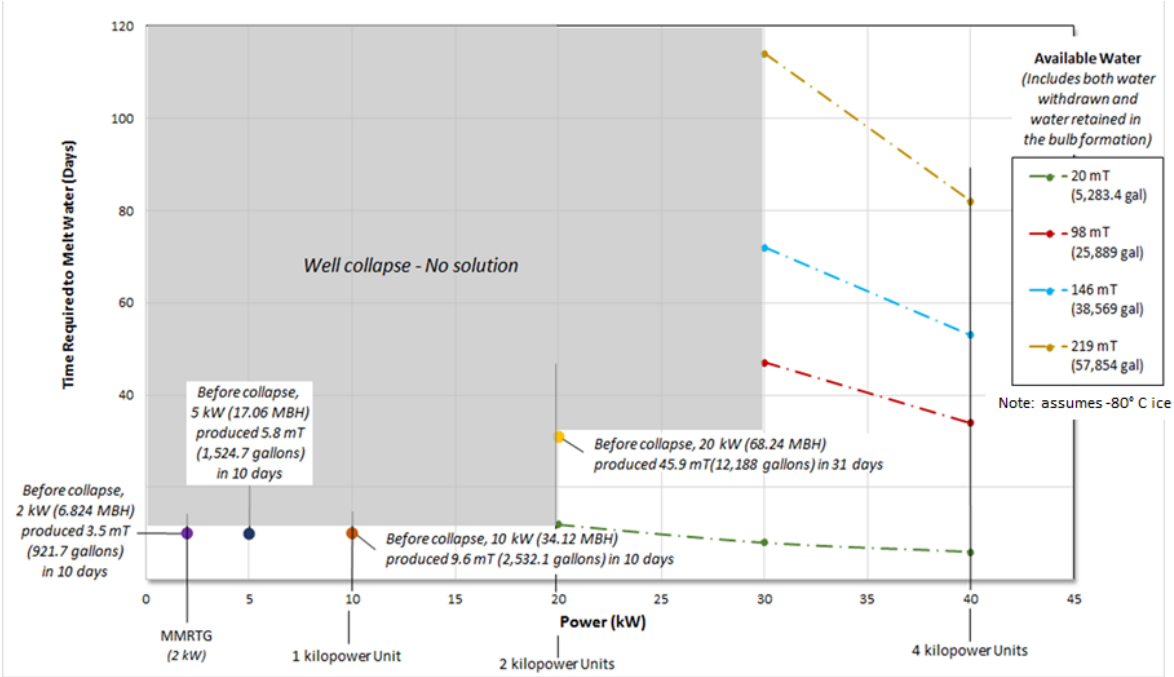

Figure 22. Withdrawal Rate Increased to 500 Gallons per Day

Figure 22 illustrates the consequences of increasing the withdrawal rate to 500 gallons/day (a somewhat arbitrary rate but chosen as significantly larger than rates identified for scenarios described in Section 2). As would be expected, the range of conditions under which the Rodwell would collapse expands significantly, but there is still a range where enough power could be drawn from those systems being considered for a Mars surface mission. Figures 23 and 24 illustrate the consequences of withdrawal rates lower than the 100 gallons/day rate used for the initial assessment of the Rodwell approach to creating and supplying potable water. Again, as would be expected, lower withdrawal rates open the range

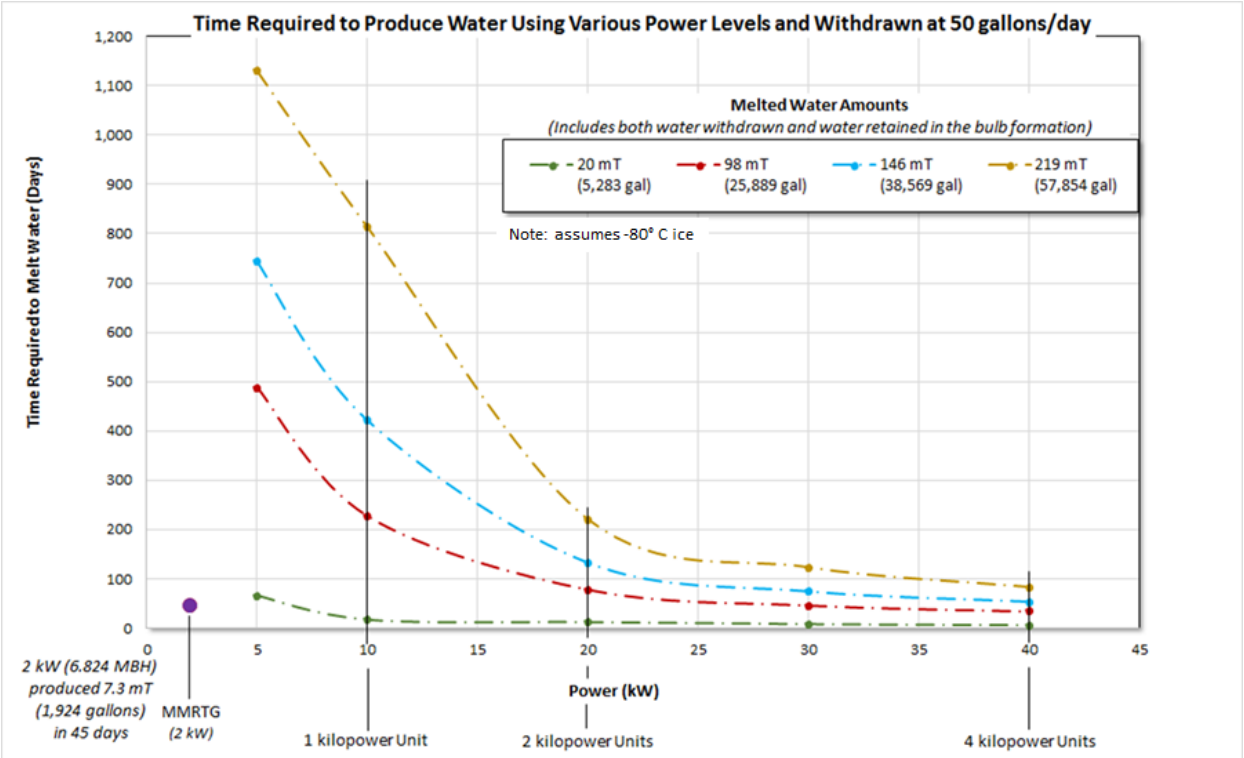

Figure 23. Withdrawal Rate Decreased to 50 Gallons per Day

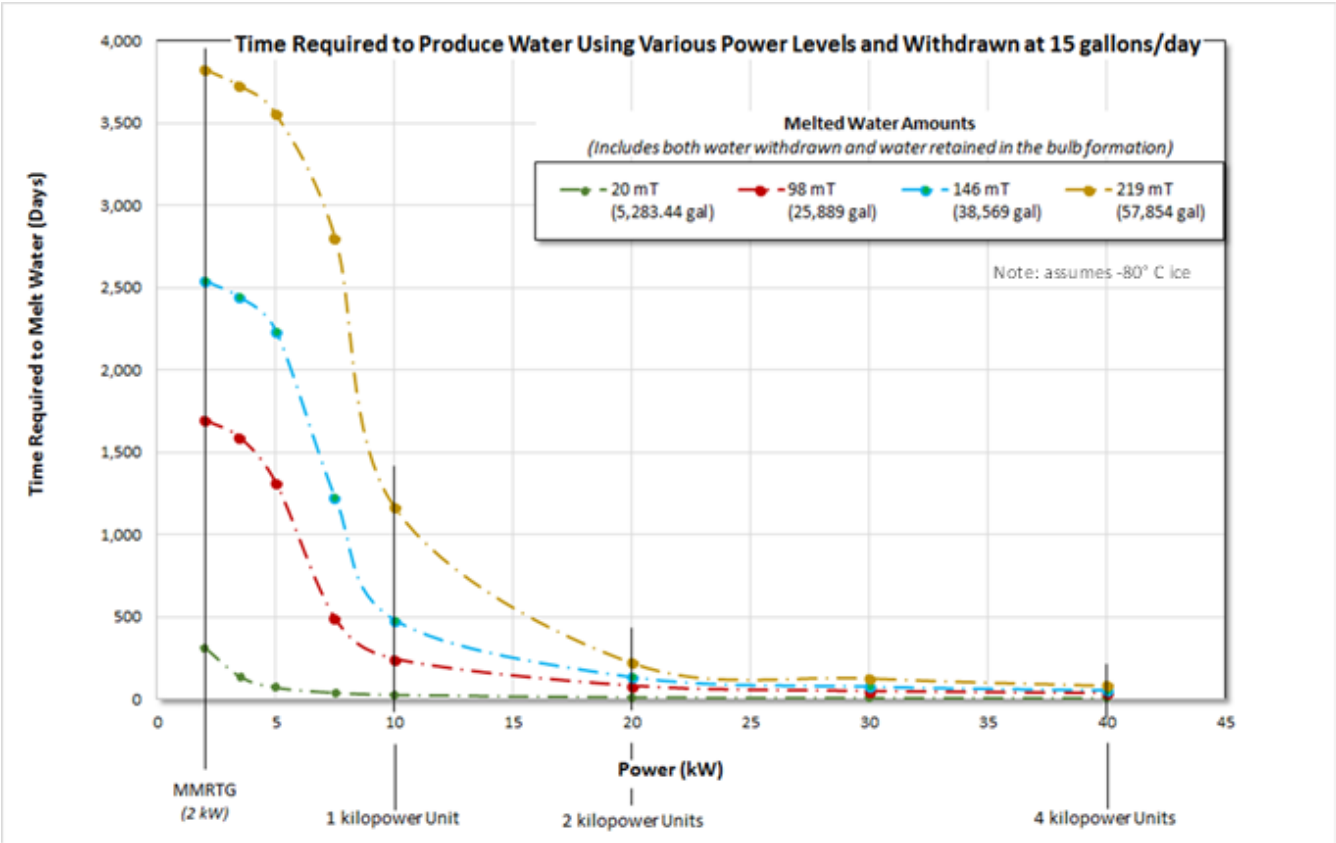

Figure 24. Withdrawal Rate Decreased to 15 Gallons per Day

under which a Rodwell can be successfully operated, including a withdrawal rate at which these simulations indicate a power supply comparable to that used for the Mars Science Laboratory *Curiosity* could support such a well. However, these power levels and withdrawal rates in Figures 23 and 24 are quite low compared to those on which the CRREL simulation was based. This indicates additional testing under similar environmental conditions and system performance characteristics is required to ensure that these simulation results are indicative of likely results on the Martian surface.

5. CONCLUSION

This paper has described studies carried out as part of NASA's Evolvable Mars Campaign effort, examining the impacts of a "water rich" human Mars mission scenario, with a focus on the implications for quantities of water needed to support these crews should a suitable feedstock be identified. For this assessment, those elements of a human Mars mission that would most benefit from the largely unconstrained availability of water were identified and the "typical" quantities of water that would be used by crews under this scenario were estimated. This was followed by a discussion of sources of feedstock material from which water could be extracted based on the most recent available data for the surface of Mars. These feedstock materials tend to fall into two broad categories: regolith/minerals and ices. Two separate assessments were carried out for each of these feedstock types. This paper discussed the assessment of ice as a feedstock; a separate paper discusses the results for regolith/minerals as a feedstock. One particular terrestrial approach for generating and storing liquid water in the Polar Regions – the Rodriguez Well – was reviewed and results from a quantitative analysis were compared with the previously described needs of the "water rich" human mission scenario. This was followed by a summary of technologies currently in use in terrestrial Polar Regions that could be applied directly to, or at least point to, a system for use on Mars. The paper concludes with findings and observations regarding approaches for generating water from ice on Mars. The terrestrial technologies for accessing subsurface deposits of ice indicate that there are several viable options available, many of which have been or could be scaled to the characteristics appropriate for a Mars surface application. While additional testing work is needed to confirm that simulation results are representative of what the actual Martian environment and appropriately scaled technologies will produce, simulation results of the Rodriguez Well described in this paper indicate that this approach is likely a viable approach that could be considered for use at Mars.

REFERENCES

[1] Di Achille, Gaetano; Hynek, Brian M., "Ancient ocean on Mars supported by global distribution of deltas and valleys," 2010, Nature Geoscience. 3 (7): 459–463, DOI:10.1038/ngeo891.

[2] Beaty, D.W., R.P. Mueller, Bussey, D.B., Davis, R.M., Hays, L.E., Hoffman, S.J., Zbinden, E., "Some Strategic Considerations Related to the Potential Use of Water Resource Deposits on Mars by Future Human Explorers," ASCE Earth and Space Conference, Orlando, FL, April 11-15, 2016.

[3] Kleinhenz, J.E. and Paz, A. An ISRU Propellant Production System to Fully Fuel a Mars Ascent Vehicle. AIAA SciTech Forum 2017. American Institute for Aeronautics and Astronautics. AIAA-2017-0423.

[4] Craig, D.A., Troutman, P., Herrmann, N. B., "Pioneering Space Through an Evolvable Mars Campaign," AIAA 2015-4409, AIAA 2015 Conference and Exposition, Pasadena, CA, Aug. 31 – Sept. 2, 2015.

[5] Zubrin, Robert M., Baker, David A., Gwynne, Owen, "Mars Direct: A Simple, Robust, and Cost Effective Architecture for the Space Exploration Initiative", 29th AIAA Aerospace Sciences Meeting, Reno, NV, Jan. 7-10, 1991.

[6] Drake, B. G., (ed.), Human Exploration of Mars Design Reference Architecture 5.0, NASA-SP-2009-566, July 2009.

[7] Polsgrove, T., Chapman, J., Sutherlin, S., Taylor, B., Fabisinski, L., Collins, T., Ciancolo, A. D., Samareh, J., Robertson, E., Studak, W., Vitalpur, S., Lee, A.Y., Rakow, G., "Human Mars Lander Design for NASA's Evolvable Mars Campaign," 37th IEEE Aerospace Conference, Big Sky, MT, March 5-12, 2016.

[8] Polsgrove, T., Private Communication, 2016.

[9] Goodlyff, C., Private Communication, 2016.

[10] Slaba, T.C., Mertins, C.J., Blattnig, S.R., "Radiation Shielding Optimization on Mars," NASA Technical Publication 2013-217983, 2013.

[11] Eagle Engineering, Inc., "Lunar Surface Transportation Systems Conceptual Design," NASA Contract Number NAS9-17878, 1988.

[12] Sanders, G., Private Communication, 2016.

[13] Carr, M.H., Head, J.W., "Martian Unbound Water Inventories: Changes with Time," Eighth International Conference on Mars, 2014.

[14] Carter, J., Poulet, F., Bibring, J.P., Mangold, M., Murchie, S., "Hydrous Minerals on Mars as seen by the CRISM and OMEGA Imaging Spectrometers: Updated Global View," Journal of Geophysical Research: Planets Vol. 118, 831-858, 2013.

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

[16] McEwan, A.S., Dundas, C.M., Mattson, S.S., Toigo, A.D., Ojha, L., Wray, J.J., Chojnacki, M., Byrne, S., Murchie, S.L., Thomas, N., "Recurring Slope Lineae in Equatorial Regions of Mars," Nature Geoscience 7, 53-58, 2014.

[17] Clifford, S.M., Lasue, J., Heggy, E., Boisson, J., McGovern, P., Max, M.D., "Depth of Martian Cryosphere: Revised Estimates and Implications for the Existence and Detection of Subpermafrost Groundwater," Journal of Geophysical Research, Vol. 115, 2010.

[18] Dickson, J.L., Head, J.W., Fassett, C.I, "Patterns of accumulation of ice in the mid-latitudes of Mars during the Amazonian," Icarus 219, 723-732, 2012.

[19] Holt, J.W., Safaeinili, A., Plaut, J.J., Head, J.W., Phillips, R.S., Seu, R., Kempf, S.D., Choudhary, P., Young, D.A., Putzig, N.E., BiccaRi, D., Gim, Y., "Radar Sounding Evidence for Buried Glaciers in the Southern Mid-Latitudes of Mars," Science 322, 1235-1238, 2008.

[20] Dundas, C.M., Byrne, S., McEwan, A.S., Mellon, M.T., Megan, R.K., Daubar, I.J., Saper, L., "HiRISE observations of new impact craters exposing Martian ground ice," Journal of Geophysical Research: Planets, 10.1002/2013JE004482, 2014.

[21] Feldman, W.C., Prettyman, T.H., Maurice, S., Plaut, J.J., Bish, D.L., Vaniman, D.T., Mellon, M.T., Metzger, A.E., Squyers, S.W., Karunatillake, S., Boynton, W.V., Elphic, R.C., Funsten, H.O., Lawrence, D.J., Tokar, R.L., "The Global Distribution of Near-Surface Hydrogen on Mars," Journal of Geophysical Research: Planets, Vol. 109, 2004.

[22] Plaut, J., A. Safaeinili, J. Holt, R. Phillips, J. Head, J., R. Seu, N. Putzig, A. Frigeri (2009) "Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars," *Geophysical Research Letters*, Vol. 36, L02203, doi:10.1029/2008GL036379.

[23] Lunardini, V. J. and J. Rand (1995), Thermal Design of an Antarctic Water Well, US Army Cold Regions Research and Engineering Laboratory, Special Report 95-10.

[24] Schmitt, R.P., Rodriguez, R., "Glacier Water Supply System," Military Engineer, 52(349), 1960.

[25] Russell, F.L. (1965) Water Production in a Polar Ice Cap by Utilization of Waste Engine Heat, US Army Cold Regions Research and Engineering Laboratory, Technical Report 168.

[26] Rucker, Michelle, "Drilling System Study; Mars Design Reference Architecture 5.0," JSC 66635, September 30, 2013.

[27] Glass, B., McKay, C., Thompson, S., Zacny, K., "Automated Mars Drilling for 'Icebreaker'," IEEE Aerospace Conference paper number 1800, Big Sky, MT, 2010.

[28] Gillet, F., Donnou, D., Ricou, G., "A New Electrothermal Drill for Coring in Ice," Laboratoire de Glaciologie CNRS, Grenoble, France, http://icedrill.org/Documents/Download.pm?DOCUMENT_ID=406.

[29] Benson, T., Cherwinka, J., Duvernois, M., Elcheikh, A., Feyzi, F., Greenler, L., Haugen, J., Karle, A., Mulligan, M., R. Paulos, R., "IceCube Enhanced Hot Water Drill Functional Description", Annals of Glaciology 55(68) 105-114, DOI: 10.3189/2014AoG68A032, 2014.

[30] United States Ice Drilling Program Office (US IDPO) Portable Hot Water Drill, http://icedrill.org/equipment/portable-hot-water-drills.shtml, accessed August 23, 2016.

[31] Makinson, K., D. Pearce, D.A. Hodgson, M.J. Bentley, A.M. Smith, M. Tranter, M. Rose, N. Ross, M. Mowlem, J. Parnell, and M.J. Siegert (2015) "Clean subglacial access: prospects for future deep hot-water drilling," *Phil. Trans. R. Soc. A* 2016 374 20140304; DOI: 10.1098/rsta.2014.0304. Published 14 December 2015.

[32] Haehnel, Knuth, "Potable water supply feasibility study for Summit Station, Greenland" (unpublished).

[33] U.S. EPA; https://www3.epa.gov/watersense/pubs/indoor.html

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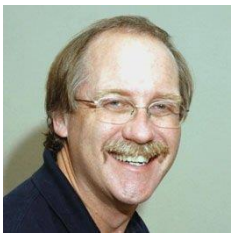

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