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ENVIRONMENTAL ASPECTS OF LUNAR HELIUM-3 MINING

WCSAR-TR-AR3-9201-5

Technical Report

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January 1992

Prepared for Space 92, The Third International Conference on Engineering, Construction, and Operations in Space, 31 May–4 June 1992, Denver CO

Environmental Aspects of Lunar Helium-3 Mining

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Abstract

Three potential detrimental effects of lunar ^{3}He mining have been identified; visual changes, atmospheric contamination, and solid waste disposal. The removal of small craters (<20 m diameter) and the change in the albedo of the surface may cause a slight darkening of the regolith. However, it is not expected that this change will be visible from the Earth even with powerful telescopes. The release of lunar volatile gases and their effect on the lunar "atmosphere" is expected to be both local and temporary (on the order of a few weeks from the time of release). The solution to solid waste disposal is to recycle as much as possible and to bury the non-recyclable waste. The lack of wind and water means that the waste will stay localized indefinitely and cause no contamination of the environment. The positive benefits of using lunar ^{3}He in terrestrial fusion plants far outweigh the detrimental effects of mining. The reduction in radioactive waste, greenhouse and acid gases, and the reduction in terrestrial mining for fossil fuels could have a major impact on the quality of life in the 21st century.

Introduction

One of the most critical problems that is facing civilization today is the development of a safe, clean and economic source of energy to support the 10 or more billion people who will inhabit the Earth in the 21st century. It has been recently proposed that the thermonuclear fusion of deuterium (D) and ^{3}He can fulfill that need (Wittenberg, et al., 1986). The D-^{3}He fuel cycle generates less than 0.01% of the long-lived radioactivity per kWh of electricity than does 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 public fatalities due to the worst possible accident (Kulcinski, et al., 1991).

The physics of the D-^{3}He cycle have been studied and found to require approximately 2 times the temperatures already achieved in the laboratory and 8 times

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the plasma density-confinement times (nτ) 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 (Emmert, et al., 1988). 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 with current fission and fossil fueled systems (Kulcinski and Schmitt, 1987).

The ^{3}He needed for such reactors (a few 100 kg) 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 (as much as a few tonnes/year) of ^{3}He will be needed. Such ^{3}He resources have been identified in many places on the lunar surface and estimates for the Mare Tranquillitatis alone run into the 10,000 tonne range (Cameron and Kulcinski, 1992). This is enough to supply the present electrical needs of the U.S. for more than 300 years and when the other Mare are included, the supply would last for over a 1000 years. The ^{3}He has been deposited by the solar wind and the gaseous resource can be removed by heating the lunar regolith, in place, and transporting the liquified ^{3}He product to the earth. No large transport of lunar material is required.

In order to assess the net effect of a D-^{3}He fusion economy, one must balance the positive effects to the Earth's environment by any negative effects to the lunar environment. This paper concentrates on the lunar environment and briefly documents the beneficial effects to the Earth's environment. More extensive studies of the terrestrial environmental effects can be found elsewhere (Kulcinski, et al., 1991; Kulcinski and Schmitt, 1991).

Projected Demand For ^{3}He

The key input parameter to lunar mining operations is the potential terrestrial demand for ^{3}He. This involves some speculation on the rate at which fusion will be developed and on the rate that fusion will penetrate the electrical generating market. Such a demand scenario has been developed for an earlier NASA study (Kearney, 1989) and is briefly summarized below.

It has been assumed that the average U.S. growth rate in electricity demand over the period from 1990 to 2050 is 2% per year. While no one can really predict this number with any great accuracy, 2% per year is less than half the growth rate of the 1970's (4.1%) and considerably lower than the current growth rate from 1986-1990 (3.3%). Most of the Department of Energy and electric utility predictions fall in the 2 to 3% range without including the possibility that electric vehicles may be used in the 21st century.

The result of a 2% annual increase in electrical demand is illustrated in Figure 1 for the total kWh's generated. For the purposes of this study we have approached the problem in 2 steps. First, it was assumed that nuclear fission power grows at 3% per year after 2000 and that the difference between the 2% overall growth and the 3% nuclear growth is made up only by coal. No change is assumed in the composition and number of electrical power plants now under construction in the 1990-2000 period. In other words, coal will provide almost all of the growth in the 1990 to 2000 period. This scenario envisions that the electrical energy consumed in the U.S. will rise from 2.8 trillion kWh in 1990 (Monthly Energy Review, 1991) to over 9 trillion kWh in 2050. Approximately 1/3 of that electrical energy in the year 2050 would be provided by fission reactors.

Next, the possible rate of penetration of fusion power into the electricity market had to be calculated. The following assumptions result from the authors' experience in the field of fusion research over the past 20 years.

- The first fusion power plant operates in the year 2015
- The penetration of fusion into the market for the first 20 years is similar to the rate of penetration of fission plants into the worldwide electrical market in the first 20 years of fission power.
- No new fission plants are ordered after the year 2025.
- No new fossil plants are ordered after the year 2030.
- All new plants ordered after the year 2030 are D-^{3}He fusion.

The penetration of fission power into the U.S. and French electricity market is shown in Figure 2. The rate assumed for fusion is consistent with these numbers.

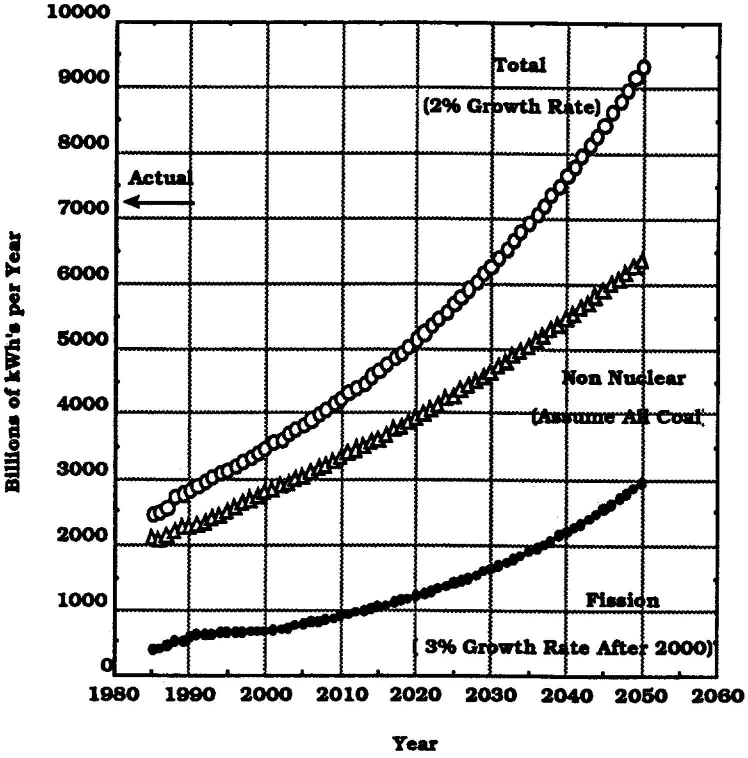

Figure 1. Projected generation of electricity in the U.S. with no fusion.

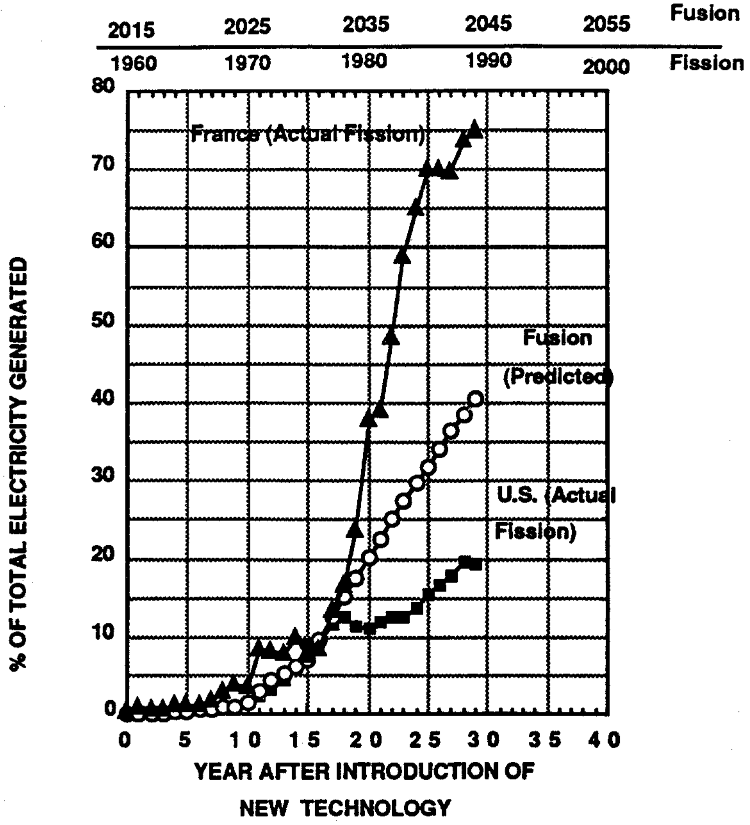

Figure 2. Comparison of historical penetration of fission to that predicted for fusion.

The net result of the above assumptions is depicted in Figure 3. The amount of electricity generated per year is dominated by coal and fission up to ≈2025 and thereafter the fusion fraction increases until it approaches ≈50% of the total market by 2050.

The demand for fusion energy in Figure 3 determines the amount of ^{3}He (Figure 4), and hence lunar mining required. Table 1 summarizes the volume, area and mass of lunar regolith that must be processed to supply the necessary ^{3}He. The resulting values are displayed graphically in Figures 5 and 6 and compared to current terrestrial activities and landmarks. It can be seen that while the amount of regolith is indeed large, it will not even approach the current level of fossil fuel procurement for the first 10 to 20 years after mining starts. Furthermore, the annual area mined will be smaller than the area of Washington, DC for the first 17 years and smaller than the area of Houston,TX when fusion provides 50% of the U.S. electrical energy demand.

Visual Changes On the Lunar Surface

The processing and redeposition of the regolith will cause the lunar surface to be smoothed of all features less than ≈20 meters in diameter. Craters larger than ≈20 meters in diameter that have penetrated into the blocky material and have such

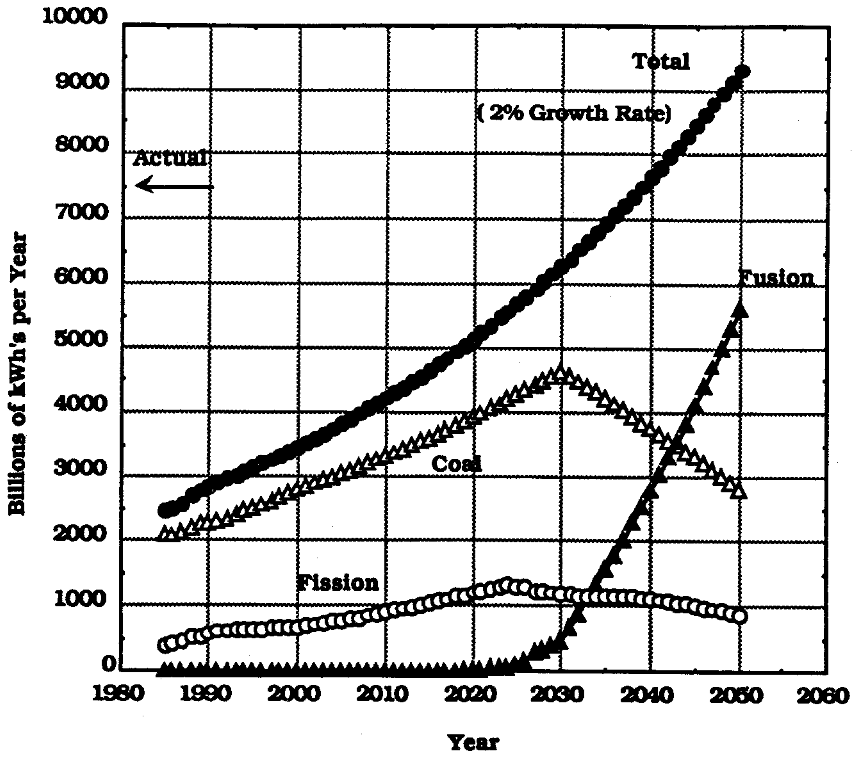

Figure 3. Fusion reactors could generate over 50% of the electricity generated in the U.S. by 2050.

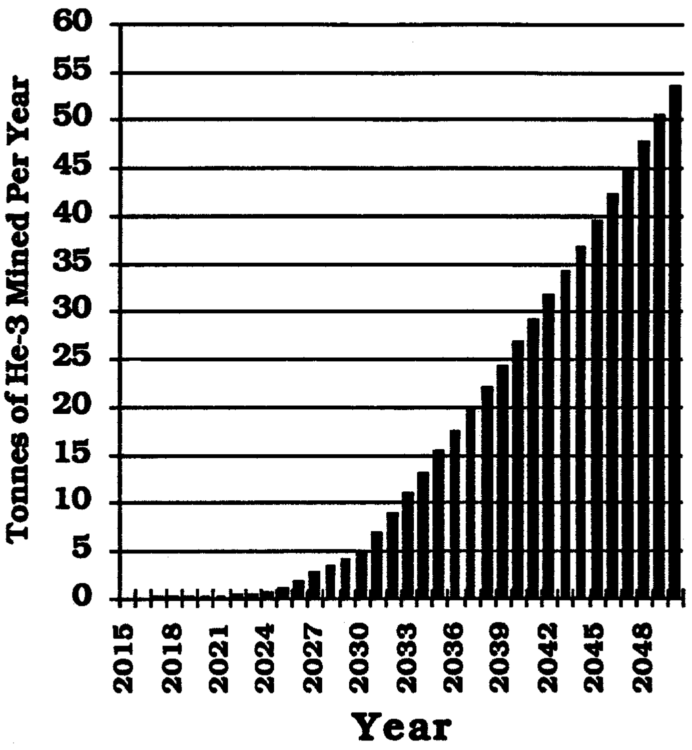

Figure 4. The mining of helium-3 could reach 50 tonnes per year by 2050.

Table 1. Summary of Lunar Mining Operations to Collect ^{3}He

Year	^{3}He/y Tonnes	Regolith Mined Million Tonnes/y	Cumulative Mass Mined Million Tonnes	Area Disturbed km^{2}/y	Cumulative Area Disturbed km^{2}
2015	0.01	1.4	1.4	0.2	0.2
2016	0.03	4.3	5.7	0.7	1.0
2017	0.04	5.7	11.4	1.0	1.9
2018	0.07	10	21	1.7	3.6
2019	0.14	20	41	3.3	6.9
2020	0.21	30	71	5.0	12
2021	0.28	40	111	6.7	19
2022	0.35	50	161	8.3	27
2023	0.45	64	226	11	38
2024	0.56	80	306	13	51
2025	1.00	143	449	24	75
2026	1.82	260	709	43	118
2027	2.79	399	1,107	66	185
2028	3.45	493	1,600	82	267
2029	4.13	590	2,190	98	365
2030	4.84	691	2,881	115	480
2031	6.84	977	3,859	163	643
2032	8.89	1,270	5,129	212	855
2033	10.97	1,567	6,696	261	1,116
2034	13.10	1,871	8,567	312	1,428
2035	15.27	2,181	10,749	364	1,791
2036	17.48	2,497	13,246	416	2,208
2037	19.73	2,819	16,064	470	2,677
2038	22.03	3,147	19,211	525	3,202
2039	24.38	3,483	22,694	580	3,782
2040	26.78	3,826	26,520	638	4,420
2041	29.22	4,174	30,694	696	5,116
2042	31.71	4,530	35,224	755	5,871
2043	34.25	4,893	40,117	815	6,686
2044	36.84	5,263	45,380	877	7,563
2045	39.48	5,640	51,020	940	8,504
2046	42.18	6,026	57,046	1,004	9,508
2047	44.93	6,419	63,464	1,070	10,578
2048	47.73	6,819	70,283	1,136	11,714
2049	50.59	7,227	77,510	1,205	12,919
2050	53.51	7,644	85,154	1,274	14,193

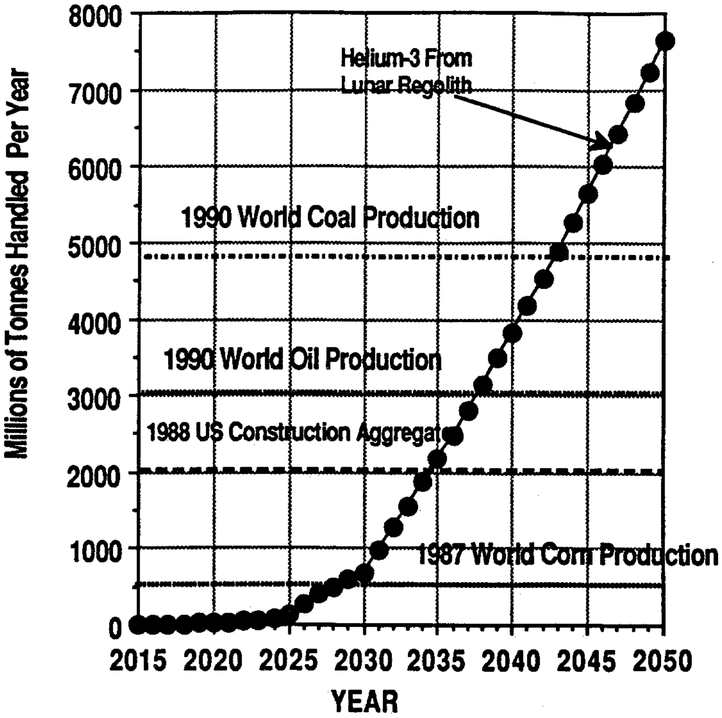

Figure 5. It would take over 25 years of He-3 use to approach the current level of coal mining.

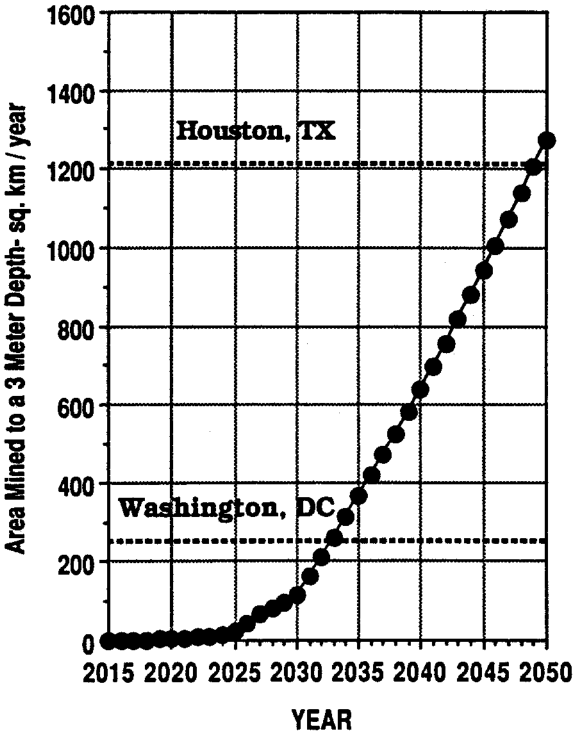

Figure 6. It will take nearly 20 years before an area the size of Washington, DC would be mined annually for Helium-3

material in their ejecta blankets, will be left largely undisturbed. It is estimated that such craters in the Sea of Tranquillity occupy 4.2% of the surface area (Cameron, 1991). The surfaces of such large craters will also contain many smaller craters which will retain the geological record of the lunar surface for future scientific studies. The removal of craters smaller than ≈20 m in diameter will not be detectable from Earth even with the most powerful telescopes now available.

The normal albedo of mare materials ranges from 7 to 10% (Wilhelms, 1987; Baldwin, 1975). 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 the albedo of the area within a few hundred meters of the LM has been increased (lightened) by the effects of the LM engine exhaust (Schmitt, 1975).

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 ^{3}He mining.

Effect on Lunar "Atmosphere"

There is some concern that in the process of recovering the solar wind volatiles from the lunar surface, enough of the gases may be released to contaminate the very tenuous lunar "atmosphere". The natural gaseous environment around the surface of the Moon ranges from ≈ 30,000 molecules/cm^3 during the lunar day and ≈300,000 molecules/cm^3 during the lunar night. The composition is given in Table 2 (Hodges et al., 1975; Heiken, Vaniman, and French, 1991).

Calculations by Vondrak (1988) showed that the release rate from the lunar mining base would have to be >0.1 kg/s to exceed the mass flux from the solar wind. If we assume that we can exceed the solar wind flux by a factor of 10 before we see significant changes in the numbers in Table 2, then a value of ≈1 kg/s release becomes important (remember that the loss of lunar volatiles is due to the low escape velocity from the Moon (2.38 km/s) and because of the ionization from the solar wind). Since the mass fraction of volatiles in the lunar regolith is ≈0.01%, this would imply a minimum mining rate of 15 billion tonnes per year if 1% the volatiles were released during the mining process. From Figure 5, such a mining rate is not reached until well after 2050. The observation that the total lunar atmosphere is only ≈10,000 kg, and each of the 6 Apollo landings released an amount equivalent to that without harmful effects (Vondrak, 1974), indicates that local mining activities for the first 50 years would not probably have any long lasting effect on the lunar atmosphere.

Table 2. The Lunar Atmosphere Depends on the Time of Day

	Maximum # of Molecules/cm^3	
Molecule	Daytime	Nighttime
^{20}Ne	10,000	100,000
He	4,700	70,000
H_2	9,900	150,000
^{40}Ar	2,000	100
CH_4	1,200	≈0
CO_2	1,000	≈0
NH_3	400	≈0

Solid Wastes

Waste products of ^{3}He mining operations will consist of the by-products of evacuation, beneficiation, and the heat treatment of the regolith. Other areas to consider include; human wastes, worn-out office, laboratory, and production (e.g., mining) equipment, along with packaging wastes associated with habitation, life support, and the necessary recreational facilities for the crews. The disposal of wastes from the mining operations will be left in place and will have only local visual effects. Human (including CO_2) and life support wastes will be treated, recycled, and partly used in food production. Other, clearly non-recyclable wastes should be buried in an adjacent mined area and covered with spent regolith so as to be indistinguishable from the surrounding area. Since there is no groundwater nor wind to transport the discarded equipment and supplies, it should stay localized for millions of years to come.

Conclusions

The potential detrimental effects of ^{3}He mining fall into three categories: (a) visual effects, (b) effects on the lunar atmosphere, (c) and the disposal of non-recyclable solid wastes. The current analysis shows that the level of mining for the first 35 years after the start of commercial use of ^{3}He, will not contribute substantially to any detrimental surface changes visible from the Earth, even with the most powerful telescopes of today. Likewise, the release of even 1% of the mined lunar volatiles will not cause any major permanent change in the lunar atmospheric composition nor in its magnitude. The disposal of solid wastes can be done in a manner which is truly permanent in nature and without contamination of other important historical and scientific sites.

There appear to be no major environmental problems associated with the extraction of lunar volatiles and when the benefits of using the low neutron cycle fuel on Earth are considered, it is expected that the net environmental effects will be strongly positive for the use of ^{3}He.

Acknowledgements

The authors wish to thank the Office of Commercialization in NASA for partial support of this research. Additional support from the Grainger Foundation is also gratefully acknowledged.

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