ACQUISITION OF WATER FROM WESTERN UTOPIA PLANITIA SUBSURFACE: THEORETICAL ANALYSIS OF SAMPLING AND PRODUCTION TECHNOLOGIES

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ABSTRACT

Mid-latitude shallow ice deposits are an abundant feature in Utopia Planitia confirmed by SHARAD georadar. Thick ice-rich subsurface makes establishing a temporal or permanent human presence on Mars more likely because water is within reach of existing sampling technologies and conceptual production mechanisms. Although such technologies have been studied, a comparison method is needed to quantify their projected results.

Herein the paper presents geological and thermal model of icy regolith created to measure water sampling and production efficiency. Various regolith and volatile sampling systems are standardized and compared using efficiency factor ε. For production purposes, a CFD heat transfer is studied for down-hole and beamed energy sources, seeking for an effective heating radius for ice sublimation. Paper concludes with the optimal architecture for Martian subsurface water acquisition.

Analysis is the key part of MSc thesis defended this year by the author (Wasilewski, 2017).

INTRODUCTION

Martian water inventory, both past and present is a problem discussed broadly and thoroughly since the beginning of exploration of Mars [for instance (Lammer, et al., 2003), (Lasue, et al., 2013), (Carr & Head, 2015)] and outlines an interdisciplinary field of studies in geology, climatology and mineralogy with extreme technological challenges. It is certain that current Martian environment is different from ancient conditions, which allowed (at least temporarily) liquid water to exist abundantly on the surface of the planet with most evidence shown in existence of extensive valley networks (Luo, et al., 2017), outflow channels (Carr & Head, 2010), possible seas and oceans (Boyce, et al., 2005) and conditions for liquid water flow in general (Adeli, 2016).

The main problem for water on Mars concerns environmental conditions and their decay towards current state implying that the planet during its early history might have been 'warm and wet' or 'cold and icy with temporary wet periods' (Wordsworth, 2016), where current research tries to answer those questions in detail with climate and water cycle studies [(Wordsworth, et al., 2015), (Turbet, et al., 2017), (Weiss & Head, 2017)].

Today however, with cold and icy conditions below water triple point, Martian water resources are a domain of solid and gas phases as well as their interactions, which result in: (1) water vapour in the atmosphere and pore space, (2) surface ice deposits (including polar deposits and surface snow and ice), (3) shallow sequestrated ice (including LDM, LDA, LVF and CCF formations), (4) ice-filled cryosphere (permafrost), (5) potential groundwater below cryosphere and (6) hydrated minerals.

Under current conditions, water resources are strongly connected with so-called regolith breathing, i.e. diffusive interactions between regolith ice and Martian atmosphere (Hudson, 2008). This infers that Martian water ice may be (and at large is) stable in high latitudes above 55□ (Schroghoffer & Forget, 2012) and at mid-latitude poleward facing slopes (Mellon & Phillips, 2001). These conditions are dynamic and strongly obliquity-driven and may change significantly over time (Head, et al., 2009). Such distribution of stable ice however means that resources are less accessible for research and acquisition during early and critical phases of human exploration of Mars, as high-latitude and polar missions invoke higher mission risks that low-latitude ones.

Recently more attention is being focused on low and mid-latitude water locations, as new and updated research finds more evidence for that state (Stuurman, et al., 2016), (Wilson, et al., 2017). Water ice presence in such conditions inherently implies its disequilibrium state with the atmosphere, however if shallow it makes a case for establishment of temporal of permanent human presence in such locations thanks to In-Situ Resource Utilization (ISRU).

ICE IN WESTERN UTOPIA

Utopia Planitia is the biggest plain and impact basin on Mars and is located between 13°-73° N and 72°-165° E (planetocentric). Its main characteristics to be considered are a plethora of periglacial features (Séjourné, et al., 2012), primarily polygonal grounds and scalloped terrains that imply existence of ice-filled cryosphere. Utopia lies within Vastitas Borealis, which had been created from Hesperian outflow channels sediments and later on has been altered periglacially (Costard, et al., 2016). Its geomorphological features have analog forms on Earth, which imply their fluvial, glacial, periglacial and aeolian alterations. Western part of the region is located around ice equilibrium zone, where ice may be stable in cryosphere at 1 metre depth (Mellon & Jakosky, 1993), meaning that subsurface may be ice filled in forms of pore ice and excess ice or even pure ice.

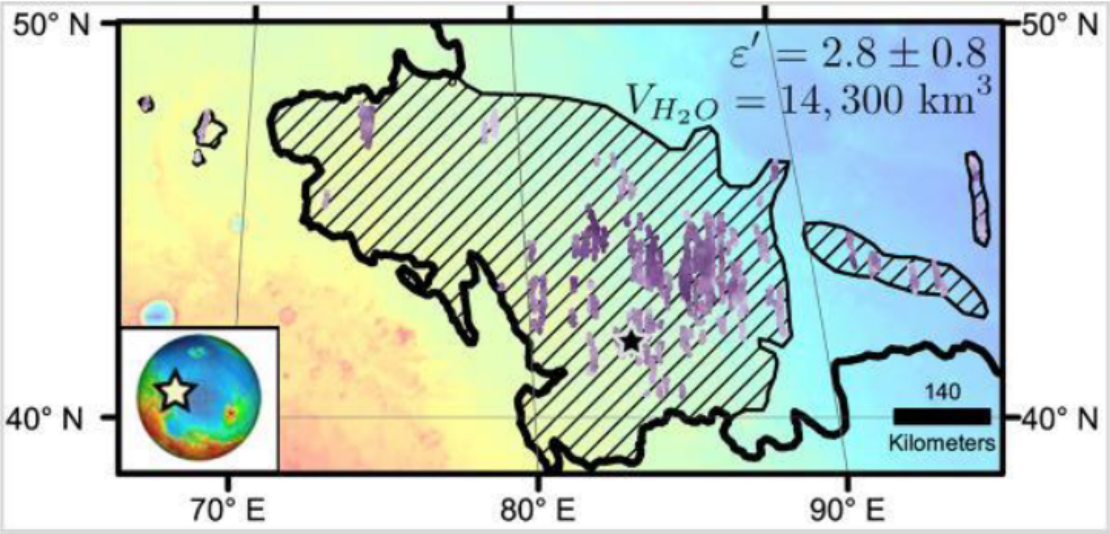

Figure 1. Western Utopia Planitia. Extent of subsurface water ice evaluated by SHARAD mapping. Dark violet stands for ice-rich formation spanning up to 170 metres below the surface, while brighter colours stand for extent to 10 metres depth.

Research done by Stuurman and others thanks to SHARAD data showed that ice deposits are indeed significant in Western Utopia and ice-rich regolith may extend from 10 to 170 metres of depth. Those findings were a substantial foundation for an ISRU-wise analysis done in this paper. Here, a cryo-geological model of shallow subsurface have been created, which utilizes general physical-chemical characteristics of JSC Mars-1 analog regolith (Allen, et al., 1998), porosity decrease function (Hanna & Phillips, 2005), regolith thermal parameters functions [(Piqueux & Christensen, 2011) , (Siegler, et al., 2012)] and ice concentration changes accordingly to boundary conditions. This allowed to create a theoretical subsurface water ice reservoir, which may be further analysed with respect to recoverable water resources.

Ice concentration growth proceeds logarithmically from 2% weighted level at the surface (WEH) towards 60% volumetric (lower limit of SHARAD mapping at 10 metres depth), with full pore space filling 1 metre below the surface (ice stability level). Afterwards, ice deposits mainly grow as excess ice, removing regolith from rock matrix.

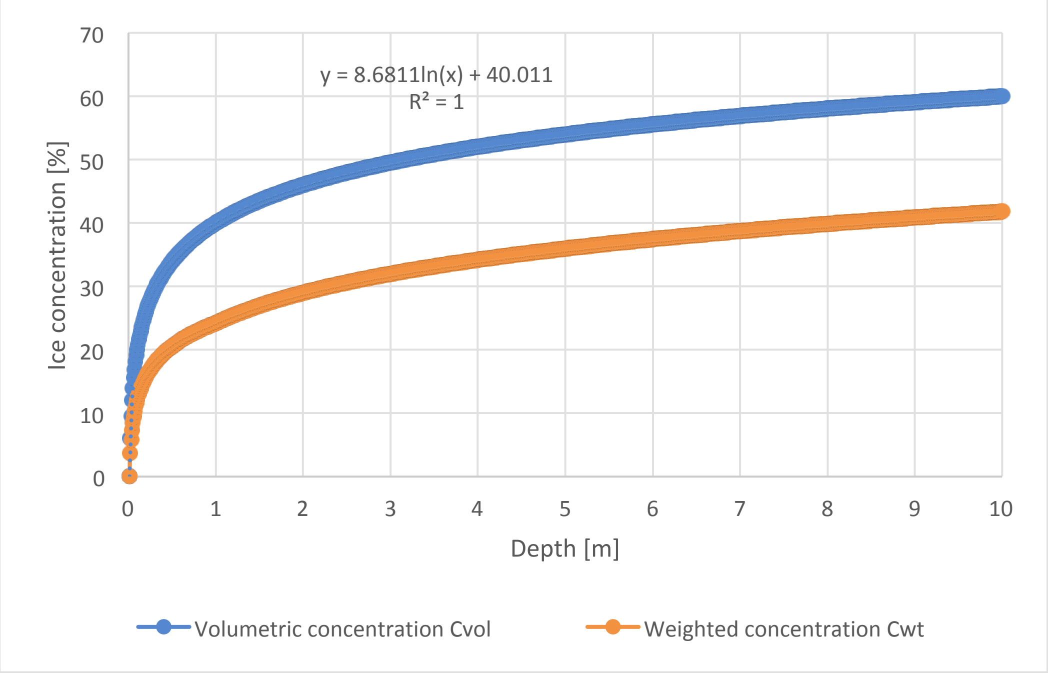

Figure 2. Ice concentration modelling in regolith.

Regolith thermal parameters were evaluated afterwards as a function of ice concentration. Both geological and thermal properties were able to create model of first 10 metres of Utopian subsurface that was used as an input for further ISRU study.

SAMPLING WATER ICE ON MARS

Technological development of planetary excavation and drilling devices, which proceeds since first Lunar surface missions, resulted in many mature systems (Bar-Cohen & Zacny, 2009). Thanks to research and development activity in this field, as well as experience and inspirations from human activity on Earth (for instance in oil & gas industry), drilling and sampling devices have been used onboard of robotic and manned space missions and allowed us to understand planetary environments better. Systems that so far have been used or are developed mainly utilize dry penetration with rotary, percussive or rotary-percussive action. Most common devices are auger-based corers or deeply-fluted augers, which allow to clean-up borehole in dry conditions and transport cuttings and cores to the surface. Such devices may have a borehole assembly (BHA) on a drill string or wireline. Water sampling devices have in general similar design to drilling and regolith sampling devices but they utilize additional core or cuttings heating system in order to change water phase (to liquid or vapour).

Table 1. Extraterrestrial volatiles sampling devices general types (Zacny, et al., 2015a), (Zacny, et al., 2016a)

	Sniffer	**Auger-corer**	**Deeply-fluted auger**
Water sampling performance	Low	Very high	High
Complexity	Low	Low	Medium

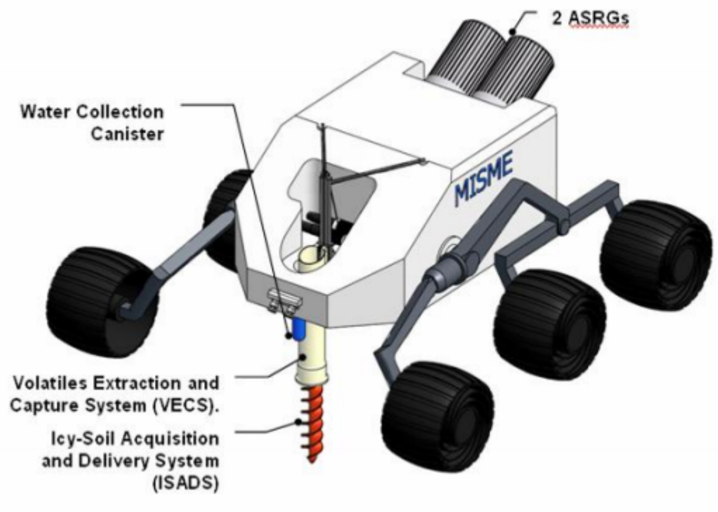

Figure 3. Honeybee's MISWE concept (Zacny, et al., 2012).

Herein, sampling efficiencies (ε) of various high technology readiness level devices (TRL>5) have been studied. That analysis makes it easier to understand and pursue a system that samples highest volume of water while using lowest amount of power and mass, which are the most important constraints in space missions. Out of 18 different devices and their iterations, sampling efficiencies could be evaluated according to technical parameters of such systems that could be utilized in an environment set by geological model created earlier.

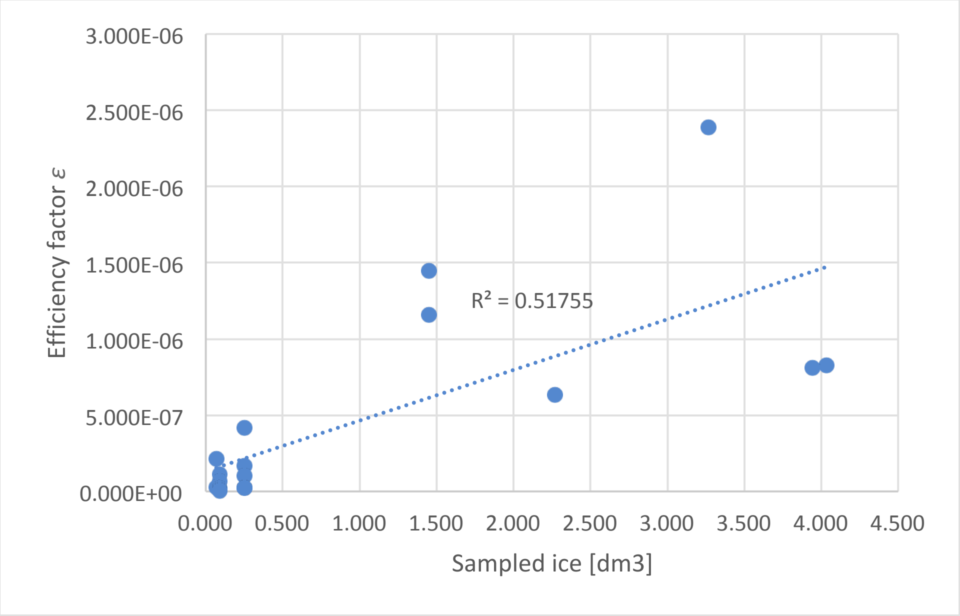

Figure 4. Sampling efficiencies and potential sampled ice volume in a set of analyzed devices.

The most crucial factors in device efficiency are diameter of created sample and maximum reach in depth. Systems that acquire small regolith samples acquire smaller volumes of ice and obtain lowest efficiencies, while bigger devices generally have higher sampling efficiency. The former are on the other hand lighter but usually have a 1 meter-class drilling system. That is why the highest-ranking device is one that has pros of both small and big devices – a lightweight, mid-diameter wireline deep drill – Auto-Gopher developed by Honeybee Robotics. This system could potentially sample around 1.5 litres of ice per every drilling in the proposed Utopian geology.

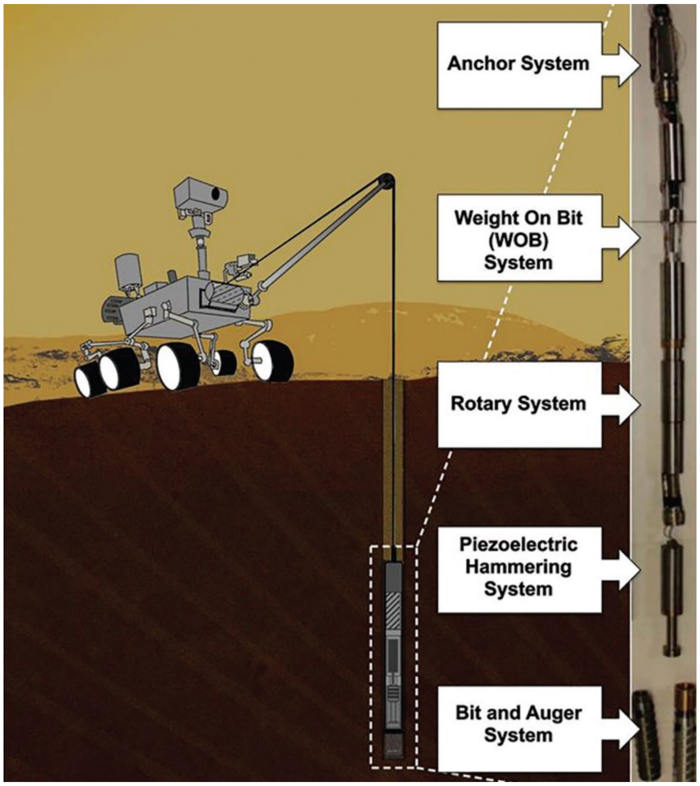

Figure 5. Schematics of Auto-Gopher (left) and the actual device (right).

WATER PRODUCTION

Water sampling allows to acquire enough water for research but not enough to utilize for mission consumables, fuel production or construction. That is why different approaches are needed in that field. Drilling however leads to completion of borehole that may be utilized as water well in which, given that special equipment would be used, liquid water of water vapour may be produced in a way closely resembling oil & gas operations on Earth. The main problem lies within water phase change and thus in suppling enough energy to icy cryosphere in order to make it melt or sublime.

There are 3 approaches to that problem: (1) scaled up sampling devices, (2) beamed energy systems and (3) downhole energy systems. The ultimate argument in favour of the first is that it loses least amount of energy because the whole process is completed in a closed environment. However, it requires multiple boreholes to be drilled, which increases chances of malfunction. The other two lose a certain amount of energy to the subsurface but are able to reach a higher volume of ice in a single heating. In these methods it is also harder to obtain a stable phase change.

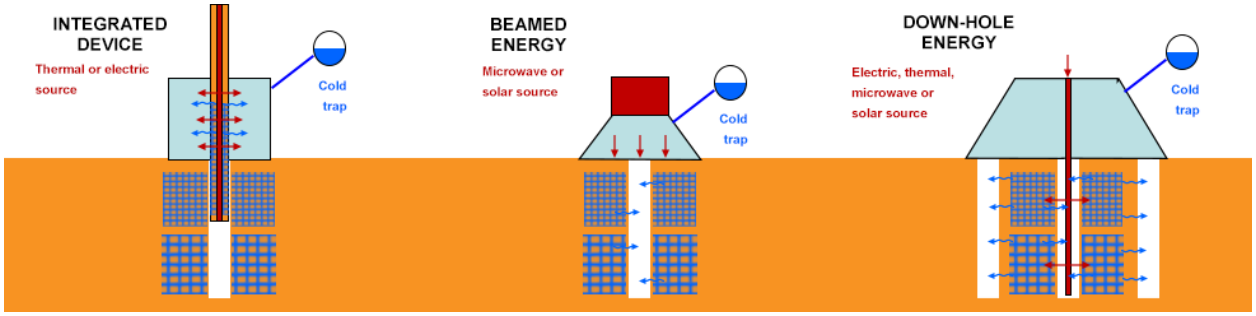

Figure 6. Modes of planetary water production.

So far, production technologies have been mainly studied with no actual device development. This particular field however experiences patenting cases, which leads to a widespread potential for engineering studies.

Skipping actual system development and design it is possible to evaluate beamed energy and downhole energy methods' potential in a way of heat transfers within the regolith, with a fixed temperature on the surface or in a well that could be applied. For that matter, geological-thermal model proposed earlier have been imported to COMSOL 5.1 modelling tool to study conductive heat transfers when using both heating methods.

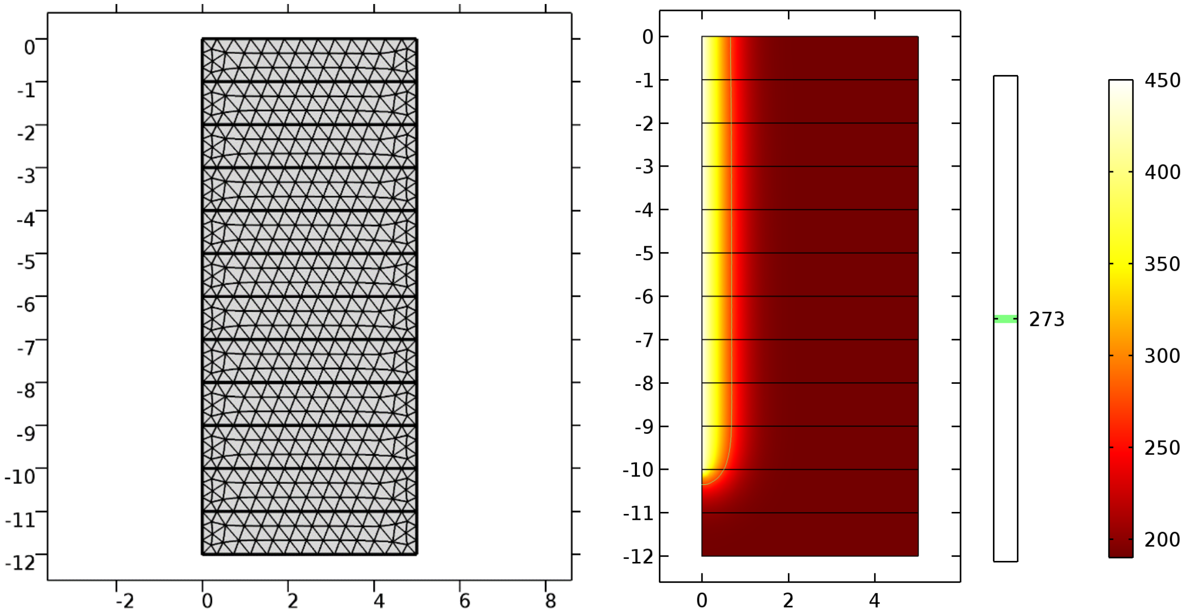

Figure 7. Heat transfers model mesh (left) and heating results (right), where 450 K source have been applied with a downhole method. The outline 273 K isotherm stands for effective heating radius (r_e).

Heating modes have been studied by applying fixed temperature (for an overall period of 7 days) from a range of 300 to 450 K for downhole and 800 to 1000 K for beamed energy sources, where downhole was applied on full borehole wall (0,0 to 0,-10), while beamed was applied in a first layer (0,0 to 0,-1) resembling single point focus. The only investigated factor for volumetric resources estimation was an effective heating radius r_e, which stands for a 273 K isotherm. With that value it is implied that all of water ice to this radius have already sublimed during heating and may be produced diffusively through well equipment.

Effective heating radius allows to evaluate water-in-place (WIP), which stands for volume of liquid water in normal conditions if all water vapour would be produced. Estimated Ultimate Recovery is WIP reduced by recovery factor (RF), that would be dependent on many factors (both geological and technological).

As seen in Table 2, both methods allow to produce around 3 cubic metres of liquid water per single heating. If both modes may produce similar volume of water, choice of the most optimal one comes from different problems, for instance do we want to utilize deep 10 metre boreholes for research and production or is it more practical to use many shallower (<2 metre) ones? Here it has been established that need of geological research and data acquisition would result in deep boreholes being completed on Mars, thus downhole energy sources should be pursued.

Table 2. Volumetric estimation of water resources

		Downhole energy				**Beamed energy**	
		300 K	**350 K**	**400 K**	**450 K**	**800 K**	**1000 K**
Effective heating radius (Re)	**[m]**	0.2	0.4	0.6	0.7	1.6 1.4	1.7 1.5
Water in place (WIP)	**[m3]**	1.518	4.250	8.197	10.626	5.377	6.482
Estimated Ultimate Recovery (EUR)	**[m3]**	0.759	2.125	4.098	5.313	2.689	3.241
Average EUR	**[m3]**	**3.074**				**2.965**	

ISRU ARCHITECTURE

The proposed ISRU architecture for Martian water acquisition is based on wireline solution, which utilizes both wireline deep drilling and regolith sampling, as outlined with Auto-Gopher, and wireline downhole heating.

Drilling device's main role is to complete a borehole, collect and log scientific data and evaluate potential for water production through determination of ice resources volumes. Surface equipment would be responsible for samples handling, measurements and thermal treatment of icy regolith.

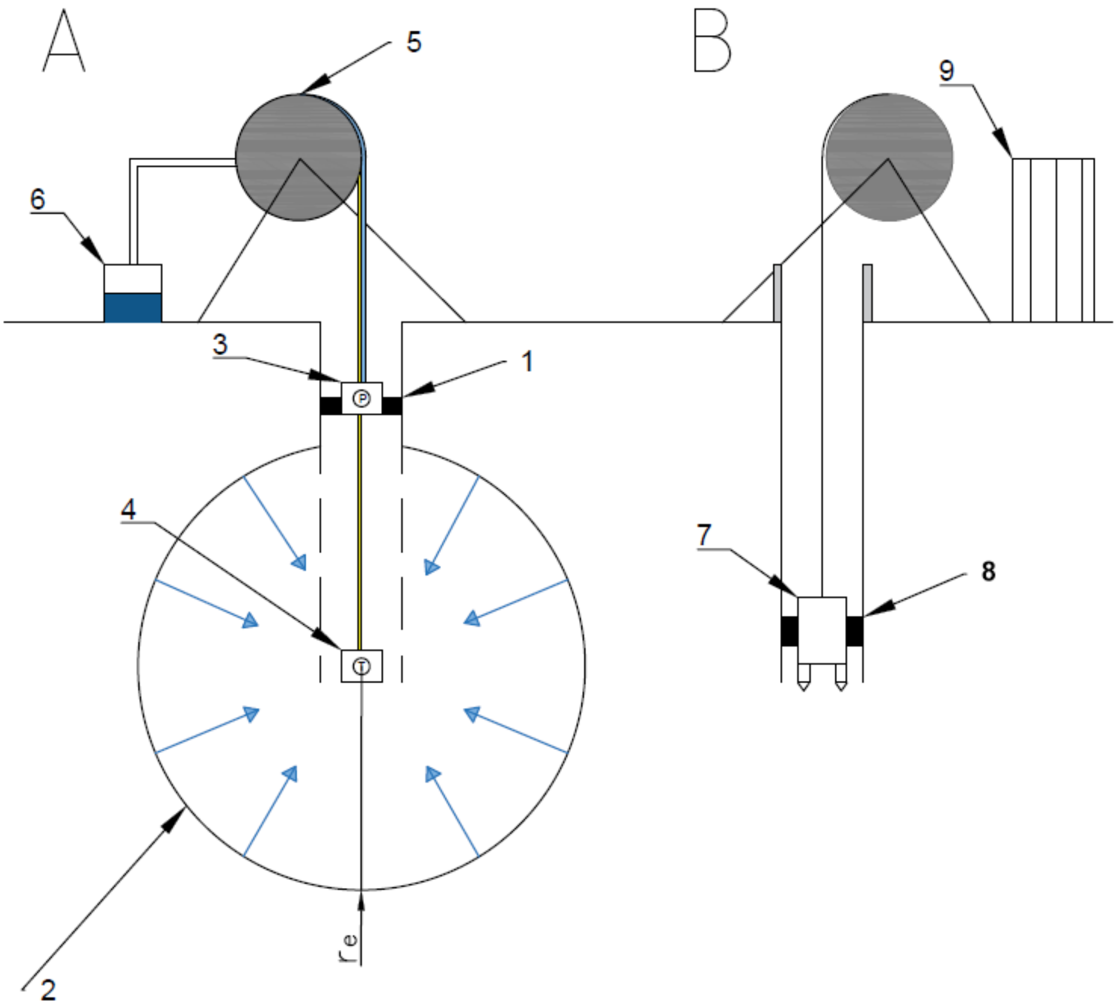

Figure 8. Wireline ISRU architecture for Martian water acquisition. (A) production device, (B) drilling and sampling device. 1 – seal, 2 – ice-vapour contact, 3 – pump or valve mechanism, 4 – heat source, 5 -wireline on pulley, 6- cold trap, 7 – auger-corer, 8 – anchor, 9 – handling and processing module.

After borehole completion and positive evaluation of resources, an additional heating and pumping mechanism would have to be applied inside a well. Such equipment might consist of a heat source (for instance RTG or magnetron), borehole seal and pumping or valve mechanism responsible for pressure control. Heat source would operate for a specific period of time in heating intervals set for a specific target depth, sublimating ice resources around the well and causing pressure increase and pressure and vapour concentration gradient between well surroundings and acquisition equipment. Consequently, water vapour would be transported upward to the condensation tank (or cold trap), that would store water before further utilization.

Important problem to solve is to stabilize borehole walls, especially in context of resources depletion and consequential mechanical instability of formation. Thus casing would have to be applied and preferably it should be produced in situ (by 3D printing or using special adhesives). Thanks to water production mode set to extract water vapour, basic water treatment is already in place, however further treatment may have to be applied, depending on target utilization product.

Crucial part of water production on Mars is development of phase change process that would guarantee phase stability accordingly to water phase diagram. In this architecture it is important to cause ice sublimation and stabilization of water vapour both around the borehole and during collection.

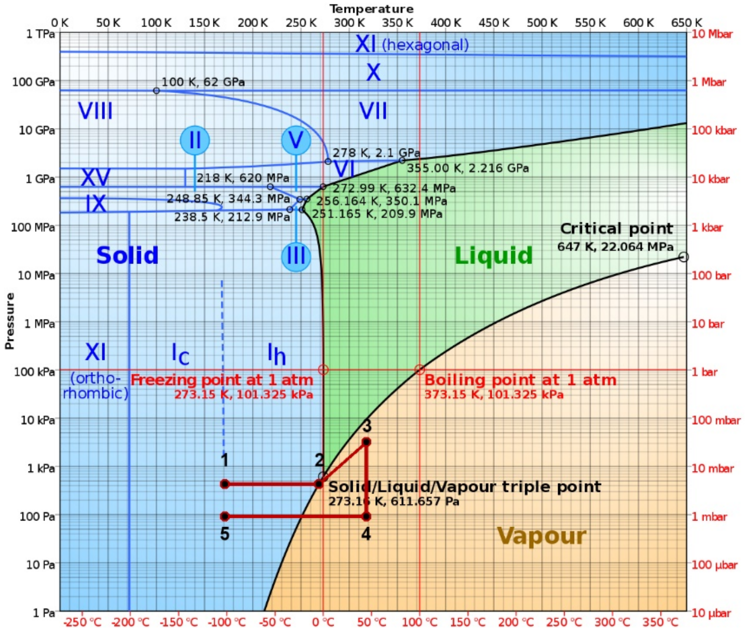

Figure 9. Phase change process. 1 – heating starts, 2 – sublimation starts and regolith pressurizes, 3 – vapour collection starts, pressure drops, 4- heating stops, 5 – regolith cools down.

Appendix

Evaluations used in this paper have been based on the following calculations and assumptions. With regard to creation of geological model of icy regolith, ice concentrations have been calculated through the use of:

- weighted concentrations function:

$$C_{wt} = \frac{m_w}{m_r + m_w} = \frac{\rho_{ice} V_p S_w}{\rho_{bulk} V} = \frac{\rho_{ice} \varphi S_w}{\rho_{bulk}} \tag{1}$$

- pore filling fraction:

$$S_w = \frac{C_{vol}}{\varphi} \tag{2}$$

- parametrized volumetric concentration:

$$C_{vol} = 8.6811 \cdot \ln(z) + 40.011 \tag{3}$$

- bulk regolith density (normal and parametrized):

$$\begin{gathered} \rho_{bulk} = \rho_{rock} \cdot (1 - \varphi), if\ S_w < 100\% \\ \rho_{bulk} = -10.007 \cdot S_w \varphi + 1920.7, if\ \ S_w > 100\% \end{gathered} \tag{4}$$

The following initial values have been taken into account: rock density ρ_{rock} = 2533 kgm^{-3}, near-surface bulk density ρ_{bulk} = 1520 kgm^{-3}, ice density ρ_{ice} = 920 kgm^{-3} near-surface porosity φ = 0.4

Thermal model of icy regolith is solely based on ice filling fraction, according to Siegler and others (2012). It has to be noted that in this analysis ice filling fraction could exceed 100%, which implied excess ice being formed. Thermal parameters are based on:

- thermal conductivity:

$$k = 0.876 \cdot S_w + k_{dry} \tag{5}$$

- thermal inertia:

$$I = -300.66 \cdot {S_w}^2 + 1314.6 \cdot S_w + 230.83 \tag{6}$$

- and specific heat:

$$c = \frac{I^2}{k \rho_{bulk}} \tag{7}$$

The proposed equations led to development of the following model:

LAYER	DEPTH	BULK DENSITY	POROSITY	VOL. CONCENTRATION	THERMAL INERTIA	THERMAL CONDUCT.	SPECIFIC HEAT
	m	kgm^{-3}	-	%	$Jm^{-2}Ks^{-0.5}$	$Wm^{-1}K^{-1}$	$Jkg^{-1}K^{-1}$
1	1	1520.17	0.3999	31.52	1264.717	0.766	1376.015
2	2	1487.05	0.3998	43.33	1652.469	1.025	1792.934
3	3	1441.47	0.3997	47.89	1802.419	1.125	2003.946
4	4	1411.90	0.3995	50.84	1899.947	1.190	2148.690
5	5	1389.92	0.3994	53.04	1972.626	1.239	2260.555
6	6	1372.41	0.3993	54.79	2030.686	1.277	2352.451
7	7	1357.86	0.3991	56.25	2079.094	1.310	2430.829
8	8	1345.39	0.3990	57.49	2120.645	1.337	2499.407
9	9	1334.50	0.3989	58.58	2157.074	1.362	2560.532
10a	10	1324.78	0.3987	59.55	2189.678	1.383	2616.046
10b	11	1324.78	0.3987	59.55	2189.678	1.383	2616.046
10c	12	1324.78	0.3987	59.55	2189.678	1.383	2616.046

With regard to sampling efficiency, proposed epsilon is evaluated as:

$$\varepsilon = \frac{Q}{P \cdot M}\left[\frac{m^3}{W \cdot kg}\right] \tag{8}$$

The power and mass parameters are technical parameters of specific sampling device. Volume of sampled ice however is evaluated from the geological model using diameter of sampling device:

$$Q = \frac{\pi {d_z}^2}{4}\Delta z \cdot \sum_{0}^{z} C_{vol}(z) \tag{9}$$

Heating is evaluated by COMSOL using conductive heat transfers model:

$$d_z \rho C_p \frac{\partial T}{\partial t} + d_z \rho C_p u \cdot \nabla T + \nabla \cdot q = d_z Q + q_0 + d_z Q_{ted} \tag{10}$$

$$q = -d_z k \nabla T \tag{11}$$

Volumetric analysis of water resources on the other hand has been conducted using the following equations:

$$WIP = \frac{\pi({r_e}^2 - {r_w}^2) \cdot \sum_{1}^{i=10} C_{vol_i} \cdot m_i}{B_w}\ [m^3] \tag{12}$$

$$EUR = WIP \cdot RF\ [m^3] \tag{13}$$

$$B_w = \frac{\rho_{water}}{\rho_{ice}} \tag{14}$$

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