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REGOLITH THERMAL ENERGY STORAGE FOR LUNAR NIGHTTIME POWER

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Abstract

A scheme for providing nighttime electric power to a lunar base is described. This scheme stores thermal energy in a pile of regolith. Any such scheme must somehow improve on the poor thermal conductivity of lunar regolith in vacuum. Two previous schemes accomplish this by casting or melting the regolith. The scheme described here wraps the regolith in a gas-tight bag and introduces a light gas to enhance thermal conductivity. This allows the system to be assembled with less energy and equipment than schemes which require melting of regolith. A point design based on the new scheme is presented. Its mass from Earth compares favorably with the mass of a regenerative fuel cell of equal capacity.

Introduction

Providing electrical power to a lunar base during the night is challenging. The long lunar night requires that energy storage systems must have great capacity. With battery technology, such as that proposed for use on Space Station Freedom, the mass of a lunar energy storage system would be prohibitively high. Regenerable fuel cell (RFC) storage systems are less massive than batteries, but would be nearly as massive as the lunar habitat modules which use the energy. Nuclear power can provide a low-mass solution, but appears costly to develop and may face political obstacles.

It has been proposed to use an indigenous energy storage medium to reduce the mass which must be transported from Earth to the Moon. In daytime, energy would be stored as heat in some form of lunar material. At night, that heat energy would be converted to electricity.

This paper presents a new concept for using thermal energy storage in indigenous lunar material. The first section discusses the problem of low thermal conductivity in lunar regolith and describes two previously proposed schemes to solve that problem. The second section describes the new scheme and computes some basic parameters. The third section derives sizing data for a point design. The final section compares the proposed system with other schemes and discusses areas for future work.

The Thermal Conductivity Problem

A major obstacle to thermal storage is that lunar regolith has very low thermal conductivity. The low conductivity is due to the fineness of the regolith particles, the small contact area between adjacent particles, and the vacuum between the particles. Low conductivity makes it difficult to pump heat in and out fast enough to provide reasonable amounts of power with a reasonably sized heat exchanger. Two general approaches have been proposed to solve this problem: using solid cast regolith, and using molten regolith.

Cast Regolith

In the cast regolith scheme,[1] regolith is melted and cast into some convenient form, typically that of a brick. A pile of such bricks is enclosed by material from Earth. Working fluid is pumped around and through the pile to heat and cool the bricks. Solid and non-porous, the bricks have much better thermal conductivity than natural regolith.

This scheme has costs beyond the equipment used to store and extract thermal energy. Making the bricks from regolith requires additional time, energy, equipment, and development effort.

Molten Regolith

The molten regolith scheme[2] uses concentrated sunlight to melt a patch of regolith. The molten puddle would be contained by the non-molten regolith in which it rests. As a liquid, molten regolith offers convective heat transfer as well as superior conductive transfer. Heat pipes (such as those developed to cool the SP-100 reactor) can be used to get heat in and out even more readily. Energy would be extracted either by driving a turbogenerator with a hot working fluid or by illuminating photocells with infrared radiation from the puddle.

Relatively little extra time or equipment would be needed to install a molten regolith power system. However, there are many technical uncertainties about this scheme. They include outgassing and contamination from the molten regolith, lateral spreading of the molten puddle, and corrosion of heat pipes.

Improving Thermal Conductivity

The scheme described here uses a gas to fill the space between regolith particles and thereby improve the regolith's conductivity. This approach does not require regolith to be melted. Therefore, this approach should use less initial equipment and energy than the cast regolith scheme and face fewer uncertainties than the molten regolith scheme.

Basic Features

A schematic of the proposed energy storage system is shown in *Figure 1*. Heat is stored in the regolith pile at left. A bag holds gas within the pile. An outer layer of regolith shields the bag from meteoroid punctures and reduces the rate of radiant cooling. The solar collector at the far right heats a working fluid, which is pumped through the flexible heat exchanger in the pile. At night, the same working fluid transfers heat from the pile to the turbogenerator. The turbogenerator produces electric power and dumps waste heat to the radiator.

In addition to the energy storage system, the total power system includes a photovoltaic array for daytime power. This array is sized to meet only the daytime power needs of the lunar base; it does not provide energy to heat the regolith pile.

Regolith/Helium Mixture

The gas pressure in the regolith must be high enough to provide good thermal conductivity between adjacent grains of regolith. The conductivity across a body of gas increases with pressure until the mean free path of the gas molecules is less than the distance between solid surfaces, as shown by the arrow in *Figure 2.* For typical lunar regolith, half of the regolith's mass is comprised of particles less than 70 microns in size. These fine particles fill most of the space between larger particles. For maximum conductivity in natural regolith, the mean free path of gas molecules would have to be much less than 70 microns, so helium pressure would exceed 1 psi (6895 Pa). To reduce the required pressure, I propose to use a sieve to remove fine particles from the regolith. In the coarse remaining regolith, the mean straight line distance between solid surfaces is 70 microns. With helium, only 0.13 psi pressure (896 Pa) is needed to achieve maximum conductivity in this coarse regolith, as shown in *Figure 2.*

The thermal conductivity of the regolith/gas mix was estimated as follows. The maximum storage temperature was assumed to be 1000 K, well below the temperature at which regolith begins to sinter. The conductivity of helium at 1000 K is 3.63 mW/cm-K. The conductivity within a grain of regolith is assumed to be the same as for granite, which is 24.6 mW/cm-K.3 The void fraction in natural regolith is about 0.33, presumably higher with the fines removed, so helium fills at least a third of the volume. The thermal conductivity of the mixture depends on the geometry of the particles. If the particles were smooth and macroscopic, this mixture would have a thermal conductivity of at least 8.41 mW/cm-K with the worst geometry (granite and helium in series) and 17.6 mW/cm-K with the best (granite and helium in parallel). However, the particles are actually rough and of the same scale as the mean free path of the gas molecules, so the thermal conductivity of the mix was assumed to be only twice that of helium, i.e. 7.26 mW/cm-K. This conservative estimate is less than the worst case calculated above but is a factor of 60 times better

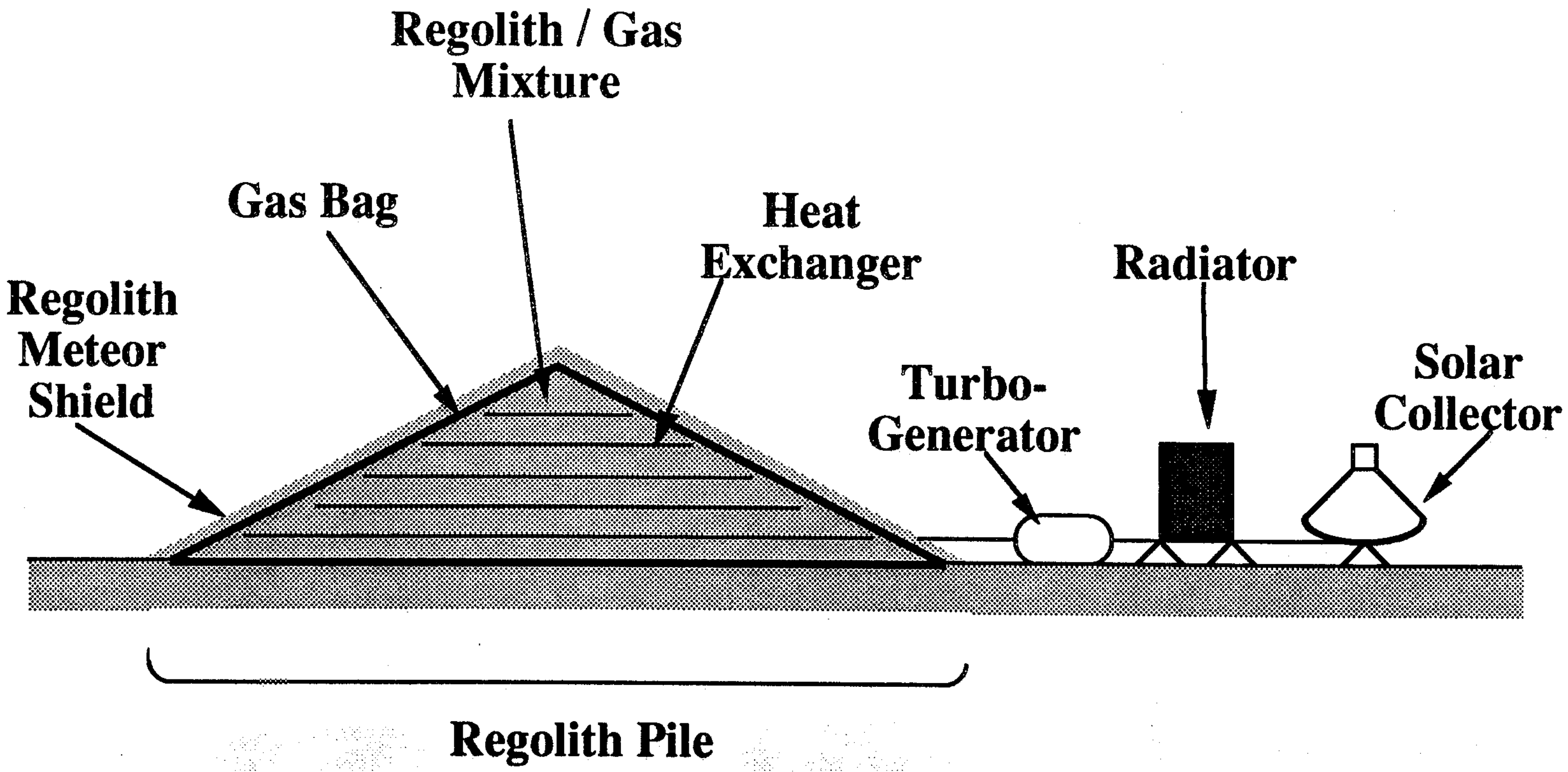
Regolith / Gas Mixture
Gas Bag
Heat Exchanger
Regolith Meteor Shield
Radiator
Turbo-Generator
Solar Collector
Regolith Pile

FIGURE 1

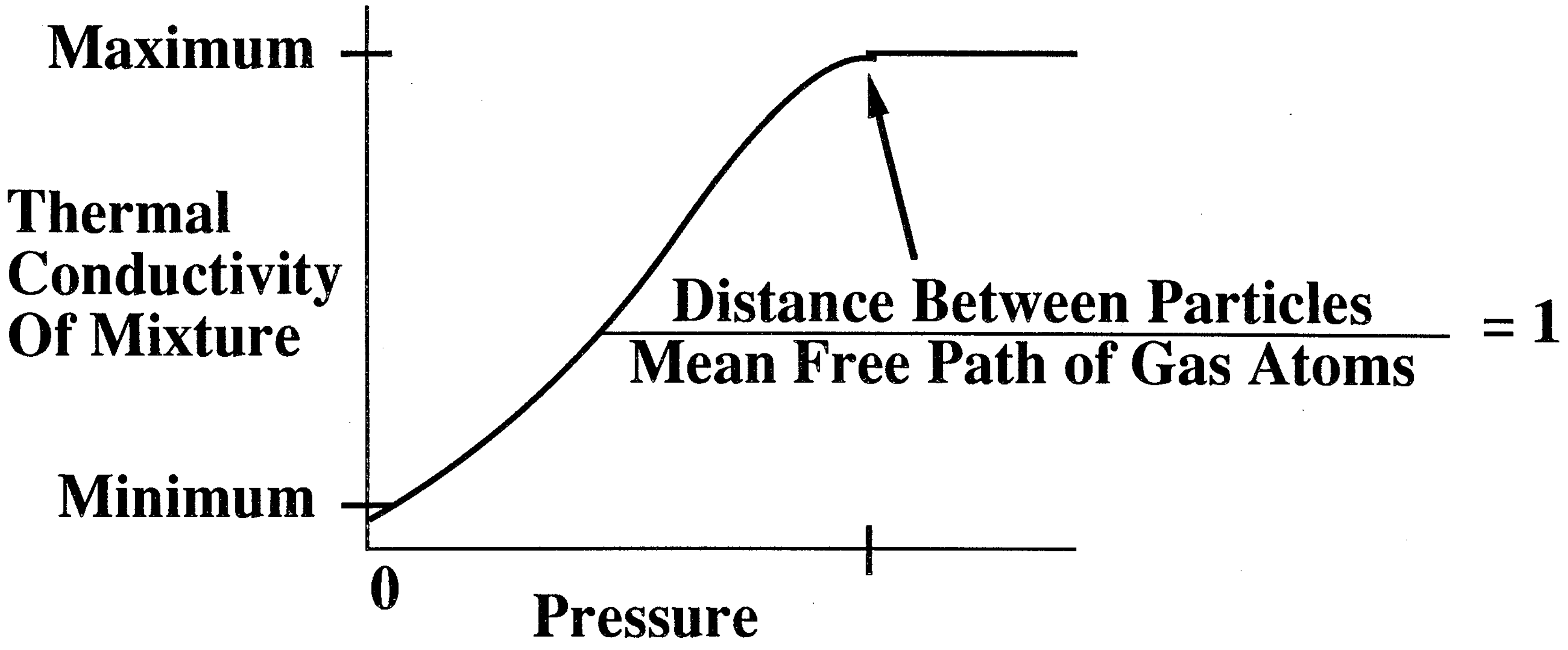
Maximum
Thermal Conductivity Of Mixture
Minimum
0
Pressure
Distance Between Particles
Mean Free Path of Gas Atoms
= 1

FIGURE 2

than the value for normal regolith, which is about 0.12 mW/cm-K.

Gas Bag and Heat Exchanger

The gas bag must be able to withstand the maximum regolith temperature and must be strong enough to contain the pressurized gas. The bag is assumed to be made of an alumino borosilicate fabric like Nextel[4] A titanium-based metal foil is diffusion bonded to the fabric, preventing gas leaks through the fabric. A Nextel/titanium material will have to be developed. Nextel/aluminum material already exists, but cannot withstand 1000 K.

The regolith pile is created by dumping loose regolith, so the sides of the pile are no steeper than the angle of repose, typically 37 degrees for lunar regolith. With the pile no steeper than the angle of repose, no structural stress is imposed on the containment bag. Steeper sides would require some structure to support the pile.

The heat exchanger must be delivered as a compact package from Earth, yet must have a large contact area with the regolith. This argues for a flexible heat exchanger, so the heat exchanger uses an "air mattress" design and is made of the same material as the gas bag. The heat exchanger is buried in the pile of regolith.

Sizing

This section derives the sizing parameters for a point design that provides an average of 20 kW electric power through the lunar night.

Regolith Pile

Assuming 20% output conversion efficiency and 20 kW electric output, the thermal output must be 100 kW. Over the 340 hour lunar night, the required thermal energy is 122 GJ. I assume that the pile temperature falls from 1000 K to 900 K as the energy is extracted, and that the specific heat of regolith is comparable to granite, i.e. 1.32 J/g-K.[5] With these assumptions, the pile must contain 924 metric tons of regolith.

Assuming the density of the uncompacted regolith is 1500 kg/m,[3] the volume of the pile is 616 m3. If the pile forms a circular pyramid whose sides slope at 37 degrees, then the height of the pile is 6.94 m and its diameter is 18.4 m.

The mass of helium in the pile is 266 grams.

Gas Bag

The maximum stress on the bag is at the edge of the pile, where the gas pressure of 896 Pa (0.13 psi) acts over an area of 266 m2 and must be contained by a band whose circumference is 57.9 m. Nextel has a tensile strength of 2.24 GPa (325 ksi), so the average Nextel thickness must be at least 184 microns (7.24 mils). For a safety factor of 1.4, the average Nextel thickness must be 258 microns (10.1 mils). This can be accomplished with 20 mil Nextel fibers in a tight weave. To enclose the pile top and bottom, the gas bag must cover an area of 599.9 m2. With the average thickness computed above, the Nextel volume is 0.155 m3. Nextel's density is 3050 kg/m3, so the mass of the fabric is 472 kg. A 254 micron (10-mil) layer of titanium (density 4.54) would add 692 kg, for a total bag mass of 1164 kg.

Heat Exchanger

The heat exchanger is made of the same Nextel/titanium combination as the gas bag, but is thinner because it need not contain pressure over large areas. I assume a loosely woven (0.75 void factor) fabric of 254 micron (10 mil) Nextel fibers with a 76 micron (3 mil) titanium layer bonded to each side. Two sheets of this material are bonded as parallel tubes to form an "air mattress" configuration. The mattress is inflated with a working fluid which flows inside the tubes.

The heat exchanger is laid between layers of regolith. The top and bottom regolith layers are 0.5 m thick, with intervening layers being 1.0 m thick. Thus the maximum distance from a regolith grain to the heat exchanger is 0.5 m. Given the size and shape of the pile, this arrangement produces 1223 m2 of contact area between the heat exchanger and the regolith. With a thermal flux of 100 kW and the assumed thermal conductivity of 7.26 mW/cm-K, the thermal gradient is 113 K/m. With the maximum distance from a regolith grain to the heat exchanger being 0.5 m, the temperature difference between the working fluid and the most distant grain is no more than 56.3 K. Thus when the regolith has cooled to 900 K, the working fluid temperature will be at least 843 K, adequate to drive a turbogenerator system during the lunar night.

With an area of 1223 m2, the mass of Nextel in the heat exchanger is 237 kg and the mass of titanium is 844 kg, for a total of 1081 kg.

This design assumes that helium is stationary within the regolith. If convection or a dust-resistant fan can induce currents in the helium, then heat transport would greatly improve and the mass of the heat exchanger could be substantially reduced.

Power System

The power system mass was estimated from the mass of a proposed solar dynamic power system for Space Station Freedom.[6] The SSF system is sized to produce 25 kW in both light and dark portions of its orbit. The elements of the system are the solar concentrator which concentrates light into the receiver and which gimbals to follow the sun, the receiver which transfers the light energy to a working fluid and to a thermal storage medium, the power conversion unit which uses a Brayton turboalternator to convert thermal energy to electrical energy, the heat rejection assembly which radiates waste heat to space, and the electrical equipment assembly which controls the system and which changes the frequency and phase structure of the electric power.

Design mass of the SSF solar concentrator assembly is 1500 kg. I scale this mass by a factor of 0.5 because the lunar concentrator needs only enough area to store energy during the day, not to simultaneously provide electric power. I further scale by a factor of 0.8 because the lunar application needs 20 kW, not 25 kW. The scaled mass is thus 600 kg.

Design mass of the SSF receiver is 1760 kg. I scale by 0.5 as above because the system does not provide power during daylight, and by 0.8 because of the lower power output. The SSF receiver includes a large amount of eutectic material to provide thermal energy storage; that function is provided by regolith in the lunar system. The mass of the eutectic material is not given by Labus, et al., but from an illustration[7] I estimate the mass at half of the overall receiver mass. Therefore, I use a further scaling factor of 0.5 to eliminate the mass of the eutectic material. The scaled mass is thus 352 kg.

The remaining elements are all scaled by 0.8 for the lower power output. The SSF power conversion unit scales from a design mass of 800 kg down to 640 kg, the heat rejection assembly scales from 1550 kg down to 1240 kg, and the electrical equipment assembly scales down from 260 kg to 208 kg.

The total mass of the scaled power system is 3040 kg.

Results and Discussion

The estimated mass statement for the 20 kW electric power system is shown in Table 1. The total mass from Earth, 5285 kg, is substantially less than the mass of a regenerable fuel cell system of equal capacity, which is estimated to be at least 12 tons8. Additional savings accrue because the photovoltaic array used for daylight power need not be oversized to charge the RFC while providing power.

Item	Mass (kg)
Gas Bag	1164
Heat Exchanger	1081
Power System	3040
Total	5285

Table 1. Estimated mass statement for 20 kW system, excluding regolith.

Several areas of further work remain to be done. DDT&E, packaging, and assembly costs are undefined, so it is currently impossible to compare total costs with other power system concepts, such as the two regolith-based concepts described earlier. More detailed analysis and tests will be needed to precisely define the thermal properties of the regolith/gas mix and to optimize that mix in terms of pressure and particle size. The material proposed here for the bag/heat exchanger must be fabricated and its properties verified. It is possible that heating the regolith will release enough trapped hydrogen from the solar wind to cause embrittlement of titanium foil in the gas bag and heat exchanger. Tests will be required to determine whether this is a problem. If so, a nickel-based foil may need to be used instead.

None of the issues above appear to be show stoppers. Thus, regolith thermal energy storage is a promising area for further work.

References

[1] Sullivan, Tom. "Process Engineering Concerns in the Lunar Environment." AIAA Space Programs and Technologies Conference, September 25-28, 1990. Paper 90-3753.
[2] Eder, Dani. "Lunar Base Logistics." *Space Manufacturing* 6, AIAA, 1987: pp. 299-301.
[3] Extrapolated from *CRC Handbook of Chemistry and Physics*, R.C. Weast, ed. Boca Raton, Florida: CRC Press (1986): p. E-14.
[4] Nextel is a product of the 3M Corporation.
[5] Extrapolated from *CRC Handbook of Chemistry and Physics*, R.C. Weast, ed., p. E-14.
[6] Labus, T. L., Secunde, R.R., and Lovely, R.G. "Solar Dynamic Power for Space Station Freedom." *Space Power* 8 (nos. 1/2) 1989: pp. 97-115.
[7] *Ibid.*, p. 106.
[8] Kohout, Lisa. "Cryogenic Reactant Storage for Lunar Base Regenerative Fuel Cells." *NASA Technical Memorandum 101980.* Prepared for IAF International Conference on Space Power, Cleveland, Ohio, June 1989.