

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

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INTRODUCTION

The surface of the moon is an abundant source of helium 3 [1]. Helium 3 and helium 4 particles, protons, and 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 helium collector. The results of degassing of lunar samples returned from the early Apollo missions [2] confirmed the presence of solar wind particles. Estimates based upon such results indicate that the lunar regolith contains more than a million tonnes of helium 3.

Helium 3 is an attractive fuel for fusion reactors because it produces "clean" nuclear power [1] with no radioactive fuel or fusion product. Unfortunately, terrestrial resources of helium 3 are scarce. Present assessments of both natural and man-made sources of helium 3 indicate that a fusion plant of 500 MW electrical power could be fueled for only a few months. In contrast, the utilization of the helium 3 resource on the surface of the moon could provide an energy source for terrestrial applications for centuries. In addition, the lunar regolith contains other elements of the solar wind which are evolved during heating, such as hydrogen, nitrogen and carbon compounds. It is expected that large amounts of these volatiles will be produced as by-products along with the acquisition of helium 3.

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 a short depth into the surface of the grains. Therefore, the fine grains which have high surface to volume ratios have high concentration of trapped particles. Secondly, the fine regolith in the maria

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extends to an average depth of at least 10 m and grains containing solar wind particles have been retrieved from core samples up to 2 m deep [3]. Thirdly, it appears that regolith high in titanium is also high in helium content. High titanium regoliths are mostly confined to maria basalts [4]. Fourthly, 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 primarily based 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 should be minimized.
4. Operations outside the lunar base should readily be automated.
5. All equipment should be maintainable.
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 be between 250 and 350 times the mining energy [5].

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 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 [6] indicated: H_2 and He evolution began $\sim 200^\circ C$ and was nearly complete by $800^\circ C$; CO and N_2 evolution began at $\sim 600^\circ C$ and continued to $1200^\circ C$; CO_2 was evolved between 700 to $1300^\circ C$; and H_2S and SO_2 evolution was initiated between 800 and $900^\circ C$. The evolution of H_2O and N_2 below $200^\circ C$ was attributed to adsorbed terrestrial impurities. These soils contain no H_2O molecules; however, release of the embedded hydrogen atoms during heating apparently reduces some of the oxides yielding water which may constitute $\sim 5\%$ of the H_2 evolved above $200^\circ C$ [7]. The appearance of methane has not been confirmed but may constitute 5% of the

total carbon. The condensation of the sulfur compounds SO_2 and H_2S from the evolved gas were observed [7] to contaminate the vacuum system with resinous products which were difficult to remove. For this reason, the proposed maximum heating temperature for the mining scenario was limited to 700°C so that the sulfur compounds would not vaporize.

Based upon the total yield reported [3] of solar wind gases evolved during the heating of Apollo 11 soils to $\sim 1300^\circ\text{C}$, first line in Table 1, the average fine regolith on Mare Tranquillitatis was conservatively assumed to contain 30 wt. ppm of He-4 with a He-3/He-4 ratio of 400 at. ppm. It was necessary, however, to estimate the amounts of the gases which would be evolved on heating to only 700°C . For this estimate, we utilized the mass spectrographic data by Oro [8] of gases evolved during the heating of Apollo 12 soils which 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 , CO_2 and N_2 as compared with the total yields from the regolith. These ratios were assumed, also, for the Apollo 11 samples. Quantitative yields of H_2 [9] and He [10] 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 H_2 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, 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 possible because the solar wind particles penetrate a short distance into the grains. Depth profiling measurements indicate that the H atom density peaks at 50-100 nm below the surface but extends to a depth of $0.2\text{ }\mu\text{m}$ [11]. Consequently smaller particles have a higher gas to solid mass ratio as confirmed by analyses [12]. When these analyses were combined with the size distribution of raw regolith [3], the results in Table 2 indicate that the particles of $< 50\text{ }\mu\text{m}$ which constitute only 47 wt.% of the soil yield 77% of the He and particles less than $100\text{ }\mu\text{m}$, which constitute 63 wt.% of the soil, contain $\sim 89\%$ of the He. In addition, we calculated that during the sieving process nearly 30% of the He had been lost as a result of either agitation of the particles or as fine particles which 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 to retain particles $< 50 \mu\text{m}$ which would constitute $\sim 45 \text{ wt.}\%$ of the soil but yield $\sim 90\%$ 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 [2] to contain up to 180 ppm of He. If the ilmenite were distributed uniformly in the soil, then, 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.

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
3. mobile excavation-beneficiation-evolution followed by centralized volatile/isotopic separation.

In what follows, we will examine each of these mining scenarios.

IN SITU MINING

"In situ mining" means to extract the embedded volatiles without removing 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, Figure 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 [13], in the lunar environment. As a consequence if the temperature of the surface were maintained at a constant 1,000 C, in order to avoid sintering, a simple calculation shows that it would need 5 hours to raise the temperature at a depth of 1 cm up 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 for the last several years [14]. Microwave radiation has been suggested as a method to heat lunar materials [15]. In addition, experimental results from sintering lunar soil simulants using 2.45 GHz microwaves have been reported [16]. These studies have shown that the coupling of the regolith to the microwave radiation is considerably increased due to the defects in the material [17], 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 [18]. Loss tangent characterizes the coupling between the substance and the microwave radiation, and it is temperature dependent, as shown in Figure 2(a) [19]. 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 [19], and, therefore, a function of temperature, as shown in the Figure 2(b). As the field of the microwave is 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 Apollo 11 mission [10]. The initial temperature distribution was assumed uniform 250 K approximately at the temperature of the regolith at a depth of > 30 cm. The frequency of the microwave and its intensity of the electrical field were 0.5 GHz and 400 volt/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 Figure 3 and 4. Figure 3 shows the temperature profile at 465 sec. (7.75

min.) when the surface reaches 1,000 C, the sintering temperature of the material, and Figure 4 shows the rate of evolved helium 3 per m^2 , by which the total yield of 23.6 cm^3 (STP) helium 3 was obtained. Finally, the total amount of microwave energy input into the regolith was 3.6 GJ. If this total yield of helium 3 were used in a fusion reactor, it would generate only 1.9 GJ of thermal energy, about half the input energy. 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 isotropically 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 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 product. For instance, 137,000 tonnes of regolith must be mined to produce one kg of He-3, yielding 6×10^8 MJ thermal energy from the D-3He fusion. At a conversion efficiency of 50% from thermal power to electrical power and mining only during the lunar day (4000 hrs/yr), we estimate that to fuel a fusion power plant of 500 MW electrical power, about 1800 tonnes of regolith must be mined per hour. The area needed to be mined consists of $1.8 \text{ km}^2/\text{yr}$ if the mining trench is 2 m deep. As a result the lengths of the conveyor belts from 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 developed. The mobile mining system consists of a bucket wheel excavator at the front followed by a series of mobile modules, Figure 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 belt conveyors, which are mounted to the modules. These belt conveyors are flexible so that the relative positions of the modules are not important. The whole assembly can move 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 the mining of beach sand 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 showed that the demand for some forms of mechanical system 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 [20].

The bucket wheel excavator (BWE) appears to be the most useful for the purpose of removing the top 2 to 5 m of regolith. The BWE has multiple buckets mounted on the circumference of a rotating wheel, and takes progressive side-ward 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 belt conveyor 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 m^3 per hour on the terrestrial base. 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, as estimated above.
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 the earth.
4. The entire machine can be returned to a lunar base for maintenance.

PROCESSING REGOLITH

Mineral processing to produce the end product of helium 3 consists of three operations, namely the beneficiation or the grain size selection, heating the beneficiated regolith, and the recovery and separation of the volatiles. Our major concerns in this aspect 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 subject to the beneficiation process, by which the finer portion of the mineral is selected and the coarser portion is rejected. As discussed early, grains of $< 50 \mu\text{m}$ retain $\sim 90\%$ 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 a electrostatic sizer. Electrostatic separation of lunar minerals requires further research [21] and testing because pristine grains of the fine regolith in the lunar environment may tend to agglomerate.

The subsequent major step of processing is the heat treatment, by which the beneficiated fines are thermally activated in order to release the trapped elements that are bound within the surfaces of the grains. As previously discussed, the heating will be limited to 700°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 for our proposed 500 MW(electric)) fusion plant. 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 170 MW. In order to reduce this energy requirement, nearly 90% of the energy is conserved by the use of solid-to-solid recuperators in

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. As a result only 17 MW of thermal energy is needed. This energy could be conveniently supplied during the lunar day by the use of 6 solar energy collectors, 50 m dia., focused upon receivers attached externally to the heater. These solar reflectors could be very simple, aluminized plastic sheets stretched over light-weight metal frames.

We propose two schemes to heat large tonnages of regolith in a closed system to capture the emitted volatiles. The first scheme utilizes the concentrated solar energy to heat a medium such as lithium in heat pipes, as shown in Figure 7, or helium 4 (by-product) in a cycling loop. The medium brings the heat to layers or cells of preheated regolith in the main heater. Dividing the main heater into layers or heating cells is necessary since the thermal conductivity of the regolith is small; however, it may be 5-10 times better than for the regolith on the lunar surface, because of the existence of the emitted gases inside the chamber. The size of the gaps between the divided layers or cells can be large enough to allow the dry regolith to flow. As an example, for a heating chamber, 2.5 m high, 10 m wide and 19.4 m long, with half of the volume occupied by 400 tonnes of preheated regolith 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 Figure 8. The microwave energy launched by antenna and reflected in all directions 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 fine in the cavity is sufficient. These features definitely 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 energy conversion would, also, be involved if solar photovoltaic devices provided the energy source.

AN ADVANCED FLUIDIZED BED REACTOR AND HYDROGEN REMOVAL SYSTEM

In a fluidized bed 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 $< 50 \mu\text{m}$ and density of 3.2 g/cm^3 , the terminal velocity of the particles in the lunar gravity is 3.7 cm/s in a hydrogen gas stream at 0.5 MPa (5 atm) pressure [22]. 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 7 times the terminal velocity, yielding a particle velocity of $\sim 22 \text{ cm/s}$. These parameters permitted a volume density of 10% solid particles in the gas phase and a particle flow rate of $2 \text{ g/cm}^2 \cdot \text{s}$, or 60 kg/s for a 2 m diameter reactor [23].

The circulating gas will be heated to 700°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 $300 \text{ W/m}^2 \cdot \text{K}$ from the gas phase to the solid, the center of the particle reaches $\sim 700^\circ\text{C}$ in 0.1 sec . Of primary importance, 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. Such measurements have been made for the diffusion of radioactive hydrogen (tritium) from Li_2SiO_4 and indicate that the H atom diffusion rate is very small, $10^{-11} \text{ cm}^2/\text{s}$ at 700°C [24]. The approximate time, t , for the bulk of the solar wind particles to diffuse from regolith particles can be calculated from the relationship, $t = D^2/\Delta$, where D = the diffusion coefficient and Δ = the depth of the gas atoms, $\sim 0.2 \mu\text{m}$. This relationship indicates $\sim 9 \text{ s}$ 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 9 s , while moving vertically at 22 cm/s ; therefore the height of the FBR should be 2 m . The FBR parameters are listed in Table 3. For a 2 m dia. FBR, 4 FBR's would be needed to process the regolith at the required rate of 810 tonnes/hr .

Air-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, [25] 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 which may adhere to the regolith is unknown; however, some experimental information indicates that this quantity should be low. Cadenhead, et al. [26], noted that the regolith reversibly adsorbed and desorbed H_2O even after being degassed up to $400^\circ C$. Conversely, Holmes, et al. [27], found that the surface area of the fine regolith decreased significantly after heating between 500 and $600^\circ C$. In addition, the latter group found that H_2O 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 non-polar molecules, such as H_2 and He, on the degassed regolith should be very small. The adsorption of the highly polar molecule H_2O would be greater; however, only small amounts of H_2O are formed during the high temperature degassing of the regolith so that its potential effect upon increasing the surface area should be very small.

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% H_2 , 18% He and 10% other gases. The high H_2 concentration must be reduced in order to eventually liquefy the He; consequently, most of the H_2 is removed from the gas stream at this stage by the technique of permeation through thin-walled, 1.27 mm O.D., palladium-silver alloy tubes [28]. The gases are cooled to $300^\circ C$ for this process and the H_2 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 dia. because of their small size. This diffuser can, therefore, be carried easily on the mobile miner. The pure H_2 from the diffuser is, then, compressed and stored in large gas cylinders which are periodically transported to a Hydrogen Storage Depot.

The He and other gases, CO , CO_2 , N_2 and a trace of H_2 , upon exit from the non-permeate stream of the diffuser can, also, be compressed and stored in gas cylinders ready for transportation to a central gas separation facility. Alternatively, the H_2 and He in the non-permeate gas stream may be selectively

recovered from the other gases by the use of specialized permeation membranes, which have recently become commercially available [29].

CONCLUSIONS

Several methods, processes and equipment types have been surveyed to provide for the recovery of solar wind particles from the lunar regolith. A mobile mining scheme has been conceptually designed. This concept utilizes a bucket wheel excavator for excavating the regolith, several mechanical and electrostatic separators for beneficiation of the regolith, a 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 in the ditch behind the miner and cylinders of the valuable solar wind gases are transported to a central gas processing facility. At this facility the gases are separated by several techniques such as chemical getters, diffusion barriers and temperature-controlled liquefaction. Finally the He isotopes are separated by a combination of the "super-leak" separation technique [30] and cryogenic distillation [31].

For the miner described herein, the He-3 production is ~ 13 g/hr. If the miner were operated only during the sunlighted periods, 4000 hr/yr, ~ 53 kg of He-3/yr would be produced, sufficient to provide 500 MW(electrical)) by fusion power. In addition large quantities of valuable H_2 , H_2O , CO, CO_2 and N_2 are produced for utilization at the lunar base [32]. 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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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)×10 ⁻³	20-45	50-60	142-226	102-153
Beneficiate	0.45	8.1×10 ⁻³	27	50	166	115
Gas Evolution	0.45	7×10 ⁻³	22	43 (H ₂) 23 (H ₂ O)	13.5 (CO) 12 (CO ₂) 11 (CH ₄)	4
Per kg He-3	1.37×10 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)	0.016 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

Table 2

Helium Content as a Function of Regolith Grain Size*

Grain Size Fraction		He-4 Content		
Sieve Size μm	Wt/Sample %	Wt/Grain Size ppm	Wt/Sample ppm	Frac./Sample %
-50	47.2	38.5	18.1	77
50-100	16.3	16.7	2.7	12
100-150	9.0	8.7	0.8	3
150-200	5.0	9.0	0.5	2
200-300	5.0	8.7	0.4	2
>300	17.5	6.0	1.1	5

*Sample 10084; E.N. Cameron, WCSAR-Internal Report

Table 3

Parameters for the Fluidized Bed Reactor

FBR Parameters

Size of reactor	2 m dia. x 2 m high
Gas pressure	0.5 MPa (5 atm)
Gas velocity	0.26 m/s
Particle velocity	0.22 m/s (in lunar gravity)
Particle residence time	9 s
Regolith flow rate	60 kg/s
He-3 yield	13 g/hr
Reactors required	4

Table 4

Parameters for the Hydrogen Diffuser

Tube Material: Palladium Alloy

Tube Dimensions: OD = 1.27 mm; wall = 0.13 mm, length = 24 m

Number of Tubes: 2500

Tube Bundle Dimensions: 0.2 m ID x 24 m length

Operational Temperature: 300°C

Operational Pressure on Tube: ID = 700 kPa (7 atm);
OD = 19 kPa (0.19 atm)

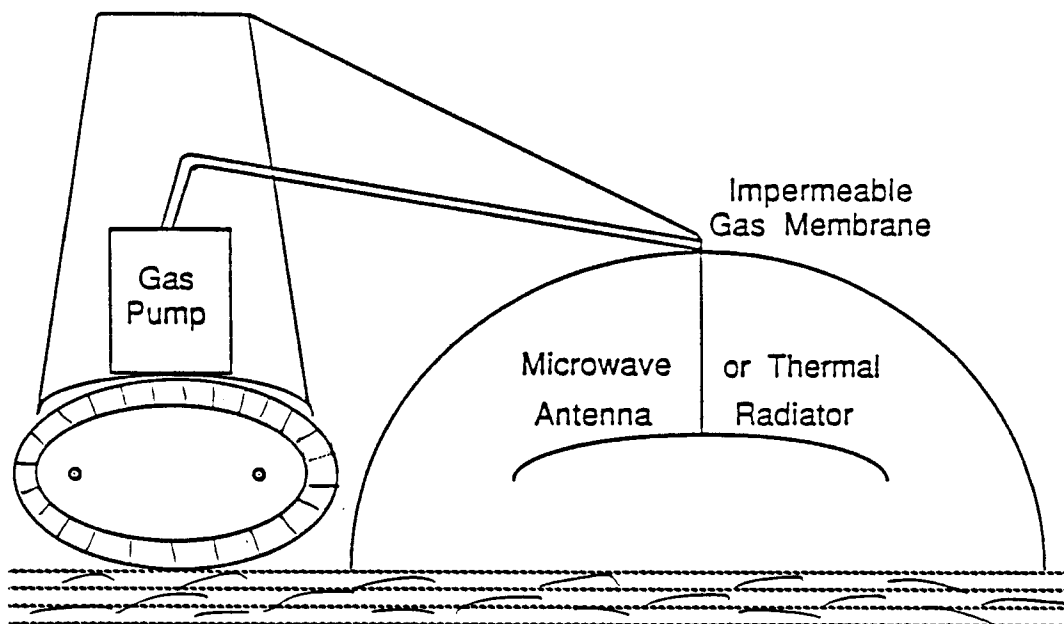
Inlet Gas Composition (Mole %): 72 H₂; 18 He; 10 Other Gases

Exit Gas Composition (Mole %): 5 H₂; 61 He; 34 Other Gases

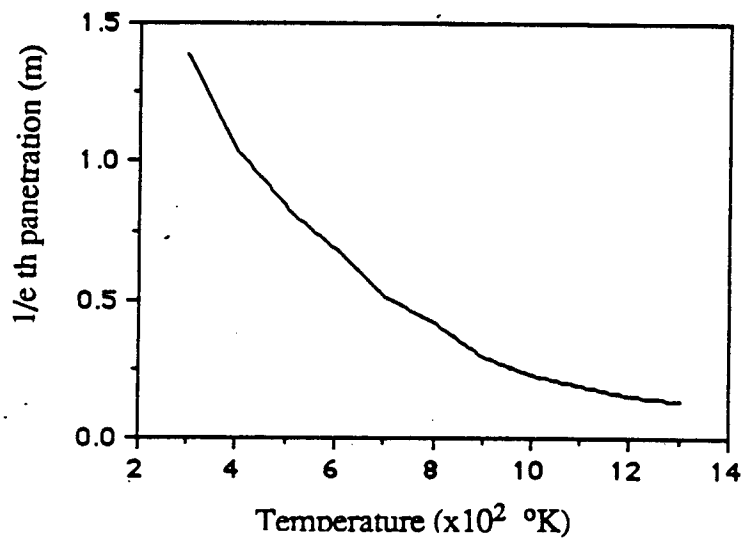
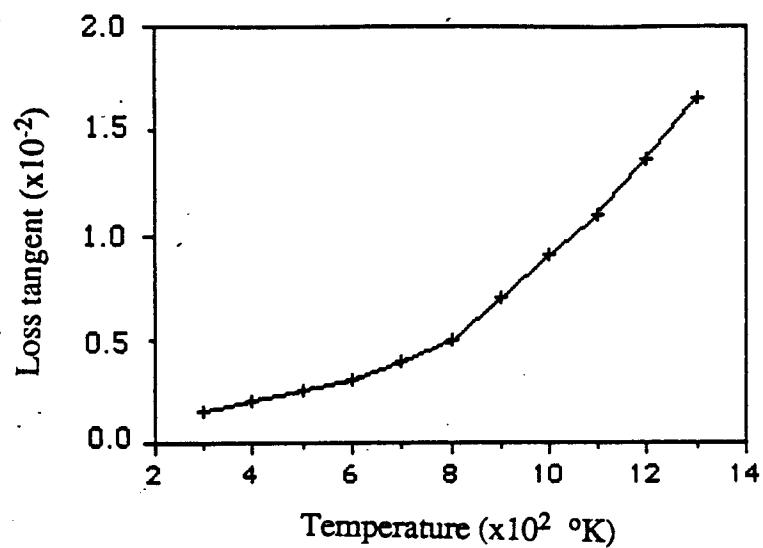
Permeate Gas Flow Rate: 4.2 millimoles H₂/s · tube

TITLE OF FIGURES

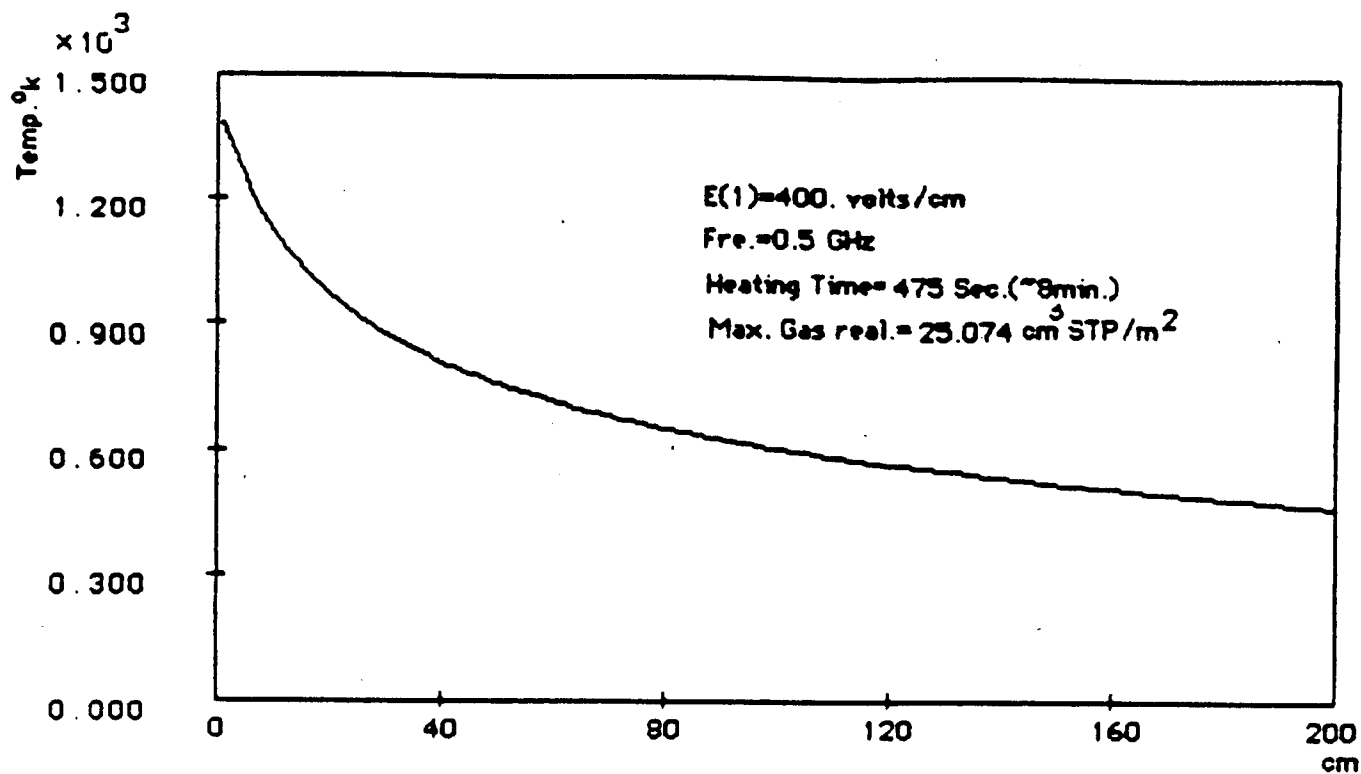
1. Sketch of in situ gas evolution device using either solar energy or microwave radiation.
2. (a) Loss tangent, and (b) Penetration depth as functions of temperature at 2.45 GHz radio-frequency.
3. Temperature profile in the regolith as a function of depth after microwave heating for 475 sec.
4. Gas release rate from the regolith as a function of heating time.
5. Excavation, beneficiation and thermal gas extraction system integration.
6. Conceptualized mobile mining arrangement.
7. Arrangement for the use of solar thermal energy to heat regolith fines.
8. Arrangement for the use of a microwave heating technique to process regolith fines.
9. A fluidized bed technique for heating regolith fines with continuous removal of the evolved gases.



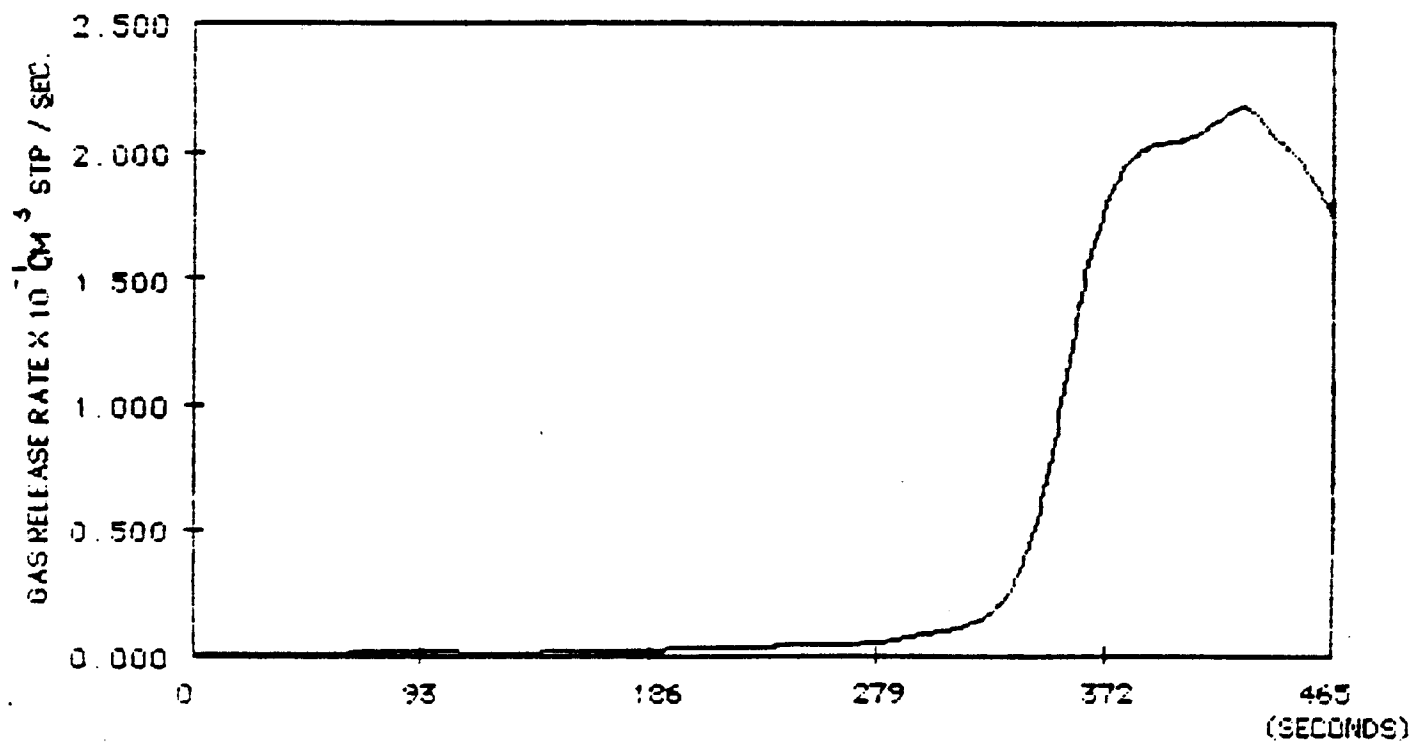
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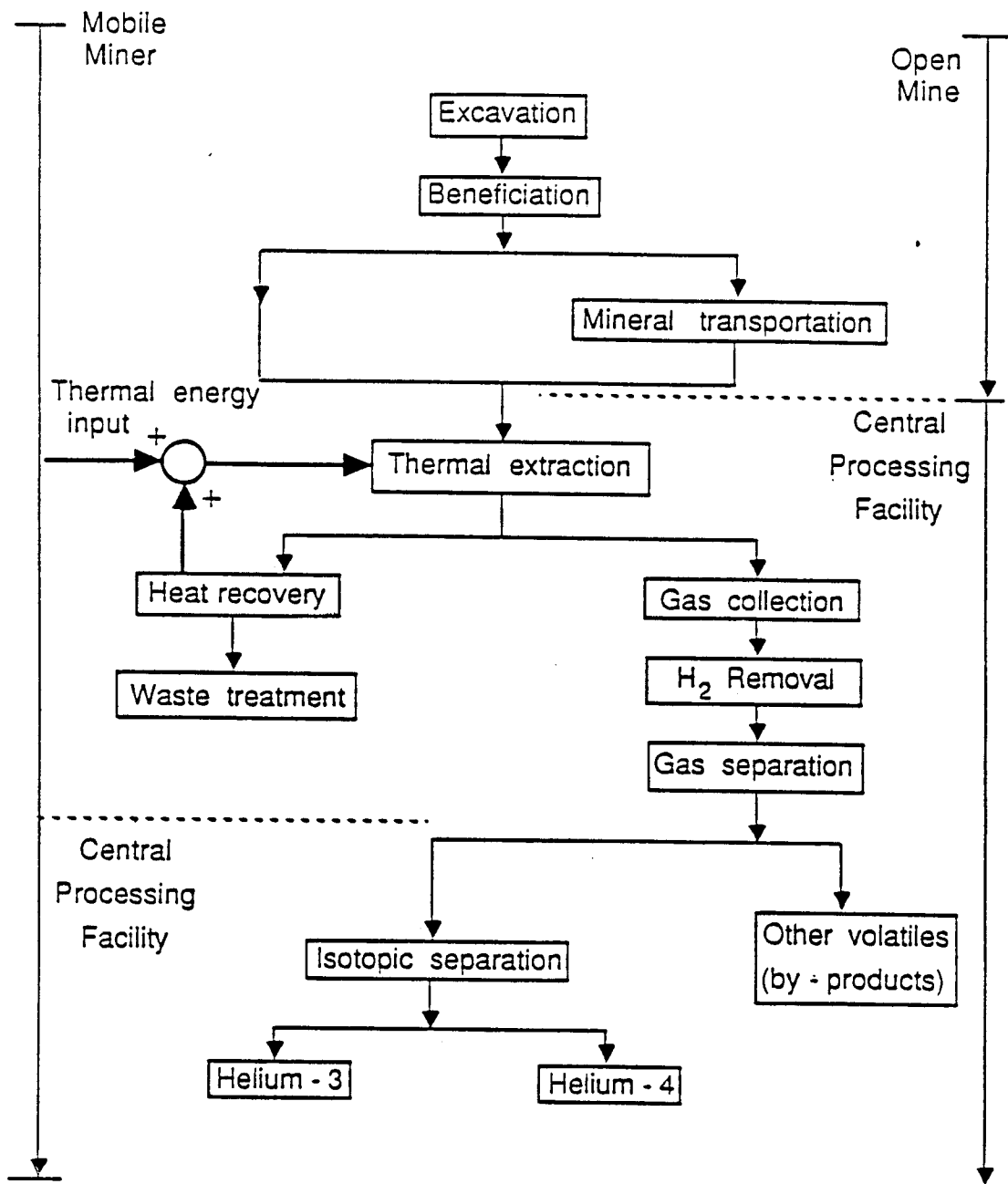
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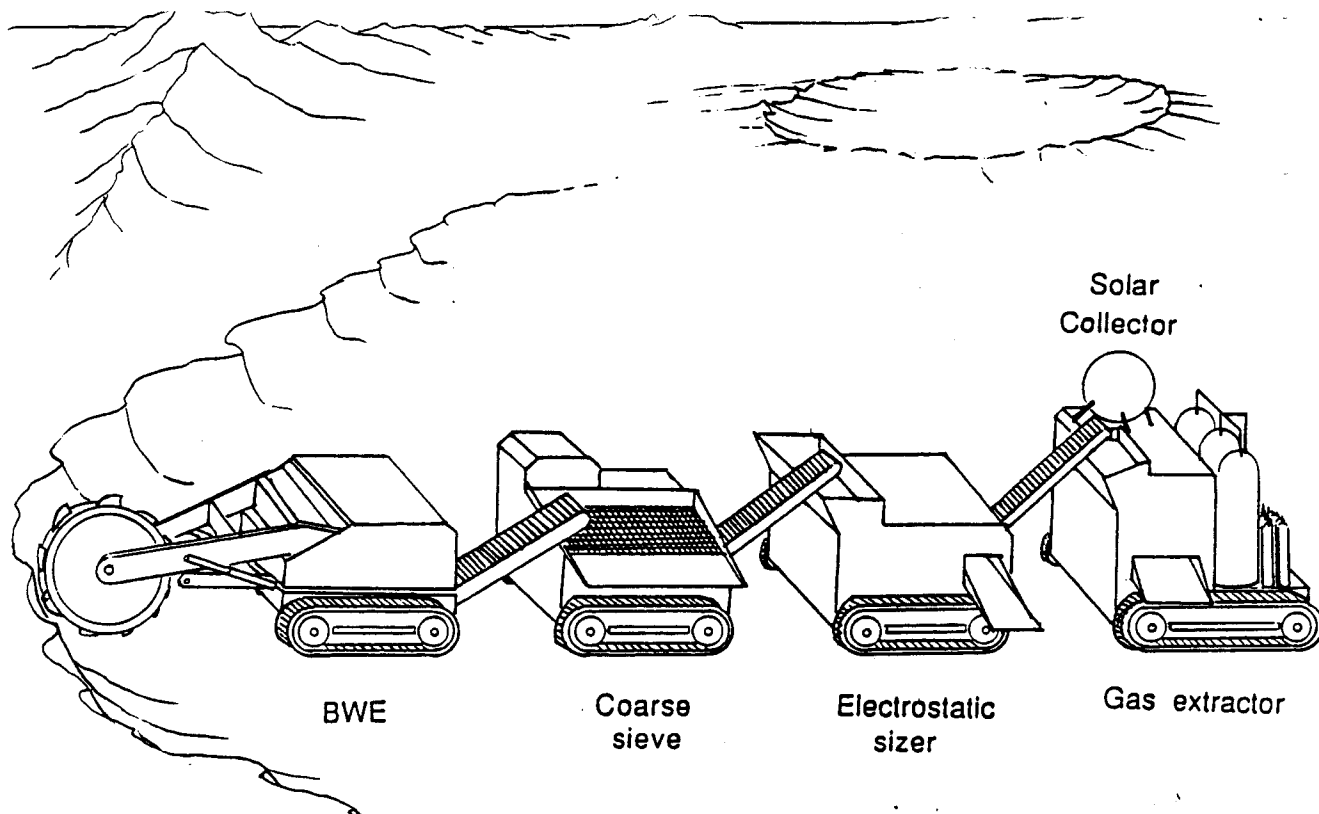
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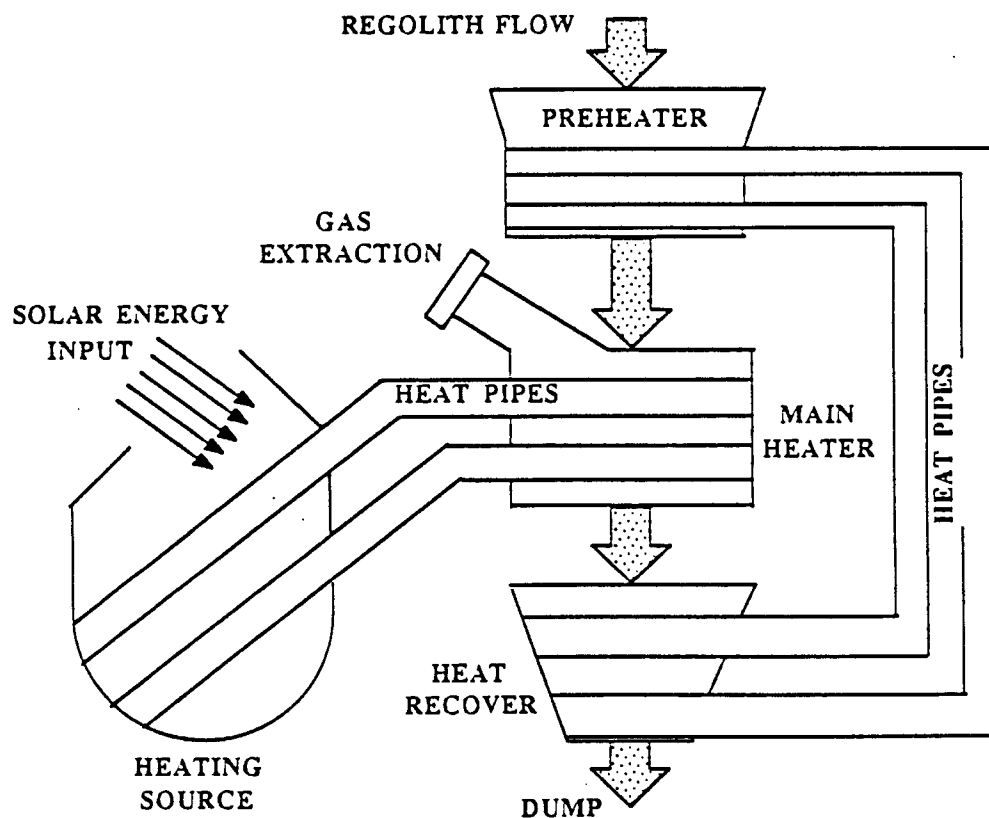
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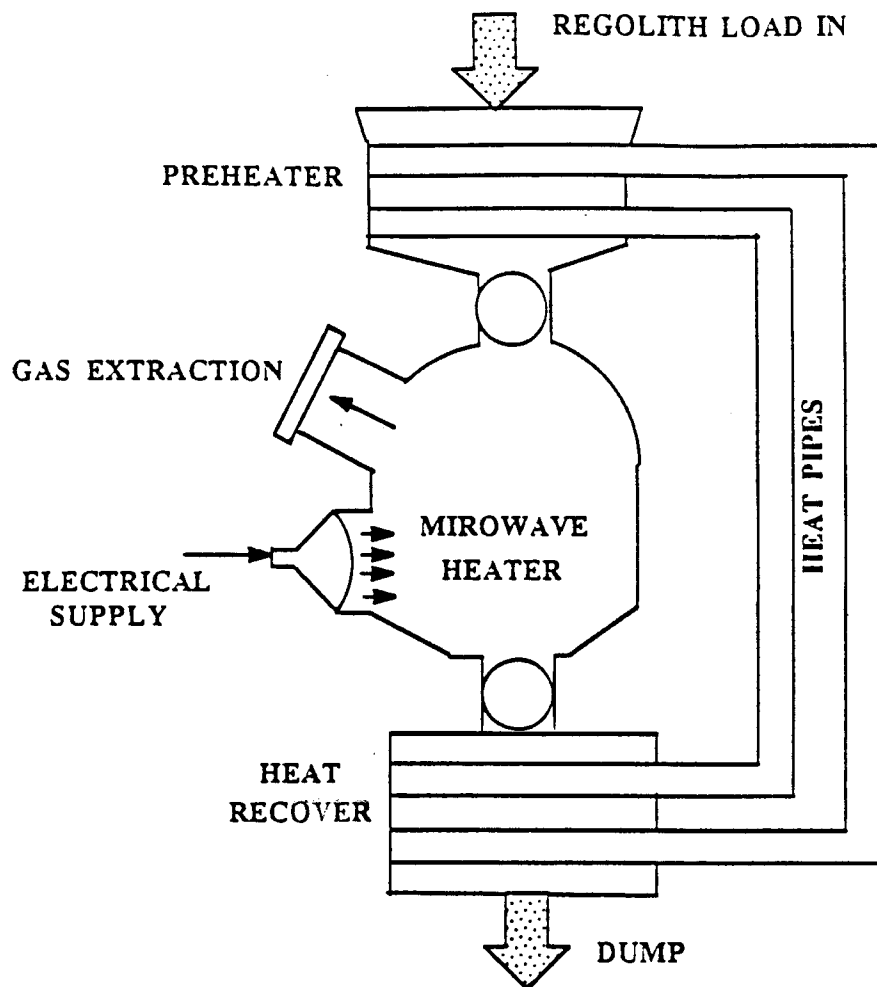
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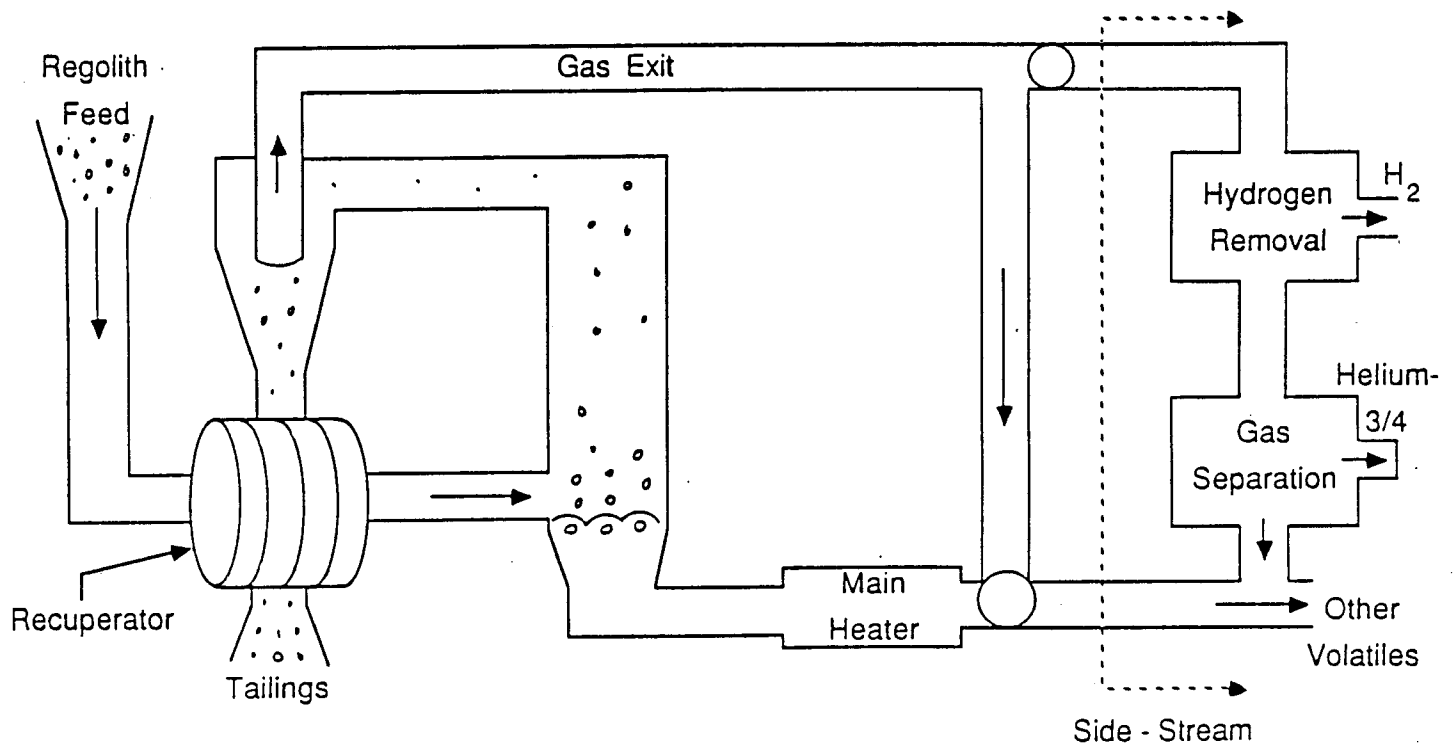
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