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L.J. Wittenberg

Wisconsin Center for Space Automation and Robotics
University of Wisconsin
1500 Johnson Drive
Madison WI 53706

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In-situ Release of Solar Wind Gases from Lunar Soil

Layton J. Wittenberg*

Abstract

A concept is described which has the potential to perform the in-situ heating of the lunar regolith in order to release the solar wind gases. The poor thermal conductivity of the lunar soil is increased approximately 100-fold by the introduction of an artificial hydrogen atmosphere at 1 atm pressure enclosed in an inflatable structure. The leakage rate of H_2 through the soil is minimal because of the close-packed nature of the soil and the design and operation of the facility.

Introduction

The potential value of the solar wind elements embedded in the lunar regolith has received considerable attention for their potential usefulness, such as H_2 for the reduction of ilmenite to form water, and ^{3}He for the production of nuclear fusion power on earth (Wittenberg, et al., 1991). The commercial viability of such resource utilization will be determined by the cost of acquiring these gases from the lunar soil, because they are in dilute concentrations, e.g., 50-60 wt. ppm for H_2 and 10^{-2} wppm for ^{3}He at Mare Tranquillitatis. As a result, large tonnages of regolith must be handled by conventional mining techniques in order to acquire useful quantities of the gases. For this reason, alternative acquisition techniques are being considered.

One possible technique visualizes the in-situ heating of the soil without disturbing it so that the volatile solar wind gases are released. This concept is somewhat analogous to a technique developed on earth; namely, the partial burning of underground coal seams to release combustible fuel gases (Stephens, 1977). Obviously, the release of gases from the lunar soil will be more difficult

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*Wisconsin Center for Space Automation and Robotics and Fusion Technology Institute, University of Wisconsin-Madison, Madison, WI, 53706-1687

than for the coal projects on earth because no buried combustible fuel exists in the lunar soil and the released gases will not be trapped by impervious layers of overburden such as exist on earth. On the other hand, abundant and free solar energy which could be used to heat the soil is incident upon the lunar surface during the long lunar day. Also, some type of inflatable structure can be designed and installed, as needed, to capture the evolved gases.

The concept of the in-situ collection of the solar wind from the lunar regolith therefore involves two technical areas; namely, (1) the heating of the regolith, and (2) the permeation and collection of the gases from the soil. Because no studies related to this concept were attempted during the American and Soviet lunar missions, this paper reviews initially the available pertinent information regarding the lunar regolith and the atmosphere to develop concepts which may be useful for the in-situ evolution of the solar wind gases.

Conditions of the Lunar Regolith and Its Atmosphere

The rocky materials which form the lunar surface are broadly similar in some respects to rocks found on earth. The lunar surface formed by these rocks appears much different, however, than the soil formed on earth because the lunar surface has been bombarded by meteorites, both large and small, since its formation over 4.3 billion years ago. These meteorites pulverized and fused parts of the lunar rocks to a fine powder, called regolith. Because active geological formation of newly formed rock ceased approximately 3 billion years ago, the regolith has accumulated to a depth of ~ 5 m over the maria and > 15 m depth covering the highlands (Heiken et al., 1991).

The size distribution of particles forming the regolith contains some large particles but most of the particles are $< 250\ \mu$m in size, called the lunar "soil". Soil particles $< 100\ \mu$m compose nearly 60 wt.% of the soil. The soil particles at the surface are repeatedly buried and re-excavated by debris ejected from nearby meteorite impacts; consequently, the soil slowly turns over, in a process called "gardening".

The basaltic lavas which formed the lunar maria regions have a density of ~ 3100 kg/m^3. When this material is pulverized, its volume increases so that the uppermost 1 cm of the surface has a density of only 1360 kg/m^3. The thermal conductivity of this material on the lunar surface is very low, $\sim 10^{-3}$ W/m·K. The density increases with depth so that between 0.4 m and 3.0 m the density rises from 1750 to 1910 kg/m^3. At this higher density, the porosity is in the range of 36-38%, much higher than loose-packed sand with a porosity of $\sim 50\%$. This closer packing in the lunar soil is attributed to the vibrations caused by the many meteoritic impacts over billions of years. The thermal conductivity at > 0.5 m increases to $\sim 10^{-2}$ W/m·K (Langseth et al., 1976).

The solar wind ions emitted from the sun bombard the lunar surface because they are not shielded by a geomagnetic field or an atmosphere. These ions are embedded in the regolith particles to a depth of $\sim$ 100 to 200 nm and become trapped. Many of the volatile solar wind ions are evolved when regolith particles are heated in a vacuum. For instance, nearly 85% of the H_2 and 86% of the ^{4}He and ^{3}He are evolved during heating up to 700°C. In addition to these two principal gases, other valuable gases are also evolved.

The density of neutral gas particles above the lunar surface is extremely small, $\sim 10^{11}/\text{m}^3$. At such a low density the probability of a gaseous molecule escaping is greater than the probability of a collision. Consequently, this gaseous layer is called an "exosphere" (Morgan and Stern, 1991).

Some of the components of the exosphere have been identified by spectrometers placed by the Apollo astronauts. The gaseous atoms He and Ar have been identified and more recently atomic Na and K. Measurements have shown that the density of Ar decreases by nearly two orders of magnitude as the lunar surface rotates from the sunlight to the dark side. Apparently, the regolith particles have many active sites which are able to absorb large quantities of Ar during the low temperature nocturnal periods. Although H ions are the predominant component of the solar wind, no conclusive evidence has been obtained for the identification of either atomic H or molecular H_2 in the exosphere.

Based upon these physical properties of the soil and exosphere, a potential concept for the in-situ recovery of the solar wind gases is proposed.

Techniques for Heating the Soil

The application of a heat source at the top surface of the regolith without disturbing the soil would not be effective in releasing the solar wind gases, because of the low thermal conductivity of the top surface. For instance, if the surface were maintained at 1000°C, it would require 40 hr for the temperature to reach 600°C at a depth of 1 cm (Carslaw and Jaeger, 1986). The thermal conductivity of the regolith does increase by an order of magnitude with depth, indicating that more points of thermal contact exist between the particles as the packing density increases. Additionally, the effective thermal conductivity of a bed of small particles in a vacuum can be increased by several orders of magnitude when gases with high thermal conductivities, such as H_2 or He, are admitted to the bed (Deissler and Boegli, 1958). With the use of such an artificial atmosphere, the thermal conductivity of the regolith at > 50 cm can be increased to 1.03 W/m·K. At this higher thermal conductivity, useful quantities of solar wind gases are released within reasonable times, as will be shown later.

Techniques for Gas Containment and Collection

As shown above, the maintenance of an artificial H_2 atmosphere in the regolith is effective in increasing the thermal conductivity of the soil. Such an artificial atmosphere could be maintained by inflatable domes above the surface and by dikes around the edges of the field, as described later; however, no easily installed device can seal the bottom of the field. For this reason, it is necessary to estimate the quantity of H_2, or other working gas, which might be lost through the open bottom of the field. This estimate is based upon the likely behavior of the H_2 in the lunar soil. When the H_2 at one atmosphere pressure is initially applied to the surface of the soil, a large H_2 pressure gradient is created in the soil because the viscous flow of gas into the porous soil is severely restricted. This pressure wave proceeds slowly into the soil. Some H_2 proceeds ahead of the viscous flow by molecular diffusion because the mean free paths of the H_2 molecules, $\sim 100\,\mu$m, are greater than the smallest pores in the soil, $< 15\,\mu$m. These molecular diffusion particles travel rapidly through the heated soil; however, their velocities will decrease when they enter the unheated soil below the heaters. Consequently, the gas molecules will accumulate at this level and form a gas pressure which eventually reaches 10^3 Pa and allows the viscous wave to reach the lower depth of the heated soil.

A one dimensional transient model for viscous gas flow in porous media (Arastoopour and Adewumi, 1984) was used for this study where the velocity distribution, $U(x,t)$ in the bed at depth x, and time t, is given by the relationship

$$U_{(x,t)} = \frac{k(P_1^2 - P_2^2)}{\varphi 2\mu(P(\bar{x},t))L} \left[1 + 2\sum_{n=1}^{\infty} \cos n\pi \cdot \exp\left(\frac{-n^2\pi^2 kP*}{\varphi\mu L^2}\, t\right)\right] \qquad (1)$$

where k = permeability, φ = porosity, μ = viscosity, L = depth of bed, P_1 = pressure at top of bed, P_2 = pressure at depth L, and $\bar{x} = \frac{x}{L}$. For this study, we are interested only in the gas flow at L so that $\bar{x} = 1$ and $P(\bar{x},t) = P_2$. The pore pressure, $P*$, is assumed to be $(P_1 + P_2)/2$. All physical values were assumed to be constant because only moderate pressures were used. As previously discussed, the porosity, φ, of the lunar soil is $\sim 38\%$ but the permeability of the soil, k, in the lunar environment has not been determined and must be estimated. It is determined, roughly, by the fraction of the porosity which is inter-connected and is difficult to estimate. Because of the high percentage ($\sim 20\%$) of fine particles, $< 25\ \mu$m, in the lunar soil, the possibility exists that many of the permeation paths are closed by such particles. The permeability would be predicted to be, therefore, between loose packed sand, 2×10^{-11} m^2, at a porosity of $\sim 50\%$, and dry soil (earthen) which has a lower permeability of 3×10^{-13} m^2, presumably due to a wide range of particle sizes. For this study, the permeability of the lunar regolith was assumed to be similar to earthen soil (Scheidegger, 1974).

Equation 1 was utilized with P_1 equal to 1 atm (10^5 Pa) and P_2 set at a small value ($\sim 10^3$ Pa) at $L = 4$ m, because the average depth of the regolith on Mare Tranquillitatis is ~ 5 m. A type of loose rubble consisting of various size boulders apparently exists below this level, which would provide easy paths for gases to escape. When these parameters are inserted into Eq. 1, it is found that there is a time delay of nearly 300 s (5 min) before the gas flow at L is detected.

It is also necessary to estimate the quantity of the working gas which would diffuse deeper into the regolith below the heated zone. Because the gas pressure at the bottom of the lower heated zone is not allowed to increase to $> 10^3$ Pa, most of the gas flow to lower depths would be in the molecular diffusion regime. The probability of the conductance of gases through a porous bed has been estimated based upon two relevant computational experiments. In one experiment, the molecular flow conductance through a straight cylinder was determined using the Monte Carlo method (Carette et al., 1983) as a function of the aspect ratio, L/R, where $L =$ the length of the cylinder and $R =$ the radius. For the largest value of $L/R = 100$, the probability of transmission is only 0.05. In the lunar regolith the radius of the smallest vacant hole is $\sim 8\,\mu$m; therefore, for $L = 1$ cm, the value of $L/R =\sim 1250$, which would make the probability for transmission of a gas molecule < 0.05/cm.

In another computational experiment, the radiative heat transfer through a randomly packed bed of spheres was determined by the Monte Carlo method (Yang et al., 1983). The results indicated that the probability of transmission was 0.02/cm of bed depth. By either experiment, it can be seen that the probability of transmission is only $\sim 10^{-130}$/m, indicating insignificant loss of gas to lower depths. In this radiation calculation, 40% of the radiant energy was assumed to be absorbed as each photon reflected from a sphere. An analogous effect can be expected to occur in the cold, uncontaminated lunar regolith which will have a high affinity to adsorb the gaseous particles.

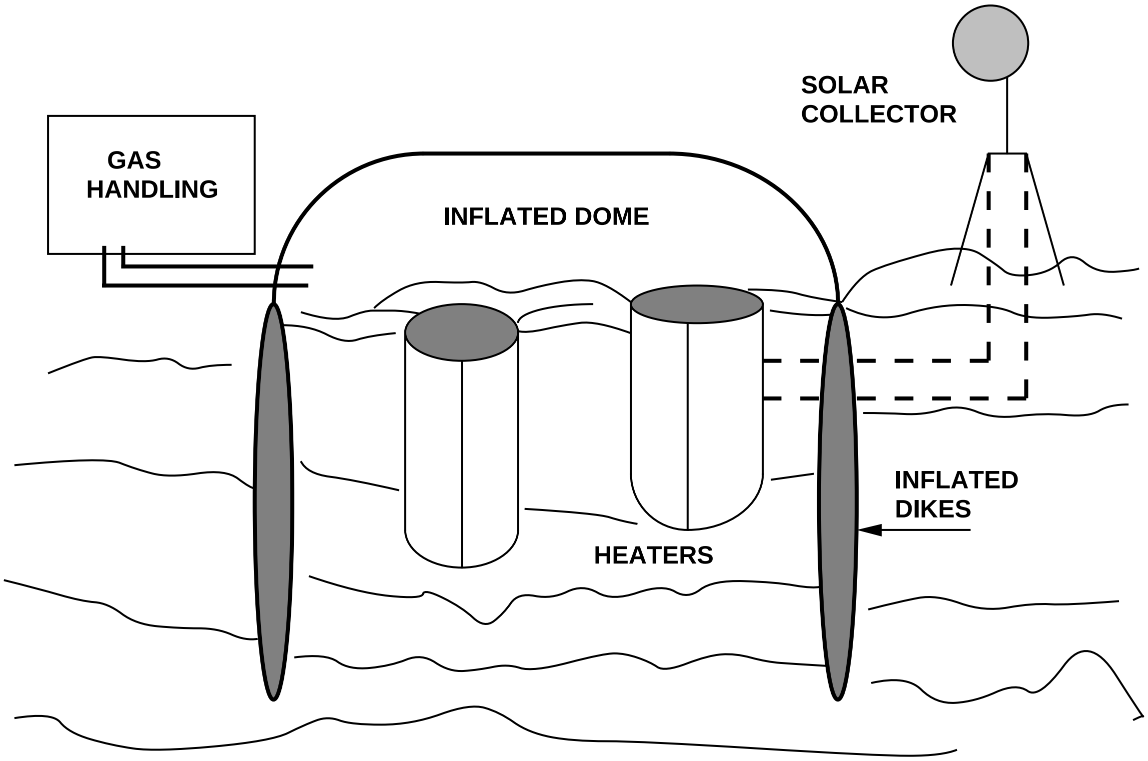

Figure 1. Conceptual design of an in-situ technique to evolve solar wind gases from the lunar regolith. Pneumatic structures are used to contain an artificial hydrogen atmosphere. The regolith is heated by buried, hollow, cylindrical heaters.

Conceptual Model of an In-situ System for the Evolution of Solar Wind Gases for the Regolith

One possible engineering concept which would utilize the previous information is illustrated by use of Fig. 1. A principal concern is the containment of the gases, both the "working" gas and the evolved gases. These gases can be contained by inflatable structures constructed of fairly thin reinforced films which have been proposed for use at 1 atm on the lunar surface (Roberts, 1988). These films will be used for the surface dome and to form dikes surrounding the mining field. The dikes are formed in a trench excavated ~ 0.1 m wide and ~ 5 m deep. This ditch is filled with a collapsed bladder, formed from the reinforced film, and then inflated to form a tight seal against the exposed wall of the regolith. A type of pneumatic device will be used to seal the top cover tightly to the dike around the complete circumference of the field.

The regolith inside of the inflated structure is heated by hot plates inserted into the soil. These plates are arranged vertically and buried in the soil so that their top is ~ 0.5 m and their bottom ~ 3.5 m below the surface. These plates are constructed as heat exchangers, with the heat transfer fluid being heated to nearly 1000°C by solar energy collectors at some distance from the field. When the heated plates attain the operational temperature, hydrogen gas at 1 atm is admitted to the structure and will slowly permeate the soil. This gas does not convectively transport the heat, but increases the conductivity of the packed bed. This gas pressure is continued until the flow of H_2 is detected at the base of the heated regolith, ~ 300 s (5 min). Then, the enclosed structure is evacuated, reversing the flow of H_2 in the soil. The evolved gases and the H_2 are transferred to a gas separation system. The purified H_2 is stored for reintroduction in the soil after ~ 5 min. The heaters are maintained at 1000° C during this operation so that the temperature of the regolith is maintained. This procedure is continued during the entire lunar day (14 earth days).

Several configurations in the design of the heaters and their arrangement in the soil were examined by the finite-element heat transfer code FEHT (Klein et al., 1990), using a thermal diffusivity value of $5.2 \pm 1.5 \times 10^{-7}$ m^2/s. As an example, if the heaters were hollow, right circular cylinders, 1.3 ± 0.2 m radius, where the deviation reflects the uncertainty in the thermal diffusivity value, the regolith in the center of the cylinder would attain the required temperature of 750°C, Fig. 2, during one lunation (~ 300 hr). A field of these cylinders could be arranged in a close-packed structure with ~ 1 m between their peripheral closest points of contact; consequently, nearly uniform heat distribution would be obtained over a large field. The heaters would need to be set back from the peripheral dikes ~ 3 m so that the inflatable fabrics were not overly heated. These heaters and the inflatable structures would be relocated to a new mining site during the long lunar nights.

Discussion

As an example of the production capability of this operation, a field consisting of 64 heaters contained in an area of 1250 m^2 would be relocated after each lunation cycle for one year. During this time, the annual production of solar wind gases would be 6 tonnes of H_2, 3 tonnes of ^4He, 5 tonnes of carbon-containing gases, 0.5 tonne of N_2 and 1 kg of ^3He. Although the frequent moving of the equipment may seem excessive, it is lightweight and in small units which would be readily transportable.

By contrast, a mobile mining technique (Sviatoslavsky and Jacobs, 1988) delivering the same yield of solar wind gases would require the excava-

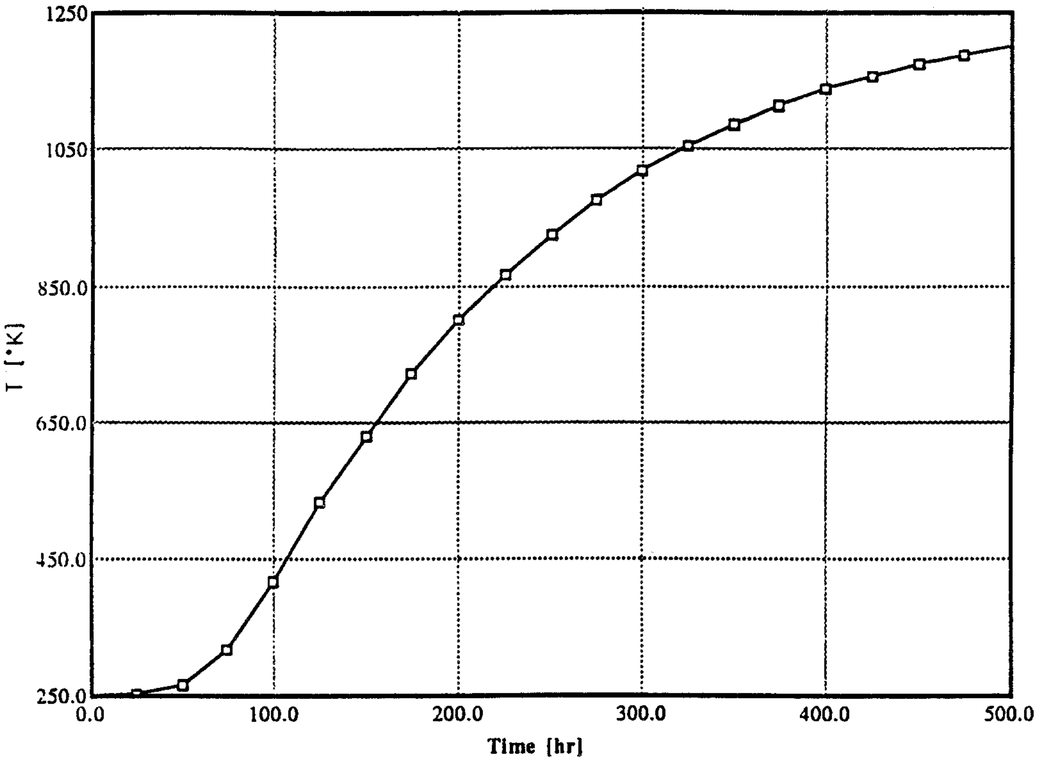

Figure 2. Center-line temperature increase as a function of time for regolith contained within a hollow, cylindrical heater with peripheral sidewalls maintained at 1273 K, calculated by FEHT Code (Klein, 1990).

tion, beneficiation, heating and subsequent disposal of 10^5 tonnes of regolith per year. An estimate of the present concept indicates that only 5% as much regolith needs to be excavated per year to relocate the dikes and the heaters. The benefits of this concept are significant; namely, less mechanical energy required to operate the excavating equipment, less dust created, lower probability of the solar wind gases being mechanically released during the excavation process and much of the lunar surface remaining in its original pristine condition.

Although the mechanical energy required for the present concept is much lower than that required for gross excavation of the regolith, the greatest energy investment in the lunar mining scheme is in the energy cost to transport the equipment to the moon. Because the equipment for the present concept would be less complex and lighter weight, such as a modified trench-digger, significant savings in the launch costs may be possible.

The adsorption of the working gas by the pristine regolith is likely and will need to be determined in the lunar environment as a function of temperature. Most of the evolved solar wind gases formed from H, C and N are too valuable to be used as the working gas. Some argon and neon exist with the solar wind gases and could be collected and used for this purpose; however, these gases do not have the high thermal conductivity of H_2 and He. Perhaps ^4He, which will be in large excess, could be utilized, but it would dilute the ^3He concentration. The usefulness of ^4He as the working gas will depend upon the success of the He isotopic separation system (Wilkes and Wittenberg, 1992).

Conclusion

The introduction of an artificial atmosphere of H_2 at 1 atm pressure in the lunar regolith significantly increases the thermal conductivity of the lunar soil. The leakage rate of the H_2 atmosphere through the soil will be minimized by the use of pneumatic enclosures, the operational procedure and the low permeability of the lunar soil. Many variations of this concept are possible which have the potential to accomplish in-situ heating of the soil in order to release the solar wind gases without disturbing the soil. Such a concept could be initiated on a small scale and additional units added as the demand and learning experience increase.

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