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ENERGY REQUIREMENTS FOR HELIUM-3 MINING OPERATIONS ON THE MOON

WCSAR-TR-AR3-8810-7

Technical Report

Wisconsin Center for
Space Automation and Robotics
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A NASA supported Center for
the Commercial Development of Space

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G.L. Kulcinski, I.N. Sviatoslavsky, J.F. Santarius,
L.J. Wittenberg, E.N. Cameron, T.M. Crabb, M.K. Jacobs

Wisconsin Center for Space Automation and Robotics
University of Wisconsin
1500 Johnson Drive
Madison WI 53706

January 1988

Presented at the Fifth Symposium on Space Nuclear Power Systems, Albuquerque NM, 11–14 January 1988

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Gerald L. Kulcinski, Igor N. Sviatoslavsky, John F. Santarius,
Layton J. Wittenberg, and Eugene N. Cameron
Fusion Technology Institute
Nuclear Engineering and Engineering Physics
University of Wisconsin-Madison
1500 Johnson Drive
Madison, WI 53706-1687

Tom M. Crabb and Mark K. Jacobs
Astronautics Corporation of America
5800 Cottage Grove Road
Madison, WI 53716

October 1988

[Presented at the Fifth Symposium on Space Nuclear Power Systems, Albuquerque, New Mexico, 11-14 January 1988]

ABSTRACT

The need for more acceptable nuclear power sources, both on Earth and in space, has prompted scientists to examine the use of the advanced fusion fuel cycle, D-He^3. It is shown that while the initial development period can be fueled by the limited terrestrial He^3 resources, a large scale economy based on this fuel cycle requires a much more extensive source of He^3. The moon has been shown to contain ~ 1,000,000 tonnes of He^3 which resulted from solar wind bombardment over the past 4 billion years. Methods to thermally recover this fuel are described in the paper. The masses of equipment required to mine He^3 are given along with the operational energy requirements. It is shown that approximately 70 kg of equipment mass must be carried from the Earth to the Moon per kg of He^3 recovered (amortized over 20 year life). The energy required for transportation, operations, and support of the incremental base camp necessary for the mining operations is shown to be approximately 2250 GJ per kg of He^3 recovered. Because 1 kg of He^3 burned with D_2 gives 600,000 GJ of energy, the payback ratio is approximately 266 to 1.

INTRODUCTION

Modern societies depend on energy for their very existence. Without it, the Earth cannot support its present population of 5 billion people let alone even dream about supporting the 8 to 10 billion people that are likely to inhabit the Earth under the so called 'equilibrium' conditions of the 21st century (Häfele 1981). As the world passes through the 21st century, two events will shape our society: the exhaustion of economically recoverable fossil fuels somewhere around the middle of the 21st century, and the transition to a nuclear energy economy at roughly the same time. Furthermore, extensive use of nuclear energy will be required if mankind is to move into space. The question today is, will the main nuclear source of the 21st century be fission or fusion? The use of fission reactors in space has been amply described in the past 4 annual Space Nuclear Power Symposia held from 1984 through 1987. The future of fission reactors on Earth has been the subject of countless articles. The object here will be to focus on the fusion option, and in particular, the use and procurement of the advanced fusion fuel, deuterium (D) and helium-3 (D-He^3).

It has been shown that the D-He^3 fusion fuel cycle has large advantages over the more traditional DT (deuterium-tritium) cycle because of its low neutron production

$$D+He^3 \rightarrow p\ (14.1\ MeV) + He^4\ (3.5\ MeV)\ .$$

Depending on the plasma temperature and the He^3 to D ratio, the fraction of energy released in neutrons can be as little as 1% (Kulcinski and Schmitt 1987). This is a factor of ~ 80 below the neutron energy fraction in the DT reactors and a factor of ~ 50 below that of the DD fuel cycles (see Figure 1). The lower number of neutrons emitted per unit of energy released will have the following benefits:

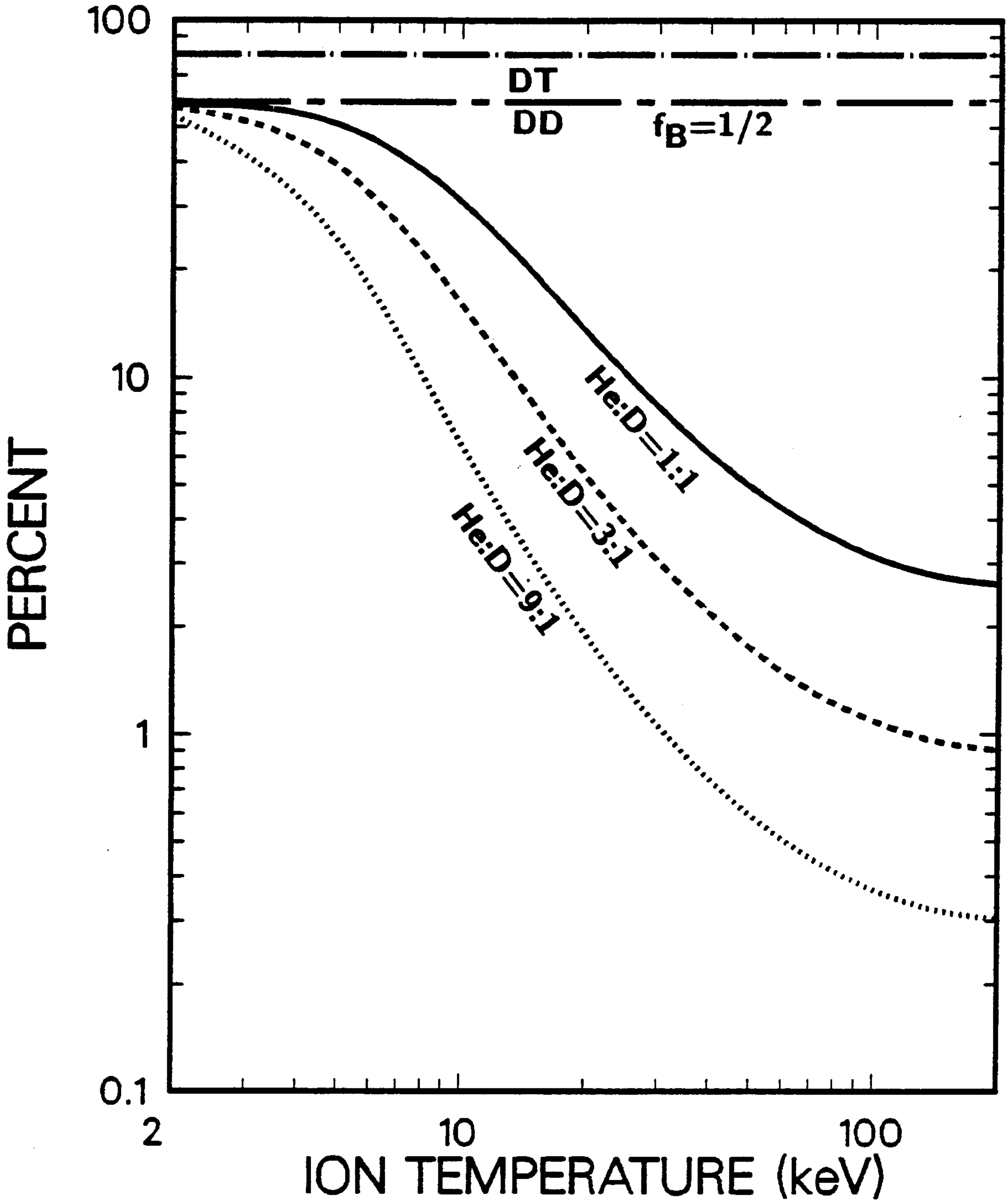

Figure 1. Percent of Fusion Power in Neutrons (50% Tritium Burnup).

- Reduced Radioactivity,
- Reduced Radiation Damage,
- Improved Safety,
- Increased Efficiency,
- Lower Cost of Electricity, and
- Shorter Development Paths to Commercialization.

These issues have been discussed previously and will not be repeated here except for the following brief comments:

- The radioactive wastes from a D-He^3 power plant qualify as class A which allows near surface land burial (Kulcinski 1988).
- The neutron radiation damage is so low that it is relatively easy to design the first wall for the full lifetime of the plant (in contrast to a 2 to 3 year life in DT plants).
- The amount of afterheat is so low (compared to both fission and DT fusion) that it is impossible to conceive of an accident that would cause a meltdown of the blanket.
- The low neutron production means that most (up to 99%) of the energy released is in the form of charged particles which can be converted to electricity directly by electrostatic means yielding efficiencies of 70 to 80% (Barr 1983).
- The cost of electricity from high efficiency and low radioactivity power plants can be as much as 30 to 50% cheaper than for DT systems.
- The large reduction in radioactivity and radiation effects should allow cheaper and fewer test facilities to be built, thus accelerating the development of fusion into a commercial option.

HELIUM-3 RESOURCES

One of the greatest impediments to the development of this fuel cycle is the lack of a large, readily accessible supply of He^3. The He^3 that is presently available for research and neutron detection monitors comes from the decay of tritium and the supplies are limited to a few 10s of kg today. Because the tritium produced for thermonuclear weapons is constantly decaying and generating He^3 at the rate of ~ 10 kg/year, it should be possible to collect enough of this isotope to conduct meaningful physics and technology tests (Wittenberg 1986). Because the energy content of He^3 is ~ 19 MWt-y per kg, it can be seen that the operation of a unit with a capacity of 200 to 300 MWt for several months a year is quite possible. It has been shown that the amount of He^3 available in the early 21st century could be a few 100 kg from T_2 sources, but that is obviously not sufficient for a large scale fusion power industry which would require up to 10 tonnes of He^3 per year.

Wittenberg et al. (1986) drew attention to the fact that there are large amounts of He^3 imbedded in the surface of the moon. This He^3 comes from the solar wind and the potential reserves are estimated at one million metric tonnes. Pepin (1970) has shown that this He^3 can be extracted by heating the lunar regolith to ~ 600 to 700°C, and work conducted at the Wisconsin Center for Space Automation and Robotics has resulted in the design of vehicles to extract the He^3 (Kulcinski et al. 1988).

The robotic unit shown in Figure 2 processes the beneficiated lunar regolith and feeds it into a solar heated lunar volatile extraction chamber (Sviatoslavsky and Jacobs 1988). This chamber is heated by solar energy which is either gathered directly by collectors on top of the Lunar Processor, or beamed to the mobile unit by a fixed solar collector on the surface of the moon.

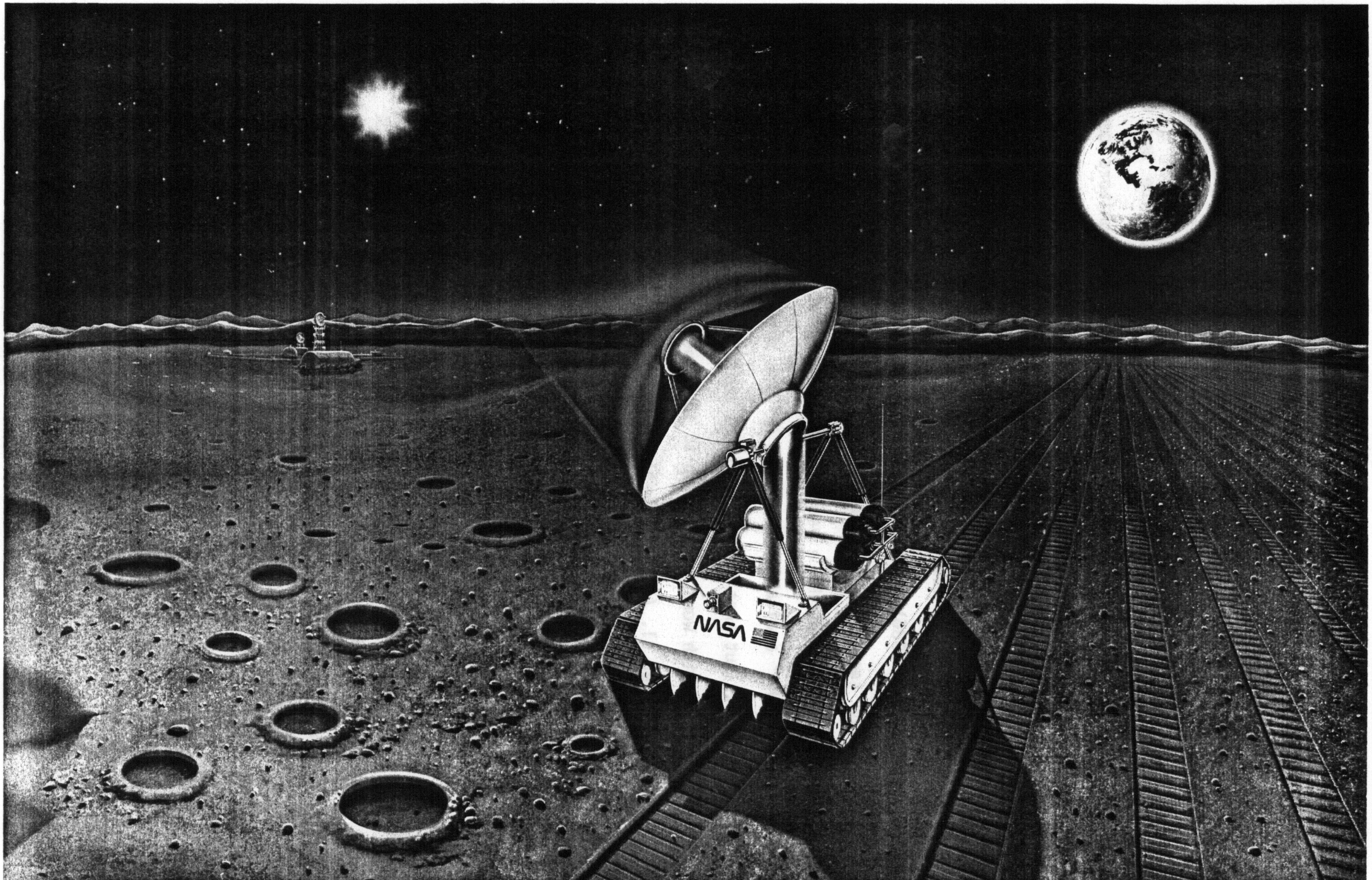

Figure 2. One Possible Version of a Lunar Miner Designed to Extract Solar Wind Volatiles - The Width of the Unit is Approximately 10 Meters.

After the regolith is heated and the solar wind and other lunar volatiles are collected, the spent regolith is passed through a recuperator to recover heat before it is discharged off the back of the unit. There are large amounts of other gases evolved by this heating process as shown in Figure 3. Note that for every tonne of He^3 extracted, over 6000 tonnes of hydrogen, 500 tonnes of nitrogen, 5000 tonnes of carbon containing molecules, and over 3000 tonnes of He^4 are collected (Gibson and Johnson 1971). These gases will be extremely valuable on the Moon for life support, atmospheric control, and chemical fuels.

Once the lunar volatiles have been collected, they must be separated from the helium-3 atoms. This is accomplished in 3 steps as shown in Figure 4:

1. The hydrogen is removed by allowing it to permeate through Pd windows;
2. The H_2O, N_2, and carbon compounds are removed by condensation during the lunar night in a large radiator/condenser unit; and
3. Finally, the He^3 is separated from the He^4 via a superleak technique (Wilkes 1978).

The liquified He^3 is then transported to the Earth.

ENERGY REQUIREMENTS TO PROCURE He-3

There are five main areas where major energy investments are required to procure He^3 (Figure 5):

- Transportation - Carrying all the equipment needed to mine, separate, and store the He^3;
- Incremental Base Camp Supply - Food, water, atmosphere and living quarters for the personnel responsible for the maintenance of the mining equipment;

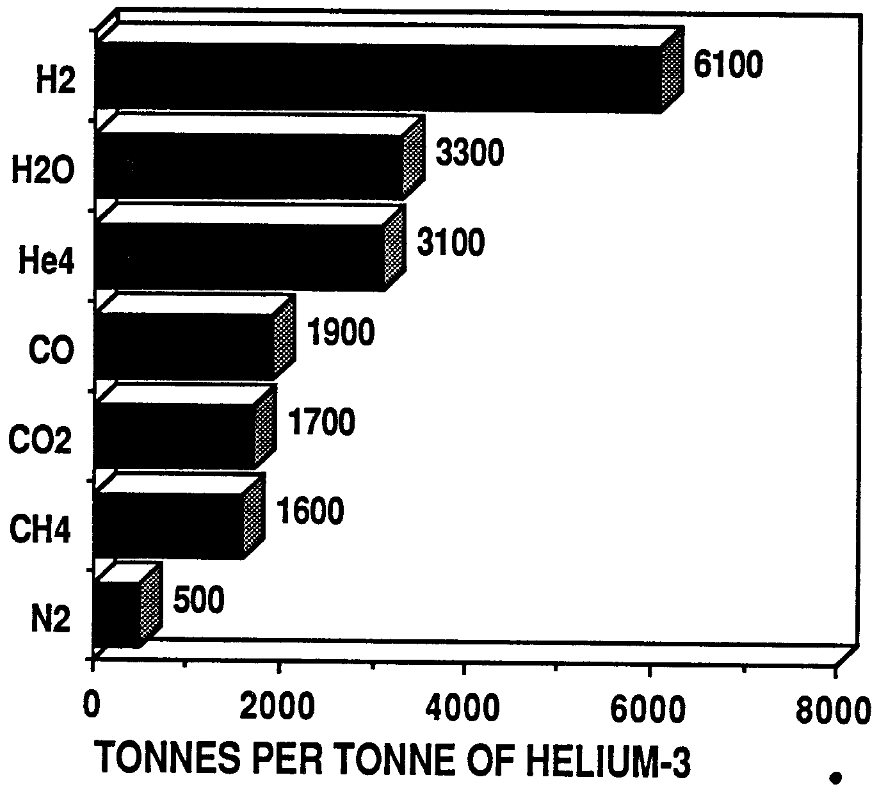

Figure 3. Gaseous By-products from He^3 Mining (700°C Extraction Temperature).

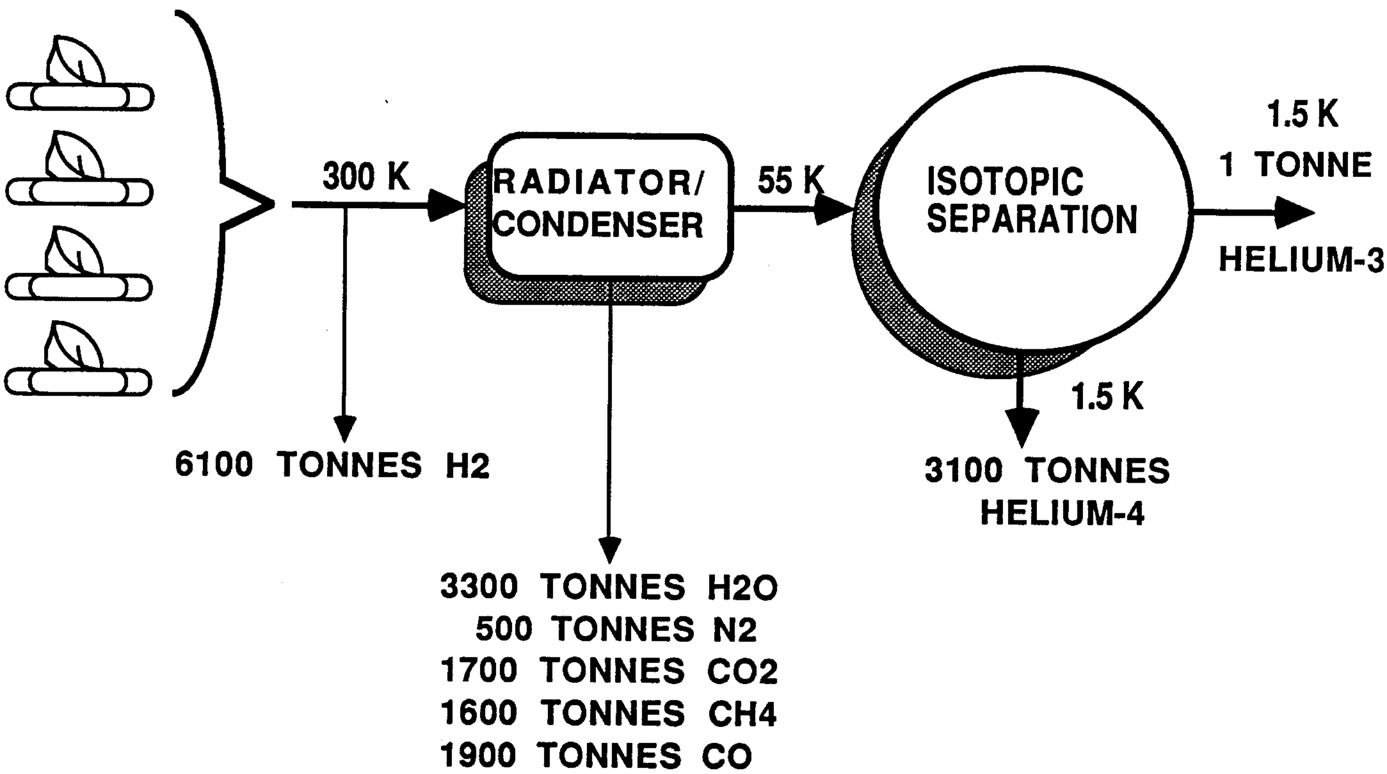

Figure 4. Process for Extracting Helium-3 from Lunar Regolith.

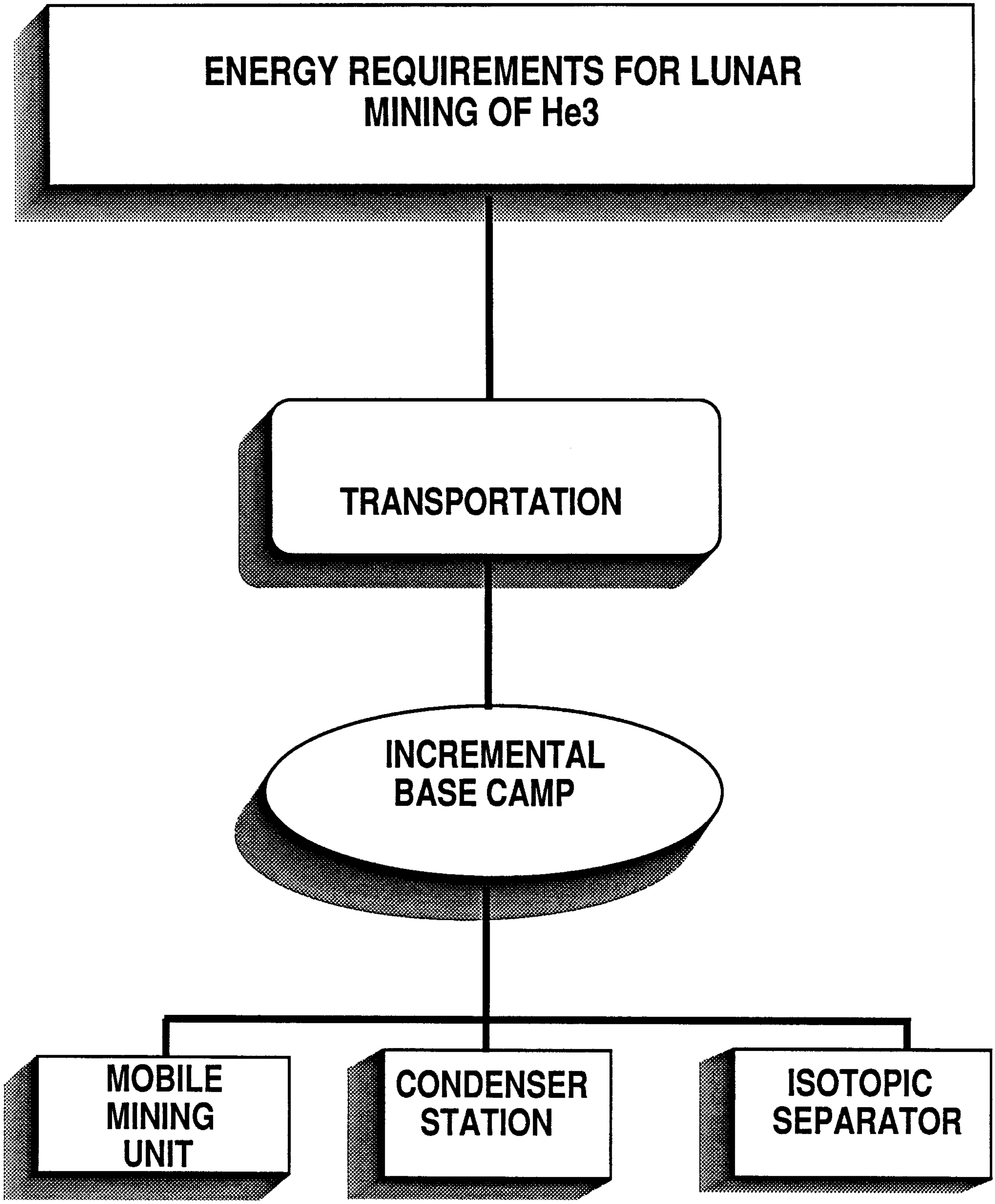

Figure 5. Energy Requirments for Lunar Mining of He^3.

- Mobile Miner - Power to move, extract, and compress lunar volatiles;
- Radiator/Condenser - Condensation of H_2O, N_2, and carbonaceous gases; and
- Isotopic Separator - Separation of He^3 from He^4 (at a 3100 to 1 He-4/He-3 ratio, it is not energetically favorable to do isotopic separation on the Earth).

The amount of equipment mass required to produce a kg of He^3 has been calculated on the assumption that the life of all components on the Moon is 20 years (see Figure 6). This particular calculation uses a basis of 1 tonne of He^3 produced per year and extrapolation to 10 tonnes per year would result in slightly better values. The major mass requirement comes from the mobile miner with 27 kg of mass required from Earth for every kg of helium-3 transported to Earth. It can also be seen that the amount of material for a 10 person crew (1 year tour of duty) including an amortized living unit and semi-closed food cycle amounts to almost 13 kg per kg of He^3 produced. Close behind is the mass for the stationary solar mirrors at 12.4 kg/kg of He^3 and the radiator/condenser at 9 kg/kg of He^3. The isotopic separator (mainly the cryogenerators) requires 4 kg/kg of He^3 extracted and the service vehicle (that unit which picks up the full gas tanks from the mobile miner and leaves empty tanks) requires only 0.8 kg of mass per kg of He^3 extracted. The total mass commitment to this scenario is 66 kg per kg of He^3. In 20 years this means over 1300 tonnes of equipment and life support chemicals would have to be brought to the Moon.

The energy required to transport a kg of mass from the Earth to the Moon depends on the configuration of the lift vehicle, space station, orbit transfer vehicle, and lunar lander fleet to be used. With today's shuttle and technology for a space station, this energy is approximately 100 GJ/kg of

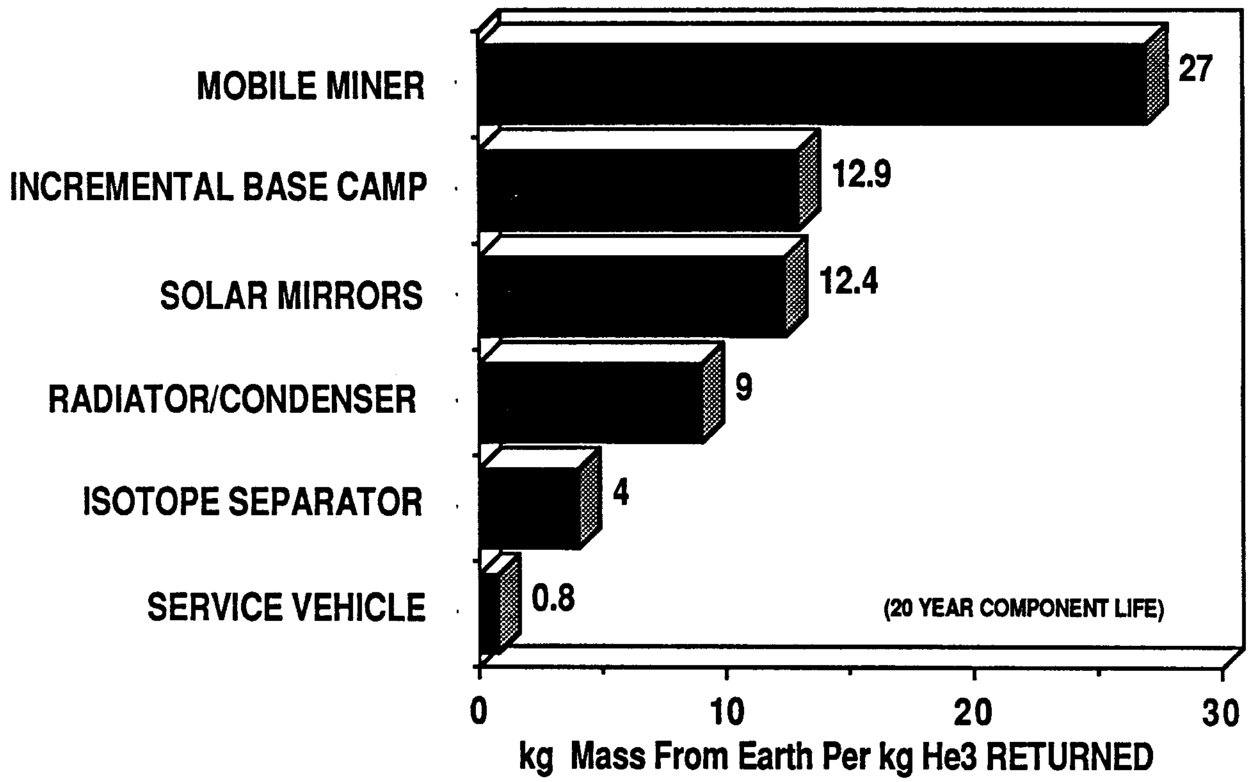

Figure 6. Mass Required from Earth to Mine He^3 on the Moon.

payload mass delivered to the moon and it is projected that this can be reduced to 30 GJ/kg with a series of heavy lift vehicles. Using the 30 GJ/kg value it is calculated that ~ 2253 GJ of energy is needed for transportation to and from the lunar base for each kg of helium-3 placed on the Earth's surface over a 20 year period.

The energy required to operate the mobile miner on the Moon has also been calculated (see Table 1). The largest energy required is obviously to heat the lunar regolith (~ 4100 GJ per kg of He^3 released). Other lesser amounts of energy are required to run the compressors, to operate the excavators and conveyors, and for locomotion of the miner and service vehicle. This electrical energy is assumed to come from photovoltaic cells and batteries. Because the process heat comes directly from the Sun it was not included in the overall balance. If the solar units were replaced with nuclear power plants, then that energy would have to be included. The total net energy required for operation of the lunar miner is ~ 28 GJ/kg of He^3 extracted.

Finally, the operational energy required to circulate the gases through the radiator as well as that required for the cryogenerator of the isotopic separation unit is given in Table 2. Essentially no energy is required for the hydrogen extraction phase and relatively small amounts are required for manipulation of equipment and for gas circulation. The major energy requirement is associated with the cryogenic liquifier. Some 184 GJ of energy is required per kg of He^3 separated.

The total energy invested in obtaining and transporting a kg of He^3 to earth is given in Figure 7. As expected the energy requirement is dominated by the transportation system. The base camp requirements are roughly 20% and the gas separation operations require ~ 10% of the total.

TABLE 1

OPERATIONAL ENERGY REQUIREMENTS FOR LUNAR MOBILE MINER

OPERATION	ENERGY SOURCE	REQUIREMENT (GJ/ kg He3)
LOCOMOTION - EVACUATION	BATTERY/SOLAR	13
CONVEYOR - BENEFICIATION	BATTERY	4
COMPRESSOR /VACUUM	SOLAR	67
TOTAL REQ'D TO PRODUCE ELECTRICITY		84
PROCESS HEAT (ESSENTIALLY 'FREE')	SOLAR	4100
TOTAL		4184

TABLE 2

OPERATIONAL ENERGY REQUIREMENTS FOR SEPARATING GASEOUS COMPONENTS FROM He3

OPERATION	ENERGY SOURCE	REQUIREMENT (GJ/kg He3)
HYDROGEN SEPARATOR	(PERMEABLE MEMBRANE)	VERY SMALL
ROBOTIC MANIPULATOR	BATTERY	1.6
GAS CIRCULATOR	BATTERY	0.5
LIQUIFIER (55 K TO 1.5 K)	PHOTOVOLTAIC	184
	TOTAL	186

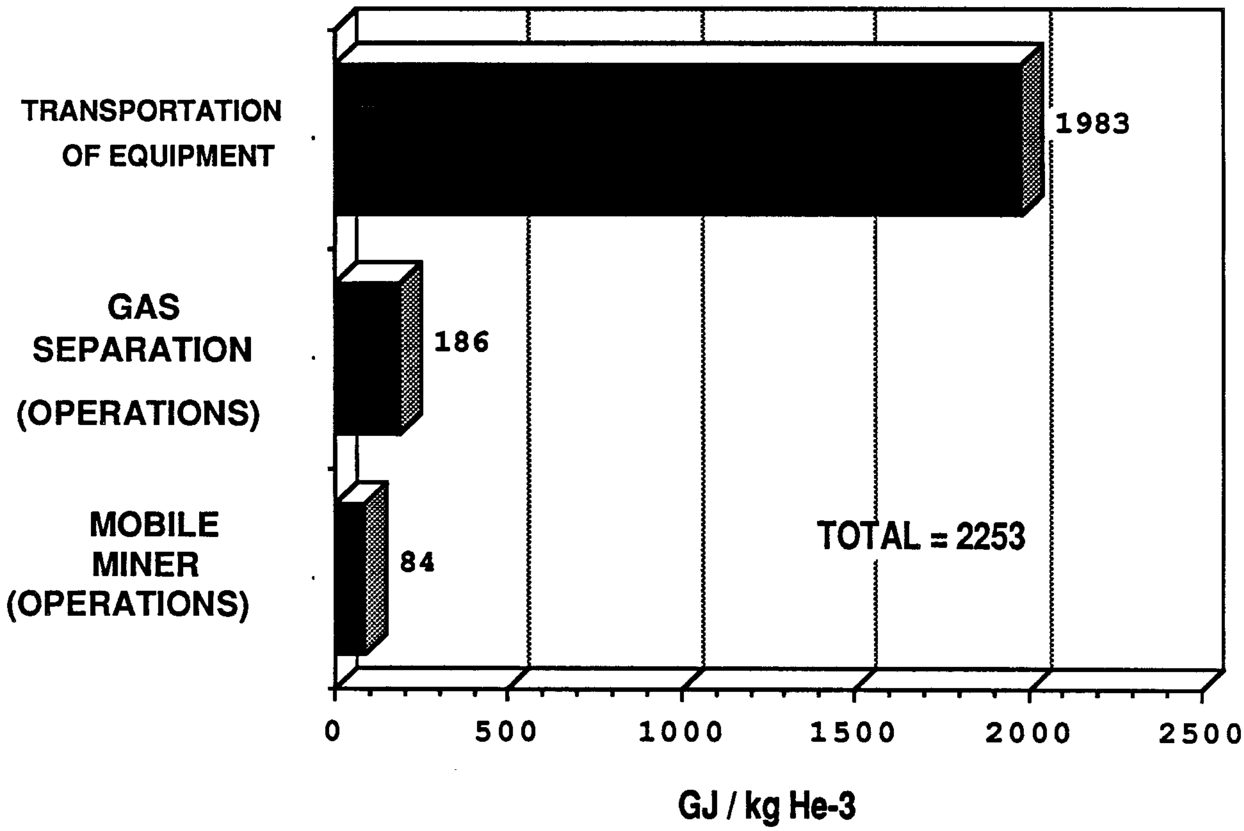

Figure 7. Energy Invested to Obtain and Transport 1 kg of He^3 to Earth.

An important number to consider is the energy payback to obtain a kg of He^3 on Earth. Ignoring the energy investment in a ground support crew, the construction of a fusion reactor, and not taking credit for the use of the by-product lunar volatiles yields a total investment of approximately 1750 GJ per kg of He^3. When this is compared to the 600,000 GJ released by burning 1 kg of He^3 with D_2, one finds a comfortable energy payback of ~ 266. Although this number certainly will fluctuate as more is learned about the conduction of industrial operations on the Moon, the value of 266 should be enough to provide an incentive to develop this resource on the Moon.

CONCLUSIONS

It has been shown that, given the potential inventory of He^3 on the surface of the Moon, it should be energetically favorable to extract this fuel for the benefit of mankind on Earth and in space. An energy payback of 266 is calculated. Future studies should include the energy investment in a fusion power plant as well as energy credits that would be applicable from the lunar volatiles on the Moon. Thus far, the forecasts appear very favorable for economic development of this very important extraterrestrial energy source.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support for this work from the National Aeronautics and Space Administration, the Wisconsin Electric Utilities Research Foundation, and the Grainger Foundation. The authors also wish to acknowledge the assistance of Dr. Eric Rice of the Astronautics Corporation of America for the transportation energy investments.

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