World Academy of Science, Engineering and Technology
International Journal of Aerospace and Mechanical Engineering
Vol:6, No:9, 2012

Preliminary Assessment of Feasibility of a Wind Energy Conversion System for a Martian Probe or Surface Rover

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Abstract**—**Nuclear energy sources have been widely used in the past decades in order to power spacecraft subsystems. Nevertheless, their use has attracted controversy because of the risk of harmful material released into the atmosphere if an accident were to occur during the launch phase of the mission, leading to the general adoption of photovoltaic systems.

As compared to solar cells, wind turbines have a great advantage on Mars, as they can continuously produce power both during dust storms and at night-time: this paper focuses on the potential of a wind energy conversion system (WECS) considering the atmospheric conditions on Mars. Wind potential on Martian surface has been estimated, as well as the average energy requirements of a Martian probe or surface rover. Finally, the expected daily energy output of the WECS has been computed on the basis of both the swept area of the rotor and the equivalent wind speed at the landing site.

Keywords**—**Wind turbine, wind potential, Mars, probe, surface rover.

I. INTRODUCTION

THE beginning of space exploration can be placed in 1957, when the Soviet Union launched the first artificial satellite, *Sputnik 1*. Since then, there has been a series of launches, which enabled the world to achieve a series of successes: from the first human flight around the Earth until the conquest of the Moon with *Apollo 11*.

Exhausted the lunar exploration, the field of investigation was extended to the Sun, planets and minor bodies, with expeditions which made possible the mapping of Mercury, Venus, Mars and also the studying of objects such as comets and asteroids.

The exploration of Mars by humans began with the launch of both *Mars1960A* and *Mars1960B* probes by the Soviet Union in October 1960. The launch was the beginning of several expeditions for the exploration of the Martian soil, carried out by both NASA (which gained the greatest successes, notwithstanding several failed expeditions) and the Soviet Union.

Among the most important expeditions to Mars, it is important to point out the first nine probes of NASA’s *Mariner* program (launched between 1964 and 1970, which provided the earliest images of the planet) in parallel with the Russian program *Mars*, which included seven shipments, all unsuccessful except for the fifth one (*Mars 5*), which sent 60 pictures before the breakdown of the telecommunication system.

In 1976, thanks to NASA's *Viking* probes, the first successful soft landing on Mars took place and it was thus possible to acquire more scientific information about the planet, in particular its data on the temperature and the atmospheric pressure, together with detailed observations on seasonal sandstorms. However, the first completely successful expedition by the United States and the first absolute success of the exploration of Mars were obtained thanks to the probe *Mars Global Surveyor*, launched in 1996, who analyzed the whole surface of the planet, with the particular aim of seeking a possible presence of water. Later on, there were many other expeditions and probes which explored the Red Planet. Noteworthy among them is *Mars Pathfinder* (landed in July 1997), which performed important chemical analysis of the rocks and also sent back information on wind and other atmospheric factors, *Mars Odyssey* (launched in April 2001), which confirmed the presence of ice in the subsoil, *Mars Exploration Rovers*, including a pair of twin rovers launched within a month of each other: *Spirit* (on 10th June 2003) and *Opportunity* (on 7th July 2003) and *Mars Reconnaissance Orbiter*, which entered into the Martian orbit on 12th March 2006.

This lead to the last full-finished expedition by NASA, the *Phoenix Mars Lander*, whose realization was entirely entrusted to the University of Arizona and ended in November 2008: the probe gave specific evidence of the evaporation of water ice on the landing site. Chemical analyses of the Martian soil were also performed, revealing its composition and also identifying the presence of perchlorate.

The high rate of failures occurred during the exploration of Mars can be attributed to a large number of factors which may affect the exploration, most of which are still unknown. One of the most serious challenge for the success of the expeditions was the power requirements of the probes and in particular of the rovers used for the exploration and the analysis of the Martian soil, which were often the cause of the total failure of the expedition, due to the impossibility of the movement of the rover itself or to the lack of sending of both data and information.

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The first probes sent to Mars (the *Viking I* and *II* are the best examples) used nuclear energy power, thanks to a small reactor which generated radioactive isotopes from the decay of plutonium. However, with the subsequent expeditions, it was decided to change to photovoltaic panels, used both for the power of the probes themselves and also for the rovers working on the Martian surface as the solar energy was considered less risky and invasive towards the Martian environment. The results were quite satisfactory, in particular for the contamination of the soil, unlike it had before happened with nuclear reaction landers generation. Despite that, the photovoltaic arrays working on the surface of Mars showed different operational problems compared to the same arrays on the Earth or in orbit. On several Martian expeditions, the performance of the solar arrays presented the main difficulty as regards the right site to land, the amount of power available for scientific operations and the duration of the efficiency of the instruments day by day. The environmental conditions on the surface of Mars are very different from the orbital environment, where space solar panels normally work. The main differences registered on the efficiency of the solar arrays working on the Martian surface and the ones on the orbit of the Earth are due to several factors:

- lower solar intensity due to a greater distance of Mars from the sun;
- suspended atmospheric dust, which modifies the solar spectrum and reduces the solar intensity;
- low operating temperatures;
- deposition of dust on arrays.

This last aspect caused several problems for some shipments: because of sand deposition on the solar panels, in some cases the production of electric energy decreased up to more than 70%. In particular, during the *Mars Exploration Rovers* mission, the efficiency of the rover *Spirit* was reduced to 50 minutes a day for a long period, as only the 25% of the solar rays could go through the layer of dust. The problem was fortunately resolved by a particular Martian breeze which swept the dust off the panels, thus allowing the rover to resume almost all its autonomy.

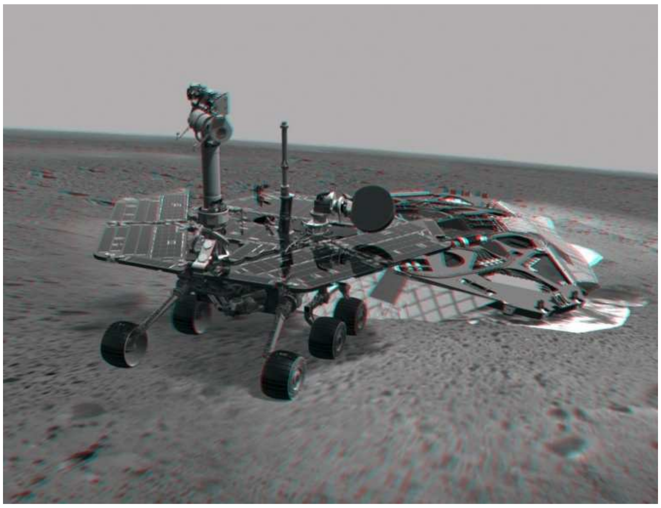

Fig. 1 Computer-generated models of the *Mars Exploration Rover Spirit* and its lander with real surface data from the rover's panoramic camera, showing the deployed solar arrays (from: [1])

Compared to solar cells, wind turbine systems used on Mars should have the advantage of producing continuously power both during dust storms and at night-time. In particular, Kumar et al. [2] designed a 500 W Darreius-type straight-bladed vertical-axis wind turbine (S-VAWT), taking into consideration the atmospheric conditions on Mars. The study of specific wind turbines for a possible use on Mars was object of interest also by James et al. [3], who published a study on a special buoyant wind turbine, designing both shape and rotor size after a precise investigation of the profile of the wind.

II. Wind Profile on Mars Surface

Wind is the main responsible of the ever-changing of the surface on Mars. The presence of the wind on Mars was supposed even before spacecrafts explored the planet: due to registered changes in the brightness of the planet, astronomers suspected that dust lifted by wind was responsible of darking the atmosphere of the planet. The presence of winds was overwhelmingly confirmed when *Mariner 9* landed on Mars in the middle of a huge dust storm. *Mariner* and *Viking* spacecrafts also revealed the features of the surface, including various types of dunes, which are widespread on Mars and are very similar in appearance to the dunes on the Earth. In fact, they change in the course of time and can indicate the main wind direction. However, the assumptions on the actual presence of wind on the Martian surface were confirmed subsequently, when, thanks to following expeditions, it was possible to analyze in detail the movements of the dust through special photographic devices.

Fig. 2 The HiRISE camera took this picture of a dune field within a crater southwest of Hershel Crater on 1st July, 2007 (from: [4])

A fundamental factor to be taken into account is that the force of the wind is lower on Mars, because of its low density (of about a factor of 100) compared to the one on the Earth. Mars has a tenuous atmosphere with a pressure which is less than one-percent with respect to the Earth. The *Mars Reconnaissance Orbiter* used a special high resolution camera (HiRISE - High Resolution Imaging Science Experiment), which provided the best images of the Martian soil.

Thanks to these photographs, the scientists were able to establish the actual presence of the wind, eliminating every doubt about the cause of the particular dunes and whirlwinds which constantly change the surface, creating special "drawings" of sand. The modification of the surface by wind is a process taking constantly place, as pointed out by the photographs of the atmospheric dust storms, whirlwinds and perhaps even tornadoes, as shown in Fig. 3.

Fig. 3 The HiRISE camera took this picture of a towering dust devil casting a serpentine shadow over the Martian surface on Amazonis Planitia on 3rd April, 2012 (from: [4])

III. ENERGY REQUIREMENTS OF MARTIAN PROBES AND SURFACE ROVERS

The first expeditions to Mars were conducted using probes mainly powered by nuclear energy, which resulted particularly effective for the purposes and tasks required. Thanks to a system able to generate radioisotopes, both *Viking 1* and *2* probes could perform significant scientific analysis in total autonomy for at least three years. Inside them, there was a radioisotope thermoelectric generator (RTG), consisting of an electrical generator which obtained its power from radioactive decay. In such a device, the heat released by the decay of a suitable radioactive material was converted into electricity by the Seebeck effect using an array of thermocouples. Thermocouples, though very reliable and long-lasting, were very inefficient: global efficiencies above 10% have never been achieved and most RTGs presented efficiencies between 3 and 7%. Thermoelectric materials which have been used up to now in space expeditions included silicon germanium alloys, lead telluride and tellurides of antimony, germanium and silver (TAGS). Several studies were performed so as to improve their efficiency, using other technologies to generate electricity from heat. Achieving higher efficiency would mean the possibility to produce less radioactive fuel for the same amount of power, and therefore a lighter overall weight for the generator. This is a critically important factor to point out, taking into consideration the costs of spaceflight launches.

RTGs have been used as power sources in satellites, in space probes without crew and in unmanned remote facilities, such as a series of lighthouses built by the Soviet Union in the Arctic Circle.

They are usually the most desirable power sources for robotic or unmaintained situations, for systems which need at least a few hundred watts (or less) of power for too long spans of time which could not be supported by fuel cells, batteries or by equipments working in places where solar cells cannot be used.

The *Viking* probes used plutonium-238 (238-Pu) for the decay inside the generator: it became the most widely used fuel for RTGs, in the form of plutonium (IV) oxide, (PuO_2). 238-Pu has a reasonable power density and an exceptionally low gamma of the levels of neutron radiation.

This type of plutonium has a half-life of 87.74 years, in contrast to the 24,110 year half-life of plutonium 239 used in nuclear weapons and reactors. A consequence of the shorter half-life is that plutonium 238 is about 275 times more radioactive than plutonium 239.

The real problem of RTGs is that they may pose a risk of radioactive contamination: if the container holding the fuel leaks, the radioactive material may contaminate the environment. As regards spacecraft, the main concern is that if an accident were to occur during a launch or during the passage of a spacecraft close to the Earth, harmful material could be released into the atmosphere. For this reason their use in spacecraft and elsewhere has attracted controversy.

There have been at least six known accidents involving RTG-powered spacecrafts and, to minimize the risk of the release of radioactive material, the fuel is usually stored in individual modular units with their own heat shielding. The units are surrounded by a layer of iridium metal and encased in high-strength graphite blocks and they result to be corrosion- and heat-resistant.

However, although the incidents in the nuclear power probes were not so serious (and found to be small), NASA decided to abandon the radioisotope generators, opting instead for a type of much more ecological source of energy. One of the main reasons of the abandonment of nuclear energy was in fact given by the risk of contaminating the landing site. In later expeditions, it was decided to change the fuel to other systems which could have no effect on the planet, using powerful solar panels, capable of giving both the lander and the rover enough energy to play all major functions provided, including movements.

When fully illuminated, solar panels generated about 140 W of power for a maximum of four hours per sol (a Martian day), while a rover needed about 100 W to drive. Comparatively, the solar arrays of the *Sojourner* rover, used in the 1997 *Pathfinder* expedition, could supply around 16 W of power at noon on Mars. *Sojourner* was also equipped with non-rechargeable lithium batteries, which could provide an output of 300 Wh, mainly as each night situation required. In 1997 there were not available rechargeable batteries with the reliability required for a space expedition in weight and cost limits imposed by NASA's *Discovery* program [5].

The electrical power provided by a solar panel of 0.3 m^2 is over 14 W on Mars, during the four hours around noon [6]. Nevertheless, the efficiency of the solar energy on the Martian surface depends on the amount of dust in the atmosphere [7]: the suspended atmospheric dust in Martian atmosphere consists of both a long-term dust and also dust storms, which temporarily add a large loading of dust into the atmosphere.

Open Science Index, Aerospace and Mechanical Engineering Vol:6, No:9, 2012 publications.waset.org/6481.pdf

Dust storms can be local storms, of a few days, regional storms, covering a larger area, or "global" storms, which spread from the southern hemisphere during the southern hemisphere summer and can last for several months. Dust deposition on the solar arrays was measured during the *Pathfinder* expedition at a rate of 0.28% per sol during the initial 30 sols of the mission [8]. Further measurements were carried out during the *Mars Exploration Rover* mission [9].

The power system of the *Mars Exploration Rover* included two rechargeable batteries, weighing 7 kg each, which would have to recharge by solar power, so the rover could operate even in extreme conditions with little presence of light (at night or in presence of strong dust storms).

Scientists were not sure about the degradation of the batteries, because the lower energy of the solar panels - covered with dust - could not fully charge the batteries. It was also believed that solar panels could still generate energy after 90 sols. Indeed, NASA scientists had predicted that the duration of the entire expedition was approximately of 90 sols, whereas both the rover *Spirit* (MER-A) and *Opportunity* (MER-B) could not overcome the third month of their activity.

These specifications have been largely superseded, as *Spiri*t continued to operate on the Martian surface for the whole of 2006 (the probe had landed on Mars in January 2004).

On 4th January 2010 the rover *Spirit* celebrated 6 years of its activity on the Martian surface, showing an amazing resistance to the weather conditions that occurred on the planet. *Spirit* was in contact with the Earth until 22nd March 2010. Operation *Spirit* was then declared closed by NASA on 25th May 2011, unlike the rover *Opportunity*, which can be considered as the expedition with the longest operation on Mars. The success of this mission is mainly due to the excellent solar panels, capable of storing energy and recharging the batteries even in unfavorable weather conditions (sand deposited on the panels during storms).

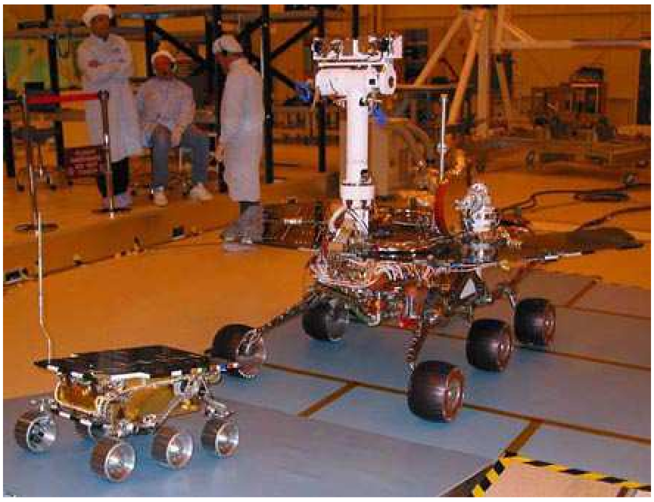

Fig. 4 Comparison between *Sojourner* (left) and *Spirit* (right) rovers (from: [10])

Mars Science Laboratory expedition (launched on 26th November, 2011: the landing of the probe, containing the rover *Curiosity*, is planned for the second part of 2012) will mark the return of nuclear power, with a new landing system.

In fact, the considerable weight of the rover (about 900 kg, unlike *Spirit* and *Opportunity*, which weighted 185 kg) has forced scientists to abandon the idea of a landing using rockets, airbags and parachutes for deceleration, due to a too thin atmosphere for effective use of these braking systems [11].

Curiosity will be powered by RTGs, as used by the successful Mars landers *Viking 1* and *Viking 2* in 1976 [12]. *Curiosity*'s power source will use the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) developed by Boeing Company's Rocketdyne Propulsion and Power Division. Based on classical RTG technology, it represents a more flexible and compact development step and is designed to produce 125 W of electrical power from about 2,000 W of thermal power at the start of the mission. During the mission, the MMRTG will generate 2.5 kWh per sol (during the *Mars Exploration Rover* mission, the global amount of energy produced was on the order of 0.6 kWh per sol [13]).

The MMRTG will produce less power over time as its plutonium fuel decays: at its minimum lifetime of 14 years, electrical power output will be down to 100 W [14].

Fig. 5 View of the MMRTG (from: [15])

IV. OVERVIEW OF MARTIAN ATMOSPHERIC DENSITY

The Red Planet is substantially exposed to the hardest elements of space weather. Unlike the Earth, which is protected by the magnetosphere, Mars does not present a global magnetic field to protect itself from solar flares and cosmic rays. While the causes of this phenomenon are still not clear, scientists agree on the fact that the internal magnetic dynamo of the planet turned off about 4 billion years ago. After that, the solar wind gradually has been eroding the Martian atmosphere up to now, making it less than 1% as thick as the earthly one.

Martian atmosphere is composed by 95% of carbon dioxide, by nearly 3% of nitrogen and by nearly 2% of argon with trace quantities of oxygen, carbon monoxide, water vapor, ozone and other gases. Because of its chemical composition, the atmosphere doesn't protect the planet from energetic protons, thus Martian air density at "sea level" is roughly equivalent to that of the earthly atmosphere at 70,000 feet altitude.

The analyses and observations carried out by *Mars Pathfinder* on density, temperature and pressure of Mars made it possible for many scientists to accurately reconstruct the general profile of the atmosphere.

In particular, Schofield et al. [16] analyzed the data reported by *Mars Pathfinder* probe (measured from the ground to 160 km above the surface) and compared them with the same values reported by *Viking 1*: very similar results were registered, except for higher altitudes (over 80 km), where the *Mars Pathfinder* atmospheric density showed a lower value (for at least a factor of 10) than *Viking 1*.

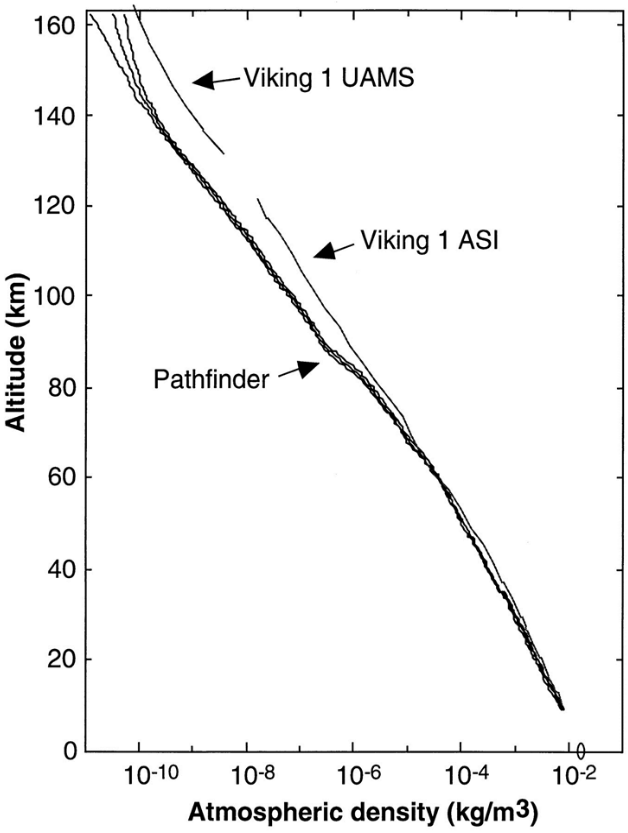

Fig. 6 Martian atmospheric density profiles derived from the accelerometer data of different probes. The registered differences are due to the uncertainties in the entry velocity and in the finite digital resolution of the measuring instruments (from: [16])

The registered values can vary on the surface of Mars, due to the range of temperatures (from 27 ºC in summer during the day to –133 ºC in winter at the pole).

In 1998, Tracadas at al. [17] presented the results of a measurement campaign of the density of the Martian atmosphere between 170 and 180 km above the surface of the planet for a period of 6 months, when the solar cycle was beginning to rise up from the minimum of its activity.

The measurements were made during the orbital decay of the *Mars Global Surveyor* spacecraft, during its Science Phasing Orbits (SPO, from April to September 1998) using X band Doppler tracking observation. The registered data showed that, depending on the measurement period and also on the site where the measurement was made, at a height of 175 km above the surface, the density of the atmosphere varied between 0.018 and 0.025 kg/km^3.

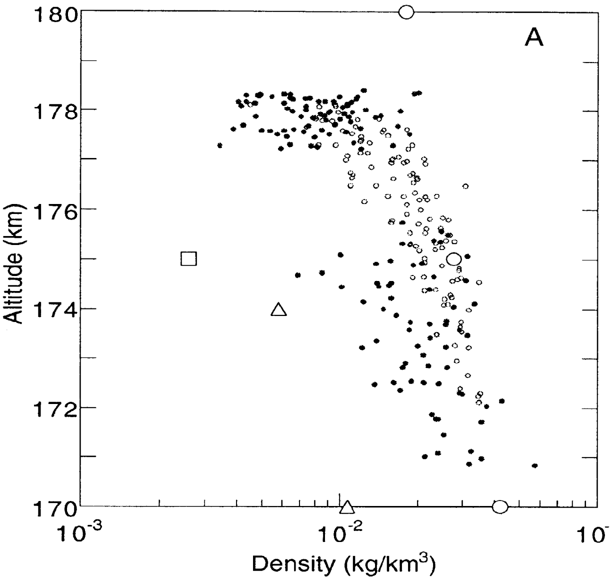

Fig. 7 Measured density of the Martian thermosphere at a height of 175 km above the surface of the planet (from: [17])

Jerolmack et al. [18] suggested a value of around 0.02 kg/m^3 for Martian air density and performed several analyses of the Martian wind, based on the shape of sand dunes and depressions on the surface of the Red Planet.

A simple interactive program was developed by NASA in order to investigate the changes in the atmosphere and their effects on aerodynamic variables [19]. The model was developed on the bases of the measurements acquired in the Martian atmosphere from *Mars Global Surveyor* in April 1996: it considers two zones with separate curve fits for both the lower atmosphere and the upper one. The lower atmosphere runs from the surface of Mars to 7,000 m. In the lower atmosphere, the temperature decreases linearly and the pressure decreases exponentially with height, according to the formulas:

$$T = -31 - 0.000998 \cdot h \tag{1}$$

$$p = 0.699 \cdot \exp(-0.00009 \cdot h) \tag{2}$$

where the temperature is given in Celsius degrees, the pressure in kilo-Pascals, and h is the altitude in meters. Also in the upper atmosphere the temperature decreases linearly, according to the formula:

$$T = -23.4 - 0.00222 \cdot h \tag{3}$$

being the evolution of the pressure the same reported in (2). In each zone, the density ρ is calculated with the equation of state:

$$\rho = p / [0.1921 \cdot (T + 273.1)] \tag{4}$$

Considering an altitude of 1 m from the surface, the results of the described model determine an atmospheric density of 0.015 kg/m^3, very similar to the value (0.02 kg/m^3) already proposed by Jerolmack et al. [18].

V. ESTIMATION OF MARTIAN WIND SPEEDS

Since the sending of the first space probes on the Red Planet, the study of wind speed on Mars has been at the centre of many debates by researchers and scientists. Several assumptions have been made in this regard, often leading to completely different results. In fact, the study of wind has never been the main aim of any Martian exploration campaign, because the main interest of space agencies has always been addressed to the analysis of the soil, in particular to look for the presence of water. None of the rover sent on the planet has ever been equipped with an anemometer aimed to measure with precision the actual speed of wind, therefore the information obtained about wind are mainly hypothetical, derived from calculations made in laboratory and not directly on the surface of the planet. However, thanks to the several images sent by the various probes equipped with cameras, it has been possible to verify the real presence of wind on the surface: the spacecraft sensors have often photographed dust storm and tornadoes, which frequently occur, as well as clearer images of the ground, which show a planet covered in large part by sand dunes similar to those of the deserts of the Earth, and altered by wind.

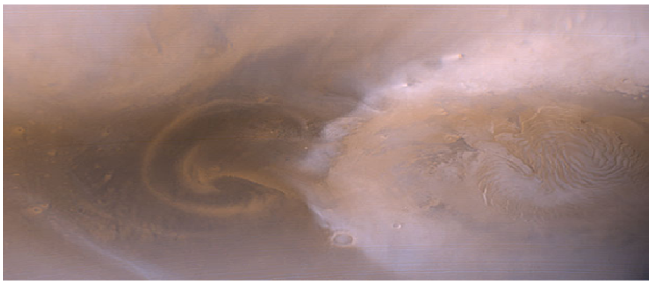

Fig. 8 Polar Martian dust storm photographed by *Mars Global Surveyor* while erupting out from the north polar cap of Mars: such dust storms are not uncommon as summer comes in the northern emisphere. The white material is frozen carbon dioxide which covers much of the extreme north. A strong central jet, about 900 kilometers long, which is creating symmetric swirling vortices, is visible in the storm (from: [20])

As already previously mentioned, atmospheric density of Mars is about 1% of the atmospheric density of the Earth. That means, the wind on Mars has to be blowing a 100 times faster than the wind on Earth to have the same momentum.

Several Martian storms have passed by rovers and landers. In fact, some of them have helped their missions, as they removed dust settled on solar panels, particularly during planet-wide dust storms.

Mars is dryer and colder than the Earth and, as a consequence, dust raised by these winds tends to remain in the atmosphere longer than on Earth as there is no precipitation to wash it away. The surface of Mars has a very low thermal inertia, which means it heats quickly when the sun shines on it. Typical daily temperature swings, away from the polar regions, are around 100 K. On Earth, winds often rise in areas where thermal inertia changes suddenly, such as from sea to land. There are no seas on Mars, but there are areas where the thermal inertia of the soil changes, leading to morning and evening winds similar to the sea breezes on Earth.

When the *Mariner 9* probe landed on Mars in 1971, the world expected to see extremely clear new pictures of surface details. Instead, a planet-wide dust storm was visible, with only the giant volcano Olympus Mons showing above the haze. The storm lasted for a month, and scientists observed that, during those global dust storms, the diurnal temperature range narrowed sharply, from fifty degrees to only about ten degrees. On the contrary, wind velocities appear to change at a considerable high rate: in fact, within only an hour from the arrival of the storm, they increased to 17 m/s, with gusts up to 26 m/s. The landscape seen by *Opportunity* (*Mars Exploration Rover*) at Meridiani Planum (a plain situated near the equator of Mars) was dominated by aeolian (wind-blown) ripples at intervals, with a surface basically composed of hematitic spherules and fragments. These ripples showed an ordered grain size, with well sorted coarse grained crests and poorly sorted finer grained troughs. These ripples were the most common bed form encountered by *Opportunity* in its passage from Eagle Crater to Endurance Crater, and they differed from more common aeolian features for having crests made of very large grains while troughs consist of much finer material.

Fig. 9 Coarse-grained ripples at Meridiani Planum (from: [18])

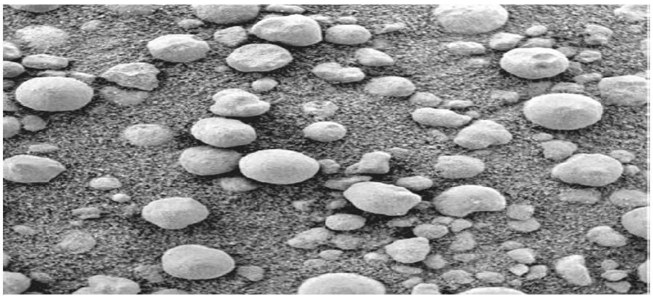

Fig. 10 Picture of typical inter-ripple zone showing hematitic spherules and fragments, as well as a basaltic sand matrix (from: [18])

On the basis of the work of Jerolmack et al. [18] it has been possible to determine how surface deposits of coarse-grained ripples can be used to obtain information on wind conditions on the surface of Mars. *Opportunity*'s track between Eagle and Endurance craters revealed that the concentration of fragments and hematitic sediment may not just be the result of simple breeze; rather, these particles seem to create marked and different forms on the surface, suggesting that lateral transport has been an additional, or even dominant, factor in their organization. Hematitic spherules are quite still, owing to their large size, and hence don't migrate to ripple crests: in fact, ripple crest grains have a diameter 6 times higher than the largest basaltic grains in ripple troughs, which therefore can't move without strong winds. At the *Opportunity* landing site, wind moved particles erasing the edges of the craters and filling them with loose sediment, sculpting moreover bedrock because of the exposure to sandblasting.

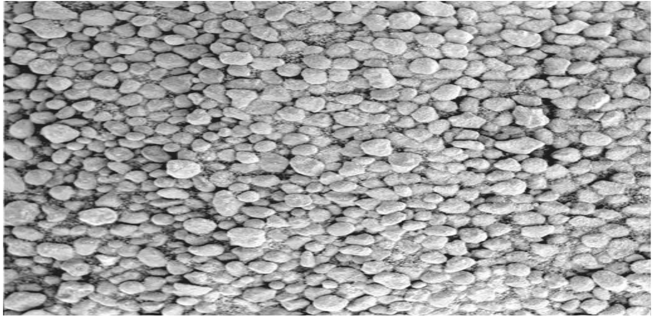

Fig. 11 Picture of typical coarse-grained ripple crests, showing monolayer of hematic fragment (from: [18])

Open field measurements were performed at White Sands National Monument (New Mexico), showing that shaping Meridiani Planum coarse-grained ripples requires a wind speed of 70 m/s (at a reference elevation of 1 m above the surface). From the images of dust streaks, taken by the Mars Orbiter Camera (MOC) during the *Mars Global Surveyor* mission, scientists estimated that surface winds reach a speed of at least 40 m/s and hence may form these ripples just occasionally. Also the conditions that would be required to move the hematitic spherules situated in the inter-ripple zones have been considered, estimating a wind velocity of at least 108 m/s.

Greeley et al. [21] analyzed the wind processes on Mars through the use of a special wind tunnel. In particular, it was proved that it is necessary a wind speed of at least 111 m/s to move the grains of sand on flat surfaces, while lower velocities would be required in regions of high surface roughness (such as cratered terrain), which could be zones of origin for some Martian dust storms.

In conclusion, it can be assumed that, although the Martian atmosphere is very rarefied, winds are capable of high velocities, driven by temperature differences between sunny and dark areas, as well as winter and summer regions. Mars is definitely a windy planet: winds are created by air being heated near and around the surface, then rising and moving towards the poles. This is the same general pattern for winds on the Earth. From satellites orbiting around Mars and rovers on the surface, clouds can be clearly seen, as well as storms, which blow across large parts of the planet.

Martian landscape shows signs of wind erosion and, thanks to probes and rovers, it was possible to observe the shape of shifting dunes and filled-dust craters. Small tornadoes or whirlwinds, known as dust vortexes, frequently move throughout the planet's surface, while regular small local dust storms, similar to those observed in the deserts of the Earth, often grow into enormous tornadoes which invade the planet for months.

VI. Preliminary Calculation of a small Martian WECS Daily Energy Output

In order to determine the energy potential of a small WECS mounted on a Martian probe/rover, a global amount of 20% equivalent hours at nominal power production per sol (yielding to 4.9 h/sol) have been prudentially estimated.

The global amount of kinetic energy flux in the flowing wind with respect to rotor swept area has been computed according to the formula:

$$E'_k = ½·ρ·A·V^3 \tag{5}$$

being A the swept area of the rotor, corresponding to $\pi·R^2$ for a horizontal-axis wind turbine (HAWT) of radius R, V the equivalent wind speed at the spacecraft landing site. The atmospheric density was prudentially assumed 0.015 kg/m^3.

In order to consider a reduced rotor aerodynamic performance due to the low Reynolds number (determined by the low atmospheric density), the HAWT power coefficient, defined as:

$$C_p = P / (½·ρ·A·V^3) \tag{6}$$

has been prudentially assumed as 0.10, being P the power produced by the wind turbine.

Figs. 12 and 13 summarize both the nominal power production and the daily energy production of the proposed Martian WECS as a function of both the rotor diameter and the equivalent wind speed at the spacecraft site. As can be clearly seen from Fig. 13, considering a daily energy requirement of 600 Wh (as for the *Mars Exploration Rover* mission), a rotor radius of 0.65 m is sufficient to power the probe/rover subsystems for an equivalent wind speed of 50 m/s, while the adoption of a 1.4 m rotor radius would be sufficient to feed the subsystems even for lower winds (equivalent wind speed of 30 m/s).

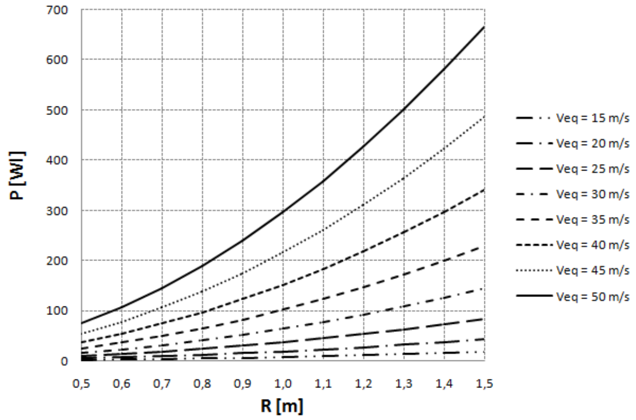

Fig. 12 Turbine nominal power production as a function of both the rotor diameter and the equivalent wind speed at the spacecraft site

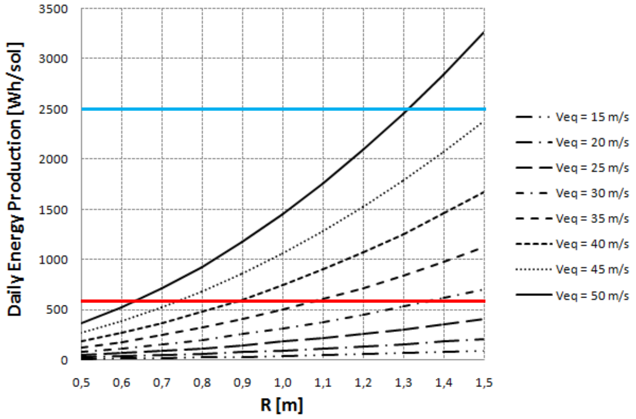

Fig. 13 WECS daily energy production as a function of both the rotor diameter and the equivalent wind speed at the spacecraft site; the red line evidences the daily energy requirement of the *Mars Exploration Rover* mission (600 Wh), while the blue line represents the much higher (2,500 Wh) daily energy requirement of the *Mars Science Laboratory* mission

Considering a daily energy requirement of 2,500 Wh (as for the case of *Curiosity*), higher rotor diameters and equivalent wind speeds should be needed.

VII. CONCLUSIONS AND FUTURE WORKS

A preliminary analysis of the wind potential on the surface of Mars has been performed on the basis of a review of both direct atmospheric density measurements and indirect wind measurements obtained from the data collected by several spacecraft missions.

Assuming prudential values for both the amount of equivalent hours at nominal power production per sol and also for the global aerodynamic efficiency of the rotor, it has been proved that a relatively small horizontal-axis wind turbine could be able to satisfy the daily energy need of a typical Martian probe/rover.

Further work should be performed in order to determine a detailed lay-out of an optimized Martian rotor blade, considering the combined aerodynamic effects of both reduced atmospheric density and high wind velocity.

NOMENCLATURE

A [m^2]	rotor swept area
C_p [-]	turbine power coefficient
E_k [W]	global amount of kinetic energy flux in the flowing wind with respect to rotor swept area
h [m]	altitude
p [kPa]	pressure
P [W]	turbine power output
T [°C]	temperature of Martian atmosphere
V [m/s]	equivalent wind speed at the spacecraft landing site
ρ [kg/m^3]	atmospheric density

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