

LUNAR SURFACE MINING FOR AUTOMATED ACQUISITION OF HELIUM-3: METHODS, PROCESSES, AND EQUIPMENT

Y. T. Li¹ and L. J. Wittenberg

University of Wisconsin-Madison
Wisconsin Center for Space Automation and Robotics
Madison WI 53706

INTRODUCTION

Helium-3 fused with deuterium is an attractive fuel cycle for nuclear fusion power reactors in the twenty-first century because it produces "clean" nuclear power (Wittenberg *et al.*, 1986) with no radioactive fuel or fusion product. Unfortunately, terrestrial resources of He-3 are scarce. Present assessments of both natural and man-made sources of He-3 indicate that a fusion plant of 500 MW electrical power could be fueled for only a few months.

In contrast, the surface of the Moon has a plentiful supply of He-3 (Wittenberg *et al.*, 1986). Helium-3, He-4, protons, and particles of other chemical elements formed from nuclear reactions in the sun have been implanted in the lunar regolith (soil) by the solar wind for the past 4 billion years. Due to constant meteorite impact, the grain size of the lunar regolith is extremely fine, which makes it an effective solar wind collector. The results of heating and degassing of lunar samples returned from the early Apollo missions (Eberhardt *et al.*, 1972) confirmed the presence of these solar wind particles. Although the concentration of these particles is low, the mass of the soil is large; consequently, the lunar regolith is estimated to contain more than a million metric tonnes of He-3.

The deuterium/He-3 fusion reactor yields 19 MW·yr (thermal) or ~10 MW·yr (electrical) per kilogram of He-3. The U.S.'s electrical power usage in 1987 was $\sim 3 \times 10^5$ MW·yr. The utilization of the lunar He-3 resource could provide, therefore, an energy source for the USA lasting for thousands of years. In

addition, the lunar regolith contains other elements of the solar wind that are evolved during heating, such as hydrogen, nitrogen, and carbon compounds. Large amounts of these volatiles, which would be useful on the Moon as rocket fuel and life-support materials (Bula *et al.*, 1991) will be produced as by-products during the acquisition of He-3, as shown in Table 1.

Lunar maria regoliths rich in titanium are considered prime mining areas. This selection is made based on several considerations. First, maria regoliths are dominated by fine grain deposits. The energy of the solar wind particles is sufficient to implant them only a short depth into the surface of the grains. Therefore, the fine grains that have high surface-to-volume ratios have high concentrations of trapped particles. Second, the fine regolith in the maria extends to an average depth of ~3 to 10 m and grains containing solar wind particles have been retrieved from core samples up to 2 m deep (Criswell and Waldron, 1982). Third, it appears that regolith high in titanium is also high in helium content. High titanium regoliths are mostly derived from maria basalts (Cameron, 1991). Fourth, from an operational point of view, mining and processing maria regolith is relatively easier than dealing with rocks or the highland areas.

In this paper, we will present several techniques considered for mining and processing the regolith on the lunar surface. These techniques have been proposed and evaluated based primarily on the following criteria: (1) mining operations should be relatively simple; (2) procedures of mineral processing should be few and relatively easy; (3) transferring tonnages of regolith on the Moon

TABLE 1. Solar wind gas release predicted from mining of maria regolith.

Operation	Regolith (tonnes)	Concentration, ppm (g/metric tonne)				
		He-3	He-4	H ₂	Carbon	Nitrogen
Surface Mining	1	$(6-13) \times 10^{-3}$	20-45	50-60	142-226	102-153
Beneficiate	0.45	$(5-11) \times 10^{-3}$	27	50	166	115
Gas Evolution	0.45	$(4-9) \times 10^{-3}$	22	43 (H ₂) 23 (H ₂ O)	13.5 (CO) 12 (CO ₂) 11 (CH ₄)	4
Per kg He-3	1.4×10^5 (mined)	1 kg	3.1 tonnes	6.1 tonnes (H ₂) 3.3 tonnes (H ₂ O)	1.9 tonnes (CO) 1.7 tonnes (CO ₂) 1.6 tonnes (CH ₄)	0.5 tonnes
Per Tonne Regolith into Heater	1 (beneficiated)	0.014 g	49 g	96 g (H ₂) 51 g (H ₂ O)	30 g (CO) 27 g (CO ₂) 24 g (CH ₄)	9 g

¹Now at Institute of Automation, Chinese Academy of Sciences, Zhong Guan Cun, Beijing, China

should be minimized; (4) operations outside the lunar base should be readily automated; (5) all equipment should be maintainable; and (6) economic benefit should be sufficient for commercial exploitation. We do not address the economic benefits in this paper; however, the energy benefits have been estimated to between 250 and 350 times the mining energy (Kulcinski *et al.*, 1988).

EVOLUTION OF SOLAR WIND GASES

Before a mining scenario could be proposed, we estimated the mass of regolith required to yield a specified amount of solar wind gases. For this scenario, we selected the continuous fueling of a 500-MW (electrical) fusion power plant that required 53 kg/yr of He-3. If the mining operation were conducted only during the lunar sunlit periods, ~4000 hr/yr, the He-3 production required is 13 g/hr. Next, we reviewed the experimental data for degassing of the regolith, selected the preferred temperature range for heating of the regolith and assessed the potential for beneficiation of the raw regolith.

Qualitative mass spectrographic analyses of the gases evolved during continuous heating of the Apollo 11 soils (Gibson and Johnson, 1971) indicated H₂ and He evolution began at ~200°C and was nearly complete by 800°C; CO and N₂ evolution began at ~600°C and continued to 1200°C; CO₂ was evolved between 700° and 1300°C; and H₂S and SO₂ evolution was initiated between 800° and 900°C. The evolution of H₂O and N₂ below 200°C was attributed to adsorbed terrestrial impurities. These soils contain no H₂O molecules; however, release of the embedded hydrogen atoms during heating apparently reduces some of the oxides yielding water that may constitute ~5% of the H₂ evolved above 200°C (E. K. Gibson, personal communication, 1987). The appearance of methane has not been confirmed but may constitute 5% of the total carbon. The condensation of the sulfur compounds SO₂ and H₂S from the evolved gas were observed (E. K. Gibson, personal communication, 1987) to contaminate the vacuum system with resinous products that were difficult to remove. For this reason, the proposed maximum heating temperature for the mining scenario was limited to the range of 700°-750°C so that the sulfur compounds would not vaporize.

Based upon the total yield reported (Criswell and Waldron, 1982) of solar wind gases evolved during the heating of Apollo 11 soils to ~1300°C (first line in Table 1), the average fine

regolith on Mare Tranquillitatis was conservatively assumed to contain 30 ± 10 wt ppm of He-4 with a He-3/He-4 ratio of 400 atomic ppm. It was necessary, however, to estimate the amounts of the gases that would be evolved on heating to only 700°C. For this estimate, we used the mass spectrographic data by Oró *et al.* (1971) of gases evolved during the heating of Apollo 12 soils that reported the total yield of all gases evolved up to 750°C. We scaled these yields to 700°C and calculated the ratios between the yields of CO, CO₂, and N₂ as compared with the total yields from the regolith. These ratios were assumed, also, for the Apollo 11 samples. Quantitative yields of H₂ (Carter, 1985) and He (Pepin *et al.*, 1970) obtained during the step-wise heating of Apollo 11 samples as a function of temperature indicated that 86% of the He-3 and 84% of the H₂ would be evolved when the regolith is heated to 700°C. From this information the yield of each gas evolved per ton of raw regolith was determined based upon 100% recovery of the evolved gases (see Table 1).

In order to reduce the volume of regolith to be heated for gas evolution, the potential advantage of beneficiation of the raw regolith was investigated. Beneficiation based upon grain size is justified because the solar wind particles penetrate a short distance into the grains. Depth profiling measurements indicate that the He atom density peaks at ~20 nm below the surface but extends to a depth of 200 nm (Waraut *et al.*, 1979) and depends upon the "maturity" of the soil. Consequently, smaller particles have a higher gas-to-solid mass ratio as confirmed by analyses (Hintenberger *et al.*, 1970) and shown in Table 2. Unfortunately, the weight fractions per sieve size were not determined for these samples and had to be taken from another data source (Criswell and Waldron, 1982). When the gas analyses were combined with the size distribution of the raw regolith, the results in Table 2 indicate that the particles of <50 μm, which constitute only 47 wt% of the soil, yield 75% of the He, and particles less than 100 μm, which constitute 63 wt% of the soil, contain ~86% of the He. In addition, we noted for this case and other samples that the He content of the unsieved soil was ~30% higher than that obtained by the summation of the grain-size fractions. Apparently during the sieving process nearly 30% of the He was lost as a result of either agitation of the particles or as fine particles that may have become airborne. If this beneficiation system were enclosed in a gas-tight chamber, as it would be on the lunar surface, then this lost He would be captured and accounted for in the inventory of the smallest grain size. Based upon these observations, we estimated that the soil should be beneficiated

TABLE 2. Helium content as a function of regolith grain size.

Grain Size Fraction		He-3 Content*			
Sieve Size μm	Wt. Sample [†] %	10 ⁻⁵ cm ³ (STP)/g		Frac/STD Sample %	Frac/Sample Corrected [‡] %
		Per grain size	Per sample		
-50	47.2	8.88	4.19	75	81
50-100	16.3	3.62	0.59	11	8
100-150	9.0	1.92	0.17	3	2
150-200	5.0	1.96	0.10	2	2
200-300	5.0	1.89	0.10	2	2
> 300	17.5	2.48	0.43	7	5
TOTAL			5.58		
Unsieved Fines			7.44		

* Sample 10084 (Hintenberger *et al.*, 1970).

[†] Criswell and Waldron (1982).

[‡] He-3 difference between original sample and sieved sample added to <50 μm sample.

to retain particles $<50 \mu\text{m}$, which would constitute $\sim 45 \text{ wt}\%$ of the soil, but yield $\sim 81\%$ of the He contained in the bulk soil. Alternatively, the regolith could have been beneficiated to concentrate ilmenite particles, which constitute 10% to 30% of the regolith on Mare Tranquillitatis because selected samples containing high ilmenite fractions are reported (Eberhardt *et al.*, 1972) to contain up to 180 ppm of He. If the ilmenite were distributed uniformly in the soil, it would be more efficient to separate the ilmenite fraction; however, the local distribution of ilmenite is unknown. For this reason it was decided to beneficiate to retain the small particles of all mineral types.

The results of these analyses indicate that $\sim 140,000$ tonnes of regolith of average He-3 content must be processed to obtain 1 kg of He-3, but only 63,000 tonnes of the beneficiated regolith $<50 \mu\text{m}$ needs to be heated for gas evolution (see Table 1). As a result, nearly ~ 1800 tonnes of regolith must be mined per hour to supply a 500-MW electrical power plant.

MINING STRATEGIES

Three strategic options for lunar surface mining and processing of regolith were considered, namely: (1) *in situ* volatilization of gases, (2) open-pit mining with central plant processing, and (3) mobile excavation-beneficiation-evolution followed by centralized volatile/isotopic separation. We will examine each of these mining options in the following scenarios.

IN SITU MINING

"*In situ* mining" proposes the extraction of the embedded volatiles without excavating the regolith. This system would consist of a mobile vehicle and an apparatus to direct thermal radiation or microwave energy onto the surface of the regolith. The escaping gas molecules would be collected in an enclosed gas-tight hood and pumped to a storage receiver (Fig. 1).

Unfortunately, *in situ* mining by applying concentrated sunlight is not practical because of the poor thermal conductivity of the regolith 0.09 to 0.13 mW/cm K (Langsten *et al.*, 1976) in the lunar environment. As a consequence, if the temperature of the surface were maintained at a constant 1000°C in order to avoid sintering, a simple calculation shows that five hours would be needed to raise the temperature at a depth of 1 cm to 600°C .

Penetration of heat can readily be gained by using microwave radiation. Some potential applications of microwave radiation to processing of lunar material have been studied (Meek *et al.*,

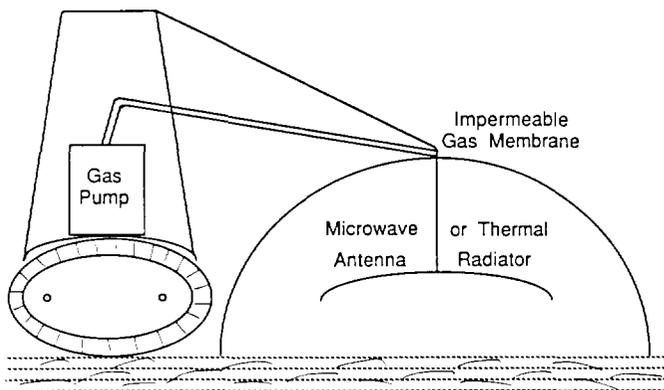


Fig. 1. Sketch of an *in situ* gas evolution device using either solar thermal energy or microwave radiation.

1985). Microwave radiation has been suggested as a method to heat lunar materials (Meek *et al.*, 1987), and experimental results from sintering lunar soil simulants using 2.45-GHz microwaves have been reported (Meek *et al.*, 1986). These studies have shown that the coupling of the regolith to the microwave radiation is considerably increased due to the defects in the material (Bassett and Shackelford, 1972), resulting from the cosmic ray and the intense impact events on the Moon.

To examine the feasibility of *in situ* mining using microwave, we conservatively took the loss tangent of the bulk regolith between 0.015 and 0.3 based on the electrical data of the lunar samples (Strangway *et al.*, 1972). Loss tangent characterizes the coupling between the substance and the microwave radiation, and is temperature dependent, as shown in Fig. 2a (Cheng, 1983). A plane wave was assumed to radiate perpendicularly to the surface for the estimation purpose. As the microwave penetrates the regolith, the strength of its electrical field attenuates and decreases to $1/e$ at a depth d , the "depth of penetration." For example, at a fixed frequency of 2.45 GHz, the depth of penetration is a function of the loss tangent and, therefore, a function of temperature, as shown in Fig. 2b. As the field of the microwave is

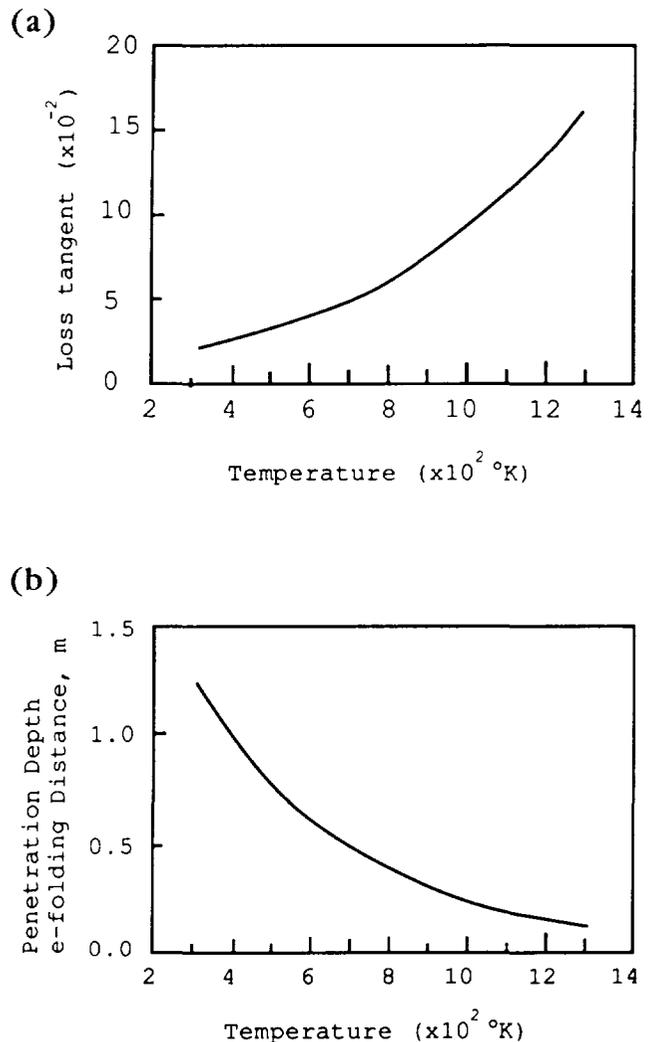


Fig. 2. (a) Loss tangent and (b) penetration depth-e-folding distance, as functions of temperature at 2.45 GHz radio frequency.

attenuated, the energy is dissipated and used to heat the regolith, changing the temperature profile. The changed temperature profile in turn alters the attenuation distribution.

To calculate how much helium would be emitted by the heating mechanism described above, we used the data obtained by a stepwise heating of the lunar fines returned by the Apollo 11 mission (Pepin *et al.*, 1970). The initial temperature distribution was assumed uniform at 250 K, approximately the temperature of the regolith at a depth of >30 cm. The frequency of the microwave and the intensity of the electrical field were 0.5 GHz and 400 V/m, respectively. The 0.5-GHz frequency was used instead of the conventional 2.45-GHz frequency because the depth of penetration at 2.45-GHz frequency is approximately 30 cm at low temperatures and decreases as the temperature of the regolith rises, which makes it difficult to heat the regolith at >0.5 m depth in a reasonable time. A typical set of the results by computer simulation are shown in Figs. 3 and 4. Figure 3 shows the temperature profile at 475 sec (7.75 min) when the surface reaches 1000°C, the sintering temperature of the material, and Fig. 4 shows the rate of evolved He-3 per m², by which the total yield of 25.0 cm³ (STP)/m² He-3 was obtained. Finally, the total amount of microwave energy input into the regolith was 3.6 GJ.

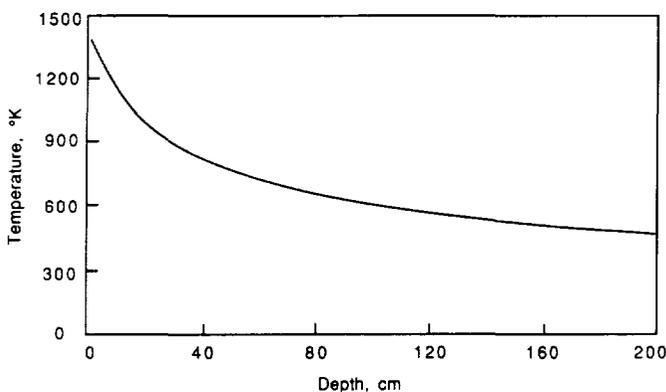


Fig. 3. Temperature profile in the regolith as a function of depth after microwave heating for 475 sec at a frequency of 0.5 GHz and an electrical field of 400 V/m.

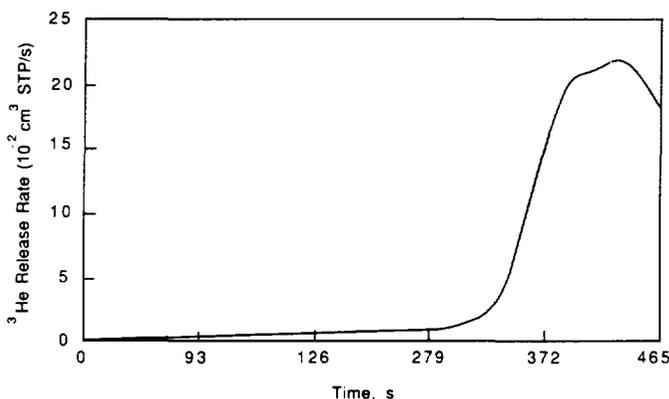


Fig. 4. He-3 release rate from the regolith as a function of heating time for the temperature profile shown in Fig. 3.

The excessively high microwave energy required is mainly due to the intrinsic nature of the method because no boundary is provided to confine the microwaves as well as the regolith. As a result, only the top layers of the regolith are heated sufficiently to release trapped volatiles and large amounts of energy are wasted on heating of the deeper regolith; consequently, the energy efficiency is <3%.

In addition, another major concern of this mining method is that the volatiles escaping from the regolith would scatter isotopically instead of rising toward the surface; consequently, a large portion of the emitted gas would not be collected. We are led to conclude, therefore, that the regolith must be excavated and heated in an enclosure.

A MOBILE MINING SCENARIO

In order to select the preferred mining scenario, the entire flow chart for He-3 recovery must be considered (Fig. 5). The process (on the right) begins with a type of open-pit mining technique in which the regolith would be placed on conveyor belts and transported to a central processing facility, as is traditionally done for terrestrial mining. At the end of the process the "tailings," which have the same mass as the original regolith but are of greater volume unless compacted, must be discarded, preferably into the original mine pit. Large volumes of the regolith must be lifted and handled in order to produce a useful amount of He-3. The area needed to be mined consists of ~1.8 km²/yr if the mining trench is 2 m deep and the soil bulk density is 1.8 to 2.0 tonnes/m³. As a result, the lengths of the conveyor belts from

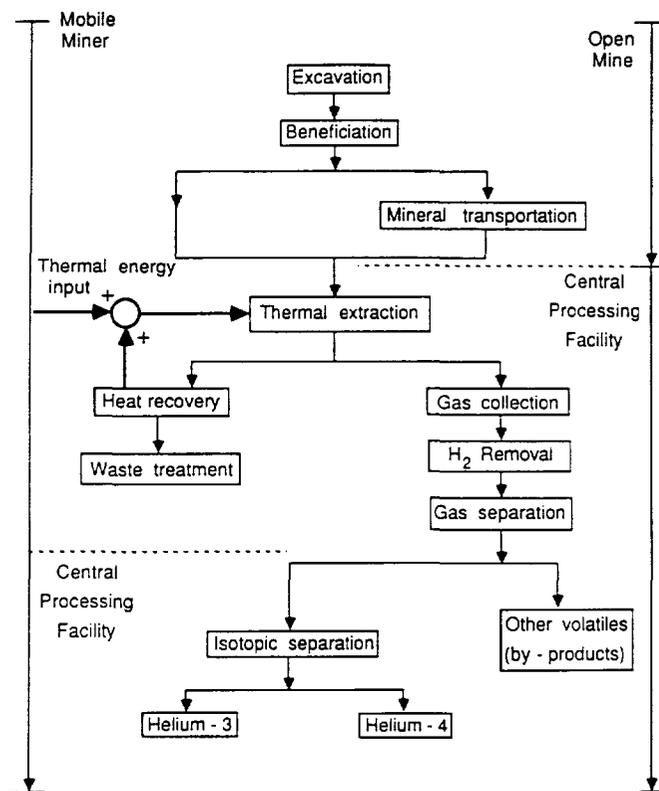


Fig. 5. Excavation, beneficiation, and thermal gas extraction systems integration required for the mobile miner concept, left, or the open mine-central processing facility, right.

the mine to the central processing plant increase rapidly each year when significant quantities of He-3 are needed. Also, additional conveyor belts are needed to return the processed regolith to the open pit.

Because of the large flow of regolith in the open-pit concept, a mining scenario based upon the use of a mobile miner was suggested. Such a mobile mining system consists of a bucket wheel excavator at the front followed by a series of mobile modules (see cartoon sketch in Fig. 6). Each module performs a single or multiple processing function(s) such as excavation, beneficiation, preheating, main heating, gas extraction, and heat recovery. Mobility is independently provided to each module. Mineral flow is handled by lifting conveyors, which are mounted to the modules. Gas-tight enclosures may be placed around each conveyor, if needed. The whole assembly moves at the rate of 23 m per hr, excavating a trench 20 m wide. In addition, it can be quickly moved from one mining site to another as a unit, or individual modules can be recalled to the lunar base for maintenance or replacement as required.

The task of excavating maria regolith on the Moon is akin to strip-mining sand and gravel on the Earth. Of course, the lunar environment is quite different from the terrestrial one and has been viewed as an obstacle to the operation of machinery. On the other hand, studies of lunar bases and other activities have constantly shown that the demand for some form of mechanical systems must be used for these enterprises. Consequently, we believe that the use of mechanical operations may be minimized, but not eliminated. The successful operation of three lunar rovers during the Apollo program suggests that sustained operation of mechanical devices is possible (Morea, 1991).

The bucket wheel excavator (BWE) appears to be the most useful for the purpose of removing the top 2-5 m of regolith. The BWE has multiple buckets mounted on the circumference of a rotating wheel and takes progressive sideward and upward cuts of the mineral as the wheel is slewed and rotated, respectively. The mineral scooped into the buckets is then discharged onto a conveyor belt when the buckets are moved to their top positions. The excavator is usually mounted on crawlers, providing mobility. This excavating method is advantageous over other systems because (1) this method provides a continuous supply of minerals, particularly favorable when the mining rate is high; (2) the effective output of a single BWE ranges from several hundred to several thousand cubic meters per hour on the

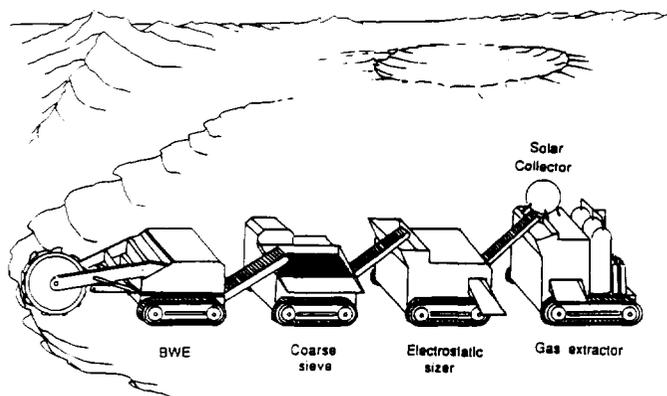


Fig. 6. Conceptualized mobile mining arrangement. Units could be combined into one vehicle.

terrestrial base, and if this output capability can be maintained on the lunar base, a single excavator can match the need for a power plant of 500 MW electrical output; (3) the BWE is physically compact and has a low mass-to-product ratio, which is desirable in regard to the transportation of equipment from Earth; and (4) the entire machine can be returned to a lunar base for maintenance.

PROCESSING REGOLITH

Mineral processing to produce the end product, He-3, consists of three operations: beneficiation or grain size selection, heating the beneficiated regolith, and the recovery and separation of the volatiles. Our major concerns in this respect have been the feasibility study of the technology involved and the energy consumption in the processing.

After the regolith has been elevated from the surface, it is first subjected to the beneficiation process, by which the finer portion of the mineral is selected and the coarser portion is rejected. As discussed earlier, grains of $<50 \mu\text{m}$ retain $\sim 81\%$ of the He but constitute only 45 wt% of the regolith so that the energy required for heating the regolith is reduced. Technically, beneficiation may be done initially by a coarse sieve followed by an electrostatic sizer. Electrostatic separation of lunar minerals requires further research (Inculet, 1987) and testing because pristine grains of the fine regolith in the lunar environment may tend to agglomerate and the distribution of agglutinates in the raw soil is ill defined.

The subsequent major step of processing is the heat treatment, by which the beneficiated fines are thermally activated in order to release the trapped solar wind elements that are bound within the surfaces of the grains. As previously discussed, the heating will be limited to $700^\circ - 750^\circ\text{C}$. Of prime consideration is the thermal energy required to heat the regolith. If the fines $<50 \mu\text{m}$ are retained, then the heater must process 800 tonnes/hr. Based upon the heat capacity of the regolith, $\sim 1 \text{ J/g}\cdot\text{K}$, and the need to heat the regolith from 250 to 973 K, the thermal power required is $\sim 160 \text{ MW}$. In order to reduce this energy requirement, nearly 90% of the energy is conserved by the use of solid-to-solid recuperators by which the heated regolith emerging from the heater transfers its thermal energy to the incoming regolith. These heat recovery units are connected by heat pipes, as shown in Figs. 7 and 8; however, the design, construction, and testing of these recuperators require further development. If the recuperators operate successfully, only $\sim 16 \text{ MW}$ of thermal energy is needed. This energy could be conveniently supplied during the lunar day by the use of six solar energy collectors, 50 m in diameter, focused upon receivers attached externally to the heater. These solar reflectors are large by terrestrial analogies; however, the lunar environment of one-sixth gravity and the absence of wind-loading should simplify their construction. Perhaps aluminized plastic sheets stretched over light-weight metal frames would suffice. The reflectors must track the sun and the miner, but both move slowly.

We propose three schemes to heat large tonnages of regolith in a closed system to capture the emitted volatiles. The first scheme uses the concentrated solar energy to heat a medium such as liquid lithium in heat pipes, as shown in Fig. 7, or He-4 (by-product) in a cycling loop. The heat transfer medium brings the heat to layers or cells of preheated regolith in the main heater. The main heater is divided into layers or heating cells because the thermal conductivity of the regolith is small; however, it may be 5-10 times better than for the regolith on the lunar surface,

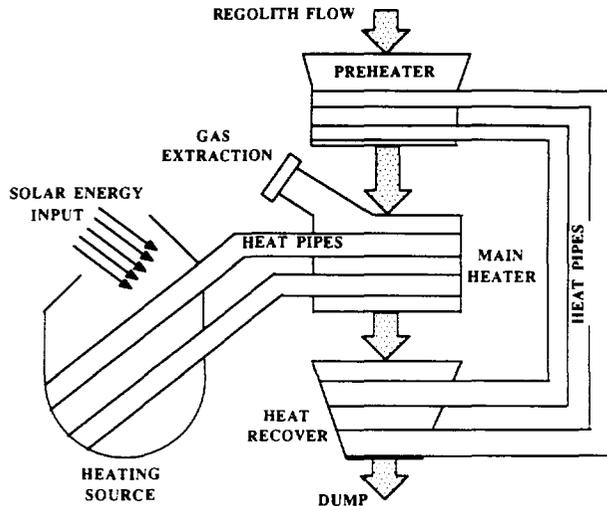


Fig. 7. Arrangement for the use of solar thermal energy to heat regolith fines in an enclosed oven.

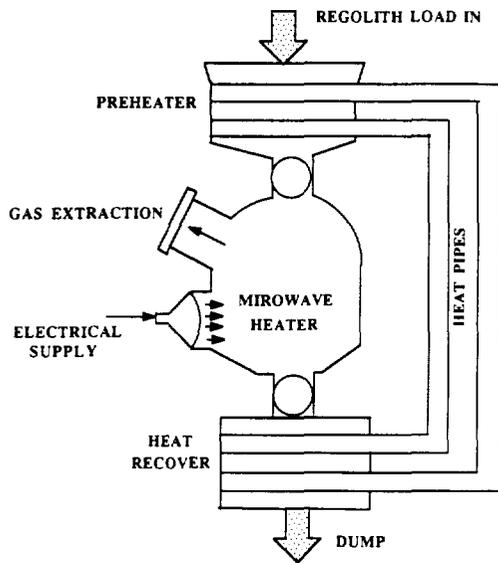


Fig. 8. Arrangement for the use of a microwave heating technique to process regolith fines.

because the existence of the emitted gases inside the chamber increases the heat transfer coefficient. The size of the gaps between the cells is large enough to allow the dry regolith to flow easily. As an example, for a heating chamber 2.5 m high, 10 m wide, and 19.4 m long, with half the volume occupied by 400 tonnes of regolith preheated to 300°C in gaps 2 cm wide, and the temperature of the heating medium at 850°C, the temperature rise of the full 400 tonnes reaches 600°C in 17 minutes.

The second heating scheme employs microwaves as the energy source for the heating process. The electrical source of the microwave generator may be supplied by either a solar-to-electrical energy converter or a nuclear power plant. As shown in Fig. 8, the microwave energy launched by antenna and reflected

in all directions inside the oven strongly couples with the regolith providing essentially a bulk heating. Consequently, the temperature of the load will increase much faster, yielding a higher rate of processing. Moreover, the equipment can be simpler as it is essentially a resonant cavity. Gravitational flow of the fines in the cavity is sufficient. These features make this scheme appealing. The disadvantage of this scheme is that it requires an electrical energy supply and the efficiency of generating microwave energy from electricity is about 50%. Low solar-to-electrical energy conversion, ~20%, would also be involved if solar photovoltaic devices provided the electrical energy source; consequently, it would be more energy efficient, requiring fewer solar collectors, if the solar thermal energy could be used directly.

AN ADVANCED FLUIDIZED BED REACTOR AND HYDROGEN REMOVAL SYSTEM

The third heating scheme considered uses a "fast-moving" fluidized bed reactor. In such a reactor the beneficiated regolith particles are introduced near the vented floor of the reactor and are levitated and transported to the top of the reactor in a heated gas stream. At the top of the reactor the particles and the gas are separated in a cyclone separator, as shown in Fig. 9. For particles <50 μm with a density of 3.2 g/cm³, the terminal velocity of the particles in the lunar gravity is 3.7 cm/sec in a hydrogen gas stream at 0.5 MPa (5 atm) pressure (Zhang and Yang, 1986). The gas velocity must be greater than the terminal velocity in order to levitate the particles and somewhat greater in order to transport the particles vertically. Because the terminal velocity is so low in the lunar gravity, the gas velocity was increased to seven times the terminal velocity, yielding a particle velocity of ~22 cm/sec. These parameters permitted a volume density of 10% solid particles in the gas phase and a particle flow rate of 2 g/cm²sec or 60 kg/sec for a 2-m diameter reactor (Yerushalmi and Avidan, 1985).

Laboratory analyses of the evolution of solar wind gases are normally conducted in a vacuum apparatus, while a sweep gas is proposed here. An important consideration for such gas emission from a surface is whether the gas pressure of the emitted species surrounding the solid is sufficiently high to increase the back reaction, namely resolution of the gaseous species in the solid. With the high gas velocity and turbulent flow of the particles within the bed, a high concentration of He surrounding the particle is unlikely. Another consideration for diatomic gas molecules, such as H₂, is that two H atoms must recombine on

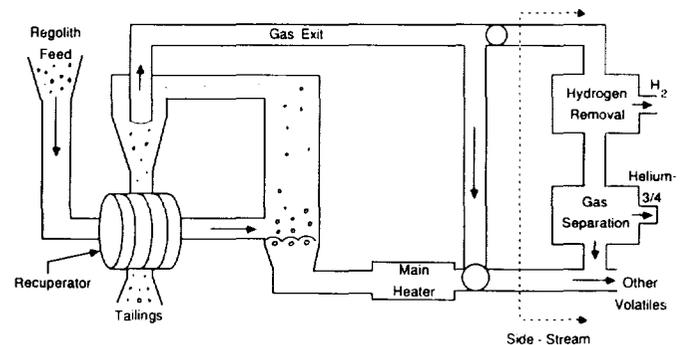


Fig. 9. A fluidized bed technique for heating regolith fines with continuous removal of the evolved gases.

the surface before the molecule can escape to the gas phase. Certain foreign gases adsorbed from the gaseous phase may retard the formation of H₂, for instance. In the case of He, however, it effuses as a single atom and, therefore, chemical interferences at the surface should not retard He evaporation. These proposed mechanisms will need experimental verification.

The circulating gas will be heated to ~750°C by use of solar energy. The regolith particles will be preheated so that they will be quickly heated by the gas. For a heat transfer coefficient of 300 W/m²K from the gas phase to the solid, the center of the particle reaches ~700°C in 0.1 sec. Of concern, however, is the time required for the implanted solar wind gases to diffuse from the particles. The diffusion rate for He atoms in this material has not been determined and may depend upon the migration of bubbles because of the low solubility of He in the ore. Such measurements have been made for the diffusion of radioactive hydrogen (tritium) from Li₂SiO₄ and indicate that the H atom diffusion coefficient D is very small, ~4 × 10⁻¹¹ cm²/sec at 700°C (Werle *et al.*, 1986). During regolith degassing analyses, the evolution of He and H₂ is similar; therefore, the use of D(H₂) may be acceptable for D(He). The approximate time, t, for the bulk of the solar wind particles to diffuse from regolith particles can be estimated from the relationship, $t = \Delta^2/D$, where D = the diffusion coefficient and Δ = the depth of the gas atoms, ~0.2 μm. This relationship indicates ~10 sec is required for H atoms and the other solar wind particles to diffuse from the particles. Because of the required diffusion time, the particles must be kept in the heated gas stream for 10 sec, while moving vertically at 22 cm/sec; therefore, the height of the fluidized bed reactor (FBR) should be 2.2 m. The FBR parameters are listed in Table 3. For a 2-m-diameter FBR, four FBRs would be needed to process the regolith at the required rate of ~800 tonnes/hr.

Vacuum locks will be required at the entry and exit ports of the reactor. Sliding seals and door apparatus such as currently used on pressurized coal combustion furnaces (Goldich, 1986) will be used so that nearly continuous feed rates can be maintained. The exit lock must be capable of evacuation before the regolith is ejected to the lunar surface. The amount of evolved solar wind gases that may adhere to the regolith is unknown; however, some experimental information indicates that this quantity should be small. Holmes *et al.* (1973) found that the surface area of the fine regolith decreased significantly after heating between 500° and 600°C. In addition, they found that H₂O adsorption, caused by terrestrial water, appeared to open the structure of the regolith and increase the surface area. Their results imply that the adsorption of nonpolar molecules, such as H₂ and He, on the degassed regolith should be very small. The adsorption of the highly polar molecule H₂O would be greater; however, only small amounts of H₂O are formed during the high temperature degassing of the regolith so that its potential effect upon increasing the surface area should be very small.

TABLE 3. Parameters for the fluidized bed reactor.

FBR Parameters	
Size of reactor	2 m diameter × 2.2 m high
Gas pressure	0.5 MPa (5 atm)
Gas velocity	0.26 m/sec
Particle velocity	0.22 m/sec (in lunar gravity)
Particle residence time	10 sec
Regolith flow rate	60 kg/sec
He-3 yield	13 g/hr
Reactors required	4

The gas stream is continuously circulated through the main heater and then returned to the reactor. A side-stream is diverted from the main gas stream in order to collect the evolved solar wind gases. The flow to this side stream equals the rate of gas evolution and has a volume composition of 72% H₂, 18% He, and 10% other gases. The high H₂ concentration must be reduced in order to eventually liquefy the He; consequently, most of the H₂ is removed from the gas stream at this stage by the technique of permeation through thin-walled, 1.27 mm outside diameter, palladium-silver alloy tubes (Ackerman and Koskinas, 1972). The gases are cooled to 300°C for this process and the H₂ concentration is reduced to ~5% in the He stream at the exit of this diffuser (see Table 4). Nearly 2500 Pd tubes are required for the diffuser, but they can be placed into a cylinder only 0.2 m in diameter because of their small size. This diffuser can, therefore, be carried easily on the mobile miner. The pure H₂ from the diffuser is then compressed and stored in large gas cylinders that are periodically transported to a hydrogen storage depot.

The He and other gases, Co, CO₂, N₂, and a trace of H₂, upon exit from the nonpermeate stream of the diffuser, can also be compressed and stored in gas cylinders ready for transportation to a central gas processing facility.

TABLE 4. Parameters for the hydrogen diffuser.

Tube material	Palladium alloy
Tube dimensions	o.d. = 1.27 mm; wall = 0.13 mm; length = 24 m
Number of tubes	2500
Tube bundle dimensions	0.2 m i.d. × 24 m length
Operational temperature	300°C
Operational pressure on tube	i.d. = 700 kPa (7 atm) o.d. = 19 kPa (0.19 atm)
Inlet gas composition (mole %)	72 H ₂ ; 18 He; 10 other gases
Exit gas composition (mole %)	5 H ₂ ; 61 He; 34 other gases
Permeate gas flow rate	4.2 millimoles H ₂ /sec · tube

CENTRAL GAS PROCESSING FACILITY

Pressurized gas cylinders containing the solar wind gases are transported to a central gas processing facility. This facility contains a variety of gas separation systems that are needed to separate and purify each of the gaseous components and finally to isotopically separate the helium isotopes. Some of this separation equipment may require specialized auxiliary items and analytical instrumentation. Also, the composition of the gases may vary as various ore bodies of the regolith are mined requiring changes in the purification schemes. For these reasons, such separation equipment is better utilized at a central facility rather than being attached to each miner unit.

The separation equipment will be similar to that found in commercial chemical operations, such as chemical getters for absorption of hydrogen; selective adsorbers, such as molecular sieves, for the adsorption of H₂O and CO₂; selective permeation barriers, which have recently become commercially available (Haggin, 1988); and temperature-controlled liquefaction equipment. The liquefaction process will require large radiator surfaces because radiation is the only method to dissipate heat on the lunar surface; consequently, liquefaction is used sparingly as a separation process. Liquefaction could be expeditiously accomplished during the long lunar night when the surface temperature decreases to ~102 K, or if operated during the lunar daylight, the radiators must be shaded. Ultimately, all the helium isotopes must be

liquefied to <4 K for isotopic separation. Numerous techniques have been developed for helium isotopic separations; however, cryogenic techniques are preferred. A cryogenic refrigerator will be needed, therefore, to operate between the liquid helium reservoir and the radiator temperature.

Partial separation of the helium isotopes at the lunar facility is needed due to the observation that the gases evolved from the regolith have a He-4/He-3 ratio of $\sim 2500:1$. The transportation system for delivery of the He from the Moon to Earth either as a gas or as a liquid has not yet been conceptually designed. In either form, however, very large amounts of inert He-4 would be transported for each small quantity of He-3. Such delivery would only be economical if a large terrestrial market developed for He-4.

The first stage of the He isotopic separation process would consist of a "superleak" apparatus (Listerman and Watkins, 1970) utilizing a filter with very fine pores. Superfluid He-4 flows through this filter when it is cooled below the lambda temperature, 2.2 K. Conversely, liquid He-3 is a normal fluid at this temperature and does not flow through the filter, but becomes enriched on the feed side of the filter. Such a technique has been proposed (Wilkes, 1978) to enrich He-3 from <1 ppm in He-4 up to $\sim 1\%$. Because this technique functions effectively regardless of the gravitational environment, it would be useful on the Moon. At a concentration of $\sim 1\%$ He-3, the solution would be transferred to a cryogenic distillation apparatus for purification to 99+% He-3 (Wilkes, 1973). The characteristics of operational distillation columns change in low gravity environments because they rely upon density differences of solutions refluxing on the column (Pettit, 1985); consequently, at a particular enrichment value of He-3, yet to be determined, the final purification, may be more effectively accomplished after its delivery to Earth.

CONCLUSIONS

Several methods, processes, and equipment types have been surveyed to provide for the recovery of He-3 and other solar wind particles from the lunar regolith. A mobile mining scheme is proposed that meets most of the mining objectives. This concept uses a bucket-wheel excavator for excavating the regolith, several mechanical and electrostatic separators for beneficiation of the regolith, a fast-moving fluidized bed reactor to heat the particles, and a palladium diffuser to separate H_2 from the other solar wind gases. At the final stage of the miner the regolith "tailings" are deposited directly into the ditch behind the miner and cylinders of the valuable solar wind gases are transported to a central gas processing facility. During the production of He-3, large quantities of valuable H_2 , H_2O , CO, CO_2 , and N_2 are produced for utilization at the lunar base. For larger production of He-3 we recommend the utilization of multiple-miners rather than increasing their size. Multiple miners permit operations at more sites and provide redundancy in case of equipment failure.

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