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MOBILE HELIUM-3 MINING AND EXTRACTION SYSTEM AND ITS BENEFITS TOWARD LUNAR BASE SELF-SUFFICIENCY

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Technical Report

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Mobile Helium-3 Mining and Extraction System and Its Benefits Toward Lunar Base Self-Sufficiency

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Abstract

The D-He3 fueled nuclear fusion reaction has long been recognized as one of the most attractive for generating clean fusion energy. Although aware of its virtues, fusion researchers had despaired of ever using it because they did not know where to obtain He3. Recently University of Wisconsin scientists upon reviewing data on constituents of lunar samples, confirmed their suspicion on the presence of He3 in lunar regolith. He3 originates in the sun and is transported by the solar wind where it has been implanted in the lunar surface over several billion years. It is estimated that about a million tonnes of He3 is stored in lunar regolith. A kg of He3 can generate 10 MW-years of electric energy on earth, worth 5-10 M$ by present day costs. The benefits for a permanent lunar base from by-products of a He3 mining operation are very impressive. In this paper we describe a mobile He3 miner and its implication toward the resupply of a lunar base.

Introduction

Modern societies are increasingly more dependent on energy for their very existence. Using todays world energy utilization and scaling by projected population growth to an equilibrium level of 8-10 billion people (Kefitz, 1977), and allowing for modest increases of energy utilization among the underdeveloped countries, it can be shown that the world will be running out of economically recoverable fossil fuel by the mid 21st century or soon thereafter (Hafele, 1981). Renewable energy sources such as solar, hydro, geothermal, biomass and nuclear will have to be relied on to fill in as the fossil fuels are depleted.

Nuclear energy in the form of fission reactors currently supplies ~17% of the world energy needs and will reach 20% by the turn of the century. Fission reactors utilize uranium for fuel which also is a finite resource and in recent years have met with public resistance to storage of radioactive wastes and issues of safety. The other form of nuclear energy is fusion, the same reaction which powers the sun and the stars. Research on peaceful application of

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fusion has been going on for more than thirty years and there are presently experiments (TFTR, Hawryluk, 1986), (JET, 1986), which can achieve breakeven in the next several years (breakeven is defined as producing an amount of energy equal to that invested). Present research has concentrated on the DT (deuterium tritium) reaction in which 80% of the energy is in the form of energetic neutrons. The worlds oceans contain abundant quantities of deuterium, and tritium can be bred by allowing neutrons to react with lithium bearing compounds, which also exist in vast supplies on earth. Although DT fusion is many orders of magnitude cleaner than fission, because of the large amount of neutrons, structures close to the plasma become activated and have to be stored as mostly low level waste upon reactor decommissioning. There are other fusion fuels which do not produce as many neutrons, among them the D-He3 reaction.

The D-He3 fusion reaction has long been recognized as the most attractive one from the standpoint of generating energy with the least amount of neutrons. The D-He3 reaction itself does not generate any neutrons, but side DD reactions do produce neutrons amounting to about 1%. The remaining energy is in the form of charged particles which do not activate structures and further, can be directly converted to electricity by electrostatic means at efficiencies of 70-80% (Barr and Moir, 1974). Conventional thermal power cycles typically achieve 30-35%. The main reason researchers have not pursued this concept more seriously is due to the lack of adequate terrestrial resources of He3 to support a fusion power industry based on this reaction. The solution to this dilemma came in 1986 when scientists at the University of Wisconsin (Wittenberg, 1986) upon reviewing data on constituents of lunar samples brought back by the Apollo astronauts and samples analyzed by the Soviet LUNA probes confirmed the presence of He3 in lunar regolith. It can be estimated that, over the 4 billion year history of the moon, it has been bombarded by ~ 500 million metric tonnes of He3 emanating from the sun and reaching the moon via the solar wind. A small fraction of this He3, about one million tonnes (Kulcinski and Schmitt, 1987) has been imbedded into the lunar regolith. Samples of lunar regolith indicate that the largest concentration of He3 is in areas containing the mineral ilmenite ($FeTiO_3$) which is primarily found in the lunar basaltic marias (Cameron, 1987). Further, some 90% of He3 is in particles smaller than 50 microns which constitute 45% of the regolith. These particles when heated to ~ 700°C release 80-86% of the He3 trapped within them. Table I gives the estimated gas released from heating maria regolith to 700°C (Gibson, 1971). The large amounts of H_2, H_2O, CO, CO_2, CH_4 and N_2 obtained in the process can be of great benefit toward lunar base self-sufficiency.

In this paper we address the issues of extracting He3 from lunar regolith utilizing mobile miners. These issues include excavating, conveying, beneficiating and heating the regolith, as well as collecting, transporting and condensing the released solar wind products. We also describe the benefits of such an operation toward lunar base self-sufficiency, as well as terrestrial benefits.

Table I. Solar Wind Gas Release Predicted for Maria Regolith When Heated to 700°C

	He3	He4	H_2	Carbon	N_2
Concentration in Maria Regolith (ppm or g/tonne mined)	9×10^{-3}	30	50-60	142-226	102-153
Concentration in Grains < 50 μm (g/tonne mined)	8.1×10^{-3}	27	50	166	115
Amount Released at 700°C (g/tonne mined)	7×10^{-3}	22	43 (H_2) 23 (H_2O)	13.5 (CO) 12 (CO_2) 11 (CH_4)	4
Mass Obtained Per Kg of He3 (tonnes)	10^{-3}	3.1	6.1 (H_2) 3.3 (H_2O)	1.9 (CO) 1.7 (CO_2) 1.6 (CH_4)	0.5

Mining Operation

General Description. The mobile lunar miner is designed to be a self contained machine which excavates the regolith down to a depth of 3 m, separates the < 50 μm particles from the rest, heats them, collects the evolved gasses in high pressure cylinders and finally ejects the processed regolith back on the lunar surface. Figures 1a and 1b show a side view and a top view of a conceptual lunar miner. A bucket wheel excavator pivoted on an arm attached to the miner executes a 120° arc as the miner slowly moves forward. The excavated regolith is conveyed to coarse and fine sieves and the rejected regolith is dropped on the sides of the mined swath as shown in the figures. The regolith is then electrostatically beneficiated to particles < 50 μm which is conveyed to the heater zone while the rest is again dropped off. In the heater, the fines are heated to 700°C, then cooled in a recouperator before being ejected out the back of the miner, filling the excavated trench. Since we depend on solar energy for process heat, we find that the rate of regolith processing is limited by the energy supply, and thus energy recovery is mandatory. In estimating the rate of He3 collection we assume that mining takes place during the lunar day at 90% availability (3940 hours/year). The energy is beamed to the mobile miner by a permanently mounted solar dish of ~ 110 m in diameter which tracks the miner while beaming the energy to a small receiver dish of ~ 10 m in diameter mounted on the miner. The energy is concentrated down into the miner to a solar oven where it is distributed on heated surfaces. The figure also shows articulated arms mounted on the miner for handling the gas cylinders. These cylinders are taken back to a central condensing station by service vehicles.

The mobile miner described here will collect ~ 33 Kg of He3 per year. To be conservative, we assume that 80% of the trapped He3 is collected. At this rate the miner excavates 1258 tonnes per hour of

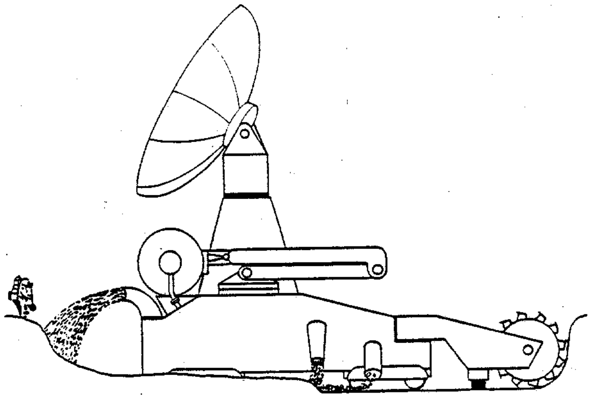


Fig. 1a. Side view of mobile miner.

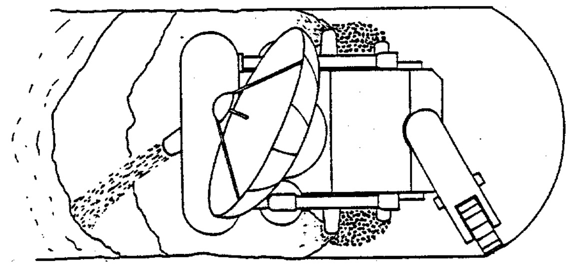


Fig. 1b. Top view of mobile miner.

which 566 tonnes/h is processed. Excavating power is estimated at 30 kW based on scaling from Cleveland Trencher Model 8700 capable of excavating 1,900 tonnes/h on earth. Table II gives the parameters for such a miner.

Table II. Selected Mobile Miner Parameters

Annual collection rate of He3 (kg)	33
Mining hours/year	3942
Excavation rate (tonnes/hour)	1258
Depth of excavation (m)	3
Width of excavated trench (m)	11
Forward speed of miner (m/h)	23
Area excavated per year (km^2/y)	1.0
Processing rate (tonnes/hour)	556
Process energy requirement (Mw)	12.3
Heat recovery (%)	85
Number of conveyers systems required	5
Assumed inlet regolith temperature (K)	300
Maximum regolith temperature in heater (K)	973
Temperature of regolith deposited back (K)	400
Pressure in heater enclosure (MPa)	.02
Pressure of gasses in cylinders (MPa)	15
Estimated operating power requirements (kw)	200
Estimated total earth mass of miner (tonnes)	18

Conveying and Beneficiation. For the preliminary design, all conveyor systems are derived from terrestrial based systems. A standard conveyor width of 2.44 m with a 45° troughed configuration was chosen to maximize mass per unit belt length. A 45° troughed configuration has a mass per unit belt length 10 times greater than for a flat belt. To determine the actual mass per unit length for such a conveyor, lunar regolith was assumed to have characteristics similar to terrestrial dry sand. For this arrangement the mass per unit belt length is 1117 kg/m (assuming 1.8 g/cc density of lunar mare regolith).

The mined regolith is initially transported to the beneficiation subsystem where only grains < 50 μm are retained for processing.

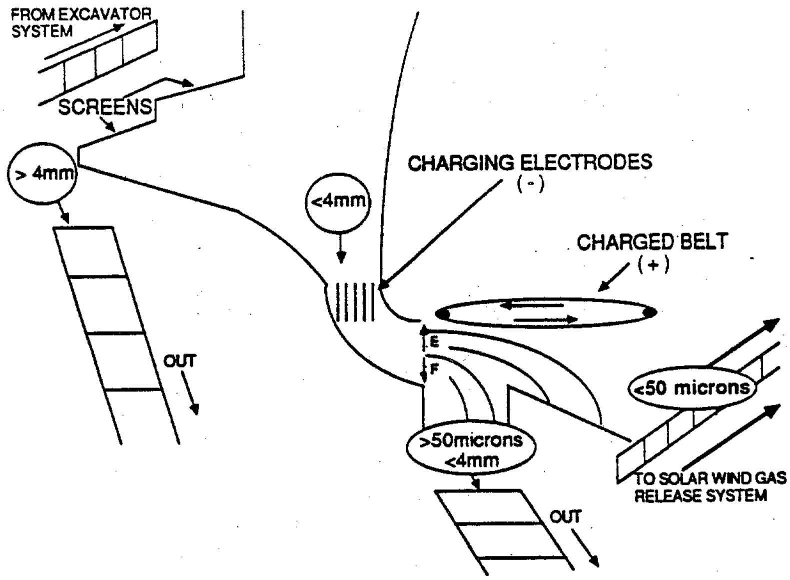
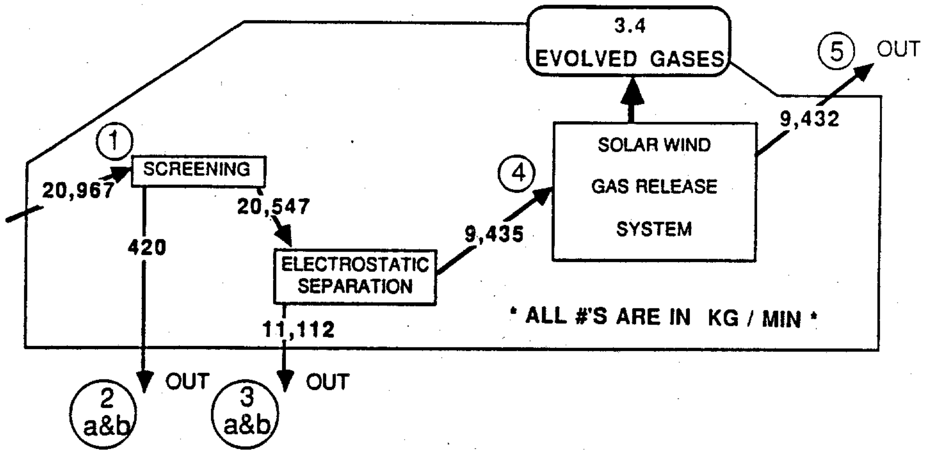


Fig. 2. Internal regolith beneficiation system.

Initial screening removes grains larger than 4 mm diameter, or 2% of the input regolith which is removed from the miner by a conveyor. The remaining fraction is directed to an electrostatic separation system where it falls through charging electrode plates. An oppositely charged belt then exerts a verticle force on the charged grains causing the smaller grains into a larger horizontal trajectory than larger grains. The larger grains fall onto a conveyor and are removed from the miner and grains < 50 μm are transported to the solar oven. Figure 2 is a schematic of the beneficiation system.

Analysis of the rates at which the miner can process regolith shows that the design is limited by the heating rate. Based on this limitation, other internal regolith conveyors will operate at rates well below maximum allowable rates found in conveyor design tables for transporting dry sand. Figure 3 is a schematic showing the regolith mass flow rates to the various systems. A total of seven conveyors has been designed to transport the regolith throughout the subsystems of the miner. Each conveyor is designed for the rates required within the subsystem. Table III gives the calculated characteristics of the conveyors where the conveyor numbers correspond to those shown in circles in Fig. 3. These designs are well within current technical capabilities. The masses and power requirements have been corrected for operation in a lunar gravity environment, (divided by 3) giving a total mass of 1.62 tonnes and a power requirement of 5.2 kW. The beneficiation subsystem mass and power was not reduced relative to earthbound designs. It has a mass of 0.65 tonnes and requires 5 kW of power.

Heating. In this design of the miner, we have assumed that process energy will come from the sun, thus limiting operation to the lunar day. It is possible to use other sources of energy such as RF and nuclear which would make it possible to operate a miner the year round. Having made the decision to use solar energy, it became



NOTE: NO.'s IN CIRCLES REPRESENT INTERNAL REGOLITH CONVEYOR NO.

Fig. 3. Regolith mass flow rates.

immediately apparent that heat recovery is essential if the mining rates we have aimed at are to be realized. We have also found that a low pressure atmosphere ~ 0.01-0.02 MPa is needed to promote heat transfer in the regolith. This means that the system must be designed to be sealed against the high vacuum of the lunar environment.

Table III. Conveyor System Characteristics

Conveyor Number	Vert./Horiz. Displacement (m)	Belt Speed (m/min)	Mass Transport Rate (kg/min)	Mass of Conveyor (kg)	Power Required (kW)
1	0.5 /1.25	15.4	20,970	120	2.35
2a & b	-0.25/2.0	0.2	210	418	0.03
3a & b	-0.25/2.0	4.1	5,767	418	0.68
4	2.25/3.5	6.9	9,437	479	1.4
5	0.5 /1.5	6.9	9,437	187	0.76

The seal problem was resolved by the use of a solar oven in which the energy is conducted across heated surfaces (see Fig. 5). The inlet and outlet columns of regolith (3-4 m long) in the supply and return hoppers act as seals for the oven enclosure. Admittedly, there will be some leakage by diffusion through the long regolith columns, but this would be minimal and can be tolerated.

Figure 4 is a side view of the heat exchanger which is made of heat pipes divided into three primary zones, the preheater, the supplemental heater and the recouperator. The regolith flows by gravity through the left and right enclosures which contain the straight parts of the heat pipes, while the U shape is the isothermal part of the heat pipes. Each enclosure is 1 m long and 2 m wide, accommodating 118 heat pipes per row. Figure 4 also shows a temperature profile of the regolith as it flows through the heat exchanger. It enters the heat exchanger at 300 K and exists at 400 K. The heat

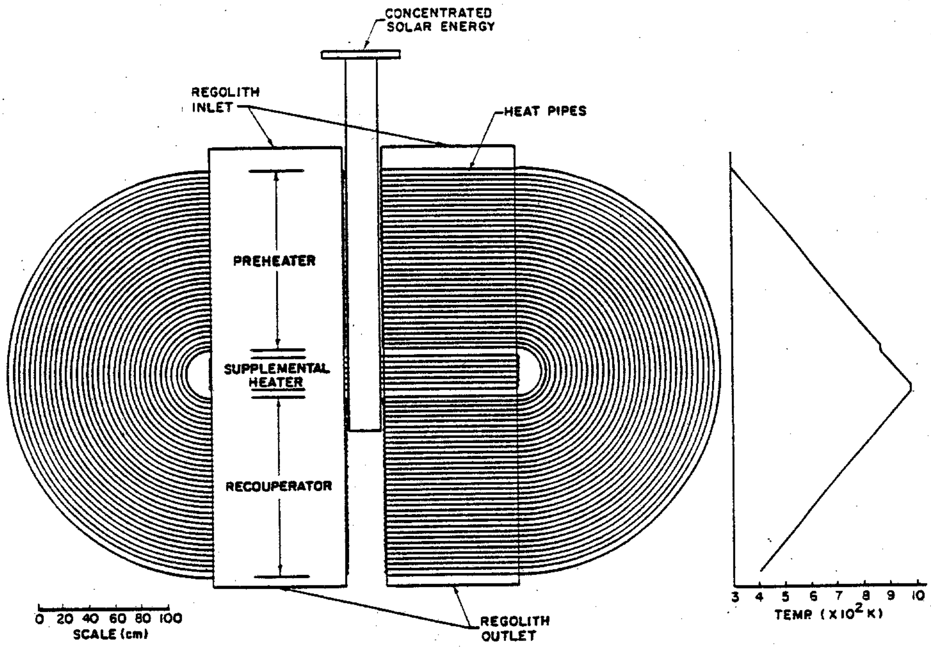


Fig. 4. Side view of regolith heat exchanger showing regolith temperature profile on the side.

pipes in the low temperature end of the recouperator transfer heat to the low temperature end of the preheater. As the regolith works its way through the 3 m high maze of heat pipes it progressively encounters higher temperatures until it exits the supplemental heater at 700°C and then it begins to cool down in the recouperator. We feel that staged heat pipes operating with water, mercury, potassium and sodium can be used to provide the temperature progression which is needed for this design.

Figure 5 shows two views of the supplemental heater with an enlargement showing details of the heat pipes in the boiler section. Solar energy enters through a flange which is sealed to the oven housing and is distributed onto surfaces immersed in liquid sodium in the boiler. In this way, the oven enclosure is sealed from the lunar vacuum. As the sodium evaporates it flows into the heat pipes where it condenses and flows back to the boiler through the wicks. To determine the heat transfer coefficients it was necessary to obtain an effective thermal conductivity for the regolith. The bulk of the released gas in the oven is He and H_2 both of which have very high conductivities down to pressures of a few torr. We have used the Deissler Boegli (Deissler, 1958) method for determining the k_{eff} which is given as a function of the ratio of conductivity of the solid to that of the gas. The conductivity and the specific heat of ilmenite as a function of temperature was taken from the 1980 Handbook of Lunar Materials. Having calculated the Reynolds and Prandtl numbers we use the Dietus Boelter formulation to obtain the Nusselt number and the heat transfer coefficients. Using a pressure of 0.02 MPa (0.2 atm.) of He + H_2 gas we obtain heat transfer coefficients ranging from 1180 w/m^2K at 300 K to 1470 w/m^2K at 750 K. We have benchmarked these values against experimental work performed at the UW in 1980-1982 (Nietert, 1982) and have found remarkable agreement.

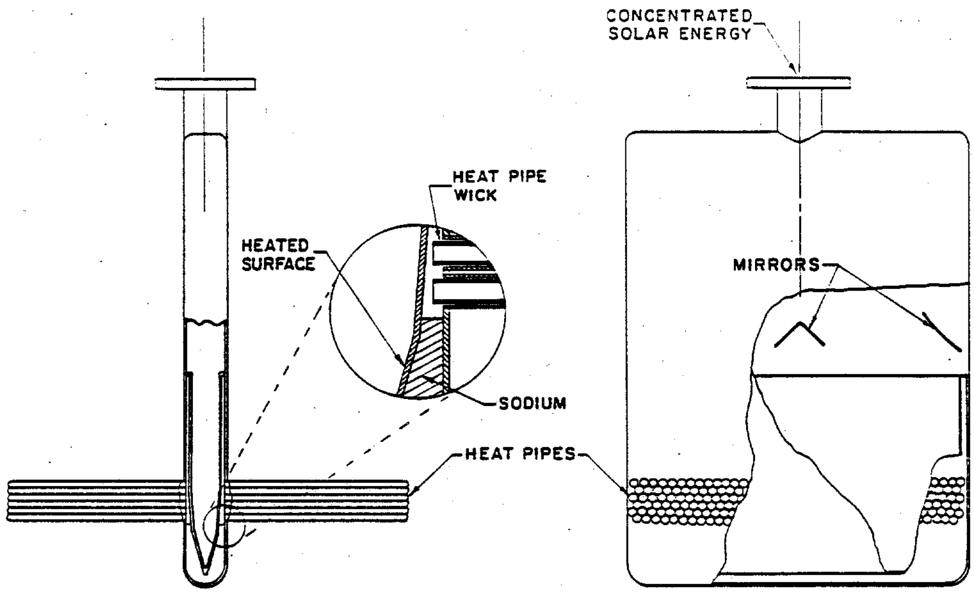


Fig. 5. Two views of supplemental heater.

In calculating the heat transfer areas needed we assume 1.5 cm diameter heat pipes spaced on a triangular pitch at 1.7 cm between centers. The effective vertical velocity of the regolith through the heat exchanger is 15 cm/s. We have used a temperature difference of 50°C between the regolith and the heat pipes. This means that the temperature of the regolith will be 400 K when it is replaced on the lunar surface, giving an energy recovery of 85% in the recouperator. At this regolith velocity erosion should not be a problem and since heat pipes operate essentially isothermally, liquid metal corrosion will not exist. Assuming the preheater and recouperator are made of stainless steel, and the supplemental heater from a molybdenum alloy, and using a heat pipe wall thickness of 0.25 mm, the total mass of the heater will be ~ 9 tonnes. Table IV gives the parameters of the heater.

Table IV. Parameters of the Heater

	Preheater	Supplemental Heater	Recouperator
Regolith inlet temp. (K)	300	873	973
Regolith outlet temp. (K)	873	973	400
Mass flow rate (Kg/s)	154.4	154.4	154.4
Actual regolith velocity (m/s)	0.20	0.20	0.20
Heat transfer area (m^2)	1012	187	1012
Depth of zone (m)	1.36	0.255	1.36
Regolith residence time (S)	9.1	1.7	9.1

Gas Collection. After the solar wind gasses are released from the regolith they must be collected. This is done with a compressor which has an inlet pressure of 0.02 MPa (0.2 atm.), and a discharge pressure of 15 MPa (150 atm.). We estimate that this will be done in six stages with cooling in between and will require 160 kW.

The cylinders will be equipped with paladium membranes which will allow the preferential diffusion of H_2 at a temperature of 350-400°C. It is desirable to separate the H_2 from the remaining species because cooling the H_2 will require a radiator five times larger than that required to cool the rest of the gases. Further, large quantities of gaseous H_2 will be needed on the moon for various uses.

Transporting of Gas Storage Cylinders. When the gas collection cylinder on the mobile miner is filled, the miner removes it and unloads it to one side of the miner, then loads an empty cylinder from the other side. Gas Storage Vessel Transport Vehicles (GSVTV) are responsible for the placement of the empty and collection of the full cylinders. The GSVTV returns the full cylinders to a central plant for further gas processing. The vehicle would be teleoperated from the main lunar base site and would be equipped with a robotic manipulator system.

Selective Condensation of Non-Helium Volatiles. The solar wind gasses will be cooled from 300 K down to 55 K in a radiator which radiates to outer space. The radiator will consist of tubes attached to the back side of plates with some fins for surface enhancement. The gasses will be continuously circulated through the radiator, and as each species begins to condense, it will drain out into a vessel and will be stored in liquid form.

Figure 6 is a plot of the radiator area time product in m^2h as a function of temperature, needed to cool the He, and condense the remaining volatiles for obtaining 1.0 kg of He3. We assume that the H_2 has been removed by diffusion and we neglect the mass of the radiator since it can be shielded from the sun and kept cold during the lunar day. The vertical parts of the graph represent condensation of the species. Nitrogen is the last to condense at ~ 78 K at this pressure. We selected 55 K as the temperature at which the He is fed into a cryogenerator for further cooling and liquifying.

It can be seen that a radiator area time product of 2.9×10^5 m^2h is needed to obtain a kg of He3. If this is done during one lunar night, this implies an area of ~ 800 m^2 or 28.3 m x 28.3 m. The radiator can be made of aluminum to minimize the mass and has an earth weight of ~ 6 tonnes. We estimate the compressor power for circulating the gasses at ~ 0.5 kW.

Condensation and Isotopic Separation of Helium Species. The He gas at 55 K is now fed into a cryogenerator where it is condensed and further cooled to 1.5 K for isotopic separation. If we assume a cryogenerator operating at 17% of Carnot efficiency and rejecting heat at 77 K it would take 180 KW of power at 300 K 15 days to liquify and cool the 3.3×10^3 kg of He down to 1.5 K.

Isotopic separation takes place by means of a super leak system in which liquid He3 is separated from He4. The energy required for this process is negligible.

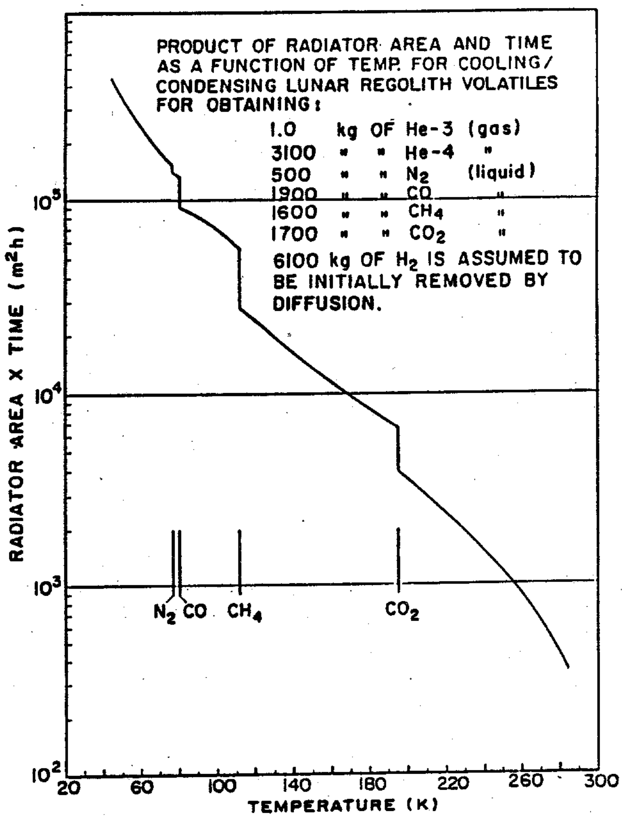


Figure 6. Radiator area time product as a function of temperature.

Benefits Toward Lunar Base Self-Sufficiency. Acquisition scenarios for Lunar He3 encourage the collection of other valuable volatiles available from the solar wind gas mixture with minimal mass and power penalties. These volatiles include H_2O, O_2, N_2 and CH_4. A lunar base supporting 15-20 crew members with a semi-closed life support system (all subsystems closed but food is 50% open), full scale mining activities, and science facilities would require over 65 metric tons of these consumable volatiles annually, over 35% of the total resupply for the base. He3 acquisition could reduce the total lunar base resupply by 3-6% for 1 kg He3 obtained, as well as obtaining excess quantitites of oxygen, nitrogen and hydrogen gases. Specific quantities required by a lunar base and quantities available as biproducts of He3 acquisition are shown in Table V. As He3 mining operations expand to meet predicted future demands, large quantities of these volatiles would be made available for base support and for the support of future space exploration missions. If oxygen, hydrogen, and methane are used as propellants, transportation vehicles for Mars and other space missions could refuel at a lunar orbiting station. This would enable space transportation systems to be designed with higher payload fractions. Because of this enhancement to future space exploration missions, the commercial value of a lunar base would be increased. Thus, the acquisition of He3 and other solar wind gas constituents becomes a critical technology for lunar and space commercialization.

Terrestrial Benefits and Energy Payback Potential. In generating a preliminary demand curve, assuming an overall U.S. annual energy

Table V. Additional Resources Available from He3 Acquisition for Lunar Base Support

Resource	Application to Lunar Base	Estimated Requirement for 15-20 Person Base (kg/yr)	kg/kg He3
H_2O	Life Support Consumable	4,280	3,300
O_2	Life Support Consumable	570	2,322
N2	Life Support Consumable	323	500
H_2	Lunar Resource Process Consumable	558	6,100
CH_4	Lunar Resource Process Consumable	60,000	1,600

growth of 2% in which the nuclear contribution grows at 3% and where all the fission reactors in the U.S. will be completely replaced with D-He3 fusion reactors by the year 2050, we estimate that 10^3 kg of He3 per year will be needed in the year 2025. It will take 30 miners of the kind described in this paper operating during the lunar day to obtain this quantity. A kg of He-3 when reacted with D_2 in a fusion reactor generates 6×10^{14} J of thermal energy equal to 19.3 MW_{th} years. If we assume ~ 50% conversion efficiency (conservative, since 70-80% is possible in electrostatic conversion, see Ref. Barr and Moir, 1974), this will produce ~ 10 MW_e years of electric energy worth 5-10 M$. Keep in mind that this energy is essentially neutron free which solves the problem of high level nuclear waste disposal and eliminates the possibility of accidents such as the one which occurred in Chernobyl.

In estimating the energy payback we have calculated that ~ 60 kg of equipment must be carried from earth to the moon for each kg of He-3 obtained, assuming a 20 year amortization of the equipment. The energy required for transportation, operation and support of the incremental base camp needed for the He-3 mining operation is estimated at 2140×10^9 J per kg of He-3. These numbers give an energy payback of ~ 280 to 1. Undoubtedly these estimates will change as the system is designed in more detail. Moreover this energy payback does not take any credit for the materials obtained in the process as discussed in the preceding section.

Conclusions

Preliminary investigations show that obtaining He3 from the moon is technically feasible and economically viable. With the exception of beneficiation, all the proposed procedures are state of the art. The beneficiation scheme, while technically sound, is yet to be demonstrated experimentally. Only the bucket wheel excavator and first conveyor will operate in the lunar vacuum. The other systems will have a gaseous environment of 0.1-0.2 atmospheres. The logistics of beaming solar energy to the miner seem to be well within present day technology. The titanium metal obtained from indigenous ilmenite ($FeTiO_3$) can eventually be used to fabricate many of the components, ameliorating the problem of resupply from earth. A projected energy payback of 280 is extremely attractive with ample incentives for commercial exploitation. Finally, such an operation can be of inestimable value to the resupply of a permanent lunar base as well as the enhancement of future space exploration.

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