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Abstract

One of the minor constituents of the solar wind which has been implanted in the lunar regolith over its several billion year history, is helium 3 (He-3), a rare isotope of helium which has two protons and a single neutron in its nucleus. Helium 3 is a potential fuel that can be used in near-aneutronic advanced nuclear fusion reactors for generating electric power on earth in a safe and environmentally clean way. Unfortunately He-3 is not available on earth. Although its existence on the moon is in a very dilute form, nevertheless, it can be shown that it is the only lunar resource which is worth bringing back to earth.

Several methods have been proposed for mining lunar He-3, one being the roving lunar miner described in this paper. The Mark II miner excavates, beneficiates, processes and redeposits the lunar regolith while moving slowly across the lunar landscape on a charted path. This miner can obtain approximately 33 kg of He-3 in one year while operating during lunar days to take advantage of solar energy. During this time it covers one square kilometer, mining the surface to a depth of three meters. One of the most limiting factors in He-3 acquisition is beneficiating the lunar regolith down to particles smaller than 50 microns. In the original design, beneficiation down to the fine fraction took place in an electrostatic separator. An alternate method is to use a fluidizing stream of gas to separate a range of particles. A preliminary analysis of such a process is addressed in this paper.

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Introduction

In man's quest for a sustained source of energy in the centuries to come, particularly after the world runs out of fossil fuels, he is investigating several forms, one of which is nuclear fusion. The only nuclear energy currently in use is nuclear fission which supplies about 17% of the world's needs at this time. Unlike fission, however, fusion will not generate the high level of activated material which will require deep geological burial under close supervision for many centuries. Nuclear fusion, which is probably one of the most difficult technological problems man has ever worked on, is not expected to make a major contribution to the world's energy supply until well into the twenty first century. The most common fuels which are currently mainlined for fusion are deuterium and tritium, two heavy forms of hydrogen. Deuterium (D_2) is found in the water we use every day and there is an enormous amount of it in the oceans of the world. Tritium (T_2) is not found in a natural state on the earth because it has a half-life of 12.3 years. It, however, can be bred by the reaction of neutrons on lithium atoms, a process that has been used in the defense industry to produce fuel for thermonuclear weapons. A fusion reactor utilizing the DT process would use deuterium from the ocean and will be equipped with a blanket surrounding the reaction chamber in which tritium will be bred by means of the neutrons generated in the reaction. Research on peaceful applications of thermonuclear fusion has been going on for forty years and there are major experiments in the US (TFTR, Bell, 1988), Europe (JET, 1988) and Japan (Aikawa, 1988). Most of these experiments can reach breakeven today, defined as producing an equal amount of energy as that expended on heating the plasma. However, investigators are reluctant to put T_2 into their devices so as not to activate them until all the possible physics experiments are concluded.

The fuel with which this paper is concerned is D-^{3}He, considered an advanced fuel for fusion. This reaction is distinctly different from the DT reaction in the form of energy which is released. Whereas in a DT reaction, 80% of the energy is released in the form of energetic neutrons (14.5 MeV) and the rest in alpha particles (3.5 MeV), the D-^{3}He reaction produces energetic protons (14.7 MeV) and alpha particles (3.67 MeV). However, some D-D reactions unavoidably take place producing lower energy neutrons (2.45 MeV). Studies have shown that reactors can be designed where only $\sim$ 3% of the energy is in low energy neutrons (Emmert et al. 1989). For the layman, this might not mean much, but for reactor designers, it means the difference between a reaction chamber which can survive the entire life of the reactor and one which will have to be periodically replaced. With such a low neutron production, the advantages are obvious: low level waste, low structure activation, much improved safety, and the potential for direct energy conversion at 80% efficiency.

Since He-3 is not found on earth in sufficient quantities to justify an energy program, DT continues to be the mainline program within the US and elsewhere. However, in recent years it has been pointed out (Wittenberg, 1986) that the moon has vast quantities of He-3 tied up in the lunar regolith as a result of implantation by the solar wind over several billion years. The He-3 is generated in the sun's fusion reaction and travels in the solar wind. Since the moon has no magnetic field or an atmosphere to attenuate the solar wind products, these energetic particles impact the lunar regolith burying themselves in the individual grains. Figure 1 shows the He content of lunar samples measured during the US Apollo missions and by USSR robots. The helium potential of the moon is very large. Detailed studies (Cameron, 1991) show that Mare Tranquillitatis alone has nearly 10,000 tonnes of He-3 in minable regolith, a quantity which can supply all the electric needs of the US for more than 400 years at the present rate of use.

Experiments have shown (Gibson, 1971) that some 80-90% of the He-3 diffuses out of the regolith when it is heated up to 700°C. Further, some 90% of the He-3 is in particles of 50 microns and smaller, which constitute 45% of the regolith. To conserve process energy it is therefore imperative that only those particles containing the bulk of the He-3 be heated. This requires a fine process of selection.

In the first two lunar miner designs, Model I and Model II, this process of selection was by means of electrostatic separation. Although there is no basis for thinking electrostatic separation would not work, it has been decided to investigate an alternate method of beneficiation, using a fluidized bed. This paper gives a preliminary report on the use of helium or hydrogen gas obtained from the solar wind products to fluidize the regolith and separate the fine particles ($< 50\ \mu$) from the coarser material.

Description of the Mark II Lunar Miner

Figure 2 is an artist's rendition of the Mark II lunar miner. The miner is designed to be a self contained machine which excavates the regolith, separates out the large aggregates, beneficiates out the fine particles, heats them up to 700°C to evolve the solar wind products, then cools them down to recover the energy and finally returns them to the lunar surface. The evolved gases are compressed into cylinders which eventually are gathered at a central station for separation into the various constituents. Helium 3 in the form of liquified gas is then shipped to the earth for use in a fusion reactor. Process energy is supplied

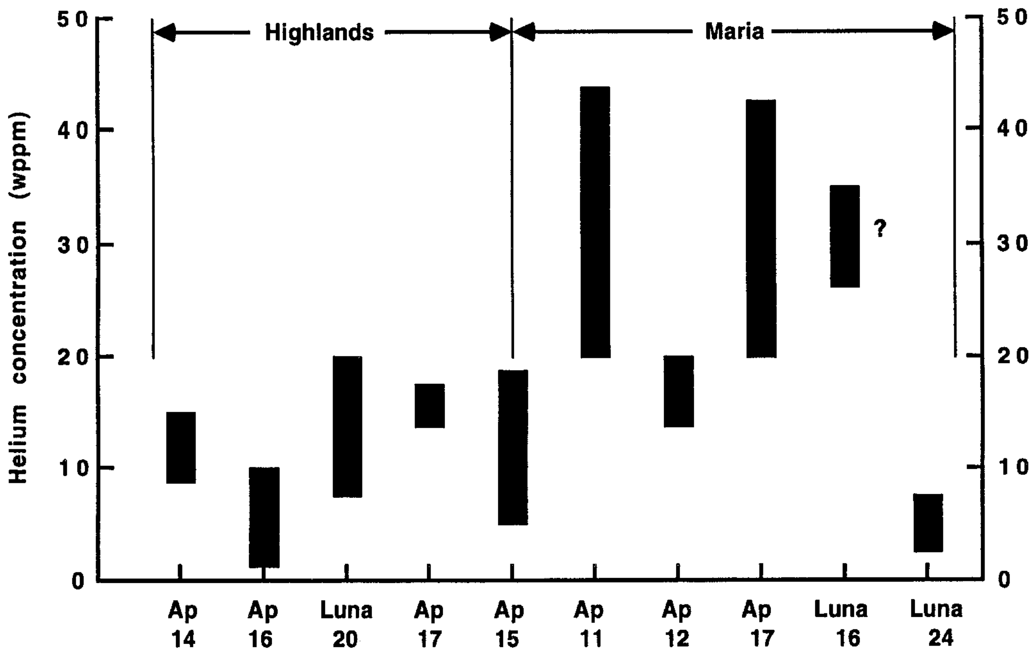

Figure 1. Measured helium content in lunar samples.

by a 110 m diameter solar dish which tracks the sun while beaming the solar energy to the miner. A 10 m diameter dish mounted on the miner receives the solar energy and concentrates it into the miner where it boils liquid sodium in heat pipes used to heat the regolith. A very large and efficient heater made entirely of heat pipes and no moving parts is capable of heating the incoming regolith up to 700°C and then cooling it down to 100°C, thus recycling 85% of the process energy. A detailed description of the miner has already been published (Sviatoslavsky, 1988). The relevant parameters of the Mark II miner are listed in Table 1.

Electrostatic Separator

Excavation takes place by means of a bucket wheel excavator which executes a 120° arc ahead of the miner opening up a ditch 11 m wide and 3 m deep. Initial separation takes place in several sieves where only particles smaller than 200 μ are allowed to pass while the remainder is returned to the lunar surface through chutes on the sides of the miner. The separated particles are conveyed to the electrostatic separator where they fall through charging electrode plates. An oppositely charged moving belt then exerts a vertical force on the charged particles causing the smaller grains to go into a larger horizontal trajectory than the larger grains. In this way the regolith particles of smaller than 50 μ are separated.

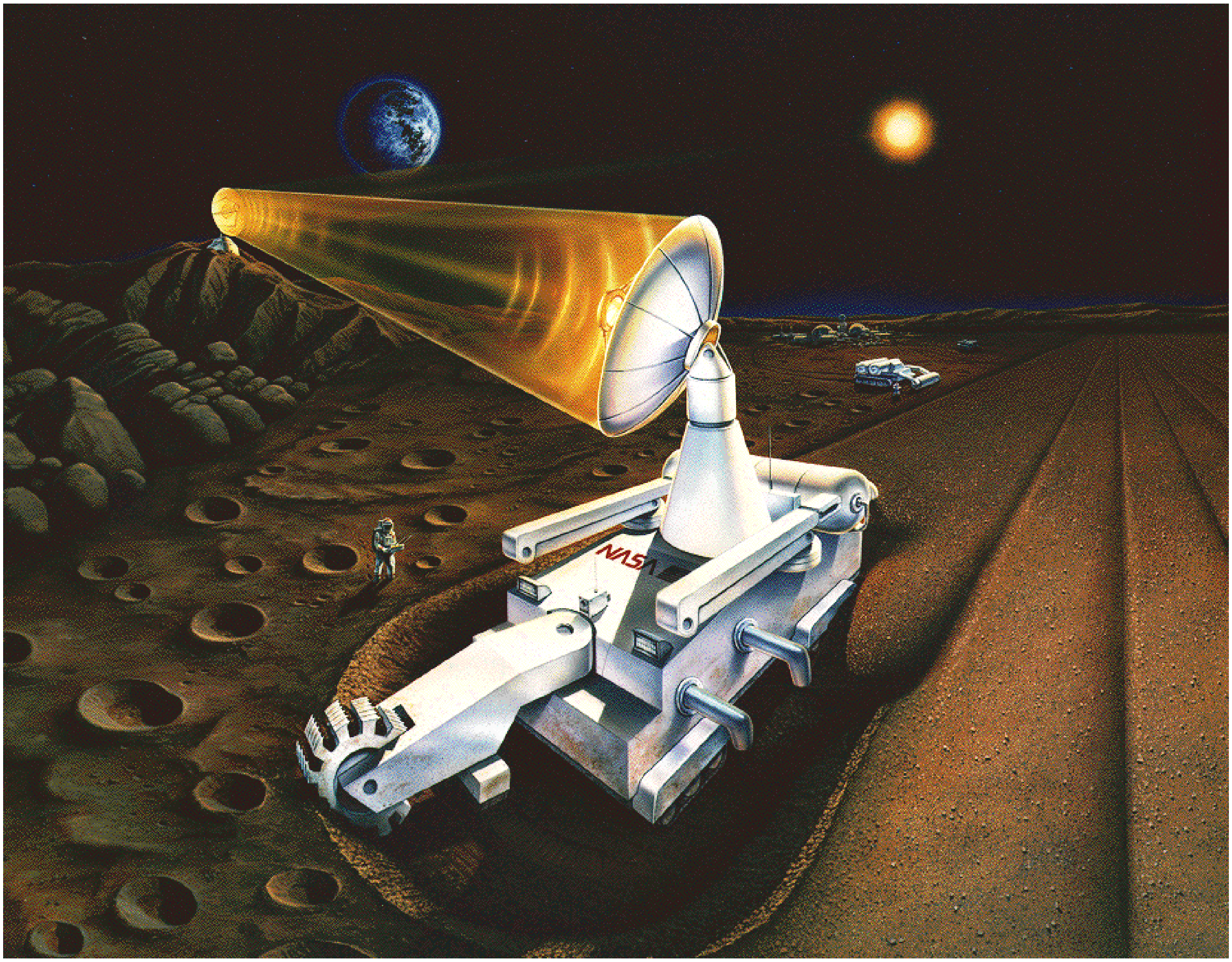

Figure 2. Artist's conception of the UW Mark II lunar miner.

Table 1

Selected Mark II Lunar Miner Parameters

Annual collection rate of He-3 (kg)	33
Mining hours per year	3942
Excavating rate (tonnes/hr)	1258
Depth of excavation (m)	3
Forward speed of miner (m/hr)	23
Area excavated per year (km^2/y)	556
Processing rate (tonnes/hr)	556
Lunar process energy (MW)	12.3
Heat recovery (%)	85
Estimated operating power (kW)	200
Estimated total earth mass (tonnes)	18

Table 1 shows that the miner must process on the order of 550 tonnes of sub-50 μ particles per hour but what goes through the electrostatic separator is 800 tonnes per hour. The volumetric throughput is 0.15 m^3/s and if we assume a velocity of 1 m/s through the separator and a 1 cm thick stream of regolith, the required length of the plates and belt is 15 m. This is not unreasonable since 3 separators can be fitted into the miner, each having a width of 5 m. However, there is some concern on whether the opacity of the falling stream will allow the finer particles to be capable of being separated. There is an obvious need for experiments on high throughput electrostatic separation to clarify such issues.

The use of fluidization gets around this problem and has the potential for being more compact. For this reason it has been decided to investigate it.

Separation by Fluidization

Fluidization is a low energy method for allowing granular solids to contact process fluids for various applications such as combustion, heat transfer, drying, coating and many other manufacturing processes. It has been used in coal gasification and transport of all kinds of granular material.

The Ergun equation (Cheremisinoff, 1984) is the most commonly used for relating the minimum fluidization velocity to the various other fluid and particle physical parameters:

$$\frac{1.75}{\phi_s \epsilon_{mf}^3}\left(\frac{d_p U_{mf} \rho_f}{\mu}\right)^2 + \frac{150(1-\epsilon_{mf})}{\phi_s^2 \epsilon_{mf}^3}\left(\frac{d_p U_{mf} \rho_f}{\mu}\right) = \frac{d_p^3 \rho_f (\rho_p - \rho_f) g}{\mu^2} \qquad (1)$$

where ϕ_s is the particle shape factor, ϵ_{mf} is the void fraction at minimum fluidization, d_p is equivalent particle diameter, U_{mf} is the minimum fluidization velocity, ρ_f and ρ_p are the fluid and particle densities, respectively, g is acceleration due to gravity, and μ is the fluid viscosity. After many experiments (Wen and Yu, 1966) it was found that for a wide variety of systems these quantities are well represented by:

$$\frac{1}{\phi_s \epsilon_{mf}^3} \simeq 14 \quad \text{and} \quad \frac{1-\epsilon_{mf}}{\phi_s^2 \epsilon_{mf}^3} \simeq 11\,. \qquad (2)$$

If these are inserted into the Ergun equation it can be reduced to:

$$\frac{d_p U_{mf} \rho_f}{\mu} = [(33.7)^2 + 0.0408\ Ar]^{0.5} - 33.7 \qquad (3)$$

where the left side of the equation is the dimensionless group of parameters representing the Reynolds number at minimum fluidization Re_{mf} and Ar the Archimedes number represented by:

$$Ar = \frac{d_p^3 \rho_f (\rho_s - \rho_f) g}{\mu^2} \qquad (4)$$

where ρ_s is the solid bulk density.

For particles of 50 μ diameter fluidized by helium gas at one atmosphere and 300 K, the following parameters are used:

$$\begin{aligned} d_p &= 50 \times 10^{-6}\ \text{m} \\ \rho_f &= 0.163\ \text{kg/m}^3 \\ \rho_s &= 1800\ \text{kg/m}^3 \\ \rho_p &= 3200\ \text{kg/m}^3 \\ \mu &= 2 \times 10^{-5}\ \text{kg/m} \cdot \text{s} \\ g &= 1.62\ \text{m/s}^2\ . \end{aligned}$$

The calculated Archimedes number is $Ar = 0.9$ and the minimum fluidization velocity, $U_{mf} = 1.34 \times 10^{-3}$ m/s. This shows that a very low velocity is needed to initiate fluidization for 50 μ particles.

The terminal velocity, or that needed to actually lift the particles and move them upwards is given as:

$$a' \left(\frac{U_{mf}}{U_t} \right)^2 + b' \left(\frac{U_{mf}}{U_t} \right) + c' = 0 \tag{5}$$

where U_t is the terminal velocity and a', b' and c' are coefficients which depend on the flow regime. For $Re < 2$ and $Ar < 36$ they are:

$$a' = 1.37,\ b' = 1650,\ c' = -17.86 \qquad \text{(Cheremisinoff, 1984)}\,. \tag{6}$$

Substituting in (5) and solving,

$$\frac{U_{mf}}{U_t} = .0108 \tag{7}$$

$$U_t = \frac{1.34 \times 10^{-3}}{.0108} = 0.124 \text{ m/s}\,. \tag{8}$$

It is interesting to note that for the same conditions using hydrogen gas, $U_{mf} = 3.19 \times 10^{-3}$ m/s and $U_t = 0.3$ m/s.

We now ask the question: What is the terminal velocity for 60 μ particles? Going through the same exercise it is found that $U_t = 0.179$ m/s or 44% higher than for 50 μ particles. It can be seen from Eq. (4) that the size leverage is high and goes as the particle diameter cubed in determining the Archimedes number. Controlling the gas velocity within these limits appears reasonable. A terminal velocity for 50 μ particles will not be able to lift larger size particles, but will lift all sizes less than 50 μ. This is precisely what we would like the fluidized separator to do. The regolith after going through the sieving processes will be dropped into a duct with He or H_2 gas flowing upwards. Particles of 50 μ diameter and smaller will be propelled upwards, while larger particles will continue falling down. At the top of the duct, the stream goes through a cyclone separator where the gas is disengaged from the particles. The particles continue on to the heater, while the gas is recycled back into the fluidizing duct.

A dense phase transport will have an 80% void fraction. We can now determine the size needed for this duct. The 550 tonnes/hr of < 50 μ particles amounts to a volumetric throughput of 0.048 m^3/s using the $\rho_p = 3.2$ g/cm^3 and will be equal to 0.24 m^3/s when entrained in the fluidizing duct at 80% void fraction. Using a terminal velocity of 0.3 m/s for the case with hydrogen gas, the area needed will be 0.8 m^2. This is a circular duct of only 1.0 m in diameter.

Pressure Drop and Pumping Power

The most widely referenced correlation for calculating pressure drops in fluidized beds was also derived by Ergun (Cheremisinoff, 1984)

$$\frac{\Delta p}{\ell}\, g = \frac{150(1-\epsilon_m)^2}{\epsilon_m^3}\frac{\mu_f U}{(\phi_s \bar{d}_p)^2} + \frac{1.75(1-\epsilon_m)}{\epsilon_m^3}\frac{\rho_f U^2}{\phi_s \bar{d}_p^2} \tag{9}$$

where ℓ is the duct length, ϵ_m is the mean void fraction, ϕ_s the particle shape factor, $\bar{d}_p$ the mean particle diameter and U the superficial fluid velocity.

At low Re_p number ($Re_p < 20$) the viscous term dominates and only the first term of the equation is used:

$$\frac{\Delta p}{\ell}\, g = \frac{150(1-\epsilon_m)^2}{\epsilon_m^3}\frac{\mu_f U}{(\phi_s \bar{d}_p)^2}\,. \tag{10}$$

The shape factor ϕ_s is defined as particle surface to sphere surface having the same volume. Since this is not known for regolith particles, we will conservatively use $\phi_s = 5$. We have the void fraction $\epsilon_m = 0.8$ and from that U, the superficial fluid velocity is equal to 0.3 m/s $\times$ 0.8 = 0.24 m/s. For d_p a mean value of 35 μ is used and the duct length ℓ is taken as 3 m.

Using these values the calculated pressure drop is 3.4×10^3 kg/m^2 or 0.34 atmospheres.

The gas volumetric throughput in a duct of 0.8 m^2 area and a velocity of 0.24 m/s is 0.19 m^3/s. We can now calculate the required pumping power:

$$P_{pump} = \dot{V}\Delta p\,. \tag{11}$$

The required pumping power is 6.3 kW. This is consistent with a dense phase lift power range of 2-15 W/m tonne/hr (Cheremisinoff, 1984) depending on the complexity of the ducting. Using these values the range of pumping power is 3.3 kW - 25 kW. For a uniform cross sectional area in cylindrical geometry, the lower value is justified. Parenthetically, the power requirement of the electrostatic separator was estimated at 5 kW.

What are the Problems

Fluidized separation appears to be feasible from the standpoint of control, and space and power requirement. However, there are some issues that have to be resolved:

- Pressure isolation having to do with inserting regolith from lunar vacuum into low atmosphere of H_2 pressure.
- Design of a high volumetric throughput, low pressure drop fluid circulator.
- Efficient separation of the particles from the fluid and the attrition effect on the circulator.
- Control of the fluid velocity to within ±25%.

There is also a range of practical issues which have not been addressed in this preliminary study. They have to do with regolith engineering issues such as cohesion, angle of repose, etc. that bear on material handling. Such problems as jamming and clogging will have an impact on the miner efficiency and availability.

Conclusions

An initial investigation using basic but practical correlations has shown the feasibility of separating regolith particles of 50 μ and smaller from the bulk regolith by means of fluidized lift in a stream of helium or hydrogen gas. Using the Mark II lunar miner parameters which will have a mass throughput of sub 50 μ particles of 550 tonnes/hr we calculate a terminal velocity, using H_2 gas, of 0.3 m/s in a circular duct of 1.0 m diameter. It has been found that the terminal velocity for 60 μ particles is 44% higher than that needed for 50 μ particles. This suggests the possibility of separating the 50 μ particles from the bulk regolith. Assuming a duct height of 3 m, the power required to circulate the H_2 gas is 6.3 kW. Among the issues which still need investigating is the pressure isolation against the lunar vacuum, disengagement of the particles from the fluid and its effect on the fluid circulator, and the control of the fluid velocity in the duct.

Acknowledgement

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Glossary of Symbols

ϕ_s	particle shape factor
ϵ_{mf}	minimum fluidization void fraction
ϵ_m	mean void fraction
d_p	particle diameter
$\bar{d}_p$	mean particle diameter
U_{mf}	minimum fluidization velocity
U_t	terminal velocity
ρ_f	fluid density
ρ_p	particle density
ρ_s	solid bulk density
μ_f	fluid viscosity
g	acceleration due to gravity
Δp	pressure drop
ℓ	duct length
$\dot{V}$	volumetric throughput
Ar	Archimedes number
Re	Reynolds number

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