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NET ENVIRONMENTAL ASPECTS OF HELIUM-3 MINING – PHASE I: EFFECT ON THE MOON

WCSAR-TR-AR3-9012-1

Technical Report

Wisconsin Center for
Space Automation and Robotics
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Net Environmental Aspects of Helium-3 Mining

- Phase I-

Effect on the Moon

by

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Preface

Since the first realization that lunar helium-3 could be a major source of energy in the 21st century, there have been many technology studies pertaining to the procurement and use of this fuel. In addition to the analysis of the lunar geology, there have been studies of the lunar mining equipment, fusion reactors utilizing helium-3, legal and international implications of procurring the fuel, and the financial prospects associated with developing this energy source. One area that has not been addressed specifically is the *net* environmental effects associated with the extensive use of helium-3. The word "net" is important in that such a study must necessarily include both the potentially detrimental effects on the Moon's environment as well as the apparent beneficial effects to the Earth's environment.

The Office of Commercialization in the NASA initiated such a study in late 1989 at the Wisconsin Center for Space Automation and Robotics (WCSAR). We are particularly indebted to Dr. Raymond Whitten who anticipated the need for such a study and who was instrumental in its expeditious implementation. It is also important for us to acknowledge the assistance of scientists in the Fusion Technology Institute, in particular, Dennis Bruggink, Layton Wittenberg, John Santarius, and Igor Sviatoslavsky.

I. Executive Summary

One of the most critical problems that is facing civilization is the development of a safe, clean and economic source of energy to support the 10 billion people who will inhabit the Earth in the 21st Century. It has been recently proposed that the thermonuclear fusion of deuterium (D) and He3 can fulfill that need. The DHe3 fuel cycle generates less than 0.01% of the radioactivity per kWh of electricity than a corresponding fission reactor. In addition, it can provide energy at a higher efficiency (approximately twice that of current fission reactors) and there is no possibility of radiation induced fatalities in the public due to the worst possible accident. The physics of the D-He3 cycle has been studied and found to require approximately 2 times the temperatures already achieved in the laboratory and 30 times the plasma density-confinement times ($n\tau$) needed for deuterium-tritium (DT) fusion reactors. Devices to achieve these parameters are already being designed and should be operating in the late 1990's or shortly after the turn of the century. Commercial power plant studies show that the electricity from such reactors will be competitive with DT systems and, when environmental credits are taken into account, will also be competitive to current fission and fossil fueled systems.

The He3 needed for such reactors can come from terrestrial sources during the development phase up to, and including, the first commercial power plant. After the first power plant (which could be as early as 2015) larger supplies (0.1 tonne/1000 MWe-y) of He3 will be needed. Such He3 resources have been identified on the lunar surface and estimates run into the 500,000 to 1,000,000 tonne range. The He3 has been deposited by the solar wind and the gaseous resource can be removed by heating the lunar regolith, in place, and transporting the gaseous products to the earth. No large movement of lunar material is required.

In order to assess the <u>net</u> effort of a D-He3 fusion economy, one must balance the positive effects to the Earth's environment by any negative effects to the lunar environment. This study concentrates on the lunar environment and subsequent studies will document the beneficial effects to the Earth's environment.

An analysis of the possible detrimental effects to the Moon is made and only a few features appear to be relevant to the extraction of lunar volatiles from He3 mining.

The current mining schemes envisioned would extract He3 from 40-50% of the lunar Mare and would have essentially no permanent effect on the lunar atmosphere (or lack of it). The change in surface reflectance may be visible to an observer on the surface of the moon but not from the Earth. The lack of any water or atmosphere on the moon means that there will be no despoilment in these areas and the only "pollution" problem is the disposal of worn out equipment and human wastes. Landfills are probably the best solution since there is no ground water.

The conclusion drawn at this time is that there are relatively few detrimental effects to the lunar environment from He3 mining. Further research with respect to disposal of wornout equipment and the byproducts of human presence needs to be conducted.

II. Introduction

The announcement by President Bush [1] that

"..., I'm proposing a long range, continuing commitment. First for the coming decade, for the 1990's - Space Station Freedom, our critical next step in our space endeavors. And next, for the new century, back to the Moon. Back to the future. And this time back to stay. And then a journey into tomorrow, a journey to another planet: a manned mission to MARS."

makes it all the more urgent that long range planning for the habitation of Space be initiated. The President's announcement was made in the midst of major worldwide environmental uncertainty, largely brought on by the extensive use of fossil fuels and LFC's. The present energy use rate (≈10 barrels of oil equivalent per person per year) has resulted in the relatively rapid depletion of valuable fossil hydrocarbons and the fouling of our air, water, and land to obtain and use those resources. Furthermore, we may be in the process of causing permanent climatic changes by expelling potential "greenhouse" gases (CO_2 and CH_4) into the Earth's atmosphere.

One obvious way to save our fossil fuels and to improve the terrestrial atmospheric environment would be to make extensive use of nuclear energy through fission reactors. This has been undertaken to varying degrees in the developed countries and some 32 nations are now operating 421 nuclear fission power plants which produced ≈17% of the World's electricity in 1988 [2]. However, nuclear fission waste issues plus concern over costs and safety have effectively halted the continued development of that energy option in the United States.

Another form of nuclear energy, nuclear fusion, promises to be much more environmentally acceptable and, because of superior safety characteristics, should be free from many of the costly delays now facing the licensing of fission power plants. Unfortunately, the control of the fusion reaction in the laboratory has proved to be harder than for the fission process, but scientists are now within a year or two of the first scientific breakeven experiments [3,4] with deuterium (D) and tritium (T) and serious planning is underway for a 1000 megawatt facility to operate at the turn of the century [5].

It has been known for some time that an even more attractive fusion fuel cycle than the DT system exists thru the combination of D and an isotope of helium, He3. The advantages of this fuel cycle will be examined in the next section, but the major impediment to its development has always been the apparent lack of a large source of He3. Such a source eluded fusion scientists until 1986 when a major deposit of He3, originally discovered in lunar samples in 1970 [6], was "rediscovered" by the fusion program [7]. Subsequent analysis of the He3 resource base [8-10], the mining equipment needed [11-12], and the design of D-He3 fusion power plants [13], has been augmented by legal [14] and financial studies [15]. It is now obvious that the energy resources on the Moon are enormous (approximately 7 times the energy in all the economically recoverable fossil fuels used to date on Earth), and the possibility now exists that we can solve both our environmental and long range energy problems by extracting this valuable fuel from the Moon and bringing it to the Earth.

Before any large scale program is instituted for the production of lunar He3, it is important to examine all of the environmental advantages and disadvantages from such an operation. This analysis is somewhat different than an Earth based EIS (Environmental Impact Statement) in that we must consider the _net_ effects in the Earth-Moon system. The major question to ask is "will the improvement of the Earth's environment be significantly more than the degradation of the Moon's environment?" The purpose of this study is to examine both sides of the issue, but this interim report will concentrate specifically on the environmental impact to the moon. The reader should be careful to balance the positives with the negatives over the entire system before drawing any conclusions.

The organization of this report is as follows. Chapter II will examine the question of "Why are we interested?" This will be followed by some details of the proposed mining and reclamation plan (Chapter III). Next, an overview of the environmental problems (Chapter IV) is given. The specific analyses of the potential environment impacts are covered in Chapter V. The possible solutions will be discussed in Chapter VI followed by conclusions (Chapter VII) and recommendations (Chapter VIII).

Phase II of this project will begin immediately after the completion of this report. The second report will concentrate on the terrestrial benefits and attempt to balance them against whatever environmental degradation may occur on or near the surface of the Moon.

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III. Significance of Helium-3

III.A. Historical Perspective

Scientists first proposed the use of thermonuclear energy for civilian applications in the 1950's. This work closely followed on the heels of the first test of the Hydrogen Bomb, and it was felt that commercial fusion energy would take only a few decades to perfect. Unfortunately, the difficulty of controlling plasmas (collections of charged particles and electrons) at temperatures 10 times hotter than the center of the sun proved to be much more difficult than originally anticipated. Most of the 1960's was spent developing the field of plasma physics and laying the ground work for a theoretical understanding of plasmas. By the end of the 1960's, and with unprecedented cooperation between U.S. and Soviet scientists, it became apparent that once the plasma physics problems were solved, significant technological progress was also needed to develop a safe and clean power source. Thus, in the 1970's, a dual approach to the problem was pursued; (1) several large plasma physics facilities were constructed to test the theories developed in the 1960's and (2) engineering analyses of power plant designs were initiated to ascertain the technological, economic, safety, and social implications of this new form of energy. Both of these lines of research were continued in the 1980's with a major milestone of energy breakeven (i.e., the point at which as much energy is emitted from the plasma as it takes to keep it hot) within our grasp as we move into the 1990's. The current plan is to construct several large reactor-like facilities in the 1990's which will produce power in the 500 to 1000 megawatt regime and to use these facilities to test materials and power conversion schemes that might be used in the 21st century.

Fundings by major players in the worldwide fusion effort are now roughly equal with the European program being slightly larger than that in Japan, the United States and the USSR. In the early 1980's, approximately 2 B$ per year was being spent on fusion research with the U.S. in the lead of that effort. Today, the total effort is slightly less but it is clear that the European program has taken the lead from the U.S. and that a strong challenge for 2nd is being made by the Japanese. Altogether over 26 B$ in then current dollars has been spent on fusion research since the early 1950's.

Further descriptions of the fusion process can be found in the references at the end of this chapter [1,2], and only those aspects of this fuel cycle important for this paper will be repeated here.

III.B Relevant Plasma Physics Principles of Thermonuclear Research

Since the early days of the civilian thermonuclear fusion program, scientists had always envisioned that fusing a deuterium (D) and tritium (T) atom at very high temperatures (see Equation.1) would prove to be the most favorable for the production of electricity.

$$D + T \rightarrow He4 + neutron \qquad (1)$$

$$\text{Energy released, } Q = 17.6 \text{ Million Electron Volts (MeV)}$$

There were several reasons why this choice was made, ranging from the fact that the DT cycle ignites at the lowest energy (see Figure III-1) to the experience gained from the thermonuclear weapon program in breeding and handling tritium. Two other reactions, listed below, were also briefly considered.

$$D + D \xrightarrow{50\%} T + H \qquad Q = 4.0 \text{ MeV} \qquad (2)$$

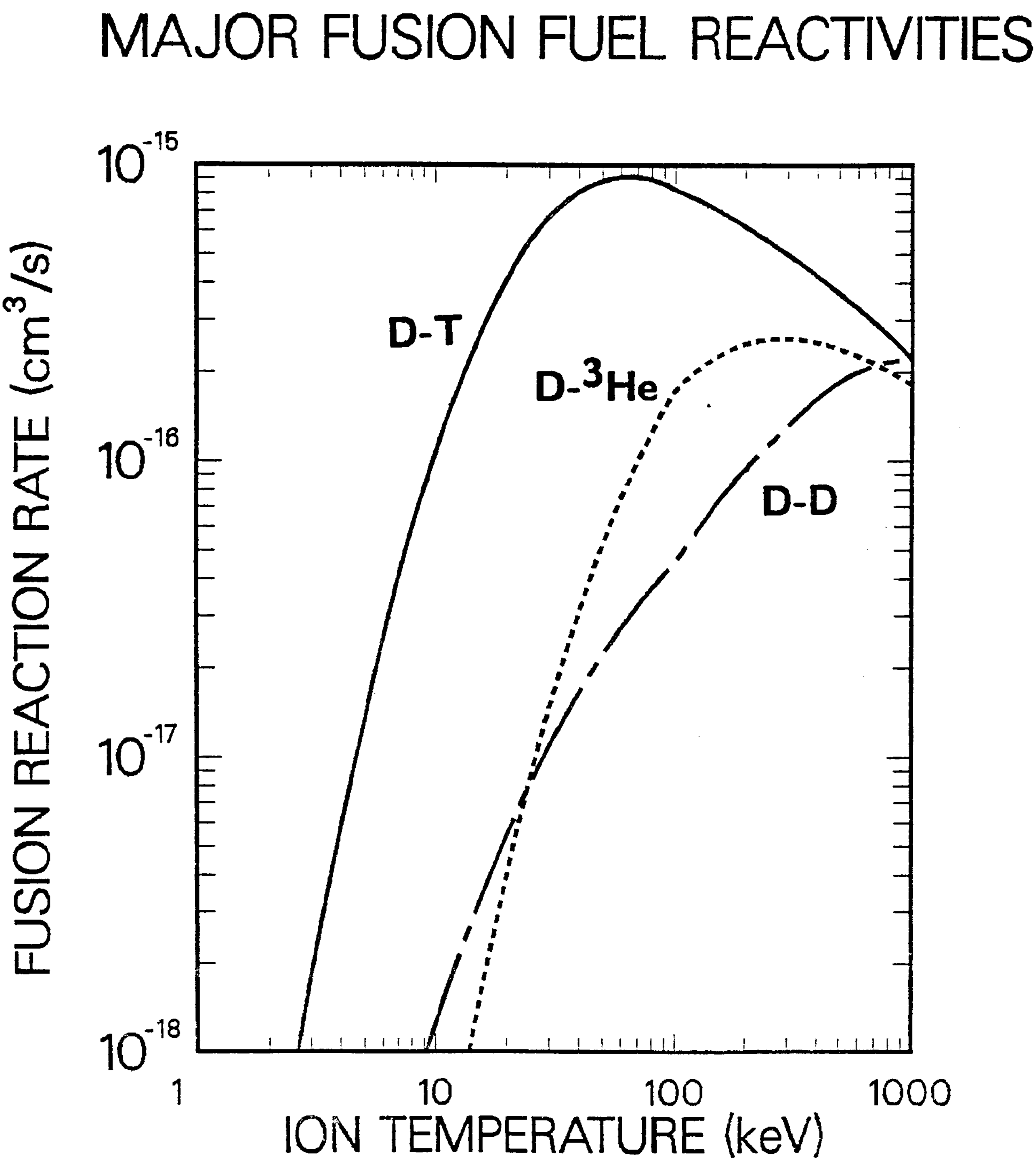
$$D + D \xrightarrow{50\%} n + He3 \qquad Q = 3.3 \text{ MeV}$$

$$D + He3 \rightarrow He4 + H \qquad Q = 18.4 \text{ MeV} \qquad (3)$$

Neither of these reactions has received much attention since the 1950's, because they both require higher temperature (see Figure III-1) to ignite and because, there was no significant resource of He3 known.

Several things have changed since those early days of fusion research, and two of these will be addressed in this chapter. First we will address the improving situation in fusion physics, and second we will address the renewed interest in the technological and environmental advantages of the D-He3 cycle. The question of the He3 fuel supply will be addressed in Chapter IV.

Figure III-1


MAJOR FUSION FUEL REACTIVITIES
FUSION REACTION RATE (cm³/s)
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
D-T
D-³He
D-D
1
10
100
1000
ION TEMPERATURE (keV)

III.C State of Plasma Physics as it Pertains to the D-He3 Cycle

Simply stated, the objective in magnetic fusion research is to heat the confined plasma fuel to sufficiently high temperatures (T), at high enough densities (n), and for long enough times (τ), to cause substantial fusion of atoms to take place. Mathematically stated for a reactor using the DT cycle, this can be given as;

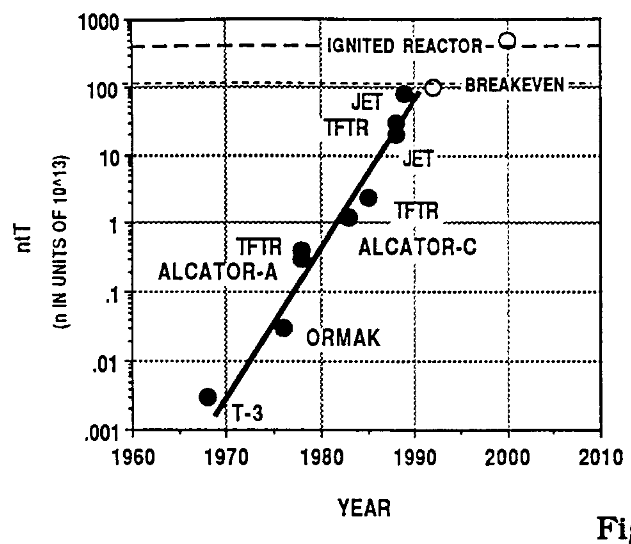
$$n\,\tau \geq 2 \times 10^{14} \text{ seconds per cm}^3 \qquad @\ T \approx 20 \text{ keV (200 million °C)} \quad (4)$$

Some perspective on the rate of progress in producing these conditions is given in Figure III-2a where the $n\tau T$ values achieved are plotted with respect to when they were first attained and Figure III-2b which shows the progress toward energy breakeven. The $n\tau T$ product has been increasing at the phenomenal rate of a factor of 100 every 10 years. In fact, in one parameter, namely the temperature T, scientists have actually produced 35 keV ions in TFTR plasmas at the Princeton Plasma Physics Laboratory (PPPL). This is 75% higher than needed for a DT reactor and less than a factor of 2 lower than needed for a D-He3 reactor. The appropriate n,τ, and T values for a D-He3 reactor are

$$n\tau \geq 4 \times 10^{15} \text{ seconds per cm}^3 \quad (5)$$
$$\text{at } T \cong 60 \text{ keV (600 million °C)}$$

A detailed physics analysis shows that the Compact Ignition Torus (CIT) at PPPL could achieve the temperatures required by D-He3 in the mid to late 1990's.

While it is necessary to reach a $n\tau T$ product (in units of 10^{13} keV-s per cm^3) of ~ 100 for breakeven in DT and a value of 400 for DT reactor operations (Figure III-2), it is necessary to achieve a $n\tau T$ product of 24,000 for the D-He3 reactor. Recent analyses show that such values could be achieved by small modifications of the Next European Torus (NET) [3] or the International Thermonuclear Experimental Reactor (ITER) currently being designed for operations around the year 2000 [4]. In other words, despite



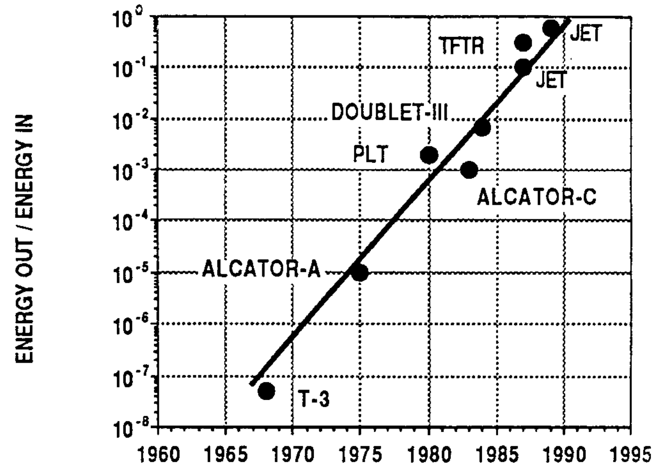


Figure III-2

A. Steady progress in the 3 major physics parameters for DT fusion.

B. The progress toward energy breakeven conditions has shown an increase of over 1000 every 10 years for the past 20 years.

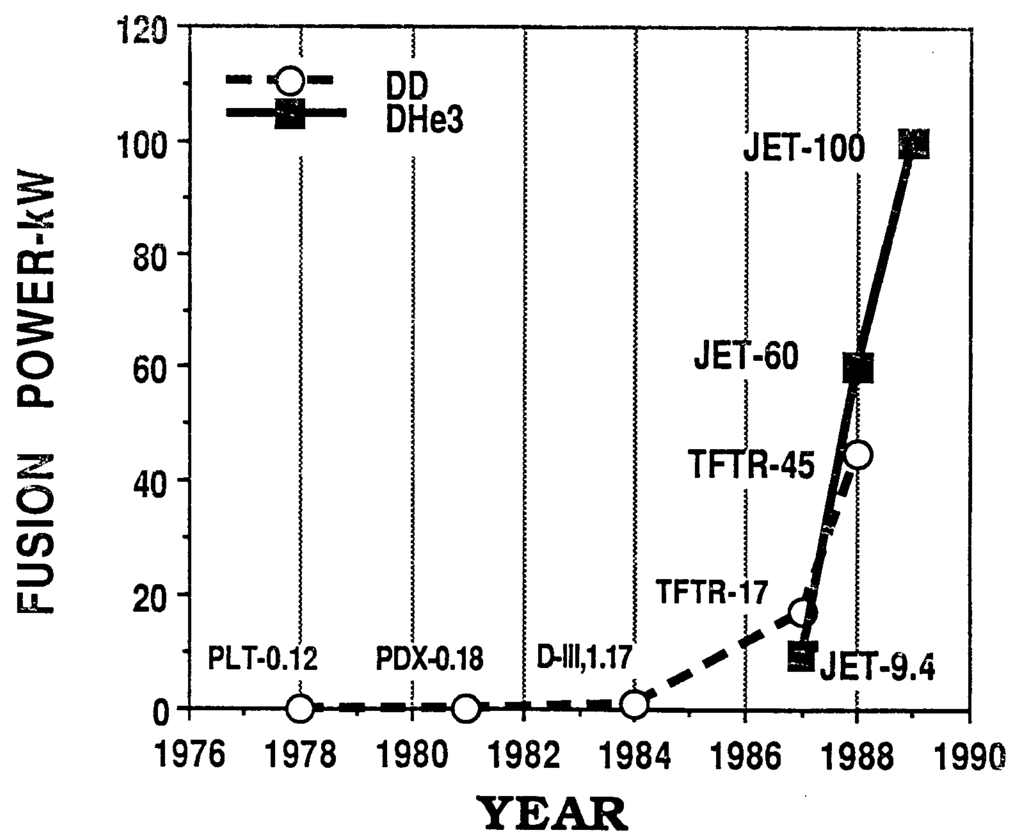


Figure III-3 Actual release of thermonuclear energy in the laboratory by the DD and D-He3 reactions from the PLT, PDX and TFTR devices at Princeton, the D-III device at General Atomic, and the JET device in Culham, England.

the factor of 60 increase required in $n\tau T$ values for a working D-He3 power plant over a DT system, several possibilities to achieve those values are available.

The surprising historical point of the previous discussion is that only a few short years ago, most scientists would have believed it impossible to produce the necessary D-He3 reaction conditions before the year 2020 or even later. However, scientists at JET have recently produced 100 kW of thermonuclear power with the D-He3 cycle [5] (see Figure III-3). The possibility that significant power could be produced with He3 before the year 2000 has opened up a whole new class of studies since 1987 and caused many to reassess of our long-range goals in fusion research.

III.D Technological Benefits of the D-He3 Fuel Cycle

One of the key features of the pure D-He3 reaction in Equation 2 is that both the fuel and the reaction products (protons and He4) are <u>not</u> radioactive. However, some of the deuterium ions do react with each other and produce a small amount of neutrons which can induce radioactivity in the reactor walls. When the cross section and fuel mixtures are included, one can calculate how much of the average energy release is in the form of neutrons (see Figure III-4). Whereas the DT cycle releases 80% of its energy in neutrons regardless of the plasma temperature (and the DD cycle releases ~ 50% in neutrons) one can see that operation at ~ 60 keV with a 3:1 ratio of He3/D, can result in release of as little as 1% of the energy in neutrons in a D-He3 plasma.

Why is this important? The radioactivity associated with and radiation damage of reactor components is directly proportional to the number of neutrons produced. Since the energy released per reaction from DT and D-He3 is roughly the same, then on a per unit of power produced, the problem associated with neutrons can be reduced by almost 2 orders of magnitude (i.e., a factor of 80).

The main technological advantages resulting from these characteristics of the D-He3 fuel cycle, when compared to the DT cycle, are summarized as follows:

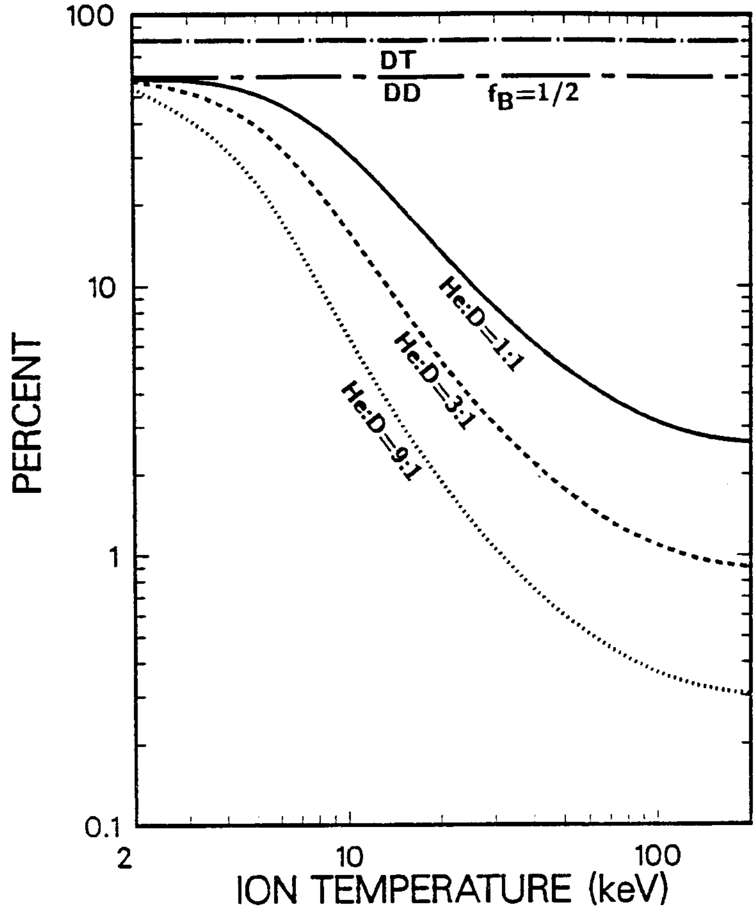


Figure III-4. The percent of thermonuclear energy released in the form of neutrons by the DT, DD, and D-He3 fuel cycles. Note the variation of He3 to D ratio.

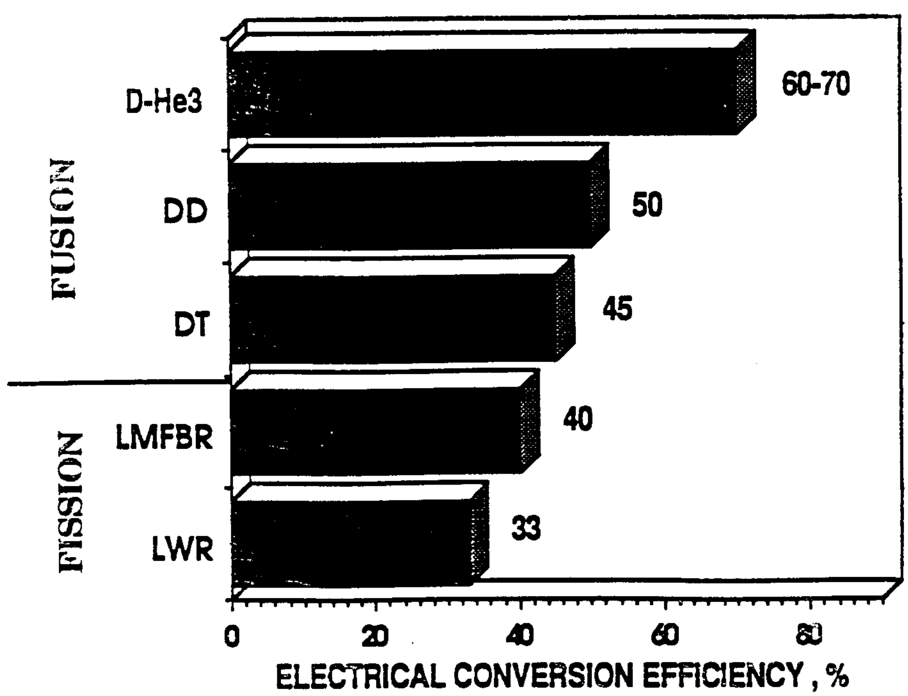


Figure III-5. A comparison of overall conversion efficiencies of nuclear energy to electricity. The use of direct electrostatic or electromagnetic energy conversion schemes greatly enhances the performance of fusion devices.

a) Increased electrical conversion efficiency.
b) Reduced radiation damage.
c) Reduced radioactive waste.
d) Increased level of safety in the event of an accident.
e) Lower cost of electricity.
f) Shorter time to commercialization.

Only a very brief comment on each of these features will be made here and the reader is referred to several recent publications by the authors for a more in-depth analysis [6-9].

III.D.1. Efficiency

If only ~ 1% of the energy is released in neutrons, then the other ~ 99% is released as charged particles or photons. In linear magnetic fusion devices where most of the energy leaks from the reactor in the form of highly energetic charged particles, one can convert their kinetic energy directly to electricity via electrostatic converters at ≥ 80%. This means that overall plant efficiencies of 60 to 70% are achievable. In toroidal magnetic devices, one can convert the synchrotron radiation emanating from the electrons (frequency ~ 3000 gigahertz) directly to electricity at roughly the same efficiencies through the use of rectenna. Depending on how the other forms of energy emitted from the plasma are utilized, the efficiency in toroidal devices may then be in the 50-60% range.

A comparison of the maximum conversion efficiencies that might be achieved by fission or fusion devices is shown in Figure III-5. The important point to note is that fusion devices may increase the efficiency of fuel usage by as much as 50 to 100% compared to fossil fuels or fission reactors. Such considerations are very important for thermal pollution in a terrestrial setting, but they are, in fact, critical to power plants that may operate in space. The rejection of heat in space is very, very costly.

III.D.2 Radiation Damage

When high energy neutrons, such as the 14 MeV neutrons emitted from the DT reactions, interact with structural reactor components, they can greatly reduce the mechanical performance of those components and induce significant long-lived radioactivity. Within our present state of knowledge it is known that it will be difficult to operate a DT fusion reactor for more than a few years before the metallic components become so brittle that they will have to be replaced. This requires shutting the reactor down, handling highly radioactive components, exposing workers to ionizing radiation, and generating large volumes of radioactive waste. Our best estimates at this time are that 2 to 3 full power years are about the limit for present day materials. Since economic reactors should operate for 30 or more full power years, such changeouts will occur 10 or more times during the lifetime of a typical DT fusion plant.

On the other hand, if one can reduce the neutron fraction to ~ 1% of the energy released in the D-He3 cycle, then the metallic components will last ~ 80 times longer than in a DT reactor. Such an extension is enough to completely obviate the necessity for component change due to neutron damage. This longer life and associated reduction in waste material will have profound economic and environmental benefits in a society based on the use of fusion energy.

III.D.3 Reduced Radioactivity

Because of the much smaller number of neutrons, the induced radioactivity in the reactor walls will also be reduced by a factor of ~ 80. In today's DT fusion reactor designs, special materials will have to be developed in order to avoid generating large amounts of high level wastes that must be placed in deep underground repositories. For example, conventional steels would become so radioactive in a DT reactor that as much as 10 m^3 per reactor year would have to be sequestered in one of the national deep repositories <u>proposed</u> for operation near the turn of the century. On the other hand, these same materials would last the 30 full power year life of a D-He3 plant and still could be disposed of as low level, class C waste buried in near-surface disposal sites. If low activation steels or other materials are developed, then such alloys, after 30 years of operation could be buried along with medical waste in near-surface sites. Aside from the tremendous savings in cost, one would find that wastes from a $D\text{-}He^3$ reactor will decay to benign levels in less than 100 years instead of the 1000's of years required for current fission and fusion devices.

III.D.4 Safety

One of the most severe accidents that could occur in a DT fusion plant is the complete loss of coolant along with a complete breach of reactor containment. The afterheat in a DT reactor can be sufficient to release large amounts of tritium and radioisotopes from the reactor structure. At present, it is not known whether we can keep critical components from melting in a commercial DT reactor during such an accident.

In a D-He3 reactor, two fundamental characteristics prevent such dire consequences from a loss of coolant. First, the afterheat (which comes directly from the neutron activation products) is so low that in the event of the most severe accident to be imagined, and if no heat leaked from the system (e.g., if the entire reactor was wrapped in a perfect, thermally insulating blanket), the maximum temperature increase in a week would be ~ 500°C (still 1000°C below its melting point). Secondly, the tritium inventory in a D-He3 plant can be as little as 10 grams [9]. The complete release of this tritium, in a rain storm, could still cause no more exposure to a member of the public living next to the D-He3 reactor than he or she typically receives from natural sources of radioactivity such as cosmic rays and radon gas in a year's time.

III.D.5 Cost of Electricity

There are features of the D-He3 fuel cycle which strongly suggest that it will provide electricity more cheaply than a DT fusion power plant. These are:

a) lower capital cost
b) lower operation and maintenance costs
c) higher efficiency
d) higher availability.

The first point is based on a comparison of two recent D-He3 reactor designs, Ra [6] and Apollo [7,9], to 17 previous DT reactor designs, most done by the same group with the same costing philosophies. The results of this comparison are shown in Figure III-6. The capital cost of the Apollo-L D-He3 system is ~15-50% lower than comparable DT plants. The reason for this has to do with the greatly reduced blanket and shield costs. It also has to do with the fact that D-He3 plants, which contain such low levels of tritium and radioactivity, could use conventional grade construction material, thus avoiding the high nuclear-grade material costs associated with fission and, probably, with DT fusion reactors.

Because of the low radioactive inventory and low level of neutron damage, there should be no required replacement of components due to neutron damage. This means that the number of plant personnel can be greatly reduced compared to a DT plant. The use of solid state electrical conversion equipment also will require less maintenance personnel.

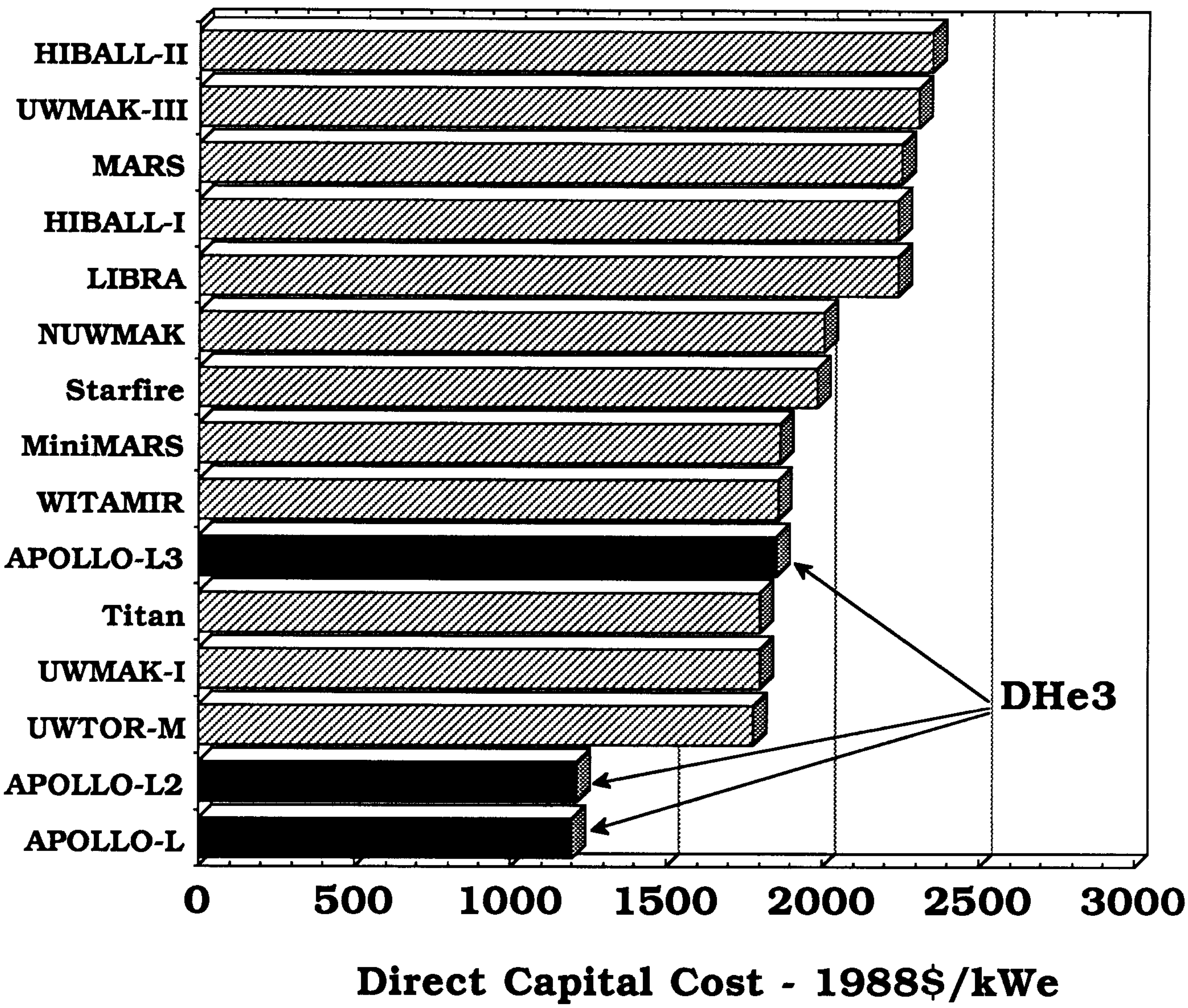
The higher electrical efficiency will have a direct effect on the specific cost parameters. For example, the capital cost per kWe will be lower for the same thermal power, and the cost of heat rejection equipment (i.e., cooling towers) will be greatly reduced.

Finally, the ultimate cost of electricity, in mills per kWh, can be reduced if the plant stays on line for a larger fraction of its total lifetime. As stated previously, a DT power plant has to be shut down frequently to change neutron-damaged components. The duration of the down time will be adversely affected by the induced radioactivity and the problems associated with tritium contamination. It is also well known that power plants, which use a high-pressure steam cycle (as would a DT plant), require on average, on the order of 10-15% of their total life time to repair steam turbines and heat exchangers. The use of solid state conversion equipment, rather than a steam cycle, should reduce that number in a D-He3 plant similar to the way solid state TV sets are more reliable than those which used vacuum tubes.

The time from now to commercialization of D-He3 fusion could be shorter than the time to commercialize the DT cycle even if it takes longer to solve the remaining physics problems associated with higher temperatures and

Figure III-6

DHe3 Fusion Power Plant Are Amoung the Lowest Cost Fusion Reactors Yet Designed



longer confinement times. The reason for this again lies in the low fraction and lower average energy of neutrons released in the D-He3 cycle and the need to develop a whole new class of metals and alloys to withstand the damage associated with the 14 MeV neutrons from the DT cycle. Conservative estimates of the cost to solve this problem include a materials test facility (1-2 B$ capital plus 10-15 years operating time costing another 1-2 B$ in operating expenses), and a completely new blanket test facility in a demonstration power plant (4-5 B$ + 10-15 years and ~ 5 B$ operating costs) before one could get to a commercial system. Add to this significant sum the cost of an auxiliary technology program for 20-30 years beyond the solution of the physics problems (another 10-20 $B) and we can see that an additional ~ 30 $B and 30 years could be required to commercialize DT fusion after the DT operation in the ITER* class of fusion devices in the year 2005.

On the other hand, if the ITER* could be slightly modified (for less than 10% of its present cost) to ignite D-He3, then the same reactor could also be used to generate electricity in a demonstration reactor mode by 2005-2010. Since there is no need for a materials test facility nor for the need of developing breeding blankets, a prototype D-He3 commercial plant could be operational by the year 2015-2020, a full 15-20 years sooner than possible with the DT cycle. This latter scenario should result in a 10-15 B$ savings just to get to the first commercial power plant. Subsequent capital cost and cost of electricity savings would result in each more savings as we move into the mid 21st Century.

*ITER stands for the International Thermonuclear Experimental Reactor which is representative of the 1000 MW class of reactors proposed by several nations (US, USSR, Japan, the European Community) for construction starts in the 1990's.

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[4] G.A. Emmert, University of Wisconsin, to be published.

[5] D.A. Boyd et al., He^3-d Fusion Reaction Rate Measurements During Fast Wave Heating Experiments in JET, Joint European Torus Report JET-P (88) 42, Culham England, September 1988.

[6] G.L. Kulcinski, G.A. Emmert, H. Attaya, J.F. Santarius, M.E. Sawan, I.N. Sviatoslavsky, and L.J. Wittenberg, "Commercial Potential of D-He3 Fusion Reactors," Proc. 12th Symp. Fusion Engr., Monterey, CA, IEEE-87CH2507-2, p. 772 (1987).

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[8] "The Moon: An Abundant Source of Clean and Safe Fusion Fuel for the 21st Century," G.L. Kulcinski and H.H. Schmitt, 11th International Scientific Forum on Fueling the 21st Century, October 1987, Moscow, USSR.

[9] G.L. Kulcinski, et al., "Apollo-L3, An Advanced Fuel Fusion Power Reactor Utilizing Direct and Thermal Energy Conversion," to be published in <u>Fusion Technology</u>, 1991.

IV. What Is Being Proposed?

IV.A. Nature of the Helium Resource

The helium resource of the Moon is contained in the regolith, the surficial layer of fragmental, mostly very fine-grained material (regolith) that almost everywhere overlies the lunar mare basalt flows. The regolith has been produced by the impacts of the innumerable bodies, very small to very large, that have collided with the Moon during the nearly 4 billion years since the Moon's older regimal mare were formed. Available information indicates that, in general, the regolith on the lunar maria, or "seas", averages 4 to about 7 meters thick depending on the age of a particular mare surface. As the regolith has formed, it has been exposed continuously to the solar wind, which mainly consists of hydrogen and helium atoms emitted from the Sun in an energetic plasma. These gases have been implanted in the surfaces of the lunar regolith particles.

Since the energy of the solar wind gases is low (a few keV), the gases are concentrated in the first few thousand angstroms of the particles smaller than 150 microns in diameter which make up about 60 percent of typical regolith. The implantation of gases in particulate material is also proportional to total particle surface area per unit of mass. When this fine material is heated to about 700 degrees Celsius, essentially all the hydrogen and about 90 percent of the helium are released and can be collected along with other gases in a suitable apparatus. This is the basis for all plans for recovery of helium, and associated hydrogen, nitrogen, carbon monoxide and carbon dioxide, water, and methane, from the Moon.

Analysis of samples from the Moon has shown that the regoliths of certain of the maria are richer in helium than those of other maria and of the highland areas [1]. The enrichment is correlatable with the presence of abundant ilmenite, an iron-titanium oxide mineral which appears to have a higher capacity for retention of helium than other minerals present in lunar regoliths. Remote sensing has shown that large areas of Mare Tranquillitatis, on which Apollo 11 landed, are covered by this type of regolith, and Mare Tranquillitatis appears at present to be the most promising initial source of He3.

IV.B. Plan of Operations

IV.B.1. General Statement

The current plan for recovery of helium from the Moon includes the following activities:

(1) Excavation of the upper few meters of regolith over areas of thousands of square kilometers.

(2) Separation and discard of coarse material present in the regolith.

(3) Heat treatment of fines to release the implanted gases.

(4) Disposal of spent fines.

(5) Collection of released gases, mainly hydrogen, carbon oxides, methane, nitrogen, water and helium.

(6) Reclamation of mined land.

(7) Separation of helium and the other gases.

(8) Separation of He3 from He4.

(9) Supporting activities:

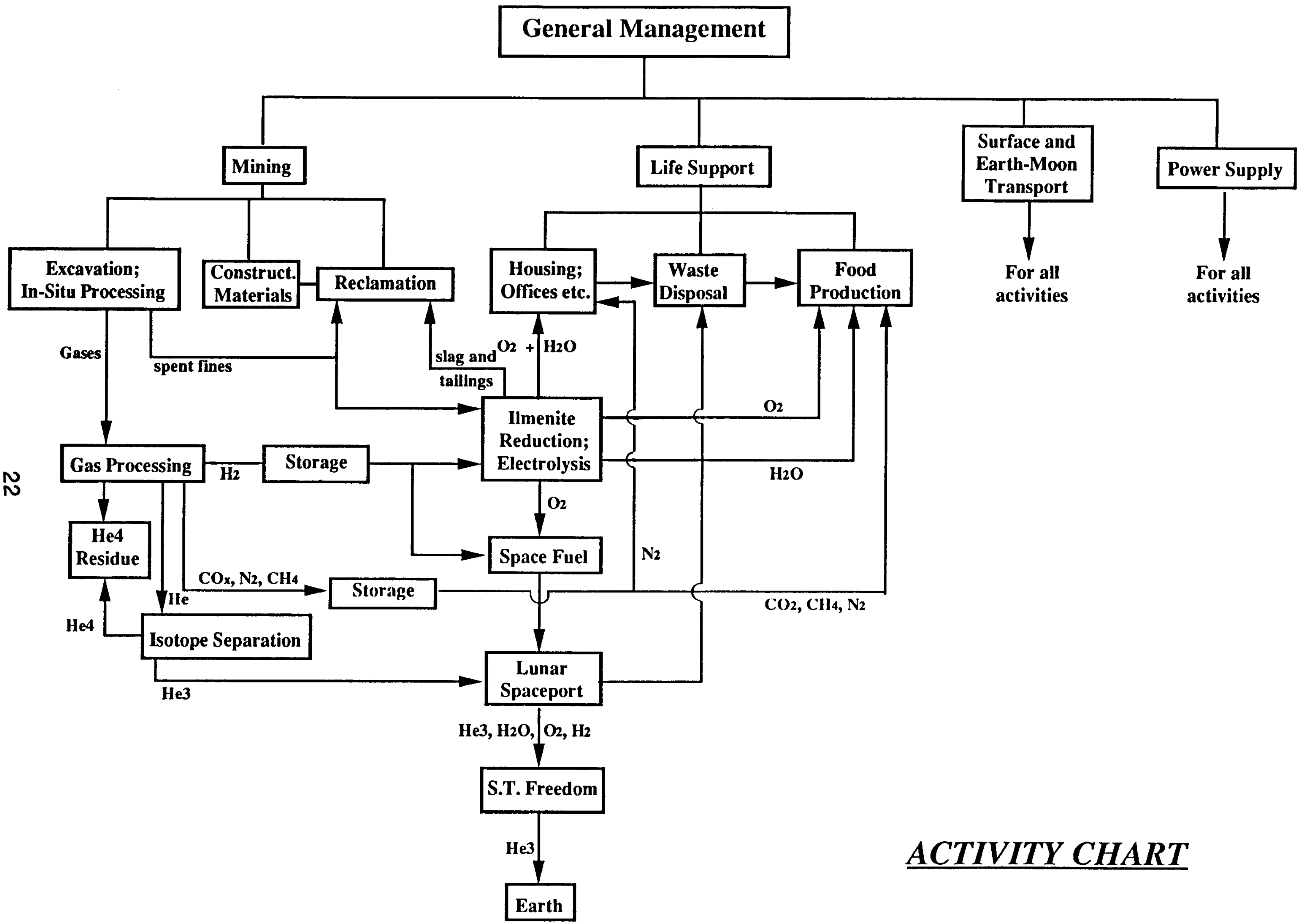
- (a) Energy generation and supply.
- (b) Surface transport.
- (c) Transport to and from Earth.
- (d) Life support (housing, oxygen and water, food production, waste disposal, and recreation).
- (e) Servicing of facilities and equipment.
- (f) Communications.
- (g) Inspection, maintenance, and repair of mining equipment.
- (h) Management.

The flow sheet of Figure IV-1 summarizes these activities and indicates their interrelations. Figure IV-2 is one possible schematic layout of the required facilities that are described below.

IV.B.2. The Mining System

IV.B.2.a. General Statement

The first six of the activities listed in IV.B.1 above, will be the responsibility of the mining system. The current plan calls for a strip mining system patterned after systems that are standard on Earth in surface mining of flat or gently-dipping, sheet-like mineral deposits that underlie flat or gently



ACTIVITY CHART

Figure IV-1

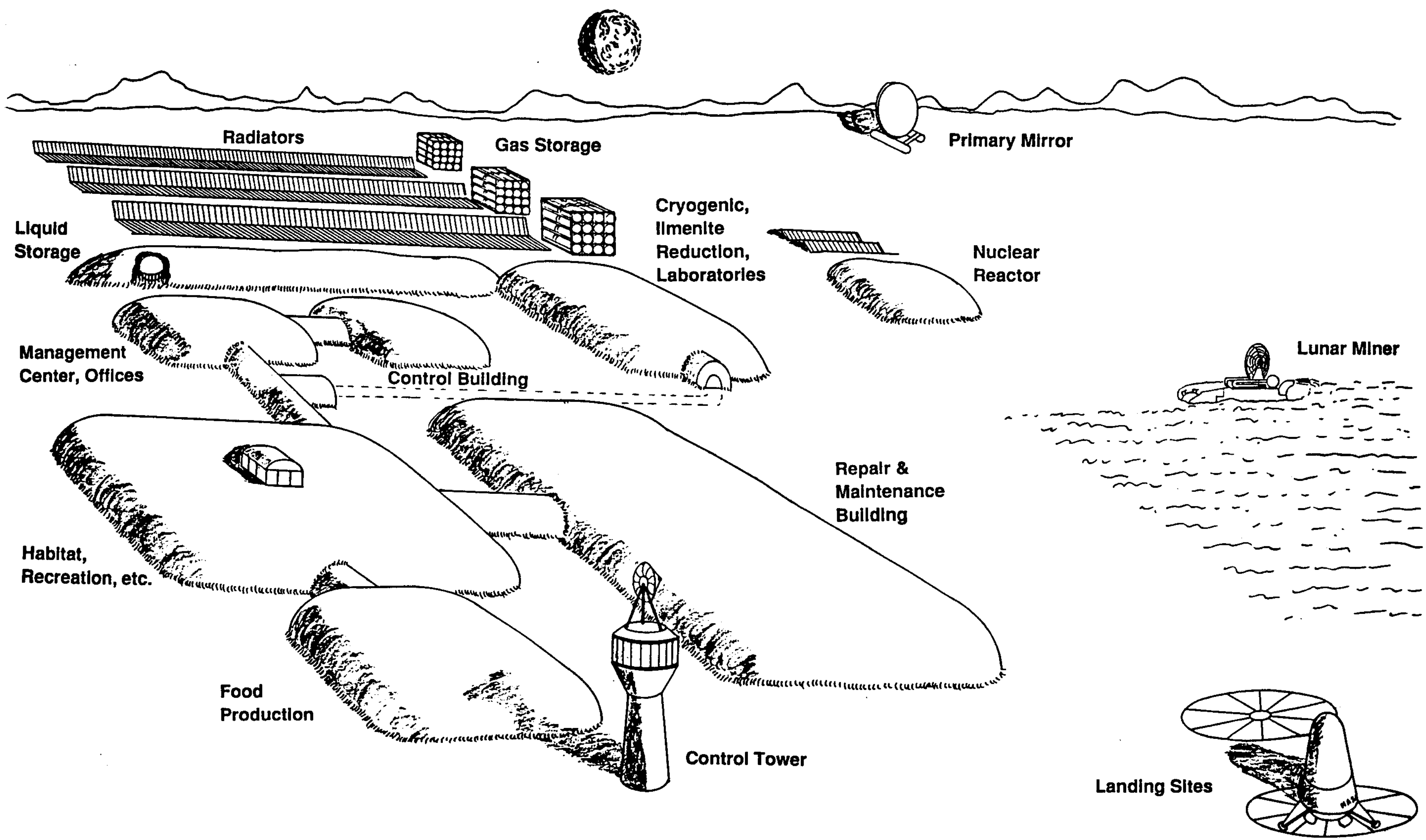

Radiators
Gas Storage
Primary Mirror
Liquid Storage
Cryogenic, Ilmenite Reduction, Laboratories
Nuclear Reactor
Management Center, Offices
Control Building
Lunar Miner
Repair & Maintenance Building
Habitat, Recreation, etc.
Food Production
Control Tower
Landing Sites

Figure IV-2

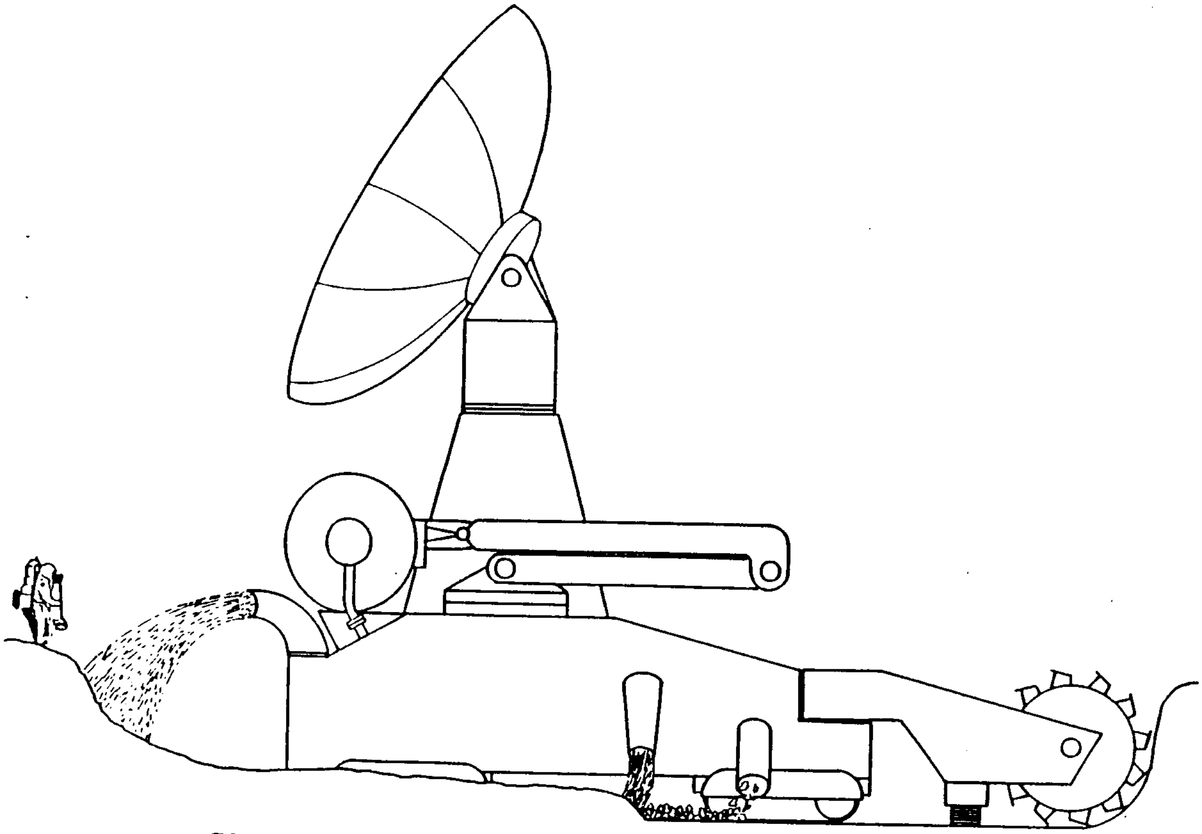
undulating terrains. Such systems are in wide use in surface mining of coal. In the following discussion and in Figures IV-1 and IV-2, a strip mining system is assumed.

IV.B.2.b. Surface Strip Mining System

Strip mining can be accomplished by a fleet of unmanned, mobile machines; one design that has been proposed is shown in Figure IV-3 [2]. Each machine will excavate regolith, separate the fine material, process it by heat treatment, collect the released gases, and restore both coarse material and spent fines to the lunar surface basically in the same place from which it was extracted. Each machine will be assigned a specific area to mine, which will be excavated in successive parallel, contiguous strips. As each strip is mined, discarded coarse material and most of the spent fines will be delivered to the already mined part of the strip behind the machine. Ilmenite in the spent fines could be sent to a reduction plant for oxygen recovery. The second component of the mining system will be a set of unmanned bulldozers that will grade the refilled strips to produce a gently undulating surface. The third component will consist of vehicles for transport of the collected gases to processing plants described below. The fourth component will consist of shops for maintenance and repair of mining machinery and surface vehicles. Space for storage of equipment not in use will be included. The fifth component will be a building housing personnel and equipment for operational control, communication, and management of the mining system. Most mining and reclamation will be done by remote control from this facility. The final component will be roads connecting the mining areas with other units of the mining system and with processing plants and other installations described below.

IV.B.3 Gas Processing Plant

Gas produced by the mining system will be transferred to a plant in which it will be processed (1) to separate helium and hydrogen from other gases, (2) to recover carbon-oxygen compounds, nitrogen, water and methane, (3) to separate hydrogen from helium, and (4) to separate He3 from He4. In the same plant it would be possible to produce H_2O by hydrogen reduction of ilmenite, and to use the H_2O to produce oxygen by electrolysis.



SIDE VIEW OF LUNAR MINER MARK-II

TOP VIEW OF LUNAR MINER MARK-II

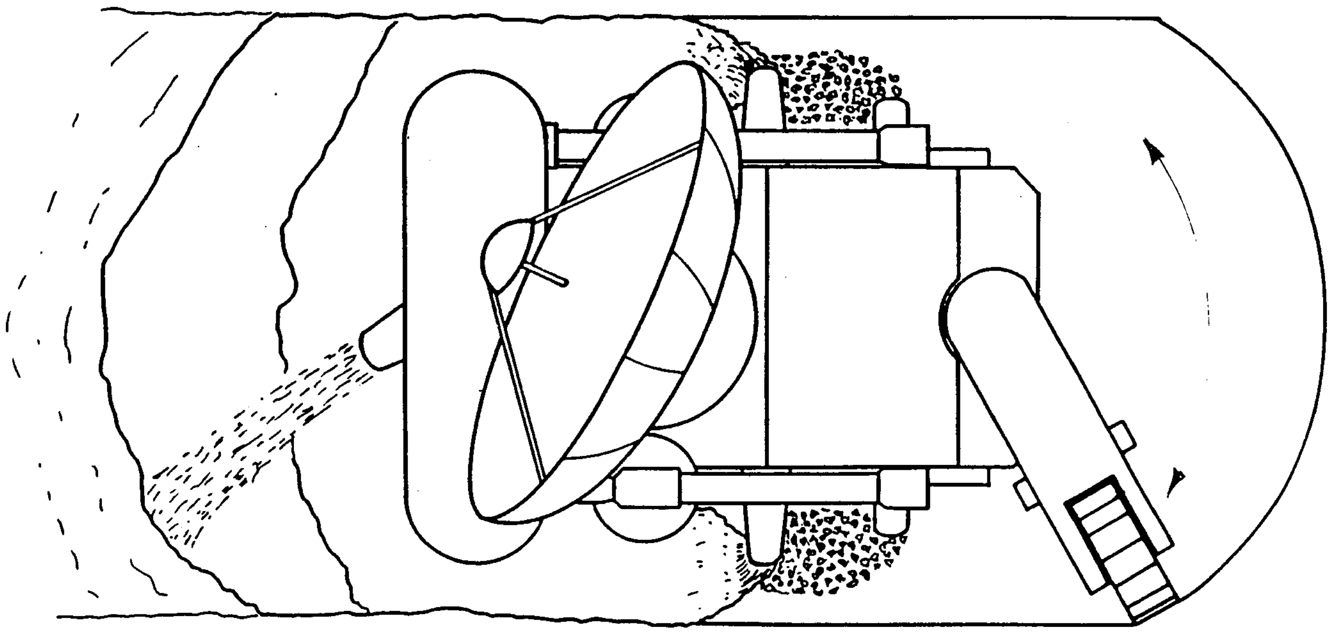


Figure IV-3. Schematic views of the lunar miner MARK-II. From Sviatoslavsky and Jacobs (1988).

The water will be used directly in life support, in human consumption, and in food production. The H_2 and O_2 will be used in part in the production of space fuel and fuel cells. Carbon-hydrogen compounds will be used in food production, along with most of the nitrogen. The methane will also be valuable for production of hydrocarbons. The He4 can be used for pressurization and as a working fluid in power systems.

Included in the facilities of the lunar base must be adequate storage facilities for supplying needs for various gases during the lunar night. As shown in Figure IV-2, the gas processing plant will be located close to the fixed installations of the mining system. It will also be centrally located relative to the various facilities requiring its products.

Although all these gases have potential value as export commodities, the need for some gases on the lunar surface may preclude their export. For example, for every tonne of He3 produced, over 18,000 tonnes of by-product gases are generated [3]. Their value raises the issue of long term and low cost storage of large volumes of gases, not only because of their intrinsic value but because their release would far exceed the quantity considered inconsequential in creating an artificial lunar atmosphere (see Section VI.D). The long term cost of storage may be mitigated by use of large permanently shaded areas (naturally available above about 78° latitude). Another solution may be to supercool stored material during the lunar night in facilities thermally insulated by lunar regolith during the lunar day.

IV.B.4. Supporting Activities

IV.B.4.a. Energy Generation and Supply

Energy for the operation of mobile mining machines will be beamed from installations (e.g., mirrors) that will collect and redirect solar energy. Energy for other activities will probably be a mix of nuclear and solar energy received from installations outside the area of Figure IV-2.

IV.B.4.b. Surface Transport

The experience of astronauts in walking and traveling in a light vehicle on the lunar surface suggests that the lunar regolith will not support continued traffic of heavy vehicles without maintenance and that some roadbeds will have to be provided for transport to and from mining areas and between various surface facilities. It has been suggested that roadbeds might be created by microwave sintering of the regolith, but field tests will be necessary to evaluate the feasibility and energy cost associated with the method. It might prove satisfactory for roads used by light vehicles, such as those provided for the transport of personnel, gases, and small equipment, but it may not be satisfactory for making roads used by heavy vehicles, such as mobile miners and heavy trucks transporting construction materials. In that case, roads for heavy traffic would have to be constructed out of aggregate produced from mining operations. A facility for maintenance and repair of road-building and road-maintenance equipment and for storage of equipment when not in use will also be required.

IV.B.4.c. Space Transport

To provide for transport of personnel, materials (including equipment that cannot be manufactured on the Moon), and supplies to and from the Moon, a spaceport will be constructed. This will include a launch and landing area, a control tower, a communications center, and facilities for receiving personnel, materials, equipment, and fuel. Appropriate storage facilities will be part of the spaceport installation.

IV.B.4.d. Life Support

Life support activities consist of construction and maintenance of all facilities necessary for housing and recreation of personnel and for production of food. A life-supporting pressurized atmosphere, waste disposal facilities, and a plant or plants for food production must be provided. Where personnel are working for extended periods of time, in special sections of various buildings and plants, and in certain areas at the spaceport, pressurized atmosphere, water, and waste disposal facilities must be provided. Such places include offices, laboratories, repair shops, control rooms, and reception rooms for personnel arriving at and departing from the spaceport.

Oxygen and water are basic ingredients of a life support system on the Moon. For this purpose, the reaction of the excess hydrogen with an ilmenite concentrate produced from spent regolith fines will be employed to increase the water supplies. Special furnaces, housed in an appropriate plant, will be required for the process. The product of the furnaces will be water, part of which could be electrolysed to recover elemental oxygen and the remainder used for a local water supply. Together with water, carbon dioxide, nitrogen, and methane, produced at the gas processing plant are essential for food production.

IV.B.4.e. Management and Control of Operations

Offices, research facilities, and all other facilities associated with management and control of operations will be housed in a centrally located building at the lunar base.

IV.B.5. Construction Materials

Apart from special components that will have to be brought to the Moon from Earth, it is anticipated that construction materials for buildings needed for the activities described above will be obtained from regolith pits at points located near the main lunar base, except as these can be provided as byproducts of helium mining. Construction materials will include those needed for thermal insulation and for shielding from cosmic radiation and solar flares. One or more plants for manufacturing concrete and special insulating materials may also be required. The design and methods of construction of facilities for a lunar base are still under discussion in the scientific and engineering community and to discuss these in detail in the present report would be premature.

IV.B.6. Establishment of Additional Bases

In Section VI.B of this report, it is estimated that, on the average, about 40 percent of the total area of Mare Tranquillitatis will be minable. If this estimate is borne out by experience, by the end of 2052 mining operations will extend over about 42,000 sq. km. (see Chapter VI), equivalent to a square area of 205 km on an edge. At some point, as mining moves away from the original base, rising costs of transport of equipment to and from active mining sites will require establishment of subsidiary bases for repair and maintenance that cannot be done if the field. Over the longer term, a series of complete bases will undoubtedly have to be established at various points on Tranquillitatis.

References for Chapter IV

[1] Cameron, E.N, "Helium Mining on the Moon: Site Selection and Evaluation," Proc. of Symposium on Lunar Bases and Space Activities in the 21st Century (1989), in press.

[2] Sviatoslavsky, I.N. and Jacobs, M., "Mobile Helium-3 Mining and Extraction System and Its Benefits toward Lunar Base Self-Sufficiency," p. 310, in Engineering, Construction and Operation in Space, Proceedings of Space 88, Amer. Soc. Civil Engr., 1988.

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V. Overview of Potential Environmental Reporting Requirements
V.A. General Requirements of Opening a Large Coal Mine on Earth (U.S.)

There are no legal or regulatory requirements presently in force regarding lunar mining and reclamation for helium-3 and other solar wind volatiles. The best terrestrial analog appears to be surface coal mining, which is an energy-related mining activity, involves large-scale earth-moving, and is highly-regulated. Hence, as an initial model, we will consider the Federal environmental impact statements associated with a US surface coal mine.

There are a number of Federal permits required in order to open, operate, and close a US surface coal mine. Among them are:

Army Corps of Engineers - Dredging and Filling in Waters of the United States
Department of Interior
- Office of Surface Mining Reclamation
  - Mine and Reclamation Operating Permit
- Environmental Protection Agency
  - Clean Air Act - Air Containment Source Permit
  - Clean Water Act - Waste Water Discharge Permit
  - Resource Conservation & Recovery Act
  - Toxic Substances Control Act

Department of Labor
- Mine Health and Safety Act - Operators License

Department of Transportation
- Hazardous Waste Materials License

In addition, each State has its own special regulations, which we will not consider in this study.

Of course, all of these permits are important. But one is particularly significant, and that is the Application for Surface Coal Mining and Reclamation Operations Permit, administered by the Office of Surface Mining Reclamation and Enforcement (OSMRE) of the US Department of the Interior, in accordance with the Surface Mining Control and Reclamation Act of 1977 (SMCRA, Public Law 95-87). This permit application form is over 100 pages long, and is divided into five sections:

(1) Administrative Information;
(2) Existing Environmental Resources--Baseline Data;
(3) Operation and Reclamation Plan;
(4) Maps and Drawings; and
(5) Supplemental Forms.

In addition, the permit applicant is encouraged to coordinate with the following agencies: US Fish and Wildlife Service;
US Army Corps of Engineers;
US Soil Conservation Service;
State Historical Commission;
State Ecological Services; and
State Wildlife Resource Agency.

Obviously, completing just this one permit application is beyond the scope of the present study. But in the following pages, we have distilled the permit application form and filled it in as if it were for a lunar helium-3 mine. In this way, we have a start on identifying and addressing the major environmental issues associated with mining on the Moon.

V.B. Specific Responses to Surface Mining & Reclamation Permit

V.B.1. Administration Information

(All information for He3 mining is in italics and N/A means that the requirement is not applicable to a lunar mine.)

1. Application Type
   A. *X* New Permit
   B. Revision to Permit No.....

2. Mine of Facility Type
   A. *X* Surface
   B. Underground ...

General Information

3. Applicant Name *Interlune, Inc.*

4. Identify the operator.

Name...

Business Street Address...

5. Mine Name/Number *Tranquility Junction*

Acreage to be Permitted *20,000 km^2*

Estimated Disturbed Acreage *17,000 km^2*

Acreage of Affected Area *17,000 km^2*

6. USGS Quadrangle *Mare Tranquillitatis - Julius Ceasar Auadrangle*

Latitude *0 to 15 ° N* Longitude *10° E to 30° E*

Designation of nearest intersection of two public roads: *N/A*

Nearest Community *Tranquility Base* Major Watershed *N/A*

Receiving Stream(s) *N/A*

7. Consulting firm providing data:

Firm *Lunar Consultants, Inc.* ...

8a. Resident agent for service of process:...

8b. Person who will pay the abandoned mine land reclamation fee:...

9. Verification

I certify under penalty of the Act (Public Law 95-87) that I am a responsible official...

Signature of Responsible Official...

Notary Public...

Ownership and Control

10a. Applicant's legal structure:

( ) Sole Proprietorship ( ) Partnership

(X) Corporation ( ) Association

( ) Other

If a Corporation, indicate date and state of incorporation...

10b. Operator's legal structure...

11a. If the applicant's legal structure is other than a sole proprietorship, provide all the information set forth below for every officer, partner, principal, principal shareholder (10% or more voting stock), and director...

11b. If the operator's legal structure is other than a sole proprietorship,...

11c. Identify below all persons who have the authority or ability to commit the financial, real estate or working assets of the applicant who are not otherwise identified in item 11a...

11d. Identify every entity owning or controlling helium-3 and by-products to be mined under a lease, sublease or other contract and having the right to receive such helium-3 and by-products after mining or having authority to determine the manner in which any entity conducts a surface helium-3 mining operation....

11e. Identify any other relationship, if any, (not listed in 11a, 11b, 11c, or 11d above) which gives one person authority directly or indirectly to determine the manner in which the applicant, operator or any other entity conducts the surface helium-3 mining and by-product operations....

12. For any other surface helium-3 mining operation on the Moon owned or controlled by the applicant or by any person or entity who owns or controls the applicant, complete the following information. Include all current as well as previous (within the past five years) operations, and any pending applications....

Violation Information

13. Have the applicant, any subsidiaries, affiliates, or persons controlled by, or under common control with the applicant had a lunar helium-3 mining permit suspended or revoked within the last five years? (Insert additional copies of this page as needed to report all such actions.)
( ) Yes (X) No
If yes, describe as follows:...

14. Have the applicant, any subsidiaries, affiliates, or persons controlled by, or under common control with the applicant forfeited a performance bond or a security deposited in lieu of a bond?... *No*

15. Provide the required information on the attached Violation Information Form for each violation notice received by the applicant in connection with any surface helium-3 mining and reclamation operation during the 3-year period preceding the application date.... *N/A*

Identification of Interests

16. Identify every legal or equitable owner of record of the surface and mineral property to be mined. Indicate surface (S), mineral (M), or fee (F) ownership for each owner. *TBD*

17. Identify holders of record of any leasehold interest in the property to be mined. *N/A*

18. Identify any purchasers of record under a real estate contract of the property to be mined. *N/A*

19. Identify names and addresses of owners of record of surface and subsurface areas contiguous to any part of proposed permit area.
N/A? TBD?

20. Provide a description of interests in all lands and/or minerals, options, or pending bids on interests held or made by the applicant for lands contiguous to the proposed permit area. *N/A*

21. A. Does the applicant have pending or active permits for lands contiguous to this proposed permit area?
(X) Yes ( ) No
If yes, provide the following information....

B. Have the proposed permit area, or portions of the proposed permit area been previously permitted?
( ) Yes (X) No
If yes, provide the following information....

Delineate the boundaries of the previously permitted areas on the Mining Operations Map [4].

Right of Entry Information

22. Insert as many completed copies of this page as necessary to cover all conveyances required for the entire proposed permit area. These conveyances must show the applicant's right to mine....

23. Has the private mineral estate proposed to be mined been severed from the private surface estate?
(X) Yes ( ) No
If yes, provide: 1) written surface owner consent for the extraction of helium-3 by surface mining methods for each surface owner, or 2) a copy of the conveyance that expressly grants or reserves the right to extract helium-3 by surface mining methods,...
Provided by Treaty...

24. Exemptions, Valid Existing Rights and Specific Approvals

A. Is an exemption being claimed for lands within the proposed permit area that have been designated as unsuitable for surface helium-3 mining and reclamation operations or is within an area under study for designation?

( ) Yes (X) No

If yes, provide documentation...

B. Indicate whether or not valid existing rights are being claimed in order to conduct surface helium-3 mining operations with the boundaries of the following areas:

(1)	The Lunar Park System	*No*
(2)	The Lunar Wildlife Refuge System	*N/A*
(3)	The Lunar System of Trails	*No*
(4)	The Lunar Wilderness Preservation System	*No*
(5)	The Lunar Wild and Scenic Rivers System	*N/A*
(6)	The Lunar Recreation Area	*No*
(7)	Within a Lunar Forest	*N/A*
(8)	Within 100 feet, measured horizontally, of the outside right-of-way line of any public road	*No*
(9)	Within 300 feet, measured horizontally, of any occupied dwelling	*No*
(10)	Within 300 feet, measured horizontally, of of any public building school, church, community or institutional building, or park	*No*
(11)	Within 100 feet, measured horizontally, of a cemetery	*No*
(12)	On any lands where mining will adversely affect any publicly owned park or any places included in the Lunar Register of Historic Places	*No*

C. If the applicant proposes to conduct surface helium-3 mining and reclamation operations within the distances specified...

25. Permit Term

A. Permit term requested

40 years.

B. If a permit term in excess of 5 years is required in order to obtain necessary financing for equipment and opening of the operation, provide a:

(1) Complete and accurate application covering the specified longer term and *TBD*

(2) Showing, confirmed in writing by the proposed source of financing, that the longer term is reasonably needed to allow the applicant to obtain financing. Insert documentation immediately following this page. *TBD*

26. Bonding

A performance bond must be posted before the permit can be issued, but the bond is not to be submitted until the application is approved....

27. Insurance

A. The applicant shall provide a certificate issued by an insurance company authorized to do business on the Moon certifying that the applicant has a public liability insurance policy in force for the proposed mining and reclamation operations,...

B. The certificate shall contain the policy number and the following riders:

> "The insurer will notify the Office of Surface Mining Reclamation and Enforcement whenever substantive changes are made in the policy including any termination or failure to renew"...

C. Minimum insurance coverage for bodily injury and property damage, including damage caused by blasting, shall be $300,000 for each occurrence and $500,000 aggregate.

Public Notice

28. Newspaper Notice

    A. Complete the newspaper notice provided below, and place this notice in a newspaper of general circulation in the locality of the proposed helium-3 mining and reclamation operations. The notice is to start when OSMRE determines that this application is administratively complete, and is to run at least weekly for four consecutive weeks....

29. Proof of Publication

    Submit to OSMRE under separate cover, no later than 4 weeks after the date of last publication, a copy of the newspaper advertisement of the application and a notarized affidavit of publication for the required publication period.

V.B.2. Existing Environmental Resources--Baseline Data

30. Cultural Resources

    To meet the requirements of the Lunar Historic Preservation Act, ...

    D. If cultural, historic or archeological resources are located with the proposed permit and adjacent area(s), provide a description and identify them on the PREMINING LAND USE MAP [2]. *TBD*

31. Plan for Protection of Public Parks and Historic Places

    Will any public parks or historic places be adversely affected by the proposed operation?

    (X) Yes ( ) No

    If so, name and locate them on the PREMINING LAND USE MAP [2], and describe the measures to be used to minimize or prevent the adverse impacts from mining on these areas....

    No mining activities will be conducted within 1 km of the landing site of any US or Soviet unmanned spacecraft. No mining activities will be conducted within 5 km of any Apollo traverse or landing site.

32. Land Use and Soils Information

A. Land Use Information

(1) Describe the land use that existed prior to any helium-3 mining activities.

Undisturbed, except for unmanned and manned exploration: Ranger, Luna, Surveyor, Lunokhod, and Apollo.

(2) Provide a PREMINING LAND USE MAP [2] and supporting narrative that describes the uses of the land existing at the time of filing of the application.... *TBD*

(3) Has a portion of the proposed permit area been previously mined?

( ) Yes (X) No

If yes, provide the following:...

(4) Provide a description of the existing land uses and land-use classifications of the proposed permit area and adjacent areas according to city or county zoning ordinances or officially adopted land-use plans, if any.... *N/A*

B. Soils Information

Provide, in the table below, land capability and productivity data for each soil type (or SCS mapping unit) located within the proposed permit area.... *N/A*

33. Prime Farmland Determination

A. The applicant shall show the probability for occurrence of prime farmland soils within the proposed permit area by either providing the information.... *N/A*

34. Fish and Wildlife Resources and Threatened or Endangered Species Information

... *N/A*

35. <u>Geologic Information - Introduction</u>

(Surface and Underground Operations)

A. The geologic description (Item 36), geologic logs, cross sections, and maps (Item 37), and analyses of samples (Item 38) must be based on the geology of the proposed permit and adjacent areas down to and including the deeper of either:

(1) The stratum immediately below the lowest helium-3 to be mined; or

(2) Any aquifer below the lowest helium-3 to be mined which may be adversely impacted by mining. *N/A*

B. If determined to be necessary to protect the hydrologic balance,... *N/A*

36. <u>Geologic Description</u>

Provide a geologic description that includes:

A. Stratigraphy and lithology *An irregular, cratored layer of impact generated debris (regolith) averaging about 10 m thick overlies highly fractured, impact melt injected basaltic rubble to mosaic breccia which in turn grades into fractured ilmenite-rich basaltic lava flows. The lithology of the ore zone (the regolith) is outlined in the following tables: (VI-3 and 4).*

B. Areal and structural geology too, including its relationship to the occurrence, availability, movement, quantity, and quality of surface and ground waters; and .... *N/A*

37. <u>Geologic Logs, Cross Sections, and Maps</u>

A. Provide geologic logs of test borings and coreholes in the proposed permit and adjacent area which include:

(1) Detailed lithologic characteristics, physical properties, and thickness of each stratum; and *TBD*

(2) Location of ground water where occurring. *N/A*

B. Provide geologic cross sections that include:

(1) Lithologic characteristics of each stratum; and

(2) Depth and thickness of each stratum.

TBD

C. Identify the locations and surface elevations of test borings, core samplings and outcrop samples on the ENVIRONMENTAL RESOURCES MAP [3]. *TBD*

D. Show all helium-3 crop lines.... *N/A*

38. <u>Analyses of Samples</u>

Samples for analysis must be collected from test borings, drill cores, or fresh, unweathered, uncontaminated samples from rock outcrops....

A. For surface mining operations and surface disturbance associated with underground operations, collect samples from each stratum with the proposed permit area TBD and provide the following:

(1) The chemical content of acid- or toxic-forming, or alkalinity-producing materials; and *N/A*

(2) A chemical analysis of the helium-3 seam for acid-or toxic-forming materials, including total sulfur and pyritic sulfur. *N/A*

B. For underground operations,... *N/A*

C. Based on the results of the survey required under item 67A, is a subsidence control plan required?

( ) Yes (X) No

If yes,... *N/A*

D. Reporting of technical data... *TBD*

39. Request for Waiver of Geologic Information

... *N/A*

40. <u>Surface-Water Resources Information</u>

A. Provide identification number, name or other description, stream type, ownership if privately owned, and usage of all surface-water bodies such as streams, lakes, and impoundments in the proposed permit and adjacent areas. Show the location of surface-water resources on the ENVIRONMENTAL RESOURCES MAP [3]...*N/A*

B. Provide, in the table below, surface-water baseline data for each surface-water resource identified above to represent areal variations in surface-water quality and quantity typically associated with seasonal variation in streamflow rates.... *N/A*

41. <u>Ground-Water Resources Information</u>

A. Provide identification number, description, ownership, and usage of existing wells, springs, and other developed or undeveloped ground-water resources adequate to describe..... *N/A*

B. Provide, in the table below, ground-water baseline data to represent areal variations.... *N/A*

.... *N/A*

42. <u>Baseline Cumulative Impact Area Information</u>

Baseline hydrologic and geologic information is necessary to conduct the probable cumulative hydrologic impact assessment (CHIA) of all anticipated mining on surface- and ground-water systems within the cumulative impact area.... *N/A*

43. <u>Modeling</u>

To establish baseline hydrologic conditions,... *N/A*

44. <u>Probable Hydrologic Consequences Determination (PHC) and Hydrologic Reclamation Plan (HRP)</u>

The PHC is a predictive estimate or judgment of potential impacts of the proposed mining and reclamation operation upon the hydrologic balance of the permit and adjacent areas. It is the sum of the effects on the hydrologic balance of all mining, remedial treatment, and reclamation practices.... *N/A*

45. <u>Supplemental Information</u>

If, in the opinion of OSMRE, the proposed mining and reclamation plan will not insure protection of the hydrologic balance,... *N/A*

46. <u>Alternative Water Source</u> (Surface Mine Applicants Only)

If the determination of the PHC indicates that the proposed mining operation may proximately result in contamination, diminution, or interruption of an underground or surface source of water... *N/A*

V.B.3. Operation and Reclamation Plan

47. A. <u>Type of Operations</u>(s)

Check all applicable items.

(*X*) Surface

( ) Underground

( ) Preparation Plant

(*X*) Tipple/Loading Facility

( ) Auger

(*X*) Refuse area

(*X*) Other:

Gas Separation Plant

Resource Storage Area

B. <u>Mining Method</u>(s) Used

(*X*) Contour mining

(*X*) Area mining

( ) Mountaintop removal

(*X*) Haul road construction

( ) Head-of-hollow/valley fill

( ) Slurry impoundment

( ) Other

48. <u>Life of Mine and Timetable</u>

A. Anticipated life of the proposed operation

38 years

B. Anticipated Production in Tonnes of Helium-3

19 annual *(average)*

712 total (over life of mine)

C. Mining and Reclamation Timetable

Complete the timetable below by indicating the anticipated starting and ending dates and area to be affected for each major step of the surface helium-3 mining and reclamation operation over the life of the mine.

Phase	Start	End	Area
Topsoil Removal	*N/A*		
Overburden Removal	*N/A*		
Solar Wind Volatiles Removal	*2015*	*2052*	*17,000 km²* *(disturbed)*
Backfilling and Grading	*Concurrent with Helium-3 Removal*		
Topsoil Redistribution	*N/A*		
Revegetation	*N/A*		
Removal of Facilities and Structures	*2053*	*2055*	
Removal of Drainage Control Structures and Access Road	*Concurrent with Helium-3 Removal or at end of mine area life.*		

49. Maximize Use of Resource and Production

Describe the measures to be used to maximize the use and conservation of the helium-3 and by-products, while utilizing the best technology currently available to maintain environmental integrity, so that reaffecting the land in the future through surface helium-3 mining operations is minimized....

Approximately 75% or more of the helium-3 and by-products will be removed from the first 6 meters of regolith. Practically all other solar wind volatiles will be removed at the same time. The economic incentive to extract the remaining He3 will be very low.

50. Mine Facilities

Provide a narrative that explains the construction, modification, use, maintenance, and removal, including a description of structural components and dimensions, of all mine facilities such as but not limited to mine buildings, helium-3 separation, storage and loading facilities, equipment and storage facilities, sheds, and shops. *(see Section B)*

51. Existing and Shared Structures

A. Describe each existing structure proposed to be used in connection with or to facilitate the proposed helium-3 mining and reclamation operation.... *See Figure IV-2.*

52. Drainage Control Plan

Provide plans for each proposed siltation structure and water impoundment within the proposed permit area.... *N/A*

53. Transportation Plan

A. Provide plan and profile of each road, conveyor, or rail system to be constructed, used, or maintained within the proposed permit area. *TBD*

B. Provide plans, drawings, appropriate cross sections, and specifications for each road, describing road width, road gradient, road surface, road cut, fill embankment, culvert, bridge, drainage ditch, and drainage structure. *TBD*

C. Provide a report of appropriate geotechnical analysis ... for steep cut slopes... *N/A (All steepenend slopes are temporary and eliminated simultaneously with backfilling.)*

D. Provide plan, profile and cross sections and a description of measures to be taken for alteration or relocation of a natural drainageway. *N/A*

E. Provide cross sections and a description of measures, other than use of a rock headwall, to be taken to protect the inlet end of a ditch relief culvert. *N/A*

F. Provide plans for removal of transportation facilities and reclamation of the facilities' sites, including volumes of material to be moved, and methods for the removal and stabilization of the sites. *TBD*

54. Topsoil/Substitute Handling Plan

... *N/A*

55. Blasting

... *Required for emergency SPE shelter preparation and for excavation of buried and partially buried facilities and cryo storage sites.*

56. Backfilling and Grading Plan

A. Describe the sequence and timing of the excavation, backfilling and grading operations, including volumes of spoil material, temporary and permanent placement of spoil material, lift depth and final grading. Describe how the type of equipment to be used will compact the material and achieve soil stabilization. ... *TBD*

B. Show the anticipated final surface configuration on contour maps or cross sections as required under Item 61C. *TBD*

57. Disposal of Excess Spoil, Processing Waste and Underground Development Waste

... *TBD*

58. Reactive and Toxic-Forming Materials Control

A. Acid/Toxic Materials Handling

(1) Check any of the potentially acid/toxic materials known or that may exist within the proposed permit area.

(X) None

... *N/A*

B. Reactive Materials

(1) The following reactive materials are expected to be used, stored, or generated during operation of the proposed surface helium-3 mine.

(X) lubricants (machine oils, etc.)

(X) paints

(X) reactive liquids

(X) garbage (paper, plastic containers, rubberized hoses and conveyor belts, etc.)

(X) conserved mine machinery

(X) treatment chemicals

( ) wood, vegetation, lumber, mine timbers

( ) none

(X) others: *TBD (all used materials will be stored for possible use or reuse at a later time)*

(2) Will the materials identified under item 58B(1) be disposed of on-site?

(X) Yes ( ) No ( ) N/A

If yes, identify and provide estimated quantities of all materials to be stored and disposed of on-site. Describe how these materials will be stored and disposed of to protect against leachates entering surface and ground waters, prevent reaction, and minimize adverse effects on plant growth. Identify the location of the disposal site on the MINING OPERATIONS MAP [4] or SITE PLAN MAP [5]. *TBD*

(3) Will the material identified under Item 58B(1) be disposed off-site?

( ) Yes (X) No ( ) N/A

... *N/A*

(4) Describe contingency plans that would preclude the sustained reaction of such materials during storage. *TBD*

59. <u>Revegetation Plan</u>

... *N/A*

60. <u>Fish and Wildlife Protection and Enhancement Plan</u>

... *N/A*

61. <u>Postmining Land Use Plan</u>

A. Description of proposed land use(s)

Submit a plan containing a detailed description of the proposed land use following reclamation of the land within the proposed permit area, including a discussion of the utility and capacity of the reclaimed land to support a variety of alternative uses, and the relationship of the proposed use to existing land use policies and plans, if any. ... *TBD (portions of the reclaimed land may be cultivated for food crops)*

B. Land use change from pre- to postmining

... *N/A*

C. Premining and postmining slope cross sections
Provide typical premining and postmining cross sections (referenced to maps) showing a return to approximate original contour (AOC) or a contour pursuant to a variance from AOC is steep-slope mining or mountaintop removal operations. These cross sections should extend down to and below the lowest helium-3 seam to be mined. .... *TBD*

62. Surface-Water Monitoring Plan

A. Provide a surface-water monitoring plan based on the PHC determination required under Item 44 and the analyses of all baseline information provided under Item 40 and other applicable information. ... *N/A*

63. Ground-Water Monitoring Plan

... *N/A*

64. Air Pollution Control Plan and Stabilization of Surface Areas

Provide a plan for fugitive dust control practices which describes measures to be used to protect and stabilize all exposed surface areas to effectively control erosion and air pollution attendant to erosion. ... *TBD (some dust may be transported ballistically during mining)*

65. Surface Mining Near An Underground Mine

... *N/A*

66. Seal or Manage Openings

... *N/A*

67. Survey, Subsidence Control and Mitigation Plan

... *N/A*

68. Compliance with Other Laws

Describe the steps to be taken to comply with the requirements of The Clean Air Act, The Clean Water Act, and other applicable air and water quality laws and regulations and health and safety standards.
TBD

69. Reclamation Cost Estimate

Summarize the cost of reclamation of the proposed operations (maximum disturbance at any one time) required to be covered by a performance bond. ...

A.	Facility and Structure Removal (It is possible that the buildings could be used for housing scientific or recreational personnel or that all facilities will be mobile.)	*TBD*
B.	Earthmoving	*0**
C.	Revegetation	*0*
D.	Other Reclamation Activities	*0**
	Total	*TBD*

**Concurrent with helium-3 removal*

70. Experimental Practices Mining

... *N/A*

71. Mountaintop Removal Mining

... *N/A*

72. Steep Slope Mining

... *N/A*

73. Variance From Approximate Original Contour for Nonmountaintop Removal Mining

... *N/A*

74. Variance for Delay in Contemporaneous Reclamation for Combined Surface and Underground Mining Activities

... *N/A*

75. <u>Auguring</u>

... *N/A*

76. <u>In-Situ Processing</u>

... *N/A*

77. <u>Operation Plan, General</u>

The purpose of Item 77 is to provide a brief overview of the operation suitable for mailing to other agencies and interested parties. Since details are provided under other items, brevity is requested here. Narratives are to be consistent with information provided under previous items. ... *TBD*

V.B.4. Maps and Drawings

78. <u>General Requirements</u>

A. Cross section, maps and plans shall be prepared by, or under the direction, and certified by a qualified, registered professional engineer or a professional geologist. ...

B. No map or drawing should be smaller than 8.5" X 11".

C. THE GENERAL LOCATION MAP [1], PREMINING LAND USE MAP [2], and SITE PLAN MAP [5] scales are as specified below.

D. Each base map shall be a topographic map of a scale of 1" = 500' or less than 500' (1:6,000 or larger scale), containing the following as well as those items specified under each map title.

(1) Map title, number, revision if any;

... *TBD*

E. Maps may be combined at the discretion of the applicant, provided such combination is reflected in the title blocks and does not crowd the maps to the extent interpretation becomes difficult. Parts of one map may not be combined with parts of another; combine only entire maps.

79. <u>Required Titles and Information</u>

A. GENERAL LOCATION MAP [1] Indicate on a County Highway Map the location of the proposed permit area, with respect to towns, roads, streams, and county lines.

B. PREMINING LAND USE MAP [2] A USGS 7-1/2 minute quadrangle (1"=2,000') 1:24,000, showing the permit area and general features of the adjacent area.

Identify the following:

(1) Permit boundaries and access roads;

... *TBD*

C. ENVIRONMENTAL RESOURCES MAP [3] Base map showing information relative to geology, hydrology, drainage, and critical fish and wildlife habitat.

Identify the following:

(1) The locations of water supply intakes for current users of surface water flowing into, out of, and within a hydrologic area defined by the regulatory authority, and those surface waters which will receive discharges from affected portions of the proposed permit area. Show the name of receiving stream(s);

... *N/A*

D. MINING OPERATIONS MAP(S) [4] Base map showing operational facilities, drainage control structures, etc. On repermit applications, show current status of the operation.

Identify the following:

... *TBD*

E. SITE PLAN MAP(S) [5] For underground mining operations, tipple facilities, preparation plant operations, and associated refuse disposal sites, provide a map on a scale of 1" = 100', or larger, identifying the following:

... *TBD*

V.B.5. Supplemental Forms

Guide to NPDES Forms and Requirements:
... *N/A*

APPLICATION FOR MINE SAFETY AND HEALTH ADMINISTRATION APPROVAL

The operator is proposing to:

- ( ) Conduct blasting operations within 500 feet of an active underground mine.
- ( ) Construct an impoundment(s) which meets or exceeds the criteria of ...
- ( ) Return helium-3 mine wastes to abandoned underground workings.

  ... *N/A*

References for Chapter V

[1] General Location Map.
[2] Premining Land Use Map.
[3] Environmental Resources Map.
[4] Mining Operations Map(s).
[5] Site Plan Map(s).

VI. Specific Environmental Problems
VI.A. Scale and Scope of Mining Operations

As indicated earlier, Mare Tranquillitatis (Figure VI-1) is the most promising area for helium mining operations. The schedule of operations on the Mare envisioned by the University of Wisconsin Task Force on Helium-3 is summarized in Table VI-1 and Figures VI-2 to VI-7. Mining would begin in 2015 and proceed on a steadily increasing scale, reaching 8,500 million tonnes per year in the year 2052. By that time about 1,420 sq. km. of the surface would be disturbed per year by direct excavation, together with about 18 sq. km. of surface that would be occupied by trunk roads from lunar base to mining areas. The total area disturbed from 2015 to 2052 would amount to 17,000 sq. km. This scale of operations may be compared with the approximately 23,200 sq. km. disturbed by mining in the United States during the period 1930-1980 [1] and to areas utilized for U.S. crop production in 1980 as shown in Figure VI-7.

At the 2052 rate of production, some 8,520 million tonnes of regolith would be mined per year. This figure may be compared with figures for production of major bulk mineral commodities as given in Table VI-2. Those figures, however, are only for production of marketed products. They do not include waste material excavated (overburden removed, waste rock mined along with ore) or losses during processing of ore. For example, production of finished phosphate rock in Florida in 1987 was 40,954,000 tonnes [2], but to obtain this amount, 460,000,000 tonnes of phosphate ore plus overburden were excavated in one year alone. In the U.S., approximately 60 percent of total coal produced in 1988 was from surface mining. Ratios of overburden stripped to coal produced vary over a wide range. Examples from surface mining of coal in the United States, given by Doyle [3], show ratios of feet of overburden removed per foot of coal mined ranging from less than 1:1 to about 33:1. It is certainly reasonable to assume an average ratio of more than 5:1. All iron ore now produced in the United States is from surface mining. Ratios of overburden to ore average more than 2:1. Most of the iron ore produced in the United States and reported in the table consists of concentrates. The tonnage of iron ore given in the table is our estimate based on an ore to concentrate ratio of about 3 to 1.

Table VI-1

Schedule of Helium Mining Operations on the Moon - 2015-2052.

YEAR	HE-3/Y TONNES	Volatiles Pro TONNES	Regolith Mine Million Tonne 7 ppb	Mass xDistanc Mtonne-km 2m Vert Lift	Cumulative Mass Mined Million Tonne	Cumulative Mt-km Assume 2m Vertical Lift	Area Disturbed 3 meter depth 1 km2=42 kg He3	Cumulative Area Disturbe Km2	Square Edge -km
..									
2015	0.01	182	1.43	0.00	1.43	0.00	0.24	0.24	0.49
2016	0.03	546	4.29	0.01	5.71	0.01	0.71	0.95	0.85
2017	0.04	728	5.71	0.01	11.43	0.02	0.95	1.90	0.98
2018	0.07	1274	10.00	0.02	21.43	0.04	1.67	3.57	1.29
2019	0.14	2548	20.00	0.04	41.43	0.08	3.33	6.90	1.83
2020	0.21	3822	30.00	0.06	71.43	0.14	5.00	11.91	2.24
2021	0.28	5096	40.00	0.08	111.43	0.22	6.67	18.57	2.58
2022	0.35	6370	50.00	0.10	161.43	0.32	8.33	26.91	2.89
2023	0.45	8190	64.29	0.13	225.71	0.45	10.71	37.62	3.27
2024	0.56	10192	80.00	0.16	305.71	0.61	13.33	50.95	3.65
2025	1.00	18200	142.86	0.29	448.57	0.90	23.81	74.76	4.88
2026	1.82	33124	260.00	0.52	708.57	1.42	43.33	118.10	6.58
2027	2.79	50778	398.57	0.80	1107.14	2.21	66.43	184.53	8.15
2028	3.45	62790	492.86	0.99	1600.00	3.20	82.14	266.67	9.06
2029	4.13	75166	590.00	1.18	2190.00	4.38	98.34	365.01	9.92
2030	4.84	88088	691.43	1.38	2881.43	5.76	115.24	480.25	10.74
2031	6.84	124488	977.14	1.95	3858.57	7.72	162.86	643.11	12.76
2032	8.89	161798	1270.00	2.54	5128.57	10.26	211.67	854.78	14.55
2033	10.97	199654	1567.14	3.13	6695.71	13.39	261.20	1115.97	16.16
2034	13.10	238420	1871.43	3.74	8567.14	17.13	311.91	1427.89	17.66
2035	15.27	277914	2181.43	4.36	10748.57	21.50	363.58	1791.46	19.07
2036	17.48	318136	2497.14	4.99	13245.71	26.49	416.20	2207.66	20.40
2037	19.73	359086	2818.57	5.64	16064.29	32.13	469.77	2677.43	21.67
2038	22.03	400946	3147.14	6.29	19211.43	38.42	524.53	3201.97	22.90
2039	24.38	443716	3482.86	6.97	22694.29	45.39	580.49	3782.46	24.09
2040	26.78	487396	3825.71	7.65	26520.00	53.04	637.63	4420.09	25.25
2041	29.22	531804	4174.29	8.35	30694.29	61.39	695.73	5115.82	26.38
2042	31.71	577122	4530.00	9.06	35224.29	70.45	755.02	5870.83	27.48
2043	34.25	623350	4892.86	9.79	40117.14	80.23	815.49	6686.32	28.56
2044	36.84	670488	5262.86	10.53	45380.00	90.76	877.16	7563.48	29.62
2045	39.48	718536	5640.00	11.28	51020.00	102.04	940.02	8503.50	30.66
2046	42.18	767676	6025.71	12.05	57045.71	114.09	1004.31	9507.81	31.69
2047	44.93	817726	6418.57	12.84	63464.29	126.93	1069.78	10577.59	32.71
2048	47.73	868686	6818.57	13.64	70282.86	140.57	1136.45	11714.04	33.71
2049	50.59	920738	7227.14	14.45	77510.00	155.02	1204.55	12918.59	34.71
2050	53.51	973882	7644.29	15.29	85154.29	170.31	1274.07	14192.66	35.69
2051	56.49	1028118	8070.00	16.14	93224.29	186.45	1345.03	15537.69	36.67
2052	59.64	1085448	8520.00	17.04	101744.29	203.49	1420.03	16957.72	37.68
TOTAL	712.21	12962222	101744.29				16957.72		130.22

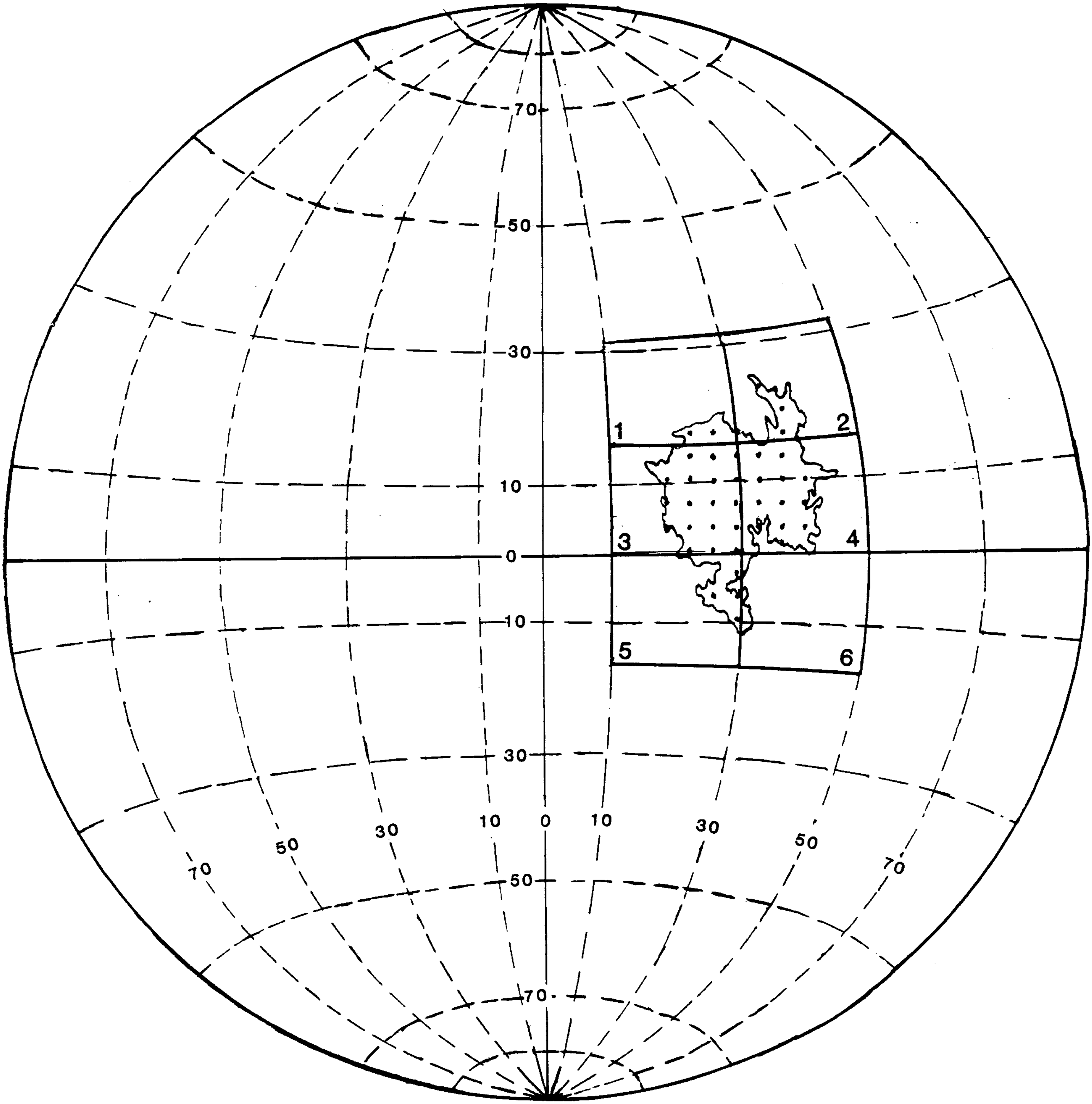


Figure VI-1. Outline map of the near side of the moon, showing the area of Mare Tranquillitatis (dot pattern). Heavy lines bound U.S. Geological Survey map quadrangles: 1-Mare Serenitatis; 2-Macrobius; 3-Julius Caesar; 4-Taruntius; 5-Theophilus; 6-Columbo. Based on Wilhelms, 1975, Plate 4A.

Figure VI-2

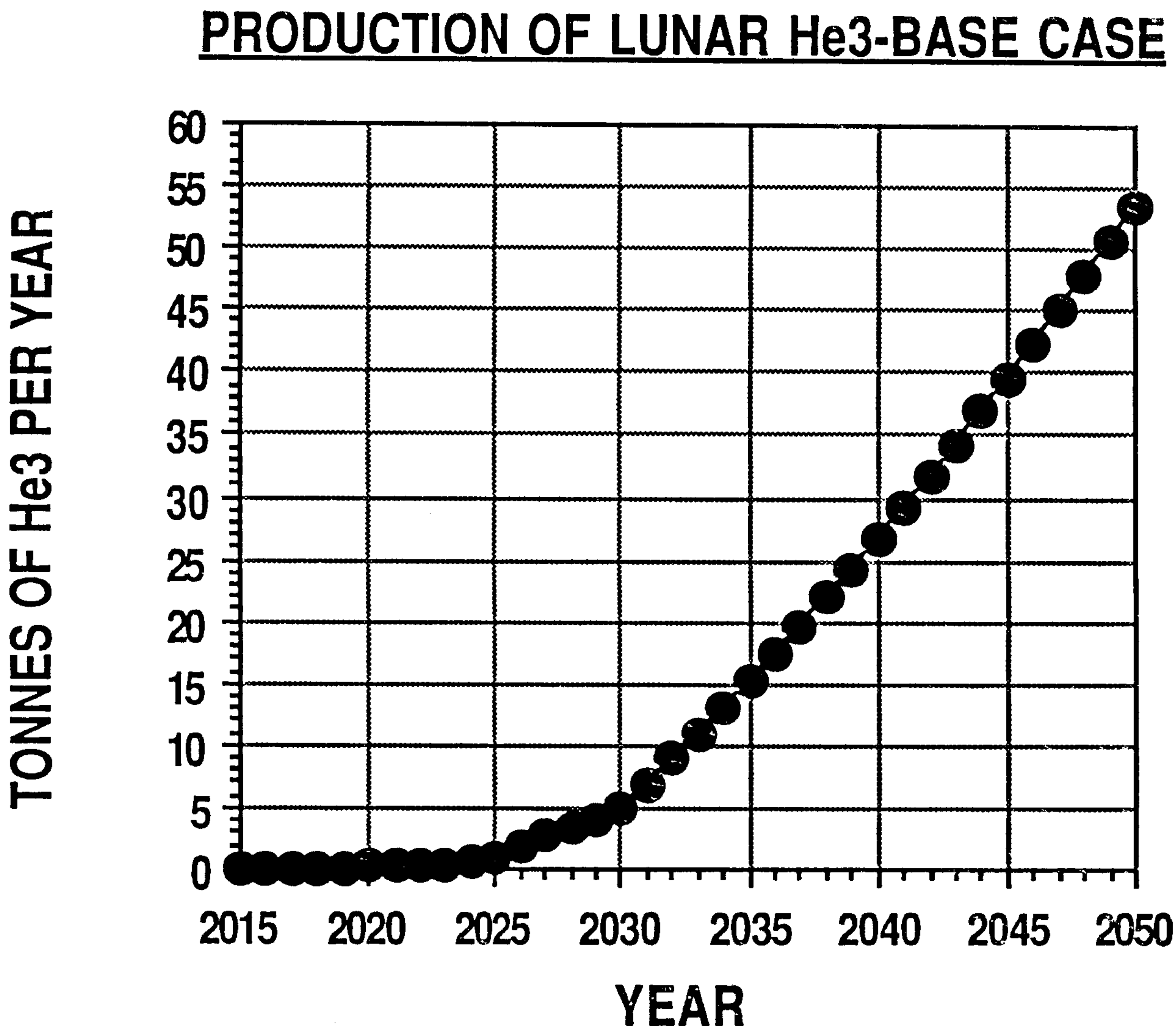
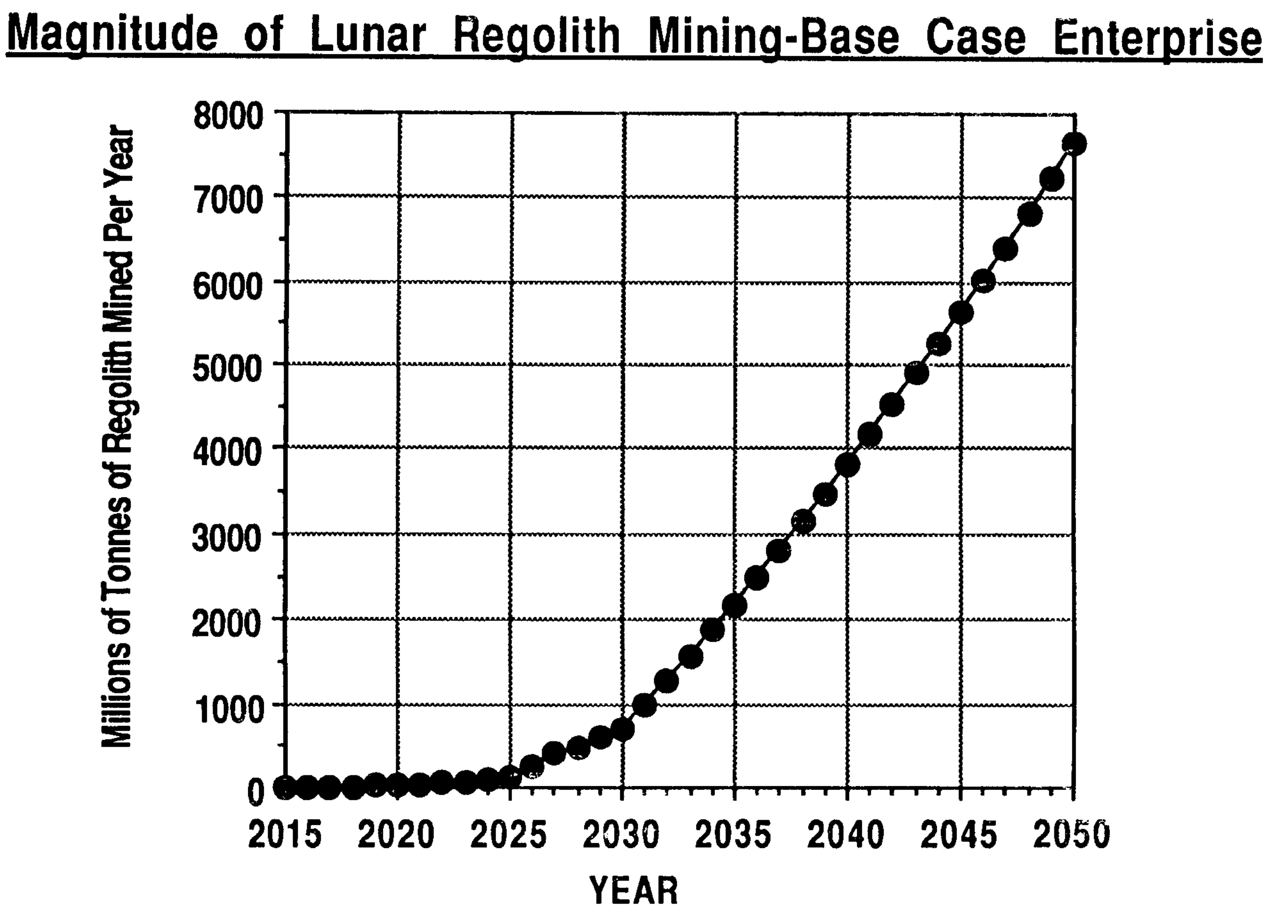

PRODUCTION OF LUNAR He3-BASE CASE
TONNES OF He3 PER YEAR
60
55
50
45
40
35
30
25
20
15
10
5
0
2015
2020
2025
2030
2035
2040
2045
2050
YEAR

Figure VI-3



Magnitude of Lunar Regolith Mining-Base Case Enterprise
Millions of Tonnes of Regolith Mined Per Year
8000
7000
6000
5000
4000
3000
2000
1000
0
2015
2020
2025
2030
2035
2040
2045
2050
YEAR

Figure VI-4

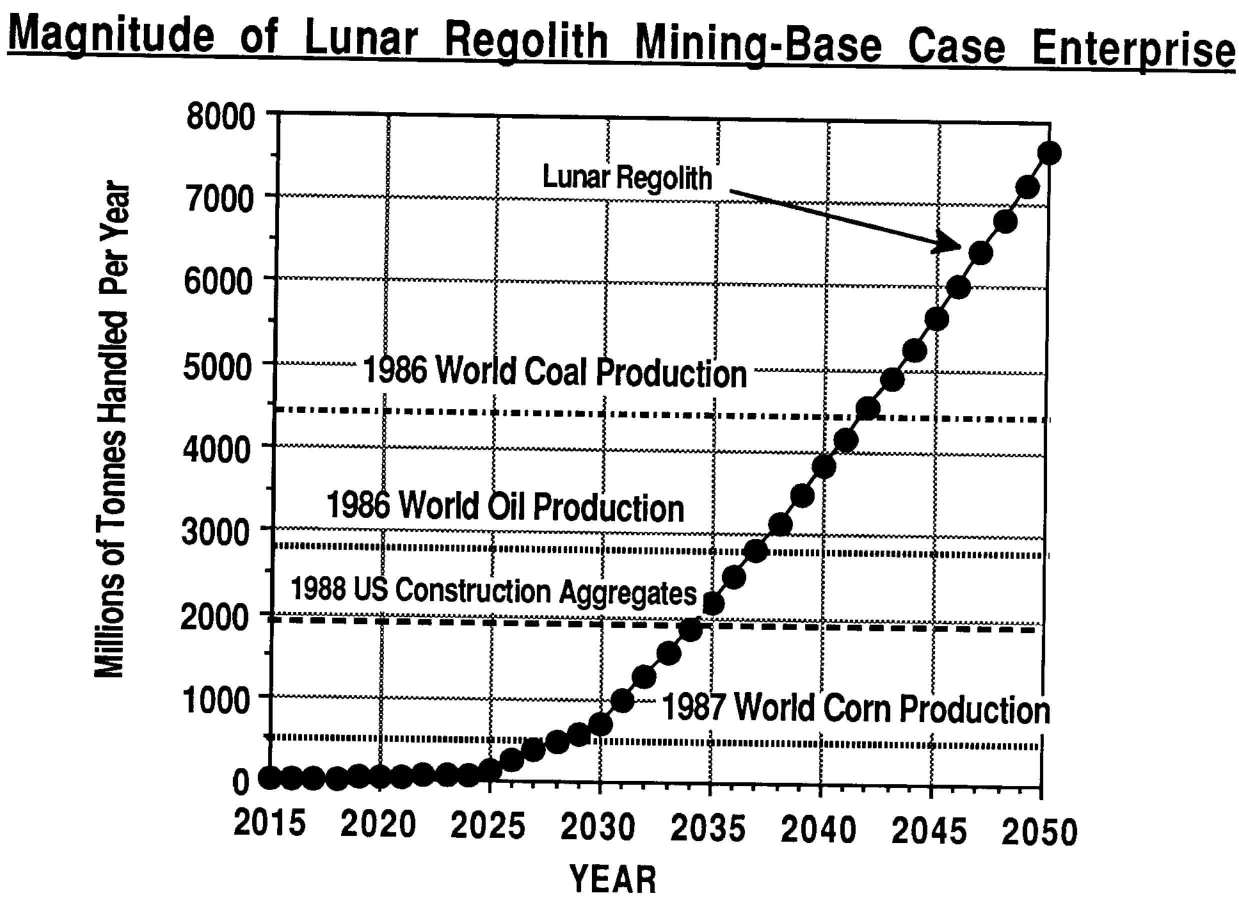
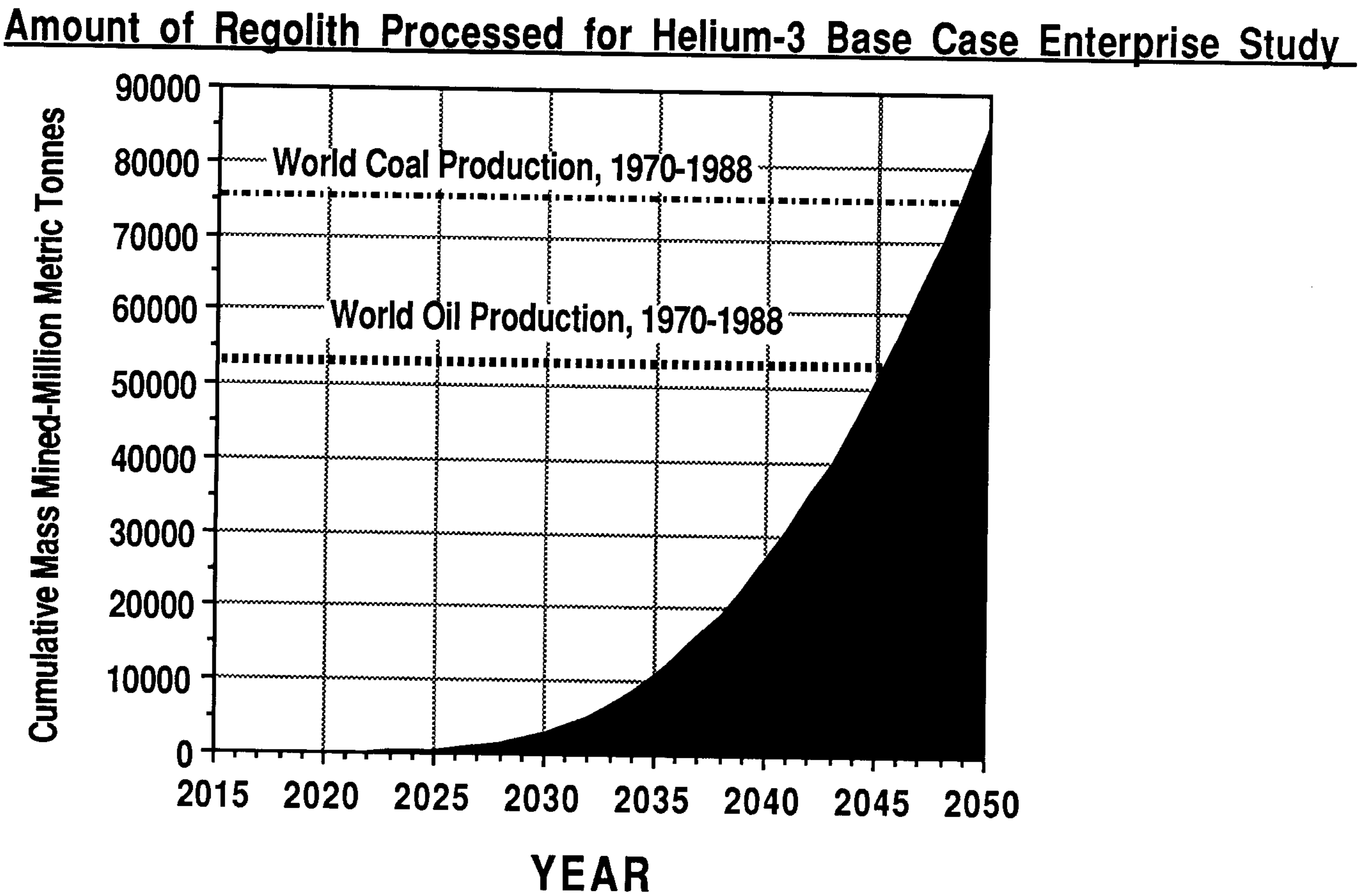
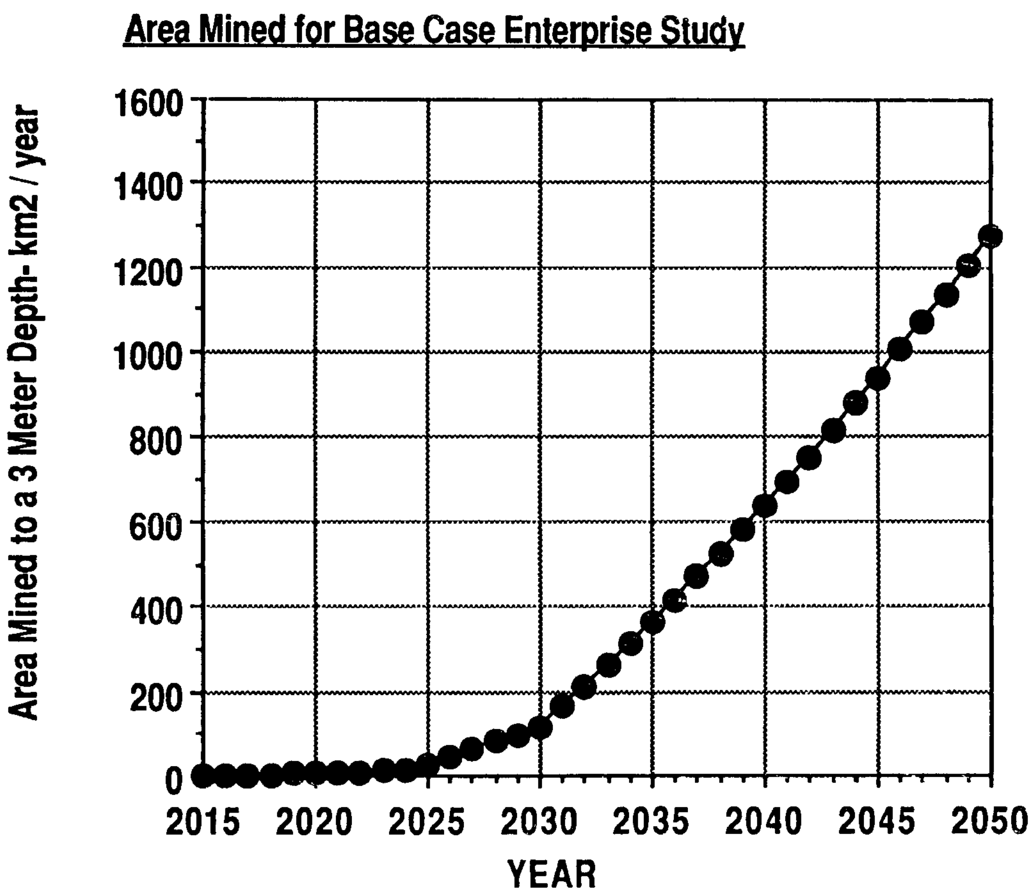

Magnitude of Lunar Regolith Mining-Base Case Enterprise
Millions of Tonnes Handled Per Year
8000
7000
6000
5000
4000
3000
2000
1000
0
Lunar Regolith
1986 World Coal Production
1986 World Oil Production
1988 US Construction Aggregates
1987 World Corn Production
2015
2020
2025
2030
2035
2040
2045
2050
YEAR

Figure VI-5



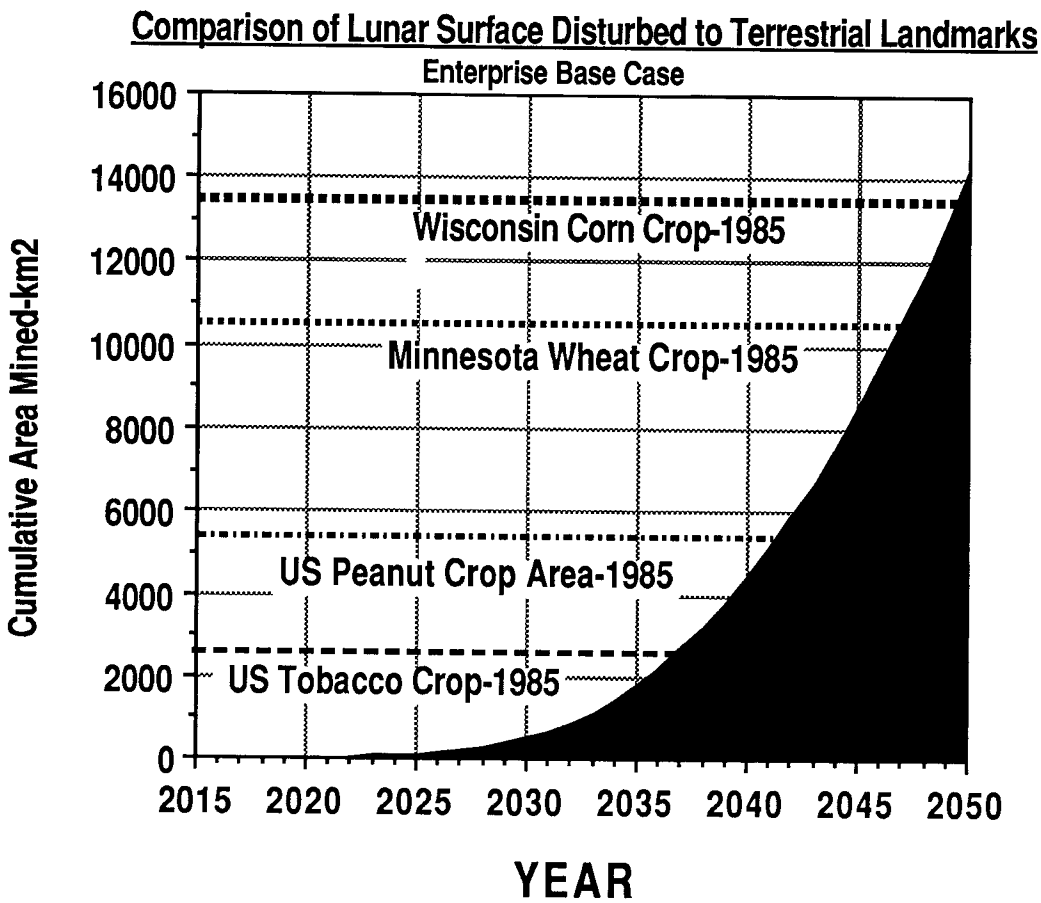
Amount of Regolith Processed for Helium-3 Base Case Enterprise Study
Cumulative Mass Mined-Million Metric Tonnes
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
World Coal Production, 1970-1988
World Oil Production, 1970-1988
2015
2020
2025
2030
2035
2040
2045
2050
YEAR

Figure VI-6



Area Mined for Base Case Enterprise Study
Area Mined to a 3 Meter Depth- km2 / year
1600
1400
1200
1000
800
600
400
200
0
2015
2020
2025
2030
2035
2040
2045
2050
YEAR

Figure VI-7



Comparison of Lunar Surface Disturbed to Terrestrial Landmarks
Enterprise Base Case
Cumulative Area Mined-km2
16000
14000
12000
10000
8000
6000
4000
2000
0
Wisconsin Corn Crop-1985
Minnesota Wheat Crop-1985
US Peanut Crop Area-1985
US Tobacco Crop-1985
2015
2020
2025
2030
2035
2040
2045
2050
YEAR

Most sand and gravel operations involve stripping of overburden; in addition there are losses in processing the mined material. Table VI-2 therefore greatly understates the amount of rock actually excavated in the United States during mining for the various commodities. If allowance for overburden and waste material is made, total rock excavated in the United States at the present time (~ 10 billion tonnes per year) is probably higher than the amount projected for helium mining on the Moon at the mining rate in the middle of the 21st century.

Table VI-2

Production of Major Bulk Mineral Commodities, 1988
Millions of Tonnes*
(Note: does not include overburden)

	U.S.	WORLD
Coal	870	4,600
Sand and gravel	799	NA
Crushed stone	1,106	NA
Iron ore	ca. 150	933
Phosphate rock	46	153
Cement	72	923
Total	3,043	NA

* Data from Energy Information Administration [4] and from U.S. Bureau of Mines [2].

VI.B. Proportion of Mare Tranquillitatis That Would Be Affected by Mining

The portions of Mare Tranquillitatis now appearing most favorable for initial mining lie within the Julius Caesar and Taruntius quadrangles (Fig. VI-1). They have an area of roughly 300,000 sq. km. Studies of photogeologic maps and photographs of the mare indicate that not all of it will be minable. The principal obstacles to mining are rilles (long, narrow, steep-walled structural troughs), ridges, volcanic domes, islands of basement rocks, and craters that penetrate the regolith. Rilles, ridges, domes, and basement islands will not be minable and must all be avoided. Measurements of these features on the photogeologic maps of the Julius Caesar and Taruntius quadrangles indicate that they occupy about 8 percent of the surface of the mare. However, the principal and most widespread obstacles to mining are the abundant craters that are too small to be shown at the 1:1,000,000 scale of the quadrangle maps but range from 24 meters to 900 meters in diameter. Most of these are too deep and too steeply walled to be minable. Furthermore, many of the craters will be accompanied by halos of ejecta containing blocks of bedrock too large to be separated from the finer regolith at acceptable cost. The effect of craters on the number and size of minable portions of a given area of the mare is a function of their number, their sizes and size distribution, and their pattern of distribution over the area. All these parameters vary widely over the area extending eastward from Tranquillity Base.

For a given area, such as that shown in Figure VI-8, the percentage of the mare that will be minable is best determined from charts such as those of Figures VI-9 and VI-10. Figure VI-8 is a copy of Lunar Orbiter II photograph II-84H3 reduced from its original size of 52.3 by 23.4 cm. The photograph covers a part of the area just east of the Apollo 11 landing site. The area covered by the photograph is 28.3 sq. km.; resolution on the original is 2 m. Figure VI-9 is an overlay (similarly reduced from the original) of the photograph. It shows all craters (including inferred ejecta halos) with diameters 23.4 m or greater. Each circle on the chart marks a crater. The center of the circle is the center of the crater, and the diameter of the circle is the diameter of the crater plus its halo of ejecta if one is inferred to be present. For purposes of estimation, minable areas are plotted in terms of unit blocks 400 by 400 m., with sideward extensions that would be minable by large mining machines. On this basis 42 percent of the area is estimated to be minable.

Assuming an average minable regolith thickness of 3 m. and a regolith density of 2.0, each unit block of Figure VI-9 contains 960,000 tonnes of regolith. The total minable regolith in unit blocks and sideward extensions is 71,400,000 tonnes. At the annual mining rate of 4,960,000 tonnes estimated for the machine designed by Sviatoslavsky and Jacobs [5], the area in Figure VI-9 would supply a single machine with regolith for at least 14.4 years.

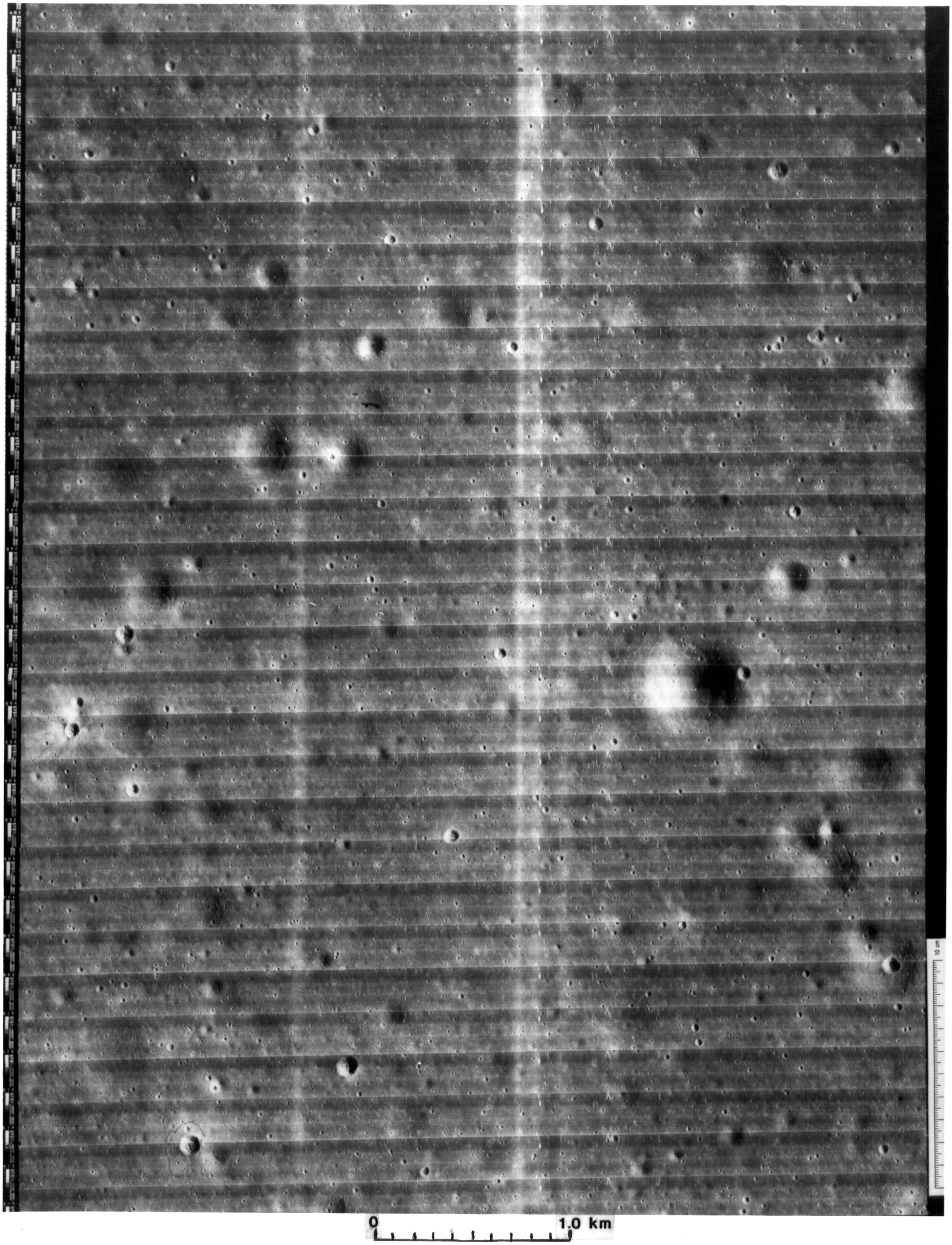


Figure VI-8 Lunar Orbiter photograph II-84H_3.

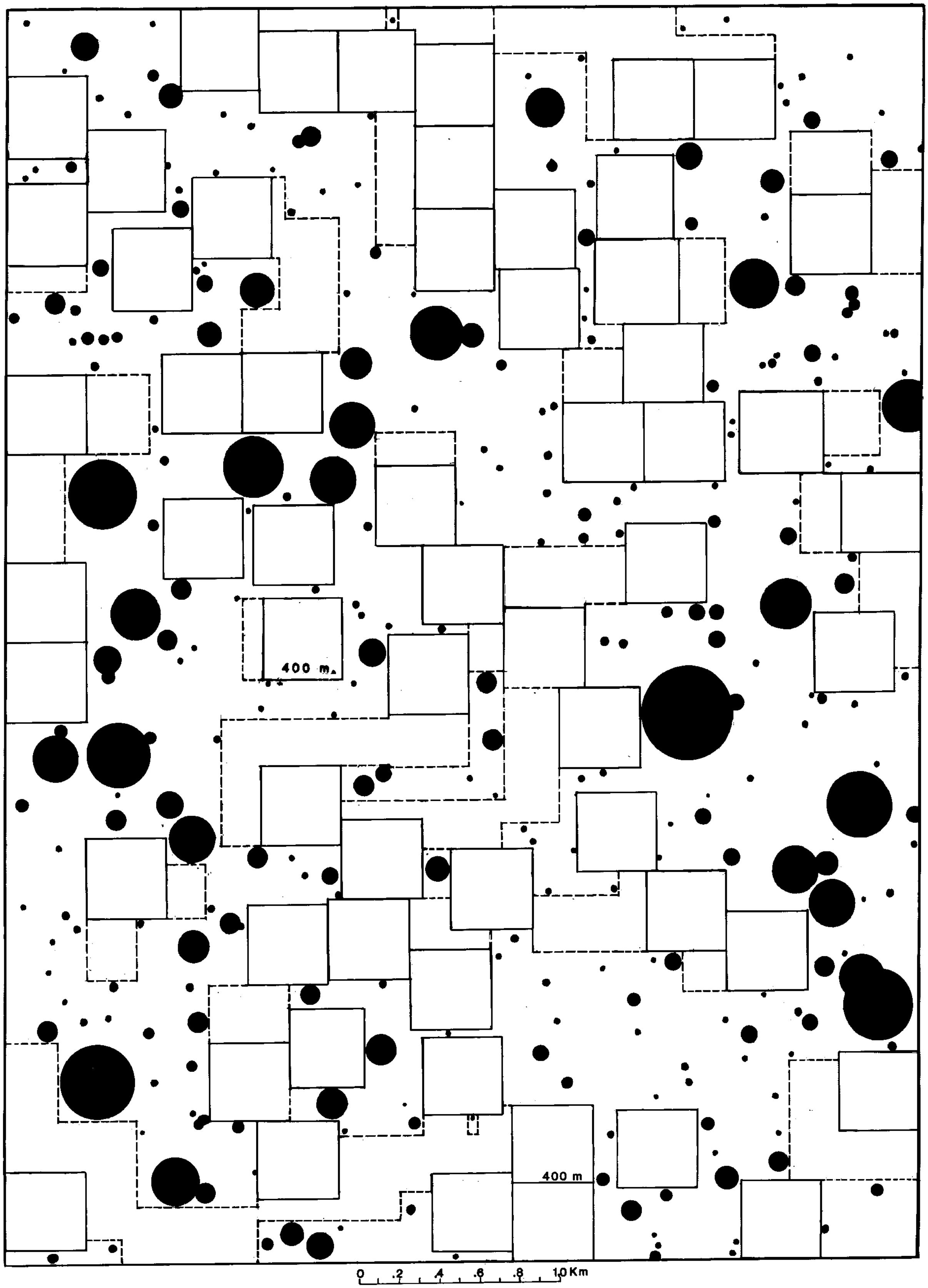


Figure VI-9 Reduced overlay of original of Figure 5. Craters 23.4 m or more in diameter (including ejecta halos where observed or inferred) shown by solid black circles. Minable area plotted in terms of 400-meter square blocks (bounded by solid lines) and extensions (bounded by dashed lines).

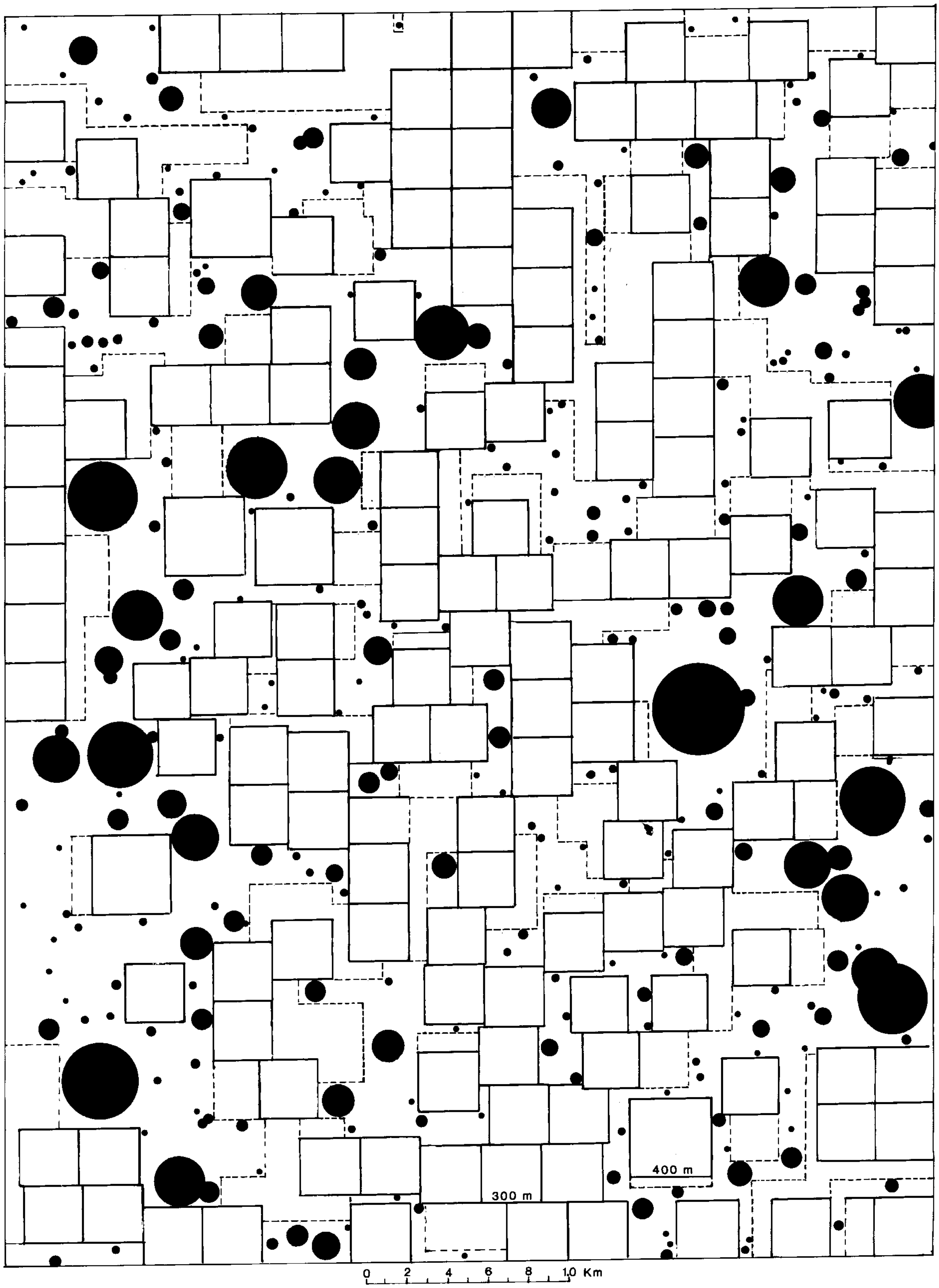


Figure VI-10 Reduced overlay of original of Figure 5. Craters 23.4 m or more in diameter (including ejecta halos where observed or inferred) shown by solid black circles. Minable area plotted largely in terms of 300-meter square blocks (bounded by solid lines) and extensions (bounded by dashed lines).

Pending analysis of the cost effectiveness of mining in relation to size of mining machines and the size of mining units required for efficient operation, the selection of a 400-meter square basic mining unit is arbitrary, though not unrealistic. If it proves economically feasible to mine smaller units, the percentage of the total area minable will be increased. In Figure VI-10 the basic mining unit is taken as 300 meters square. The minable percentage in unit blocks and sideward extensions is 56 percent, and the amount of regolith available is 95,200,000 tonnes.

For the area extending east and north from the Apollo 11 landing site, 48 high-resolution prints covering about 1050 sq. km. are available. Craters have been measured on 15 of the prints and used to calculate, for each print, the percentage of the total area that is occupied by craters approximately 24 m or more in diameter and their visible or inferred blocky halos. The calculated crater percentages range from 7.6 percent to 22.1 percent. The average is 12.2 percent. For the photograph of Figure VI-8 the value is 8.3 percent.

Charts similar to those of Figures VI-9 and VI-10 have been constructed for three other prints for which the calculated crater percentages are 12.1 (II-88H2), 15.2 (II-86H2) and 22.1 percent (II-83H2). The effect of unit block size on percentage of total area minable is shown in Figure VI-11. For each print, minable percentage reaches its maximum when the unit block edge becomes zero, at which point the unminable area is equal to the percentage of the total area occupied by craters and halos.

The study suggests that for the Apollo 11 area, minable portions will range from 17 percent to 42 percent if the basic mining unit is 400 m square, or from 28 percent to 57 percent if the basic mining unit is taken as 300 m square. An average of 40 percent seems a reasonable estimate.

From the environmental standpoint, two features brought out by study and analysis of lunar photographs are important. One is that the total area over which mining operations will ultimately extend will be larger than suggested by the figures in Table VI-1 for total area disturbed by mining in successive years. The total area will depend on the average minable percentage. At an average of 40 percent, mining operations through 2052 will extend over an

Effect of Square Unit Mining Block on The Fraction of Minable Area in Unit II of Mare Traquilitatis

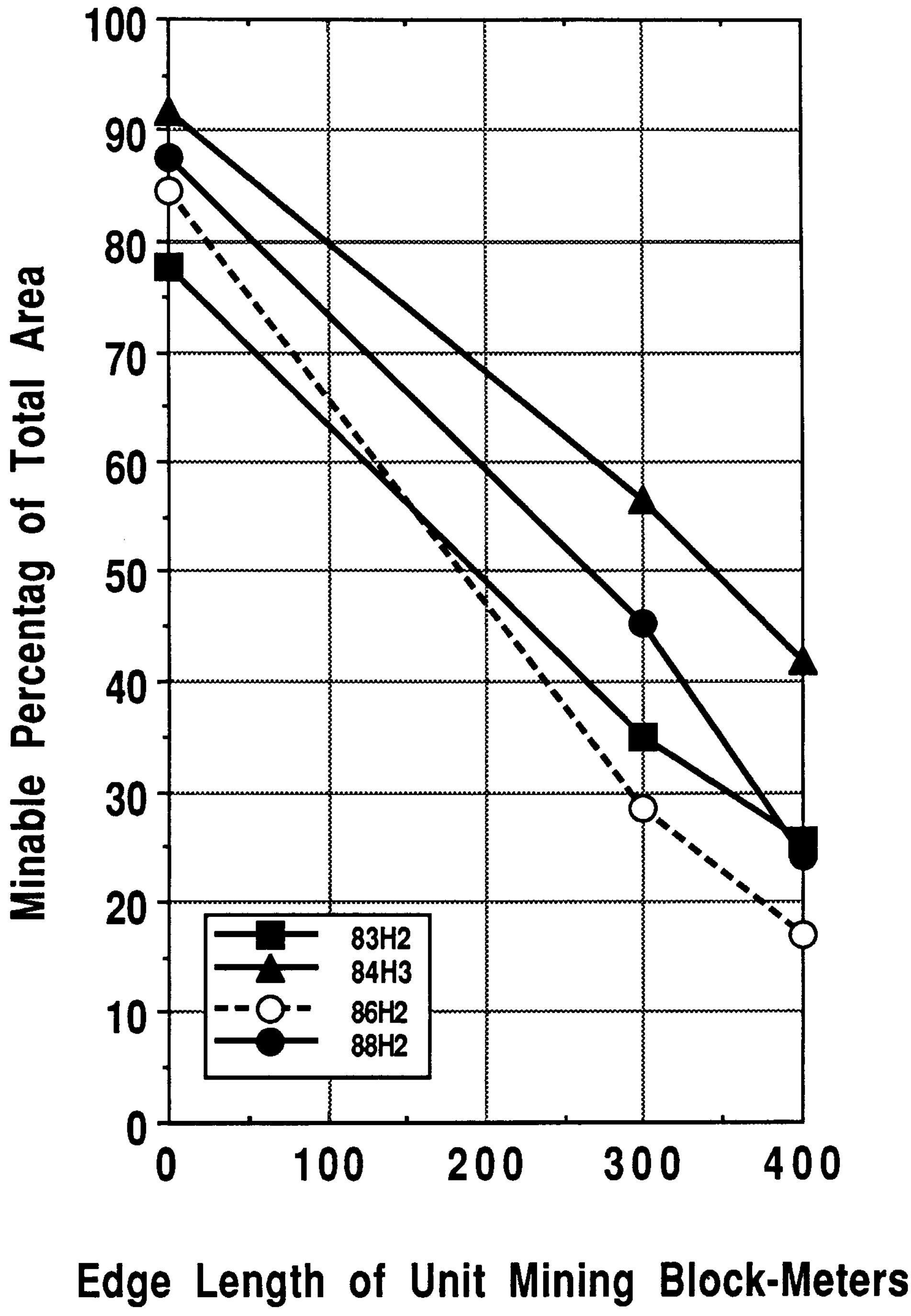


Figure VI-11. Relation between size of unit mining block and minable percentage of area, as illustrated by areas covered by Lunar Orbiter photographs, II-83H2, II-84-H3, II-86H2, and II-88H2.

area of 42,000 sq. km. The second is that if conventional methods of surface mining are used, it is very unlikely that more than 50 to 60 percent of any sizeable portion of the mare will be minable. The mare surfaces will therefore not be totally destroyed. All major features of the mare will remain untouched; they will be unminable. Smaller features of all kinds will be preserved in each of a very large number, certainly thousands, of areas, some large, some small, scattered over the entire mare.

The foregoing discussion is directed solely toward the physical minability of Mare Tranquillitatis. The proportion of the mare that will ultimately be minable will be influenced by variations in helium content of the regolith; the helium content of the regolith that may be found from part to part of the mare. Such variations are suggested by spectral reflectance maps.

VI.B.1 Albedo

The normal albedo of mare materials ranges from 7 to 10 percent [6,7]. Many of the Apollo photographs taken in the vicinity of the Lunar Modules (LM) indicate that the activities of the astronauts exposed material of lower albedo (darker) than the apparently undisturbed surface. However, visual observation of the surface around the LM from a distance, and even from orbit, shows that albedo of the area within a few hundred meters of the LM has been increased (lightened) by the effects of the LM engine exhaust [8].

No chemical alterations of the surface materials around the LM have been detected, so it must be assumed that the change in albedo results from a physical disruption of the original surface texture. Indeed, zero phase angle (down sun) photographs of mare areas disturbed by the astronauts at several hundred meters or more from the LM show no visually obvious change in surface albedo.

These considerations suggest that there will be little or no visually detectable change in surface albedo due to He-3 mining.

VI.B.2 Crater Distribution

In portions of the mare excavated, He-3 mining will destroy all craters below about 24 m in diameter (this assumes mining to about 3 m depth of regolith). Mature craters with diameters about 4 times the depth of the local regolith will be significantly subdued in shape as mining operations proceed through them. Larger craters that have penetrated to blocky material and have such material in their ejecta blankets will be left largely undisturbed.

None of these changes will be visible from the Earth even through the use of telescopes. Over geologic time, the disturbed regolith will gradually be restored to its original condition by the continued impact of meteors.

VI.C. Atmosphere and Precipitated Volatiles

Several facts and logical considerations suggest strongly that no indigenous water exists on or within 200-300 km of the lunar surface:

1. No indigenous water has been detected in the analysis of lunar samples [9].
2. Very strong arguments can be made for the early melting of the outer portions of the moon [8,10]. In the extraordinarily violent and hot splashing of the melted shell by residual debris, any indigenous water would have been lost to space [8].
3. The lunar rocks and regolith form a highly reducing environment (ferrous sulfide is a stable phase) and would tend to react with most water present. Although a great amount of work was undertaken to determine the origin of the "rusty rocks", it was generally concluded that the "rust" was the consequence of post sampling contamination.
4. No water has been detected in core tube samples that penetrated the -20°C minimum isotherm (70 cm) in the lunar regolith.

On the other hand, Watson and others [11] and Arnold [12] have calculated that a proportion of any water released on the lunar surface will be precipitated and retained in the permanently shaded regolith above about 78°N and 78°S latitudes (5×10^{-3} of the lunar surface). They calculate that the lunar permanently shaded area of about 1.9×10^{15} cm^2 could hold water as ice with a loss rate at a vapor pressure of 1.4×10^{-12} mm (120°K) of 3×10^{-16} g/cm^2/sec averaged over the area of the entire lunar surface. This loss rate at equilibrium would correspond to a lunar atmosphere water mass of 6.6×10^8 gms. The loss rate drops by a factor of 10^4 for a surface temperature of 100° K. (As no indigenous water has been detected in the lunar atmosphere, this further argues that no indigenous water ice exists on or near the moon's surface.)

Although the accumulation of artificially produced water and other volatile precipitates (Watson and others conclude that only water and mercury will be trapped in appreciable amounts) in permanently shaded regolith would tend to sustain a steady state supply of gases to the lunar atmosphere in the vicinity of cold traps, the work of Fernini and others [13] suggests that the effect will be unimportant more than a few km from each source.

An analysis also should be carried out to estimate how rapidly would water released in the vicinity of human activities accumulate in permanently shadowed regolith. In this case, such regolith acts as a "getter" to reduce atmospheric (vacuum) contaminants. The analysis by Fernini and others indicated that physical adsorption and rebound dominates gas molecule movement across the lunar surface at both low (100° K) and high (273°K) surface temperatures with the rebounding molecule equilibrated thermally with the adsorbing surface. However, their analysis did not include the case where water molecule adsorption occurs on the surface of a stable phase such as ice. Watson and others [11] concluded that the permanently shaded areas at 120°K are very efficient cold traps and water molecules caught as ice in them will have a mass loss rate of only 4 g/cm^2/billion years averaged over the total lunar surface. At 100°K, the more likely temperature, the loss rate is 10^4 less than at 120°K.

Arnold [12], supported by the later experimental work of Lanzerotti and Brown [14], suggested that sputtering of ice by charged particles may significantly increase the loss rate of water ice even from permanently shaded areas (exposed to the isotropic particle environment in the tail of the Earth's magnetosphere). However, as also pointed out by Arnold, the steady mixing of ice and regolith would tend to protect the ice from the effects of sputtering.

For completeness, the contribution of ice derived from human activities to a future lunar atmosphere should be included in models such as those of Fernini and others (such as Milford and Pomilla [15], Vondrak [16,17] and Taylor [18]). However, such considerations should not alter their conclusions that an artificial lunar atmosphere resulting from foreseeable human activities "is not a serious detriment to astronomical observation and high-vacuum materials processing" [13-18]. See a discussion on the chronology of this work in the Appendix.

VI.D. Other Environmental Effects

Dust will be produced in quantity both during mining and during reclamation, but owing to the absence of an atmosphere, settling will be ballistic, rapid, and confined to the immediate vicinity of mining equipment.

The writers have discussed, among themselves and with others, the question of whether significant amounts of gases will be released during mechanical handling of regolith on the Moon. This question can only be resolved, if necessary, by acquisition and testing of appropriate additional samples from the Moon during a future lunar mission.

VI.E. Reclamation

It will be impossible to restore the excavated portion of the regolith to its original contour, since there is no feasible method of recreating the untold millions of smaller craters that will be destroyed by mining. The only feasible reclamation will be grading of mined areas to produce smoothly undulating surfaces. When access roads to mining areas are abandoned during the advance of mining, roadbeds should be torn up and their material blended with adjoining regolith.

Over the longer term, bases constructed at various points on Mare Tranquillitatis will be successively abandoned or moved as mining moves away from earlier locations. Except for those that may be needed for research or other purposes not directly related to mining, the installations should be torn down. Their sites should be graded to original contours and perhaps covered with regolith skimmed from adjacent mining areas.

As mining operations proceed, there will be a gradual accumulation of warrant machinery, equipment and other non-recyclable materials. A landfill site in a nearby portion of the mined out area should be constructed for disposal of the materials.

V.F. Other Environmental Considerations

VI.F.1. Effects of Processing on the Mineralogy of Regolith

Petrographic analyses of the regolith of the regolith of Mare Tranquillitatis as the Apollo 11 landing site (Tables V1-3 and VI-4) show that it is a complex mixture of rock fragments, fused soil aggregates (fused component), silicate minerals, oxide minerals, and rock glass, with a few percent of native iron, troilite (FeS), and other minerals. None of these phases, except possibly ilmenite, will be affected by heating to 700 degrees Celsius, hence will be unchanged during processing of regolith fines for release of hydrogen, helium, and associated gases.

Table VI-3

Grain Count Modal Data for the 90-20 mm Fraction of Apollo 11 Sample 10084 [18]

Plagioclase	21.4%
Pyroxene	44.9
Olivine	2.1
Silica	0.7
Ilmenite	6.5
Mare glass	16.0
Highland glass	8.3
Total	99.9%

The products of reduction of ilmenite to produce oxygen will depend on the process used. If reduction with hydrogen is done at about 900 degrees Celsius [19], reaction products will be metallic Fe and TiO_2, which will be discarded with the residue of concentrate, all as particulate solids. Silicates and remaining oxides in the spent concentrate will be unaffected.

Table VI-4
Grain Count Modal Data for the 1000-90 mm fraction of sample 10084 [11]

Lithic fragments	
Mare basalt	24.0%
Highland component	2.3
Fused soil component	59.5
Mineral fragments	
Mafic	4.2
Plagioclase	1.9
Opaque	1.1
Glass fragments	4.5
Devitrified glass	1.8
Other	0.3
Total	99.9%

If, however, reduction is done at very high temperatures by a plasma process [20], regolith processed will be converted to a slag. This would either have to be piled in dumps or buried in mined areas beneath regolith processed for gases.

VI.F.2. Waste Products

Waste products of helium mining operations will consist of waste products of excavation, beneficiation, and heat treatment of regolith, human wastes, and other wastes (paper, packaging, and wornout office, laboratory, and production equipment) associated with habitation, life support, and various operations at the lunar base. The disposal of wastes from mining and processing (spent regolith fines, ilmenite reduction) is discussed in previous sections of this report. Human wastes will be treated, then partly recycled (water supply), partly used in food production. Other clearly non-usable wastes from habitation, office, laboratory, and shop activities should be buried in an adjacent mined area and covered with spent regolith so as to be indistinguishable from the surrounding area.

A special waste product of human activity will be carbon dioxide. We have not yet calculated the volume of the gas that will be produced at various levels of mining operation and numbers of personnel and cannot yet predict whether the gas thus produced, plus carbon oxides produced during gas processing, will be in excess of that required for food production. If there is an excess, it will have to be stored or so gradually released that it will not contribute significantly to a lunar atmosphere. The problem needs further study in consultation with those engaged in developing methods of food production.

VI.F.3 Radioactivity

The long lived radioactive isotopes generated by the production of 1 MWe-year of nuclear energy from a fission reactor are listed in Table VI-5. The exact level of electricity consumption for the lunar base is unknown at this time, but a value of ~ 1 MWe continuous is a reasonable value for a base of 20 people.

The isotopes of major concern are Sr-90, Cs-137, and the isotopes of Pu from 238 to 241. At shutdown these isotopes represent ≈ 25,000 Curies but this decays by approximately a factor of 1000 in 300 years to ~ 22 Curies. The hazard presented by these radioactive isotopes depends on how they are shielded and the degree of containment. Unlike the situation on Earth, even if the isotopes were to be released into the lunar regolith, there is no aqueous transport mechanism to move them around. Obviously, airborne migration is also not a problem. A preliminary assessment of the threat to humans reveals no major problems unless subsequent visitors or settlers were to dig inadvertently to the waste burial sites.

Table VI-5

Inventory of Long Term Radioactive Fission Product Isotopes Resulting From the Generation of 1 MW-Year of Electricity

Isotope	Half Life Yr	Mass g	Activity (Ci) At Shutdown	Activity (Ci) at 300 Years
Sr-90	28	89	12,400	8.7
Cs-137	30	141	12,300	12.3
Pu-238	89	0.0063	0.11	0.011
Pu-239	24,000	20	1.23	1.23
Pu-240	6,700	0.026	0.006	0.006
Pu-241	13	3×10^{-5}	0.003	Negligible
		Total	≈ 24,700	≈ 22

References for Chapter VI

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VII. Conclusions

The detrimental effects of He3 mining on the lunar surface seem to fall into 3 categories; visual, atmospheric release, and solid waste disposal. The visual degradation has two potential components; the removal of small ($\leq$ 20 m diameter) craters from roughly half of the surface area mined in the lunar Mare; and the change in the albedo of the surface of the Mare. The smoothing of the surface between large ($\geq$ 20 m diameter) craters is only of aesthetic interest and not of scientific importance. The geological record of the lunar surface can be preserved by observing smaller impact craters within the larger craters which would not be mined. The change in surface reflectance may be visible to a person on the lunar surface, but would not be detectable from the Earth even with high powered telescopes.

The potential for increasing the background atmosphere on the Moon is certainly of concern due to release of gases from the mining operation or due to transport (rockets) or even human presence. However, due to the low gravity of the Moon such effects will be both local (within ~ 1 km) and transient (~ on the order of days from time of release). Mining locations can be chosen to be far enough from scientific outposts so as to have little or no effect.

The disposal of worn out equipment and human waste products can be closely controlled. The most obvious solution, aside from recycling a large fraction of the material, is to construct land fill locations in the area already mined. The volume of unrecycled waste will be small and the lack of water or air means that there is no potential for the migration of any harmful elements should they be included in the wastes.

Overall, there appears to be no major environmental problem associated with the extraction of lunar volatiles. Further research on methods to reduce the amount of nonrecyclable material used on the lunar surface would be of use to any lunar colony which may be envisioned for the future.

VIII. Appendix IX
Annotated Chronology of "Atmospheric" Contamination on the Lunar Surface

[1] Watson, K., Reference [VI-11] and others (1961a, 1961b): Analysis of the precipitation and loss of water ice and other volatiles from hypothetical deposits in permanently shaded cold traps near the lunar poles. Although no water has been found on the moon, the analysis applies equally to water and other volatiles produced by human activities.

[2] Milford, S.N., and Pomilla, F.R. (1967) Reference [VI-15]: Developed and utilized a two-dimensional diffusion model to predict propagation of Lunar Module effuents around the moon.

[3] Vondrak, R.R. (1974) Reference [VI-16]: Discussion of the stability of a lunar atmosphere if created rapidly at a mass (108 kg) where mass loss due to thermal energy reaches a constant.

[4] Arnold, J.R. (1979) Reference [VI-12]: Review and confirmation of work of Watson and others (1961b) relative to permanently shaded cold traps on the moon. Suggests that sputtering from charged particles may significantly increase the loss rate of water from cold traps, however, also suggests that ice will be protected by mixing with the regolith.

[5] Lanzerotti, L.V., and Brown, W.L. (1981) Reference [VI-14]: Estimated the loss ratio of lunar ice due to particle sputtering as determined by experiments on water ice.

[6] Taylor, J (1989) Reference [VI-18]: Considerations of mining for He-3, O_2, and glass as sources of lunar atmospheric contamination. Concludes that mining of 20 tonnes of He-3/year, with 20% gas loss to atmosphere, results in 1 kg/sec gas release.

[7] Fernini, I, and others (1989) Reference [VI-13]: Discusses the potential sources and sinks of a lunar atmosphere, develop two models for describing a variable lunar atmosphere, and concludes that the lunar base that includes He-3 mining will not be a serious detriment to lunar astronomical observations or high vacuum materials processing.

[8] Vondrak, R.R. (1989 Reference [VI-17]: Considered what level of human activity could contribute to the growth of a lunar atmosphere. His conclusions were that even the mining of 1 million tonnes per day of lunar regolith would not release more than 0.1 kg/s into the lunar environment. He also calculates that one would have to release 60 kg/s in order to exceed the gas input to the lunar surface due to the solar wind. This would mean mining a mass of ~0.6 billion tonnes per day.