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IN-SITU EXTRACTION OF LUNAR SOIL VOLATILES

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In-situ Extraction of Lunar Soil Volatiles

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Abstract

Techniques for their recovery and utilization of the potentially valuable solar-wind elements embedded in the lunar regolith have been proposed. In order to acquire quantities of ^3He for significant production of fusion-electric power on Earth, large tonnages of the regolith must be processed by normal mining procedures. An alternative concept is presented here in which the volatile gases are released while the soil is heated it in-situ. Temporarily constructed pneumatic structures surround the field to collect the gases. The low thermal conductivity of the lunar soil is increased by a factor of 100 by the inject of H_2 gas. The energy costs for transporting the required equipment from Earth plus the operation of the equipment on the lunar surface were estimated and a positive energy benefit was obtained, when the ^3He was used as fuel to an Earth-based fusion power system.

Introduction

The potential value of the volatiles which are released during heating of the surface soils from the lunar maria has received considerable attention. For instance, the release of the solar wind embedded ions yields principally H_2 which can be used as rocket fuel or used as a reductant for the formation of water from the indigenous mineral, ilmenite (Taylor and Carrier, 1992). Also, the release of solar wind He results in a product with a high $^3He/^4He$ ratio as compared to the Earth's atmosphere. This ^3He has been proposed for use as a nuclear fusion fuel for energy production on Earth (Wittenberg, 1992a). The commercial viability of such resource utilization will be determined by the cost of acquiring these volatiles from the lunar soil because they exist in dilute concentration, e.g. 50-60 ppm for H_2 and 10^{-2} ppm for ^3He. Conventional

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(Earth-based) mining and processing schemes have been proposed to acquire these gases (Sviatoslavsky, 1994); however, some uncertainties exist with these schemes; namely, (1) large tonnages of soil must be processed in order to acquire useful quantities of the gases because they are so dilute in the soil; (2) the characteristics of the lunar soil are very different from any soils on Earth and the appropriate mining techniques can only be estimated based upon the drive-tube samples acquired by the Apollo astronauts (Heiken 1991); and (3) mechanical stress on the soil particles was observed to release helium (Carrier, 1993) and sieving the soil may have evolved 20-30% of the He (Cameron, 1987). Consequently, alternative acquisition techniques need to be considered.

One potential concept proposed the in-situ heating of the lunar soil so that the volatile gases would be released (Wittenberg, 1992b). The in-situ recovery of certain lunar minerals has been proposed (Pereira, 1992) although the technique would not be useful for the volatile gases. Because the lunar regolith is porous and the atmospheric pressure is very low, the heated area and the released gases must be confined within a temporarily constructed inflatable structure. This paper presents a revised design for the structure and a simpler design for the heaters. In addition, the energy pay-back resulting from harvesting lunar ^{3}He and importing it to Earth for use in fusion-electric power plants has been determined and appears to be encouraging.

Techniques for Heating the Soil

The thermal conductivity of the surface layer of the lunar regolith is very low, 10^{-3} W/m·K at the surface and 10^{-2} W/m·K at >0.5 m (Langseth, 1976). Conversely, when a simulated lunar soil was placed in a conductivity cell at $\sim 27°$C and He was introduced into the sample, the thermal conductivity of the sample increased to 0.6-0.7 W/m·K at 1 atm pressure (Horai, 1981). Because the thermal conductivity of He increases with temperature, an empirical relationship (Deissler and Boegli, 1958) predicted that the conductivity of the bed would be 1.03 W/m·K. This value was utilized in the following calculations based upon the assumption that a 1 atm of He or H_2 could be temporarily maintained in the lunar soil.

The configuration of the heaters in the soil becomes important because solar energy must be utilized to provide the thermal energy during the solar daylight period, $\sim$ 320 hr. If the heater were a flat-plate held at 1000°C under 1 atm of H_2, the minimum temperature for volatile release, 650°C, would only extend $\sim$ 0.5 m into the soil; however, the solar-wind elements are known to exist to at least 3 m depth. Consequently, the heaters must be placed vertically into the soil to a depth of 3 m. Cylindrical heaters $\sim$ 2 cm diameter. are the most convenient shape and would be similar to the drive-core tubes

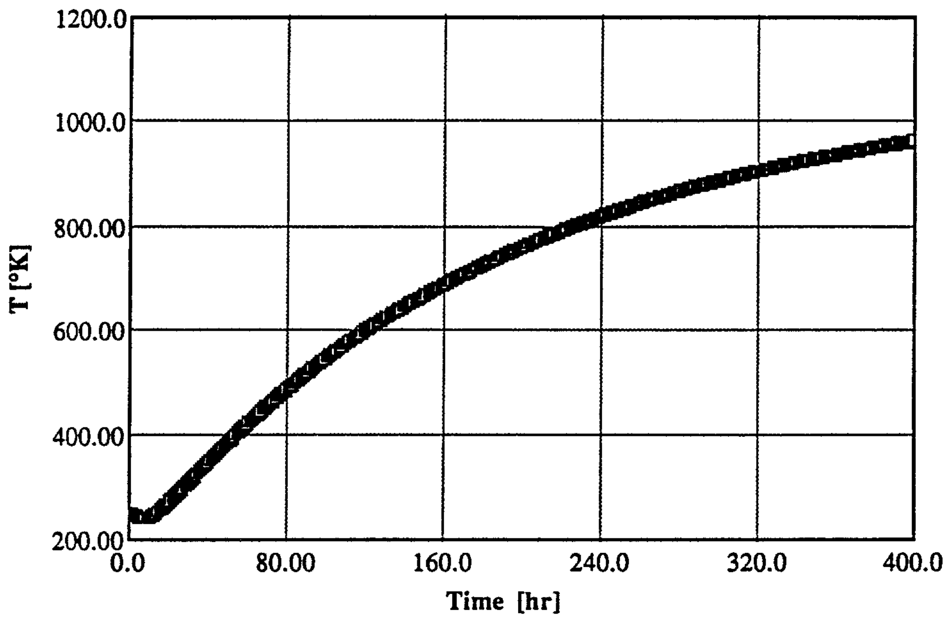

Figure 1. Temperature increase of the soil as a function of time at the boundary between two cylindrical soil configurations of 0.5 m radius with the axis of each cylinder maintained at 1073°K.

which the Apollo astronauts utilized. A close-packed configuration of these heaters was simulated, using a Finite-Element Heat Transfer Code (Klein, 1990). A cylindrical model was utilized in which the center-line was maintained at 1073 K while zero heat flow was maintained at the outer radius, simulating the boundary between two adjacent cylinders. Preliminary calculations showed that at a radius of 0.5 m, the boundary temperature reached $\sim$ 1000 K in 400 hr. The number of nodes at this radius was systematically increased to 136 and the time-steps were increased to 800 to yield the more rigorous results given in Fig. 1, which indicates the boundary temperature approaches 900 K in 320 hr. Such a time-temperature correlation should be sufficient to release $\sim$ 90% of the H_2 and He, $\sim$ 10% of the volatile C compounds but only 4% of the N_2. Higher heater temperatures could be utilized for greater volatile release.

Configuration of the Mining Site

Based upon the above information the general configuration of the mining site can be specified, Figure 2. A dome of an inflatable fabric would be erected to temporarily cover the field. This dome would be filled with one atmosphere of H_2. The flexible fabric for the dome should be fabricated of carbon fibers which maintain their strength to high temperatures, although hot gases do not normally exist in the dome. Based upon a hemispherical

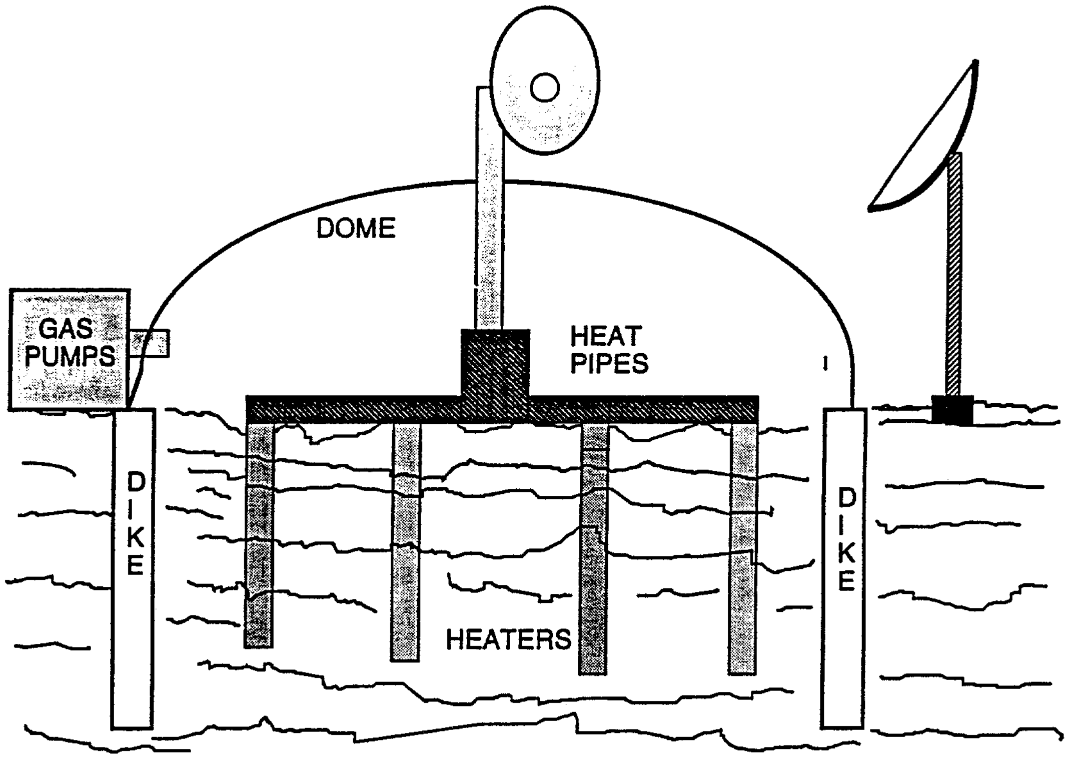

Figure 2. Conceptual design of an in-situ technique to evolve volatiles from the lunar regolith. Pneumatic structures are used to contain the gases and an artificial H_2 atmosphere. Small heaters, utilizing solar energy, are placed vertically in the soil.

shape of the dome and the strength of the fibers, the woven fabric thickness required is 5.6 mm, which is too thick to be flexible. Consequently, restraining cables are secured over the dome in two directions so that fabric is divided into individual cells $\sim$ 5 m $\times$5 m. In this case, the woven carbon fabric needs to be only 0.4 mm thick, which would have good flexibility. The dome principally contains H_2; consequently, a butyl rubber elastomer is recommended to impregnate the fibers and form a 1 mm thick fabric. Based upon the permeation of H_2 through butyl rubber (Steinmeyer and Braun, 1976), $\sim$ 80 kg/yr of H_2 permeates the dome fabric, which is only 1.3% of the H_2 collected from heating the soil. Because butyl rubber abrades easily, it will be coated with a more resistant elastomer. The dome may be covered with a thin layer of lunar regolith for protection from micrometeorites; however, high radiation protection is not needed.

In order to confine the outward diffusion of gases through the soil, an inflated pillow fills a trench 0.3 m wide by 5 m deep, the nominal depth of the regolith. The rotating-brush concept (Boles, 1992) would be well-suited for the preparation of the trench. The joint between the trench and the dome would be made by a pneumatic seal.

The heaters would be inserted vertically into the soil by use of the core-drill apparatus (NASA Report, 1980), which has been demonstrated to be useful to a depth of 3 m. The heaters would be configured as heat-pipes composed of Mo alloy shells containing Na or Li. A distance of one meter would separate each heater from its 6 surrounding close-packed neighbors. At the edge of the heated field a distance of 1.5 m is needed to separate the outer heater from the trench so that this fabric is not unduly heated. The heaters are only 2 m long but are inserted to a depth of 3 m, so that one-meter of unheated regolith extends above the heaters. This soil will be heated by the hot gases rising from the soil; consequently, the fabric in the dome would not be exposed to radiation from a 1073 K source.

The field will be heated by the use of solar energy which is reflected, from four heliostats, to a collector mounted in the center on top of the dome. The concentrated solar energy would be reflected through a small aperture into a long Mo furnace tube. At the base of the Mo furnace, heat would be extracted by heat pipes which would conduct the heat to the heat pipes inserted in the soil (Sviatoslavsky 1992).

A Gas Pumping Station is attached externally to the dome so that the H_2 cover gas can be periodically recirculated and evacuated from the mining site. This facility will also contain equipment to separate the evolved gas from the H_2 cover-gas.

Techniques for Volatiles 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 an inflatable dome above the surface and by dikes around the edges of the field; however, no easily installed device can seal the bottom of the field. For this reason, it is necessary to limit the quantity of H_2, or other gases which might be lost through the open bottom of the field. 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 path of the H_2 molecules is greater than the pore diameter between the particles. This transition occurs between $10^2 - 10^3$ Pa. Consequently, these diffusing particles traveling rapidly through the heated soil accumulate ahead of the viscous wave and form a gas pressure which eventually reaches 10^3 Pa and allows the viscous wave to penetrate to lower depths in the heated soil.

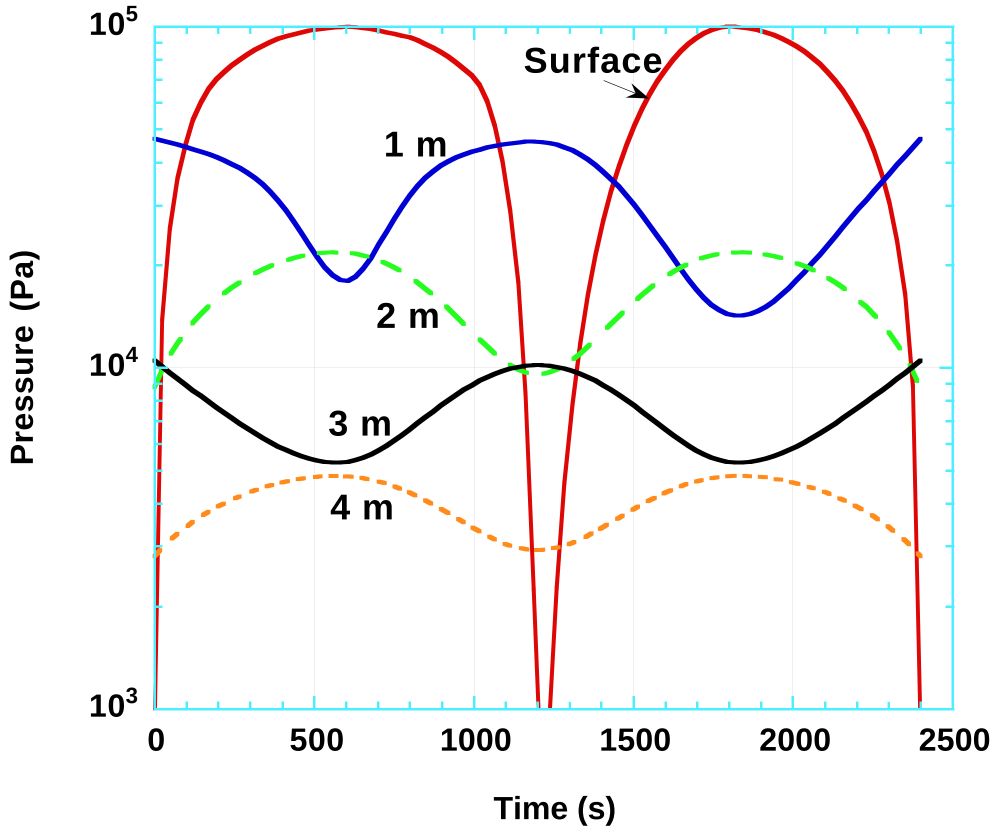

Figure 3. Periodic hydrogen pressure at several depths in the regolith as a function of time.

A one dimensional transient model for viscous gas flow in porous media (Arastoopour 1984) was used for this study as previously described (Wittenberg 1992b). As sinusoidal representation of the results, Fig. 3 was prepared in which the H_2 pressure was increased from 10^3 Pa to 10^5 Pa over a period of 1200 s (10 min) and then decreased to 10^3 Pa during 1200 s. At 4 m below the surface the pressure fluctuated between $(2-5) \times 10^3$ Pa; the value where H_2 flow changes from viscous to molecular flow.

The average depth of the regolith on Mare Tranquillitatis is ~ 5 m. A type of loose rubble apparently exists below the regolith, providing an easy path for gases to escape. A 1 m zone exists, therefore, between the viscous flow regime and the bottom of the regolith; consequently, the quantity of the gas which would escape deeper into the regolith by molecular diffusion needs to be estimated. Such a computation has apparently not been published; however, the radiative heat transfer through a randomly packed bed of spheres was modeled by the Monte Carlo method (Yang et al., 1983), which is similar to molecular diffusion. The results indicated that the probability of transmission (λ) decreases with depth, d, according to the equation $\log \lambda = -1.11$ d (cm). 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 molecules. By this experiment, the probability of transmission is only $\sim 10^{-111}$/m; hence, an insignificant loss of gas to lower depths.

Energy Cost of ^3He Production

Significant costs in manpower, energy, money and materials would be required to determine the feasibility of such a lunar mining endeavor. Estimating the financial costs of such a future project requires many assumptions regarding the cost of developing new technologies and the value of risk capital which are difficult to predict. A more straightforward technique to determine the pay-back from an energy fuel is to determine all the energy expended to acquire the fuel and construct the generating station and compare it with the energy (kWh) delivered by the generating station (Spreng, 1988). In order to make such a calculation for a lunar fuel resource, it is necessary to determine the energy required to deliver all the mining equipment to the moon plus additional energy required at the lunar base. At the same time the energy cost of construction of a fusion-electric power plant on Earth must be estimated. For this calculation a lunar field of 100 m diameter was considered which would be moved to a new field after each lunar day (13 times/Earth year) and produce 10 kg of ^3He/yr.

The mass of materials which must be transported to the moon to support a mature industry is based upon estimates of the individual materials required, their Earth masses, with the assumption of a 20 yr lifetime (Kulcinski et al. 1989). The largest mass item is the pneumatic fabric needed to construct the inflated dome. It has a diameter of 100 m (1 mm thick) and is constrained by cables which is equivalent to a 5.6 mm thickness. For an area of 8200 m^2, and a specific density of 1800 kg/m^3, the total mass is 80 tonnes. The fabric in the trench has a mass of only 0.6 tonnes. The second largest mass transported is the 52 tonnes of food, clothing, and shelter, required for 2 persons to be stationed at the moon base for 20 yrs, although the crews will periodically rotate to Earth. The power required to operate the compressors to circulate and evacuate the H_2 cover gas is 18 MW and will be supplied by photovoltaic cells located on the moon having a mass efficiency of 400 W/kg; consequently, their Earth mass for shipping will be 36 tonnes. The 7800 heat pipes in the soil have a mass of 1.3 kg/each for a total mass of 10 tonnes and 35 tonnes of connecting pipe will be required. The central solar collector and the Mo solar furnace are 7 tonnes. Ten core-drive tube boring machines at a mass of 40 kg each will be needed to set the heaters during one solar night while only one brush sweeper will be needed to dig the outer trench for a total combined mass of only 0.5 Mg. Miscellaneous items such as stationary solar reflectors, product gas radiators, a helium isotope separator system, and a service vehicle will have a total mass of 5.3 Mg.

The total mass to be transported to the moon in 20 years is $\sim$ 226 tonnes. Presently the energy cost from Earth to moon is $\sim$ 100 GJ/kg; however, with advanced heavy-lift vehicles this energy required should decrease to 30 GJ/kg; the total transportation energy cost will be 6.8×10^6 GJ while nearly 200 kg of ^{3}He is being produced, i.e. 3.4×10^4 GJ/kg of ^{3}He.

Operational energy is needed to operate the core-drill apparatus, 6.3×10^{-2} kWh/hole, and for the Brush Sweeper excavator, 532 kWh/trench. Additionally, the He liquefier and He isotopic separation system require 5.25×10^5 kWh/yr. The total energy consumed by this equipment per year is 1890 GJ/10 kg of ^{3}He produced, i.e., 189 GJ/kg of ^{3}He.

To these energy costs of fuel must be added the energy cost for construction of the fusion power plant, which have been estimated to be 4.8×10^3 GJ/kg (^{3}He). Hence, the total energy cost would be $\sim 3.9 \times 10^4$ GJ/kg (^{3}He), i.e., 1.24 MW·yr/kg (^{3}He). The electrical energy produced from d-^{3}He fusion is 10-11 MWe·yr/kg ^{3}He depending upon the efficiency of the plant; hence, the energy pay-back is $\sim$ 8.5 MWe·yr/MW·yr (thermal).

Discussion

This alternate technique for release of volatile gases is encouraging because an energy pay-back of 8.5 MWe·yr/MW·yr (th) compares favorably with 11 for a coal-fired plant without SO_2 removal, or 3 with SO_2 removal while a solar powered satellite concept is predicted to be only 2 to 4 (Spreng, 1988). The predicted energy pay-back using a mechanical miner is $\sim$ 33. However, the lunar soil that must be lifted for the in-situ concept is only 10^{-4}% of that required for a full mining scenario which will reduce the environmental impact of the operation. The in-situ concept principally utilizes a core-drill tube equipment to penetrate the soil which has been demonstrated on the moon. Additionally, the loss of 20-30% of the volatile gases by mechanical handling should be reduced in half by the pneumatic structure. Further trade-off studies are needed to optimize the in-situ concept.

Acknowledgement

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