

# SYNERGISM OF $^3\text{He}$ ACQUISITION WITH LUNAR BASE EVOLUTION

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*Researchers have discovered that the lunar surface contains a valuable fusion fuel element that is relatively scarce on Earth. This element,  $^3\text{He}$ , originates from the solar wind that has bombarded the surface of the Moon over geologic time. Mining operations to recover this resource would allow the by-product acquisition of hydrogen, water, carbon dioxide, carbon monoxide, methane, and nitrogen from the lunar surface with relatively minimal additional resource investment when compared to the costs to supply these resources from Earth. Two configurations for the  $^3\text{He}$  mining system are discussed, and the impacts of these mining operations on a projected lunar base scenario are assessed. We conclude that the acquisition of  $^3\text{He}$  is feasible with minimal advances in current state-of-the-art technologies and could support a terrestrial nuclear fusion power economy with the lowest hazard risk of any nuclear reaction known. Also, the availability of the by-products of  $^3\text{He}$  acquisition from the Moon could significantly reduce the operational requirements of a lunar base and increase the commercialization potential of the base through consumable resupply of the lunar base itself, other components of the space infrastructure, and other space missions.*

## INTRODUCTION

Great advances in the exploration of space will take place in the twenty-first century. Beginning with a space station in low-Earth orbit and moving toward the settlement of the Moon and Mars, the exploration and development of space will broaden mankind's horizons. The establishment of a permanently manned lunar base would create an excellent stepping stone to future space exploration missions. These advanced missions may support development of a large inexpensive power system on Earth through the evolution of a very attractive fusion reaction involving deuterium and an isotope of helium,  $^3\text{He}$ . The advantages of this reaction vs. fission reactions and conventional D-T fusion include reduced radioactivity due to a reduction of neutrons emitted, improved safety over other fusion reactions and all fission reactions, increased efficiency, and lower electricity costs. Because terrestrial quantities of  $^3\text{He}$  would not support a fusion energy economy, researchers are looking to the Moon as a source of  $^3\text{He}$  (Wittenberg *et al.*, 1986). It has been estimated that the Moon contains approximately 1,000,000 metric tons (MT) of  $^3\text{He}$  from solar wind bombardment over the past 4 by.

Here we show how acquisition of  $^3\text{He}$  affects lunar base development and operation. We summarize a four-phase evolutionary lunar base scenario with initial equipment mass and resupply requirements. Requirements for various  $^3\text{He}$  mining operations are shown, and available by-products are identified. Impacts of mining  $^3\text{He}$  on lunar base development include increases in equipment masses to be delivered to the lunar surface and a reduction of lunar base resupply based on availability of by-products. We conclude that the mining of this valuable fusion fuel element greatly enhances the commercial potential of a lunar base.

## EVOLUTIONARY LUNAR BASE SCENARIOS

To determine requirements for the establishment of a lunar base, various phases of base development must be identified. Subsystems required for base operation must be defined. Mass, power, and resupply requirements for these operations must be determined to address overall transportation requirements and cost of operations. A four-phase evolutionary lunar base scenario was created from previous work on lunar base concepts and from current technology projections (Crabb and Jacobs, 1987a,b). This scenario is used here to assess impacts of integrating  $^3\text{He}$  mining into lunar base development.

The four phases of the evolutionary lunar base scenario include (1) a man-tended science base; (2) a manned science and technology base; (3) a manned science and manufacturing base; and (4) a manned science, manufacturing, and export base. Each phase builds on an evolutionary operating capability. The base's manned capability grows from 4 to 6 crew members to 15 to 20 crew members over a period of 23 years.

The initial lunar base scenario can support 4 to 6 persons for a 10-day mission. Missions performed at this lunar base would be mainly science oriented. Science missions include geology, life sciences/medicine, astronomy, technology testing, and study of energy systems. No provisions for processing lunar regolith for rocket propellant or other resources are provided in this stage of lunar base development.

The next stage of lunar base development would allow for continuous occupancy of the base by four to six persons. General science operations would be expanded to include specific studies of geology, life sciences/medicine, and technology testing. Oxygen would be produced in this stage via chemical processing lunar regolith by hydrogen reduction of ilmenite using Earth-supplied

hydrogen. A small-scale mining operation would be initiated to supply the base with the needed regolith for oxygen production (6.6 MT lunar regolith per 1 MT oxygen).

In the third stage of lunar base development, continuous support for 10 persons is provided. Carbothermal reduction is added to hydrogen reduction to expand regolith processing capability allowing for production of lunar resources beyond oxygen [29.2 MT lunar regolith per 1 MT oxygen + 1 MT silane (SiH<sub>4</sub>) + 0.4 MT silicon for carbothermal reduction]. The additional lunar resources produced can be used for fabrication of structures, solar panels, and various other products useful to the base. Provisions for the manufacture of these types of products must be provided in this stage of base development. Mining operations are expanded to provide the needed additional lunar regolith for manufacturing and production. This expanded mining scenario may include the initial development of a conveyor network to enable acquisition of larger quantities of lunar regolith.

In the fourth stage of the evolutionary lunar base scenario, the base is capable of supporting 15 to 20 persons continuously. To increase the self-sufficiency of the base, a process similar to HF acid leach would be added to the chemical processing facility to obtain aluminum and provide the potential to obtain other elemental resources for structures (8.7 MT lunar regolith per 1.0 MT oxygen + 0.6 MT aluminum). Magma electrolysis is added to obtain iron for structures (132.5 MT lunar regolith per 1.0 MT oxygen + 0.8 MT iron). Shiftable conveyors would be added to the mining scenario to provide the additional regolith needed for manufacturing and production. Shiftable and permanent conveyors could be added as the demand for regolith increases.

**Lunar Base Subsystems**

The required lunar base subsystems are determined from the three major operations to be performed by a lunar base, which include science, manufacturing and production, and infrastructure/support. These operations expand differently as a lunar base scenario evolves. Table 1 summarizes mass delivery requirements for each subsystem of the evolutionary lunar base scenario.

Science missions are an important part of any lunar base scenario. These missions are needed to provide information on lunar geology, life science/medicine, astronomy, technology testing, and the study of energy systems. The science system for these lunar base scenarios was modeled from the current space station laboratory modules (JSC, 1986). In the early stages of lunar base development, one module might support small-scale experiments for many of these science missions. As the base grows, modules dedicated to a specific type of science mission may be added.

The manufacturing and production system is the main contributor to self-sufficiency. While emphasis on this system is low in the early stages of base development, it has the highest priority in an evolved base configuration. Manufacturing and production operations include chemical processing for lunar resources,

fabrication of hardware or structures from lunar and terrestrial materials, and mining operations for acquisition of regolith. Chemical processing may only involve extraction of oxygen from lunar regolith in the early stages of base development. As the base grows, processing for additional lunar resources will be required. Fabrication of hardware or structures will only be required in fairly evolved lunar base scenarios, because larger-scale structures and hardware are required before the additional mining and processing operations become cost effective. Mining operations eventually include surface transport vehicles, permanent and shiftable conveyor systems, and beneficiation systems to remove specific grain-size fractions and to remove specific ores from the regolith.

The lunar base infrastructure consists of habitats, surface transportation, launch/landing facilities (including a mass driver system), maintenance facilities, and power. The infrastructure can be thought of as a base on which all lunar operations are built. It must provide all resources (mainly life support and regolith processing consumables, electrical and thermal energy, and life support for crew members) to support science and manufacturing operations. The power plant within the infrastructure can be thought of as LP&L (Lunar Power and Light) and must provide sufficient power for all community needs.

The lunar base is capable of utilizing lunar resources after initial operating capability is reached for the second phase of development. Initially, production will be centered on acquisition of lunar oxygen. As the base evolves, structural materials would be needed to ease expansion requirements by using lunar-derived materials. Figure 1 shows the production capability of each phase of base development. The results from science activities may not be quantifiable products, but would contribute to advancing knowledge and technologies for future systems to improve operating efficiencies.

**Lunar Base Resupply**

Resupply mass requirements include mass for hardware refurbishment, as well as for consumable replenishment. Resupply requirements have been divided into the three major subsystems. Figure 2 summarizes operational resupply requirements for each lunar base subsystem and for each phase of base development.

Resupply for the science system is partly made up of hardware for refurbishment of laboratory modules, but it is mainly made up of science payloads that are delivered from Earth to conduct scientific experiments on the lunar surface.

TABLE 1. Subsystem mass requirements for the evolutionary lunar base scenario.

Lunar Base Subsystem	Phase of Evolutionary Lunar Base Scenario			
	Surface payload delivered (MT)			
	1	2	3	4
Science	25	125	175	200
Manufacturing & Production	—	12	431	1115
Infrastructure	28	58	133	590

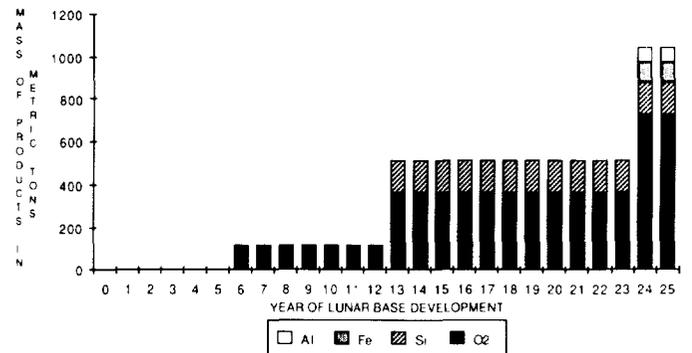


Fig. 1. Annual lunar base production capabilities.

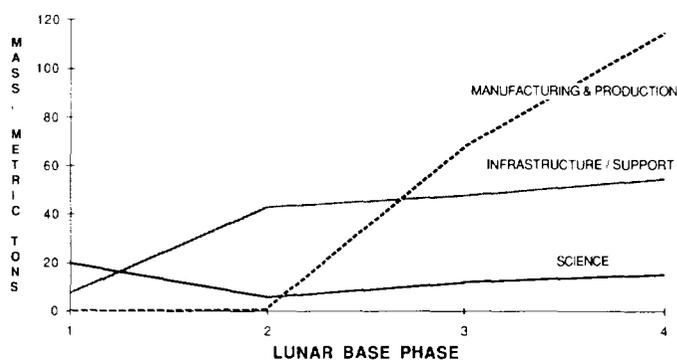


Fig. 2. Lunar base annual resupply masses.

Over 75% of the resupply in the manufacturing and production system is to replenish unrecycled reactants used for processing regolith. Some hardware resupply is required to refurbish failed mining system components. Required resupply for unrecycled reactants/consumables and hardware refurbishment is not assumed to be from a lunar source, although many of the consumables required for regolith processing may be made available from extractions of  $^3\text{He}$  and other solar wind gases (discussed later). The major contributor to resupply requirements for the infrastructure/support system originates from life-support consumables. Water, the largest consumable in the life-support system, may be available in sufficient quantities as a by-product of a  $^3\text{He}$  mining operation.

A major advantage of  $^3\text{He}$  mining at a lunar base is to make quantities of many consumables that would need to be delivered from Earth available from local resources. To identify these benefits, specific quantities of consumable resources required by a lunar base must be identified. Consumable resource requirements can be obtained from analysis of resupply requirements for the manufacturing and production system and the infrastructure/support system. Resupply breakdowns for these lunar base systems can be found in Table 2. These resupply requirements determine transportation requirements for normal lunar base operation without expansion considerations. Acquisitions of  $^3\text{He}$  may increase hardware mass supply requirements but can relieve the requirement for consumables to be transported to the lunar surface from Earth.

TABLE 2. Breakdown of consumable resupply.

Lunar Base Subsystem	Phase of Evolutionary Lunar Base Scenario Resupply payload to surface (kg/yr)			
	1	2	3	4
<b>Process Consumables</b>				
H <sub>2</sub>	—	186	372	558
CH <sub>4</sub>	—	—	60,000	60,000
HF	—	—	—	33,000
<b>Life-Support Consumables</b>				
H <sub>2</sub> O	3,350	1,834	3,668	4,280
O <sub>2</sub>	450	247	493	570
N <sub>2</sub>	250	137	275	323

## LUNAR $^3\text{He}$

Lunar sources of  $^3\text{He}$  were first discovered in 1970 by R. O. Pepin (Pepin *et al.*, 1970). In 1986, a study conducted by scientists at the University of Wisconsin (Wittenberg *et al.*, 1986) estimated the potential  $^3\text{He}$  reserves on the Moon to be one million metric tons. Terrestrial sources of this resource are from the decay of tritium and are estimated at a few hundred kilograms per year. Terrestrial quantities of  $^3\text{He}$  are not sufficient for a large-scale fusion power industry, which would require up to 10 MT of  $^3\text{He}$  per year (Kulcinski *et al.*, 1988). This section defines requirements of a lunar  $^3\text{He}$  mining operation and potential by-products that could be acquired with minimal additional resource requirements.

The advantages of fusion energy using  $^3\text{He}$  are many (Wittenberg *et al.*, 1986; Kulcinski *et al.*, 1988). Approximately 600,000 GJ of energy, or 19 MW<sub>th</sub>, is released upon burning 1 kg of  $^3\text{He}$  with deuterium. Thermal-to-electrical conversion efficiency for the D- $^3\text{He}$  fusion reaction is high, approximately 70%. This would yield an electrical energy content of 11.4 MWy per kg of  $^3\text{He}$ . Lunar  $^3\text{He}$  production levels are estimated to start at approximately 10 kg/yr and would increase to several thousand kilograms annually within 30–40 years of the initiator of lunar  $^3\text{He}$  mining. The impacts on North American energy production are very significant and may prove even more significant on future energy requirements in space.

Lunar  $^3\text{He}$  sources originate from the solar wind that has bombarded the lunar surface over geologic time (approximately 4 b.y.). Analyses of lunar samples returned from the Apollo missions show helium concentrations in lunar mare regolith of about 30 ppm (Williams, 1980). The concentration of  $^3\text{He}$  in the total helium content has been estimated to be about 300 ppm (Pepin *et al.*, 1970). Although the degree of homogeneity of the mare regolith is yet unknown,  $1.11 \times 10^8$  kg of unbeneficiated lunar mare regolith would contain about 1 kg of  $^3\text{He}$ . Because the mare regolith samples collected to date show a high degree of homogeneity, it is assumed that these concentrations are consistent to at least a 3-m depth. Thus, a volume 3 m deep by 25,370 m<sup>2</sup> would contain 1 kg of  $^3\text{He}$ . Although these estimates are based on lunar sample analyses, further sampling would be required to provide a stronger basis for estimates of  $^3\text{He}$  concentration in specific sites on the lunar surface and at various depths in the mare regolith.

Because the heat capacity of lunar regolith is so low (0.784 J/g K), regolith should be beneficiated as much as possible to reduce the quantities that must be heated. Because the solar wind is implanted near the surface of each grain in the regolith, smaller grains, which have a higher surface area-to-volume ratio, appear to have higher concentrations of implanted solar wind gases. Thus, beneficiation to remove larger grains can yield reductions of lunar regolith that must be heated by almost 50% while maintaining acquisition of 70–80% of the total  $^3\text{He}$  available.

### Requirements for $^3\text{He}$ Acquisition

Helium-3 and other solar wind gas constituents can be removed from lunar regolith through heating. Regolith is collected, beneficiated to a specific grain size fraction, and heated. After heating to approximately 700°C, many of the adsorbed solar wind gases are released. The processing temperature was chosen to optimize the release of helium without release of implanted sulfur, which begins at approximately 750°C (Williams, 1980). Further processing of these gases would remove  $^3\text{He}$  from the solar wind

gas mixture. Alternative technologies for the various systems required for lunar <sup>3</sup>He acquisition are included in Fig. 3.

Two scenarios have been conceptualized for the mining of lunar <sup>3</sup>He. The first envisions a mobile miner that would collect the regolith, remove larger grains, and provide thermal energy to release the solar wind gases. The gases would then be collected and stored in storage vessels that would be transported to a central facility for further processing. The second scenario is a centralized mining concept where sufficient quantities of bulk lunar regolith would be collected and placed on a conveyor system that would transport the regolith to a central facility for processing. A summary of mass and power requirements for each of the <sup>3</sup>He mining scenarios is provided in Tables 3 and 4, respectively.

Both <sup>3</sup>He mining scenarios are based on an annual <sup>3</sup>He production rate of 1 MT. Thermal energy requirements for solar wind gas evolution are based on the heat capacity of lunar regolith and assume 85% heat recovery. The major difference in the solar wind gas extraction subsystem designs among the alternatives is the source of thermal energy. The mobile miner uses a solar collector-concentrator of smaller thermal output, while the centralized system uses the high thermal energy output of a nuclear SP-100 reactor. It should be noted that the requirements for the centralized mining concept depend upon movement of the regolith collection subsystem from a mined area to a different unmined area. Surface preparation requirements for this transportation are not included in either concept. Also, storage requirements for resources obtained following selective condensation are not included in either mining concept.

**Mobile vs. Centralized Mining Concepts**

To evaluate and compare each mining concept, advantages and disadvantages of each concept must be identified; they can be found in Tables 5 and 6.

When studying the advantages and disadvantages of each concept, many tradeoffs become apparent. Because the solar wind gas extraction system in the centralized concept is in one central location, a nuclear reactor could be used to deliver required thermal power, enabling gas extraction to occur in the lunar day

and night. Implementing the use of nuclear reactors on the mobile miner would create many maintenance and safety problems because the systems would be more difficult to closely monitor. An advantage of the mobile miner is that large areas may be easily mined at any distance from the central base. As <sup>3</sup>He production requirements increase, and as <sup>3</sup>He is removed from regolith near the central base, mining operations must extend to distances far from the central base. Because movement of excavation systems

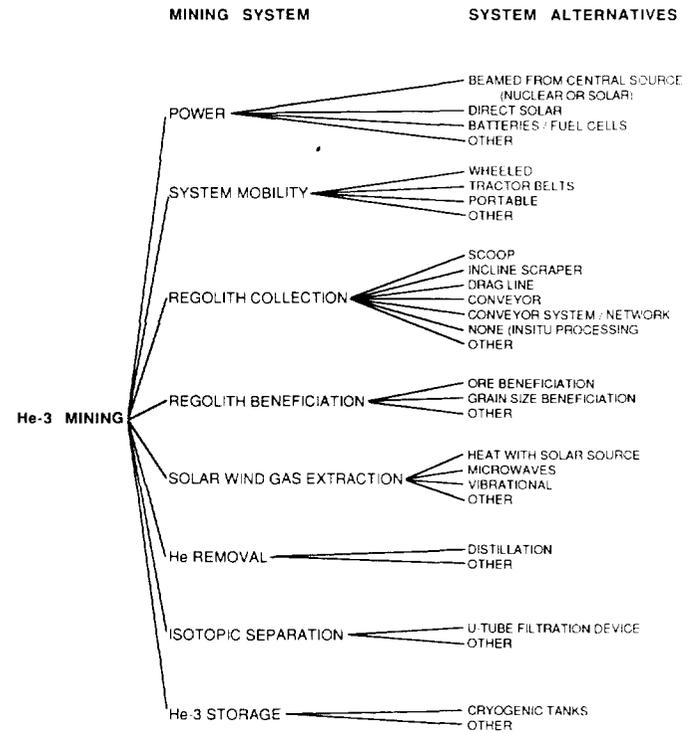


Fig. 3. Helium-3 mining system alternatives.

TABLE 3. Mass summary for <sup>3</sup>He mining scenarios.

Lunar <sup>3</sup> He Mining Concept	Regolith Collection	Regolith Beneficiation	Solar Wind Gas Extraction	Selective Condensation	Additional
<b>Mobile Miner - 1000 kg <sup>3</sup>He/yr</b>					
Bucket Wheel	152				
Internal Regolith Transport	49				
Grain Size Separator		20			
Thermal Power from Direct Solar			242		
Selective Condensation Unit				180	
Gas Storage Vessels					67
Gas Storage Vessel Transport Vehicle					18
Miner Mobility System & Body					83
<b>Totals</b>	<b>201</b>	<b>20</b>	<b>242</b>	<b>180</b>	<b>168</b>
<b>Centralized Concept - 1000 kg <sup>3</sup>He/yr</b>					
Bucket Wheel Excavators	200				
Conveyor System	645				
Grain Size Separator		20			
Nuclear Thermal Power			10		
Selective Condensation Unit				180	
<b>Totals</b>	<b>845</b>	<b>20</b>	<b>10</b>	<b>180</b>	

All masses are in metric tons. Total mass for mobile miner = 811 MT. Total mass for centralized concept = 1055 MT.

TABLE 4. Power summary for  $^3\text{He}$  mining scenarios.

Lunar $^3\text{He}$ Mining Concept	Regolith Collection	Regolith Beneficiation	Solar Wind Gas Extraction	Selective Condensation	Additional
Mobile Miner - 1000 kg $^3\text{He}/\text{yr}$					
Bucket Wheel	910				
Internal Regolith Transport	152				
Grain Size Separator		150			
Thermal Power from Direct Solar			4848		
Selective Condensation Unit				5450	
Gas Storage Vessels					—
Gas Storage Vessel Transport Vehicle					242
Miner Mobility System & Body					1110
Totals	1062	150	4848	5450	1352
Centralized Concept - 1000 kg $^3\text{He}/\text{yr}$					
Bucket Wheel Excavators	870				
Conveyor System	6105				
Grain Size Separator		150			
Nuclear Thermal Power			5675		
Selective Condensation Unit				5450	
Totals	6975	150	5675	5450	

All power values are in kilowatts. Total power for mobile miner = 12,862 kW. Total power for centralized concept = 18,250 kW.

TABLE 5. Advantages/disadvantages of the mobile miner.

Advantages	Disadvantages
Minimal alteration of lunar surface	Predicted $^3\text{He}$ demands would require over 100 mobile miner systems by the year 2050 Operation only during the lunar day reduces potential $^3\text{He}$ production rates Because maintenance of several mobile miners, some many kilometers from the central base, is very resource intensive, systems within the miner, must have minimal complexity (or maximum reliability)
High degree of automation possible	
No tear-down/set-up requirements for mining different areas far from central base	
Multiple miners can cover a very large surface area	
Operates fairly independently of other lunar base operations	
Has a lower mass per kg $^3\text{He}$ obtained than centralized concept	

TABLE 6. Advantages/disadvantages of the centralized mining concept.

Advantages	Disadvantages
Much of the hardware required could be utilized by a lunar base for oxygen production and other mining activities	Has a higher yield than mobile Moving the mining operation to another location would be very resource intensive Because more systems are located in the central facility than with the mobile miner, there will be more significant impacts on the lunar base infrastructure Since large quantities of regolith need to be delivered to the central facility for processing, problems of accumulation of processed regolith stockpiles may arise
Operation during the lunar day and night	
Since many of the gas removal/collection systems are centrally located, servicing/maintenance is less costly than in mobile systems and may be designed with higher levels of complexity using SOA technologies	

in the centralized concept would be very costly, the mobile miner has a greater potential to meet long-range  $^3\text{He}$  production requirements.

A major advantage of the centralized mining concept over the mobile miner is commonality of hardware. The excavation and conveyor systems required by the centralized concept can be used to collect regolith for oxygen and other lunar resource processing schemes. This would reduce the mass delivery requirements for the manufacturing and production lunar base system. The excavation systems of the base and the centralized  $^3\text{He}$  mining concept are identical. The entire conveyor system mass of the fourth phase of the evolutionary lunar base scenarios could also be provided by the centralized concept. Considerations of shared hardware reduces mass delivery requirements for the manufacturing and production system by 8% for the centralized  $^3\text{He}$  mining concept.

## IMPACTS OF $^3\text{He}$ ACQUISITION ON LUNAR BASE DEVELOPMENT

To determine the impacts of mining lunar  $^3\text{He}$ , we must first identify the advantages and disadvantages of each mining concept. We must then consider how the implementation of each mining concept affects the mass delivery requirements of the lunar base. The delivery of mining hardware generally increases mass delivery requirements, but the use of by-products made available by such mining would reduce the mass delivery requirements and increase the efficiency of the hydrogen/oxygen-based Earth-Moon transportation systems. The value of  $^3\text{He}$  and the significant quantities of the by-products available enhance the commercialization potential of the lunar base.

**Available By-products**

Many of the other constituents of the solar wind gas mixture are valuable to lunar base operations and are obtained with minimal additional resource requirements through "synergistic" processing. Table 7 lists these available by-products and the quantities available upon heating lunar regolith to 700°C. The markets for these by-products is discussed later.

**Reduction in Lunar Base Logistics**

Figure 4 shows the overall mass delivery requirement for the evolutionary lunar base scenarios without <sup>3</sup>He mining. The impacts of each <sup>3</sup>He mining concept on a lunar base can be determined by comparing the mass delivery requirements of the lunar base without <sup>3</sup>He mining to a lunar base implementing a <sup>3</sup>He acquisition scenario.

Figure 2 showed resupply requirements for the manufacturing and production system and the infrastructure. Some of the consumables that require resupply may be provided from by-products of <sup>3</sup>He acquisition. Table 8 shows the lunar base consumable requirements and the quantities available as by-products of <sup>3</sup>He mining scenarios.

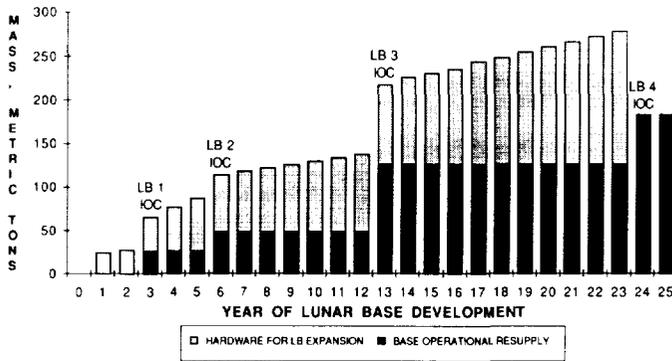


Fig. 4. Overall mass delivery requirements for the evolutionary lunar base scenarios.

It is important to note the quantity of water shown here may be high because of potential water contamination in the Apollo samples (used to derive this data) when returned to and analyzed on Earth. Also, there would be additional requirements to purify the water obtained. Oxygen may be obtained from further processing of CO and CO<sub>2</sub>. The effect of supplying lunar base consumables from <sup>3</sup>He mining on the overall lunar base scenario development can be seen in Fig. 5. To accurately compare the two <sup>3</sup>He mining scenarios, similar criteria must be applied. Both scenarios have similar <sup>3</sup>He production rates for each year. Both mining concepts assume mass delivery increases of 25% from one year to the next. Both concepts are capable of obtaining 1000 kg of lunar <sup>3</sup>He per year by the initiation of the fourth phase of the lunar base (year 23).

The mass delivery for a lunar base with <sup>3</sup>He mining is actually less than the baseline lunar base (without <sup>3</sup>He mining) for <sup>3</sup>He acquisition rates of 100-300 kg/yr and a lunar base with a permanent crew of 10. This occurs because the <sup>3</sup>He mining operation can resupply the lunar base with consumables for life support, atmosphere maintenance, and manufacturing and production processes. In addition to resupplying consumables, the centralized concept delivers all the excavation equipment needed for

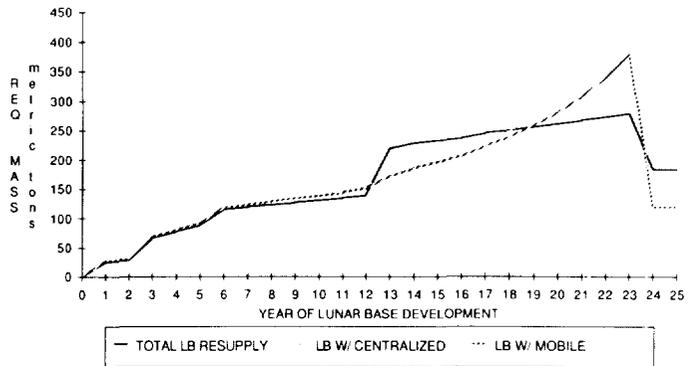


Fig. 5. Base resupply with and without <sup>3</sup>He mining.

TABLE 7. Gas release predicted from heating mare regolith to 700°C.

Operation	Regolith (MT)	Concentration, ppm (g/MT)				
		He-3	He-4	H <sub>2</sub>	Carbon	Nitrogen
Surface Mining	1	9 × 10 <sup>-3</sup> 90%	30 90%	50-60 90%	142-226 90%	102-153 90%
Beneficiate <50 μm	0.45	8.1 × 10 <sup>-3</sup>	27	50	166	115
Heat to 700°C	0.45 (beneficiated)	86% 7 × 10 <sup>-3</sup>	81% 22	85% 43 (H <sub>2</sub> ) 23 (H <sub>2</sub> O)	3.5% 2% 5% 13.5 (CO) 12 (CO <sub>2</sub> 11 (CH <sub>4</sub> ))	3.2% 4
Per 1 kg He-3	1.37 × 10 <sup>5</sup> (mined)	1 kg	3.1 MT	6.1 MT (H <sub>2</sub> ) 3.3 MT (H <sub>2</sub> O)	1.9 MT (CO) 1.7 MT (CO <sub>2</sub> ) 1.6 MT (CH <sub>4</sub> )	0.5 MT
Minor gases: neon 0.3 MT; argon 0.2 MT						
Per Tonne Regolith into Heater	1 (beneficiated)	0.016 g	49 g	96 g (H <sub>2</sub> ) 78 g (H <sub>2</sub> O)	30 g (CO) 27 g (CO <sub>2</sub> ) 24 g (CH <sub>4</sub> )	9 g
Minor gases: neon 4.8 g; argon 3.2 g						

TABLE 8. Additional resources available from  $^3\text{He}$  acquisition for lunar base support.

Resource	Application to Lunar Base	Estimated Requirement for 15-20-Person Base* (kg/yr)	kg/kg $^3\text{He}$
H <sub>2</sub> O	Life Support Consumable	4,280	3300
O <sub>2</sub>	Life Support Consumable	570	2322
N <sub>2</sub>	Life Support Consumable	323	500
H <sub>2</sub>	Lunar Resource Process Consumable	558	6100
CH <sub>4</sub>	Lunar Resource Process Consumable	60,000	1600

\* Lunar base includes full-scale mining operations, science facilities, semiclosed life support system, and MMW nuclear power source.

manufacturing and production operations in the fourth phase of the lunar base. The fourth phase is reached by the twenty-third year of base development, but hardware delivery for this phase is begun at year 13. After year 23, no expansion of operations is assumed, and the lunar bases with the  $^3\text{He}$  mining operations operate with reduced logistic requirements compared to the nonmining option. Also, the effect of  $^3\text{He}$  mining will be even greater when lunar-derived sources of both hydrogen and oxygen have been realized in the space transportation system design. The total Earth launch mass per pound of payload to the Moon may be reduced by 50% when this source of propellants becomes available (Crabb et al., 1987).

Another measure of the effects of lunar base concepts on the space infrastructure is the amount of mass needed to be launched from Earth to deliver all payloads, transport vehicles, and other support needs to the Moon. To determine Earth launch mass, the lunar mass delivery curves (Fig. 5) are used to generate an annual mission model. The mission model is then manifested on orbital and launch/landing vehicles that are conceptually defined using ASTROSIZ, a computer model used to design conceptual vehicles from propulsion system characteristics, aerobrakes, landing systems, thrust structures, and other factors. Total propellant and vehicle requirements are accounted with various sources of propellants considered. The mission model, with space transportation vehicle descriptions (including OTV and lander design), is entered into ASTROFEST, a computer code that uses the mission model and vehicle descriptions to determine quantities of Earth propellants, lunar propellants, and overall Earth launch mass required. Here the vehicles are sized to account for availability of lunar oxygen and lunar hydrogen if they are available. From these data, the total support of lunar base concepts may be evaluated based on the total Earth launch mass including payloads, propellants, and vehicles. The results are shown in Fig. 6.

The results of the Earth launch mass analysis show that  $^3\text{He}$  acquisition can reduce the Earth launch burden of establishing a lunar base through the provision of consumable gases and propellants. Without  $^3\text{He}$  acquisition, O<sub>2</sub> is the most likely propellant candidate from lunar sources. With  $^3\text{He}$  acquisition, H<sub>2</sub> can also be obtained as a by-product and used for propellant. Using H<sub>2</sub> and O<sub>2</sub> from lunar sources provides enough credits to the lunar base with  $^3\text{He}$  acquisition to make this scenario less resource intensive than the baseline lunar base without  $^3\text{He}$  acquisition.

#### Increase in Lunar Base Commercialization Potential

In addition to reducing resupply requirements,  $^3\text{He}$  acquisition would enhance the commercialization potential of the lunar base in several ways. The  $^3\text{He}$  could be used to provide large quantities

of power to a lunar base or for the support of other space exploration missions. The by-products could be used by the entire space community. Quantities of  $^3\text{He}$  could also be shipped to Earth to support the nuclear energy economy of the twenty-first century with the safest form of nuclear power known. These applications of  $^3\text{He}$  are discussed in the following sections.

**Space markets for  $^3\text{He}$  and its by-products.** As fusion technology advances, many new applications of  $^3\text{He}$  will be determined. Researchers are already investigating fusion-powered space transportation vehicles. In addition to transportation, quantities of  $^3\text{He}$  could provide sufficient power to conduct tasks that would require large amounts of power. A central power plant on the lunar surface operating on a D- $^3\text{He}$  fusion cycle could beam sufficient energy via microwaves to run a space station in low lunar orbit. This power plant could also beam energy to other locations on the lunar surface using a network of surface and/or orbital reflectors, thus extending the lunar base's range of operation. This energy could also be used to establish and operate other base camps.

A more immediate market that  $^3\text{He}$  acquisition opens up is the availability of the by-products of  $^3\text{He}$  acquisition. By the tenth year of base development, excess quantities of  $^3\text{He}$  acquisition by-products could be made available for the support of other space activities. These activities include (1) resupplying the space station with life-support and atmosphere-maintenance consumables at a much lower cost than having supplies delivered from Earth, and (2) providing needed resources for a lunar refuel/resupply station for support of other space exploration missions. Figure 7 shows the quantities of by-products that could be made available for uses other than the support of a lunar base. Many other applications of the resources  $^3\text{He}$  acquisition makes available

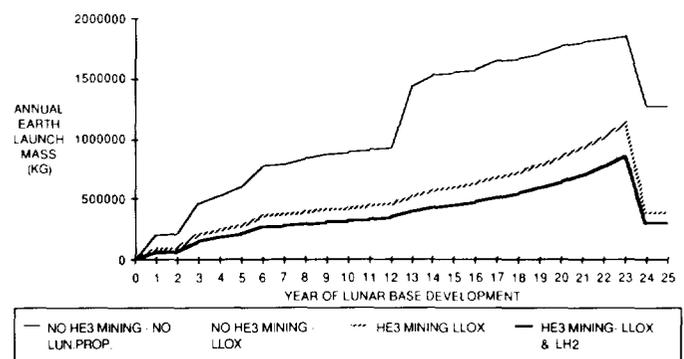


Fig. 6. Total Earth launch mass required for establishment of a lunar base with and without  $^3\text{He}$  mining.

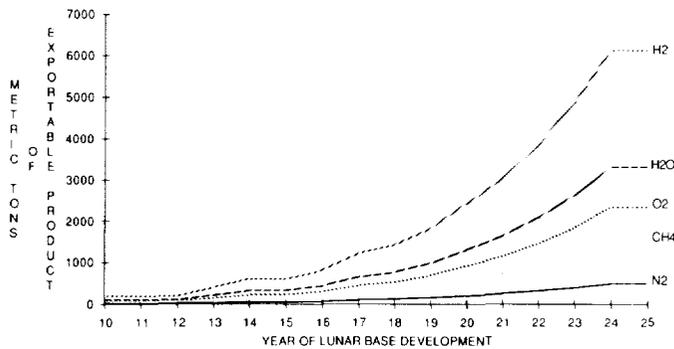


Fig. 7. Annual production of exportable resources from lunar  $^3\text{He}$  acquisition by-products.

may be discovered as human presence in space grows. The availability of these resources significantly enhances the feasibility of many space exploration missions.

**Terrestrial market for  $^3\text{He}$  as a fusion fuel.** As the twenty-first century approaches and fossil fuel supplies diminish, Earth's economy will require much greater amounts of power and energy. Nuclear power seems to be an answer to the problem, but the safety hazards associated with fission reactors has sparked sufficient public concern to hold up development of more nuclear power plants. Nuclear fusion has significantly lower safety risks, and the D- $^3\text{He}$  cycle has the lowest safety risk factor of any of the known fusion cycles. Although terrestrial quantities of  $^3\text{He}$  are not sufficient to support large-scale D- $^3\text{He}$  fusion power development, lunar  $^3\text{He}$  is abundant enough to support large-scale fusion power on Earth and may provide a strong impetus to return to the Moon on a commercial and cost-effective basis.

## SUMMARY AND CONCLUSION

We have shown the value of  $^3\text{He}$ , a resource scarce on Earth but relatively abundant on the Moon. An evolutionary lunar base scenario was presented, and impacts of two  $^3\text{He}$  acquisition concepts on this base were determined. A centralized  $^3\text{He}$  mining concept, in which regolith is excavated and returned to a central facility where the  $^3\text{He}$  is removed, has a more significant impact on the lunar base than the mobile miner concept, in which solar wind gases are extracted from lunar regolith, and the gas storage

vessels are returned to the central facility for further processing. The availability of  $^3\text{He}$  acquisition by-products reduces the operating requirements of a lunar base and provides the base with greater potential for commercialization by making these by-products available for the support of other space missions. Finally, lunar  $^3\text{He}$  could support a terrestrial nuclear power economy with the lowest safety risk of any nuclear reaction known. We conclude that  $^3\text{He}$  acquisition enhances the feasibility of establishing a permanently inhabited lunar base in the early part of the twenty-first century.

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