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# On the feasibility of a thermodynamic combined heating-depressurization process and the direct use of surface wind energy for mining the Martian regolith for water.

Francisco J. Arias

PhD in Engineering Science.

**Author Affiliations:** a) Department of Engineering, University of Cambridge. Trumpington Street, Cambridge, CB2 1PZ, United Kingdom;

b) Department of Applied Physics, University of Cadiz Avenida Republica Saharaui, s/n, 11510 Puerto Real, Cadiz, Spain.

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**URL:** <http://www.eng.cam.ac.uk/>, **Corresponding author:** [fja30@cam.ac.uk](mailto:fja30@cam.ac.uk)

**Abstract.** In this paper a combined heating-depressurization process for mining water from the regolith of Mars is proposed and its feasibility discussed. It is shown that for water content in the regolith  $\leq 4wt\%$ , as found in latitudes between  $-45^\circ$  and  $45^\circ$ , a combined heating-depressurization process offers better energy usage performance, with savings up to 40% possible. Utilizing a simplified geometrical model, an analytical expression for the performance of such combined processes in comparison with traditional heating is derived. Finally, the direct use of surface wind energy as a driving force for depressurization-sublimation is assessed, showing that for any season and any water content in the regolith a rudimentary low-tech windmill could provide the water for the design reference missions for human exploration of Mars. These results can make an important contribution to the design of energy strategies for water mining from the regolith in, for example, the conception and design of new rover vehicles.

**Keywords:** In-Situ Resource Utilization (ISRU), Water mining on Mars, Water phase diagram, martian wind energy.

## Nomenclature.

$A$ = area	$P_p$ = piston power
$A_p$ = cross-sectional area of the piston	$P_w$ = windmill power
$A_w$ = cross-sectional area of the windmill	$p$ = pressure
$\bar{c}$ = water-soil mixture specific heat capacity	$R$ = radius
$C_p$ = power coefficient	$\bar{R}$ = universal gas constant
$E$ = energy	$T$ = temperature
$\dot{E}$ = power	$u$ = speed
$L$ = latent heat of sublimation	$v$ = volume
$L_p$ = Length of piston	$\beta$ = fraction of water which can be sublimated by using the sensible heat of the regolith as latent heat
$l$ = thickness of the slab	
$m$ = mass	

$M$ = molecular weight of local atmosphere	$\epsilon$ = concentration of water in the soil
$\dot{m}$ = mass flow rate	$\eta$ = efficiency energy conversion
$n$ = number of moles	$\kappa$ = thermal conductivity
$P_e$ = electrical heater power	$\Phi$ = combined process efficiency factor
$\tau_p$ = piston system timing	$\rho$ = density
$\tau_c$ = time constant for heat transfer	$H_2O$ = water
$\Psi$ = excess of energy from electric heating, Eq(32)	$p$ = piston
$i$ = initial energy source	$r$ = regolith
$e$ = earth	soil = soil-regolith
$m$ = mars	$t$ = thermal energy
	$v$ = vapor phase
	$w$ = mechanical work / wind

## 1. Introduction.

One major barrier to the successful placement of humans on Mars is a lack of water on the Martian surface. Because of the large amount of water that would be necessary for a manned mission to Mars, it is not feasible to transport the amount necessary from the Earth to Mars. Water would be needed for human consumption and as a base for jet propulsion fuel. Past unmanned missions to Mars, such as the Viking missions of the 1970's, have revealed the presence of small quantities of water in Martian soil [1].

Evidence of significant quantities water in Martian surface soils in the form of ice particles or hydrated minerals was found by the 2001 Mars Odyssey [2], with concentrations approaching 10wt%, in places [3] where wt% stands for weight percent. Little Martian water is visible, with what there is confined to the polar caps, but in a stunning discovery the Mars Odyssey's gamma ray spectrometer (GRS) showed that near-surface water deposits reach far into temperate latitudes, as far as 60° from the poles. The mass of water required to explain the data indicates ice or ice-cemented ground meters thick. In more equatorial latitudes water concentrations of only 1-10 wt% have been detected in the soil [3], where the top 5 cm of the soil is loose and easy to dig, avoiding deeper hard permafrost material.

Fig. 1 shows the water concentration in the upper few tens of centimeters of the Martian surface, as measured from orbit by the Mars Odyssey GRS.

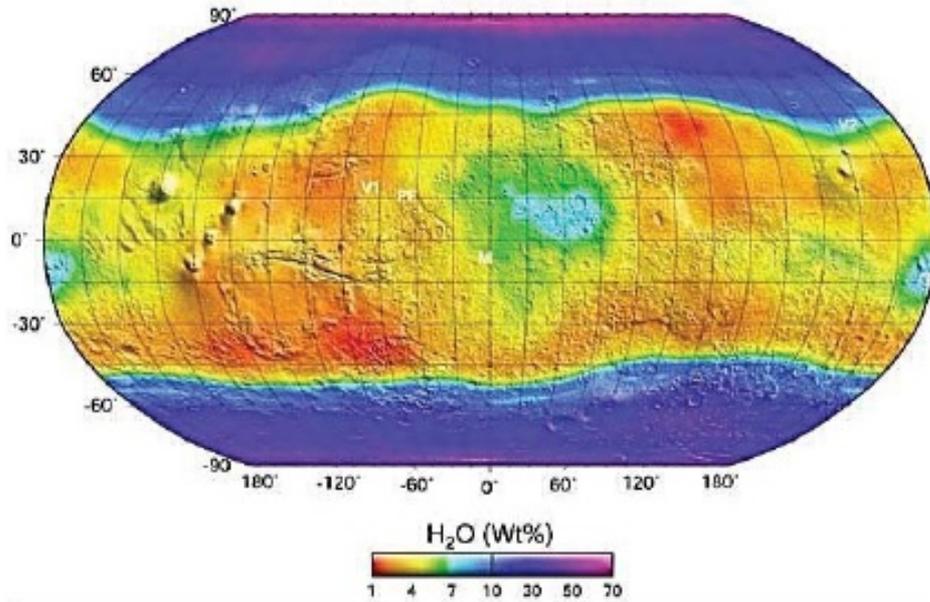


FIG. 1: Map of the H<sub>2</sub>O concentration in the upper few tens of centimeters of the Martian surface, as measured from orbit by the Mars Odyssey gamma ray spectrometer [2].

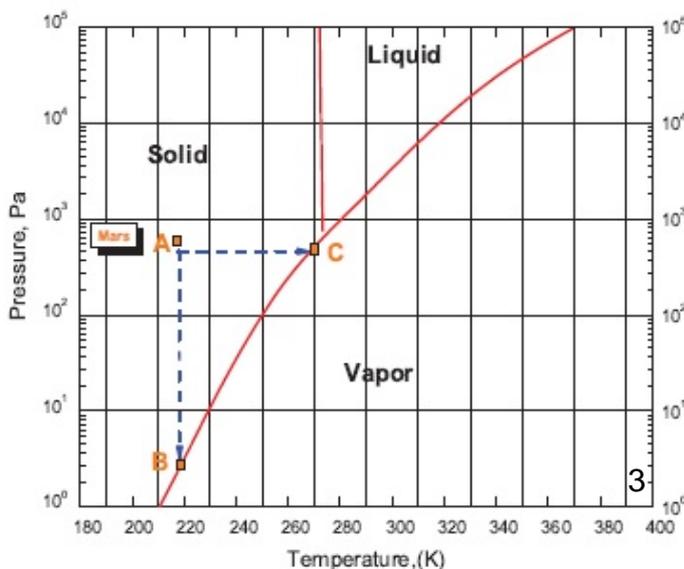
Equatorial Mars (between 40° north and south) contains 2-7 wt% H<sub>2</sub>O, while the polar regions contain much more. The GRS actually measured hydrogen (H) concentrations, but these have been converted to equivalent concentrations of H<sub>2</sub>O. In reality, much of the water may be in the form of OH bound in minerals [2]. This abundant source of water from the regolith may therefore contain corrosive or toxic substances (presenting health risks to humans and hazards, such as pipe corrosion, to equipment). Sublimating and recondensing the water would ensure it was suitably clean.

Techniques for the sublimation and extraction of water from the Martian regolith are being extensively studied. Although a variety of approaches for water extraction from the soil are under consideration, all of them rely on heating of the regolith for water sublimation [4], [5]. The idea that pure heating is the best technique for water extraction on Mars seems to have become accepted wisdom without sufficiently careful consideration of possible alternatives. As will be demonstrated in this paper, when the water content is low ( $\leq 7\text{wt}\%$ ), which is predominantly the case (see Fig. 1), due to the special conditions on Mars a combined heating and depressurization process offers a considerable improvement in terms of energy efficiency. This might be easily inferred from the low content of water of the regolith. If it is pretended to sublimate the water from the regolith, it would be needed to heat all the regolith to the temperature sublimation of water, so, with a content of 1% of water in the regolith you can say that you process would be above 1% of efficiency because the other 99% of energy will be lost in heating the regolith free of water. The only possibility to overcome this

issue would be by a selective system of heating the water, it could be thought that microwaves is a solution, however the magnetic properties of the regolith can preclude this possibility (see Appendix A).

### A. Statement of the model.

Fig. 2 shows the phase diagram for water for states corresponding to the conditions that prevail on Mars, with pressures in the range 600-1000 Pa and

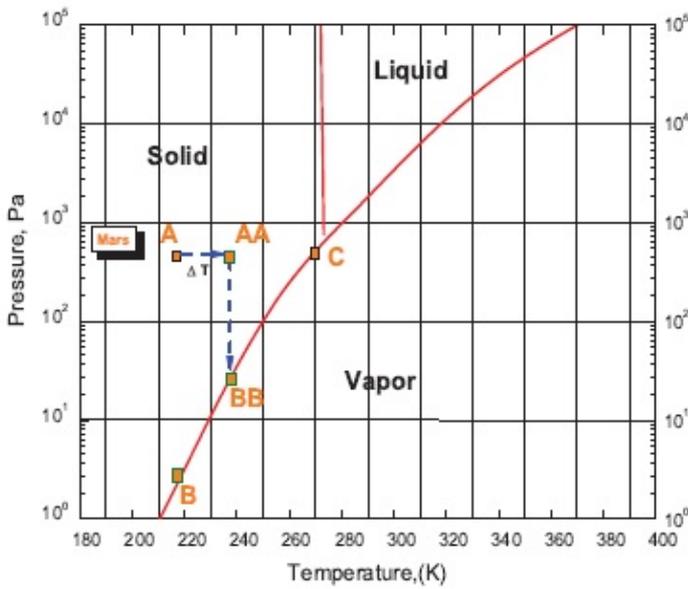


temperatures between 220 K to 240 K. Looking at Fig. 2, it is apparent that, because of the proximity of the equilibrium curve for water vapor, there are two equally feasible paths for water sublimation (energetically speaking), which are not viable in the conditions that prevail on the Earth. On the one hand, there is the classical isobaric path  $A \rightarrow C$ , but, for Martian conditions, it appears that an isothermal path  $A \rightarrow B$  may be equally energetically viable.

Fig. 2: The pressure-temperature phase diagram for water in log-linear form showing two paths that lead to the sublimation state: the isothermal path  $A \rightarrow B$  and the isobaric path  $A \rightarrow C$ .

That offers the best performance from an energy usage perspective (see Fig. 3). Although the conceptual idea is clear, it is not immediately obvious which path is best and this question therefore needs to be investigated. That is the goal in this section.

Utilizing a simplified but rather conservative geometrical model, we seek to determine whether a combined heating-depressurization process can offer the best water sublimation performance from an



energy usage perspective, and, if so, the regime in which this occurs, e.g. for what water content levels in the regolith, etc.

Moreover, at this point, it is also apparent that perhaps the best path may be neither isobaric nor isothermal but between these extremes, i.e. a combination of the two. Although there are many (potentially infinite) possible device designs, for the sake of generality we consider a simple cylinder with a moving piston to model the chamber in which sublimation occurs.

Fig. 3: The pressure-temperature phase diagram for water in log-linear form. The most suitable path for sublimation may be neither isobaric nor isothermal but a combination of the two. In this example, the system is first heated isobarically  $A \rightarrow AA$  and then depressurized isothermally  $AA \rightarrow BB$ .

### A.1. Heating $\rightarrow$ depressurization.

Let us consider an initial thermodynamic state  $A$ , as depicted in Fig. 3, with initial pressure and temperature  $(p, T)$ . Let us consider also a piston with a cross-sectional area  $A_p$  that moves a distance  $L_p$ . Under these circumstances and as a first approximation, the work necessary for the displacement  $L_p$  to bring the system from an initial pressure  $p$  to the equilibrium vapor pressure  $p^v$  is given by

$$E_w = (p - p^v) A_p L_p \quad (1)$$

It will immediately be apparent that the above assumption is rather conservative, because it overestimates the work necessary to move the piston from the initial to the final state.

The power  $\dot{E}_w$  necessary to achieve the displacement  $L_p$  may, as a first approximation, be calculated as

$$\dot{E}_w = \frac{(p - p^v) A_p L_p}{\tau_p} \quad (2)$$

where  $\tau_p$  is the elapsed time for the motion of the piston.

This time will be limited mostly by the capability of the system in intaking the hydrated regolith and ejecting the dehydrated regolith as well as the mechanical source used for motion of the piston itself.

For example. If wind power is to be used (see section III), then, using a windmills of 1 meter of wingspan and wind velocities of  $2m/s$ , the period of the piston would be proportional to the period of the windmill, i.e., on 3 seconds. However, if the capability of motion of the regolith (introduction in the chamber and ejection of the dehydrated regolith) is limited to, say, 20 seconds, then the piston will move approximately  $20/3 \approx 6$  cycles. On the other hand, the water mass flow  $\dot{m}_{H_2O}$  that is sublimated within the chamber during the motion of the piston can be written as

$$\dot{m}_{H_2O} = \frac{\varepsilon m_{soil}}{\tau_p} \tag{3}$$

where  $m_{soil}$  the mass of soil and  $\varepsilon$  is the concentration of water in the soil.

Combining Eqs. (3) and (4), we obtain:

$$\dot{E}_w = \frac{(p - p^v) A_p L_p}{\varepsilon m_{soil}} \dot{m}_{H_2O} \tag{4}$$

The vaporized water that is deposited into the chamber must be in equilibrium, i.e.

$$p^v v_p = n \bar{R} T \tag{5}$$

where  $p^v$  is the saturation vapor pressure at temperature  $T$ ,  $v_p$  is volume of the chamber,  $n$  is the number of moles of water and  $\bar{R}$  is the universal gas constant.

The number of moles of water is given by

$$n = \frac{\varepsilon m_{soil}}{\bar{m}_{H_2O}} \tag{6}$$

where  $\bar{m}_{H_2O}$  is the molar mass of water, i.e.  $18 \text{ g/mol}$ .

Then, combining Eqs. (5), (6) and (7), we obtain:

$$\dot{E}_w = \frac{p - p^v}{p^v} \frac{\bar{R} T}{\bar{m}_{H_2O}} \dot{m}_{H_2O} \tag{7}$$

Finally, it is necessary to take into account the efficiencies of energy conversion in order to determine the real power. The total efficiency of the system will be the product of the efficiency of the conversion of the initial source of energy  $\eta_i^w$  and the efficiency of the transformation of this energy into the motion of the piston  $\eta_w$  (see Fig. 4). Then a more realistic expression for  $\dot{E}_w$  will be

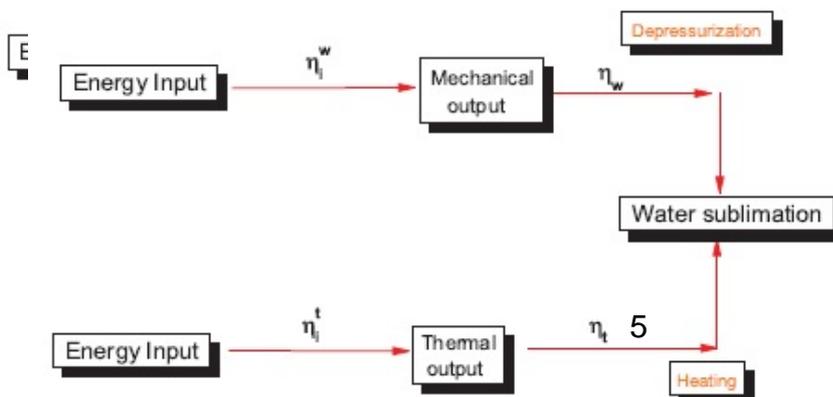
$$\dot{E}_w = \left[ \frac{1}{\eta_i^w \eta_w} \right] \frac{p - p^v}{p^v} \frac{\varepsilon \bar{R} T}{\bar{m}_{H_2O}} \dot{m}_{H_2O} \tag{8}$$

Now the analysis of a combined preheating  $\rightarrow$  depressurization process is straightforward. Let

A) Thermodynamic despressurization/heating process sharing the same energy input source.



B) Thermodynamic despressurization/heating process with different energy input sources.



us assume that initially the regolith is preheated an amount, say  $\Delta T$  (see Fig. 3), followed by a depressurization process. In this scenario, the total mechanical depressurization power is given by

Fig. 4: Thermodynamic combined heating-depressurization processes for water sublimation: A) the mechanical and thermal energy are drawn from the same energy source; B) the mechanical work for depressurization and the thermal

energy are drawn from different energy sources.

$$\dot{E}_w = \frac{p - p_{T+\Delta T}^v}{p_{T+\Delta T}^v} \frac{\bar{R}(T + \Delta T)}{\eta_i^w \eta_w \bar{m}_{\text{H}_2\text{O}}} \dot{m}_{\text{H}_2\text{O}} \quad (9)$$

where  $p_{T+\Delta T}^v$  denotes the vapor pressure at temperature  $T + \Delta T$ .

The thermal power  $\dot{E}_t$  required for the isobaric shift  $\Delta T$  is the sensible heat given by

$$\dot{E}_t = \left[ \frac{1}{\eta_i^t \eta_t} \right] \frac{\dot{m}_{\text{H}_2\text{O}} \bar{c} \Delta T}{\varepsilon} \quad (10)$$

where  $\bar{c}$  is the average specific heat capacity of the regolith, and, as before, the efficiencies of the energy conversion processes have been considered. These can be equal to those for the mechanical work or not, depending on whether the sources of energy for the mechanical work and the heating are the same or different (see Fig. 4).

It is also important to note that, in order to increase the temperature of the water by  $\Delta T$ , all the regolith must be heated, and thus the mass that must be included in these evaluations is not  $m_{\text{H}_2\text{O}}$  but  $m_{\text{soil}} = m_{\text{H}_2\text{O}} / \varepsilon$ .

The average specific heat capacity of the regolith-water system can be evaluated as the heat capacity of a mixture as

$$\bar{c} = (1 - \varepsilon) c_r + \varepsilon c_{\text{H}_2\text{O}} \quad (11)$$

where  $c_r$  and  $c_{\text{H}_2\text{O}}$  are the specific heat capacities of the regolith and the water, respectively.

Upon summing Eqs. (9) and (10) the total power of sublimation using the combined preheating  $\rightarrow$  depressurization process is obtained as

$$\dot{E}_s = \left[ \frac{\bar{c} \Delta T}{\varepsilon \eta_i^t \eta_t} + \frac{p - p_{T+\Delta T}^v}{p_{T+\Delta T}^v} \frac{\bar{R}(T + \Delta T)}{\eta_i^w \eta_w \bar{m}_{\text{H}_2\text{O}}} + \frac{L}{\eta_i^t \eta_t} \right] \dot{m}_{\text{H}_2\text{O}} \quad (12)$$

where the latent heat power for sublimation  $L \dot{m}_{\text{H}_2\text{O}}$  has been included. According to Hess' Law, this enthalpy, being a state function, is independent of the thermodynamic cycle.

Finally, in order to evaluate the performance of the combined heating-depressurization process in comparison with a pure heating process, a helpful expression is the ratio between sublimation power given by Eq. (9) and the thermal power used if the system is sublimated by pure heating.

If the sublimation of the water in the sample is achieved by pure heating, the total power  $\dot{E}_0$  needed is given by

$$\dot{E}_0 = \left[ \frac{\bar{c}(T_p^v - T)}{\varepsilon} + L \right] \frac{\dot{m}_{\text{H}_2\text{O}}}{\eta_i^t \eta_t} \quad (13)$$

where  $T_p^v$  is the vapor temperature at a pressure  $p$ .

We are interested in suppressing the heating of the sample, i.e., the sensible heat, and using instead depressurization, it is interesting to express the above equation as function of the power associated only with the latent heat, i. e.,  $P_L = \dot{m}_{H_2O} L / \eta_i' \eta_t$ , as

$$\dot{E}_0 = \left[ \frac{\bar{c}(T_p^v - T)}{\varepsilon L} + 1 \right] \cdot P_L \quad (14)$$

With typical values of  $L = 2600 \text{ kJ/kg}$ , this would require almost 6000W for 200kg/day as latent heat, which considering average values of  $\bar{c} = 1100 \text{ J/kg}^\circ\text{K}$  and  $T_p^v - T \approx 50\text{K}$ , then the total power needed would be on  $\dot{E}_0 = \left[ \frac{0.021}{\varepsilon} + 1 \right] \cdot 6000\text{W}$ . With a regolith with a content of water of just 1%, i. e.,  $\varepsilon = 0.01$  the total power would be increased a 300% or 18692.3 W.

Taking into account Eq.(13) then Eq. (912) can be rewritten as

$$\dot{E}_s = \Phi_{(\Delta T, \varepsilon)} \dot{E}_0 \quad (15)$$

where

$$\Phi_{(\Delta T, \varepsilon)} = \left[ \bar{c} \Delta T + \frac{p - p_{T+\Delta T}^v}{p_{T+\Delta T}^v} \frac{\bar{R}}{\bar{m}_{H_2O}} \frac{\varepsilon(T + \Delta T) \eta_i' \eta_t}{\eta_i^w \eta_w} + \varepsilon L \right] \left[ \frac{1}{c(T_p^v - T) + \varepsilon L} \right] \quad (16)$$

which is the expression that we seek: if  $\Phi_{(\Delta T, \varepsilon)} < 1$  the combined heating-depressurization process could be energetically more favorable than pure heating.

## A.2. Depressurization $\rightarrow$ heating.

If the independent input variable is  $\Delta p$  rather than  $\Delta T$ , then proceeding in the same way as in the previous section, but for a combined process where first a depressurization  $\Delta p$  is made followed by heating (see Fig. 5), then the equivalent of Eq. (16) is

$$\Phi_{(\Delta T, \varepsilon)} = \left[ \bar{c}(T_{p-\Delta p}^v - T) + \frac{\Delta p}{p - \Delta p} \frac{\bar{R}}{\bar{m}_{H_2O}} \frac{\varepsilon \eta_i' \eta_t T_{p-\Delta p}^v}{\eta_i^w \eta_w} + \varepsilon L \right] \left[ \frac{1}{c(T_p^v - T) + \varepsilon L} \right] \quad (17)$$

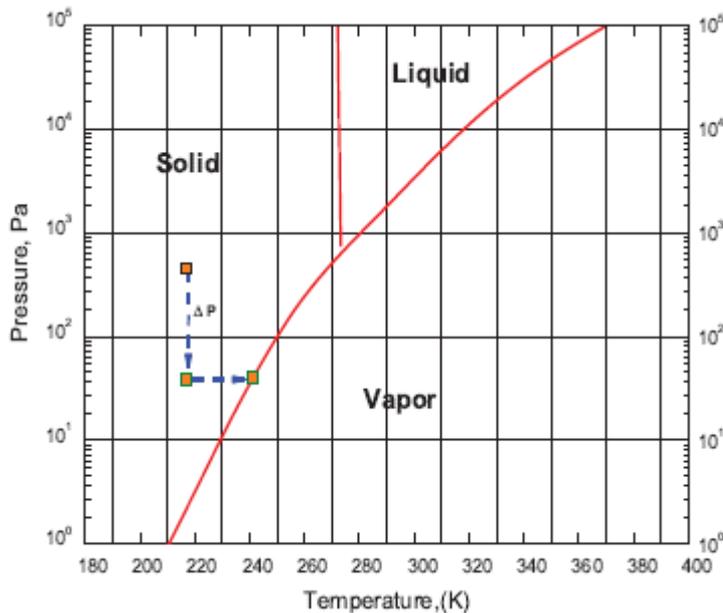


Fig. 5: The pressure-temperature phase diagram for water in log-linear form. The most suitable path for sublimation may be neither isobaric nor isothermal but a combination of the two. In this example, the system is first depressurized isothermally and then heated isobarically.

To obtain some idea of the shapes of the curves predicted by Eqs. (16) and (17) we assume typical values of the parameters for Mars:  $p = 600 \text{ Pa}$ ; average diurnal temperatures of  $T = 250\text{K}$  (diurnal temperature);  $\bar{m}_{H_2O} = 18 \text{ g/mol}$ ;  $\bar{R} = 8.314 \text{ JK}^{-1} \text{ mol}^{-1}$ ;  $\bar{c} = 1100 \text{ JKgK}^{-1}$  [6], and  $L = 2600 \text{ kJ/kg}$ . The conversion

efficiencies for electricity-to-mechanical work ( $\eta_w$ ) and electricity-to-microwaves ( $\eta_t$ ) were taken to have typical values of 0.95 and 0.60, respectively. For the sake of generalization, we assume that the system is energetically coupled, i.e. they share the same source of energy: say, a photovoltaic array with an efficiency of 20% (GaAs technology). Thus, in this case,  $\eta_i^w = \eta_i^t = 0.2$ . Also, for the evaluation of the vapor pressure and vapor temperature, although many semi-empirical derivations from the Clausius-Clapeyron equation are available, in view of uncertainties in the model, the simplest expression, known as the Magnus formula, seems preferable [7]:

$$\log_{10} p = 10.550 - \frac{2667}{T} \tag{18}$$

with the pressure expressed in mbar.

## 2. Results.

The resulting curves for  $\Phi_{(\Delta T, \epsilon)}$  and  $\Phi_{(\Delta p, \epsilon)}$  are shown in Figs. 6 and 7 respectively for

different values of the water content ( $\epsilon$ ) in the regolith.

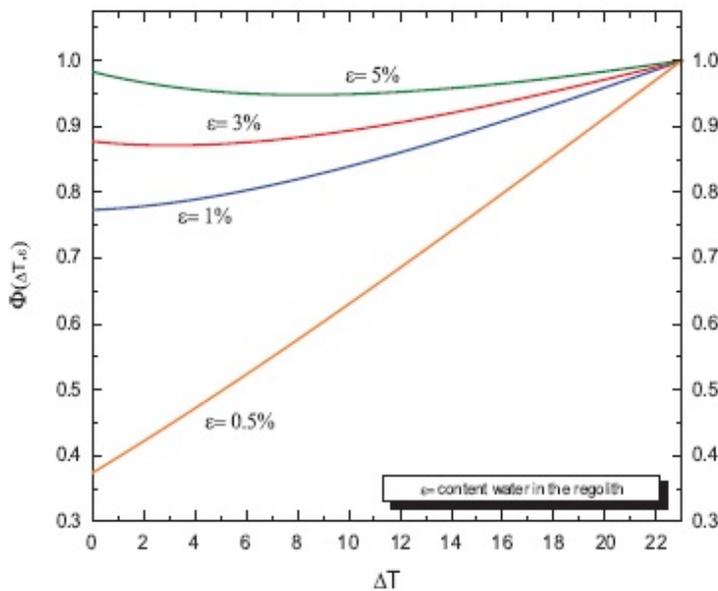


Fig. 6: Fraction of power  $\Phi(\Delta T, \_)$  needed for sublimation with a preheating step  $\Delta T$  followed by depressurization according to Eq. 16).

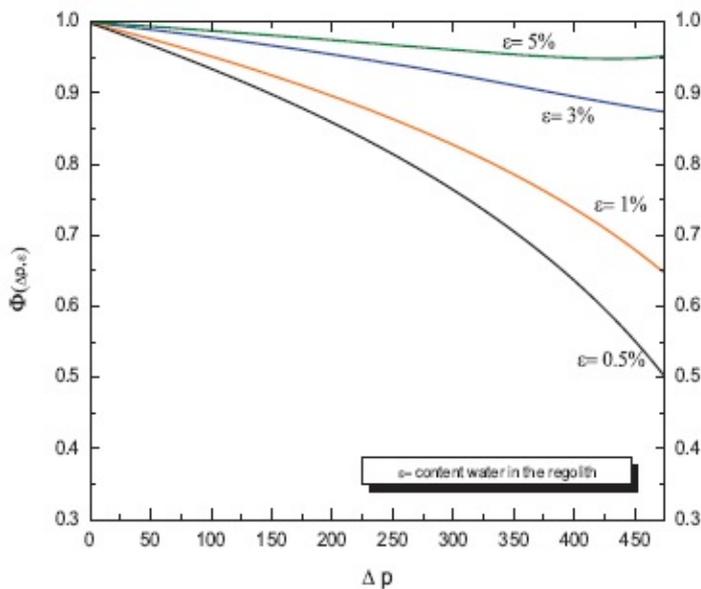


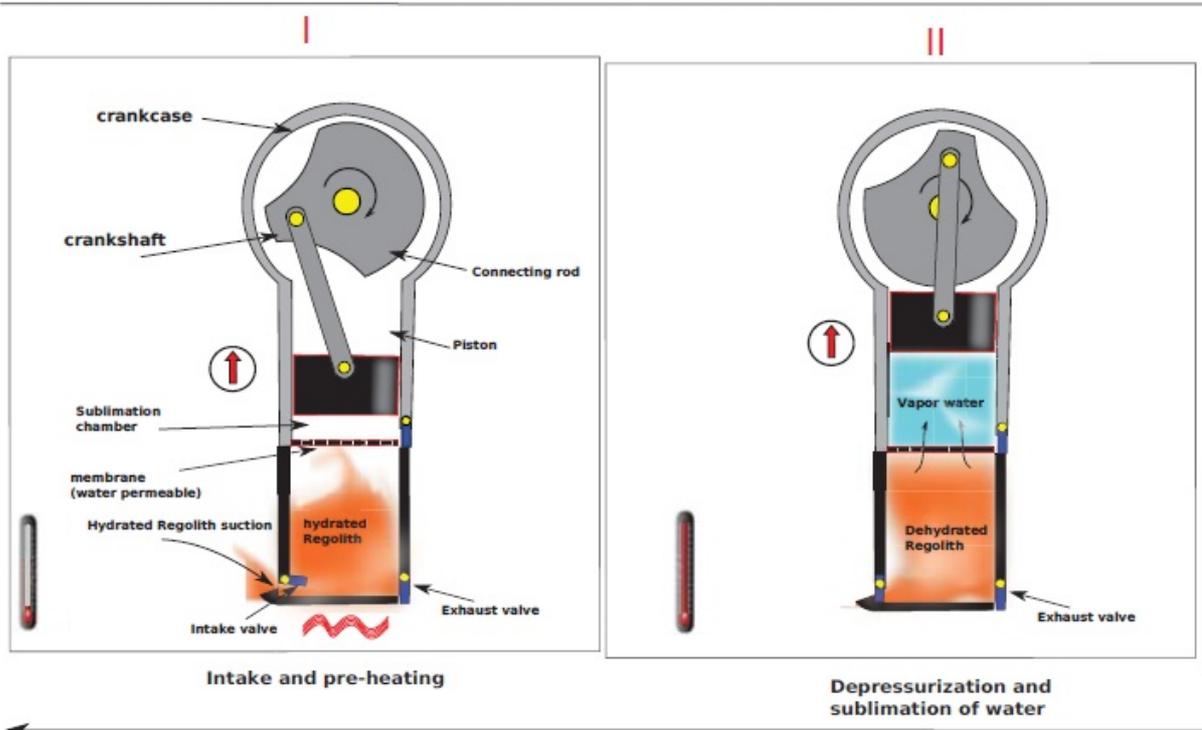
Fig. 7: Fraction of power  $\Phi(\Delta p, \_)$  needed for sublimation with a pre-depressurization step  $\Delta p$  followed by heating according to Eq. (17).

It can be seen that for Martian regolith with low water content ( $\leq 3wt\%$ ) a combined process of heating/depressurization offers a more attractive way for extracting water, at least from an energy usage point of view. For instance, according to Fig. 6, the use of a combined heating-depressurization process enables energy savings of up to  $\sim 60\%$  to be made in comparison with pure heating for regolith with water content as low as  $0,5wt\%$ .

**Discussion (1).** Because the equatorial regions of Mars, which are more suitable for early manned Mars missions, with flat terrain, low latitude and low altitude, have regolith with low water concentrations (see Fig. 1), the use of a combined heating-depressurization process rather than the traditional use of pure heating for water extraction can play an important role in the logistics of the such missions.

Fig. 8 presents a sketch of a possible combined preheating-depressurization cycle for mining the Martian regolith for water.

**Combined depressurization/pre-heating process for regolith dehydration**



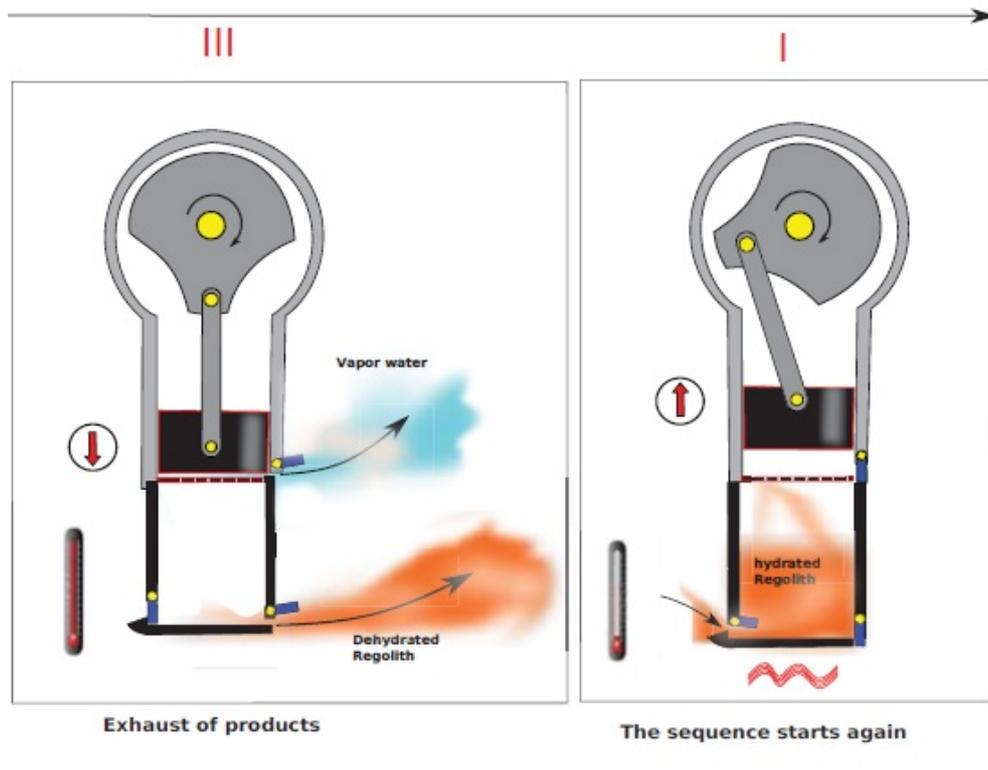


Fig. 8: Sketch of a hypothetical device to implement a combined process of heating-depressurization for mining the Martian regolith for water. Such a device could be used in a stationary reactor or mounted on a rover. In the latter case, water could be directly extracted from the regolith by the rover continuously.

Referring to Fig. 8, probably the reader envisages that there is a conspicuous source of mechanical energy for the motion of a simple piston in depressurization chamber. In fact, this source of direct mechanical energy is so propitious for the depressurization process for Mars than depressurization could be favorable for any water content in the regolith and any season as well. The low-tech nature of this technology is an additional point in favor for its use. This source of energy is call wind.

### 3. The use of the surface wind energy.

Windmills have operated of Earth for centuries, and their low-tech nature makes them attractive potential item for Mars.

However, the low density of air on Mars-only 1 percent as thick as Earth's - has precluded the use of wind turbines and wind power as a source of energy and only winds at altitudes well above the surface would create the same amount of power per unit of windmill area as a breeze on Earth, [8]. Although it is true that the Martian wind power has a negligible potential for energy production - at least form surface winds- however, for a water depressurization process -as depicted in Fig. 8- it could be not the case. In the next theoretical treatment and using a very conservative model we will find that surface winds on Mars could play a very predominant role in the Martian endeavor.

For the sake of simplicity, let us assume a piston or depressurization chamber as depicted in Fig. 8, where depressurization of the regolith takes place.

Let us call the area of the piston as  $A_p$ . Then, the necessary work for the displacement of the piston from an initial volume  $v_o$  to a final volume  $v_f$  is given by

$$W_p = \int_o^f p dv \quad (19)$$

which, for conservative calculations with an overestimation of the work required becomes as

$$W_p = A_p L_p p_o \quad (20)$$

Where  $L_p$  is the length of chamber i.e.,  $v_f - v_o = A_p L_p$  and  $p_o$  is the environmental atmospheric pressure. The power is given by

$$P_p \sim A_p p_o u_p \quad (21)$$

where  $u_p$  is the mean velocity of the piston.

However, we know that the water mass flow extracted by the piston is given by

$$\dot{m}_{h_2o} = \varepsilon \rho_r u_p A_p \quad (22)$$

where  $\varepsilon$  is the weight fraction of water in the regolith with density  $\rho_r$ .

Inserting Eq.(22) into Eq.(21), the total power becomes

$$P_p = \frac{\dot{m}_{h_2o} p_o}{\varepsilon \rho_r} \quad (23)$$

The global amount of kinetic energy flux in the flowing wind with respect to rotor swept area of a windmill can be calculated according to the formula

$$P_w = \frac{1}{2} \rho_w C_p A_w u_w^3 \quad (24)$$

where  $\rho_w$  is the density of the wind,  $A_w$  is the swept area of the rotor, corresponding to  $\pi R_w^2$  for a horizontal axis rotor of radius  $R_w$ ,  $u_w$  the wind speed and  $C_p$  is the power coefficient.

The interested parameter to evaluate the feasibility of harnessing martian wind energy for regolith-water depressurization is the rotor radius  $R_w$  i. e., the dimensions of the device.

This can easily calculate by equating Eq.(23) with Eq.(24), obtaining the following relationship,

$$A_w = \frac{2 \dot{m}_{h_2o} p_o}{\varepsilon C_p \rho_r \rho_w u_w^3} \quad (25)$$

or with  $A_w = \pi R_w^2$ , Eq. (25) gives the radius of the rotor as

$$R_w = \sqrt{\frac{2}{\pi} \frac{\dot{m}_{h_2o}}{\varepsilon C_p \rho_r \rho_w u_w^3}} \sqrt{\frac{p_o}{\rho_w}} \quad (26)$$

Now is straightforward. From the available literature on design reference missions for human exploration, the water mass requirements based in a crew of six for 600 days is on  $\sim 200kg/day$ , [9], i. e,  $\dot{m}_{h_2o} \sim 2.3 \times 10^{-3} kg/s$ . On the other hand, the martian atmospheric density and pressure could be assumed as, [10]:  $p_o \sim 600Pa$  and  $\rho_a \sim 0.02kg/m^3$ , [11], respectively; and the density of the regolith as  $\rho_g \approx 2000kg/m^3$ , [12].

Finally, we need an estimation of the performance of the specific windmill design, i.e, the parameter  $C_p$ . Because the Betz'law, [13], the maximum theoretical value for  $C_p = 16/27$  or 59.3%. Modern large wind turbines achieve peak values for  $C_p$  in the range of 0.45 to 0.50, or about 75% to 85% of the theoretically possible maximum. However, in view of several uncertainties, let us assume a conservative and poor value, say  $C_p = 0.1$ , [14] -although certainly it is hard to believe that aerospace engineers cannot obtain better windmill designs. Anyway, using the mentioned values, the resulting curves for the radius of the rotor  $R_w$  as function of the content of water in the regolith are show in Fig. 9 and Fig. 10 considering the wind velocity profiles for fall and summer seasons, respectively.

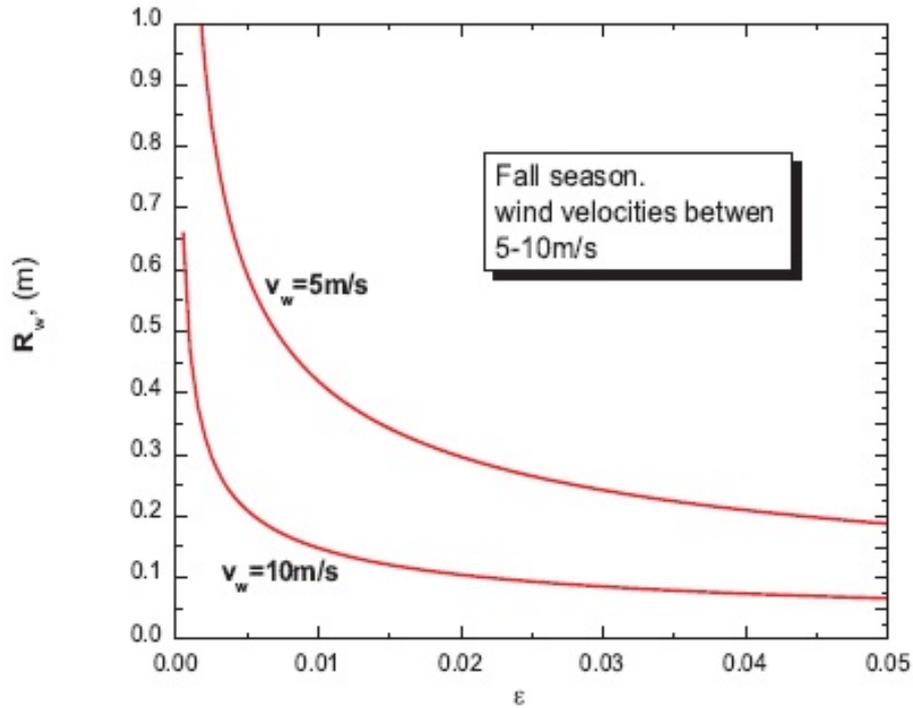


Fig. 9: The required windmill radius for water depressurization during in the fall season. Wind speeds profiles courtesy of Dr. David R. Williams at NASA Goddard Space Flight Center, [10].

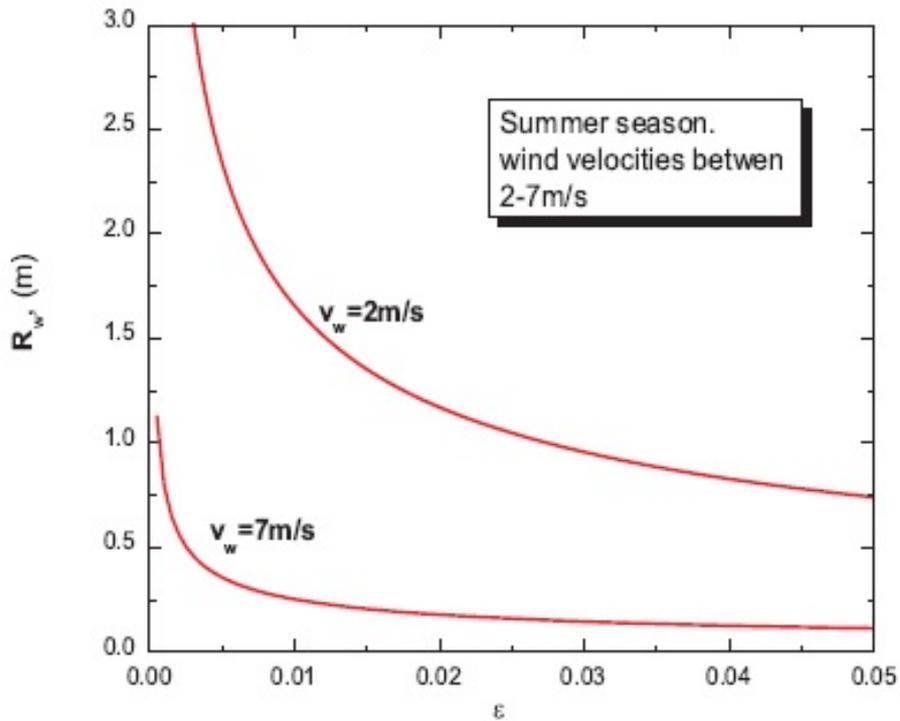


Fig. 10: The required windmill radius for water depressurization during in the summer season. Wind speeds profiles courtesy of Dr. David R. Williams at NASA Goddard Space Flight Center, [10].

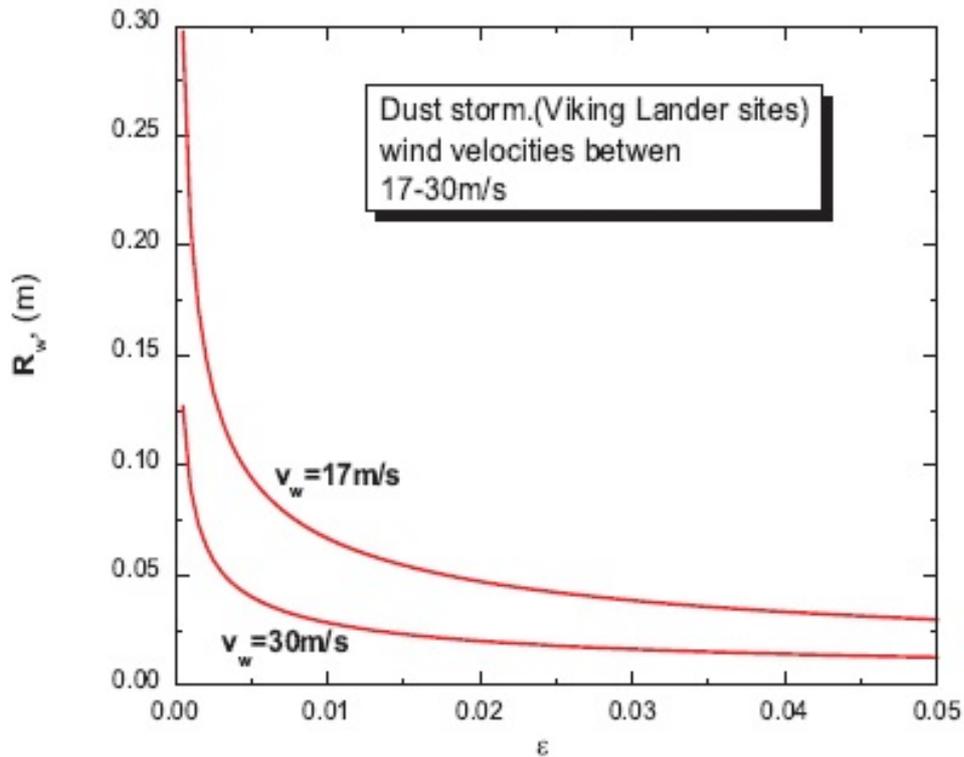


Fig. 11: The required windmill radius for water depressurization during in dust storm (Viking Lander sites). Wind speeds profiles courtesy of Dr. David R. Williams at NASA Goddard Space Flight Center, [10].

**Discussion (2).** It is seen that with a single windmill with a radius of the rotor no larger than 1.5 m, all the power for water sublimation using a simple decompression chamber are available for any season and for any content of water in the regolith.

This result is extremely important because is opening a door to a mechanism for water extraction using an almost handicraft technology as is a rudimentary windmill with a  $C_p = 0.1$

#### 4. Latent heat from the sensible heat store in the regolith.

In previous sections it was assumed an external heat source for the supply of the latent heat required for the sublimation.

However, this latent heat can be supplied by the regolith itself by reduction of its own temperature, i.e., by the partial use of the sensible heat stored as temperature in the regolith. Therefore, the maximum capability for water extraction from the regolith will be limited by the sensible energy stored in the regolith which can be supplied as latent heat.

The maximum fraction of water, let us call this by  $\beta$ , that can be sublimated obeys the following energybalance relationship

$$m_{soil}(1-\beta)\bar{c}\Delta T = m_{soil}\beta L \quad (27)$$

where  $m_{soil}$  is the total mass of regolith,  $\beta$  the fraction of water which can be sublimated,  $\bar{c}$  the heat capacity of the regolith,  $L$  the latent heat of the water, and  $\Delta T$  the regolith drop temperature Solving Eq.(27) we have

$$\beta = \frac{1}{1 + \frac{L}{\bar{c}\Delta T}} \quad (28)$$

## 5. Rovers.

There are several ways in which the proposed system might be developed. Fig. 12 is depicting a possible application of a depressurization system in a rover.

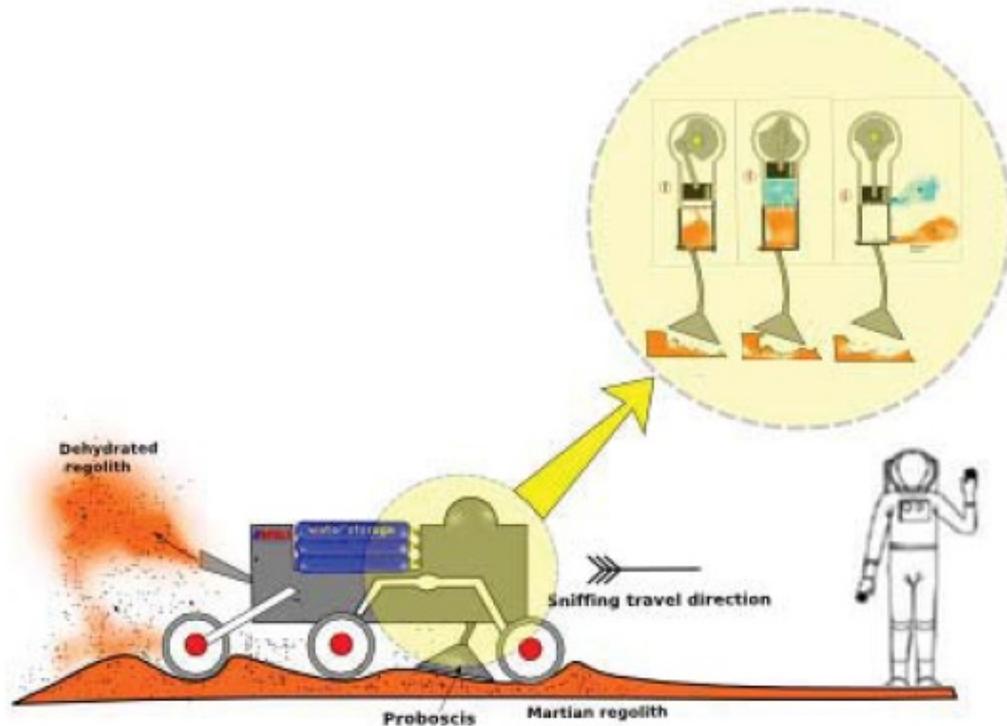


Fig. 12: Depressurization-rovers for water extraction from the Martian regolith.

In this *proboscis-concept* the rover collects the regolith (sniffing) and then water is separated *in-situ*.

However, this kind of rover only works with finely pulverized soils. For an extensive exploitation, it will be required a previous fragmentation of extensive areas of regolith, say from the permafrost - for example using explosive charges, then the tons of fragmentized regolith could be transported to a central depressurization facility (using windmills) which could be located kilometers away from the water mine, and then water separated.

## 6. Appendix.

It is worth briefly reviewing some of the difficulties that may arise with direct thermal heating in the process of water-mining on Mars. The two options are direct electrical heating and the use of microwaves.

### A. Electrical heating.

Although electric heaters have an efficiency of nearly 100% in the conversion from electrical to thermal energy, because of the conductive thermal gradient, there is an excess of energy needed that must be taken into account.

The excess of energy required due to the temperature difference due to thermal conduction can be estimated by assuming the simplest case of an infinite slab. In this case, the temperature profile is

$$T(x) = T_s + \frac{P_e}{A\kappa}(l - x) \quad (29)$$

where  $T(x)$  is the temperature at a distance  $x$  from the side that is being heated,  $T_s$  is the temperature at the free surface of the slab,  $P_e$  is the electrical heater power,  $A$  is the area of the heater,  $l$  is the distance between the heated and free surfaces of the slab, and  $\kappa$  is its thermal conductivity. If  $T_s$  is the temperature at which the phase transition occurs, then the total sensible energy needed for the phase transition from a slab with initial temperature  $T_0$  will be

$$\Delta E = \rho \bar{c} A \int_0^l \left( T_s + \frac{P_e}{A\kappa} (l-x) - T_0 \right) dx \quad (30)$$

where  $\rho$  is the density of the slab and  $\bar{c}$  its heat capacity. Resolving Eq. (30), one obtains

$$\Delta E = \rho A l \bar{c} (T_s - T_0) + \rho \bar{c} \frac{P_e l^2}{2\kappa} \quad (31)$$

Because the mass of the sample is  $m = \rho A l$ , then the first term on the right side is the sensible heat required to heat all the sample from a temperature  $T_0$  to  $T_s$  and therefore the second term on the right side may be defined as the excess of the energy  $\Psi$  due to the gradient of temperature, i. e.,

$$\Psi = \rho \bar{c} \frac{P_e l^2}{2\kappa} \quad (32)$$

and noting that the mass of the sample is  $m = \rho A l$ , then Eq. (32) can be rewritten as

$$\Psi = \frac{\bar{c} P_e m^2}{2\kappa \rho A^2} \quad (33)$$

Thus, energy losses increase with the square of the mass of the soil to be dehydrated and linearly with the heater power. In order to reduce these losses, large cross-sectional areas and/or the use of agitators would be required, neither of which is particularly practicable, certainly not for initial highly automated missions.

## 6.2. Heating time.

Finally, an important fact that needs to be considered is the heating time. The quantity,

$$\tau_c \sim \frac{\rho \bar{c}}{\kappa} l^2 \quad (34)$$

Being  $\rho$ ,  $\bar{c}$  and  $\kappa$  the density, heat capacity and thermal conductivity of the material to be heated, respectively;  $l$  is the is the length -or bed depth- of the material (measured on a path parallel to the heat flow). The quantity  $\tau_c$  is generally called as the time constant, [17]. It is a measure of how much time is required to transport heat from the heat source to the sample. It is easy to observe that as a result of the low thermal conductivity of the martian regolith ( $\kappa \sim 1.0W / mK$ ), its high heat capacity ( $\sim 400J / kgK$ ), [18], and the quadratic dependence with the bed depth, the heating time should be an important parameter to be considered. For example, processing a large amount of hydrated regolith will require a large surface area where the regolith is heated in order to keep a reduced bed depth, otherwise the heating time and then the time needed for dehydracetic could be unacceptable. However, increasing the heat surface also will increase the heat losses by conduction and convection with the surroundings and then a per cent of the energy used for regolith dehydration will be lost as waste heat. Nevertheless, during a depressurization process, as depicted in Fig. 8, sublimation would be almost instantaneous.

## Conclusions.

In this paper a combined heating-depressurization process for mining the Martian regolith for

water has been proposed and analyzed in comparison with the traditional pure heating approach. It is shown that for regolith with low water content, characteristic of equatorial regions on Mars, the combined process offers a more attractive (from an energy usage perspective) way of extracting water. Because the equatorial regions are more suitable for early manned Mars missions, with flat terrain, low latitude and low altitude, the use of this combined process rather than the traditional use of pure heating can potentially play an important role in improving the practicality of such missions.

On the other hand, it was assessed the possibility to use the sensible heat stored in the regolith as supplier of the sublimation latent heat and then eliminating the need of external heat source. preliminary rough calculations are showing that with the temperatures of the regolith of Mars, regolith with water concentration up to 8% can use it sensible heat as latent heat to sublimate its own water.

Finally it was demonstrated the attractiveness of the surface wind energy as feasible and reliable source of direct mechanical energy for water sublimation via depressurization during all seasons and for any water content in the regolith. Preliminary calculations are showing that with a small windmill no longer than 2 meter of radius and working with a poor efficiency could be enough to supply the required water for a crew of six for 600 days on Mars according with a typical design reference missions for human exploration of Mars.

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