

**A REVIEW OF HELIUM-3 RESOURCES AND
ACQUISITION FOR USE AS FUSION FUEL**

WCSAR-TR-AR3-9107-1

Technical Report



**Wisconsin Center for
Space Automation and Robotics**



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the Commercial Development of Space**

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Abstract

A combination of man-made and natural resources on earth could provide sufficient ^3He fuel for the technological development of D- ^3He fusion reactors. Helium exists in natural gas wells; however, at the present rate of natural gas usage this resource would provide < 5 kg/yr of ^3He . The radioactive decay of ^3H produced in fission production reactors could yield 110 kg of ^3He by the year 2000 if it were retained. Apparently, large amounts of ^3He exist within the earth's mantle but it is inaccessible.

A significant quantity of ^3He exists on the moon which could be imported to supply a fusion power industry on earth for hundreds of years. The solar wind has deposited more than a million tonnes of ^3He in the fine regolith which covers the surface of the moon. The presence of this solar wind gas was confirmed by analyses of the lunar regolith samples brought to earth. A strong correlation is noted between the He retained and the TiO_2 content of the regolith; consequently, remote sensing data showing high-Ti-bearing soils in the lunar maria areas have been used to locate potentially rich sites for He extraction. Surface photographs of Mare Tranquillitatis have shown that nearly 50% of this Mare may be minable and capable of supplying $\sim 10,000$ tonnes of ^3He . A mobile mining vehicle is proposed for use in the excavation of the soil and the release of the He, and other solar wind gases. The evolved gases would be purified by a combination of permeators and cryogenic techniques to provide a rich resource of H_2 , He, CO_2 , H_2O and N_2 , followed by He isotopic separation systems. The energy and financial payback from those operations are substantial when this fuel is utilized in a D- ^3He fusion reactor located on earth. The implementation of this mining operation would have minimal impact upon the lunar environment. Several legal regimes insure that such a lunar enterprise can be implemented without severely disrupting international order.

1. Introduction

The need for increased electrical power generation in the 21st century has been well-documented. For instance, during 1990 the electrical power sales in the U.S.A. were 2706 billion kilowatt hours (kWeh), an average of ~ 11 MWeh/person-yr [1] for the nearly 250 million citizens. The demand for electrical power in the U.S.A. continued to increase in 1990 at a rate of 2.3%/yr while the total use of all fuels increased only 0.1%. This increasing demand for electrical power over other energy systems is typical of the developed countries while its use in the lesser developed countries is small. Demographic predictions indicate that the world's population will swell to 10-12 billion persons in the 2050-2060 time frame, chiefly in the lesser developed countries. The demand for electrical power in these countries will increase rapidly as they become industrialized [2]. It is reasonable, therefore, to speculate that the average use of electrical power could be 5 MWeh/person per year by the year 2050. When this demand is coupled with the expected world's population, the total power demand could be 50×10^{15} Weh/yr or ~ 6 TWe·yr/yr.

The question of how this electrical power demand will be satisfied without further degradation of the environment requires careful study while there is still time to make a choice. Some fossil fuels will continue to be used, but the three less polluting energy conversion technologies, namely solar power, nuclear fission and fusion are expected to supply the majority of the load. Because of the diurnal solar cycle on earth, some form of extraterrestrial solar power system will need to be developed [2]. The choice between nuclear fission or fusion will probably hinge upon the public's perception as to which system is the safest and has the least environmental impact.

In order for nuclear fusion to be considered in the 21st century as an electric power source, a sustained and reliable nuclear fusion reactor must be developed and demonstrated with close attention to the factors of public safety and environmental impact. The implementation of the D-³He fusion fuel cycle should be able to meet these public goals because

it has no radioactive fuel or fusion products [3]. Some neutrons and radioactive tritium are produced by side-reactions in the reactor but they can perhaps be minimized by adjusting the fuel mixtures and utilizing polarized fuel. The development of D- ^3He fusion technologies required to meet these goals and still provide competitively priced electrical power is being considered in several studies [4, 5] based upon the magnetically confined tokamak configuration.

The objective of this paper is to show that the earth-based resources of ^3He are sufficient to supply all the fuel required for the research and development of the experimental reactors. Additionally, as nearby extraterrestrial resources are exploited in the early 21st century, the ^3He available will be sufficient to contribute to the earth's electrical generating capacity for several centuries.

This review is divided into four categories, namely (1) the cosmological synthesis of ^3He ; (2) the earth's terrestrial resources of ^3He , both man-made and natural; (3) the lunar and other planetary resources; and (4) the techniques considered to recover these extraterrestrial ^3He resources economically with regard to environmentally sound and legally justified criteria.

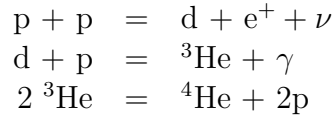
2. Cosmological Synthesis of Helium and Its Isotopic Ratio

The present inventory of ^3He in the universe is ascribed to three phenomena, namely (1) nuclear synthesis during primordial creation, (2) nucleosynthesis in the stars, and (3) cosmic particles bombarding planetary atmospheres.

The “Big-Bang” hypothesis for the creation of the present universe ~ 15 billion years ago postulates that a small, highly compact core of elementary, subatomic particles which were held together by “gluons” began to explode. As this milieu began to expand the elementary particles coalesced into protons and neutrons. Further expansion cooled the photon energy to < 2.45 MeV which permitted the formation of deuterium. Binary deuteron and deuteron-proton reactions were initiated leading to the formation of ^3He , ^4He , and

^3H , which subsequently decayed to ^3He . These reactions ceased after approximately 10 minutes, creating the primordial abundances [6] of ^1H , ^2H , ^3He and ^4He and ^7Li . Computer simulations of such a postulated event are in agreement with the astrophysical measurements and indicate the primordial $^3\text{He}/^4\text{He}$ atomic ratio was $\sim 140 \times 10^{-6}$.

After several billion years, the expanding cloud of primordial matter began to coalesce into clumps forming galaxies with thousands of individual clouds the size of which deflated as gravitational forces became dominant. As the density and temperature of these clouds increased, nucleosynthesis was initiated in these stars by the principal fusion reactions [7],



where e^+ is a positron, ν a neutrino, and γ a gamma ray.

Our sun is relatively young, 4.5 billion yrs old; consequently, it was formed from interstellar material which included not only the primordial gases but also, the entire suite of chemical elements which had been formed in previous stars which died by explosions and scattered these elements throughout the galaxy. The composition of the sun is determined by spectrographic measurements of the photosphere and also, by the measurements of the ionized particles emanating from the sun by the continuous solar wind and intermittent solar flares [8]. The solar wind is due to the open-geomagnetic flux lines which radiate from the sun. Gases in the sun's atmosphere are heated to very high temperature forming ions which are entrapped on the magnetic flux lines and travel outward throughout the solar system. The solar wind composition is principally protium, but usually contains $\sim 4\%$ He, traveling at a velocity of ~ 450 km/s with a flux of $\sim 6 \times 10^{10}$ ions/ $\text{m}^2 \cdot \text{s}$. This He has an unusually high $^3\text{He}/^4\text{He}$ ratio of ~ 480 atomic ppm, indicating that some of the ^3He escapes from the sun's interior without undergoing nuclear fusion.

A minor cosmological mechanism which forms ^3He is due to spallation reactions caused by energetic cosmic ray particles interactions with gases such as the atmosphere surround-

Table 1. Estimated Earth’s Inventory of ^3He .

	^3He Metric Tonnes			
	<u>Proved</u>	<u>Probable</u>	<u>Possible</u>	<u>Speculative</u>
Atmosphere	4,000	–	–	–
Oceans	13	–	–	–
Crustal Natural Gas (U.S.A.)	0.23	0.18	0.20	0.08
Subduction Zone Natural Gas	0.03	–	1,000	25,000
Mantle Gas	–	–	–	$10^6 - 10^7$
	4×10^3	0.18	10^3	$10^6 - 10^7$

ing the earth [9]. These nuclear reactions chiefly produce ~ 2 kg/yr of ^3H in the earth’s atmosphere which subsequently decays to ^3He .

3. Natural ^3He Reservoirs

This section provides an update of a previous [10] survey of the terrestrial sources of ^3He , assesses their inventories, and estimates their potential rates of production. The earth is protected by a magnetosphere which shields the earth from the solar wind; consequently, nearly all of the ^3He presently on earth existed in the primordial material which accreted to form the planet.

The present terrestrial ^3He reservoirs considered are: (1) the atmosphere and oceans, (2) continental crustal deposits associated with natural gas, (3) mantle-derived outgassing from the earth’s interior, and (4) tectonic plate subduction zone gas. Each of the resources has a characteristic $^3\text{He}/^4\text{He}$ ratio which aids in its identification [11, 12]. These reservoirs are described and their estimated ^3He inventories are summarized in Table 1.

3.1. Mantle-Derived Helium

Primordial material of our solar system which accreted to form the earth approximately 4.5 billion years ago is believed to have had a helium content and an isotopic ratio similar to that analyzed for the carbonaceous chondritic meteorites [13]. As the primordial matter continued to accrete, its temperature increased and most of the volatile materials, including helium, vaporized and escaped from the new earth. In order to explain the present inventory of helium, water and other volatiles, one theory suggests [14] that comets and asteroids, similar to the chondritic meteorites, impacted on the preformed core of the earth to form a veneer constituting approximately 20-30% of the weight of the earth. This veneer constitutes the present upper mantle. Many of the volatile gases including helium remain dissolved in the molten mantle.

The primordial helium in the terrestrial environment has been diluted, however, by the α -particles (^4He) emanating from the radioactive decay of Th and U ores. On the other hand, some ^3He is formed in the earth by neutrons, emitted by the spontaneous fission of U-235, reacting with ^6Li in the soil. These combined reactions yield a $^3\text{He}/^4\text{He}$ ratio of ~ 0.015 at. ppm. Gases venting from earth with higher $^3\text{He}/^4\text{He}$ ratios are considered to have mantle constituents.

Although no experimental technique is available to measure the mantle's primordial He reservoir, its presence has been detected in gases with high $^3\text{He}/^4\text{He}$ ratios emitted from oceanic island volcanoes, geothermal waters and along mid-ocean ridge vents. The highest ratios, 20-30 at. ppm $^3\text{He}/^4\text{He}$, have been detected in volcanic gases in Hawaii and geothermal wells in Yellowstone Park [11]. The primordial $^3\text{He}/^4\text{He}$ ratio has been diluted apparently by either the radiogenic ^4He in the mantle or in crustal deposits of radiogenic helium entrained in the magma as it ascends toward the surface. The largest volume of helium venting from the earth occurs along mid-ocean vents, particularly in the Pacific Ocean and has a $^3\text{He}/^4\text{He}$ isotopic ratio of ~ 14 at. ppm. Craig [15] has estimated the ^3He

flux from these vents to the atmosphere at $4 \text{ atoms/cm}^2 \cdot \text{s}$ ($\sim 3 \text{ kg/yr}$). This flux is believed to be the largest source of ^3He to the atmosphere. Some He vents directly from volcanoes to the atmosphere with high ^3He content as inferred by the high ^3He content found entrapped within Hawaiian island basalts [16].

Of interest as a source of ^3He is the reservoir of helium dissolved in the mantle which supplies the flux to these vents. Tolstikhin [17] constructed crude models of the degassing rate of the mantle and assumed that the degassing properties of the helium isotopes were similar to those measured for the isotopes of Ne and Ar. His model estimated that the mantle contains from $(1.4 \text{ to } 20) \times 10^{13}$ atoms of primordial He per g of earth indicating that 10^6 to 10^7 tonnes of ^3He may exist in the mantle.

Efforts to tap the mantle have been suggested in a search for new sources of nonbiogenic methane fuel. In an effort to test the deep gas hypothesis, a deep drilling project has been initiated in the Siljan Lake District of central Sweden; however, the search for abiogenic gas has been unsuccessful, thus far [18].

3.2. Tectonic Plate Subduction Zones

The entire surface of the earth is postulated to be composed of huge tectonic plates which support the continents and the oceans and move at rates up to 1 cm/yr . The driving force for the motion is caused by new magma from the mantle rising through cracks in the ocean floor and solidifying as the plates move. When an oceanic plate of higher density collides with a plate carrying a continent, the heavier oceanic plate subducts below the continent. These subduction zones can be potentially rich sources for ^3He because they serve as probes into the mantle with its high inventory of ^3He . As the subduction plates recede into the mantle and are heated, the biotic marine sediment accumulated along the top of the plates decomposes due to the thermal and hydraulic pressure, forming natural gas and petroleum reservoirs which can be accessed by deep drilling. These gas reservoirs, which are particularly abundant along the Western Pacific Basin [19], accumulate helium

released from the mantle gases. The helium content of the gas varies from 50-200 ppm and the $^3\text{He}/^4\text{He}$ ratio ranges from 2 to 10 at. ppm. The calculated inventory of ^3He in these gas wells plus the subduction zone remnants from past epochs may be as high as 25,000 tonnes.

3.3. Crustal, Sedimentary Gas Wells

Crustal gas and petroleum reservoirs have been formed by the decay of ancient flora and fauna buried within the earth which were subsequently subjected to both heat and pressure. In order to constitute a gas reservoir, the methane formed had to be absorbed in a porous structure, such as sandstone, and the reservoir had to be capped by an impervious rock structure to prevent the escape of the gas. Such gas reservoirs are also capable of occluding He released from the radioactive decay of U and Th ores in the crust with $^3\text{He}/^4\text{He}$ ratios of 2×10^{-8} at. fraction. In the U.S.A., the Hugoton natural gas fields in Kansas and Texas were discovered during the early 1900's to contain high He contents, up to 8% in some wells, and the $^3\text{He}/^4\text{He}$ isotopic ratios were in the range of 0.1 to 0.2 at. ppm. Additional fields have been discovered in Colorado and Wyoming. The high ^3He content of these gases indicates that some primordial He seeped into these reservoirs.

Because of the increasing use of He and the apparent limited supply, the U.S. government implemented the Helium Acts of 1925 and 1960 which instructed the Bureau of Mines to purchase, produce and sell helium to government agencies [20]. As a result, the Bureau of Mines entered into contracts with four producers and stored $\sim 10^9 \text{ m}^3$ (NTP) of He, containing $\sim 30 \text{ kg}$ of ^3He , in the partially depleted Cliffside natural gas field near Amarillo, Texas. These purchasing contracts were terminated in 1973, and have not been reinitiated. The Bureau of Mines continues to estimate annually the reserves of helium contained in the natural gas wells of the U.S.A. and classifies natural gas wells according to their helium content. The potential helium content in each of the natural gas reservoirs is combined

with the estimates of the gas reservoirs to give the potential He reserves [21]. The ^3He inventories were determined, Table 1, based upon the $^3\text{He}/^4\text{He}$ ratio of 0.2 at. ppm.

3.4. Atmospheric Helium

The earth's atmospheric helium budget represents a steady-state between the outgassing of helium derived from the earth plus several extraterrestrial sources and the escape of helium from the stratosphere. The helium concentration in the atmosphere, recently measured with high precision [22], gives a value of $5.2204 \pm .0041$ ppm (vol) and a $^3\text{He}/^4\text{He}$ isotopic ratio of 1.393×10^{-6} . When these values are combined with the weight of the total atmosphere the quantity of ^3He is calculated to be 4000 tonnes.

3.5. Oceanic Helium

Helium exists in the oceans from two different sources; namely, (1) gas solubility due to the equilibrium with atmosphere helium, and (2) the injection of mantle helium at mid-ocean ridge vents. The total ^3He in the oceans has been calculated [23] to be ~ 13 tonnes. This value is greater than that calculated in equilibrium with the atmosphere because an excess of total He ($\sim 3\%$) is entrained in the oceans and the $^3\text{He}/^4\text{He}$ ratio of the mantle gases is ~ 8 times the atmospheric ratio.

3.6. Potential Terrestrial Production of ^3He

Review of Table 1 indicates that potentially large quantities of ^3He exist in the terrestrial environment. On the other hand, Table 2 shows that the presently accessible ^3He is a dilute constituent of other gases. In most cases, the ^3He would be economically recovered only as a byproduct during the utilization of the host gas.

The most directly accessible source of ^3He would be the ^3He which could be isotopically separated from the helium sold by the Bureau of Mines from the He in storage. In 1986 the production of helium by the Bureau of Mines totaled $\sim 10 \times 10^6 \text{ m}^3$ (NTP)/yr. The

Table 2. ^3He Content of Various Terrestrial Gases.

	<u>Volume Fraction ^3He</u>
Atmosphere	7.3×10^{-12}
Helium-Rich ($>0.3\%$) Natural Gas	$(4.2 \text{ to } 6.7) \times 10^{-10}$
Subduction Zone Natural Gas	$(1.4 \text{ to } 8.8) \times 10^{-10}$

total ^3He in these gases, at an isotopic ratio of 0.2 ppm, would be only 0.3 kg/yr. The total sales of U.S. produced He in 1986 were 53 million m^3 (NTP), containing ~ 1.4 kg of ^3He . Because of the demand for liquified He as a cryogenic coolant for medical diagnostic equipment, additional commercial suppliers have installed helium liquefaction plants to separate He from natural gas [24]. If isotopic separation facilities were installed at these plants, they would produce ~ 1 kg/yr of ^3He . In addition to these North American reserves, some helium, $\sim 6 \times 10^6$ m^3 /yr, is derived from natural gas wells in Poland and the U.S.S.R.; however, its He isotopic ratio is unknown. For potentially larger amounts of ^3He , additional facilities for the separation of He from natural gas must be considered. For instance in the U.S.A. during 1989, 464×10^9 m^3 of natural gas were used, containing an estimated 174 million m^3 (NTP) of helium, (~ 4.7 kg of ^3He); however, most of the helium was vented. New energy demands worldwide could be considered as potential sources of ^3He because of the increased use of natural gas containing He, but natural gas reserves are limited.

4. Terrestrial Man-Made ^3He Resources

Helium-3 forms as the radiolytic decay product of tritium (half-life = 12.3 yr) which has been produced in nuclear fission reactors. During the storage of tritium, some of the ^3He has been collected and is available from several sites (see Table 3).

Table 3. Potential ^3He Availability from Natural and Man-Made Resources on Earth for Use in Demonstration Fusion Reactors.

Resource	Present Availability		Potential Availability by Year 2000		Potential Availability
	Inventory kg	Production Rate kg/yr	Inventory kg	Production Rate kg/yr	by Year 2010 kg
Decay of Tritium					
USDOE					
Inventory	16	~ 1	100*	5	150
CANDU Reactor					
Separation Plants	0	~ 1	10	2	30
Natural Gas Wells (USA)					
Helium in Storage	30				
Proved Reserves	230				
Potential Production		$\sim 1^\dagger$	5	5	55
TOTAL					235

*Based Ref. #3 and #27

† No isotopic He separation facilities are in place.

The U.S. Department of Energy (DOE) has an unclassified inventory of ^3He that is supplied by EG&G Mound Technologies Facility where it is purified and sold chiefly for research and development activities [25]. In 1991, a reserve of 120,000 ℓ (STP) of ^3He (16 kg) was on-hand that could be processed on special request. In large quantities ($> 500 \ell$ or 70 g), the USDOE cost of ^3He is approximately $\$100/\ell$ (about $\$700/\text{g}$).

The Canadian CANDU reactors produce tritium by neutron capture in the D_2O moderator. The total T_2 produced from the present time to the year 2000 is projected to be 30 kg. A separation plant became operational in 1990 to remove tritium from the heavy water at the rate of 2 kg/yr of tritium [26]. Due to the decay of tritium into ^3He , it is calculated that at least 10 kg of ^3He will be available by the year 2000 and, thereafter, ^3He will be produced at $\sim 2 \text{ kg/yr}$.

The total amount of ^3He from the decay of tritium in thermonuclear weapons throughout the world can be only approximately estimated as a potential resource. For instance, an unclassified estimate [3] suggested that the U.S. weapons stockpile could accumulate 300 kg of ^3He by the year 2000 and continue to generate 15 kg (^3He) per year. An unclassified estimate [27] of tritium production at the Savannah River Plant was made to 1984 and indicated that the decay of tritium produced up to that time could have resulted in the generation of 118 kg of ^3He if it had been collected and would generate an additional 45 kg by the year 2000. Apparently production continued until 1987, at which time a Safety Review Committee cited [28] concerns regarding the operation of the reactor and it was shut down. Although several deficiencies have been corrected the reactor has not been reactivated by 1991. If no further production occurs and ^3He were collected, it is reasonable to assume that by the year 2000 at least 100 kg of ^3He would be available from this source.

5. Extraterrestrial Resources

Rich sources of ^3He are predicted to occur in the Jovian planets – Jupiter, Saturn, Uranus, and Neptune, which have high He compositions [29]. Unfortunately, the He isotopic

ratio has not been determined for any of these planets and none is planned for the Galileo probe which will reach Jupiter in 1995. As a result, the He isotopic ratio is assumed to be the primordial value giving total ^3He resources in these planets of $\sim 10^{20}$ tonnes; however, mechanisms such as heterogeneous accretion or polar escape phenomenon could have caused preferential loss of ^3He . In order to make use of these ^3He resources considerable space exploration and development, including nuclear powered rockets, will be required; consequently, the use of such a resource for earth is at least a century away.

In contrast to the gaseous planets, helium is a rare element for the inner-solar system, terrestrial planets. The only He retained by these planets would be that which was trapped in their rocky interiors or their atmospheres during their formation; however, helium is lost by diffusion from the atmospheres of all these planets. As a result the inventory of primordial ^3He in these planets is limited, such as previously described for the earth.

Entrapment of the solar wind is a possible mechanism by which these planets could enrich their ^3He content; however, Mercury, earth and Mars have sufficiently strong geomagnetic fields that their surfaces are protected from the solar wind by a magnetosphere. Some of the solar wind particles do reach the earth's atmosphere through the polar, auroral flux lines, yielding a small ^3He flux of ~ 3 kg/yr. Mercury, being closer to the sun, has a larger auroral flux providing ~ 5.4 kg/yr of ^3He . Dawson [30] suggested, therefore, that Mercury could provide a resource for ^3He . The atmosphere is very thin [31], however, with a vertical column density of only $2 \times 10^{14}/\text{cm}^2$. If this entire atmosphere were He, it would contain only 360 kg of ^3He . Additionally, the auroral flux of He appears to be in a steady-state with the He loss from the planet; consequently, it is impossible to estimate the quantity of the He flux ions which might have penetrated into the lithosphere and have been trapped.

Venus does not have a magnetosphere, but it does have a thick carbon dioxide atmosphere, ~ 8 MPa, and a He pressure of 0.6 MPa. Dawson has suggested that the Venusian atmosphere could intercept the solar wind which would mix with the gases present to yield

an atmosphere which would be isotopically similar to He in the solar wind. If this mechanism were demonstrated, the Venusian atmosphere may contain 2×10^9 tonnes of ^3He .

The earth's moon, Luna, is unique because it has neither a geomagnetic field nor an atmosphere; therefore, solar wind particles impinge directly upon the lunar surface and are captured. This hypothesis was proved when special solar-wind traps (aluminum foil) were exposed to the solar wind on the lunar surface by the Apollo astronauts. When these foils were later analyzed, they were found to contain the predicted solar wind elements [32].

The Apollo astronauts returned, also, with samples of the fine powder which covers the lunar surface. When these samples were heated in vacuum furnaces at laboratories on earth, the gases released had the solar wind composition. Apparently, the powdery lunar regolith is able to retain significant quantities of the solar-wind ions which impinge upon them. From this information, the potential amount of ^3He in the lunar regolith was crudely estimated to be greater than a million tonnes [3] and suggested that the moon might, therefore, be a source of large amounts of this gas. Because this is such a large, potentially available resource of ^3He , this paper reviews our subsequent studies directed toward the procurement of the lunar ^3He for use in fusion power plants on earth. These studies include: (1) further assessments of the ^3He resource based upon information presently available, (2) techniques potentially applicable to the recovery of the He from the lunar soil, (3) analyses of the payback of energy and financial capital which would be invested in such an enterprise, (4) the environmental impact of such an operation upon the moon, and (5) the legal precedent for implementation of such an enterprise.

6. Lunar ^3He Resource Assessment

The lunar regolith is the surficial layer of fragmental material, generally meters thick, that overlies the lunar bedrock. The regolith has been produced by the impact of innumerable bodies, very large to very small, that have bombarded the moon in the 4.5 billion years since it was formed. The impacts of these high velocity bodies often eject regolith

from below the surface up to the exposed surface level. By such a continuous process called “gardening”, the regolith has been homogeneously mixed to a depth of several meters [33].

The surface layer of regolith is bombarded by the solar wind particles, therefore, whenever it is exposed to the sun. These ionic particles do not follow a straight line from the sun to the moon, such as the photon flux, because the sun revolves giving the magnetic flux lines a spiral twist; consequently, the solar wind ions impinge upon the moon at $\sim 45^\circ$ from the direct sun to moon line. Also, the moon’s revolution about its axis coincides with its rotational velocity around the earth; therefore, any area on the moon is exposed to the solar wind only half the time. In addition, the earth’s magnetotail shields the moon from the solar wind for ~ 4 days per lunar cycle whenever the moon is directly behind the earth [34, 35]. As a result, the center of the lunar near-side, which constantly faces the earth, receives little particle flux during the period known as full-moon. Consequently, this center section may have lower concentrations of solar wind gases than areas along the limbs of the moon and the far-side. Such a difference has not been verified because regolith samples from the limbs and far-side are not available.

Highland regoliths, 10-15 m thick, cover the bright, mountainous areas of the moon, whereas mare regoliths, 4-5 m thick, cover the darker, more level areas that have long been called the maria [36]. Highland regoliths are derived mainly from plagioclase-rich rocks whereas mare regoliths are mainly derived from underlying basaltic lavas. Highland regoliths are rich in calcium, alumina, and silica but low in TiO_2 . Mare regoliths are rich in iron, magnesium, and titanium and relatively low in calcium and aluminum.

6.1. Correlation of ^3He with Respect to Regolith Grain Sizes

It is generally recognized that the smaller the particle size of the regolith, the higher the concentration of solar wind gases. This stems from the fact that the solar wind gases penetrate less than a μm into the regolith particles and, therefore, the higher the surface area to volume ratio, the higher the concentration of embedded gas atoms. This principle

is illustrated from samples analyzed from Mare Tranquillitatis. When the gas analyses [37], Fig. 1, were combined with the size distribution of the raw regolith [38], the results by Cameron [39] indicated that the particles of $< 50 \mu\text{m}$ which constitute only 47 wt.% of the soil yield $\sim 75\%$ of the He and particles less than $100 \mu\text{m}$, which constitute 63 wt.% of the soil, contain $\sim 86\%$ of the He. In addition, it was noted for this and other samples that the He content of the unsieved soil was $\sim 30\%$ higher than that which is obtained by the summation of the grain-size fractions. Apparently during the sieving process nearly 30% of the He was lost as a result of either agitation of the particles or as fine particles which may have become airborne.

In addition to the effect of the apparent He concentration increasing as the particle size decreases, an effect due to the mineral ilmenite ($\text{FeO} \cdot \text{TiO}_2$) was noted by Eberhardt [40] during the examination of the early Apollo soil samples. For instance, for a bulk regolith sample which had an average He concentration of 17 wppm, when particles $< 125 \mu\text{m}$ with a high ilmenite content were selected, the He concentration increased to ~ 360 wppm. A strong correlation of He with ilmenite in the soil has been noted, subsequently, by many investigators. Beneficiation to obtain soil with a high ilmenite component would yield, therefore, a product with a high He content. This type of beneficiation would be difficult, however, because examination of many soil samples indicates that ilmenite seldom exists as a free-particle. Instead, it usually occurs as needles or platelets constituting $\sim 9\%$ of a rock particle [41]. As a result, extensive grinding of the soil would be required to free the ilmenite. Taylor and Oder [42] have shown that beneficiation of the lunar soils by sizing and electromagnetic separation can effectively concentrate the important components of the soil, such as ilmenite; however, some ilmenite is lost with the chards and a significant quantity of He could be lost in the fine, non-ilmenite particles.

Based upon these observations, beneficiation of regolith to remove the coarser fractions would be highly desirable. Removal of particles $> 100 \mu\text{m}$, for example, would reduce the

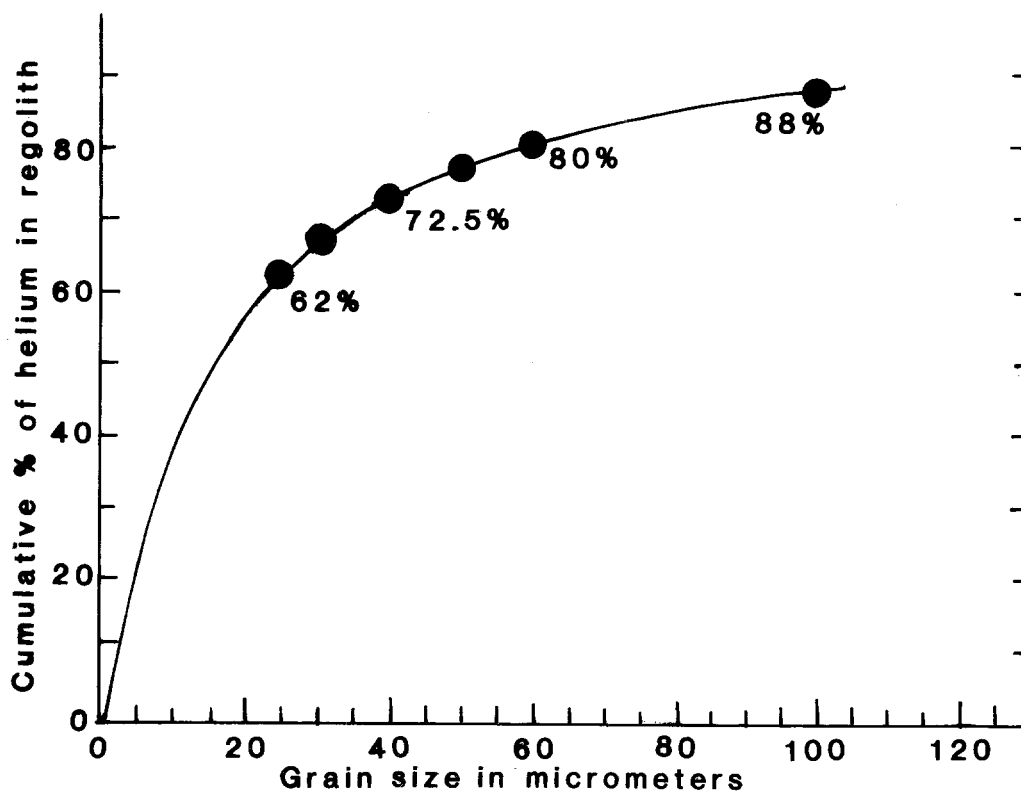


Figure 1. Cumulative percentage of total helium in relation to grain size in Apollo 11 regolith sample 10084, based on data from Criswell and Waldron [38] and Hintenberger et al. [37].

amount of regolith to be treated by $\sim 40\%$ leaving $\sim 80\%$ of the He in the remaining regolith. The development of methods of sizing the regolith on a large mass scale could, therefore, be very important.

6.2. Evolution of Solar Wind Gases

The solar wind particles, chiefly H and He, which impinge directly upon the lunar regolith, penetrate into the crystals and are retained. Depth profiling measurements [43] indicate that initially the maximum He concentration peaks at 20-30 nm (200-300 Å) below the surface of the particle. Further exposure to the solar wind causes radiation damage in the near-surface layers of the particle and when coupled with the solar heating causes the He concentration maximum to move toward the surface, often peaking at 5 to 10 nm (50-100 Å) below the surface. Long-term exposures causes the near-surface layers to amorphize with the subsequent loss of the retained gases. Glass spherules often show a depleted surface layer and a He peak ~ 110 nm below the surface. Olivine particles display a second peak ~ 50 nm below the surface.

The principal method to release the implanted atoms has been by heating in a vacuum. Qualitative mass spectrographic analyses of the gases evolved during continuous heating of the Apollo 11 soils [44] indicated: H₂ and He evolution began $\sim 200^\circ\text{C}$ and was nearly complete by $\sim 800^\circ\text{C}$; CO and N₂ evolution began at $\sim 600^\circ\text{C}$ and continued to $\sim 1200^\circ\text{C}$; CO₂ was evolved between 700 to $\sim 1200^\circ\text{C}$; and H₂S and SO₂ evolution was initiated between 800 and $\sim 900^\circ\text{C}$. These soils contain no H₂O 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 H₂ evolved above $\sim 200^\circ\text{C}$. The appearance of methane has not been confirmed but may constitute 5% of the total carbon. The condensation of the sulfur compounds SO₂ and H₂S from the evolved gas was observed to contaminate the vacuum system with resinous products which were difficult to remove [45].

For this reason, the proposed maximum heating temperature for the mining scenario was limited to the range of 700 – 750°C so that the sulfur compounds would not vaporize.

The total yield of solar wind gases evolved during the heating of Apollo 11 soils to $\sim 1300^\circ\text{C}$, was calculated per tonne of average fine regolith on Mare Tranquillitatis conservatively assumed to contain 30 ± 10 wt. ppm of ^4He with a $^3\text{He}/^4\text{He}$ ratio of 400 atomic ppm. (first line in Table 4). 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 scaled the mass spectrographic data by Oró [46] of gases evolved during the heating of Apollo 12 soils which reported the total yield of all gases evolved up to 750°C . Quantitative yields of H_2 [47] and He [48] obtained during the step-wise heating of Apollo 11 samples as a function of temperature indicated that 86% of the ^3He , Fig. 2, and 84% of the H_2 would be evolved when the regolith is heated to 700°C .

The volatile gases evolved during a proposed scenario for mining, beneficiation and heating to 700°C have been estimated per tonne of raw regolith, Table 4, based on maria containing 8-10% ilmenite, but not as a free particle of which some would be dissolved in agglutinates. For this preliminary estimate, electrostatic beneficiation or another advanced beneficiation process was assumed to be developed by the year 2015 so that $\sim 80\%$ of the ^3He could be retained in the $< 50 \mu\text{m}$ regolith particles which constitute ~ 45 wt. % of the soil, and that 85% of the contained He would be released during heating up to 700°C . Review of Table 4 indicates that large quantities of other gases will be released during the process. Hydrogen, a potential rocket fuel, will be in abundant supply and processes using this H_2 to provide O_2 and H_2O from the regolith are under investigation [49]. Of interest for human habitation of the moon is the quantity of nitrogen and carbon compounds released. The N_2 and CO_2 could be useful for plant growth in a Closed Ecological Life Support System [50]. The N_2 and O_2 (formed by the electrolysis of H_2O or decomposition of CO_2) would also be useful for the atmosphere in habitats.

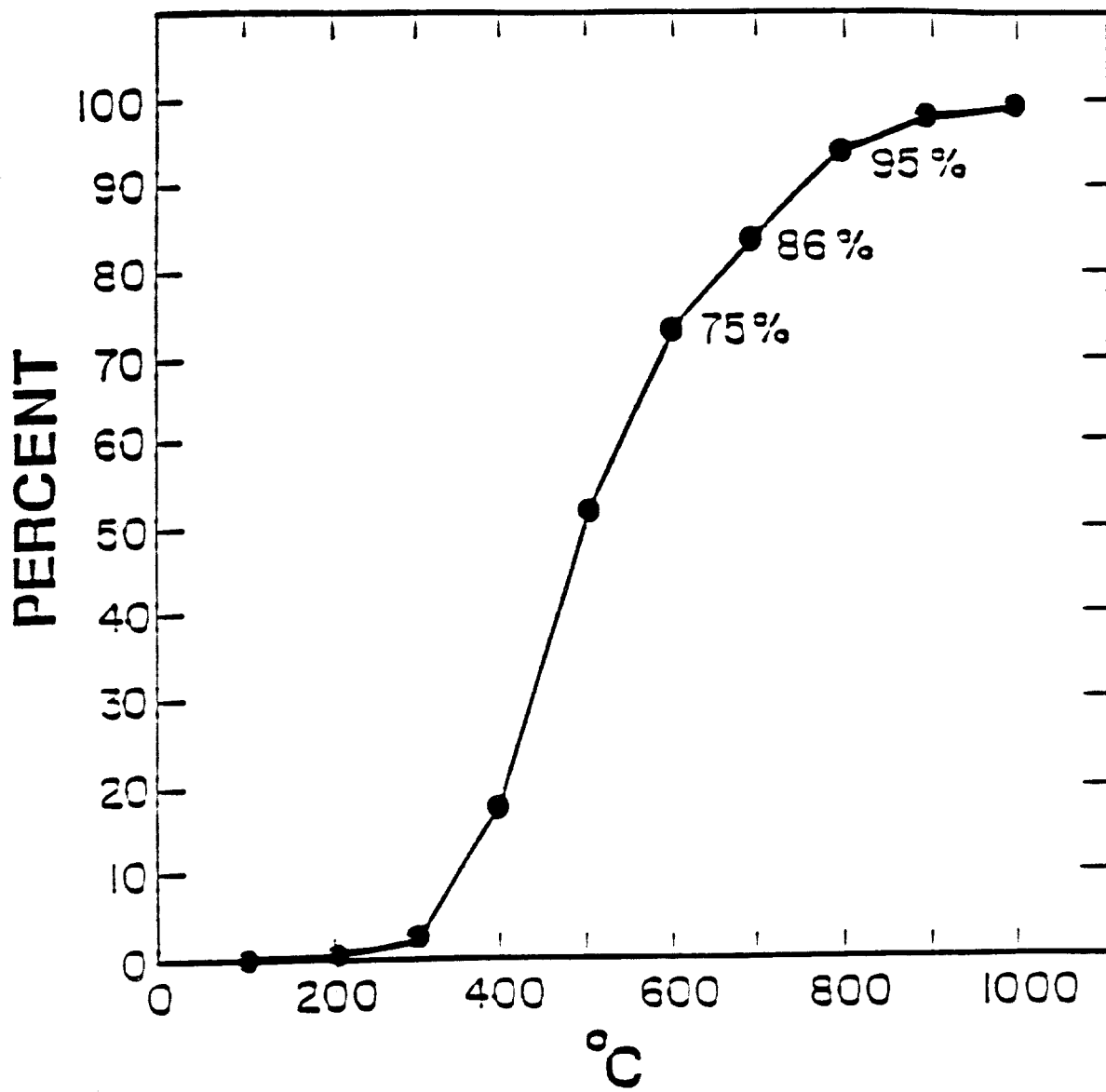


Figure 2. ^3He evolution from lunar soil as a function of temperature (data from Pepin) [48].

Table 4. Solar Wind Gas Release Predicted from Mining of Maria Regolith.

Operation	Regolith (tonnes)	³ He	<u>Concentration, ppm (g/metric tonne)</u>			
			⁴ He	H ₂	Carbon	Nitrogen
Surface Mining	1	0.006-0.013	20-45	50-60	142-226	102-153
Remaining After Beneficiation	0.45	0.005-0.011	27	50	166	115
Used for Gas Evolution at 700°C	0.45	0.004-0.009	22	43 (H ₂) 23 (H ₂ O)	13.5 (CO) 12 (CO ₂) 11 (CH ₄)	4
Mass Per kg (³ He) Collected	1.4 × 10 ⁵ (mined)	1 kg	3.1 tonnes	6.1 tonnes (H ₂) 3.3 tonnes (H ₂ O)	1.9 tonnes (CO) 1.7 tonnes (CO ₂) 1.6 tonnes (CH ₄)	0.5 tonnes

6.3. Association of Ti and He in Lunar Regoliths

The first step in assessing the ^3He resource and selecting sites for mining and extraction of helium on the moon is the identification of areas in which the regolith is enriched in helium. Normally, this is accomplished at proposed mining sites on earth by assays of extensive bore-hole samples, but such extensive sampling of the moon does not exist. Alternatively, some minerals can be located by remote sensing techniques; however, sampling of He by remote sensing is not possible. As a result, the association of He with other lunar materials has been developed to aid in the resource site selection. Three salient findings by the various investigators of regolith samples returned from the Apollo and Luna missions, as summarized by Cameron [39], are relevant for the remote sensing of He. These findings are as follows:

1. Regoliths from areas underlain by highland materials predominately contain less than 10 wppm of He although some samples from Luna 20 approach 20 wppm.
2. Regoliths of some maria or parts of maria contain less than 20 wppm He, but others have He contents ranging from 25 to nearly 50 wppm.
3. The helium content of a mare regolith is a function of its composition. In particular, the helium content appears to be directly correlated with the titanium content, which is largely bound in the mineral ilmenite (FeTiO_3). The reason for this correlation is not well understood, although the crystal structure of the mineral may be important.

The composition of the lunar mare regolith is considered to be controlled by the nature of underlying basaltic rocks. More than a dozen different types of basalts have been described from various maria, distinguished on the basis of mineral and chemical composition. In terms of titanium content, however, these are assigned to three principal groups, as follows:

1. very high titanium basalts (VHT) sampled by Apollo 11 and Apollo 17;
2. low-titanium basalts (LT) sampled chiefly by Apollo 12, Apollo 15, Luna 16, Luna 20, and Luna 24, plus some samples from Apollo 17;
3. very low-titanium basalts (VLT) sampled by Luna 24.

This grouping of maria basalts is important because of the relation between the titanium content of basaltic regolith and its helium content, Fig. 3. The VHT samples show a marked clustering in the upper, right-hand part of the diagram, whereas LT and VLT samples are clustered in the lower, left-hand part. There is a dearth of points in the range from 3.5% to 6.5% TiO_2 when samples are neglected which appear to be mixtures from several lunar sources. Of more than 70 mare regolith samples analyzed for TiO_2 , only three (with 3.53%, 5.6% and 5.8% TiO_2 respectively), fall in this range. Of these, the last two have not been analyzed for He. These data, Fig. 3, show a broad correlation of He content with Ti content. The Ti content of regolith can be used, therefore, as a general guide in selection of areas where the regolith contains more than 20 wppm He. This Ti/He relationship is assumed to hold for all areas, but this can not be confirmed until samples are analyzed from many more locations.

Taylor [51] has suggested that soil “maturity” can be correlated with the solar-wind gases in the soil. Soil maturity occurs when the regolith particles at the lunar surface are bombarded by micrometeorites often causing melting followed by the solidification of glassy particles, called agglutinates. Before the melting occurred the soil particles were exposed to the solar wind implanting H^+ and other solar-wind ions. Consequently, when the soil particles melted a chemically reducing atmosphere of hydrogen was present which reduced some of the FeO in the soil to fine particles of elemental Fe^0 . It has been shown that the intensity of ferromagnetic resonance, as measured by the unit I_s , is caused by the small

particles of Fe in the agglutinates. Consequently, the ratio of I_s/FeO has been used as a measure of the maturity of the soil.

As shown by Taylor, a reasonable correlation occurs between soil maturity and solar-wind implanted carbon; however, the correlation of soil maturity with He is poor especially when the He concentrations are high. In addition, Jordan [52] has discussed the possibility of using maturity as a prediction of He distribution on the lunar surface. He emphasized that before such a remote-sensing concept can be utilized, a quantitative relationship between spectral reflectance data and the ratio of I_s/FeO in the regolith must be established. Spectral reflectance measurements of the lunar surface would attempt to correlate the grain size and the accompanying concentration of agglutinates with the reflectance of the soil. These two conditions of the soil, decreased grain size and increased number of agglutinates, increase with the exposure time of the soil at the surface would also indicate increased implantation of solar wind particles. Other conditions, however, can affect the grain size and its reflectivity, such as ejecta from recent craters, ray materials, and the impact resistance of various types of mare basalts. As a result, the correlation between spectral reflectance measurements and the ratio of I_s/FeO is poor. For these reasons, the concept of soil maturity has not been used in this study to delineate He-rich areas of the maria.

6.4. Information from Remote Sensing

Two general types of remote sensing have furnished information on the titanium content of lunar regolith; namely gamma-ray spectroscopy performed by Apollo 15 and Apollo 16 orbiters, and earth-based telescopic measurement of lunar reflectance. The results of both types of measurements have been calibrated against titanium contents of lunar samples assayed on earth. The existing lunar samples cover, however, only a small fraction of the lunar surface; hence, the use of these remote sensing techniques to unexplored areas may lead to large errors.

Gamma-ray spectroscopy makes use of radiation produced mainly by cosmic ray bombardment of the lunar regolith. Its advantage is that it measures a property that is directly related to titanium content. Resolution is very low, 60 by 60 km to 320 by 320 km, and coverage by Apollo 15 and Apollo 16 orbiters is limited to two bands lying between 30 N and 15 S. Interpreting the data is difficult, in part owing to interference by Fe and O. However, Metzger and Parker [53] have used gamma-ray spectroscopy to show that there are two principal areas of high-titanium regolith in the parts of the lunar surface covered by the orbiters – Mare Tranquillitatis in the eastern, near-side of the moon and a part of Oceanus Procellarum located in the far western, near-side of the moon.

A map of the entire near side lunar surface has been prepared based on spectral ratio mapping [54], from earth-based observatories. This technique makes use of ultraviolet negatives superimposed upon infrared positives to show color groups of basaltic regoliths, with various TiO_2 values. The association of colors with Ti content is an empirical relationship and is particularly misleading for low Ti ores. Figure 4 shows, however, that the only sizeable area of high-Ti regolith in the eastern hemisphere is that of Mare Tranquillitatis, with its small extension northward toward the Apollo 17 site. Large areas of high-Ti regolith appear in the western hemisphere including the large Oceanus Procellarum. Compared to gamma-ray spectroscopy, spectral ratio mapping has the advantage of higher resolution (1 to 3 km), and provides better coverage of the lunar surface. Maps prepared by gamma-ray spectroscopy and the color ratio method are in general agreement for the high Ti locations.

6.5. Quantification of the He Resource of Mare Tranquillitatis

Quantification of the He resource of Mare Tranquillitatis is discussed in detail by Cameron [39] and by Cameron and Kulcinski [55]. The following is a summary of their findings. They addressed four questions:

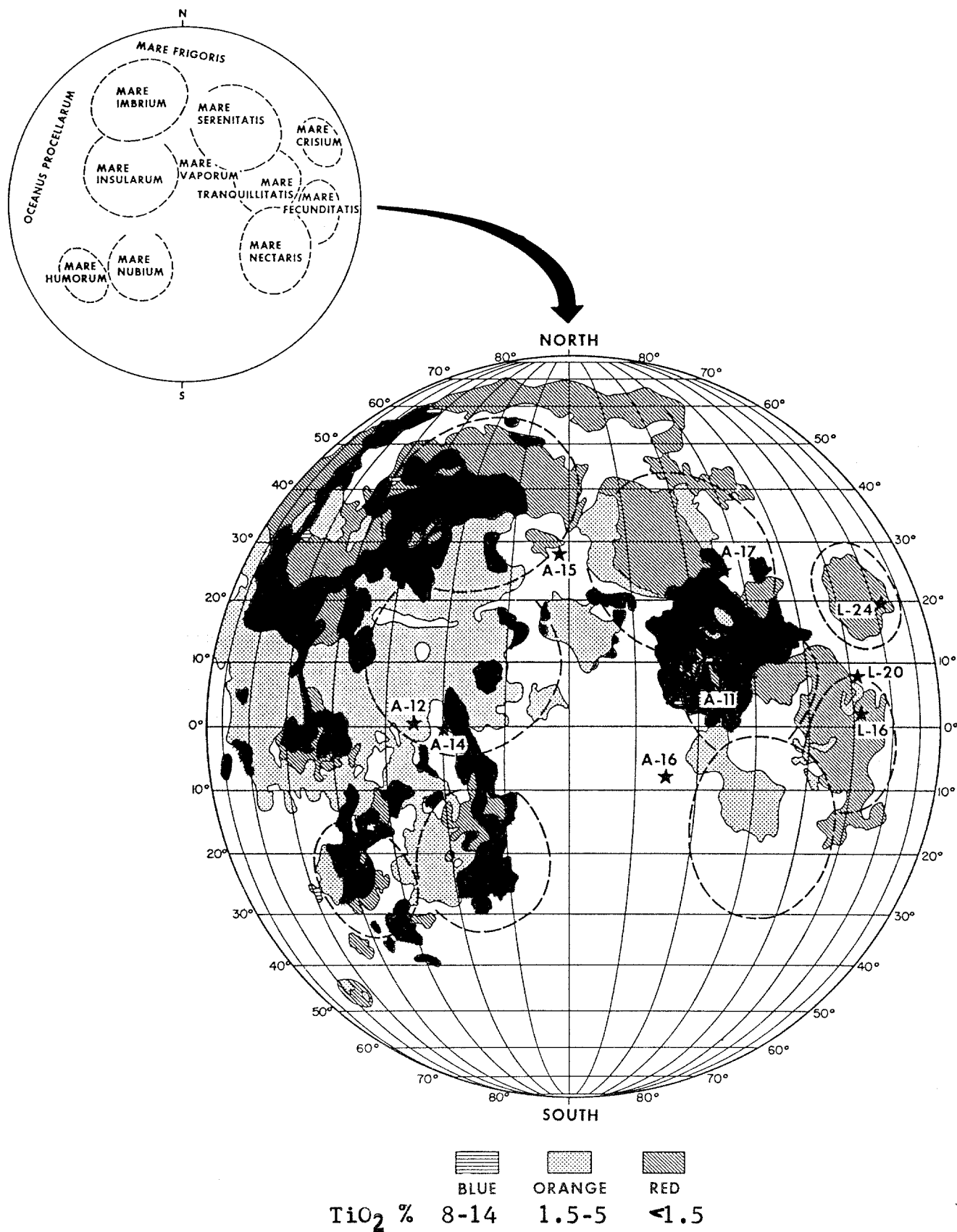


Figure 4. Lunar sample localities and spectral determinations of the color-groups of mare basalts used as an indicator of TiO₂ content of lunar regolith [54].

- (1) What is the distribution of high-Ti regolith on Mare Tranquillitatis and what variations in helium content are to be expected within it?
- (2) What is the depth of the regolith?
- (3) What is the variation in the helium content of the regolith with depth?
- (4) What percentage of the total area of Mare Tranquillitatis is likely to be minable?

The color difference photograph by E.A. Whitaker [56] and the spectral ratio map of Johnson et al. [57] are used to delineate the distribution of high-Ti regolith ($\text{TiO}_2 > 6\%$) and variations of TiO_2 content within it, Fig. 5. About 28% of the mare is occupied by regolith with 7.5% or more TiO_2 and about 65% by regolith containing 6.0 to 7.5% TiO_2 . The inferred He contents of the two categories are respectively 30 to 44 wppm and 20 to 30 wppm.

All Apollo 11 samples are surface samples, <10 cm deep; hence, there is no direct information on variation in the He content of the regolith of Mare Tranquillitatis with depth. Core samples from the drillholes at the Apollo 15, 16, and 17 sites are relevant; however, the deepest core is only 299 cm deep at an Apollo 17 site [58]. Those at the Apollo 15 and 16 sites show variation in He content with depth but no correlation with depth. The average He content of the Apollo 15 core samples is 10.8 wppm; the average for 11 surface samples 11.1 wppm. The average for Apollo 16 core samples is 6.5 wppm; the average for 22 surface samples is 6.7 wppm. The Apollo 17 core samples show an increase in He content with depth. At any rate, core and surface samples give no indication of a systematic decline, or increase, in the He content of regolith with depth. This is hardly surprising. Given the repeated overturn of regolith due to impact gardening during the more than 3 billion years since Mare Tranquillitatis was formed, no systematic pattern of variation is likely to be found. Instead, an irregular pattern of small-scale variation, both laterally and vertically, is to be expected.

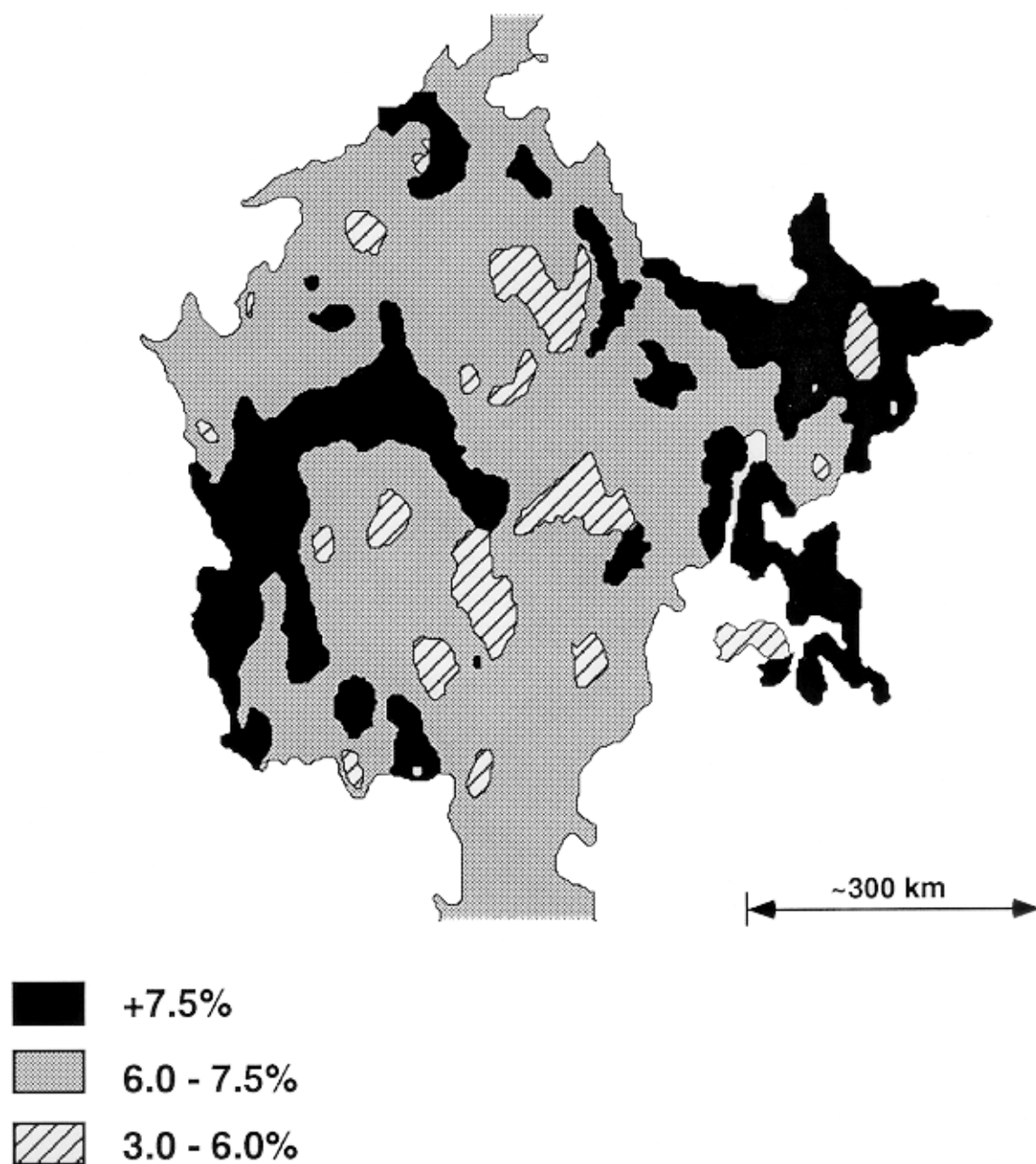


Figure 5. Inferred variations in TiO_2 content of regolith of Mare Tranquillitatis, based on an enlargement of part of the color difference photograph by Whitaker [56].

The depth of regolith is indicated by studies of very small craters (< 24 m in diameter) on Lunar Orbiter II high resolution photographs of the Apollo 11 and Ranger VIII areas. The average depth away from larger craters and their ejecta halos is about 4.5 m. An average depth of 3 m used later in calculating resources of He in minable regolith is, therefore, a conservative figure.

The percentage of the total area of Mare Tranquillitatis that will be minable has been determined [55] from study of geologic maps of the mare and Lunar Orbiter II high-resolution photographs of the Ranger VIII area (24 prints covering an area of about 540 km^2) and the Apollo 11 area (48 prints covering an area of about 1050 km^2). The minable percentage is dependent on the size and distribution of ridges, rilles, domes, islands of basement rocks, rays, and craters, all potential obstacles to mining. The size, distribution, and patterns of distribution of craters larger than 12 m in diameter and their inferred ejecta halos are especially important. Areas occupied by such craters and their inferred ejecta halos have been measured on 15 of the prints of the Apollo 11 area and 12 of the prints of the Ranger VIII area. To examine the effect of crater distribution on minable percentage, all craters 12 m or more in diameter, plus inferred ejecta halos, have been plotted on 4 representative photographs of the Apollo 11 area as illustrated in Fig. 6. The clear areas in this overlay are assumed to be suitable for mining although they may contain some rocks up to a decimeter in diameter as well as larger rocks below the surface. The relation between minable percentage and the size of an efficient mining unit has been examined, Fig. 7, using units of two different sizes, 300 and 400 m squares. These studies of maps and photographs indicate that with suitably maneuverable mining equipment and the ability to handle small rocks, as much as 50% of the total area of Mare Tranquillitatis will be minable.

Using the information summarized above regarding the surface coverage and an assumed minimum depth of 3 m for the regolith, we estimate that the amount of ^3He in

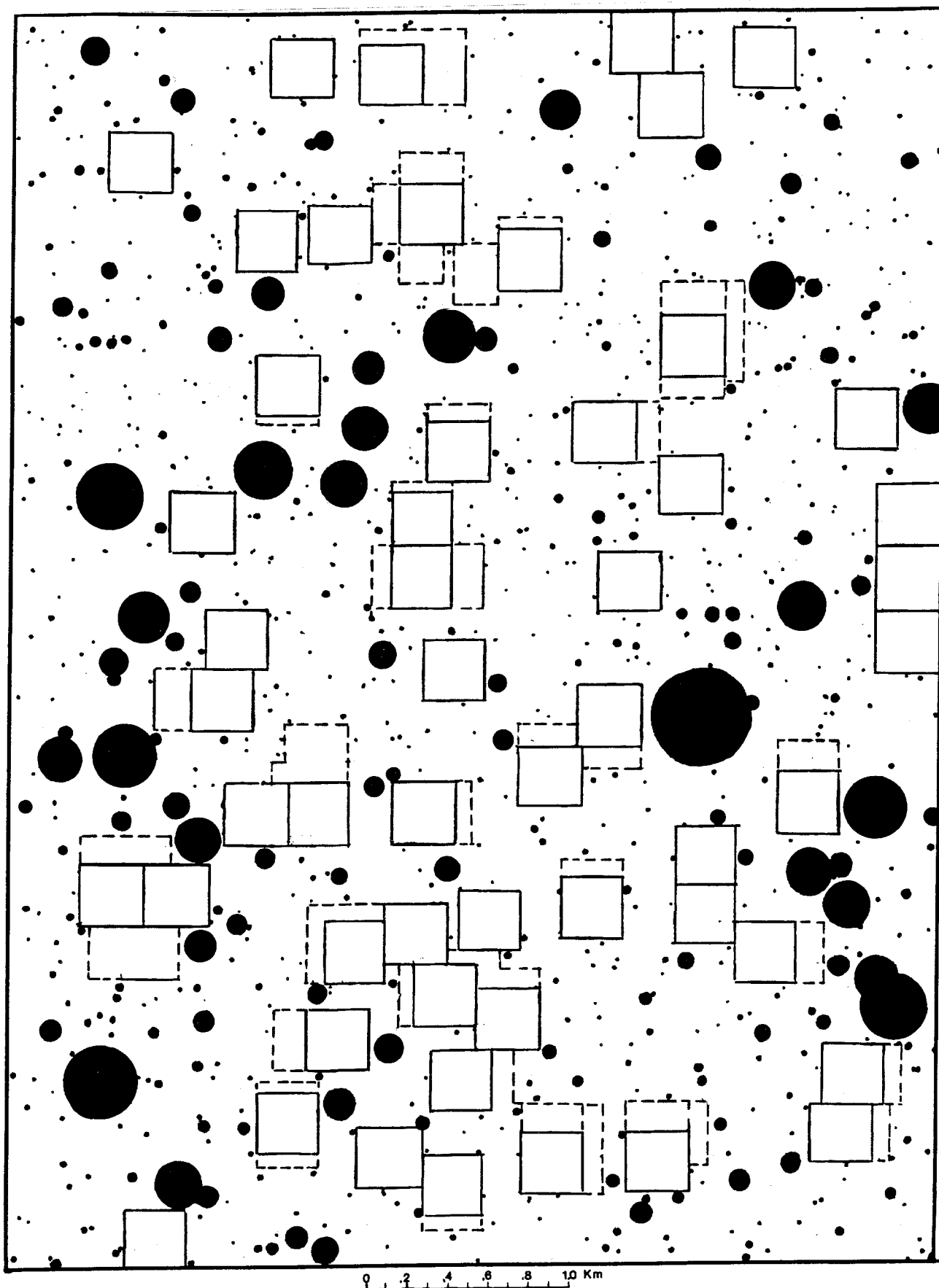


Figure 6. Craters (black circles) 12 m or more in diameter, plotted on an overlay of photograph II 84 H₃ obtained from Ranger VIII Lunar Orbiter. Squares are 300 m unit blocks, and their extensions, which could be mined without intrusion into the ejecta of a 12 m diameter crater.

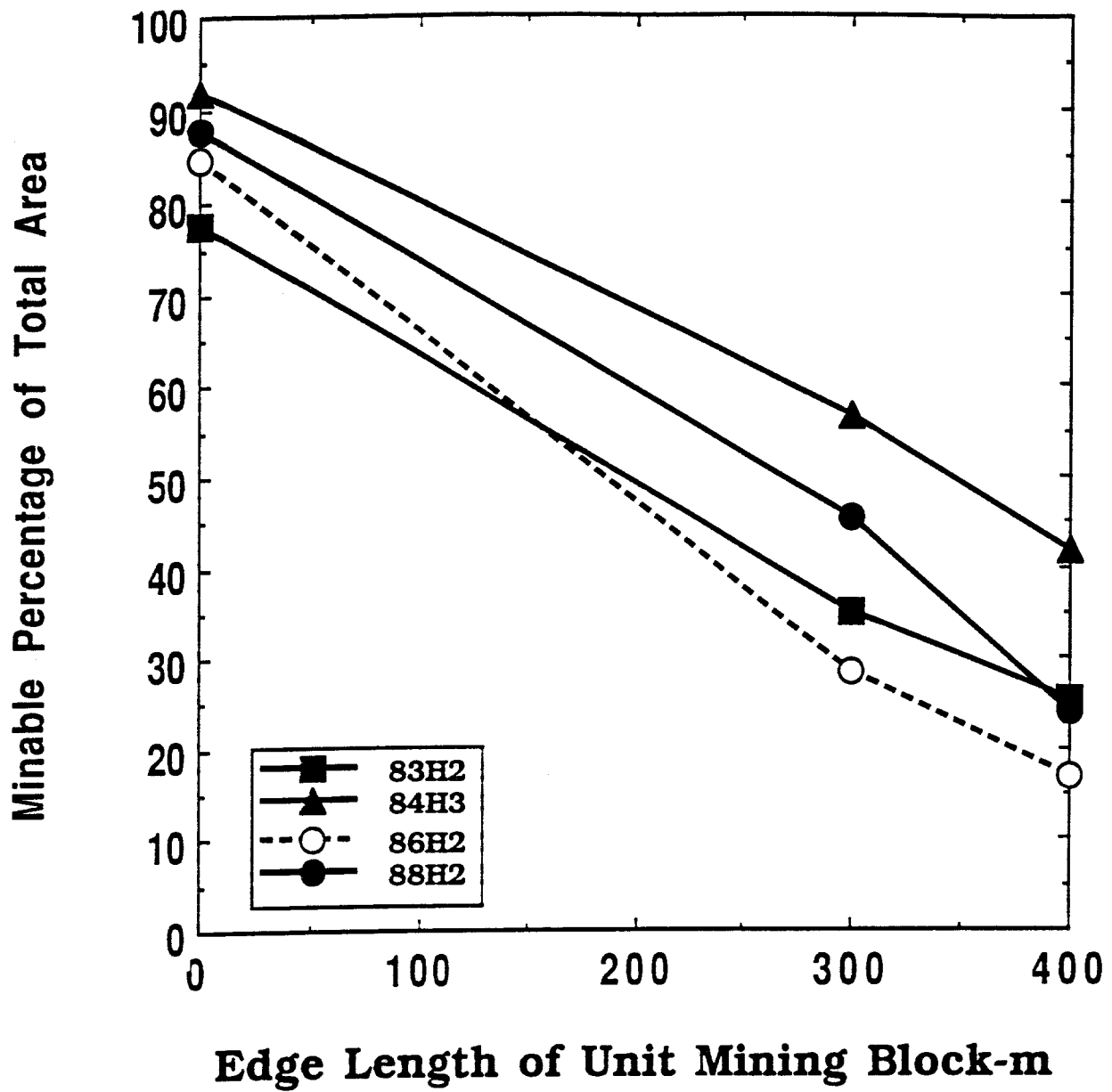


Figure 7. Percentage of minable area as a function of the length of the edge of a unit block for different locations on Mare Tranquillitatis. The identification number refers to different sites.

minable regolith containing 20 wppm or more of He of Mare Tranquillitatis alone is at least 9430 tonnes.

6.6. Mining Strategies

Before a mining scenario can be proposed, we estimated the mass of regolith required to yield a specified amount of solar wind gases. For this scenario, we selected the continuous fueling of a 1000 MWe fusion power plant which requires 106 kg/FPY (Full Power Year) of ^3He . If the mining operation were conducted only during the lunar sunlit periods, ~ 4000 hr/yr, the ^3He production required is 26 g/hr. Based upon the previously described ^3He resource in Mare Tranquillitatis and the gas evolution technique, nearly 3300 tonnes of regolith must be mined per hour (a cube of roughly 11 meters on an edge).

Three strategic options for lunar surface mining and processing of the large quantities of regolith required were considered [59], 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.

Each of these mining options are examined in the following scenarios.

6.7. In situ Mining

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

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 [60], in the

lunar environment. As a consequence, if the temperature of the surface were maintained at a constant 1000°C , in order to avoid sintering, a simple calculation shows that 5 hours would be needed to raise the temperature at a depth of 1 cm to 600°C .

Penetration of heat can readily be gained by using microwave radiation [61]. Studies have shown that the coupling of the regolith to the microwave radiation is considerably increased due to the defects in the material, resulting from the cosmic ray and the intense impact events on the moon.

The feasibility of in situ mining using microwave radiation was examined for a plane wave radiating perpendicularly to the surface. The loss tangent of the bulk regolith was calculated to be between 0.015 and 0.3 based on the electrical properties of the lunar samples [62]. Loss tangent characterizes the coupling between the substance and the microwave radiation, and it is temperature dependent. As the microwave penetrates the regolith, the strength of its electrical field attenuates because the energy is dissipated and used to heat the regolith, changing the temperature profile which in turn alters the attenuation.

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. The initial temperature distribution was assumed uniform at 250 K, approximately the temperature of the regolith at a depth of > 30 cm. The frequency of the microwave and the intensity of the electrical field were 0.5 GHz and 400 volt/m, respectively. The 0.5 GHz frequency was used instead of the conventional 2.45 GHz frequency because the depth of penetration is deeper. Figure 8 shows the temperature profile at 475 s (7.75 min) when the surface reaches 1000°C , the sintering temperature of the material, at which time a total yield of $25.0 \text{ cm}^3 \text{ (STP)}/\text{m}^2$ of ^3He was obtained. Finally, the total amount of microwave energy input into the regolith was 3.6 GJ. The excessively high microwave energy required is mainly due to the fact that 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

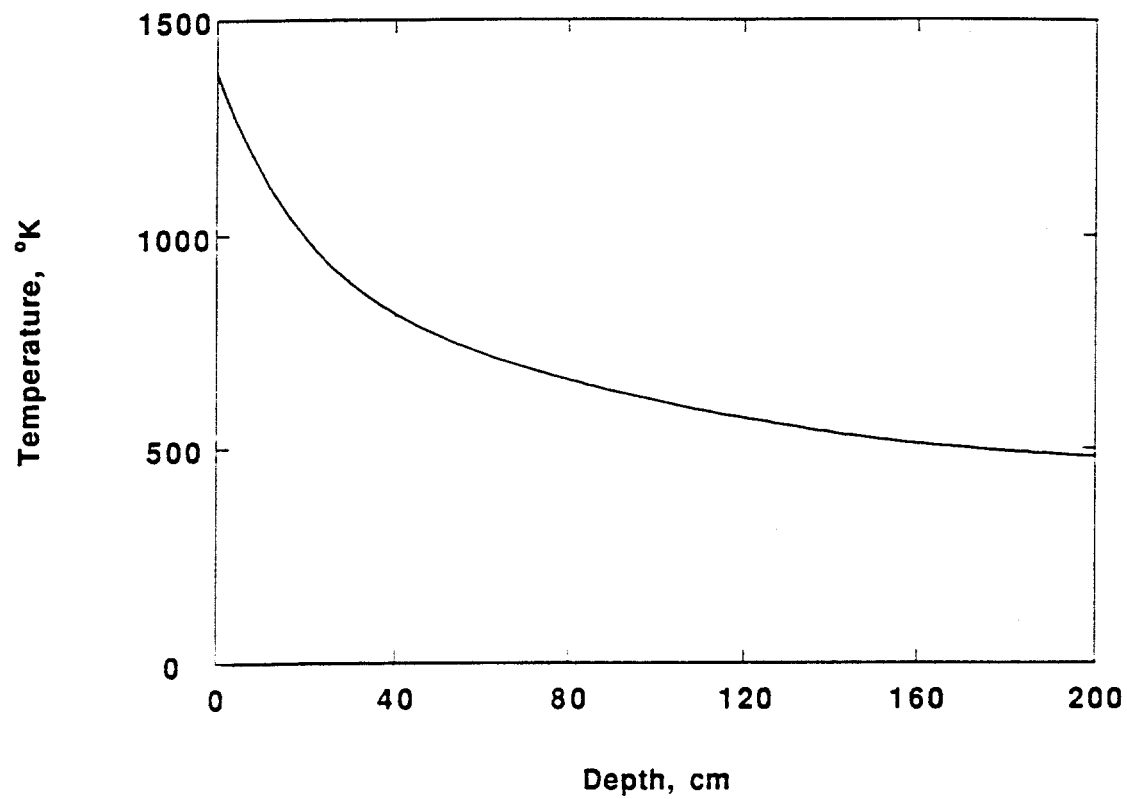


Figure 8. Temperature profile in the regolith as a function of depth after microwave heating for 475 s for a total yield of $25 \text{ cm}^3 \text{ (STP)}/\text{m}^2$ of ^3He .

energy efficiency is $< 3\%$. Further, even if it were possible to release the gases from the static regolith, they would be dispersed isotropically in all directions with only a small fraction being captured.

6.8. Mining Scenarios

In order to select the preferred mining scenario, the entire flow chart for ^3He recovery was considered [59]. The process of open-pit mining usually practiced on earth begins with the regolith being placed on conveyor belts and transported to a central processing facility. At the end of the process the “tailings”, which have the same mass as the original regolith but are of greater volume, must be discarded, preferably into the original mine pit. Large volumes of the regolith must be lifted and handled in order to produce a useful amount of ^3He . The area needed to be mined is $\sim 2.4 \text{ km}^2/\text{yr}$ if the mining trench is 3 m deep and the soil bulk density is 1.8 to 2.0 tonnes/ m^3 . As a result the lengths of the conveyor belts from the mine to the central processing plant would increase rapidly each year when significant quantities of ^3He 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 robotically controlled, mobile miner was considered [63]. Such a mobile miner, Fig. 9, consists of a bucket wheel excavator at the front followed by an enclosed series of modules. Each module performs a single or multiple processing function(s) such as excavation, beneficiation, preheating, main heating, gas extraction and heat recovery. Thermal energy for gas evolution is provided by solar energy beamed to the vehicle from fixed solar reflectors on the surface of the moon. Mineral flow is handled by lifting conveyors between the modules. Gas-tight enclosures are placed around each conveyor and component. The whole assembly moves at the rate of 23 m per hr, excavating a trench 11 m wide and 3 m deep, and processing regolith at the rate of 1260 tonnes/hr; consequently, ~ 2.5 mobile miners are required to supply the 1000 MWe power plant.



Figure 9. One possible version of a lunar miner designed to extract solar wind volatiles. The width of the trench is approximately 11 m and the depth ~ 3 m. The solar energy collected is used to heat the regolith and will require one heliostat, 100 m diameter, reflecting sunlight onto the mobile receiver.

After the regolith is heated and the solar wind and other lunar volatiles are collected, the spent regolith is passed through a recuperator, to recover heat before it is discharged from the back of the unit into the open trench. The gases recovered are compressed into storage tanks which are transported by a service vehicle to a central processing facility. At this facility the ^3He constituent is separated from the other lunar volatiles in three processing steps; namely,

1. The hydrogen is removed by permeation through Pd windows.
2. The H_2O , N_2 , and carbon compounds are removed by condensation during the cold lunar night in a large radiator/condenser unit.
3. The ^3He is isotopically separated from the ^4He via a superleak technique followed by distillation.

The liquified ^3He is then transported to earth.

6.9. Energy Requirements to Procure ^3He

There are five main areas where major energy investments are required to procure ^3He [64]:

- Transportation - Carrying all the necessary equipment from earth to the moon to mine, separate and store the ^3He .
- Incremental Base Camp Supply - Food, water, atmosphere and living quarters for the personnel responsible for the maintenance of the mining equipment.
- Mobile Miner - Power to move, extract and compress lunar volatiles.
- Radiator/Condenser - Condensation of H_2O , N_2 , and carbonaceous gases.
- Isotopic Separator - Separation of ^3He from ^4He .

The transportation energy cost was based upon the amount of earth mass required to produce a kg of ^3He based upon the assumptions that the life of all components on the moon is 20 years and that 1 tonne of ^3He would be produced per year. The mass of material for a 10 person crew (1 year tour of duty) including an amortized living unit and semi-closed food cycle was estimated to be 13 kg per kg of ^3He produced. The aluminum radiator/condenser and the stationary solar mirrors required 12-13 kg, the mobile miner only 8.4 kg, the isotopic separator 4 kg and the service vehicle only 0.8 kg of mass per kg of ^3He extracted, respectively. The total mass commitment is 51 kg per kg of ^3He . In 20 years this means nearly 1000 tonnes of equipment and life support chemicals would have to be brought to the moon.

The energy required to transport a kg of mass from the earth to the moon depends on the configuration of the lift vehicle, the space port in low earth orbit, the orbital transfer vehicle, and the lunar lander fleet to be used. With today's shuttle and technology for a space station, this energy is approximately 100 GJ/kg of payload mass delivered to the moon but it is projected that this can be reduced to 30 GJ with a series of heavy lift vehicles. Based upon the 30 GJ/kg value, nearly 1540 GJ of energy is needed for transportation to and from the lunar base per kg of ^3He .

The energy required to operate the mobile miner on the moon has also been calculated. The largest energy usage is required to heat the lunar regolith (~ 4100 GJ per kg of ^3He released); however, since the process heat comes directly from the sun it was not included in the overall balance. Other lesser amounts of energy are required to run the compressors, to operate the excavators, conveyors, and for locomotion of the miner and service vehicle. The total net energy required for operation of the lunar miner is ~ 28 GJ/kg of ^3He extracted.

Finally, the operational energy required to circulate the gases through the radiator as well as that required for the cryogenerator of the isotopic separation unit is small and essentially no energy is required for the hydrogen extraction phase and relatively small

amounts are required for manipulation of equipment and for gas circulation. A major energy requirement is associated with the cryogenic liquifier, 184 GJ of energy required per kg of ^3He separated.

The total energy invested in obtaining and transporting a kg of ^3He to earth is given in Fig. 10. As expected the energy requirement is dominated by the transportation system. The base camp requirements are roughly 20% and the gas separation operations require $\sim 10\%$ of the total.

The energy required to obtain a kg of ^3He on earth was calculated at approximately 1750 GJ per kg of ^3He when the energy investment in a ground support crew and the construction of a fusion reactor were ignored and no credit was taken for the use of the byproduct lunar volatiles. Compared to the 600,000 GJ released by burning 1 kg of ^3He with D_2 , one finds a comfortable energy payback of ~ 340 .

Estimates have been made regarding the energy costs to construct and maintain a nuclear fusion power plant. For such a power plant the proportionate share of the construction energy required to fuse the 1 kg of ^3He is ~ 4800 GJ to produce $\sim 3 \times 10^5$ GJ (electric). When this is combined with the mining energy requirement the figure-of-merit (kWeh/kW(th)h) is 33. This value greatly exceeds those for a pressurized power reactor (nuclear fission) at ~ 10 or a coal-fired electrical generating station (without SO_2 removal) at ~ 11 [65].

7. Financial Factors Governing the Profitability of Lunar ^3He

An initial assessment was made [66] to quantify the economic benefits of using lunar ^3He in the D- ^3He fusion fuel cycle to provide some of the electricity needed in the USA during the first half of the 21st century. The profitability was considered from three different industrial viewpoints, namely: (a) Utility - to provide a reliable form of safe, clean, and economical electricity; (b) Lunar Resource Developer - obtain an attractive rate of return on an investment to mine and sell ^3He ; and (c) Integrated Energy Company - manage a “mine to

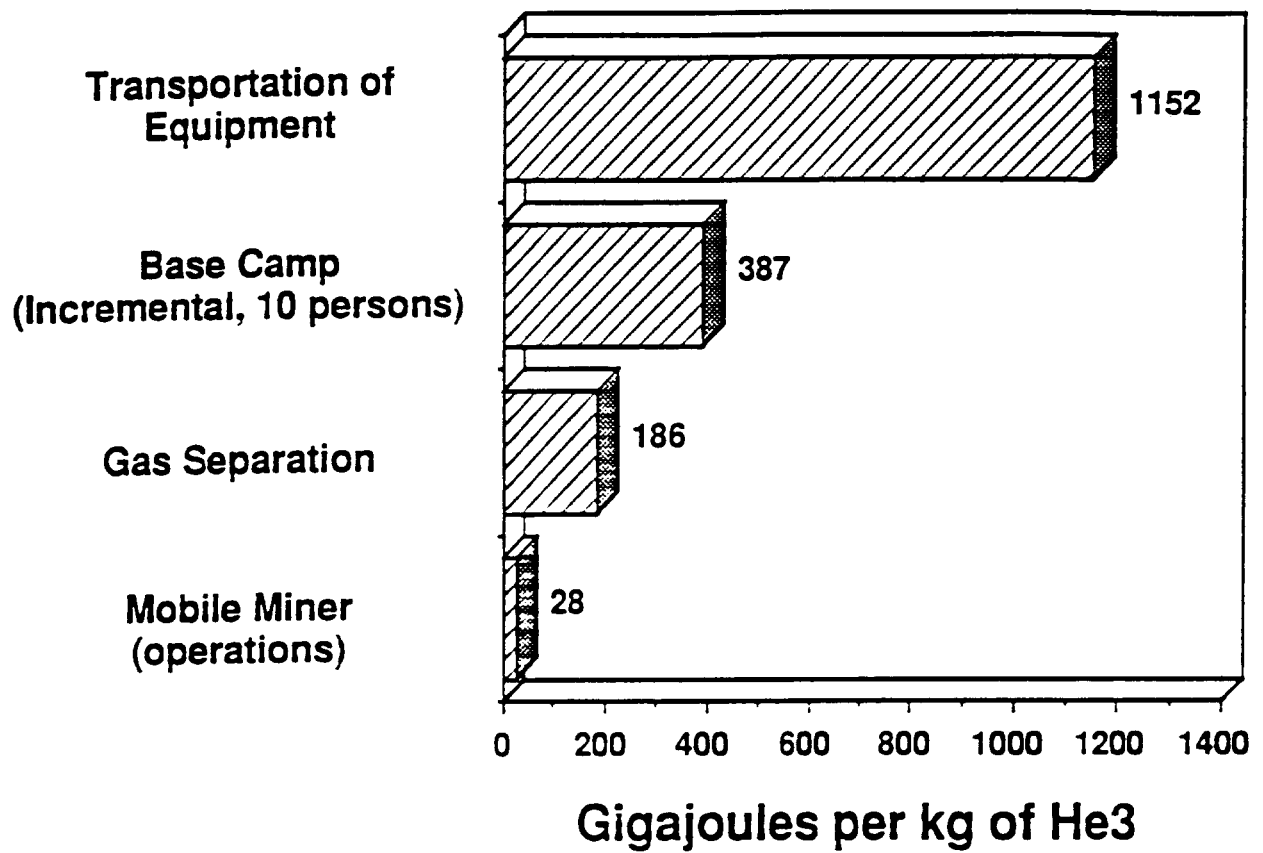


Figure 10. Energy invested to obtain and transport 1 kg of lunar ^3He to earth.

power plant” infrastructure to sell safe, clean, and economical electricity. These economic benefits were assessed using the Real Rate of Return (RRR) on incremental investment required for each of these industries to meet the electrical power requirements. Real returns and costs are generated by deleting the effect of inflation; therefore, the actual return received will be increased by the inflation rate.

The first step in this calculation was to establish the future electrical demand. For the purpose of this study, the U.S. growth rate for electricity demand was assumed to be 2%/yr from 1995-2050. Next, two scenarios to satisfy this demand were constructed as follows.

1. Electrical Generation Without Fusion

Nuclear fission power was assumed to grow at 3% per year after 1995 and the difference between the overall growth rate and the nuclear component would be made up by coal. The total cost for generating electricity in this case is the proportionated sum of coal and fission produced energy. Four cost factors were considered: capital costs, fuel costs, O&M costs and the R&D required to keep the plants running competitively.

The current capital costs for coal plants were assumed to be 1400 \$/kWe and the corresponding value for fission plants is 2650 \$/kWe. Current fuel costs for coal plants average 33.13 \$/ton which translates into 19 mills/kWh for fuel alone. Similarly, current fission reactor fuel costs are about 7 mills/kWh. The lower fission fuel costs are countered somewhat by its higher O&M costs. Presently, fission O&M costs average 10 mills/kWh versus 4 for coal. In order to reflect environmental factors, we have allowed the fuel and O&M costs to escalate by 2% per year. These environmental costs include mine and plant cleanup, increased emission reduction costs and increased waste management costs.

The current R&D costs are taken to be the same as those currently funded by the USDOE. The fission and coal technologies are currently funded at ~ 800 \$M/y each

and because of the concern over the environment, we have allowed 4% escalation in these costs.

2. Electrical Generation With Fusion

An aggressive growth rate was projected for fusion reactors fueled with lunar ^3He after the year 2025. This growth rate was accomplished by the following scenario: (a) no new coal plants after 2025, (b) no new fission plants after 2030, (c) only fusion power plants constructed after 2030.

This calculational procedure is identical to that without fusion. The capital cost for a D- ^3He fusion reactor was taken from the Apollo reactor study [67]. The 1200 MWe facility was costed at ~ 2000 \$/kWe and the O&M costs amounted to 5 mills/kWh. The fuel cost is the cost of operating the moon base including the transportation costs of materials taken to the moon and the cost of transporting the fuel on the return flight.

The current USDOE magnetic fusion R&D costs are ~ 350 \$M/y and were assumed to escalate at 4%/y, exclusive of inflation. Finally, the R&D costs needed for space research were included based upon the assumption that R&D for the development of heavy lift vehicles, a scientific base on the moon as well as the basic research needed to return to the moon for scientific reasons would be part of the national program. The specific ^3He space related research was assumed to start in 1991 at 10 \$M/y, rapidly escalate to 100 \$M/y by the mid-1990's and, thereafter, grow at a real rate of 4%/y.

Once the amount of energy produced by each energy producing system was calculated, the incremental investment and cash flows for each scenario were determined. The difference in total cash flow between the two scenarios is then the incremental investment required cash flow generated from reduced costs. The RRR on the incremental investment measures the benefit to society from the increased capital investment in the fusion alternative. It

is important to note that both methods understate the RRR because we have arbitrarily cut-off the calculation at the year 2050 even though much of the equipment and power plants still would produce electricity into the future.

7.1. Effect of ^3He Price on the Profitability of D- ^3He Fusion

The analyses showed that ^3He could cost as much as \$1000-\$2000/g and still allow D- ^3He fusion to be economically competitive compared to the coal plus nuclear power option. The base case value of \$1000/g was chosen and the sensitivity of the RRR of the three model companies was tested to a wider variation in the ^3He price, Fig. 11. Two important observations are noted with respect to our strawman companies. On the low side, it appears that even at a ^3He price of \$500/g there is an attractive ($\sim 25\%$) return on investment in the Lunar Company. It is also shown that even if ^3He were free, the profitability of the utility would not be more than 20%, which is well above the $\sim 7.5\%$ real return allowed for most regulated utilities.

On the high side, it was found that the ^3He price needs to be below \$4000/g to insure a 10% return on the Utility Company. At a price of \$3000/g, the profitability of the Lunar Company will exceed 30%. The profitability of the Integrated Company is unaffected by the ^3He price because it balances the profits of one company against the losses of another company.

The “Real” Cost of Lunar ^3He

A variation on this study was made [68] to determine the real cost of lunar helium-3 acquisition. This cost was considered to have chiefly two components; namely, (1) the cost of the moon base, and (2) space research and development costs.

The cost of the moon base includes all costs for transportation of miners, personnel, personnel habitats, and consumable life support commodities. The cost of transportation was assumed to be \$1000/kg from earth launch to the lunar base. The number of lunar

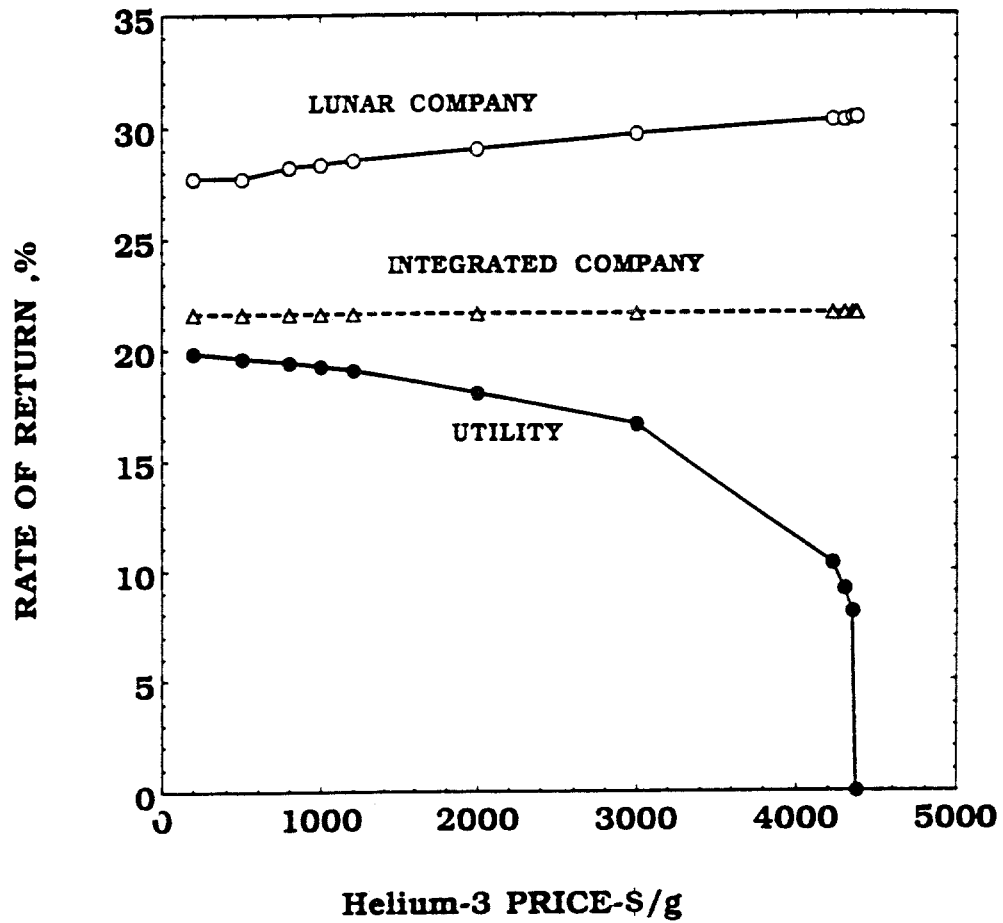


Figure 11. The effect of ^3He price on the profitability of three business groups involved in an industry to supply electrical power on earth by the utilization of lunar ^3He as a fuel for $\text{D-}^3\text{He}$ fusion power plants.

miners required with a launch mass of 18 tonnes/miner was determined by the need to fulfill the previously described aggressive schedule for the introduction of fusion electric power plants on earth beginning in the year 2015. The personnel and personnel habitats requirements were determined by the need for personnel to service and operate the miners. It was assumed that one person would operate one machine in the year 2015. With the progressive introduction of advanced automated equipment, one person (on an 8 hr basis) could operate 2 miners by the year 2020, 3 miners in 2025, 4 miners in 2030 and 5 miners in 2035. Personnel habitats and consumable needs were projected to be 820 kg/person a year. The habitats, which would require annual upgrading, were depreciated as an annual cost.

The space research and development costs, as previously described, included only those expenditures related to the acquisition of lunar ^3He . Based upon these assumptions, the cost of a gram of ^3He was determined for specific years during the mining scenario. As noted in Table 5, the unit cost is high in 2015 because of the startup of the lunar operation. After 10 years of operation the unit cost decreases to $< \$2000/\text{g}$ of ^3He ; thereafter, the cost per gram of ^3He in constant 1990 dollars decreases rapidly and reaches a plateau of $< \$300/\text{g}$ after 2040.

A recent study of a proposed D- ^3He fueled fusion power reactor utilizing direct and thermal energy conversion [4] indicates that the above costs of ^3He fuel could lead to attractively priced electrical power production. At $\$1000/\text{g}$ the ^3He fuel contributes ~ 11 mills to the electrical generation cost of 69 mills/kWeh.

8. Legal Regimes for Mining ^3He from the Moon

An initial study [69] examined the question, “under what legal regime could such a major undertaking be accomplished and what should the U.S.A. be doing now to insure that if we choose to pursue this energy form in the 21st century, we will be able to do so without severely disrupting international order?”

Table 5. Projected Cost of Lunar ^3He to Fulfill Earth-Based Fusion Power Requirements.

Calendar Year	Accumulated Cost \$10 ⁹	Accumulated Production tonnes	Average Cost/g (^3He) (\$1990)
2015	0.245	0.016	15,300
2020	2.59	0.59	4410
2025	6.34	3.67	1730
2030	16.2	22.0	735
2040	54.8	215.2	255
2050	105.5	704.9	150

The major precedents which were reviewed included terrestrial mining law, the Law of the Sea Convention, the Antarctic Treaty system, the Outer Space Treaty, the Moon Agreement, INTELSAT (International Telecommunications Satellite Consortium), INMARSAT (International Maritime Communication Satellite Consortium), and the Space Station Agreement. Many lessons can be learned from these international endeavors, some positive and some negative. For one thing, it seems clear that western industrialized nations and private commercial enterprises will only commit resources to a ^3He resource development program under a legal and economic regime which permits those engaged in such activities a major voice in managing the regime, as well as security of and a fair return on their investments. Thus, arrangements which appear inconsistent with free enterprise principles or which provide control by less-committed and less-involved nations on a “one nation - one vote”

principle (as in the 1982 Law of the Sea Treaty, Seabed resources provisions) will probably be unsuccessful in stimulating resource development. More successful arrangements such as INTELSAT and INMARSAT have proved durable over time and have resulted in significant financial benefits to those nations willing to invest resources in projects which are clearly long range and international in nature.

While no single solution was recommended, two statements were presented at the conclusion of this study; namely, (1) it is in the U.S. national interest, in the near future to establish an acceptable lunar resource regime; and (2) three potential alternatives for international agreements were suggested, as summarized below.

Ratification of the Moon Agreement

First seek prior consensus among space powers and ratify the moon Agreement. Then, rapidly call for a conference on Article 11 & 18 and include new consensus into the Moon Agreement. (Article 11 provides that “the moon and its natural resources are the common heritage of mankind.” Article 18 provides for a possible conference to review the Agreement with the concurrence of a majority of the States Parties.)

“Go It Alone” Philosophy

Past economic, political, and legal experience of the U.S. (along with the current environmental emergencies) suggest that the U.S. may have to consider unilateral development of the D-³He fuel cycle if other nations choose not to participate. Arrangements could be made to voluntarily share the benefits with developing countries. However, international agreements usually reduce the likelihood of disputes.

INTERLUNE, A User Based Organization [70]

The difficulty experienced by “one nation-one vote” organizations in the management of international enterprises is in sharp contrast with the success of organizations like INTELSAT or INMARSAT, suggesting, therefore, that a user based organization might be acceptable. This intermediate approach would be to form an international entity patterned

after INTELSAT but modified to incorporate the unique features of ^3He mining. Such an organization called INTERLUNE (short for International Lunar Enterprise) would be non-discriminating in that any nation could join and its financial return and operational control would be proportional to its investment.

9. Environmental Considerations

The net environmental effects of the deuterium/ ^3He fusion fuel cycle upon both the lunar surface and the terrestrial environment are being considered. This study initially compared the magnitude of the lunar ^3He mining endeavor with that of current terrestrial activities [71]. Large amounts of lunar regolith must be mined in order to obtain a significant quantity of ^3He . The quantity of lunar regolith which must be handled per year to accomplish the scenario used in the economics study (base case) is shown in Fig. 12 and compared with several past world resource handling systems. The lunar regolith handled by the year 2050 is seen to be only twice as large as the world coal production in one year (1988). It should be noted, also, that once the coal is mined on earth it must be transported long distances to the user. By contrast, the lunar regolith is only transported a few meters during its mining operation.

The conclusions of this part of the environmental study is that the tonnages of lunar regolith moved and the area of the lunar surface disturbed by the year 2050 is not unusual as compared to large-scale terrestrial industrial enterprises especially when it is considered that the lunar ^3He would be used to produce 60% of the U.S. electrical power needs by 2050.

The processing of the lunar soil would have some environmental effects upon the moon. For instance, the use of a mobile miner on the lunar surface maria regions would disturb the regolith to a depth of 3 m. After processing in the traveling miner, the warm regolith would be deposited in the trench behind the miner. As a result, the surface of the mined area would be smoother and show slightly elevated, undulated rows, but the mined areas could

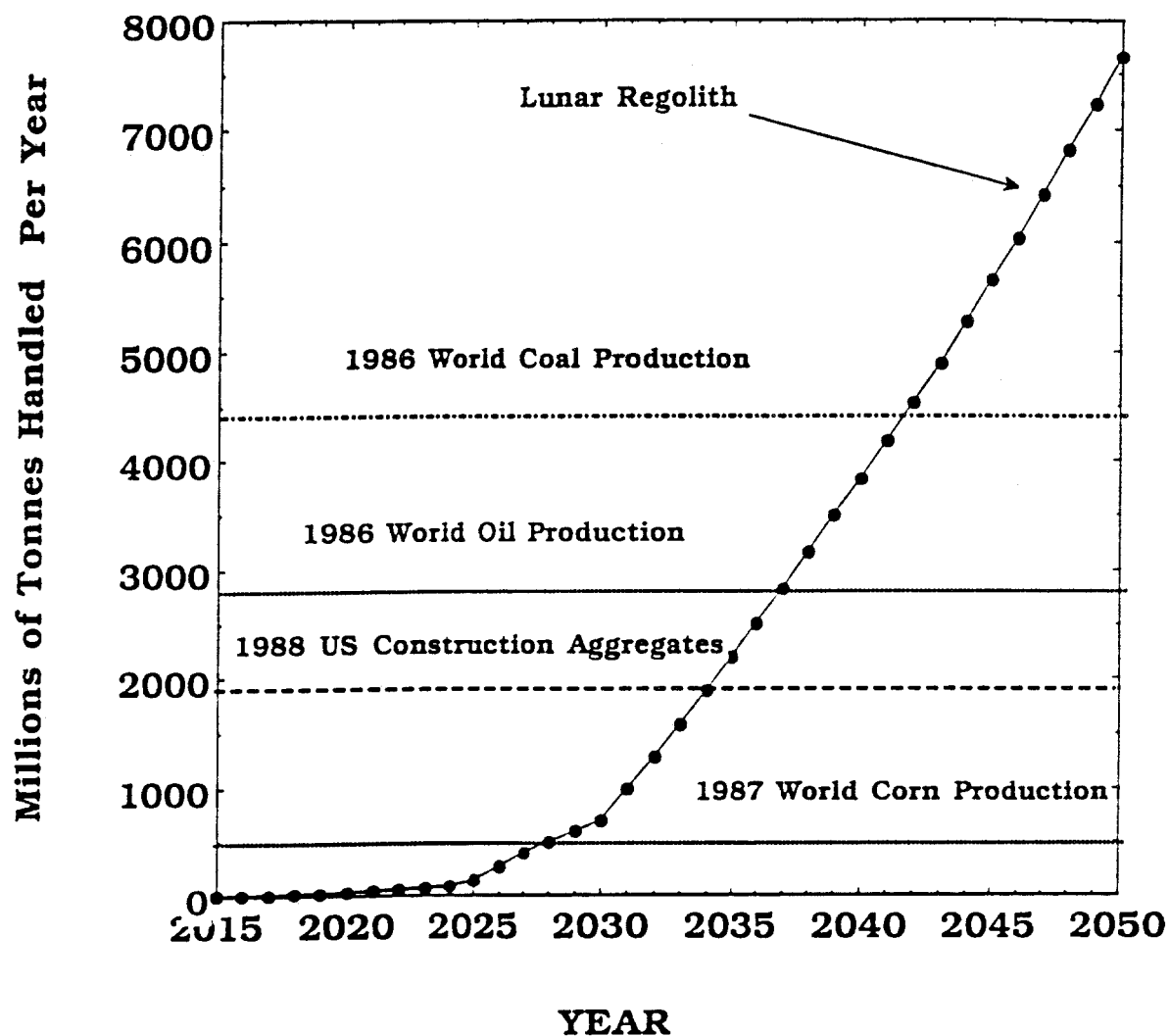


Figure 12. Magnitude of lunar regolith mining compared to annual world mining endeavors for the case of aggressive fusion power expansion in the U.S.A. beginning in the year 2025.

easily be regraded. Small craters less than 12 m diameter would be obliterated; however, substantial portions of the mare would not be mined and in those the full range of lunar features would be preserved. Heating of the regolith to only 700°C for release of the He would not chemically alter the ores.

The albedo, surface reflection, of the mined areas might be changed due to the physical disturbance of the regolith, but this effect should be very small. Photographs taken of areas close to the lunar modules used in the Apollo program indicate that the albedo is slightly brighter; however, areas several hundred meters away which were physically disturbed by the astronauts show no visually obvious change in albedo.

Dust will be produced during mining and reclamation; however, because of the absence of an atmosphere, settling will be ballistic, rapid and confined to the vicinity of the miner. The possibility exists that as the regolith is disturbed some of the solar wind gases which are not tightly bound in regolith may be released and locally form an artificial atmosphere. On the other hand, some of the undisturbed regolith, which has highly reactive surfaces, may act as a trap for gases, especially the water vapor derived from human habitation.

Reclamation of the sites after human habitation and the mining operation will require careful planning. The waste products from human habitation will be continuously recycled through a Closed Ecological Life Support System which will also supply fresh foodstuff and oxygen. The processing wastes and obsolete equipment will be buried in trenches or stored inside of hollow lava tubes which exist at certain locations on the lunar surface. After such reclamation the visible effects of the mining operation will be difficult to detect.

10. Discussion

The U.S. Department of Energy together with an international consortium of scientific and engineering partners are committed to the development of fusion reactor technology [72]. Furthermore, the benefits derived from the use of the D-³He fuel cycle in such reactors has been well documented [4].

This discussion will focus, therefore, on two issues, namely:

1. Is sufficient ^3He available on earth to conduct the R&D required to develop a commercial D- ^3He fusion power plant?
2. Is the lunar resource sufficient to meet the world's electrical power needs by the mid-21st century?

10.1. Availability of ^3He on Earth

Preliminary goals suggested for NASA (National Aeronautics and Space Administration) propose a return to the moon expedition [73] by the year 2005; consequently, deliveries of lunar ^3He to earth would not begin until ~ 2015 . As a result, sufficient ^3He must be available from earth-based resources to conduct the plasma engineering experiments required to determine the viability of a D- ^3He commercial fusion power industry. An estimate of the ^3He required can be based upon the USDOE plans for the development of d/t reactor technology. These plans indicate that following the d/t experiments in the Tokamak Fusion Test Reactor a test reactor capable of ignition, currently called the Burning Plasma Experiment (BPX), should be constructed and operational by the year 2000 and operate for 6 years [74]. This device could be useful for D- ^3He experiments with slight modifications but would have very low availability consuming only ~ 0.4 kg/yr of ^3He . Beyond the BPX, the international fusion community is considering the construction of the International Thermonuclear Experimental Reactor (ITER) [72] which would begin operation in ~ 2006 and provide a test-bed for materials irradiation studies for 10 yrs. The device would be followed by a power reactor-relevant demonstration reactor in ~ 2020 . A large test device similar to ITER would be required for D- ^3He studies but with modifications to provide the higher plasma temperatures; however, the D- ^3He device would not require the irradiation materials test cells because the neutron flux is sufficiently reduced that most of the irradiation data is already in hand. As a result, this advanced fueled ITER could also become a demo plant

in its later stages and the technology would be available to construct an operational plant by the year 2011. If an ITER-type test device were operated at 30% availability and fusion power of 800 MW for 10 years it would require ~ 150 kg of ^3He . The total need for ^3He in the R&D phase is ~ 152 kg.

This required amount of ^3He could be accomplished by the following scenario (Table 3). The quantity of ^3He from the tritium held by the USDOE could reach 100 kg if it were retained by the year 2000 and continue to produce ~ 5 kg/yr thereafter. The tritium separation plant of Ontario Hydro would accumulate ~ 10 kg by the year 2000 and continue to produce ~ 2 kg/yr. Some ^3He product could be obtained also from the AECL, Chalk River Laboratory following the installation of a new facility for the tritium separation from heavy water. Additionally, the suppliers of cryogenic helium, U.S. Bureau of Mines, and commercial sources, could be given financial incentives to install He isotopic separation systems. By 1995 these natural gas facilities could be collecting ~ 1 kg/yr of ^3He for a total of 5 kg on hand by 2000. If the need for cryogenic helium continues to expand as projected, these commercial suppliers might increase their rate of ^3He product after the year 2000 to ~ 5 kg/yr. The total ^3He available from all resources would be 115 kg by the year 2000 and at a production of 12 kg/yr for 10 years the combined resources could yield a total of 235 kg during the lifetime of the ITER/demo device. This total excludes any ^3He which might be made available from other nuclear reactors, natural gas sources, or obsolete weapons stockpiles.

11. Extraterrestrial Resources

The lunar regolith contains a vast inventory of ^3He and other solar wind gases. The basaltic regolith of the maria appear to contain the highest concentration, from 0.01 to 0.02 ppm ^3He and it is distributed fairly uniformly to a depth of 3 m. Our estimate indicates that up to 50% of Mare Tranquillitatis is readily minable. The maria bodies cover $\sim 17\%$ of the total lunar surface of 38×10^6 km²; however, nearly 50% of all the maria examined

by remote-sensing techniques have low Ti soils and, presumably, low He content. If the remaining maria with high Ti soils are similar to Mare Tranquillitatis in regard to minable areas and ^3He content, then the total ^3He readily available from the maria is $\sim 1 \times 10^5$ tonnes.

The highland areas of the moon cover the majority of the surface, $\sim 83\%$, but have a lower ^3He content for the regolith (0.004 to 0.008 wppm); however, the average regolith depth appears to be > 5 m. When these factors are considered and perhaps 10% of the highland could be mined by some advanced technique, the total ^3He from the highlands of the moon could produce another 1×10^5 tonnes of ^3He .

The total estimated readily recoverable lunar ^3He would be $\sim 2 \times 10^5$ tonnes and if utilized in a fusion power reactor which produces 10 GWe·y/tonne of ^3He , the total energy available represents 2×10^3 TWe·yr. If the world's population requires 6 TWe·yr per year by the year 2050, then this resource could supply all of the world's required electrical power for 330 years. By that time, techniques for recovering ^3He from the low Ti-bearing mare basalts should be in-hand, and space exploration will be developed so that the vast ^3He resources on other planets could be imported.

The extent of this lunar energy resource is similar to that for d/t fusion power which relies upon the availability of Li. A recent survey of the earth's Li resource [75] indicates that 13×10^6 tonnes of Li (containing 6.5 wt% of ^6Li) are located in several areas of the world with the biggest reservoirs located in the brine deposits of Chile. If 50% of this ^6Li could be recovered and utilized in a fusion reactor with an energy efficiency of 5 GWe·yr/tonne of ^6Li , then this resource could provide 2×10^3 TWe·yr of electrical power. With an electrical demand of 6 TWe·yr per year, this resource would provide 350 years of service. The likelihood of finding an extraterrestrial Li ore-body is highly unfavorable. Also, neutrons produced by the d/t fusion cause safety and environmental concerns not inherent in the D- ^3He fuel cycle.

The only fusion fuel which has a more extensive and readily available resource is the deuterium located in the earth's hydrosphere for the d/d fusion reaction. This resource contains 6×10^{13} tonnes of d and if 50% were utilized for fusion with an energy equivalent of 1.4 GWe·yr/tonne of d, then this resource could provide 4×10^{10} TWe·yr and last for $\sim 6 \times 10^9$ yr. Unfortunately, a credible design for a commercially viable d/d fusion reactor has not been demonstrated and the neutron flux emitted from such a reactor would be comparable to that of a d/t reactor.

12. Conclusions

This review has shown that consideration of the use of lunar ^3He for fusion fuel is justified because it is a significant resource that could provide long-term electrical power generation for use on earth. The assessment of the lunar resource is based upon a collection of returned lunar samples, remote-sensing data and topographical photographs of large areas of the lunar surface. Although this information is limited, it should be indicative of the geology and topography of the lunar surface. The real rate of return for the financial investment in such an industry is attractive and a legal precedent exists for commercial development of this resource.

The development of the D- ^3He fusion power reactor technology concomitant with the development of the lunar resource is technically and financially justified. The implementation of the lunar ^3He industry coincides with the challenge to NASA enunciated by President Bush in 1989 to develop a "Space Exploration Initiative" for early in the 21st century [76]. In this regard, the other solar wind gases released during the quest for ^3He would also be of high value to support manned scientific colonies planned for the moon in the early part of the 21st century.

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