Chapter 12
POWER ON MARS

A technical point is explained.

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SURVIVING ON MARS WITHOUT NUCLEAR ENERGY

George James, Gregory Chamitoff and Donald Barker

Current strategies for early missions to Mars are highly dependent on the assumption of nuclear power as the primary near-term energy supply. Since political considerations may prohibit the launch of nuclear systems, this paper investigates the potential for utilizing in situ energy sources on Mars to either supplement or replace nuclear power. The current knowledge of solar, wind, and areothermal energy resources on Mars is discussed, and the studies required to identify these resources and further characterize their distribution and abundance is given. A non-nuclear power system for the first Mars mission could be based on a combination of solar and wind energy coupled with a liquid fuel storage system. Indications are that such a system, using the latest solar cell technology, could be cost competitive with nuclear power in terms of kiloWatts per kilogram delivered to the Martian surface. Areothermal energy has significant potential, but the development of this resource will require longer term space and surface based exploration. The work reported herein advances the current knowledge base with the following accomplishments: (1) collecting models to jointly estimate solar and wind power production; (2) utilizing terrestrial geothermal exploration techniques coupled to remote sensing data from Mars to refine potential regions of exploitable planetary heat sources; and (3) suggesting that an early Mars mission that relies heavily on in-situ energy sources will require additional precursor information on energy resource location, extent, and accessibility. It is proposed that the production of energy on Mars, solely from local resources, may be practical enough to render a small outpost completely self-sufficient. Moreover, the addition of in-situ energy resource development to that for life support and transportation may advance the development of larger permanent self-sufficient human colonies on Mars.

INTRODUCTION

The development of economical strategies for the first human missions to Mars has been increasingly focused on the utilization of in-situ resources for providing required supplies for life support, surface mobility, and return-to-Earth capability. It has been demonstrated that mission robustness and affordability can been drastically improved by “living off the land.” Recently, the Mars Direct plan (Zubrin 1996) and elements of the NASA Design Reference Mission (NASA 98) illustrate the importance of this concept. A common feature to most mission plans, however, is the transportation of a nuclear energy source to the Martian surface. While this may be the simplest short-term solution for meeting the energy requirements of a human base on Mars, it also has the potential to be the show-stopper due to the current political climate regarding the safety of launching nuclear materials and/or polluting another planet with nuclear waste.

The objective of this paper is to present alternative means for providing energy on Mars through the development of local resources. Available indigenous energy alternatives include solar power (photovoltaic, solar dynamic, or solar satellites coupled to power beaming), areothermal energy (Martian geothermal), and wind energy. The potential for exploiting photovoltaic solar energy on Mars is well established. However, the cost is high and the implementation involves certain obstacles, such as maintenance and restrictions in output performance due to aeolian deposition and dust storms. Solar dynamic power is even more susceptible to atmospheric dust than photovoltaic systems. Solar power satellites with power beaming to the surface has not yet been demonstrated on a large scale, although, in-situ construction of the rectenna may be quite feasible on Mars. Areothermal energy is a potential longer-term resource that could be plentiful in certain regions, but the utilization of this resource requires further remote sensing data as well as subsurface drilling and other surface based exploration. Wind energy has surprising potential for Mars due to the magnitude of geological features and temperature extremes that can produce highly reliable and localized winds. Therefore, the near-term energy system proposed herein couples a wind energy conversion system to photovoltaic power production. These two technologies are complimentary since wind energy tends to be active during times when solar energy is reduced or unavailable; and some locations are subjected to stronger winds during dust storms. Beyond the initial outpost on Mars, once areothermal resources are located, this form of energy may complete the energy equation for permanent, self-sufficient, and productive bases on Mars.

ENERGY REQUIREMENTS FOR A MARTIAN OUTPOST

Energy is a dominating factor in the design of a human mission to Mars. Long flight times and an extended surface interval requires an optimum combination of energy resources for redundancy, storage, and eventual indefinite self-sufficiency of a Martian base. Solar power is a reliable source of energy for meeting daily demands on the outbound and return flights. On the surface of Mars, however, a combination of nuclear or isotope generators, solar power, wind energy, or areothermal energy can be considered. The Mars Direct plan proposed by (Zubrin 1996), which is a low cost strategy for achieving the goal of putting humans on Mars and working toward permanent inhabitation, has become the guiding philosophy for a near-term mission. This plan, like others, assumes that the first manned mission to Mars will include at least one 100 kW nuclear generator. In addition to life support, energy production would be required to produce some 108 tonnes of methane and oxygen to fuel a return rocket as well as to provide fuel for local surface exploration in a Martian rover. The fundamental concept of the Mars Direct plan is to “Live off the Land” using in-situ resources to the greatest extent possible. This is of primary importance as a means of reducing the required payload delivered to Mars to support initial exploration initiatives. As such, fuel, oxidizer, water, and breathable air would be produced on Mars from local resources. Only a small supply of hydrogen is required until a local resource for this element can be developed. Eventually, many other materials could be processed on Mars, including cement, glass, iron, steel, even fertilized soil. Other than the exploration required to locate resources, and the refinement of resource utilization and extraction techniques, the only other major requirement is that of energy production.

The energy required for early missions to Mars is highly dependent on the mission design and objectives. Life support energy requirements per crew member is a function of living volume, mobility, quality of food provided, activity level, and so on. To this must be added requirements for scientific and resource exploration and research. The power to operate Biosphere 2, a closed ecological system that supported a crew of 8 for two years (Nelson

1996), was approximately 100 kW per person. However, this did not include the power required for materials production and pressurization which would raise the energy requirements. Nor did the program include the ability to extract new resources from the environment or to exchange wastes with the outside, which would lower the anticipated energy needs (Meyer 1996). Moreover, the habitable space in Biosphere 2 was 1335 cubic meters per person, perhaps 50 to 100 times that which is likely for a first human Mars mission. A Japanese study placed a value of 20 to 50 kW per person as the value needed for a 150 person Mars settlement. The current NASA Mars Reference Mission suggests a value of 60kW to support the first crew of 6 astronauts on Mars, including the life support cache, ascent fuel propellant production, and surface exploration (NASA 1998). By the time the third crew arrives, this is expanded to a total of 160kW, which supports increases in habitable volume, life support capability, science and exploration. Based on this study, a power supply system on the order of 60 to 200 kW appears to encompass the reasonable range of current estimates for an initial Martian outpost.

ASSESSMENT OF APPLICABLE ENERGY SOURCES

Nuclear Energy

Nuclear power is typically assumed as the baseline power supply for Mars missions (Zubrin 1996; Meyer 1996; Duke 1985; NASA 1998). From the late 50's to 1972, a series of analytical and experimental projects were undertaken to produce viable space nuclear power systems (Colston 1985). One high point of this work was the 1965 flight of the 0.5 kW SNAP 10A reactor which operated in space for 40 days. The NASA sponsored SP-100 project was initiated in 1981 and targeted the production of a 100 kW system with a seven year lifetime. Estimates of the power output of the SP-100 class reactors as a function of mass range between 37 W/kg and 17 W/kg (Zubrin 1996; Haslach 1989). Although these projects remain uncompleted, the technological foundation has been laid and no stumbling blocks are seen. The Russians however, continued development of a space nuclear reactor to produce the 6 kW TOPAZ II with a three year life (Voss 1994).

Nuclear power is a compact method for generating power in the 100 to 500 kW range. The technology is well understood and at least one space qualified system has been produced. However, most power plants envisioned would produce radioactive wastes after a 7 to 10 year lifetime that would require disposal. The power units could not be recharged or repaired in-situ without a great deal of high technology and mineralogical support. Also, there is a great deal of political and public resistance to building and using nuclear reactors at this time. In view of the political, legal, and technological hurdles involved, for a near term Mars mission, the longest lead time item could be the ability to build and launch a significant nuclear energy source.

Solar Energy

Solar power is readily available on Mars, but dependent upon latitude, seasonal variation (due to orbital eccentricity and inclination), daily variation, day/night cycles, suspended aerosols, and dust storms (Zubrin 1996; Meyer 1996; Geels 1989; Meyer 1989). Orbital eccentricity causes a variation in the surface solar constant from 718 to 493 Wm^{-2}. On average, the Martian surface receives about 50% less solar flux on the surface when compared to Earth (mainly due to its distance from the sun). On Earth, the average daily insolation is 75 to 200 Wm^{-2} at the surface. On Mars, though, global dust storms occur one to two times a year, roughly at perihelion, and can last for months. Local dust storms may also last for several days (Meyer 1996). Martian dust storms do not render solar power ineffective, however, since the dust has a scattering effect rather than a blocking effect. Hence an all-sky, scattered light collector would continue to produce power at a reduced percentage of its maximum output.

Potential Solar Energy Extraction Systems

There are three extraction mechanisms for solar power: solar dynamic, photovoltaic, and space-based. Solar dynamic systems utilize collected light to heat a working fluid which drives a turbine. Such systems would convert 15 to 25 percent of the incident energy into electricity. The major components of these systems (pipes, boilers, and collectors) are “low tech” and would be amenable to repair and eventual manufacturing on Mars (Zubrin 1996). However, solar collectors generally require a point source of light. Hence dust storms are estimated to drastically reduce the output of these systems - by as much as 95% (Geels 1989).

Space-based solar energy collection and microwave beaming for baseload power has only recently been studied for Martian applications (Mankins 1997), however, it has received a great deal of attention for Earth orbiting (Collins 1996) and Lunar surface installations (Criswell 1996). Space-based collection systems would not be subject to the power reductions due to atmosphere absorption and dust storms. Assuming a .25% conversion efficiency as provided by (Criswell 1996) for a lunar installation providing terrestrial power with 1980’s technology, an equivalent Martian power density would be 0.0025 x 590 W/m^2 or 1.48 W/m^2. Hence such a system would require a solar array area of 68000 m^2 to produce 100 kW. This translates into a very large planar array of solar cells arranged in a 259 m x 259 m square. The Japanese are currently considering producing a technology demonstrator satellite of these dimensions to produce solar energy in Earth orbit and beam the power to Earth (Collins 1996). The footprint of the ground-based rectenna for the Earth orbiting Solar Power Satellite (SPS) is 1 km square. Although the rectenna is “low tech” and could be produced from Martian resources, it represents a longer term investment than this project is considering.

Photovoltaic systems do not require a single point source of light and would be less affected by global dust storms. These systems operate at about 13-15% efficiency for silicon and around 20% for advanced GaAs models and produce no excess heat. The specific power of state-of-the-art solar cells has now been demonstrated to exceed that expected from a nuclear power source. Space qualified silicon solar arrays producing 66 W/kg have been flown on the Space Shuttle. Arrays producing 130 W/kg have been manufactured, and the latest thin film solar cell technology promises specific powers from 1 kW/kg to 15 kW/kg. Comparing solar and nuclear energy for an average 100 kW power supply at the Viking 1 landing site, it has been estimated that a solar array of 1850 square meters (41 x 45 m - about half a football field) could provide the equivalent energy of a nuclear source (Haberle 1993). This assumes average daily insolation based on solar flux models accounting for latitude, absorption, season, and dust, but not storms. Conversion efficiency of 20% was assumed, specific mass was 0.9 kg/m^2, and the time interval for this study was 155 days during the Spring and Summer. The weight of the solar cell assembly is estimated to be around 1.67 metric tons, as compared to 3.96 tons for the nuclear generator. Accounting for the effect of dust storms, the irradiance at the surface is expected to diminish by a maximum of about 60%. For the Martian atmosphere, it has been shown that while the direct irradiance drops off quickly with increased optical depth, the light is largely scattered into diffuse radiation even up to high optical depths. For a solar flux of 200 W/m^2 at a typical optical depth of 1.0, this drops to about 100 W/m^2 for an optical depth of about 4.0, and to about 80 W/m^2 at an optical depth of 5.0. Typical values for optical depth during a global dust storm would range from 2 to 5, and nominal values for Mars are expected to be about 1.0 or less. It has been shown that for optical depths of 1.0 or greater, the efficiency of solar cells collecting diffuse radiation exceeds that for directed light (Haberle 1993). Therefore, a reasonable approximation for the area and mass required for a photovoltaic array to reliably produce the equivalent average energy of a 100 kW nuclear generator, despite a continuous dust storm, would be about 4000 square meters (slightly larger than the size of a football field) and 3.5 metric tons. This is comparable to the payload mass required for nuclear power.

Model of Available Energy

Several studies have been performed which assess the available solar energy on Mars (Haberle 1993; Appelbaum 1989 a, b; Geels 1989; Landis 1990; Appelbaum 1990). The following work utilizes the model of available solar energy which is common to many of the studies listed above. The primary equation for modeling the solar radiation S, at the top of the atmosphere is provided by the following (Haberle 1993):

$S = S_0 R^2 \cos(z)$ (1)

where

S_0 is the average solar insolation at Mars (590 Wm^{-2});

R is a nondimensional Sun-Mars distance parameter: and

z is the solar zenith angle.

Equation 2 (2)

where

e is the orbital eccentricity (.0934);

L_s is the areocentric longitutde; and

L_s^p is the areocentric longitude at perihelion (250°)

$\cos(z) = \sin(q)\sin(d) + \cos(q)\cos(d)\cos(h)$; (3)

where

q is the Martian latitude;

d is the solar declination; and

h is the hour measured in angular units.

Equation 4 (4)

where

e is the current Martian obliquity (25.2°)

Equation 5; (5)

where

t is the time in seconds measured from noon; and

D is the length of the Martian day (88775 s).

The most important additional factor in modeling the available solar power on Mars is the effect of dust in the atmosphere. One approach adopted in (Haberle 1993) includes calculating the total downward irradiance which includes the incident solar radiation seen by a flat plate collector due to both direct illumination and scattered light:

Equation 6 (6)

where

I_{NN} is the normalized net irradiance; and

A is the surface albedo (typically assumed to be .25).

The normalized net irradiance is a function which quantifies the effects due to surface albedo, solar zenith angle, and optical depth (or opacity of the atmosphere). The function is provided in tabular form in (Haberle 1993). The power produced by a photovoltaic array at any given time is then obtained by multiplying by the area of the collector and the efficiency of the solar cells (note that this model does not take into account losses due to dust loading on the array):

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$P_s = eff*Area*I_{TD}$. (7)

Figure 1 provides graphical information covering several parameters relating to the estimation of available solar power. The Viking 2 lander data was used in this example. The upper left hand plot provides the estimated solar insolation calculated above the Viking 2 lander site. Although, this calculation did not depend on measured data, the drop-out regions correspond to times during which the Viking 2 lander was not providing data. The upper right hand plot provides the optical depth data as measured by the Viking 2 lander and interpolated to match other meteorological measurements. The higher optical depth values denote times of a dust laden atmosphere. The normalized net irradiance function estimated using the Viking 2 data and the tables provided in (Haberle 1993) is provided in the lower left hand plot. The instantaneous power which would have been produced by an 1850 m2 photovoltaic array with 20% efficiency is provided in the lower right hand plot of Figure 1. Note the wide variation in power produced which is due to the orbital eccentricity, the dust laden atmosphere, and the seasonal solar zenith angle effects.

Figure 1 Variation in Solar Energy Parameters Using Viking 2 Lander Data.

Implementation Issues

Surface-based solar power offers several advantages for a Martian base. First of all, much terrestrial and space experience exists for solar energy production systems. Once sized correctly, solar power production would be sustainable indefinitely and would not produce any wastes. While the output would be degraded by dust accumulation on the collectors surface, this degradation is graceful, not catastrophic, and can likely be easily removed by manual or automated systems. Furthermore, a solar cell energy system could be designed to be robust enough to sustain substantial localized damage without significant effect on the total power production. One potential advantage due to the new thin film solar cell technology is the possibility of a mobile energy platform comprised of a balloon or other inflatable structures covered with solar cells. The feasibility of this concept has been demonstrated by (Ramohalli 1998). Other advantages include safety, global access to the resource, reliability, and expandability. It has also been suggested that in the future, solar cell sheets could be manufactured directly on Mars. However, since such production facilities represent a "high tech" endeavor, a mature base or colony would need to be in place.

Models of the distribution of solar radiation on Mars are well established and the availability and distribution of this resource is already well understood. Improvements in the fidelity of these models will come from new knowledge about the specific composition and size distribution of aerosols and dust particles in the Martian atmosphere. Nevertheless, enough is presently know about the Martian atmosphere and its effect on the incident radiation at the surface to design a robust solar power system for worst-case conditions.

An important consideration for solar energy on Mars, however, is the storage of energy for night time loads. Ultimately, development of a robust locally derived power system, would require the integration of multiple alternative sources, such as wind or areothermal energy, both of which supplement solar power, and reduce the cyclic storage requirements. Solar systems could function in a hybrid mode with other systems to create a redundant base-load system. Although assessing or examining energy storage techniques is beyond the scope of this paper, the potential for combined solar/wind energy systems will discussed in following sections.

Wind Energy

Although the atmospheric density is about 100 times less than the Earth, Mars has several advantages for successful wind power applications: less gravity (less massive components), large temperature and pressure swings (producing high winds), and tremendous surface relief and low atmospheric thermal inertia (produces consistent wind patterns). Unfortunately, the most direct observations of wind speed on Mars are limited to the Viking landers and from Pathfinder. Wind speeds at these locations were observed to average about 5 m/s, with a peak of 25 to 30 m/s recorded at the Viking Lander 1 site. A local dust storm over Chryse Planitia accompanied these peak readings which was also observed from orbit (Greeley 1982). The Viking landing sites, however, were selected on the basis of mission safety, which precluded complex or steep terrain that is more likely to harbor the high winds of interest. Computer models of the Martian atmosphere based on longer range observations and extrapolations from the wind blown sand streaks on Mars have predicted significantly larger values for surface wind speeds (Haslach 1989). It has been estimated that a well chosen site could harbor sustained speeds approaching 14 m s^{-1}. Possible sites include the horseshoe vortices around raised rim craters (as seen by dark streaks), and natural wind channels due to the topography of hills and valleys (such sites have been used successfully on Earth). Also, regions such as Hellas basin (the lowest region on Mars) have up to a 44% denser atmosphere (and hence a 44% increase in power). These regions would be favorable sites if high local wind speeds can be identified. Long low angle slopes (as seen on the shield volcanoes or slopes of large basins) may produce winds of 25 to 33 m s^{-1} at approximately 25 meters above the surface. It should be noted that the wind patterns at the Viking 1 landing site were believed to be dominated by this type of slope wind pattern (Zurek 1992). Recent measurements made at the nearby Pathfinder landing site further support this conjecture (Schofield 1997).

Martian Wind Exploration Techniques

A significant amount of observational evidence exists for the location and regularity of Martian winds. Sand and dust deposits, wind streaks, and erosional features are good indications of potential regions with significant winds. Wind streaks are present in the Tharsis region near the large volcanoes and in the Elysium region around Elysium Mons. Such streaks are the most numerous of the eolian markings in these regions and are accurate recorders of the direction of near-surface winds (Lee 1982). Observations of dark streaks in regions without visible points of origin have been identified as occurring in regions with extended slopes of 1 to 10 degrees. Similar concentrations of dark streaks on long slopes have also been found in the planet's southern hemisphere. A model of Martian slope winds, developed by (Magalhaes 1982), has predicted that slope winds will occur for slopes greater than 0.02 degrees, late at night and during the early morning, with maximum speeds being attained immediately before sunrise when the ground is at a minimum temperature. For slopes of more than 0.1 degrees, fully developed wind profiles would take less than 200 km to be achieved. For the central volcanoes, these conditions would occur along most of the flanks. It was also found that regions with low thermal inertia and high surface roughness tend to favor intense slope winds.

The majority of sediment deposits on Mars are composed of either sand or dust sized particles. The functional difference being that sand is transported by saltation and dust by suspension. In (Thomas 1982) the relationship between Martian winds and these deposits is investigated by comparing global wind streak data to the major deposit locations. Dunes tend to form in the large north polar erg, in craters, canyons, and similar topological traps. The largest concentration of sand on Mars lies in the north polar erg, mostly on erosional troughs in and around the polar layered deposits. Dunes in the low-latitude canyons are subject to complex wind patterns because flow up and down the canyon competes with north-south polar circulation. Dark streaks are found in the Juventae Chasma and Coprates Chasma indicating strong winds in these areas. Dunes in the south polar region are constrained by local topography. In the north polar region, winds show a strong outward flow (i.e., radially away from the topographic north pole). At low latitudes, wind streaks and eolian deposits seem to be a result of Hadley cell circulation (Thomas 1982).

While eolian processes on Mars provide clear evidence of wind on Mars, the transport of visible deposits can occur over long periods of time and do not necessarily imply recent high velocity winds. This evidence can be used, however, to identify likely locations for significant wind energy resources. Other than direct wind measurements taken at specific locations by robotic landers, the only other mechanism for global measurement of surface winds is via spaced-based remote sensing techniques. A recent technology called Coherent Doppler Lidar will soon be tested as an instrument on the Shuttle to perform space-based wind vector measurements (Kavaya 1998). Such an instrument could be incorporated in a near-term Mars orbiting spacecraft to identify and map ideal landing sites for maximizing wind energy resources.

Coherent Doppler Lidar (CDL), which has recently become a viable option for space-based wind vector measurements on a global scale, has the potential to drastically improve current knowledge of atmospheric processes on Earth and Mars. A precursor lidar mission for mapping winds on Mars could contribute significantly to the feasibility of a self-sufficient human mission to Mars. The concept of Doppler lidar is about 20 years old, and has been applied to the detection of aircraft wave vortices, pollution studies and high stack emissions, as well as the study of weather phenomenon such as tornado's and wind shear in thunderstorms. Developments in laser and signal processing technology have been instrumental in producing systems that enable the consideration of space-based lidar applications to the mapping of global winds from an orbiting platform. The technical obstacles for developing such a system were mainly due to power requirements and efficiency of the detection of the backscattered signal over long ranges. Presently, a NASA mission named SPARCLE (SPAce Readiness Coherent Lidar Experiment) is under development and is scheduled to fly on the Space Shuttle in 2001 (Kavaya 1998).

A space-based coherent Doppler lidar instrument for observations in the Martian atmosphere would serve dual purposes in terms of achieving scientific objectives and preparing for human missions to Mars. With respect to wind measurements, a CDL system could specifically determine global circulation patterns, closely track the full development of Martian dust storms, measure the annual variation in global and local winds, and locate target base locations with optimal wind characteristics for supporting wind energy generation.

An important issue in the design of a Martian CDL system would be the determination of required laser power for successful coherent backscatter measurements. The efficiency with which aerosol particles would scatter the laser light back to the detector is unknown for Mars, and this value is critical in determining the minimum energy required to obtain the minimal number of coherent photons for successful wind vector determination. Designs for a Mars mission would necessarily be conservative, thus affecting solar panel sizing and overall spacecraft design as well. The low atmospheric density and pressure at Mars is another related factor in the design of a Martian CDL instrument. The particle size distribution of suspended aerosols can be expected to be quite different from Earth. Optimal lasing frequencies for observing Martian winds would require models of the size distribution for these particles. In order to calibrate a CDL lidar system in Martian orbit, one concept could employ a series of ground-based observational stations. These stations could provide ground truth data that are matched simultaneously with space-based measurements to refine atmospheric model parameters, and improve the quality of lidar observations. Such a system is described by (Crisp 1994). The Mars Environmental Survey (MESUR) Program is envisioned as a network of micro weather stations for making in-situ meteorological measurements in the Martian boundary layer. This system would use micro sensors for measuring pressure, temperature, winds, humidity, and dust/ice optical depth. To maximize the scientific value of this program and provide ground truth data for remote sensing satellites, a network of at least 20 of these stations is required with sampling rates of at least 1 Hz. Wind measurements for these stations would be accomplished by micro-machined pitot-static ports or sonic anemometers. Each micro station would consume less than 0.1 Watt and be capable of communicating directly with a space-based instrument.

Given a CDL equipped spacecraft orbiting Mars, the objective of locating optimal sites for wind energy generation is not difficult to accomplish. The primary question is “Where on Mars can one expect high enough average wind speeds to justify an energy management approach partly based on wind energy ?” Solar energy considerations would also play a role in defining the optimal combination of the two resources. From the wind mapping perspective, however, a global assessment of boundary layer winds for a complete solar cycle would provide the necessary information. In particular, space-based observations could be guided to focus more on high probability regions, such as the north polar erg, low latitude canyons, long slopes in the Tharsis and Elysium regions, around large crater rims, and so on. Targeting specific sites with multiple pulses can be used to obtain better resolution. An important long term question that might be answered by a Mars CDL system is the relationship between local winds, dust storms, and solar flux attenuation at specific sites. An ideal location for cooperative solar and wind energy generation would be one where wind speeds increase significantly at night and during dust storms, at the same time that incident solar flux is absent or reduced. A CDL system is one promising approach to answering these fundamental questions, which in turn would enable the system trade studies required to design a self-sufficient, locally powered, human base.

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Implementation Issues

Fortunately, for Martian utilization of wind energy, the power from a wind turbine is more a function of the wind velocity than the atmospheric density. The power available from a wind turbine is given by the following (Haslach 1989):

Equation 8 (8)

where

P is the power produced by the turbine;

A is the swept area of the wind turbine;

n is the wind velocity

r is the density of the atmosphere; and

c is the power coefficient.

It can be seen that although the atmospheric density is 100 times less on Mars, the dominate term is the wind speed. Hence, assuming a r of .01665 kg/m^3 for Mars, a 30 m/s Martian wind will provide the same power a 6 m/s wind on the Earth (Zubrin 1996). Using an efficiency value of $c = 0.4$, as is common on terrestrial turbines, a 200 m^2 turbine could produce 2 kW in a 14 m/s wind and 12 kW in a 25 m/s wind (Haslach 1989). Haslach produced a concept which called for a 17.25 meter tall giromill turbine situated atop a 21.5 meter landing vehicle with a weight of 175 kg.

Wind power produces no wastes and is totally sustainable. Also, it requires “low tech” extraction technology. Hence, it would be easily maintainable and potentially expandable. In fact, most of the mass and volume of a wind turbine are in the blades and tower. These are components that could be manufactured early in a Martian outpost’s life from native metallic or composite materials. Terrestrial experience has shown that wind/solar and wind/combustion hybrid systems are extremely effective and can provide near continuous power. Also the generator systems could be common to solar dynamic, combustion, and some nuclear systems. The power to mass ratio for wind power generated using a design suggested by (Haslach 1989) ranges from 7.64 W/kg for 14 m/s winds to 44.1 W/kg for 25 m/s winds. However, wind power is a variable and limited resource when used alone. The extraction system also would have to be sited appropriately to make full use of the resource. Current models suggest that the most effective winds could be as much as 25 meters above the surface.

Model of Available Energy

Currently wind speed measurements exist at only three sites on the Martian surface. This information can be utilized to assess the potential wind energy resource available on Mars. The model suggested by (Zurek 1992) was used to estimate the potential wind speeds that would have existed above the Viking 1 and Viking 2 lander measurement sites. This model takes the following form:

Equation 9 (9)

where

U is the wind speed estimated at altitude;

u_* is the friction velocity which varies with time;

k is von Kármán’s constant

z is the altitude desired;

z_o is the surface roughness height; and

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y_u is a function modeling atmospheric stability.

The stability function is based on Earth derived boundary layer results and is expected to be universally applicable (Sutton 1978):

Equation 10a; for stable conditions (when $L>0$);

Equation 10b; for neutral conditions; (when z/L=0); (10)

Equation 10c; for unstable conditions (when L<0);

where

L is the Monin-Obukhov height which varies over time; and

Equation

Values for *L* and u_* for the first part of each Viking lander mission are provided in Zurek (1992) and Sutton (1978). These parameters were estimated using wind measurements at an altitude of 1.6 m. Estimates of wind speeds at other altitudes over the Viking landing sites can be then be produced. Figure 2 provides the wind speed estimates produced by this model for ten days at the Viking 2 Lander site at 25 meters above the surface. The total wind speed peaks at 19 m/s as seen in the upper left plot. The neutral component of this model has a maximum speed of over 7 m/s as seen in the upper right plot. The stable component, shown in the lower right, tends to add up to 18 m/s to the neutral component during the night. The unstable component (lower left) reduces the wind speed by almost 3.5 m/s during the day. Equation (8) can then be utilized to estimate the power produced by a wind turbine of a specific design. Utilizing the parameters listed above for the wind turbine concept provided in (Haslach 1989), the power produced by the Viking 2 winds would peak over 4.5 kW and produce an average power of slightly under .5 kW per day.

Figure 3 provides the wind speed estimates 25 meters above the Viking 1 lander. The model predicts that the wind speeds peak at 60 m/s. The stable part of the winds are the largest component of these wind speeds with peaks of 55 m/s which is related to a nocturnal jet occurring after sunset. A second peak occurs pre-dawn and is likely related to the slope wind phenomena. The neutral component peaks at 15 m/s. The unstable component reduces the total wind speed by up to 10 m/s. This data represents a ten day window out of the 15 day window over which the model parameters are valid.

The expected power produced by the turbine design parameters listed above is shown in the lower graph of Figure 4. This figure provides estimates of the instantaneous power expected at 25 sample times per day. The associated estimates of the solar power (using the solar array size and efficiency provided earlier) for the same period of time are shown in the upper graph of Figure 4. The wind power is seen to peak at almost 150 kW. However, this power level is not maintained for an extended period of time. Daily averages are 58 kW per day for solar power and slightly less than 7 kW per day for wind power. Since these wind power production is extremely sensitive to the peak wind speed estimate, uncertainties in the model could significantly affect these estimates. Ongoing efforts include validating and expanding the wind speed estimation model (to other seasons, altitudes, and locations) as well as performing energy system trade-off studies.

Figure 2   10 Day Wind Speed Estimates 25 Meters above the Viking 2 Lander.

Figure 3   10 Day Wind Speed Estimates 25 Meters above the Viking 1 Lander.

Figure 4 10 Day Solar and Wind Power Estimates at the Viking 1 Lander.

Areothermal Energy

This section discusses the availability of planetary heat sources on Mars. This resource will be labeled as Areothermal, in order to distinguish the Martian expression from the terrestrial resource which is labeled as Geothermal. Geological measurements are required to determine the heat flux on Mars. However, a current estimate suggests that the average value is close to 35 mW/m^2. This is less than the average terrestrial value of 80 mW/m^2. On the Earth, the process of plate tectonics typically serve to concentrate this energy (Meyer 1996). This process is not currently seen or believed to be possible on Mars. However, young volcanic features are also indicative of underground geothermal sources (Zubrin 1996). Seven percent of the Martian surface was geologically emplaced during the Upper Amazonian period (this dating comes from an impact crater count of less than 40 craters larger than 2 km per 10^6 km^2). Of this, about 3.1% is covered with formations resulting from young igneous intrusions or various fluvial processes which are indicative of near surface volcanic heating. Hence, 4.5 million km^2 of the Martian surface area is likely to have experienced volcanism in the last 700 to 250 million years. In fact, it is possible to have had active volcanism until recent times or even ongoing today. These regions are more likely candidates to harbor near surface reservoirs of areothermal energy (Fogg 1996). It should be noted that significant near-surface areothermal energy may not have a surface manifestation. With this in mind, (Fogg 1996) points out that most Amazonian volcanism (which is less than 2 billion years old) lies on the 28% of the surface (40 million km^2) contained between 20° and 220° W and 50° N to 15° S. This area may contain many regions of such cryptovolcanic or subsurface volcanism, which may be a result of a huge mantle plume of ascending magma (Fogg 1996). As such, there seem to be many potential regions on Mars which could provide areothermal resources.

The general model of an exploitable geothermal resource includes a heat source of magma or a cooling intrusion of volcanic material. In general, a supply of water in a permeable reservoir is heated by the source and contained by an impermeable cap rock layer. Therefore most terrestrial exploration techniques assume that heated water is available and is assisting in the modification of the environment surrounding the heat source. There are terrestrial applications where hot dry rock can be used for energy production assuming a ready supply of fluid is available. Also, there are postulated heat sources which are driven by concentrated radioactive materials as opposed to magma sources (Fogg 1996; Wright 1985).

Geothermal Exploration Techniques

The current techniques available for geothermal exploration are based on thermal, electrical, gravitational, magnetic, seismic, and radiometric methods, geophysical well logging, and studies of borehole geophysics. The thermal techniques measure elevated temperatures of rock or any nearby fluids. Hence, these techniques represent the most direct indication of geothermal reserves. Thermal studies include thermal gradient and heat flow, shallow-temperature surveys, snow-melt photography, and thermal-infrared imagery. An additional technique which has received little terrestrial attention is microwave emission mapping. The electrical techniques are the second most important procedures (after thermal) for locating geothermal resources when heated water is present. High temperatures, increased porosity, increased salinity, and the presence of certain clays and zeolites increase the ionic mobility (and hence conductivity) of the fluid-rock volume. All of these conditions may be present in Martian hydrothermal systems. Also, partial melts and magma can become very conductive, especially when water is present. The electrical exploration techniques include a variety of surface-based techniques in which an electromagnetic field or current is produced in the rock volume under test and the modifications due to the surrounding rock are interpreted to perform the exploration (Wright 1985).

Local gravity is modified by volcanic intrusions and changes in geologic structures. Typically, positive gravity anomalies are sought which indicate the presence metamorphic rock, alteration of rocks by hot water, and granitic intrusions. Negative gravity anomalies imply the presence of hot silicate magmas. Magnetic methods are useful for mapping regions where water or heat has modified the magnetic properties of the rock. Typically, these measurements indicate where magnetite has been modified to form nonmagnetic pyrite by interacting with hydrogen sulfide in the presence of heat. This creates a magnetic low (which will remain even after the source becomes extinct). Another utility of magnetic surveys is the ability to determine Curie point depth. This is the depth at which the temperature is high enough to destroy magnetite. Seismic events are usually associated with hydrothermal systems. There is some indication that these water/heat systems radiate seismic energy in the range from 1 to 100 Hz. There are also modifications which result when seismic waves pass through magma reservoirs that can be used to map the resource (Wright 1985).

Radiometric mapping is used to determine the extent of systems that have surface manifestations of hot springs containing radioactive elements. Geophysical well logging records physical properties of the lithosphere, which can be used to determine properties related to geothermal production issues. Finally, borehole geophysics utilizes surface and subsurface instruments to map electrical or seismic phenomena with greater depth resolution (Wright 1985).

Martian Thermal Mapping

In thermal mapping studies of Mars, the temperatures just before dawn are of particular interest. This is the coldest time of the day and the results are less dependent on albedo or terrain slope. The results are then most indicative of surface properties. Mariner 9 acquired the first predawn temperature measurements during the first successful orbital Martian orbital mission in 1972. The Mariner 9 results showed that there was a warm region along the northern edge of Hellas Planitia and high local temperatures in Valles Marineris. The area around the south of Tharsis Ridge was, in contrast, found to be cooler than the surrounding area. The Viking results showed that warmer regions were associated with Valles Marineris and extending into the Chryse Basin as well as the southern border of Isidis Planitia (Kieffer 1977). Upon comparison with a Viking thermal model, the Valles Marineris anomaly showed the largest temperature differences T_r (>16K). The floors of Ophir Chasma and Ganges Chasma also show T_r values comparable to Valles Marineris. Additionally, a region to the east of the Valles Marineris canyon system (-17°, 28° W) showed similar residual temperature values. Since none of these regions were found to be especially dark, the original authors assumed that high thermal inertia material was present (Kieffer 1977).

High residual temperatures (>10K) were also found in the Isidis Planitia region which had high actual temperatures. This region was on the boundary between Isidis Planitia, Syrtis Planitia, and the southern highlands (+5°, 270° W). Two adjacent regions (+30°, 255° W and +10°, 220° W) were indicated to contain high to moderate slopes. However, this is not expected to have had a serious effect on the residual temperature calculations. No other explanation was provided for these anomalies (Kieffer 1977).

The Viking data showed several areas with T_r values of 2 to 8 K. The most extensive of these is the Hellas Basin with a 4 K value. There were localized areas to the west and northeast of the basin which also showed similar values. Again, the Mariner 9 data suggests that these areas might contain higher thermal inertia material. Argyre Basin showed the same trend as Hellas but with a smaller magnitude. A few other localized areas such as the crater Huygens and the region of Solis Lacus (-20°, 90° W) also exhibited some residual temperature anomalies (Kieffer 1977).

Limitations in Areothermal Interpretation of Thermal Mapping Results

The primary limitation in using the thermal mapping studies performed to date for areothermal exploration is in spatial resolution. The level of detection of extremely localized thermal phenomena is dependent on size and temperature of the anomaly. As an example, a lava field or lava lake with a brightness temperature of 500K would need to be at least 200m in diameter to produce a 4K change in the 7 mm band. The Viking or Mariner 9 data did not show any regions with a 4K increase over adjacent measurements (Kieffer 1977).

Variations in albedo and thermal inertia can also have an effect on the measurements. However, the Viking instruments allowed the albedo to be measured using the solar reflectance channel. Thermal inertia then remains as one of the primary unknowns in understanding the residual temperature anomalies. Surface roughness and slope of the terrain are other important modifiers of the temperature profile (Kieffer 1977). Currently, the Mars Global Surveyor mission is carrying a thermal emission spectrometer which will function as an infrared spectrometer and radiometer. One study will be to determine the extent of the surface covered by rocks and boulders and to determine grain size (Smith 1996).

The atmosphere can also have a significant effect on the measured temperatures. In fact, the Viking analysis showed variations in residual temperature of up to 10K within a region between Olympus Mons and the Tharsis ridge. These variations were believed to be due to winds. It is expected that this region will contain some of the strongest winds on the planet. Modifications in the thermal profile due to ground ice can also be expected but as yet have not been measured (Kieffer 1977).

Photographic Analysis

Although not all areothermal energy sources can be expected to have a surface manifestation, those that do can be expected to have produced young terrain. The late Amazonian regions of Mars include the youngest surfaces, assumed to be less than 0.7 to 0.25 billion years old. There are a few localized areas which are largely uncratered and may be the youngest surfaces on the planet (Tanaka 1986). One of these regions is the Ceberus Plains in SE Elysium (5° N, 190° W). This region appears to be a flood basalt extrusion of significant depth (Fogg 1996). Another region is the western slope of Hecates Tholus in the Elysium province which is largely devoid of impact structures. This construct appears to be an ash-fall which would suggest a heated source of water (Moginis-Mark 1982).

The Medusa Fosse formation south of Amazonis Planitia appears to be a large pyroclastic emplacement which has been built up over extended periods of time (Scott 1982). The Tharsis region and especially the large Olympus Mons are covered with young lava flows. Some constructs in northwest Tharsis (16° N, 129° W) appear to be cut by water as opposed to lava and appear to postdate the lava flows (Mouginis-Mark 1990). The floor of Valles Marineris including the Ophir, Candor, and Coprates Chasmas show dark splotches which may be pyroclastically emplaced materials that have not been extensively weathered. These deposits appear to follow the fault line which forms the canyon system (Luchitta 1990).

Microwave Emission Mapping

Microwave emission mapping holds some promise as it can extract information from a few meters below the surface (Bowen 1979). Unfortunately, no current data exists for Mars.

Gravity Mapping

An analysis of the Doppler shift in the radio frequencies of the Viking Orbiters has allowed a determination of a gravity model for Mars. This model has gravity highs associated with Olympus Mons, Elysium Mons, Arisa Mons, Pavonis Mons, Ascraeus Mons, Alba Patera, and Utopia Planitia. Gravity lows are associated with Hellas Planitia, and Valles Marineris.

Isidis Planitia has a gravity high in the center and a gravity low on the edges (Esposito 1992). The Mars Global Surveyor will be providing more detailed measurements of the gravity field (Smith 1996).

Local Magnetic Mapping

Regional magnetic mapping of Mars has been performed. In fact, the Martian Global Surveyor has begun the measurement of global Martian magnetic properties (Smith 1996). Although the results are not complete at the time of this writing, there are several localized crustal magnetic anomalies which have been reported (Acuna 1998).

Radioisotope Mapping

Radioisotope mapping of the Martian surface has not yet occurred. However, a gamma-ray spectrometer is planned for the 2001 Mars Surveyor Orbiter (Covault 1996).

Water Vapor Sources

Although there has not been a formal study of the relationship between water vapor sources and areothermal heat sources, the connection is plausible. In fact, it is analogous to the relation between terrestrial fumaroles and geothermal sources (Wright 1985). One study identified potential Martian water vapor sources based on terrestrial, Mariner 9, and Viking observations. The most probable source regions include Solis Lacus (25° S, 85° W) which has shown activity throughout the observational record. In fact, this is the probable source region for the clouds which form in the Tharsis and Syria Planum regions. Another strong source region for water vapor is the Noachis-Hellespontes region (30° S, 310° W). The winter clouds which form in Hellas are most likely derived from this source. The clouds which form around the Elysium construct are likely derived from a source on the border regions of Syrtis Major which is adjacent to Isidis Planitia. Other potential source regions of lesser importance include Argyre Planitia, Arcadia Planitia, Tempe Fosse, Candor Chasma, and Lunae Planum (Huguenin 1982).

Terrestrial Analogs

The most successful geothermal source on Earth is at the Mid-Atlantic Rift as it crosses Iceland. Since Mars is a one plate planet, such sources would not have analogs. However, rift valleys and large graben have produced exploitable energy sources on the Earth. This means that the Valles Marineris and many other smaller tectonic features associated with the volcanic regions represent potential sources of areothermal energy. Also, good geothermal sources exist in turbidite areas which are formed when intrusions are trapped under thick plastic sediments. This is believed to be especially true on Mars where buoyancy forces are less. Also, since water erosion and eolian deposition are postulated to have occurred over long periods of Martian history, such sedimentary layers can be postulated to exist (Wright 1985; Fogg 1996).

Correlation of Areothermal Indicators

The analysis of the Viking thermal mapping data required the use of a fairly crude model. Additional information will be available in the future concerning surface roughness, local slope, ground ice, atmospheric effects, and even more detailed soil information. When factored into the model along with more detailed experimental spatial resolution, the model could be much more precise. Additionally, several ground truth measurements should be available from the unmanned landers over the next few years. Hence, the thermal imagery results can be expected to improve in terms of data return and enhanced understanding. Nonetheless, it is possible to augment current understanding of the data by correlating the thermal imagery with other indicators of areothermal energy sources. Figure 5 collects this information on a single map. Potential areothermal regions dictate exploratory sites which stand out as the locations where several indicators converge.

The chasmas of Valles Marineris and the associated outflow regions have emerged as the most likely candidates for providing areothermal resources. Thermal imagery, visual imagery, gravity mapping, water vapor production, and terrestrial analogs all point to the large canyon system as a candidate. The regions around the Hellas basin especially to the west and northeast are also strong candidates based on thermal, gravity, and water vapor sources. Also, if the basin is filled with a thick sediment load, it could be a candidate area for turbidite deposits. The border area between Syrtis Major and Isidis Planitia is also a candidate given the thermal, gravity, and water vapor indicators. Again if the Isidis basin is sediment filled, then it could be trapping a rising magma source. The residual temperature anomaly and strong water vapor production source in Solis Lacus also provide indications that further study is needed in that region. Other regions such as the Ceberus Plains, Medusa Fosse, Hecates Tholus, and northwest Tharsis are potential candidates based on the photographic analyses.

New information from additional thermal infrared studies, gravity studies, magnetic mapping, and radioisotope mapping should be available in the next few years. This database will add significant knowledge to that which is discussed in this paper. The ability to perform microwave emission mapping could also add significant detail to the areothermal energy exploration efforts. However, surface studies will be needed to finally answer the question of energy source exploitability once remote sensing has defined the search areas.

Key:

Shaded Regions or **RC** - Photography (Recent Construct)

M9 - Mariner 9 Thermal Imaging

VITM - Viking Infrared Thermal Mapper

GM - Viking Gravity Mapping

MAG - Global Surveyor Magnetic Mapping

CF - Cloud Formation

TA - Terrestrial Analogs

Figure 5 Map of Potential Areothermal Sites.

The question of how deep and where these resources are will only be answered, conclusively, by drilling missions. However, some estimations are possible. Table 1 is provided in (Zubrin 1996) as a guide to the depth needed to reach areothermal resources given different geological ages. As a point of reference, a single-well areothermal source of 150° would produce 10 MW of power. This assumes that heated fluids are available to directly drive the energy production turbines. Fogg (1996) also discusses extraction techniques when lower temperatures are available and when areothermal fluids are not available. Electricity production represents an indirect use of geothermal energy and has a maximum conversion efficiency of about 20%. On the other hand, direct use of geothermal energy for heating has been demonstrated to attain efficiencies of close to 90% (Fogg 1996).

Fogg (1996) also suggests a 10 km limit of the depth of available resources. This maximum depth is set for two reasons. First at 10 km most pore spaces in the crust will be closed by compaction and heated fluids would not be available. Also, 10 km is an accepted maximum limit for terrestrial drilling technology. It can be seen from Table 1 that the capability to drill from 2 to 3 km holds the potential for utilizing significant areothermal resources. However, the early capabilities of a Mars outpost will only allow drilling to a few hundred meters for water exploration or extraction purposes. It should be noted that the current Mars reference mission is only assuming a 10 meter drill (NASA 1998). Unless near surface sources are found, full scale (i.e., deep drilling operations) use of areothermal energy will not be feasible until the capability exists to produce material supplies such as pipe and drill rod directly on Mars.

Table 1

DEPTH OF MARS AREOTHERMAL RESERVES AS A FUNCTION OF YEARS SINCE LAST VOLCANIC ACTIVITY (Zubrin 1996)

Unfortunately, the true extent and location of areothermal energy is not known at this time. Hence, the initial mission planning could not rely on an areothermal source and successful exploitation will require a long term build-up of mass intensive components or a Martian manufacturing capability (Fogg 1996). Areothermal prospecting, in the long term, will be an important activity, however, to ensure future growth and prosperity of a permanent Mars colony.

INTEGRATED POWER SYSTEMS

While the preceding discussions have shown the potential for the utilization of in situ energy resources on Mars, a reliable power system for a first mission must necessarily depend upon known capability supplemented by auxiliary resources as they become available. Hence a strategy of “living off the land” while conducting resource exploration is the key to development of a substantial self-supporting base on Mars. An initial power supply based on a combined solar and wind energy conversion and storage system would be the best option for leveraging the best available information for system sizing and storage capacity to guaranty that minimal energy requirements can be met. The system should be designed in such a way as to benefit from additional wind, if available. A mobile system that could be relocated to local areas with more wind would be ideal. As mentioned previously, areothermal energy extraction will require additional surface and space-based exploration to identify useful sources. This is considered to be a long term solution with the potential to allow large scale development on Mars. As such, geothermal exploration should be an important aspect of the first missions, but a non-nuclear power supply for these missions will necessarily depend strictly on solar and wind energy.

The extraction of solar energy on Mars has several advantages and few significant obstacles. More than any other resource, the availability, distribution, and seasonal variation of solar energy on Mars is well known (or well modeled). Even if more information was obtained to further characterize atmospheric properties and dust particle size/composition distributions, this would not affect, at this point, the ability of current models to characterize the worst-case scenario. If a solar power system is designed for robustness and reliability, then it must provide acceptable power production in the worst-case. This is possible, now, without requiring new atmospheric data. Another advantage is that the latest technology points to solar power becoming cost competitive with nuclear, due to higher specific powers, especially with thin film solar cells. Independent of development and material costs, the cost of mass delivered to the Martian surface per kW is perhaps the best measure of economical power. Solar and nuclear are becoming close competitors in this regard. Furthermore, solar energy is reliable, sustainable, and expandable, well beyond the lifetime of a nuclear power source. Models indicate that while solar energy availability decreases during dust storms, losses are limited to about a 60% drop in output, due to the conversion of direct light into scattered light. Doubling the capability for ideal conditions would assure required energy supplies are satisfied.

While the availability and distribution of wind energy on Mars is not well known at this time, it is possible to achieve reliable, continuous power, with reduced energy storage requirements using a system based on combined solar and wind resources. As discussed earlier, wind energy can be more significant on Mars than is commonly assumed. Large diurnal temperature variations and massive topographical relief produce reliable, consistent winds. Since power is proportional to the cube of velocity, high local winds can make up for the loss of density as compared to Earth. Moreover, wind energy may be complementary to solar, due to day/night cycles, dust storms, and the fact that slope winds and global circulation are increased during times when solar energy is decreased. Since solar power alone requires cyclic energy storage to provide continuous power, and energy storage involves a significant weight penalty, wind energy would help to reduce cyclic storage requirements. Using the models described in this paper for solar and wind resource variation, current research aims to develop trade study codes to determine the optimal combination of solar, wind, and energy storage elements as a function of landing site location and atmospheric parameters. Diurnal and seasonal variations in solar flux and wind near the surface, combined with mass estimates for power and storage systems, can be used to determine optimal specific power configurations with robust margins above given energy requirements. In considering energy storage devices, it is preferable to use liquid fuels with high energy content and useful products of reaction. A dual use concept that combines life support and surface transportation systems with energy storage will reduce overall mission cost and provide redundancy. Regenerative fuel cells (H_2-O_2) and/or methane/oxygen systems are likely candidates.

Aspects of the Martian climate may dictate a solar/wind power system design that differs from Earth-based systems. One of the major problems with solar power on Mars is the degradation of efficiency due to Martian dust. Either solar panels would require periodic maintenance or an automatic system must be devised to remove dust accumulation from panel surfaces. Another option, however, might be to remove the panels from the dustiest environment, which is in the saltation flow at ground level. Another driver for elevating the power system is that the highest wind energy on Mars is expected to be found at about 25m off the ground. This is difficult to accomplish, however, with conventional terrestrial wind mill designs. Higher winds may also help to keep solar panels clean. These considerations suggest a new approach for a combined solar/wind system that is airborne and tethered to a mobile base station. A similar concept, called an Aerobot, has already been examined by (Romohalli 1998), consisting of a balloon made from a substrate material for thin film solar cells. Such a system could use solar and wind power to process the Martian atmosphere physically or chemically to control buoyancy and/or store energy. A mobile airborne power platform would be especially desirable for exploration, rover support, and for relocating the system to ideal locations for wind energy, once those sites are locally determined.

CONCLUSIONS

In summary, this paper has discussed alternatives for locating and extracting native resources that are essential to survive on Mars without nuclear energy. A nuclear-free Mars mission is possible and achievable within the bounds of current technology. The latest solar cell technology has demonstrated capabilities that are comparable to nuclear systems, due to specific power performance and the cost of payload delivery to Mars. Models of wind are encouraging for the utilization of wind resources combined with solar. Implementation issues and the Martian environment suggest the possibility of a combined airborne solar/wind design for maximum efficiency. While more research is needed to characterize aerosols (dust particle composition and size distribution), this should have little impact on solar energy system designs aimed to guaranty robustness in the worst-case conditions. More research is needed, however, to identify and characterize wind resource distribution. The concept of a space-based Coherent Doppler Lidar system is one promising approach for detailed mapping of the global Martian winds. Significant space-based and surface-based research will be required to determine the feasibility of utilizing Areothermal energy resources. This has huge potential, however, for long term energy supply and for supporting large scale development on Mars. Precursor missions designed to conduct specific research aimed at identifying these resources can expedite the possibility of a nuclear free Mars mission and the development of a permanent human base.

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