Non-Lunar ^{3}He Resources

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Abstract

The earth's reservoirs and proposed nuclear reactions to produce significant quantities of ^{3}He were considered. No natural resources were identified which could produce ^{3}He in either the quantities required or with a net energy payback. Nuclear reactions for the production of ^{3}He did not appear viable because of the required storage of large quantities of radioactive products. These combined reservoirs, however, could provide sufficient ^{3}He for the research and demonstration phases of a D-^{3}He fusion reactor.

1. Introduction

The potential environmental and safety benefits from the use of the D-^{3}He fusion fuel cycle as compared to the D-T fusion system have been well documented [1]. Although the reaction conditions required are more strenuous to achieve for the D-^{3}He fuel versus the D-T system, several advanced confinement concepts are being developed which can lead to the development of economically attractive D-^{3}He fusion reactors [2]. As the reactor development projects progress, the search for ^{3}He resources to fuel these proposed reactors intensifies. An inventory of ∼one million metric tons (tonnes) of ^{3}He deposited in the lunar regolith by the solar wind has been well-established and concepts for its production are being developed [3]. Conversely, an initial survey of ^{3}He reservoirs on earth indicated that no large recoverable reservoirs exist [4].

Because ^{3}He is scarce on earth, it is often used by geologists as a tracer for ancient gas reservoirs. Conversely, ^{3}He exists in the cosmos at a ^{3}He/^{4}He ratio of ∼300 ppm (atomic) and ^{4}He is the second most plentiful element in the universe [5]; consequently, the ^{3}He inventory in the cosmos is very large-comparable to the abundance of sulfur. Unfortunately, the earth, being a terrestrial planet, accreted more sulfur than He, while the gas-giant planets, Jupiter and Saturn, probably contain millions of tonnes of ^{3}He, but the utilization of such reservoirs may require centuries to develop. Entrapment of the solar wind is a possible mechanism by which the terrestrial planets could have enriched their ^{3}He content; however, Mercury, earth and Mars have sufficiently strong geomagnetic fields that their surfaces are protected from the solar wind by a magnetosphere. Some of the solar wind particles do reach the earth's atmosphere through the polar, auroral flux lines, yielding a small ^{3}He flux of ∼3 kg/yr. Mercury, being closer to the sun, has a larger auroral flux providing ∼5.4 kg/yr of ^{3}He. Dawson [6] suggested, therefore,that Mercury could provide a resource for ^{3}He. The atmosphere is very thin [7], however, with a vertical column density of only $2 \times 10^{14}/\text{cm}^2$. If this entire atmosphere were He, it would contain only 360 kg of ^{3}He. Venus does not have a magnetosphere, but it does have a thick carbon dioxide atmosphere, ~8 MPa, and a He pressure of 0.6 MPa. Dawson has suggested that the Venusian atmosphere could intercept the solar wind which would mix with the gases present to yield an atmosphere which would be isotopically similar to He in the solar wind. If this mechanism were demonstrated, the Venusian atmosphere may contain 2×10^9 tonnes of ^{3}He.

Of more immediate concern are the quantities of ^{3}He which will be available on earth during the research and development of the D-^{3}He fusion reactors and the startup of a fusion power industry. This review provides an update of the earth's ^{3}He reservoirs and discusses nuclear reaction schemes proposed to produce significant quantities of ^{3}He.

The requirements for ^{3}He during the fusion development phase are modest, ~150 kg through the power demonstration reactor operation [3]. Much of the supply might come from the radioactive decay of ^{3}H which is stored in nuclear weapons stockpile of several nations — if it were collected. Before a fusion industry could develop the assured availability of tonnes of ^{3}He per year would be required. For instance, the electrical power usage in the USA during 1992 was 3.15×10^5 MWe·yr. During the next 25 years, while fusion is being developed, this usage could increase to 5.16×10^5 MWe·yr [8]. If D-^{3}He fusion were to provide 25% of this power, the assured fuel supply of ^{3}He must be 13 metric tonnes/yr, for just the USA.

2. Terrestrial Helium Reservoirs

Significant earthen ^{3}He reservoirs are considered and their ^{3}He inventories are estimated, Table 1. Each of these reservoirs has a distinct ^{3}He/^{4}He ratio, Fig. 1, which aids in its identification. Insignificant He-bearing reservoirs are excluded such as diamonds [9], because the host mineral is so rare, and Li/U-bearing rocks because the concentrations of ^{3}He per weight of rock is so small.

Table 1

Estimated Earth Inventory of ^{3}He

	^{3}He (tonne)			
	Proved	Probable	Possible	Speculative
Atmosphere	4000	—	—	—
Oceans	13	—	—	—
U.S. crustal natural gas	0.23	0.18	0.20	0.08
Subduction zone natural gas	0.03	—	1000	25,000
Mantle gas	—	—	—	10^6 to 10^7
	4×10^3	0.18	10^3	10^6 to 10^7

2.1. Mantle-Derived He

The earth is shielded from the solar wind because of its geomagnetic field and the amount of ^{3}He produced as spallation products from energetic cosmic rays reacting with the atmosphere and rocks is small. Consequently, the terrestrial ^{3}He is believed to have existed since the formation of the earth.

The earth is believed to have accreted ∼4.5 billion years ago from asteroids which have compositions similar to the chondritic meteorites [10]. During the accretion phase, the temperature rise due to frictional heating was sufficient to evolve occluded gases, including He, due to diffusion and gaseous hydrodynamic flow. As a result the earth was depleted of volatile gases except for water which may have been borne by comets which accreted on the new earth. Some of the volatile gases were trapped, however, in the mantle of the earth and slowly trickle to the surface.

The ^{3}He/^{4}He ratio of these primordial gases was 200-300 ppm; however, ^{4}He is continuously produced in the earth by the α-particle decay of U and Th ores so that the primordial ^{4}He accounts for only ∼7% of the total He [11]. Some ^{3}He is formed in the earth as a result of neutrons produced by the α-bombardment of oxides. These neutrons

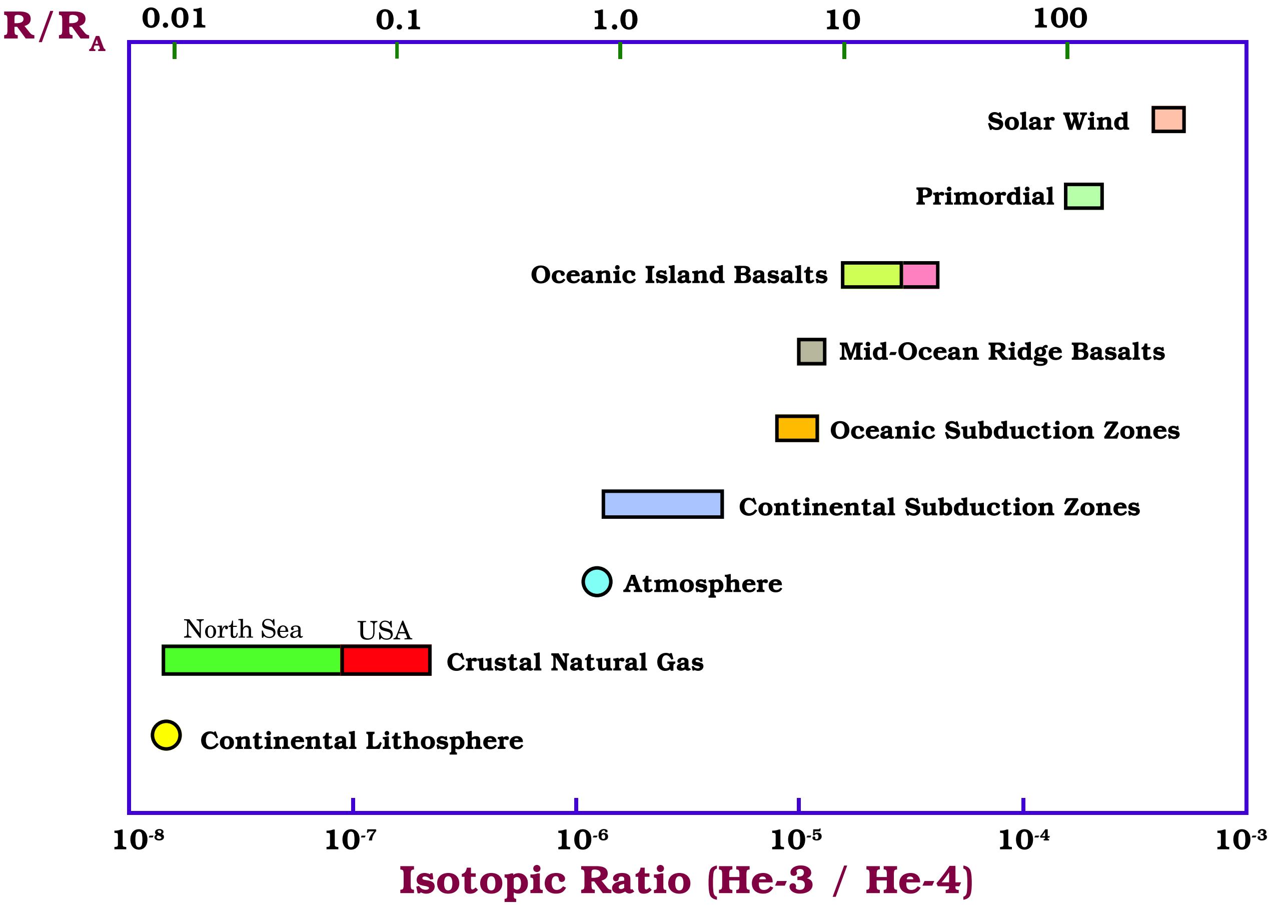

Figure 1. Helium isotopic ratios for major natural reservoirs; R/R_A = isotopic ratio of a sample compared to the earth's atmospheric ratio.

are captured by ^{6}Li in the rocks to form tritium (^{3}H) which decays to ^{3}He. Based upon this reaction an assessment of U, Th, and Li in the primitive rocks predicts a He ratio of 1.5×10^{-8}. Gases with higher ratios are considered to have gaseous mantle constituents.

Gases emitted from Hawaiian volcanoes have the highest ^{3}He/^{4}He ratios (up to 30 at.ppm) and are believed to arise from the deepest mantle, which contains only a small amount of U and Th. These gases have been diluted with α-decay He during their passage through the upper mantle and crust. Gases, CO_2 and ^{3}He, emitted from such subaerial volcanoes have been estimated based upon the simultaneous emission of the radioactive tracer polonium -210. Marty and Le Cloarec [12] suggest that this total world-wide emission is only 100 mol/yr (300 g ^{3}He)/yr). Clearly, this is not a large, potential ^{3}He resource.

Additionally, Kurtz has measured the He occluded in vesicles of the lava from the Hawaiian volcanoes [13]. This He is released when the lava is crushed in a vacuum system and analyses indicate the gas concentrations are in the range of 1.2×10^{-17} mole (^{3}He)/g of rock. The edifice of Mauna Loa, for instance, contains 4.25×10^5 km^3 of solidified lava at $\sim$3 tonnes/m^3; consequently, the total ^{3}He available in all this rock would be only 47 kg, an insignificant amount compared to the energy required to mine such a resource.

The discovery of He and other gases venting from the mid-ocean ridges suggested another potential resource of He. Craig et al. [14] estimated that these vents provided a ^{4}He flux of $\sim 3 \times 10^5$ atoms/cm^2·s to the atmosphere, with a ^{3}He/^{4}He ratio of 14 at.ppm. The calculated ^{3}He flux averaged over the entire surface of the earth is, therefore, only $\sim$3 kg/yr.

Recognizing the dynamic nature of the evolution of He from the upper mantle of the earth to the atmosphere, Tolstikhin [11] in 1975 proposed a degassing model for the earth. This model assumed a primordial concentration of ^{4}He in the early earth of 5.5×10^{-6} cm^3/g with a ^{3}He/^{4}He ratio of 3×10^{-4}. The degassing of He was constrained by the fact that the other primordial rare gases ^{20}Ne and ^{36}Ar, which would be evolved with the He, have remained in the atmosphere while the He isotopes have escaped. Based upon this model, the present ^{3}He inventory in the upper mantle was calculated to be $10^6 - 10^7$ tonnes. This value is very tentative because a subsequent article by Azel and Tolstikhin [15] indicates that the degassing process is more complex than originally assumed. For instance, the degassing rate was much higher during the early stages of the tectonic plate formation. Also, the subducting plates were found to become contaminated with atmospheric concentrations of ^{20}Ne and ^{36}Ar which were eventually recycled as fresh magma at the mid-ocean ridges [16].

2.2. Oceanic ^{3}He

Craig and Lupton [17] described in detail the He isotopic ratios determined by degassing of oceanic waters collected at numerous stations and a series of depths in the Atlantic and Pacific oceans. The waters with the highest ^{3}He/^{4}He ratios were collected at the undersea vents associated with sea-floor spreading zones. For instance, waters near the East Pacific Rise spreading-zone (104°W, 15°S) had an $R/R_A = 1.5$, where R is the ^{3}He/^{4}He ratio of the sample and R_A is the corresponding ratio for the ^{3}He/^{4}He in the atmosphere, $\sim 1.4 \times 10^{-6}$. As these waters flowed away from the vents, the He gases were diluted with gases derived from the atmosphere and ^{4}He derived from the outgassing of U/Th ores; however, the enriched ^{3}He waters which peaked at a depth of 2.5-3 km below the surface could be traced for thousands of km westward of the vents. Based upon such measurements and using the Ne isotopes as an internal standard, the authors estimated the He inventory in the oceans to be 5.9×10^{13} liters (STP) and 9.5×10^7 liters (STP) ^{3}He (~13 tonnes of ^{3}He). The ^{3}He flux was estimated to be 24,000 liters/yr with a residence time of 4000 yr, resulting in very strong ^{3}He gradients both horizontally and vertically as confirmed by experiments. The total quantity of ^{3}He in oceanic waters and its rate of replacement are too small to be of interest as a major fusion fuel. Additionally, it is spread around the world.

Confirmation of the occurrence of primordial gases deep within the earth has initiated one attempt to search for it. For a deep gas reservoir to be present, it must be capped by an impermeable granite rock structure. The Siljan Lake District of Central Sweden was selected as a deep drilling site because it was the impact point for a large meteoroid 360 Myr ago which fractured the granite bedrock causing large fissures in the base rock [18]. The drilling project has proceeded to a record depth of 6 km in granite rock and fissures have been found; however, all the fissures have been infiltrated with carbonate deposits from surface waters [19]. Consequently, no mantle gases have been found, thus far.

2.3. Tectonic Plate Subduction Zone Gas Wells

The formation of new oceanic crust at the mid-ocean ridges previously described initiates tectonic plates which move several cm/yr until they encounter a continental plate of lower density. The oceanic plate of higher density subducts below the continental plate, returns to the mantle, dissolves into the mantle and eventually is recycled. These subduction zones are rich sources of ^{3}He because they serve as access probes into the ^{3}He enriched mantle. In addition, the sediments on the oceanic plates collect interplanetary dust particles [20] which contain ~ 0.1 cm^3 (STP) ^{4}He/g with an R/R$_\mathrm{A}$ ratio of 100-150. This source has provided $\sim$ 200 tonnes of ^{3}He world-wide to these sediments during the 200 Myr of the present tectonic plate epoch. Anderson [21] has suggested that the recycle of these IDP's within the mantle may be related to the high ^{3}He/^{4}He ratios found in gases emitted from intraplate (Hawaiian) volcanoes; however, the ability of the IDP's to retain He during subduction has not been demonstrated [22].

As the subducting plates recede into the mantle, the pelagic biotic residues decompose because of the thermal and hydraulic pressure, forming natural gas and petroleum reservoirs which entrap helium. These reservoirs are abundant in the Western Pacific and can be accessed by deep-drilling and supply natural gas for Japan, Taiwan and the Philippines [23]. The He content of these gases varies from 50-200 ppm with R/RA ratios of 2-7. The calculated reservoir in this natural gas is based upon an estimate that 200 Mkm^3 of sediment has been subducted in 200 Myr; containing approximately 1 wt% carbon compounds. If 0.1% of the carbon is converted to methane then these reservoirs would contain 10^{16} m^3 (STP) of methane; hence, the ^{3}He inventory is $\sim 10^3$ tonnes. The present geological epoch represents only $\sim$ 4% of the total accumulated subduction zone sites which have been identified from past epochs. If previous subduction zone accumulates contain gas mixtures similar to the present zones, then these potential gas wells could have an inventory of up to 25,000 tonnes of ^{3}He.

2.4. Continental Gas Wells

During previous geological epochs, ancient flora and fauna were buried within the earth and subjected to heating and pressure forming our present fossil fuels, natural gas, petroleum and coal. In order for the methane to be retained, the gas had to be absorbed in a porous structure, such as sandstone, and capped with an impervious rock structure to form a reservoir. Such reservoirs are also capable of occluding He release from the radioactive decay of U and Th ores. This He should have a ^{3}He/^{4}He ratio of 10^{-2} R/R$_A$, in agreement with natural gas derived from fields in the North Sea.

In the USA during the early 1900's, the Hugoton gas fields of Kansas and Texas were discovered to contain high He contents, up to 8%, with a ^{3}He/^{4}He ratio of $\sim 10^{-1}$ R/R$_A$. The occurrence of this He has never been adequately explained; however, the high ^{3}He content indicates that some primordial He has seeped into this reservoir. For many years these fields were the only known source of He in the world and much of it was lost as the natural gas was burned as fuel. Because of the increasing uses of He and the apparent limited supply the U.S. Government implemented the Helium Acts of 1925 and 1960. These acts authorized the Bureau of Mines to purchase helium from private contractors and store it in the partially depleted Cliffside gas fields near Amarillo, Texas. This field presently contains 1.1×10^9 m^3 of He containing ~ 30 kg of ^{3}He. By 1967 the production of He by the private contractors greatly exceeded the anticipated demand. All purchasing contracts were terminated in 1973 and have not been reinitiated. In 1987, private producers [24] requested that federal agencies should not be required to purchase He solely from the Bureau of Mines which has the effect of establishing a market price for this commodity. Because of the recent demand for liquid He at medical facilities for cryogenic purposes, two private suppliers have opened He separation facilities to supply $\sim 5 \times 10^7$ m^3 (STP)/yr of He (containing ~ 1.7 kg of ^{3}He).

The Bureau of Mines periodically estimates the reserves of He contained in the natural gas wells of the USA [25]. These reserves increased nearly 230% from 1980-1982 as the newly discovered He-bearing wells of the Riley Ridge field in Wyoming was added. These gas wells are classified according to their He content as: $> 0.3\%$, 0.29% to $> 0.1\%$, and $< 0.10\%$. In order to evaluate the proved and potential He reserves, the proved and potential resources of natural gas are surveyed and their He contents are estimated with the results noted in Table 1. Consequently, the calculated ^{3}He in all these categories is only ~ 0.7 tonnes, insignificant to supply a fusion industry.

2.5. Atmospheric He

The He concentration in the atmosphere has been measured [26] from samples collected at 12 locations in the USA, giving a value of 5.2204 ± 0.0041 ppm(vol) and a ^{3}He/^{3}He ratio of 1.393×10^{-6}. Based upon these values and the weight of the atmosphere, the total quantity of ^{3}He is calculated to be 4000 tonnes, in good agreement with the value by Craig of 2.9×10^{10} liters (STP) ^{3}He (3900 tonnes).

A review of the He flux into and out of the atmosphere indicates that the atmospheric inventory appears to have attained a steady-state [10]. The He escape flux is chiefly due to diffusive thermal escape; however, a non-thermal factor such as a hydrodynamic flow, has also been postulated. The influx from the mid-ocean ridges, through the oceans as previously discussed, is a large factor, while the degassing of the continental crust is much smaller. Cosmic ray spallation contributes a small influx by forming ^{3}He and ^{3}H which decays to ^{3}He. A significant influx is attributed to "auroral precipitation" when He in the solar wind leaks through the earth's magnetosphere at the magnetic poles.

3. Potential Production of ^{3}He from Earth's Reservoirs

This review of the earth's reservoirs of ^{3}He indicates that several of the sources would not be sufficient to supply a fusion power industry. For instance, the quantity of ^{3}He in the deep mantle appears to be very large; however, this estimated value has many assumptions which can not be verified. Also, no known technique is available to stimulate the release of this gas from the molten magma within chambers below island volcanoes or mid-ocean ridges. Encouraging the degassing of such chambers could lead to large-scale natural disasters. The normal evolution from these sources contributes only ~ 5 kg of ^{3}He per year, an insignificant amount. These gases, which are released under water, form an inventory of only 13 tonnes which is spread throughout the world's oceans and is replenished at the rate of only 4 kg/yr.

Most of the world's He needs are supplied from natural gas wells in the USA, although a small amount, $\sim 6 \times 10^6$ m^3/yr, is produced in Poland and Russia. The He content in the natural gas presently consumed as fuel is estimated to be 1.7×10^8 m^3 (STP)/yr, containing ~ 4.5 kg of ^{3}He. Past experience has shown that only 50% of this He can be profitable separated from the methane. Consequently, if the ^{3}He were separated from this He, its rate of production would be only 2-3 kg (^{3}He)/yr.

The 4000 tonnes of ^{3}He in the atmosphere and the potential 25,000 tonnes of ^{3}He in subduction zone natural gas appear attractive; however, the energy expended to retrieve the ^{3}He from the resources must be considered. The operation of the most efficient helium production plant, the National Helium Corp. at Liberal, Kansas, requires the liquefaction of all the methane, which aids in the removal of undesirable water, sulfur-bearing gases, CO_2, and some nitrogen [27]. The unliquefied gas, called "Crude Helium," contains 86% He with mostly nitrogen as the impurity. The operators of this plant have found that 242 kWh of energy is required to supply 5 kg (10^3 ft^3) of He. Another facility, the Greenwood Plant of Phillips Petroleum, also removes He from natural gas but prepares "pure" liquefied He at an energy cost of 1520 kWh/5 kg of He. The ^{3}He/^{4}He isotopic separation would require very high purity for the He and is conducted in the liquid state at 1.6-2 K. Some of "waste" liquefied ^{4}He from this operation would be utilized to cool the incoming He stream; consequently, the energy cost for obtaining pure ^{3}He were estimated by the following procedure. The energy expended in cooling the methane from 300 K to its condensation temperature of 111 K was assumed to be 242 kWh/(5 kg He) The remaining He was cooled and condensed at 4.2 K and a 60% recovery of this cryogen energy was assumed; therefore, the energy cost for He (mixed gas) at 330 K to liquid at 4.2 K was 750 kWh/5 kg ^{4}He 1.2×10^9 kWh/kg (^{3}He).

After the He isotopes were liquefied at 4.2 K, the energy required to isotopically separate the He isotopes was determined. First, the energy needed to cool the mixture to 1.6 K was determined based upon the Cp (2.25 kJ/kg·K) of liquid He and the assumption that 75% of the cryogenic energy would be recovered in a recuperator at 4 K. This sensible heat removal would require 2.7×10^3 kWh/kg (^{3}He). The isotopic separation techniques used a "superfluid/superleak" to enrich the ^{3}He from 2×10^{-7} to 10^{-2} fraction of the ^{4}He. The enriched product was enriched further to 99.9% by a cryogenic distillation which operated at a boiler temperature of 2.4 K and a condense temperature of 1.6 K, as described by Wilkes [28]. The "superleak" apparatus required 1.1×10^3 kWh/kg (^{3}He) of heat and the distillation system boiler required an additional 3×10^4 kWh/kg (^{3}He). Because these separation energies would be rejected at nearly 300 K, each of the latter two values were multiplied by a factor of 10^3.

Based upon the above values the energy required to separate high purity ^{3}He from USA natural gas wells (> 0.3 vol % He and ^{3}He/^{4}He ~ 0.2 ppm at.) was calculated. As noted in Table 2, the energy required to separate the methane from the He and provide liquid He at 4.2 K is 1.2×10^9 kWh/kg (^{3}He). The isotopic separation energy is small, 3×10^7 kWh/kg (^{3}He), making the total energy requirement at 1.23×10^9 kWh/kg (^{3}He).

As noted, however, the energy produced by the fusion of D-^{3}He is only 1.7×10^8 kWh/kg (^{3}He); therefore, the energy multiplication for this process is negative. The only means by which this system could have a positive energy payback would be to separate the methane for other purposes, such as removal of undesirable impurities, and charge this separation cost to the sale of the methane. In such a case, however, the availability of ^{3}He would be determined by the production requirements for natural gas, which at present consumption would yield only 2-3 kg (^{3}He)/yr.

A similar calculation was performed for the ^{3}He recovery from subduction zone gas, taking into account that the ^{4}He content in this gas is 50 to 200 ppm (vol) with a ^{3}He/^{4}He isotopic ratio 2-10 ppm. The energy cost for separation of the He from the methane is in the range of 0.3 to 6×10^9 kWh (^{3}He). The cost of isotopic separation using the "superleak" and liquid distillation is very small by comparison, only 7×10^5 kWh/kg (^{3}He), Table 2; consequently, the ratio, ^{3}He fusion energy produced/energy cost of ^{3}He production, is marginally unfavorable for even the best case.

The possibility of extracting He from the atmosphere was considered. Several successful permeator systems have been designed recently which separate certain trace gases from air or other gases. Such systems have been successful because the permeating gas demonstrates some solubility in the separation membrane. Unfortunately, He is not soluble in any membrane and has a very low liquefaction temperature. Consequently, all the other gases are removed so that He remains as the non-condensable gas and the energy cost for He is related to the compressive work required in handling the other gases. The energy cost of producing He from air at the National Helium Corp. plant has been estimated to be 1.5×10^5 kWh/5 kg of He, approximately 10^3 times higher than for He production from natural gas; however, the plant would need to be redesigned to handle air instead of natural gas. This He would be only 86% pure, and as previously noted, the energy cost should be increased significantly in order to obtain high purity liquid ^{4}He,

Table 2

Energy Payback from Earth's ^{3}He Resources

	Energy Expended, kWh/kg (^{3}He)				
Source	Separate from Carrier Gas Cool to 4.2 K	Isotopic Separation	Total Energy	Fusion Energy Payback*	Potential Product (as a By-Product) kg(^{3}He)/yr
USA natural gas	1.2×10^9	3×10^7	1.23×10^9	Negative	2.5
Subduction zone gas	1×10^9	7×10^5	1×10^9	Negative	< 0.1
Air	9×10^{10}	4×10^6	9×10^{10}	Negative	0.02

*Energy produced by D-^{3}He fusion = 1.7×10^8 kWh/kg (^{3}He).

Table 2. The energy cost for production of liquid He from air is 9×10^{10} kWh/g (^{3}He) while the isotopic separation requires only 4×10^6 kWh/kg (^{3}He); hence, the energy cost for the production of ^{3}He is 450 times greater than the fusion yield. If these energy costs were borne by the sales of other gases, such as liquefied nitrogen, then the amount of ^{3}He recovered would be only 0.02 kg (^{3}He)/year in the USA.

4. Artificial Production of ^{3}He

Recognizing the scarcity of ^{3}He on earth, several investigators have proposed nuclear reaction schemes to produce ^{3}He. These concepts include: (1) production of tritium followed by β-decay to ^{3}He; (2) fusion of D-D to produce ^{3}H, ^{3}He, p and neutrons; (3) fusion of ^{6}Li + p to give ^{3}He + ^{4}He. Each of these schemes will be reviewed briefly.

4.1. Production of ^{3}He by Tritium Decay

Any source of neutrons can be used to interact with Li and form ^{3}H. Both fission and fusion reactors have been designed to be net tritium breeders. A review [29] of such reactors which have been proposed in the USA for large-scale production of tritium reveals that there can be an order of magnitude difference in the cost of the tritium, depending upon the reactor facility. For instance, the use of an accelerator to produce a high energy proton beam which bombards a Pb target forming neutrons by spallation was estimated to produce tritium at the highest cost, nearly \$160,000/g of ^{3}H. When a U fission pile was utilized with a low-temperature, heavy water (D_2O) moderator the cost was $\sim \$100,000$/g(^{3}H). If a High Temperature Gas-Cooled reactor were utilized which sold excess electrical power the cost dropped by $\sim$ 50% to \$55,000/g(^{3}H). Two types of magnetically confined fusion reactors were designed using D/T fuel, one a tokamak and the other a tandem mirror. The devices operated at low temperature so that no fusion power was utilized and electrical power had to be purchased; consequently, the costs were 36,000 and 49,000 \$/g of ^{3}H for the tandem mirror and tokamak, respectively. Another set of conceptual fusion reactor designs was based upon the Inertial Confinement Fusion concept, using laser beam irradiation of fuel targets. In each case liquid Li was used as the high temperature coolant so that sufficient thermal power could be recovered and used to generate all the electrical power needed in the facilities. In these ICF facilities, the costs decreased to between 10,000 to 12,000 \$/g of ^{3}H.

The cost and safety associated with storage of ^{3}H while it decays to ^{3}He must also be considered. A recent study of storage of $\sim$ 45 kg of ^{3}H indicated [30] that if the ^{3}He were collected for 10 half-lives (123 yr) the additional cost of ^{3}H storage was $\sim$ \$420/g of ^{3}He; consequently, the lowest total cost (production of ^{3}H plus storage) would be $\sim \$10,500$/g of ^{3}He. Consequently, the fuel cost from a 1000 MWe plant using the D-^{3}He fusion fuel cycle would be 130 mills/kWh(e). At such a high cost, the generation of electrical power by fusion on a large scale would probably never be competitive with alternative fuel systems.

In addition, the generation of 1000 MW(e) requires $\sim$ 100 kg/yr of ^{3}He for a D-^{3}He fusion plant. If the ^{3}He were produced from ^{3}H, the ^{3}He would need to be continuously separated from 1.8 tonnes of ^{3}H. The storage of such a large quantity of a potentially gaseous, radioactive material would be difficult to license, probably impossible in the present political climate.

4.2. D-D Fusion Reactions

The D-D fusion produces ^{3}He via one of two reaction channels according to:

$$\mathrm{D} + \mathrm{D} = {}^3\mathrm{He} + \mathrm{n}$$

and

$$\mathrm{D}+\mathrm{D} = {}^3\mathrm{H} + \mathrm{p}\ ,$$

where the channel probabilities are $\sim$ 50:50 at $>$ 1 keV. The ^{3}He produced can be allowed to react with the excess D or it can be rapidly extracted and used in a D-^{3}He satellite fusion reactor, as reviewed by Miley [31]. If the latter option were utilized, in what is known as the semi-catalyzed mode, the D-D breeder operates at a temperature of $<$ 40 keV while the satellite power-producing reactor would operate at a higher temperature of $80-140$ keV. A detailed study of a combined breeder-satellite system was reported by Shuy, et al. [32], basing both plants on a tandem mirror reactor. The optimum operating temperature for the breeder was found to be 28 keV while the satellite operated at 75 keV. In addition, the ^{3}H was extracted from the recycled plasma fuel and stored along with ^{3}H generated by the neutron absorption in a Li blanket. These ^{3}H batches were stored and allowed to decay to form additional ^{3}He fuel. By such a method, they were able to supply 12,000 MW(e) satellite power reactors at a cost of 43.4 mills/kWh (1985) with 3000 MW of fusion power in the breeder.

The environmental impact of such a system must be considered. The breeder reactor would have the same safety and radioactive waste disposal ratings as a D/T reactor, and the breeding of tritium with its long-term storage in large amounts ($\sim$ tonnes) would be an additional concern. In addition, two operational licenses would be required, the breeder and the satellite.

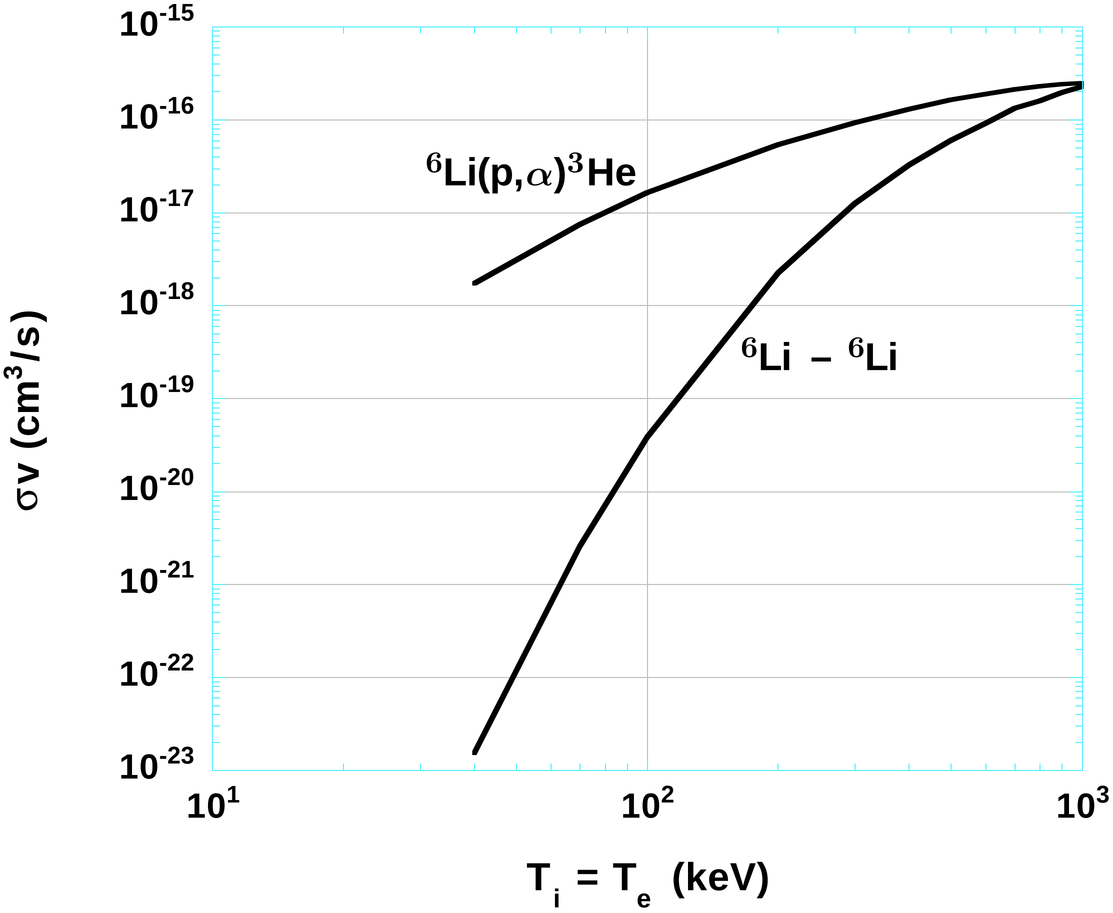

Figure 2. Reaction parameters versus ion temperature.

4.3. The p + ^{6}Li Reactions for Breeding ^{3}He

The p - ^{6}Li fusion reaction, i.e. p(^{6}Li,α)^{3}He, has been studied [31] as a potential supply route for ^{3}He, because no radioactive reactants or products are produced in the principal channel. Such a reaction, however, requires operational temperatures of several 100's keV in order to obtain a reasonable reaction rate (Fig. 2). Because of the high electron density, in an equilibrium plasma where $T_i = T_e$, the proton rapidly loses energy, decreasing the reaction probability. As a result, no viable steady-state burn prospects for p - ^{6}Li have been demonstrated. Consequently, supplementary power would be required for proton heating, which would decrease net power from any D-^{3}He satellite reactor which would use the ^{3}He which is produced. The viability of such a breeder-satellite reactor has not been investigated. The possible use of proton beams interacting with a Li plasma may deserve further study [33].

In addition to the principal reaction p(^{6}Li,α)^{3}He, ^{6}Li - ^{6}Li reactions have been calculated. For instance at ~ 300 keV, these ^{6}Li - ^{6}Li side reactions can be 10% of the principal reaction [34], Fig. 2. These ancillary reactions include a significant production of ^{7}Be + n, leading to high radioactivity in the confinement device. Such radioactive waste products would be no better than those from a D-T reactor and the development costs for the p - ^{6}Li system may be formidable.

5. Summary

This study leads to the following conclusions:

1. No natural sources have been identified which can produce ^{3}He either in the quantities required for a fusion power industry or with a net energy payback.

2. The production of ^{3}He by the decay of tritium produced in a fission or fusion reactor is uneconomical and the tonnes of tritium which must be stored are environmentally unacceptable.

3. The production of ^{3}He via D-D fusion carries all the undesirable safety and environmental aspects of D-T fusion. A p - ^{6}Li fusion reactor has not been demonstrated to be viable and ancillary ^{6}Li - ^{6}Li reactions could lead to undesirable radioactive products.

The outlook for obtaining ^{3}He for research and demonstration D-^{3}He fusion reactors is much better. Commercial vendors who produce liquid helium could be given incentives to isotopically separate the helium isotopes. This ^{3}He separated at the rate of 4-8 kg/yr could be stored for several years and combined with the ^{3}He resulting from several tritium stockpiles. These combined stores could produce up to 100 kg of ^{3}He required for research and development projects.

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References

[1] G.L. Kulcinski, etal., "Safety and Environmental Characteristics of Recent D-^{3}He and D-T Tokamak Power Reactors," *Fusion Technology*, **21**, 1779 (1992).

[2] R.F. Post and J.F. Santarius, "Open Confinement Systems and the D-^{3}He Reaction," *Fusion Technology*, **22**, 13 (1992).

[3] L.J. Wittenberg, etal., "A Review of He-3 Resources and Acquisition for Use as Fusion Fuel," *Fusion Technology*, **21**, 2230 (1992).

[4] L.J. Wittenberg, "Terrestrial Sources of ^{3}He - A Trip to the Center of the Earth," *Fusion Technology*, **15**, 1108 (1989).

[5] B.A. Mamyrin and L.N. Tolstikhin, *Helium Isotopes in Nature*, Elsevier, Amsterdam (1984).

[6] J.W. Dawson and W. Livesy, "^{3}He on Venus and Mercury," *Bull. Amer. Phys. Soc.*, **31**, 1393 (1986).

[7] R.E. Hartle, S.A. Curtis and G.E. Thomas, "Mercury's Helium Exosphere," *J. Geophys. Res.*, **80**, 3689 (1975).

[8] Monthly Energy Review, DOE/EIA-0035 (93/03), March 1993.

[9] M.D. Kurz, J.J. Gurney, W.J. Jenkins and D. E. Lott III, "Helium Isotope Variability Within Single Diamonds from the Orapa Kimberlite Pipe," *Earth Plant. Sci. Letters*, **86**, 57 (1987).

[10] M. Ozima and F.A. Podosek, *Noble Gas Geochemistry*, Cambridge University Press, Cambridge (1983).

[11] I.N. Tolstikhin, "Helium Isotopes in the Earth's Interior and in the Atmosphere," *Earth Plant. Sci. Letters*, **26**, 88 (1975).

[12] B. Marty and M.F. Le Cloarec, "^{3}He and CO2 Fluxes from Subaerial Volcanos Estimated from Polonium-210 Emissions," *J. Volcano. Geothermal Res.*, **53**, 67 (1992).

[13] M.D. Kurtz, M.O. Garcia, F.A. Frey and P.A. O'Brien, "Temporal Helium Isotope Variations Within Hawaiian Volcanoes: Basalts From Mauna Loa and Haleckalei," *Geochem. Cosmochem. Acta*, **51**, 2903 (1987).

[14] H. Craig, W.B. Clarke and M.A. Beg, "Excess ^{3}He in Deep Water on the East Pacific Rise," *Earth Planet. Sci. Letters*, **26**, 125 (1975).

[15] I.Ya. Azel and I.N. Tolstikhin, "Geodynamics, Magnetism and Degassing of the Earth," *Geochimica Cosmochimica Acta*, **54**, 139 (1990).

[16] K.A. Farley and R.J. Poreda, "Mantle Neon and Atmospheric Contamination," *Earth Plan et. Sci. Lett.*, **114**, 325 (1993).

[17] H. Craig and J.E. Lupton, *Helium-3 and Mantle Volatiles in the Ocean and the Ocean Crust*, in The Sea, Vol. 7, The Oceanic Lithosphere, C. Emiliani (Ed.), Wiley-Interscience, New York, 391-428 (1981).

[18] T. Gold and S. Sater, "The Deep-Earth Gas Hypothesis," *Scientific American*, June 1980, pp. 154-161.

[19] J.W. Valley, S.C. Komor, K. Baker, A.W.A. Jeffrey, I.R. Kaplan, *Calcite Crack Cement in Granite from the Siljan Ring*, in Deep Drilling in Crystalline Bedrock, Vol. 2, Eds. B.Boden and K.G. Eriksson, Springer-Verlag, 156 (1988).

[20] M. Takayanagi and M. Ozima, "Temporal Variation of the ^{3}He/^{4}He Ratio Recorded in Deep-Sea Sediment Cores," *J. Geophysical Res.*, **92**, 12531 (1987).

[21] D.L. Anderson, "Helium-3 from the Mantle: Primordial Signal or Cosmic Dust," *Science*, **261**, 170 (1993).

[22] K.A. Farley, "Is Primordial Helium Really Extraterrestrial?" *Science*, **261**, 166 (1993).

[23] A.W.A. Jeffrey, "Detection/Differentiation System Development for Deep Source Gases, Completion of Phase I," DOE/MC 21131-2350 (Feb. 1987).

[24] M. Crawford, "Dismantling the Helium Empire," *Science*, **237**, 238 (1987).

[25] R.D. Miller and J.E. Hamak, "Helium Resources of the United States, 1989," Bureau of Mines Information Circular, IC-9267 (1990).

[26] P.W. Holland and D.E. Emerson, "A Determination of the ^{4}He Content in Near-Surface Atmospheric Air Within the Continental USA," *J. Geophysical Res.*, **92B**, 12557 (1987).

[27] R.C. Seamans, "The Energy Related Applications of Helium and Recommendations Concerning the Management of the Federal Helium Programs," ERDA-13 (April 11, 1975).

[28] W.R. Wilkes and L.J. Wittenberg, "Isotopic Separation of ^{3}He/^{4}He from Solar Wind Gas Evolved from the Lunar Regolith," SPACE'92, *Proc. of the Conf. Engineering, Construction and Operation in Space*, Amer. Soc. Civil Eng., New York, 1992, p. 547-554.

[29] L.J. Wittenberg, "Comparison of Tritium Production Reactors," *Fusion Technology*, **19**, 1040 (1991).

[30] F. Najmabadi, R.W. Conn and the ARIES Team, "The ARIES-III D-^{3}He Tokamak-Reactor Study," UCLA 1993 (in press).

[31] G.H. Miley, "^{3}He Sources for D-^{3}He Fusion Power," *Nucl. Instr. Methods Phys. Res.*, **A271**, 197 (1988).

[32] G.W. Shuy, A.E. Dabiri and H. Gurol, "Conceptual Design of a D-^{3}He Fueled Tandem Mirror Reactor Satellite/Breeder System," *Fusion Technology*, **9**, 459 (1986).

[33] G.H. Miley, Personal Communication, July 20, 1993.

[34] L. Ruby and T.-P. Lung, "Effect of ^{6}Li + ^{6}Li Reactions in a Fusion Reactor Operating on ^{6}Li (p,α)^{3}He," *Nucl. Sci. Eng.*, **69**, 107 (1979).

Addendum

Helium-3 Inventory in Oceanic Sediment

Introduction

The flux of meteoric and cometary material impacting the earth has been estimated to be 50 to 100 Gg/yr. This incoming material flux includes large objects, such as meteorites, and small particles $< 50\ \mu$m diameter, known as Interplanetary Dust Particles (IDPs). These particles occlude helium and other noble gases, which are chiefly associated with the mineral magnetite. The isotopic ratios of these gases bear a signature of solar origin and probably indicates that the particles were bombarded by the solar wind during their travels through the solar system. Most of the IDPs are believed to originate as fragments caused by collisions of asteroids in the Main Asteroid Belt. The ^{3}He/^{4}He ratios in gases released from IDPs are $\sim$ greater than 2×10^{-4}, nearly 100 times the value for the earth's atmosphere.

The small IDPs apparently retain the enclosed noble gases during their descent through the earth's atmosphere. Many of these particles, together with terrestrial dust from the continents, eventually settle into the pelagic sediments of the oceans. Deep-sea sediment cores up to 10 m long have been obtained from the mid-Pacific Ocean at water depths up to 6 km. At sedimentation rates of ~ 3 mm/10^3 yr, these sediment cores span a period of ~ 3 million years. Noble gases have been extracted from aliquotes of these dried sediments (Takayangi and Ozima, 1987). The ^{3}He/^{4}He ratios of these gases ranged up to 50 to 100×10^{-6} ($\sim$ 35 to 70 times the atmospheric ratios) with the highest ^{3}He concentrations of $\sim 3 \times 10^{-11}$ cm^3 (STP)/g (4×10^{-15} g(^{3}He)/g) of sediment. Based upon such sampling, Anderson (1993) has estimated the inventory of ^{3}He occluded in the earth's oceanic sediments via the following manner: Total ^{3}He in sediment equals the average concentration (5×10^{-11} cm^3/g) times the density of sediment (2 g/cm^3) times the area of the oceans (3×10^8 km^2) times the sediment depths (300 m) $= 9 \times 10^{12}$ cm^3 (1200 metric tone of ^{3}He). This value is nearly the same as the previously noted value for ^{3}He in the earth's atmosphere, 4000 metric tons.

The IDPs have been separated from the oceanic sediment, visually examined, and their evolved gases determined following their heating in a vacuum (Nier, et al., 1990). These samples were collected in the mid-Pacific Ocean at a depth of 5300 m. The collector consisted of a 300 kg sled which was towed directly along the ocean floor. The sled collected magnetic particles by attraction to the edges of holes in fully magnetized steel screens. Following recovery of the sled, adhering particles were removed and sieved. Samples designated as "magnetic fines" were $< 100\ \mu$m particles which could be extracted from a water slurry by direct contact with an Alnico magnet. Particles $> 100\ \mu$m were hand-picked from magnetically sieved separates and examined. Their texture, mineralology and elemental compositions were consistent with the characteristics of chondritic, meteoric materials.

Magnetic fine samples were heated for mass spectrographic analyses of the gases which were evolved during heating, "stepwise" to 850, 1200 and 1600°C. Nearly 96% of the gases were released below 1200°C. The ^{4}He evolved from these samples was 7.1×10^{-5} cm^3 (STP)/g, their isotopic ratios were $^3\text{He}/^4\text{He} = 3.1 \times 10^{-4}$ and $^{20}\text{Ne}/^{22}\text{Ne} = 11.7$, both being typical of extraterrestrial (solar) materials. The ^{3}He content of these particles was, therefore, 2.2×10^{-8} cm^3/g (3×10^{-12} g(^{3}He)/g); hence, the ^{3}He in the magnetic paarticulates was concentrated by a factor of 10^3 as compared with the bulk sediment.

Anderson (1993) further suggests that upon subduction of the oceanic tectonic plates the noble gases are released from the oceanic sediments and supply the extraterrestrial signals to the gases venting from the earth's interior. Conversely, other geophysicists suggest that such subducted gases probably vent at volcanoes near the subduction zone; however, highly enriched ^{3}He gases which vent at the intraplate volcanoes, such as the Hawaiian chain, are derived from the deep mantle or perhaps from the earth's core (Davies, 1990). Recently, Wittenberg (1994) has postulated a mechanism by which primordial gases could be occluded deep within the mantle and even in the metallic core during the early accretion of the earth.

Potential Utilization of the ^{3}He in Oceanic Sediment

With such a large potential inventory of ^{3}He in the oceanic sediment, the possibility of its recovery and utilization as a fusion fuel can be considered. Such a consideration is based upon a proposed scheme for the acquisition of the IDPs from the oceanic sediment followed by the heating of these particles to release the noble gases. The separation of the ^{3}He from the gases would follow. The energy required for these acquisition procedures could then be compared with the fusion energy released upon utilizing the ^{3}He as a fusion reactor fuel, hence determining the energy payback.

As previously noted, the He is occluded in magnetic particles existing in oceanic sediment approximately 300 m thick. The proposed scheme visualizes the separation of these particles from the pelagic sediment. Because the sediments occur underwater, hydraulic pressure would be used to dislodge the sediment and form a suspension of the particles in the water. This suspension would be channeled through pipes containing magnetized steel screens which would collect the magnetic particles while the non-magnetic particles would be returned to the oceanic floor. The screens would be periodically recycled and the magnetic particles removed. After drying thse magnetic particles would be heated to $\sim$ 1200°C and the evolved gases collected. Specific details of this scheme follow.

Hydraulic Suspension of the Oceanic Sediment

In order to provide 1 kg (^{3}He)/yr nearly 6.2×10^{10} m^3 (sediment)/yr would be processed. A suspension would be formed with $\sim$ 5 volumes of water per volume of sediment. Such a suspension would have to be processed at the rate of $\sim 10^4$ m^3/s. Approximately 100 flexible pipes, 1 m^2 cross-section (0.56 m diameter) × 50 m long, would be utilized to convey the suspension through the screens and return it to a suitable location. The pumping power required for each straight pipe was determined to be 3.2×10^3 MW, based upon a reasonably smooth pipe with a friction factor of 0.018.

The additional pumping power through the screens was assumed to be similar to the excess power required to pump water through a 20% contraction in a pipe where the effective friction factor is 0.2 (Casey, 1992). With 10 screens in series the total pumping power would be 4.5×10^3 MW per pipe. The total pumping power, 7.7×10^3 MW, must be multiplied by 1.5 because a sludge is being pumped (Casey, 1992); consequently, for the total 100 pipes pumping for a year to collect 1 kg (^{3}He), the pumping power would be 1.13×10^6 MW·yr.

The separated particles which are mostly magnetite must be heated to 1200°C. With the Cp of $Fe_3O_4 \sim 1$ J/g·K, the total heat required would be 3×10^{11} MJ/kg (^{3}He) or 1×10^4 MW·yr. Clearly, the pumping power predominates at $\sim 1 \times 10^6$ MW·yr. By contrast, the fusion power derived from the ^{3}He is only 19 MW·yr/kg (^{3}He). Consequently, the energy payback is negative. Perhaps a renewable energy system could be utilized, such as Ocean Thermal Energy Conversion for the pumping power plus Solar Thermal Energy for heating the paricles. Such systems may make the system energy payback more attractive.

A comparison of terrestrial sources of ^{3}He (Table 1) indicates that the oceanic sediment is the most costly in terms of energy required to supply a kg of ^{3}He. The least energy requirements are for the natural gas sources at $\sim 10^9$ kWh/kg of ^{3}He, but still a factor of 10 greater than the fusion energy yield. Such resources might be considered if non-energy uses of ^{3}He were developed. If the natural gas resource were utilized and low cost hydroelectric power were available at < 1 cent/kWh, the ^{3}He cost would be \$10 million/kg (\$10,000/g). Perhaps some valuable non-energy product may be developed which could utilize this high-priced ^{3}He.

Table 1

Energy Requirement for Utilization of Earth's Major ^{3}He Resources in kWh/kg(^{3}He)

Source	Separate From Host	Isotopic Separation	Total Energy	Fusion Energy Payback*	Potential Product (as a By-Product) kg (^{3}He)/yr
<u>From Gases</u>:					
USA natural gas	1.2×10^9	3×10^7	1.23×10^9	Negative	2.5
Subduction zone gas	1×10^9	7×10^5	1×10^9	Negative	<0.1
Air	9×10^{10}	4×10^6	9×10^{10}	Negative	0.02
<u>From Solid</u>:					
Oceanic sediment	9×10^{12}	7×10^5	9×10^{12}	Negative	None

*Energy produced by D-^{3}He fusion = 1.7×10^8 kWh/kg (^{3}He).

References

Anderson, D. L., 1993, "Helium-3 from the Mantle: Primordial Signal or Cosmic Dust?" Science, **261**, pp. 170-176.

Casey, T.J., 1992, Water and Waste Water Engineering Hydraulics, Oxford Press, Oxford, pp. 43-50.

Davies, G.F., 1990, "Mantle Plumes, Mantle Stirring and Hotspot Chemistry," Earth Planet. Sci. Lett., **99**, pp. 94-109.

Nier, A.O., D.J. Schlutter and D.E. Bromlee, 1990, "Helium and Neon Isotopes in Pacific Ocean Sediments," Geochim. Cosmochim. Acta, **54**, pp. 173-182.

Takayanagi, M. and M. Ozima, 1987, "Temporal Variations of ^{3}He/^{4}He Ratio Recorded in Deep-Sea Sediment Cores," J. Geophys. Res., **92**, pp. 12531-12538.

Wittenberg, L.J., 1994, "The Early Sun: Precursor to Helium and Neon in the Earth," (Abstract) Int'l. Conf. Geochemistry, Cosmochemistry and Isotope Geology, Berkeley, CA, June 5-11, 1994.