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ABSTRACT

An analysis of astrophysical information indicates that the solar wind has deposited an abundant, easily extractable source of ^{3}He onto the surface of the moon. Apollo lunar samples indicate that the moon's surface soil contains approximately 10^9 kg of ^{3}He. If this amount of ^{3}He were to be used in a 50% efficient d-^{3}He fusion reactor, it would provide 10^7 GW_e-yr of electrical power. The energy required to extract ^{3}He from the lunar regolith and transport it to earth is calculated to be approximately 2200 GJ/kg. Since the d-^{3}He reaction produces 6×10^5 GJ of energy per kg of ^{3}He, the energy payback ratio is ~ 270. Implications for the commercialization of d-^{3}He fusion reactors and for the development of fusion power are discussed.

I. Introduction

The fusion reaction,

$$d + {}^{3}He \rightarrow p(14.7\ MeV) + {}^{4}He(3.6\ MeV)$$

has long been recognized as an attractive candidate for producing "clean" fusion power.(1-4) This reaction is particularly important because the fuel and the main reaction products are charged particles which are not radioactive. In addition, the small number of neutrons that are produced result from d-d side reactions which can be minimized by the proper choice of fuel mixtures and plasma temperatures.

The chief impediment to the utilization of this fuel on a commercial scale, aside from plasma physics issues, is the scarcity of naturally occurring ${}^{3}He$ on earth. As a consequence, even the ${}^{3}He$ known to be contained in terrestrial natural gas deposits could not power a modest sized electrical power plant of 500 MWe for more than a few months.

Extraterrestrial sources of ${}^{3}He$ on Jupiter and Saturn have been identified and estimated to be extremely large, i.e., in the 10^{23} kg range. In 1978, scientists of Project Daedalus(5) postulated that one could extract ${}^{3}He$ from the Jovian atmosphere to provide fuel for rocket propulsion for deep space exploration. However, even with an aggressive space program, such possibilities are probably a century or more away.

The objectives of this paper are to show that there is a closer large source of relatively easily extractable ${}^{3}He$ on the lunar surface, and that the use of this fuel on earth could dramatically improve our energy future. This lunar based resource is so large (approximately equivalent to 10^{7} GW_e-years) that it could provide the ultimate "clean" energy source for terrestrial applications for centuries, or at least until even larger sources of ${}^{3}He$ can be tapped from the outer planets in our solar system.

II. Cosmological Abundance of Helium And Its Isotopic Ratio

Current astrophysical theories advance the hypothesis that the formation of all the elements and their isotopes occurred during the "big-bang".(6) Implicit in these theories is the assumption that these primordial elemental and isotopical compositions were trapped in the suns and gaseous planets which formed from this elemental milieu. The atomic composition of the cosmos is estimated to be 93.4% H and 6.5% He while the $^3He/^4He$ atomic ratio is ~ 140 x 10^{-6}.(7) These primordial compositions do not exist on the rocky planets and moons because of processes during their formation and the following reactions:

(1) radioactive decay of the unstable nuclei;
(2) formation by spallation of new nuclei caused by bombardment with energetic nuclear particles - such as cosmic rays;
(3) preferential diffusion and loss of elements or isotopes to space, especially the light, gaseous elements; and
(4) synthesis of new elements in the stars.

Terrestrial - Natural He-3 Resources

The search for primordial helium in our solar system has been pursued through astronomical observations and by the analyses of samples taken from diverse sources. Helium appears as a minor constituent of the earth's atmosphere, 5.24 (vol.) ppm and the $^3He/^4He$ isotopic ratio is only 1.4 (at.) ppm.(8) However, the present terrestrial atmosphere is not considered to be of primordial origin.

The accumulation of α-particles from the decay of uranium and thorium ores has greatly disturbed the isotopic ratio of helium associated with both the earth's atmospheric and sub-surface sources. For instance, the highest concentration of terrestrial helium occurs in Texas natural gas wells(9) which contain up to 8 vol.% He. As a result of alpha particle accumulation, the $^3He/^4He$ ratio is only 0.2 (at.) ppm in these gases associated with crustal deposits. Gases collected from vents(10) leading to the terrestrial mantle, such as volcanic gases from Kilauea, Hawaii, have higher isotopic ratios, up to 21 (at.) ppm (^{3}He). Recently, ^{3}He/^{4}He ratios up to 11 (at.) ppm, have been discovered associated with the gases evolving from the deep ocean fumaroles along the Eastern Pacific Rise.(10) The helium venting from the mantle is not considered primordial in isotopic composition because the quantities of uranium and thorium ores associated with the mantle are unknown and during tectonic subsidence, the magma could be diluted by atmospheric helium. The ^{3}He emission from the mantle to the atmosphere has been estimated to be 4.2 atoms/cm^2 s or 3 kg/yr for the entire earth's surface.(7) This injection of ^{3}He into the atmosphere has apparently reached a steady state with the rate of its loss by diffusion out of the atmosphere.

The abundance of natural ^{3}He from terrestrial sources is summarized in Table 1. The quantity of ^{3}He in the stored United States helium reserves,(9) 28 kg, is an assured supply if isotopic separation is performed before the helium is used. The quantity of ^{3}He in the known natural gas reserves with He content > 3,000 vol. ppm is not assured because the United States sponsored program for separation of He may not be continued. The ^{3}He associated with vents from the magma is small and no simple collection system is evident. Finally, the atmospheric resource represents a significant quantity of ^{3}He although its concentration is very low. The utilization of the atmospheric resource would only be cost effective when combined with the industrial separation of He from air.

Table 1. Terrestrial Natural Resources of Helium-3

Sample	He Content vol. (x 10^{-6})	$^3He/^4He$ (atoms x 10^{-6})	^3He Potential kg
Atmosphere	5.24 (vol.)	1.4	4 x 10^6
Mantle Gas Vents	--	11-21	3/yr.
U.S. Natural Gas Wells			
Present Storage	10^6	0.2	29
Known Reserves	3000 (vol.)	0.2	187

Terrestrial - Man-Made ^{3}He Resources

Helium-3 forms as the radiolytic decay product of tritium (half-life = 12.3 years) which has been produced in nuclear fission reactors. During the storage of tritium some of the ^{3}He has been collected and is available from several sites (see Table 2).

The United States Department of Energy has an unclassified inventory of ^{3}He which is supplied to Monsanto Research Corp.-Mound Facility (MRC) where it is purified and sold chiefly for research and development activities throughout the world.(11) At the present time, MRC is permitted to sustain annual commercial sales up to 10,000 liters (STP) of ^{3}He (~ 1.34 kg/y). In addition, MRC has on hand a reserve of 100,000 liters of ^{3}He (13.4 kg) which could be processed on special request. In large quantities (> 500 liters or 70 grams), the present cost of ^{3}He is approximately 94 \$/liter (~ 700 \$/g). Additional costs would vary depending upon the purity, type of shipping container, special handling, etc.

The Canadian CANDU reactors naturally produce tritium in the D_2O moderator of their reactors. The total T_2 produced from the present time to the year 2000 is projected to be 30 kg.(12) Due to the decay of tritium into ^{3}He, it is calculated that at least 10 kg of ^{3}He will be available by the year 2000 and, thereafter, ^{3}He will be produced at roughly 2 kg/year.

The total amount of ^{3}He from the decay of tritium in thermonuclear weapons can be very approximately estimated as a potential resource. For instance, it has been estimated that the U.S. Strategic Forces had over 4400 megatons (MT) of deliverable weapons in 1983(13) and that the energy equivalent of complete d-t fusion is 0.08 MT/kg DT. If we assume that only 1% of the final yield of the weapons comes from d-t fusion, then this would imply

Table 2. Reserves of ^3He That Could be Available in the Year 2000

Source	Cumulative Amount To Year 2000 kg	Production Rate Post Year 2000 kg
Decay of T_2		
U.S. Dept. of Energy		
MRC Annual Sales	--	1.3
MRC Inventory	> 13.4	--
CANDU Reactors	10	2
U.S. Weapons (approx.)	~ 300	~ 15
Natural Gas Wells		
Underground Storage	29	--
Known Reserves	187	--
Total	500-600	~ 18

that there is currently some 300 kg of tritium in U.S. weapons. Since 5.6% of the tritium decays per year, there should be approximately 15 kg of ^{3}He produced per year. If this ^{3}He were collected, it is reasonable to assume that by the year 2000, nearly 200-300 kg of ^{3}He from this source could be made available.

The accumulated amount of high purity ^{3}He produced by tritium decay from all sources by the year 2000 might conceivably reach 500-600 kg and, thereafter, approximately 18 kg/yr could be produced.

Extraterrestrial

During space flight probes beyond the earth's magnetosphere, the composition of the solar wind has been analyzed. Although protons dominate this flux, the He particles in this "wind" which travel at an average velocity of 450 km/s have a flux of 6 x 10^{10} atoms/$m^2 \cdot s$; however, the ^{3}He/^{4}He ratio is high ~ 480 (at.) ppm.(14) The high ^{3}He composition relative to the primordial composition is apparently due to the nuclear reaction $d(p,\gamma)^3$He which occurs in the high gravitational field of the sun.

The lunar surface which has been receiving solar wind particles for > 4 x 10^9 years has been found to serve as a collector. Samples(15) of lunar soil returned by the American Apollo astronauts and analyses by the Russian Luna probes confirm that the lunar soil contains He with an isotopic ratio near to that of the solar wind, Table 3. Our estimates indicate that this soil contains multi-megagrams of ^{3}He.

The characteristic of the lunar soil (regolith) which makes it an effective He collector is its extremely fine grain size; over 80% by weight of the soil is between 8-125 μm. This fine grain size is due to constant meteorite

Table 3. Extraterrestrial Resources of Helium-3

Sample	He Content µg/g	$^3He/^4He$ (atoms x 10^{-6})	^3He Potential kg
Solar Wind	(1.4 x 10^5 ions/m^3)	480	(3 x 10^7 ions/m^2•s)
Lunar Surface			
Maria	30 (20% of surface 5 m depth)	400	6 x 10^8
Highlands	7 (80% of surface 10 m depth)	400	5 x 10^8
Total	-	-	1.1 x 10^9
Jupiter	(2.2 to 3.5) x 10^5	140	7 x 10^{22}
Saturn	(2.2 to 3.5) x 10^5	140	2 x 10^{22}

impact which has pulverized nearly the entire surface to a depth of ~ 5 to 15 m. The solar wind particles are implanted to a depth of < 0.02 μm in the soil granules; consequently, small particles with a high surface to volume ratio have a high He to soil weight ratio. Also, soils of the lunar maria have a higher He content than soils in the highlands because the solar wind particles appear to be concentrated in ilmenite granules, a $FeTiO_3$ ore which comprises up to 10% of the maria soils.

Degassing of lunar soils returned from the Apollo 10 and 12 missions vividly demonstrates the relatively greater He abundance as the grain size decreases,(16) for samples taken from the maria near the equator at depths up to 2 m (see Table 4). Some of the finest ilmenite particles yield up to 2 cm^3 (STP)/g of soil (360 wt.ppm). As the grain size decreases, however, there is a slight (about 10%) decrease in the $^3He/^4He$ isotopic ratio, presumably due to higher diffusion and loss of the lighter isotope.

In order to calculate the potential quantity of lunar ^3He, an average ^4He concentration of 30 ppm was taken for the maria surface to a depth of 5 m and an average ^4He concentration of 7 ppm was taken for the highland regions to a depth of 10 m. The lunar surface, 38×10^6 km^2, was assumed to be 20% maria and 80% highlands. The average helium content in the highlands was reduced by a factor of 2 in order to account for geometrical effects of the solar wind on a spherical surface. The potential ^3He associated with the lunar surface soil is therefore conservatively estimated as 1.1×10^9 kg. The fraction of this total inventory which can be economically utilized can only be addressed by further exploration and study of the lunar surface. This inventory represents less than 1% of the ^3He which has impacted the lunar surface for the past 4 billion years (assuming a constant solar wind).

Table 4. Helium Content and Isotopic Ratio for Mature Lunar Soils(16)

Sample No.	Particle Size μm	^4He Content $\mu g/g$	$(^3He/^4He)$ Avg. (at. x 10^{-6})
12001	unseparated	17	409
12001[a]	1.3 - 10	24 - 104	423
12001[a]	11 - 125	34 - 360	370
10046[a]	14 - 114	25 - 360	327

(a) Associated with the mineral ilmenite.

The outer planets, Jupiter and Saturn, are believed to have compositions of nearly 25 wt.% He.(17) If they contain a primordial ^{3}He/^{4}He ratio, ~ 140 (at.) ppm, then the total potential quantity of ^{3}He is exceedingly large, > 10^{23} kg. Uranus and Neptune have solid ice surfaces below an atmosphere of H_2 and He,(18) with a total ^{3}He resource of about 10^{20} kg -- which may be more accessible than that of the gas giants. The energy cost of returning ^{3}He from orbit around any of the outer planets is about 1 GJ/kg.(19) Possible ^{3}He resources on Mars, Mercury, the asteroids, or various solar system moons besides Earth's remain to be investigated. This helium can be considered as a resource for future generations as a space transportation industry develops.

III. Energy Costs for Helium-3 from Natural Sources

Terrestrial

Studies considering the recovery of He from natural gas or the atmosphere find it to be economically feasible when the separation is made in conjunction with a primary process, such as the liquefaction of air. Then, only additional costs are borne by the helium product. Wilkes(20) estimated that a full-size isotopic separation plant using natural gas at a concentration > 3000 ppm He, could produce 99% pure ^{3}He at cost \$156/liter (STP). If this ^{3}He were utilized in a d-^{3}He fusion power plant, the fuel cost would be 14 mills/kWh.

Lunar Soil

In order to determine the economic viability of mining the moon for ^{3}He we have initially chosen to focus upon energy payback rather than dollars of profit. The energy cost required to produce ^{3}He from lunar soils for terrestrial applications would consist of the following: (1) mining, (2) degassing, (3) isotopic separation, and (4) transportation to earth. Initially, only maria soils with high ilmenite and, consequently high ^{4}He concentration will be mined, such as the soils at the Apollo 17 site which contain 36 g He/Mg of soil.(15) Associated with this soil, at concentrations up to 2 to 3 times by weight of He, is also H implanted from the solar wind. Several groups(21,22) have studied the reclamation of H from these soils in order to provide H_2O for use on the moon or H_2 for rocket fuel. Also, these high ilmenite soils might be processed to recover oxygen and iron.(23) It is conceivable, therefore, that a multiple use processing facility could be built so that the cost of mining could be shared among the products. For our study, however, we have attributed the total energy cost solely to ^{3}He.

(1) Mining

The recovery of He from the lunar soil involves only a simple process; however, many tonnes of soil must be handled. The soil at the mining site has an assumed concentration of 36 ppm to a depth of 2 m. This soil will be removed by excavators, working remotely, and highly automated, and placed onto conveyor belts and delivered to a central processing plant approximately 2 km from the mining site. At the processing facility the ore will be beneficiated by electrostatic and electromagnetic techniques so that a concentrated product can be delivered to the vacuum degassing equipment.

In order to assess the quantity of raw ore which needs to be mined the efficiencies of the processing steps must be evaluated. Recently, Carter(21) has shown by statistical analysis that 91% of the H is contained in the $\leq$ 20 μm size fraction which constitutes 23 wt.% of the soil. The lunar mining study by Williams, et al.,(22) proposes the beneficiation process retains 16.5 wt.% of the soil in the $\leq$ 20 μm size range, which we estimate to contain ~ 80% of the He. The subsequent heating process for the evolution of the solar wind gases should release $\geq$ 90% of the ^{4}He at 600°C. The complete process efficiency of 72% requires, therefore, that a 40% excess of soil be mined.

In order to produce 1 kg of ^{3}He, approximately 1.2 x 10^5 Mg (tonnes) of soil must be mined and beneficiated. For the large-scale mining of the lunar regolith to a depth of 2 m, Williams(22) estimated the number of excavators, conveyors, trucks and classification units required. The total weight of this equipment, 965 tonnes, is capable of mining 737 tonnes of soil per hour and requires 2918 kW of power; consequently, the energy cost for this mining is 14 MJ/tonne of soil. Additionally, an energy cost of about 60 MJ/kg must be paid for the transportation of this equipment from the earth to the lunar surface.(19) If this equipment operates for 10 years, the proportionate amount of the equipment weight distributed to each tonne of soil is 3.3 x 10^{-2} kg (equipment)/tonne of soil; therefore, an energy cost of 2 MJ/tonne of soil must be added to the operational energy cost, for a total of 16 MJ/tonne of soil. The total energy cost to produce a kg of ^{3}He is estimated to be 2 x 10^3 GJ.

(2) Gas Evolution

The beneficiated soil of $\leq$ 20 μm size range is delivered to the vacuum degassing furnaces for heating to approximately 600°C where $\geq$ 90% of the ^{4}He is evolved. This soil contains 1.12 kg (^{3}He) in 2 x 10^4 tonnes of soil, for a ratio of 180 g (^{4}He)/tonne (soil). The degassing operation could be conducted during the lunar daylight hours in order to utilize only solar energy for the thermal power requirements. No vacuum equipment would be needed because the lunar atmospheric pressure is $\sim 10^{-10}$ Pa. Because the temperature of the lunar surface is nearly

130°C during the lunar day, the soil needs to be heated only an additional 470° in order to reach 600°C. With an estimated heat capacity of 1.3 kJ/°C•kg, the total thermal power required is 1.2×10^4 GJ/kg of ^{3}He. After degassing the soil at 600°C, nearly 50% of this heat is captured to preheat the next batch.

Because only solar energy would be utilized in this process, no additional man-made energy would be required. However, energy costs will be associated with the transportation from the earth to the lunar surface of the solar energy collectors, their support structures and the furnaces. Initially, all this equipment would be transported from earth; however, as the lunar base matures, much of this equipment, such as the support structures, and parts of the furnaces can be fabricated from indigenous lunar materials. Highly sophisticated collectors would not be required because the solar flux is very high, 1.34 kW/m^2. In the absence of clouds or inclement weather the total collection efficiency of the collectors will not be degraded.

Based upon the results of the study by Ho and Sobon(24) for the operation of a lunar fiberglass facility, we estimate that a processing rate of 1.3 kg/s of soil would require 410 kW of solar power. From the Ho and Sobon study we estimate that the mass of these collectors and support structures would be 7 tonnes. This solar power would be utilized to heat 8 furnaces which are estimated to weigh 22 tonnes. A total mass of 29 tonnes is required, therefore, to process 1.3 kg/s of soil. If this equipment operates for 10 years, as it should in the high vacuum of the moon, then the incremental weight of equipment assigned to each tonne of soil processed is only 0.15 kg. Using the previous transportation energy and the fact that 2×10^4 tonnes of soil must be processed per kg of ^{3}He, we estimate that the transportation of this equipment from earth to moon costs 180 GJ/kg of ^{3}He.

(3) Isotopic Separation

Cryogenic distillation provides one of the highest separation factors for the helium isotopes, 3.0 at 2°K. Wilkes(25) has demonstrated that 99.99% pure ^{3}He can be obtained from such a distillation column at an energy cost of 40 mJ/cm^3(STP)^{3}He when the feed gas contains ~ 7% ^{3}He. In order to achieve such a concentrated feed gas, he suggests the use of a "superleak" separator.(20) A "superleak" separator utilizes the unique superfluid properties of liquid ^{4}He which occurs when the liquid is cooled below the lambda temperature of 2.1°K. Below this temperature liquid ^{4}He has a negligible viscosity and flows through very fine filters. When mixtures of liquid ^{3}He and ^{4}He are placed on one side of such a filter, only the liquid ^{4}He transits the filter so that the original mixture becomes enriched in ^{3}He. The only energy required for this separation is the thermal energy equivalent to the heat of mixing of the two isotopes.

If only a cryogenic distillation system were utilized for the entire isotopic separation process, the system would require 70 MJ/kg (^{3}He) at 2°K. Operation of the distillation columns only during the lunar night when the ambient surface temperature is 120°K, requires 9×10^3 MJ of thermal energy per kg of ^{3}He. Development of the "superleak" technique to upgrade the ^{3}He to 1% followed by cryogenic distillation to produce a product of 99%, reduces the thermal energy required to only 281 MJ/kg of ^{3}He.

(4) Transportation

An unmanned earth/moon transportation vehicle of the same size as the present space shuttle was assumed to depart empty from the earth, land on the lunar surface and return with a payload of 30 tonnes of liquid ^{3}He. The energy cost for this round trip has been estimated to be approximately 1 x 10^3 MJ/kg of ^{3}He.

The total energy cost which must be borne by the ^{3}He fuel is approximately 2.2 x 10^6 MJ/kg (^{3}He), Table 5. Since the thermal energy yield from the d-^{3}He fusion is 6 x 10^8 MJ/kg (^{3}He), the energy multiplication is ~ 270. This energy payback should be compared with that for U-235 production(26) of nuclear fuel which is ~ 20 and for coal mining which is ~ 16.

IV. d-^{3}He Fusion Reactor Design Considerations

The advantages and disadvantages of the d-^{3}He fuel cycle in terms of fusion reactor design have been discussed qualitatively for some time.(1,2,3,4) The main advantages of d-^{3}He follow from Fig. 1, which shows the charged particle energy to neutron energy ratio for the main candidate fusion fuels (three ratios of ^{3}He to d are shown). These advantages are:

- The small fraction of fusion power produced in the form of neutrons leads to lower cost and mass for the blanket, reflector, and shield system.
- The potential for converting much of the fusion power at high efficiency by electrostatic direct conversion of charged particles, thus allowing fusion reactors which have very high net plant efficiencies.
- The removal of the requirement for breeding tritium.
- The inherent safety due to a low afterheat density and a low inventory of radioactive isotopes.
- The increased plant lifetime and availability due to the low neutron flux.

Table 5. Energy Costs of Producing ^{3}He on Lunar Surface and Transporting to Earth

	GJ/kg (He-3)
Mining (120,000 tonnes of soil)	2000
Gas Evolution (20,000 tonnes of soil) (100% solar energy plus 50% reheat)	180
Isotope Separation (Superleak plus distillation)	1
Transportation	1
Total	2182

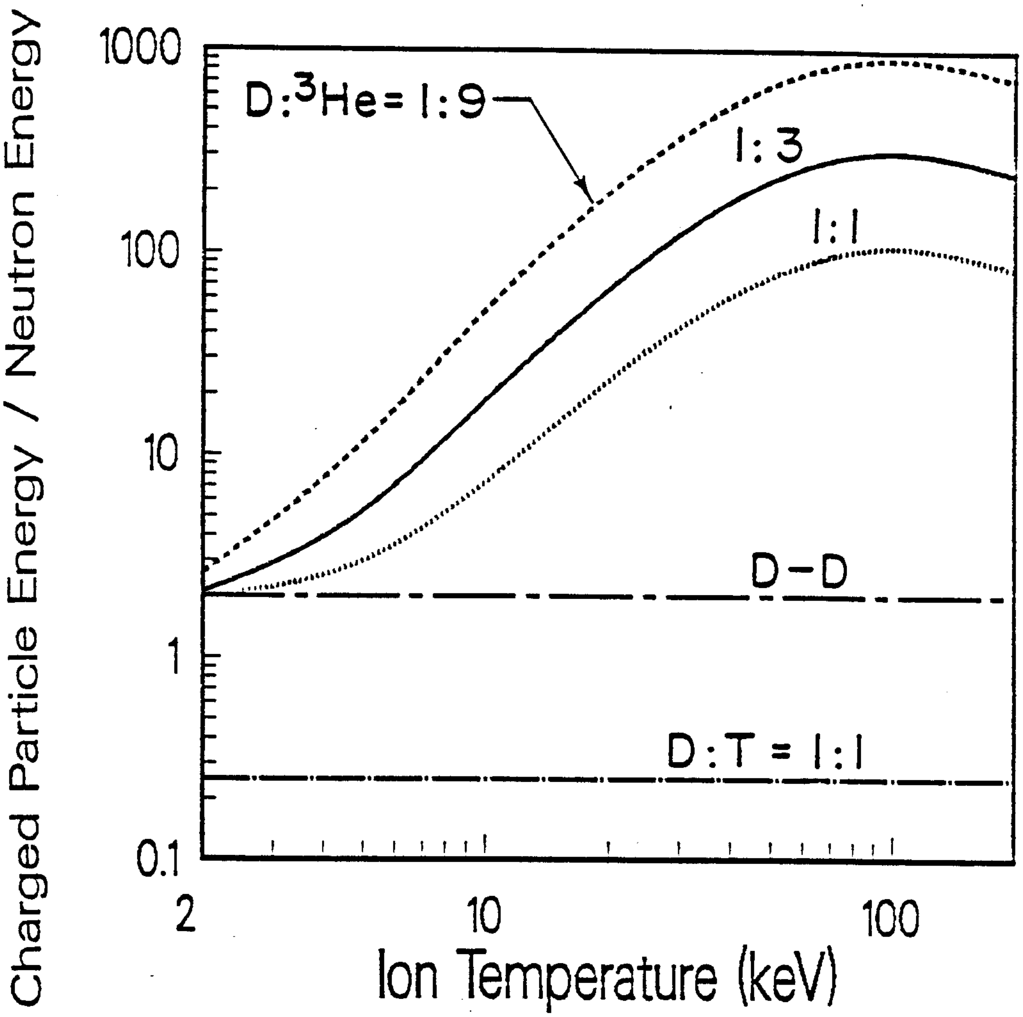

Fig. 1. Ratio of charged particle power to neutron power as a function of ion temperature for selected fusion fuels.

The chief disadvantages of the d-^{3}He fuel cycle are:

- The low power density imposed by a lower fusion cross-section than d-t and by a higher operating temperature.
- The problem of obtaining a sufficient supply of ^{3}He.
  The difficulty of fueling, since ^{3}He is not easily incorporated into pellets.

The first disadvantage follows from Fig. 2, which shows the normalized fusion power density at constant beta and magnetic field, for the same reactions as in Fig. 1 (d-^{3}He ratio = 1).

The fusion power density varies as $\beta^2 B^4$ but, due to limits on the maximum neutron wall loading and the minimum plasma size, reactor parameters for a given configuration may optimize at magnetic fields lower than technological constraints allow. High beta operation is desirable both from the power density standpoint and because beta-depression of the magnetic field in the plasma helps reduce synchrotron radiation. Thus, devices which have the design freedom to increase fields at the magnet coils in the fusion power producing region and which operate at relatively high beta appear to be best positioned to take advantage of the d-^{3}He fuel cycle. Configurations such as tandem mirrors, reversed-field pinches (RFP's), field reversed configurations (FRC's) and spheromaks are prime candidates. Tokamaks and stellarators will have difficulty taking full advantage of the d-^{3}He cycle unless they can achieve substantially higher beta ($\gtrsim$ 15%) or magnetic fields ($\gtrsim$ 11 T at the magnet) than postulated in most reactor studies. One interesting possibility is that a compact toroid with normal-conducting coils may effectively utilize d-^{3}He,(27) since designs for compact d-d and d-t fusion concepts already appear promising.(28)

The large volume of thick neutron shielding of magnets required in d-t reactors could be replaced by d-^{3}He plasma or by a reduction in the magnet radius, thus lowering the coil to plasma magnetic field ratio. The advantage

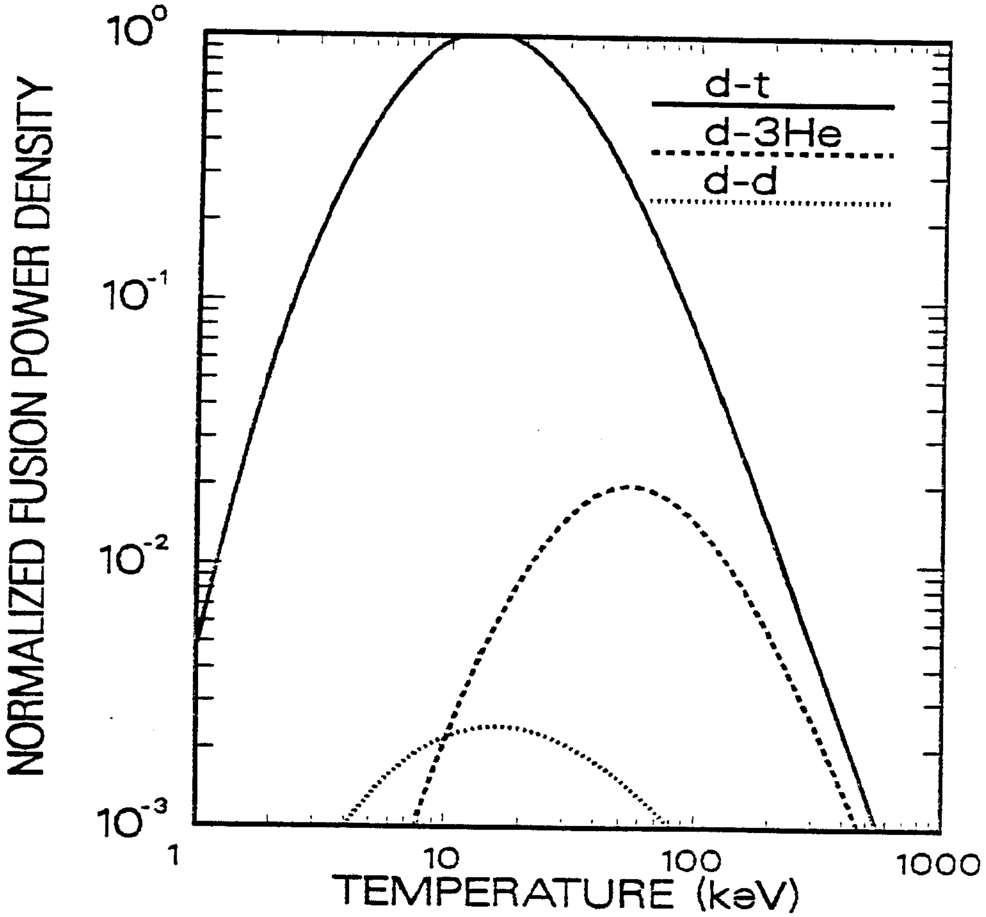

Fig. 2. Normalized fusion power density as a function of ion temperature for selected fusion fuels.

of the lower neutron wall loading using d-^{3}He fuel is obtained by accepting a higher first wall surface heat due to an increase in bremsstrahlung and synchrotron radiation.(29) However, such surface heat loads are acceptable, especially in low neutron fields.(30,31,32) An intriguing possibility exists that polarizing the d-^{3}He fuel may enhance reactivity or suppress d-d neutrons, further improving this advantage.(33)

The d-^{3}He fuel cycle is naturally suited to open confinement schemes because of the potential for high direct conversion efficiencies (~ 90%) and high overall net plant efficiencies (~ 70%), but there are also attractive options for toroidal systems. A thermal conversion system could operate at very high temperatures (e.g. 600-1000°C), the limit being much higher than in the case of d-t because of the lack of 14 MeV neutrons, which produce copious amounts of He and embrittle metallic structure. Net plant efficiencies of 50% should be possible for such a toroidal reactor.

A toroidal system might also use a toroidal divertor coupled with direct conversion to yield even higher overall efficiencies. One of the reasons that toroidal divertors have not been popular in the past is due to the large amount of shielding required for the "bucking coils" and the limited space between shielded toroidal magnets for particle leakage. Such constraints would be greatly relaxed with d-^{3}He systems. Because of the high bremsstrahlung radiation, MHD blanket designs such as proposed by Logan(34) could also be considered. The production of large amounts of synchrotron radiation and the fact that it could be "channeled" out of the torus presents entirely new options for utilizing fusion energy.

Only a relatively modest effort to investigate these technology considerations has been expended in the past, chiefly due to the perceived difficulty in providing a sufficient supply of ^{3}He for a fusion economy. A large fraction of the d-^{3}He reactor design effort has focussed on a solution for the resource problem by pursuing "satellite" d-^{3}He reactors with separate d-d or p-^{6}Li reactors providing the ^{3}He.(3,35,36,37) The ^{3}He supply limitation has also caused a large amount of advanced fuel effort to concentrate on finding a means of enhancing power density or fusion reactivity in fuel cycles such as d-d or p-^{11}B, where the fuel is plentiful.(38) Consequently, even though over 80 major conceptual fusion reactor designs have been conducted using the d-t cycle,(39) no d-^{3}He reactor design of the scope of recent major tokamak(40,41) and tandem mirror(42,43) designs has been performed.

Some of the earliest d-^{3}He reactor scoping studies were based on the single-cell mirror concept.(44,45,46) These were severely constrained by the very low Q (fusion power/input power) values available from such devices. Subsequently, mirror devices evolved into classical tandem mirrors(47,48) and then into thermal barrier tandem mirrors.(49) Tandem mirrors allow direct conversion and are well suited to the requirements on beta, magnetic field, and energy confinement imposed by the d-^{3}He cycle, although only preliminary experimental work has been done. Preliminary quantification of this has been presented in Ref. 37, for a d-^{3}He thermal barrier tandem mirror, satellite reactor based on the MARS(42) design. Radioactivity and safety considerations were also discussed there.

Tokamak d-^{3}He reactors have been investigated in more detail than have tandem mirrors.(27,30,31,32,50,51) Parametric power balance analyses demonstrated that burning d-^{3}He fuel in tokamaks could lead to ~ 50% net efficiency at 12-30% beta values. The engineering analyses contained in Refs. 30, 31 and 32 discuss a variety of issues, including blanket design, materials, heat and neutron fluxes, safety, and fuel handling. Initial work on compact, d-^{3}He tokamaks also shows promise, both for a reactor and for a compact ignition tokamak.(27)

A d-^{3}He fueled Field-Reversed Mirror (FRM) study has also been performed.(30,52) The FRM (one type of FRC) study focussed on very small unit sizes, which led to high capital cost but lower indirect costs. A number of engineering trade-offs were discussed; these tend to be configuration-specific.

As an example of the possible benefits of the d-^{3}He fuel cycle in an advanced linear system, a short overview of a recently proposed d-^{3}He tandem mirror reactor concept(53) which offers the prospect of very high net plant efficiencies (~ 70%) is presented here. This efficiency is a factor of about 1.5 times higher than today's best power plants can achieve. The key feature of the new concept is the breaking of adiabaticity (conservation of perpendicular energy/magnetic field) for that class of fusion products whose energy is not required to sustain the d-^{3}He fuel ion temperature. Adiabaticity could be broken by a strong (~ 2 T/m) gradient in the magnetic field. Since nonadiabatic particles scatter stochastically, they enter the mirror loss cone before losing a significant amount of energy to the electrons and fuel ions. The resultant, almost monoenergetic end loss stream of 14.7 MeV protons could be directly converted into electricity at very high efficiency (> 90%). With 50% of the energy directly converted through this process and the remainder through normal tandem mirror power conversion methods, a very high net efficiency (65% at 600 MW_e) reactor results.(53) Parameters for this case are shown in Table 6. The primary engineering questions relate to fueling and to direct convertor design for high energy ions and high heat flux. It is worth

Table 6. Reference Design Parameters for an Advanced Linear Fusion Reactor(45)

Parameter	Value
Net efficiency	65%
Net power	600 MW_e
Fusion power	930 MW
Q	17
Central cell ICRF power	25 MW
End cell power	30 MW
Barrier pumping power loss	15 MW
Central cell	
Volume	2.9×10^{8} cm^3
Beta (RF stabilized)	0.9
Vacuum magnetic field (on axis)	4.0 T
^{3}He ion temperature	97 keV
Deuterium temperature	100 keV
Electron temperature	75 keV
Electron density	2.6×10^{14} cm^{-3}
^{3}He to d density ratio	1
Assumed fusion ash density	8.7×10^{12} cm^{-3}
Ion confining potential	400 keV
Deuterium $n\tau$	8.4×10^{15} cm^{-3} s

stressing that adiabaticity and its limits are well-established,(54,55) and that the power balance analysis leading to the reference parameters utilizes essentially the same assumptions as used for previous thermal barrier tandem mirror reactor studies.

The amounts of ^{3}He required if highly efficient, toroidal or linear d-^{3}He reactors were to replace the entire 1985 U.S. electrical consumption (2.6 x 10^5 MWe-y) are listed in Table 7.

Table 7. He-3 Required to Replace the 1985 U.S. Electrical Consumption

d-^{3}He Reactor	Conversion Scheme	Approx. Net Eff. %	Required to Supply U.S. 1985 Electrical Consumption kg-^{3}He	 % of Moon Surface[a]
Toroidal	High Temp. Blankets	50	27,400	0.001
Linear	High Eff. Dir. Conversion	70	19,500	0.0007

(a) Assume mining in mare areas.

The ^{3}He fuel to supply the entire U.S. electrical consumption in 1985 could come from an area on the lunar surface equivalent approximately to the size of Washington, DC. Furthermore, the ^{3}He could fit in the volume of the cargo bay of only one current U.S. shuttle vehicle.

V. Implications for the Ultimate Usefulness of Fusion Power

If it is accepted that space scientists will be able to tap into the lunar source of ^{3}He on the same time scale that we solve the confinement problems of fusion plasmas (i.e., 2000-2010), then what does this mean to our energy future? First of all, it would provide a bridge between the use of the present limited sources of ^{3}He, for the next 20 to 25 years, and the "ultimate" source of ^{3}He in Jupiter. This line of reasoning is illustrated in Fig. 3 where the lunar source of tritium connects the near term research phase (1990-2010) to the very long term (> 2100) needs of society. We have already shown that a resource of 600 kg of ^{3}He would be sufficient to power a small (100-200 MWe) terrestrial electrical demonstration plant for several decades. Another application could be for compact electrical power plants of ~ 10-100 MWe to be deployed in space (e.g., orbiting space stations, propulsion units, lunar or martian base camps).

The second implication of a d-^{3}He fusion economy would be its effect on the thrust of fusion technology research programs around the world. The need for radiation damage information, tritium breeding and extraction programs, and blanket design research would be greatly reduced. Other areas such as remote maintenance would become less critical to the plant operation and the issue of reactor safety (i.e., release of volatile radioactive gases or meltdown due to afterheat) would become less of a dominant consideration. Furthermore, there would be no need to focus on long term radioactive waste disposal and thermal pollution would be greatly reduced by operation at high efficiency, as in an advanced linear fusion reactor.(53)

The third point would be the impact on the worldwide plasma physics program. As seen in Section IV, high beta, high magnetic field systems would be favored for the d-^{3}He cycle. Specifically, compact ignition tokamaks may not only provide important information on d-t ignition, but they could also be used to demonstrate the viability of the d-^{3}He cycle at an early stage. The attractive possibility of utilizing highly efficient direct conversion schemes also provides an increased incentive for continuing high beta tandem mirror research.

Potential Uses of D/He-3 Fusion Fuels

TIME FRAME

		1990–2010	2010–2100	>2100
He-3 Resource ●kg ●Source		600 T_2 Decay	$1x10^9$ Lunar Surface	$7x10^{22}$ Jupiter
Application				
EARTH	Demo	■		
	Commercial		■	■
Orbiting Space Station Power		■		
Space Propulsion			■	■
Base Camp, Moon, Mars, etc.		■	■	

Figure 3

Finally, Fig. 4 illustrates the immense energy content in the lunar ^{3}He resources. Even if the U.S. electrical demand doubled every 25 years (from now until the year 2100) and d-^{3}He fusion provided all the electrical energy required after the year 2020, only 3% of the moon's ^{3}He resources would be used. After that time, "freighters" to Jupiter could return to earth with large quantities of ^{3}He and obviate the need for further mining of the moon. Our horizons would indeed be pushed beyond our solar system and fuel shortages would become a distant memory.

VI. Conclusions

It is shown that there is enough ^{3}He contained in the lunar surface to provide a long lasting source of energy for terrestrial applications. The energy payback for extracting and transporting this resource to earth is extremely favorable. It should also be possible to use the lunar surface as a source of fuel for power plants in earth orbit, on the moon, or on other planets. This lunar source of ^{3}He is sufficiently large to provide for a century or more of space research to exploit the extremely large ^{3}He reserves on Jupiter. Thus, the lunar ^{3}He can help deliver the "clean" energy source that fusion scientists have been promising for over 30 years.

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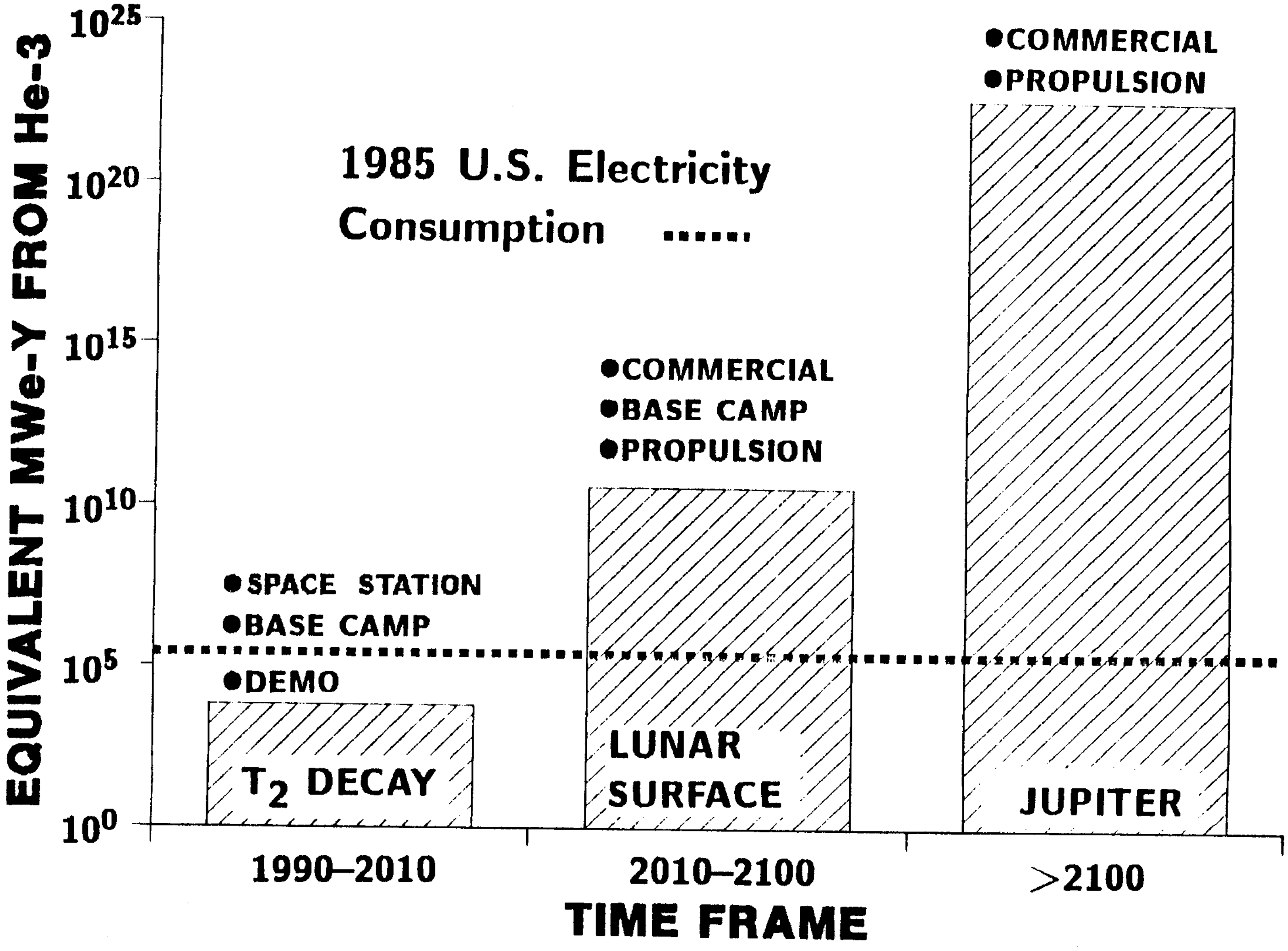

Fig. 4. Equivalent electrical energy content of He-3 sources.

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