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FEASIBILITY STUDY OF WATER VAPOR ADSORPTION ON MARS FOR IN SITU RESOURCE UTILIZATION

S.C. Coons, J.D. Williams, and A.P. Bruckner Aerospace and Energetics Research Program University of Washington, Box 352250 Seattle, WA 98195-2250

ABSTRACT

This paper presents the results of a feasibility study of the extraction of water vapor by adsorption from the Martian atmosphere, for in situ resource utilization (ISRU) purposes. Past proposals for extracting atmospheric water have invoked a compression-cooling process, which requires a prohibitively high specific power input. At the University of Washington the Water Vapor Adsorption Reactor (WAVAR), a highly effective water extraction concept based on adsorption processes in zeolite molecular sieves, is being developed. In this device, Martian atmosphere is forced over a zeolite bed which adsorbs the trace water vapor. Once the zeolite bed is saturated, it is removed from the flow, placed in a sealed chamber, and the water vapor desorbed by microwave heating of the bed, all in a continuous batch process. The water vapor thus obtained is condensed and electrolyzed into H₂ and O₂. The H, can be combined with the atmospheric CO₂ in a Sabatier reactor to produce CH₄ and additional water that is recycled. The resulting ratio of O_2 to CH_4 is 4.0, very close to the optimum ratio of 3.5 for a CH₄/O₂ rocket. Based on the encouraging performance comparison of the WAVAR concept with the compression-cooling process, a detailed simulation was run, using the first 250 sols of Viking Lander 1 meteorological data. A successful preliminary experiment on the microwave reactivation of the molecular sieve, zeolite 3A, was performed as well. The use of realistic Mars atmospheric data, however, highlighted the importance of landing site selection when using the WAVAR, as available atmospheric water quickly becomes minuscule if the ambient temperature drops below about 200 K.

1. INTRODUCTION

The future of cost-effective exploration of Mars, and indeed the solar system, depends strongly on the development of a strategy known as *in situ* resource utilization, or ISRU.¹ In situ resource utilization is defined as the use of indigenous resources at the site of an interplanetary mission for the production of propellant and/or life support consumables. For the past five years Mars mission analyses for both piloted and robotic exploration have been conducted at the University of Washington.^{2,3,4,5} All of these missions have used ISRU propellant production plants and all have shown the significant merit of the ISRU approach over more conventional designs in which the return propellants are brought from Earth.

The UW designs have incorporated the Sabatier/electrolysis (S/E) cycle for production of methane/oxygen propellant. In the past, these propellant plants, based on designs by Zubrin, et al,^{67,8} have required hydrogen feedstock, which must be transported from Earth. The severe problems associated with long-term cryogenic hydrogen storage prompted the search for alternative methods for getting hydrogen to Mars. If a reliable source of water on Mars were accessible, a completely ISRU mission could be undertaken, with no dependence on imported feedstock.

The existence of water on Mars is undisputed - water is present in the soil, very likely as subsurface permafrost or aquifer, in the polar caps, and as vapor in the atmosphere.⁹ Extracting water from the polar caps would involve minimal mining and processing, but would entail landing on rough terrain and at high latitudes which preclude effective solar power generation. Moisture concentration and distribution in the regolith is poorly understood and extraction would be both energy and equipment intensive.¹⁰

The atmosphere of Mars is the most highly characterized water source on the planet.¹¹ The need to access this atmospheric water led to the development of the Water Vapor Adsorption Reactor (WAVAR) concept by the authors.¹² Adsorption is a separation process that utilizes molecular sieves, which selectively attract specific molecules of a fluid mixture as that fluid passes through a fixed bed of adsorbent. Adsorption itself is an exothermic process requiring no energy input, other than that required to move the fluid. Removal of the adsorbed molecules from the bed, however, does require energy. Water vapor separation by adsorption has fewer moving parts, and is both less massive and much less energy intensive than the compression-cooling processes proposed in the past.¹³

^{*} Graduate Student, Student Member AIAA.

[†] Professor, Fellow AIAA. Corresponding Author.

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The possible uses of a WAVAR unit on Mars are as numerous as the number of ways water is used here on Earth. For example, the extracted water could be used for direct human consumption, for cooling, and for life support (horticulture, waste reclamation, etc.) during piloted missions. The WAVAR unit, combined with a Sabatier reactor, could also produce methane/oxygen propellant entirely from indigenous resources. This process is highly amenable to automation and could be used to produce return propellants for an unmanned sample return mission or scaled up for a manned mission.

Figure 1 shows the process diagram for an S/E cycle with the WAVAR. Martian atmosphere is brought into the system with the WAVAR unit, which removes the water vapor. The water vapor is electrolyzed into H, and O₂. The O₂ is stored for use as an oxidizer while the H₂ is combined with CO, from the atmosphere in the Sabatier reactor, where the ruthenium-on-alumina catalyst converts the reactants into CH₄ and H₂O. The CH₄ and H₂O are separated in the storage tank, with the CH₄ sent to storage for use as the fuel and the H₂O sent back through the system for reprocessing. Beginning the Sabatier reaction of the S/E cycle with H, from Earth feedstock (imported for Mars-based applications) results in an O/F ratio of 2, much lower than the optimum of 3.5 for a CH₄/O₂ rocket⁴. However, beginning the S/E cycle with in situ H₂O as the feedstock results in an O/F ratio of 4, much closer to the optimum.



Figure 1 Process diagram for WAVAR with Sabatier/electrolysis cycle

The WAVAR concept was originally introduced in 1995,¹² and the preliminary mass and power estimates indicated it should be an attractive answer to the hydrogen transportation problem. This paper presents the follow-on work that has transpired since the original introduction of the WAVAR. Section 2 discusses the availability of water in the Martian atmosphere. Section 3 describes the WAVAR concept, while Section 4 details the adsorption process under Martian ambient conditions. A preliminary experiment on the microwave desorption of water from zeolite 3A is presented in Section 5, and the pressure drop

and power requirements for the system fan are evaluated in Section 6. Finally, Section 7 discusses a performance simulation using the first 250 sols of Viking Lander 1 temperature, pressure, and humidity data, and conclusions are presented in Section 8.

2. ATMOSPHERIC WATER ON MARS

Water vapor in the atmosphere of Mars has been studied for more than 30 years, from ground-based observatories, from orbit (Mariner 9 and Viking 1 and 2), and from Mars' surface (Viking 1 and 2).¹⁴⁻²⁰ Although considerable information has been obtained about the seasonal and hemispheric distribution of water vapor, specific local water vapor data, in the form of local concentrations, are available only at the Viking landing sites. The bulk of the data on Mars atmospheric water was obtained by the Viking orbiters' Mars Atmospheric Water Detectors (MAWD). These were spectrometric instruments that monitored three water vapor absorption lines near 1.38 μ m and two adjacent continuum regions.¹⁵

Water vapor was found to be a highly variable component of the Martian atmosphere. Both seasonal and daily cycles were observed and the amount of water vapor varied strongly with latitude. The total mass of water per unit area of a vertical column extending from the ground to the top of the atmosphere was determined by MAWD for a period of nearly 1¹/₂ Mars years (2.7 Earth years).¹⁵ This amount, expressed as precipitable micrometers (pr µm) ranged from less than 1 pr µm at high southern latitudes in midwinter to 100 pr µm in high northern latitudes in midsummer. The results are shown in Figure 2,16 which shows the column abundances of water vapor as a function of latitude and season, as zonally averaged abundances in pr µm. Such small amounts appear to indicate an extremely dry atmosphere compared to Earth's (the total water content of Mars' atmosphere is between 1 and 2 km³, compared to 13,000 km³ for Earth). However, when compared to the total amount of water in Earth's atmosphere above the level (~33,000 m) at which its pressure matches the surface pressure on Mars (~6 torr), the atmosphere of Mars is very wet.¹⁷ It has been observed that, on the average, the atmosphere of Mars is holding as much water as it can on a daily basis (i.e., 100% relative humidity at night throughout the lowest several kilometers, at most seasons and latitudes).18

Because both the MAWD and Earth-based instruments have provided integrated data, translating column abundance in pr μ m to water concentration (kg/m³) near the surface is not straightforward without knowledge of the vertical distribution of vapor. There is some evidence that water vapor may be somewhat uniformly mixed with altitude,¹⁹ but this condition does not apply at all geographic locations, during all seasons, or during dust storms.^{18,20} The global average volume fraction of water vapor is 3×10^{-4} , i.e., a concentration of 2.3×10^{-6} kg/m³ at 220 K and 6 torr. (For the analysis of the performance of their compression-cooling water extraction scheme, Meyer and McKay¹³ assumed a humidity equivalent to saturation at 213 K, which gives a volume fraction of 1.35×10^{-3} or 4.5 times the global average).



Figure 2 Column abundance of water vapor in Martian atmosphere from Viking MAWD.¹⁶

Ryan *et al.* were able to deduce local near-surface water vapor concentrations at the two Viking landing sites from the temperature data obtained by the landers 1.6 m above the surface.^{20,21} They observed that the nighttime cooling curves exhibited an inflection point, which they interpreted as the freeze point.²¹ They hypothesized that at this temperature an ice fog should form and, indeed, atmospheric opacity data²² showed that opacity was always greater at night than during the day, consistent with the appearance of nighttime fog. However, there are other possible explanations for the behavior of the nighttime cooling curve.²³ The water concentration plots that Ryan *et al.* published²⁰ are reproduced here in Figure 3 and Figure 4.

Figure 3 shows the absolute water vapor concentration (circles) at the Viking Lander 1 (VL-1) site, 1.6m above the surface, the values given being a direct conversion from the frost point temperature as measured by the ambient temperature sensor aboard the lander. The data cover one Mars year (about 669 sols). Most data points represent a single frost point occurrence, but some are composites of two or three adjacent sols. Also shown is water vapor column abundance (crosses) at the VL-1 site (10° by 10° boxes containing VL-1) for the same time period. These data were obtained by the MAWD aboard the Viking orbiters. The counting of VL-1 sols begins at the landing of VL-1.



Figure 3 Water vapor concentration (circles) and column abundance (crosses) at VL-1 site.²⁰

Figure 4 shows the same type of data as Figure 3, except for the VL-2 site and using the reference temperature sensor. The counting of VL-2 sols begins at the landing of VL-2. VL-2 landed 44.5 sols after VL-1.²⁰ At the Viking 1 site the maximum water concentration was about 1.8x10⁻⁶ kg/m³, or somewhat below the global average, and occurred during the summer. The minimum concentration was $\sim 1.8 \times 10^{-7} \text{ kg/m}^3$, and occurred, as expected, during the winter. At the Viking 2 site the seasonal variation was even more extreme: $3x10^{-6} - 4x10^{-10}$ kg/m³, primarily because it is at a much more northerly latitude than the Viking 1 site, i.e., 48.0° N vs. 22.5° N, and thus its winter is much colder. At both sites the minima of humidity were far below the global average. At the Viking 1 site the column vapor abundance, which varied between a high of 26 pr µm and a low of $2 \text{ pr} \mu \text{m}$, tracked the surface vapor data fairly closely (Figure 3), indicating uniform mixing with height. At the Viking 2 site the situation was different. Figure 4 shows that although surface humidity varied by almost four orders of magnitude at the Viking 2 site, the column abundance varied by only about one order of magnitude $(30 - 2 \text{ pr } \mu\text{m})$, indicating that water was not uniformly mixed vertically in the atmosphere. The discrepancy was particularly noticeable during the northern summer.



Figure 4 Water vapor concentration (circles) and column abundance (crosses) at VL-2 site.²⁰

It is interesting to compare Ryan *et al.*'s data with saturated water vapor data, i.e., frost point data, computed at various temperatures. These are shown in Table 1, from 180 K to 220 K in 10 K increments, for an average atmospheric pressure of 6 torr. (Note that data for 213 K are also shown, for reference to the work of Meyer and McKay¹³). The global average volume fraction of $3x10^{-4}$ corresponds to a frost point at about 203 K.

It is also useful to compare Ryan *et al.*'s data to the diurnal temperature data obtained by the Viking 1 lander.²⁴ For the first 380 sols, the maximum, mean (sol-averaged), and minimum temperatures prior to the onset of the first

dust storm (at about sol 210) were approximately 245 K, 218 K, and 188 K respectively. The saturated water concentrations at these temperatures are respectively 4.0×10^{-4} , 2.0×10^{-5} , and 2.6×10^{-7} kg/m³ Thus the relative humidity, defined as the ratio of actual concentration to saturated concentration, was 0.45% during the peak daytime temperature, 9% on a diurnal average, and 100% at the nighttime low. The daytime and diurnal relative humidities were thus well below saturation but the atmosphere reached saturation at night.

It is evident that the conditions assumed by Meyer and McKay¹³ (and used by us for direct comparison of our WAVAR concept¹² to their compression-cooling concept) were optimistic, at least when compared to the global average or to the Viking sites. This is not to say that sites on Mars with equivalent or higher humidity do not exist. For example, in Figure 2, it can be seen that there is an area in the vicinity of the north polar cap, where during the summer the column abundance of water vapor approaches 100 pr μ m. Proximity to the pole is disadvantageous during the winter, however. Thus water vapor extraction at high northern latitudes would only be feasible during northern summer. Of greater interest may be certain features on Mars, such as several craters and canyons that in the Viking orbiter images showed ongoing visible signs of moisture, namely early-morning fog.¹⁷ In addition to the nighttime fog producing mechanism mentioned above, these fogs may have been created by the conversion of ground frost into vapor by the morning sun. The vapor would have condensed again as it rose through the frigid atmosphere of the early morning. These fogs were seen repeatedly, day after day in some locations, indicating that theses sites had higher than average humidity. One such case was the canyon Noctus Labyrinthus (Figure 5), located at the western end of Valles Marineris. The white areas are blanketed by fog. (These areas are known to be fogs rather than frost on the ground because no surface details are visible there). A possible downside of this site is that it is about 3 km deep and may experience "interesting" drainage winds.25

ТЕМР. (К)	VAPOR PRESSURE* (torr)	VAPOR CONCENTRATION (kg/m ³)	VAPOR VOLUME FRACTION	VAPOR MASS FRACTION	VOL. MARS AIR REQUIRED† (m ³ /kg H ₂ O)
180	4.04E-05	6.39E-08	6.73E-06	2.79E-06	1.56E+07
190	2.43E-04	3.65E-07	4.05E-05	1.68E-05	2.74E+06
200	1.23E-03	1.75E-06	2.04E-04	8.47E-05	5.73E+05
210	5.29E-03	7.18E-06	8.82E-04	3.66E-04	1.39E+05
213	7.99E-03	1.07E-05	1.33E-03	5.53E-04	9.35E+04
220	2.00E-02	2.59E-05	3.33E-03	1.39E-03	3.86E+04

Table 1 Saturated (frost point) water vapor data at 6 torr.

* Vapor pressure calculated from Clausius-Clapeyron equation curve fit to water vapor over ice data in CRC Handbook of Chemistry and Physics, 1982 Edition.

† Volume of Mars atmosphere that must be processed to obtain 1 kg of water.



Figure 5 Noctus Labyrinthus showing ground fog in upper left.²⁵

3. THE WAVAR PROCESS AND DESIGN

WAVAR is conceptually very simple, as can be seen from Figure 6. Martian atmosphere is drawn into the system through a dust filter by the fan. The filtered gases are passed through the adsorbent bed, where the water vapor is removed from the flow. Once it has reached saturation, the bed is regenerated and the desorbed water vapor condensed and piped to storage. The design has only six components: a filter, a fan, an adsorption bed, a regeneration unit, a condenser and an active-control system. Figure 7 shows a vertical configuration and the dimensions used for the simulations in this paper. The critical subsystems are shown in the figures and described below.



Figure 6 Process diagram of WAVAR, the Water Vapor Adsorption Reactor.



Figure 7 WAVAR side view, vertical configuration used for simulation

The WAVAR fan has to move a low temperature (~215 K), low pressure (4-6 torr) gas, deal with frequent off-design operational periods, and work continuously and reliably for long periods (500 sols typical surface stay for low-energy Mars transfers). Because the flow will already be rigorously filtered to minimize fouling of the adsorption bed by Martian dust, abrasive wear on the fan can be kept to a minimum. The motor used for the WAVAR pump is of a high-speed, low-torque design. It must operate over a range of loadings because of the variable nature of the ambient density.²⁶ The filter used to remove ambient dust is of the fibrous bag-type, which can be easily cleaned with periodic blasts of compressed atmosphere and reused.

Adsorption is a process used to concentrate a substance (the adsorbate) out of a fluid as it is passed through a fixedbed (the adsorbent). Molecules are attracted to the surface of the adsorbent by Van Der Waals forces.²⁷ Selectivity is a result of two microscopic phenomena: 1) molecular sizeexclusivity of the adsorbent's micropore structure, and 2) the difference in sorption rates between the flow constituents.²⁸ Because the adsorbency of a bed is finite, the adsorptiondesorption cycle is necessarily a batch process. For water vapor adsorption on Mars, the choice of adsorbent is limited to those with an aperture of 3 Å (slightly larger than a water molecule), such as UOP (formerly Union Carbide) Molecular Sieve 3A. (Section 4 provides further details about zeolites and the adsorption/desorption process). In the WAVAR concept, the pelletized adsorbent is packed into a disc-shaped bed (Figure 8), that is divided radially into sectors. Each of these sectors is sealed from the others with insulated dividers to prevent lateral heat and mass flow during regeneration. The bed is rotated stepwise, with one sector at a time brought into the regeneration unit while the

others are adsorbing water from the flow. The bed's rotation is timed by the control system so that the sector about to enter the regeneration unit is just reaching saturation. The control system monitors the humidity of the output and adjusts the rotational rate and regeneration time for maximum efficiency. condenser unit is then opened and the microwave emitter turned on. Water vapor begins to desorb and is piped to the condenser and then to storage. The control system monitors the regeneration of the sector, adjusting power and bed rotation for maximum efficiency.



Figure 8 WAVAR zeolite bed and regenerator

Regeneration, or desorption, of the bed can be achieved by one of two means: pressure swing regeneration and thermal swing regeneration.²⁸ Pressure swing regeneration involves reducing the pressure to drive off the adsorbate. Thermal swing regeneration involves heating the bed until the thermal energy of the adsorbed molecules is greater than the adsorbent/adsorbate bond strength. Thermal swing regeneration is preferred for strongly adsorbed species such as water and can be accomplished either through resistive heating or with microwaves, as shown here. The use of microwaves for the regeneration of adsorbent media is not unprecedented. It has been shown for different adsorbents in work by Grimes²⁹ and Balbaa, et al.³⁰ The major advantage of using microwave energy over conventional conductive heating is that it provides rapid uniform heating for reduced regeneration time and can be tailored to specifically heat water molecules.

In the WAVAR, the microwave regeneration unit remains in place while the adsorbent bed rotates through it stepwise (Figure 9). A saturated section rotates into the regeneration unit. Each sector is isolated with insulated separators and an insulated endcap. The sealing mechanism of the regeneration unit consists of two plates with teflon seals that engage the separations and endcap, forming a sealed chamber for regeneration. The valve for the



Figure 9 Edge-on view of regeneration unit.

The condenser shown in Figure 7 is one possible configuration for this stage. Care will have to be taken to ensure that the water does not freeze before storage. However, the use of a vapor-feed electrolyzer within an ISRU propellant plant could preclude the need for any condensation.

4. ZEOLITE ADSORPTION UNDER MARTIAN CONDITIONS

Zeolite Type A (sometimes referred to as LTA, or Linde Type A) is an alumino-silicate characterized by an even number of aluminum oxide, silicon oxide, and cation molecules in a cubic array.²⁷ The structure of a typical LTA zeolite (4A) is shown in Figure 10. The pore size of a molecular sieve adsorbent determines its sieving properties, as fluid molecules larger than the pore size are excluded from the tightly binding internal cages. Molecules allowed through to these internal cages are bound to the internal surface by Van Der Waals forces.

The baseline LTA molecule has a sodium cation and a pore size from 3.6 to 3.9 Å. However, replacing the sodium with other cations changes the pore size. To reduce the pore size to the level required to exclude CO_2 , the sodium cation is completely replaced with potassium, resulting in Type 3A with a pore size of about 3 Å.³¹ Figure 11, which plots the adsorbent loading fraction, x/m, in grams adsorbate (x) per gram adsorbent (m), shows the effect of the exchange of sodium with potassium on the sieving properties of this zeolite.



Figure 10 The molecular structure of LTA zeolite, type 4A.²⁷

The important curves in Figure 11 are curves 1 and 3, which show that CO₂ adsorption drops to zero as Na is completely replaced with K, while H₂O adsorption remains fairly constant. According to Suzuki,³² zeolite 3A will have a pore size such that "...only H₂O and NH₃ can penetrate through the window."



Figure 11 Effect of potassium exchange for sodium on the sieving properties of zeolite A.³¹

Figure 12 shows the correlation between effective pore size of various zeolites with the kinetic diameters of various molecules. The apparent pore sizes of these zeolites show a temperature dependence. For example, in Figure 12 it can be seen the pore size of zeolite 3A (KA) varies from 2.9 Å. at 77 K to a maximum of 3.4 Å at 420 K.³¹

At the low adsorption temperatures that zeolite 3A would see on Mars, an interpolation of the temperature dependent line gives a pore size of 3.1 Å. From Table 2 it can be seen that CO₂ has an effective kinetic diameter of 3.3Å based on the Lennard-Jones potential relation, while H_2O has a kinetic diameter of 2.65 Å.³¹ This explains the behavior of the CO₂ curve in Figure 11. As the extent of exchange of Na by K goes from 0 to 100%, the pore size is continually reduced until the adsorption of CO₂ becomes negligible (even though at 700 torr) while H₂O adsorption at 4.5 torr is unaffected. Given the polar nature of the water molecule and the fact that the heat of adsorption for H₂O on LTA is typically 2-3 times that of CO_2 ³¹ the indication is that H₂O would be adsorbed preferentially, even if CO₂ were not otherwise excluded. With a completely potassiumexchanged Type 3A, the adsorption of CO₂ will be external, amounting to only 0.2-1% of the bed mass,³³ and will have negligible effect on the maximum loading of H₂O at equilibrium. The performance of zeolite 3A should. nevertheless, be experimentally confirmed at Mars ambient conditions.



Figure 12 Effective pore size of various zeolites in equilibrium adsorption.³¹

Adsorption Isotherms

Derivation of the adsorption isotherms for zeolites can be done using any of a number of adsorption equations, since no universal adsorption equation exists that applies to zeolites under all conditions. Typically, experimental data are used to fit a particular model over a set range and the model is not expected to be as accurate outside of that range. For zeolites, the classical Langmuir model has frequently been applied successfully. The Langmuir equation is:³¹

$$\frac{x}{x_m} = \frac{Bp}{1+Bp} \tag{1}$$

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	Pauling		Lennard	dJones
	Length (A)	Width (A)	$r_{min}(A)$	$\sigma(A)^{a}$
He		~ 3	3.0	2.6
H ₂	3.1	2.4	3.24	2.89
Ne		3.2	3.08	2.75
Ar		3.84	3.84	3.40
02	3.9	2.8	4.02	3.46
N ₂	4.1	3.0	4.09	3.64
Kr		3.96	3.96	3.60
Xe		4.36	4.45	3.96
NO	4.05	3.0	3.58	3.17
N_2O	4.2	3.7		3.3
õ	4.2	3.7	4.25	3.76
CO2	5.1	3.7	· · · · · · · · · · · · · · · · · · ·	3.3
Cl ₂	5.6	3.6	·····	3.2
Br ₂	6.2	3.9		3.5
H ₂ O	3.9	3.15		2.65
NH ₃	4.1	3.8		2.6
SO ₂	5.28	4.0		3.6
CH4		4.2	4.25	3.8

 Table 2
 Dimensions of various molecules.³¹

where x is the quantity adsorbed, x_m the maximum adsorbate holding capacity of the adsorbent, p is pressure, and B is a temperature-dependent parameter. This parameter is typically derived experimentally, but no data for water on 3A were found, though it could be estimated by comparing with the Dubanin-Polanyi (D-P) model, which has been found to apply to zeolites in many instances.³¹ The D-P equation is:

$$\frac{x}{x_m} = \exp\left[-\frac{b}{\beta^2} \left(T\log\frac{p_s}{p}\right)^2\right]$$
(2)

where b is a constant, T is temperature, p is pressure, p_s is saturation pressure, and β is an affinity coefficient, assumed to be temperature-independent. The D-P equation does not require determination of a temperature-dependent parameter but was found to break down below 298 K. It was therefore modified to more closely reflect the Langmuir model by setting the isotherms in the lower temperature ranges, where the model was breaking down, to the maximum loading once the curve reached this maximum. The D-P model is plotted in Figure 13 in terms of the loading fraction for 200, 298, 373, and 450 K isotherms. A maximum pore volume of 21% was assumed for 3A, based on 20% equilibrium loading at 298 K from a UOP product information sheet,³³ the extra 1% representing the asymptotic maximum.

Desorption

From the isotherms, isobaric curves can be derived. If we assume there is little or no hysteresis, then these adsorption curves become desorption curves. Using the modified D-P model, Figure 14 shows desorption isobars plotted for desorption pressures of 6, 8, and 760 torr. The isobar for 760 torr is included only for comparison purposes. The water vapor output does not need to be immediately compressed to this level to meet system pressures, however, only to a high enough pressure to drive the vapor from the regeneration chamber to the condenser and/or electrolyzer. The water can then be compressed mechanically or through another means to meet system pressure requirements. As can be seen in Figure 14, desorption at 1 bar (760 torr) requires higher temperatures and should be avoided.



Figure 13 Adsorption isotherms for H_2O on Zeolite 3A, modified D-P model.

Figure 14 also shows the desorption approaching 100% asymptotically for the 6 and 8 torr isobars as the temperature rises. There is, therefore, an optimum desorption temperature at which the amount of water desorbed begins to decrease and the system starts seeing diminishing returns. This optimum desorption temperature varies with desorption pressure, and can be derived by determining the specific energy isobars.



Figure 14 Desorption isobars for H₂O on Zeolite 3A.

Figure 15 shows a plot of the specific heat of the zeolite bed and the adsorbed water vapor. The total energy is the integration of the curve from the minimum temperature to the maximum (desorption) temperature, plus the desorption energy times the total water desorbed based on the desorption curve. The desorption energy is a function of the loading of the bed, varying from a minimum in a fully loaded bed to a maximum in a completely desorbed bed. For the purposes of these calculations, the desorption energy was conservatively assumed to be the maximum of 4.2 kJ/g^{33} throughout the desorption process.



Figure 15 Specific heat for zeolite and water vapor vs. temperature for 6 and 8 torr

From the calculation of the total energy, the specific energy, in megajoules per kilogram water, is calculated. The optimum final desorption temperature corresponds to the point where the specific energy reaches a minimum. Figure 16 shows a plot of specific energy versus final desorption temperature, and identifies the minima for 6 and 8 torr. The figure for a 6 torr desorption pressure is 5.48 MJ/kg water recovered, rising to 5.54 MJ/kg at 8 torr. These particular numbers are for an ambient temperature of 220 K and will become larger at colder ambient temperatures. These figures also assume an adiabatic system. Of course, heat loss from the chamber (though well insulated) will at some point need to be accounted for.

5. EXPERIMENTAL MICROWAVE DESORPTION OF ZEOLITE

As stated above, the use of microwave energy for the regeneration of zeolites has been demonstrated.^{29,30} However, there are several questions particular to the needs of the WAVAR device which can be addressed with some simple experiments, namely, the effectiveness of microwave regeneration and the long-term reliability as the same zeolite

sample is repeatedly microwaved. The preliminary experiments described here sought to address these concerns.



Figure 16 Specific energy (MJ/kg H₂O) for water desorbed at 6 and 8 torr

The equipment necessary for a series of well-controlled adsorption and desorption experiments under simulated Martian conditions was not yet available to the authors at the time of writing. However, a rough experimental evaluation of microwave desorption of zeolite 3A can easily be performed with minimal equipment and setup: some zeolite, a microwave oven, and a scale.

The zeolite 3A used in the experiment was pelletized 8-12 mesh from Aldrich Chemical (Figure 17). Saturation of the sample was done passively with the zeolite in a flat metal dish placed in a freezer at 260K (adsorption increases at lower temperatures as noted above) and exposed to humidified air. When saturated, the sample was placed in a 150 ml beaker for heating in the microwave oven, a 700 W commercial type. Desorption was determined by weighing the sample on a triple-beam balance. The necessity of making the experiment a discrete process introduced some error as the sample began to cool once removed from the oven. However, a rapid cycle time kept such error to a minimum. Ideally, of course, such experiments would be performed entirely in a humidity-, temperature-, and pressure-controlled chamber.

A roughly 50 g sample of zeolite 3A was saturated and desorbed with the microwave several times before any data were taken. This was so that data would be taken on a sample that had already been repeatedly exposed to microwave energy. Adsorption was done passively, with final loading determined by weight. The sample was then continuously heated and weighed to determine the dry mass. During this preparation, the sample was accidentally overheated and the center of the sample melted into glass (see Figure 18). This exposes the danger of microwaving zeolite, especially if the adsorbent bed cannot be easily mixed during heating. However, overheating can be avoided by carefully monitoring the water content and temperature of the zeolite bed to ensure that the bed is never completely desorbed, and by desorbing at a slower rate with a lower microwave power level. In the laboratory, zeolite can be completely regenerated using microwaves if some care is taken in the desorption process.



Figure 17 Pelletized zeolite 3A.



Figure 18 Glass nodule formed by overheating zeolite sample.

A step by step desorption experiment was then run with the same sample (with melted material removed) freshly saturated. The sample was heated for 10-second intervals in the microwave and quickly weighed after each heating. Figure 19 shows a plot of the data. Maximum loading of water vapor on zeolite 3A is typically 20-23%. As the figure shows, this sample had not reached this level when the desorption experiment was begun. However, a typical desorption curve is evident.

The first heating interval resulted in very little desorption, as most of the microwave energy went into

heating the sample up to desorption temperature. For the next 90 sec, heating resulted in condensation on the container, which had to be quickly wiped off before weighing. After 100 sec, less condensation became noticeable as the rate of desorption decreased.



Figure 19 Microwave desorption of zeolite sample.

Other desorption experiments were run with similar results. During one of the subsequent experiments, the sample was weighed, stirred, then weighed again. This was done to determine whether mixing during desorption was a necessity, which could be a considerable problem for an automated process. It was noted that mixing of the sample produced noticeable mass change only when at the very top of the desorption curve, when the sample was most highly loaded. Mixing would of course be necessary if a complete desorption of the sample were attempted, to avoid excess heating of the zeolite itself.

6. WAVAR PUMPING REQUIREMENTS

There are four main power draws during operation of the WAVAR device: the microwave heating unit, the actuators to seal the regeneration chamber and rotate the bed, the computer control system and sensors, and the fan. The desorption process was outlined in Section 4, though no efficiency factors (such as microwave efficiency and extraction efficiency) were included in that analysis. The mechanisms to rotate the adsorption bed and seal the regeneration chamber require much less power than the microwave itself, and since the two are never running the microwave heating requirements concurrently, dominate. The power requirements for the computer and sensors can be considered constant and minimal (~5 Watts). The largest power draw for the system is that of the fan, and determining its power requires examination of all the pressure drops throughout the system.

Identification of the sources of pressure loss through the system is simple. A quick look at Figure 20 shows the two main sources of pressure drop, ΔP : the filter and the adsorption bed. A third source, the ductwork, is comparatively negligible.¹² All sources of ΔP are functions of the flow velocity.



Figure 20 System control volume for determination of pressure drop.

Filter ∆P

Filter pressure drop is proportional to the flow velocity and dependent on the type of filter medium. For the pressure drop calculations, a Filtrete Type G filter from 3M was chosen.³⁴ Filtrete is an electrostatically enhanced nonwoven fiber and is available in numerous grades, each having different filtration efficiencies and associated pressure drop. For WAVAR applications on Mars, a Filtrete G-200 will provide 95% efficiency, or greater, over the applicable velocity range. Based on pressure drop data listed in Ref. 34, which was then dimensionalized by density, a linear pressure drop correlation was determined as:

$$\Delta \mathbf{P}_{\text{filter}} = \mathbf{P}_1 - \mathbf{P}_2 = 127.46 \cdot \boldsymbol{\rho} \cdot \mathbf{V} \tag{3}$$

This relation will give pressure drop in Pascals provided fluid density ρ and fluid velocity V are in SI units. Filtrete has been reported to have a longer life and greater temperature stability compared to similar media³⁴ and should be acceptable for the ambient conditions that WAVAR will see on Mars.

Bed ΔP

There are a number of ways to estimate pressure drop across a packed bed. If the flow through the bed can be considered purely laminar, the Poiseuille flow equation can be used:³⁵

$$\Delta P_{bed} = \frac{32V L\mu}{D^2} \tag{4}$$

where L is the bed depth, μ is the viscosity, V is the flow velocity, and D is the pellet diameter. However, a laminar

flow assumption is not always valid, especially for tightly packed beds with small pellet diameters. Ergun added a term to the Poiseuille equation to account for turbulent flow.³⁶

$$\Delta P_{bed} = f \cdot \frac{(\varepsilon V)^2 L \rho}{D}$$
⁽⁵⁾

where ε is the void fraction, ρ is the fluid density, f is the Ergun friction factor given below, L is the bed depth, μ is the viscosity, V is the flow velocity, and D is the pellet diameter. The Ergun friction factor is

$$f = \left(\frac{1-\varepsilon}{\varepsilon^3} \int \frac{150(1-\varepsilon)}{Re_p} + 1.75\right]$$
(6)

where Re_p is the Reynolds number based on bed particle diameter and superficial fluid velocity (flow speed without bed).

The first term of Ergun's friction factor represents laminar flow while the second represents turbulent flow. The coefficients 150 and 1.75 were determined experimentally by Ergun.^{36,37} The Ergun equation is very sensitive to small changes in void fraction ε , requiring that a very accurate value for bed voidage be available. If no such measurement exists, then another correlation should be used. For LTA zeolites of nominal pellet size 3.25 mm. the typical void fraction is between 0.34 and 0.32.³⁷ However, within this range, the Ergun equation appears to overestimate the pressure drop when compared to other correlations.

A more recent correlation attributed to Gupta and Thodos makes use of the Chilton-Colburn J Factor Analogy.^{38,39} They recommended a correlation for gas flow in a packed bed of spheres in the form

$$\varepsilon J = 2.06 R e_D^{-0.575}$$
 (7)

where J is the Colburn J Factor, ε is the void fraction, and Re_D is the Reynolds number based on pellet diameter and upstream velocity. To develop a pressure drop relation from this, the Chilton-Colburn J Factor Analogy for mass transfer is used^{38,39}

$$J = \frac{F_f}{2} \tag{8}$$

where F_f is the Fanning friction factor (often simply referred to as the *friction coefficient*). Then the pressure drop equation for laminar flow is used³⁵

$$\Delta P_{bed} = F_f \cdot \frac{2\rho V^2 L}{D} \tag{9}$$

with the final correlation becoming

$$\Delta P_{bed} = \frac{8.24\rho V^2 L}{\varepsilon D} \cdot R e_D^{-0.575}$$
(10)

with ρ , V, L, ε , D, and Re_{D} defined as above. This relationship is effective for Reynolds numbers between 90 and 4000.

A correlation that is valid for Reynolds numbers less than 40 begins with the same pressure drop relation as Ergun with a simpler friction factor attributed to Chilton and Colburn.³⁷

$$\Delta P_{bed} = \frac{805}{Re_D} \cdot \frac{(\varepsilon V)^2 L\rho}{D}$$
(11)

This expression, while attractive in its simplicity, would underestimate pressure drop drastically for higher Re_D . The operating conditions on Mars generally result in values for Re_D of between 20 and 120. For higher Re_D , Chilton and Colburn derived the following model for pressure drop³⁷

$$\Delta P_{bed} = \frac{38}{Re_D^{0.15}} \cdot \frac{(\varepsilon V)^2 L\rho}{D}$$
(12)

Figure 21 shows a comparison of several of the pressure drop models for a void fraction of 0.33. The two Chilton-Colburn models above (for $Re_p < 40$ and $Re_p > 40$) are labeled as CC < 40 in CC > 40, while the Colburn-J model is shown labeled as ColJ. The Chilton-Colburn models seem to agree well with the Colburn-J model for the assumed void fraction and the plotted range of Re_p , while the Ergun correlation is much higher than the other models. For higher void fractions (>0.4), the Ergun correlation more closely matches the other models.

The two correlations with close agreement (Chilton-Colburn and Colburn-J) both have Re_p raised to a power. However, a simpler linear approximation is desired to enable the combination of the filter and bed pressure drop correlations into a single expression for power as a function of flow velocity. Such an expression can be derived by increasing the constant term in the low Re_p Chilton-Colburn correlation. If the model is taken as

$$\Delta P_{bed} = P_3 - P_4 = \frac{1800}{Re_D} \cdot \frac{(\varepsilon V)^2 L\rho}{D} = 1800 \cdot \frac{\varepsilon^2 V L\mu}{D^2}$$
(13)

the simplicity of a linear model can be retained for use with the assumed void fraction ($\varepsilon = 0.33$) as an acceptable (and conservative) correlation within the desired flow regime. This final model is plotted in Figure 21 and will be considered valid only for Re_n less than 120.



Figure 21 Comparison of pressure drop models within Martian operating conditions ($\varepsilon = 0.33$).

All the models detailed here have their roots in experimental measurements, but most of the research with packed bed flow is with atmospheric pressures or higher, and at ambient temperatures. While it is risky to apply any correlation outside of the range in which it was developed, there is little choice until low-pressure, low-temperature packed bed pressure drop is experimentally investigated and a more accurate empirical correlation derived.

Power Calculation

With the expressions for the ΔP introduced by the filter and the bed, a calculation of the power requirement for the fan is possible. For the performance calculations presented here, a four-bladed propeller (NACA 5868-9, Clark-Y section) was used to model the fan blades. A fan of this type with a 35° blade will yield an efficiency of 85% with an advance ratio J_{adv} of 1.5.⁴⁰ The dimensionless advance ratio J_{adv} is defined as

$$J_{adv} = \frac{V}{nD} \tag{14}$$

where V is the flow velocity, n is the number of revolutions per unit time period, and D is the diameter of the propeller. To maintain this advance ratio and thereby the maximum propeller efficiency, the ratio of V to nD must remain constant. The speed of the fan motor would therefore be continuously adjusted to maximize efficiency for the required velocity.

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The power requirement for the fan can be found using classical momentum theory in propeller analysis. The power required by the propeller equals the product of the thrust produced (flow area times pressure differential) and the velocity through the propeller $(V_3 = V_2)$ divided by efficiency.⁴⁰ Thus

$$Fan Power = \frac{V \cdot A \cdot \Delta P}{\eta_{fan}}$$
(15)

The power required for the fan is then dependent on the total ΔP , and the pressure drop for both the filter and the adsorption bed are functions of velocity, as discussed above. Equation 15 can now be rewritten as

Fan Power =
$$\frac{V \cdot A \cdot (\Delta P_{filter} + \Delta P_{bed})}{\eta_{fan}}$$

$$= \frac{V^2 A}{\eta_{fan}} \left(127.46\rho + 1800 \frac{\varepsilon^2 L\mu}{D^2} \right)$$
(16)

With an expression for the fan power incorporating the two ΔP sources, the total system power requirements can be modeled and performance calculations made.

Temperature Effects

Temperature across the filter is considered constant $(T_2 = T_1 = T_{amb})$. The temperature across the fan increases from the basic adiabatic energy balance:⁴¹

$$C_{p}(T_{3}-T_{2})+\frac{(V_{3}^{2}-V_{2}^{2})}{2}=\Delta W$$
(17)

where C_p is the specific heat of the atmosphere and ΔW is the specific energy of the flow (kJ/kg). As mentioned above, the velocity across the fan is considered constant⁴⁰ ($V_s = V_s$), so Eqn. 17 becomes:

$$T_3 - T_2 = \frac{Power_{fan}}{\rho AVC_p} \tag{18}$$

The exothermic adsorption process, and the cooling of bed sectors after they leave the regeneration chamber, heat the temperature at the outlet (T_4) . Because of the low mass flow rates of H₂O, the adsorption process does not heat the flow to any appreciable extent (less than 0.5 K for frost point temperatures of 200 K). Cooling of the justregenerated sectors will result in heating of the flow immediately aft of the regeneration chamber, but that flow quickly leaves the system and will not adversely affect the performance of the WAVAR.

7. PERFORMANCE CALCULATIONS AND SIMULATION

As stated at the beginning of the previous section, there are four major power draws in the WAVAR system, only two of which require analysis: the desorption power and the pumping power. It will now be necessary to combine the two analyses into a single performance calculation.

Performance Function

The fan power equation given in Section 6 above does not represent a maximum fan power, as flow velocity is only a limiting factor with regards to the RPM limits placed on the motor for a constant advance ratio (and thereby constant fan efficiency). For a 50 cm duct diameter and an advance ratio of 1.5, if the maximum flow velocity is 30 m/s, then the RPM requirements on the fan motor would be only 2400. Because power is the primary limiting factor, Eqn. 16 can be rearranged in terms of flow velocity as a function of fan power available. The electric motor itself will also have an efficiency, η_{mugr} , associated with it. Thus

$$V = \sqrt{\frac{\eta_{fan} \eta_{motor} P_{motor}}{A}} \left(127.46\rho + 1800 \frac{\varepsilon^2 L\mu}{D^2} \right)^{-1}$$
(19)

where P_{motor} is the electric power input to the motor.

Once the flow velocity is known, the desorption power requirements can be determined. The desorption power is dependent on the mass flow of water, which is derived from the mass flow of atmosphere multiplied by its absolute humidity (kg H_2O/kg atm). Using the same process which produced Figure 16 above, the optimum desorption energy is found for the given environmental conditions, and multiplied by the mass flow of water. Substitutions result in the equation below, giving desorption power as a function of flow velocity.

$$P_{desorp} = \frac{E_{opt} \cdot \dot{m}_{water}}{\eta_{micro}} = \frac{E_{opt} \cdot H_{abs} \cdot \rho VA \cdot \eta_{extract}}{\eta_{micro}}$$
(20)

where E_{opt} is the optimum specific energy as given by the analysis in Section 4 and Figure 16, \dot{m}_{water} is the mass flow of water, H_{abs} is the absolute humidity, ρ is the atmospheric density, V is the flow velocity, and A is the cross-sectional area of the duct. The expression above also includes an extraction efficiency $\eta_{extract}$ to account for any extraction losses (from unadsorbed vapor and regeneration chamber cycling, estimated at 90%). The microwave efficiency η_{micro} is 70% for a 915 MHz microwave.³⁰ Now, power for the fan motor and the desorption power are added together with the control system power, which is considered constant.

$$P_{tot} = P_{desorb} + P_{motor} + P_{control}$$
(21)

To ensure that the total power required does not exceed the maximum mission-allowable power, an iteration loop is required. The algorithm for this loop is shown below in Figure 22. As can be seen in this flowchart, the limiting design parameter is power, as is often the case for space missions. If large amounts of power were available, say several kilowatts, then the design algorithm would have to be rewritten to consider mechanical constraints. As will be seen in the next section, these do not need to be considered in the range of conditions that would be seen on Mars.

Performance Simulation under Martian Conditions

In their 1984 paper, Meyer and McKay described performance calculations for extracting water vapor from the Martian atmosphere using a compression-cooling process.¹³ The atmospheric parameters used in the Meyer and McKay paper were optimistic, as Table 3 shows. The same parameters Meyer and McKay used were also used for the original publication describing WAVAR,¹² to allow a direct performance comparison for the two processes. These parameters can be run through the design algorithm shown in Figure 22, allowing for a more accurate performance comparison, based on the present performance model. Using the same bed geometry and power as Ref. 12 (30 cm duct, 4 cm bed depth, 100 W),¹² the results of the performance calculations are shown in Table 4.

Table 3	Comparison of Martian atmospheric
	parameters

VL-1 Avg. *	Meyer &	
Sols 1-350	McKay	
0.0044	0.06	
208	253	
193	213	
774 [5.8]	800 [6]	
	VL-1 Avg. * Sols 1-350 0.0044 208 193 774 [5.8]	

* Viking Lander 1 site, 22.5° N, 48° W, in Chryse Planitia. Data from PDS⁴²

Table 4Performance calculations based on Meyer
and McKay Mars parameters.

Duct Diameter	30 cm
Actual Power Requirement	100 W
Water Extracted	0.44 kg/sol
Total Energy Requirement	2.46 kW-hr/sol
Specific Energy	5.6 kW-hr/kg
Atmospheric Flow Velocity	7.8 m/s
Average Motor Speed	1040 RPM



Figure 22 Algorithm flowchart for the iterative WAVAR performance calculation.

The specific energy of 5.6 kW-hr/kg water compares with 70 kW-hr/kg for the Meyer and McKay compressioncooling process as optimized by Clapp,⁴³ and 5.0 kW-hr/kg in the original calculations for WAVAR.¹² Although using realistic data will make a significant difference in the performance calculations, the WAVAR process will continue to outperform the compression-cooling process by an order of magnitude.

Viking Lander 1 Data

To make a more credible determination of performance for the WAVAR device, actual Martian data must be used. Fortunately, the Viking landers returned a wealth of meteorological data from which to draw, though only from two planetary sites. The largest batch of contiguous pressure and temperature data is from VL-1, sols 1-350, downloaded from the Planetary Atmospheres Node of NASA's Planetary Data System (PDS).⁴² This data set consists of binned and splined data obtained from the Viking Meteorology Instrument System (VMIS) through portions of the Viking Lander 1 mission, with mean values of pressure, temperature, and wind speed (zonal and meridional) calculated for 25 bins of equal duration per day. These data were parsed for temperature and pressure and averaged across the 25 bins of daily data. The daily average pressure data are shown in Figure 23 while daily temperature data are shown in Figure 24. The temperature plot shows the average and minimum temperatures from VL-1, frost point temperature (T_{frost}) based on the temperature inflection point data from Ryan *et al*,²⁰ and the arrival times of the two global dust storms during 1977.



Figure 23 Ambient pressure data from VL-1, sols 1-350.⁴²



Figure 24 Temperature data from VL-1 used for simulation, sols 1-350⁴²

The frost point temperature T_{frost} determines the water vapor concentration. As noted earlier, Ryan determined T_{frost} from inflection points in the nighttime temperature curves, and converted the data into water vapor concentrations for multiple discrete points (Figure 3). Using these data, the T_{frost} curve shown in Figure 24 was derived and thereby the water vapor concentrations shown in Figure 25. The derivation began with Ryan's discrete data points and then variations based on the VL-1 temperature minimum curve were introduced to form a continuous curve. The result was a curve mirroring the random scatter of the real data, which provides a realistic approximation of the water vapor concentration at the VL-1 site. From this, a sol-by-sol simulation could be run.



Figure 25 Water vapor concentration based on T_{frost} for VL-1.

Assumed Parameters for simulation

Table 5 shows assumed design parameters used for the following simulation with the VL-1 data set. Nominal duct diameter was set at 50 cm, with a hub diameter of 10 cm. Bed depth remained at 4 cm.* The simulation was run as a continuous process for maximum power levels of 100, 200, and 400 W, with the listed efficiencies. The simulation was run for sols 1-250, as the flow velocities were not high enough to extract measurable water amounts at the lower power levels beyond sol 260. If the available power is 400 W or higher, then the entire 350 sol simulation can be run. The 250 sol simulation will be sufficient, however, to evaluate the performance of the process and still includes the 1977a dust storm for additional realism.

^{*} It was assumed that a single pass through a bed of this size would be sufficient to extract the water vapor from the atmosphere with an extraction efficiency of 90%. This assumption remains to be demonstrated, however.

Bed Geometry	Diameter: 50 cm Bed Depth: 4cm		
Zeolite Type 3A Data	Void Fraction: 0.33 Pellet Dia: 3.25 mm		
Maximum Total Power	100, 200, and 400 W		
Control System Power	5 W		
Motor Parameters	1⁄2 hp max, 6000 RPM max		
Efficiencies	Motor: 0.90 Fan: 0.85 Microwave: 0.70 ³⁰ Extraction: 0.90		

Table 5Design parameters used for simulation at
VL-1, sols 1-250.

Simulation Results

Figure 26 shows the variation in water extracted each sol across the 250 sol run, while the totals for the entire run are shown in Table 6. The curves in Figure 26 are similar to the water vapor concentration curve in Figure 25, and scale according to power. The highest power level simulated, 400 W, reaches 0.33 kg/sol at its peak, averaging 0.165 kg/sol.



Figure 26 Mass flow of extracted water, sols 1-250 at VL-1 site.

The flow velocities and RPM numbers listed in Table 6 are well within the assumed Reynolds number and mechanical limits. As can be seen, the use of real Viking data results in a significant deterioration in predicted performance for water vapor extraction. This not only highlights the overly optimistic assumptions made by Meyer and McKay¹¹ (and later by Clapp⁴⁴) in their performance calculations, but the importance of site selection. For instance, if a site is selected with an average frost point temperature of 210 K (instead of the 193 K at VL-1), the effectiveness of water extraction improves by a factor of 10. Whether such a landing site can be located remains to be seen, although, as discussed earlier, there are locations on Mars, such as Noctus Labyrinthus, that do appear to harbor higher than average humidity.

Table 6Sol 1-250 simulation results.

<u></u>	100 W	200 W	400 W
Total Energy (kW-hr)	615	1230	2460
Water Extracted (kg)	20	29	41
Specific Energy (kW-hrs/kg)	31	43	60
Average Flow Velocity (m/s)	6.1	8.8	12.6
Average Motor Speed (RPM)	485	703	1010

8. CONCLUSIONS

As stated in the previous section, the conditions assumed by Meyer and McKay for their compressioncooling process were optimistic best case scenarios, and when the WAVAR process was considered under the same conditions, WAVAR proved to be a more energy-efficient solution by an order of magnitude. However optimistic, the assumed ambient conditions on Mars were chosen by Meyer and McKay for a good reason, as the available water is cut roughly in half for every 5 K drop in the frost point temperature. Comparing how much water is available at the VL-1 site (based on average frost point) with the optimistic assumed value, there is 20 times more water available at 213 K than at 193 K. The available water quickly becomes minuscule if the frost point temperature begins dropping below 200 K, and correspondingly, the energy requirements for extraction become unacceptably high. The recent indications that Mars is now colder than during the Viking period will only exacerbate the problem.⁴⁵ However, while colder temperatures mean less atmospheric water, it may make plans to extract water from the Martian regolith more attractive, perhaps incorporating some of the WAVAR concepts.4

The use of actual temperature and pressure data from Viking in the performance calculations leads to the conclusion that the feasibility of water vapor extraction from the atmosphere is limited to areas that feature higher water vapor concentration levels. Without more extensive mapping of near-surface water vapor concentrations, the selection of a high water vapor site is difficult. The most likely areas are near the North Pole during summer, when

16

the ice cap is revealed, or the bottoms of impact craters or canyons such as Noctus Labyrinthus.

However attractive the use of Martian atmospheric water resources may be, it is unlikely that a mission design will be pursued that is dependent on such resources, without some assurance that atmospheric water available for extraction at the chosen site is present in sufficient quantities to complete the mission profile. It remains to be seen whether current and future exploratory missions will provide enough data to provide for a more thorough mapping of near-surface water vapor and allow a WAVAR ISRU mission to be undertaken.

If attractive landing sites with $10-20^{\circ}$ C warmer frost points than at the Viking sites are found, then WAVAR has the potential to become an enabling technology for

advanced unmanned exploration, as well as providing supplemental water supplies for the first human colonization of the red planet. Initially, for unmanned and manned exploration missions, using Mars' atmosphere for ISRU remains an attractive option, due to the global distribution of atmospheric resources, and because water will be a critical resource for the exploration and colonization of Mars. For a permanent human presence, even given the discovery and utilization of larger water deposits, the WAVAR device might be useful on exploratory rovers and for use on field expeditions away from a fixed base, providing back-up and emergency water supplies. In addition, development of this technology for Mars could lead to development of an associated Earth-specialized version, to bring water to the arid regions of the world.

* * *

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