Terrestrial Sources of Helium-3 Fusion Fuel – A Trip to the Center of the Earth

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October 1988
Revised November 1988

UWFDM-769

Presented at the 8th Topical Meeting on the Technology of Fusion Energy, 9–13 October 1988, Salt Lake City UT

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TERRESTRIAL SOURCES OF HELIUM-3 FUSION FUEL -

A TRIP TO THE CENTER OF THE EARTH

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ABSTRACT

Several thousand tonnes of He-3 have been identified in various terrestrial reservoirs. The He-3 exists, however, as a dilute component, 10^{-9} to 10^{-12} volume fraction, of host gases such as the atmosphere or natural gas (methane). The production of He-3 is controlled, therefore, by the usage of the host gases. If the He-3 were separated from the host gases currently used, only 6 kg/yr would be obtained. With a vigorous expansion in the use of natural gas containing significant quantities of He-3, the production of He-3 could be increased to ~ 25 kg/yr by the year 2000. This quantity of He-3 utilized in the d/He-3 fusion reaction would be sufficient to supply continuously several 100 MW fusion electrical power demonstration plants.

INTRODUCTION

Over the past 35 years nuclear fusion research has been directed toward the development of the fusion reaction, d(t,n)α as a commercial power source. A more environmentally benign fusion reaction, d(^{3}He,p)α, has been recognized which embraces neither a radioactive fuel nor fusion product. The only neutrons produced result from d-d side reactions; consequently, the radiation damage to the structural components of the reactor is reduced by a factor of ~ 25 as compared to d-t fusion. Although the required plasma temperature for d/He-3 fusion is higher than for d/t, this temperature is only a modest extrapolation from present technology. The major impediment to d/He-3 fusion research has been the scarcity of He-3. Recently, we identified an inventory of over one million tonnes[1] existing in the fine regolith of the lunar surface, as a result of implantation by the solar wind. The technical and economic viability of harvesting the He-3 on the moon and exporting it to earth to fuel commercial fusion power plants is being studied.

A small, manned lunar base may be established[2] by the year 2005. This small base would gradually grow to 25 persons during the following 10 to 15 years. Site selection and the preliminary establishment of a lunar He-3 mining operation would be undertaken during this time. During this interval, He-3 from terrestrial sources will be needed for research, development and demonstration of proposed fusion reactors.

This paper surveys the principal terrestrial sources of He-3, assesses their inventories, and estimates their rates of production. The earth is protected by a magnetosphere which shields the earth from the solar wind; consequently, nearly all of the He-3 presently on earth existed in the primordial material which accreted to form the planet. Excluded is the He-3 derived from the decay of tritium produced by the several national nuclear weapons programs. For instance, the tritium stockpile for the USA has been estimated[3] to produce ~ 5 kg/yr of He-3.

HELIUM RESERVOIRS

The present terrestrial He-3 reservoirs considered are: (1) the atmosphere, (2) continental crust deposits associated with natural gas, (3) mantle-derived outgassing from the earth's interior, and (4) tectonic plate subduction zone gas. Each of the resources has a characteristic He-3/He-4 ratio which aids in its identification[4,5] (see Fig. 1). These reservoirs are discussed sequentially from the center of the earth, Fig. 2. Their estimated He-3 inventories are summarized in Table 1.

A. Mantle-Derived Helium

Primordial material of our solar system which accreted to form the earth approximately 4.5 billion years ago is believed to have had a helium content and an isotopic ratio similar to that analyzed for the chondritic meteorites.[6] As the primordial matter continued to accrete, its temperature increased and many of the volatile materials, including helium, vaporized and escaped from the new earth.

Table 1. Estimated Terrestrial He-3 Inventory

	He-3 Metric Tonnes			
	Proved	Probable	Possible	Speculative
Atmosphere	4,000			
Crustal Natural Gas (USA)	0.2	0.15	0.26	0.10
Subduction Zone Natural Gas	0.03		1,000	25,000
Mantle Gas				10^6-10^7
	$4x10^3$	0.15	10^3	10^6-10^7

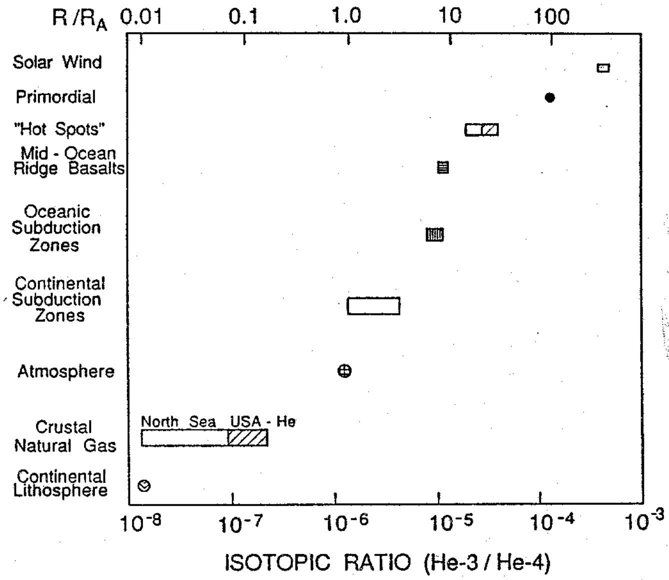

Fig. 1. Helium isotopic ratios for major natural helium reservoirs; R/R_A = isotopic ratio of a sample compared to the earth's atmospheric ratio.

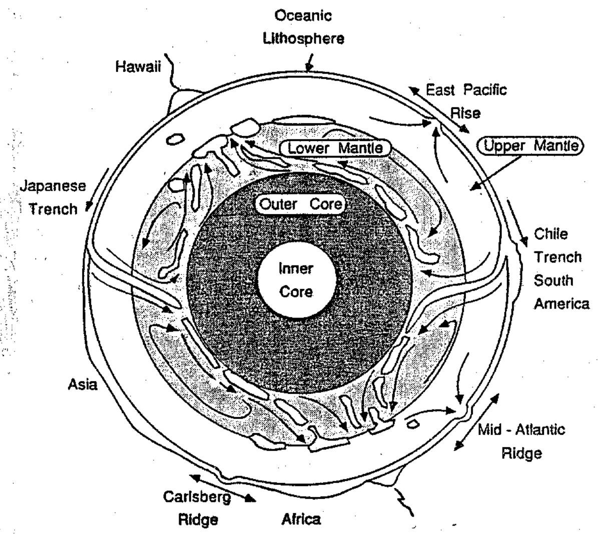

Fig. 2. Cross-sectional diagram of the earth showing the subduction of oceanic lithospheric plates.

In order to explain the present inventory of helium, water and other volatiles on earth, one theory suggests that further asteroids, similar to the chondritic meteorites, impacted on the preformed core of the earth to form a veneer constituting approximately 20-30% of the weight of the earth.[7] This veneer constitutes the present upper mantle and crust. Many of the volatile gases including helium remain dissolved in the upper molten mantle of the earth.

The primordial helium in the terrestrial environment has been diluted, however, by the α-particles (He-4) emanating from the radioactive decay of Th and U ores. On the other hand, some He-3 is formed in the earth by neutrons, emitted by the spontaneous fission of U-235, reacting with Li-6 to produce tritium (^3H) which decays to He-3. An assessment of these reactions for average U, Th and Li in the soil yields a He-3/He-4 ratio of ~ 0.015 at.ppm. Gases with higher He-3/He-4 ratios are considered to have mantle constituents.

Although no experimental technique is available to measure the mantle's primordial He reservoir, its presence has been detected in gases with high He-3/He-4 ratios emitted from volcanoes, geothermal waters and along mid-ocean ridge vents. The highest ratios, 20-30 at.ppm He-3/He-4, have been detected in volcanic gases in Hawaii and geothermal wells in Yellowstone Park. The primordial He-3/He-4 ratio has been diluted apparently by either the radiogenic He-4 in the mantle or in crustal deposits of radiogenic helium entrained in the magma as it ascends toward the surface. The largest volume of helium venting from the earth occurs along mid-ocean vents particularly in the Pacific Ocean with a He-3/He-4 isotopic ratio of ~ 14 at.ppm. Craig[8] has estimated the He-4 flux from these vents to the atmosphere at 0.3×10^6 atoms/$cm^2 \cdot s$, averaged over the entire earth's surface. When this value is combined with the isotopic ratio, the calculated flux of He-3 is 4 atoms/$cm^2 \cdot s$ and is believed to be the largest source of He-3 to the atmosphere. For the entire surface of the earth, the He-3 annual flux is ~ 3 kg/yr but is widely scattered.

Of greater interest as a source of He-3 is the reservoir of helium dissolved in the mantle which supplies the flux to these vents. In order to make an estimate of this reservoir, it is necessary to construct crude models of the degassing rate of the mantle and to assume that the degassing properties of the helium isotopes are similar to those measured for the isotopes of Ne and Ar. Tolstikhin[9] employed such a model and estimated that the mantle contains from $(1.4 \text{ to } 20) \times 10^{13}$ atoms of primordial He-4 per g of earth. This value combined with the primordial isotopic ratio of He-3 and the weight of the upper mantle indicates that 10^6 to 10^7 tonnes of He-3 may exist in the mantle.

Efforts to tap the mantle have been suggested recently in a search for new sources of natural gas fuel.[10] Such interest is based upon the fact that non-biogenic methane sources from deep within the earth have been observed in rift valleys and in the famous mud volcanoes near Baku in the USSR. Most often, however, these deep sources are vents for CO_2, not CH_4; however, the chemical equilibrium,

$$CH_4 + 2H_2O = CO_2 + 4H_2,$$

is controlled by temperature and pressure so that CH_4 can be the predominant gas under high pressure and low temperature.

In an effort to test the deep gas hypothesis, a deep drilling project has been initiated in the Siljan Lake District of central Sweden. For a deep reservoir to be present, it must be capped by an impermeable granite rock structure to prevent its escape. This site was selected because it was the impact point for a large meteoroid 360 M years ago which fractured the base rock and caused large fissures to extend deep into the granite below the impact point. The drilling process has proceeded to a depth of 6 km and evidence for the fissures has been found; however, all the cracks have been filled with carbonates deposited by the infiltration of surface waters.[11] As a result, the search for abiogenic gas containing a high He-3 content has been unsuccessful, thus far.

B. Tectonic Plate Subduction Zones

The present geophysical concept of the earth visualizes the entire surface to be composed of huge tectonic plates which support the continents and the sea beds of the oceans. These plates are in constant motion at rates up to 1 cm/yr. The driving force for the motion is caused by new magma from the mantle rising through cracks in the ocean floor. The newly ascending magma forces the solidified magma away from the vents so that the plates move and increase in density as they cool. When an oceanic plate of higher density collides with a plate carrying a continent, the heavier oceanic plate subducts below the continent. By this mechanism the oceanic plate dissolves into the mantle and eventually recycles.

These subduction zones can be a potentially rich source for He-3 because they serve as probes into the mantle with its high inventory of He-3. In addition, recent measurements of deep sea sediment cores[12] indicate that the sediment deposited on the oceanic plates is seeded with interplanetary dust particles which contain 0.1 cm^3 (STP) ^{4}He/g with, a He-3/He-4 ratio of ~ 200 at.ppm and are estimated to precipitate at the rate of 400 tonnes/yr worldwide. This source has provided nearly 200 tonnes of He-3 to these sediments since the present tectonic plate epoch began approximately 200 M years ago.

As the subduction plates recede into the mantle and are heated, the sediment accumulated along the top of the plates dehydrates forming steam which is vented through volcanoes. Also, the biotic marine residue begins to decompose due to the thermal and hydraulic pressure. This decomposition leads to the formation of natural gas and petroleum reservoirs which can be accessed by deep drilling,[13] Fig. 3. These gas reservoirs also accumulate the helium released by the sediment and the mantle gases. These gas wells are particularly abundant along the Western Pacific Basin and supply natural gas for local use in Japan, Taiwan and the Philippines. The helium content of the gas varies from 50-200 ppm and the He-3/He-4 ratio ranges from 2 to 10 at.ppm.

The calculated reservoir of natural gas in these subduction zones is based upon an estimate

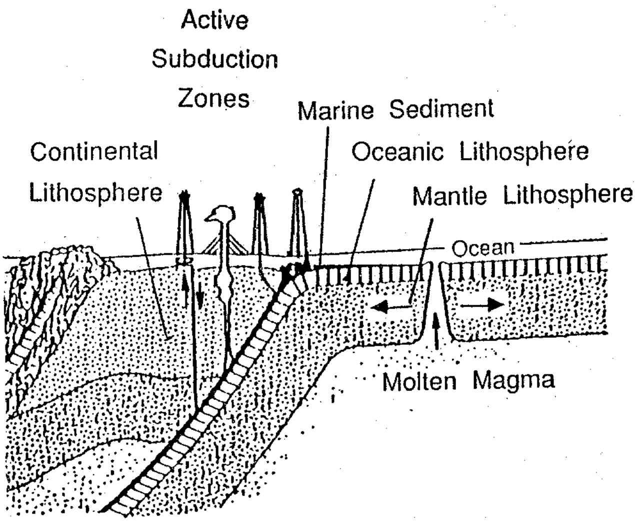

Fig. 3. Sketch of potential natural gas and petroleum deposits at an oceanic lithospheric plate subduction zone.

that 200 million km^3 of sediment has been subducted in the past 200 million years. These sediments contain approximately 1 wt.% carbon and if 0.1% of this carbon is converted to methane, then these reservoirs would contain 10^{16} m^3 (STP) of CH_4; consequently, the potential He-3 inventory in these subduction zone gases is about 1000 tonnes. The present geological epoch of subduction zones represents only a small fraction, ~ 4%, of the subduction zones which have been identified from past epochs. If the previous subduction zones contain similar gas mixtures as the present ones, then the total amount of He-3 in such gas wells may be as high as 25,000 tonnes.

C. Crustal, Sedimentary Gas Wells

Crustal gas and petroleum reservoirs have been formed by the decay of ancient flora and fauna buried within the earth which were subsequently subjected to both heat and pressure. In order to constitute a gas reservoir the methane formed had to be absorbed in a porous structure, such as sandstone, and the reservoir had to be capped by an impervious rock structure in order to prevent the escape of the gas. Such gas reservoirs are also capable of occluding He released from the radioactive decay of U and Th ores in the crust. The helium from such wells should have a He-3/He-4 ratio of 2 x 10^{-8} at. fraction, as previously noted, and is in agreement with the natural gas derived from fields in the United Kingdom and the North Sea.

In the USA, during the early 1900's the Hugoton natural gas fields in Kansas and Texas were discovered to contain high He contents, up to 8% in some wells, and the He-3 isotopic ratios were in the range of 0.1 to 0.2 at.ppm. The occurrence of the large amount He in this reservoir has never been adequately explained; however, the high He-3 content indicates that some primordial He seeped into this reservoir in a previous era.

For many years the Hugoton field was the only known source for He in the world and much of it was being lost as the natural gas was burned as fuel. Because of the increasing use of He and the apparent limited supply, the U.S. Government implemented the Helium Act of 1925 that instructed the Bureau of Mines to produce and sell helium to government agencies.[14] By 1960, an interagency study found that the existing helium program would not meet the future anticipated demand. As a result, the Helium Act was revised to permit the Bureau of Mines to purchase and store helium from private contractors. The Bureau of Mines entered into contracts with four producers and stored approximately 1.1 x 10^9 m^3 of He, containing ~ 30 kg of He-3, in the partially depleted Cliffside natural gas field near Amarillo, Texas. By 1967, the anticipated demand for He was less than predicted and the production by the private producers significantly exceeded the projected demand. As a result, the Secretary of the Interior terminated all purchasing contracts in 1973, and they have not been reinitiated. During 1987, private producers requested that the federal agencies should not be required to purchase helium solely from the Bureau of Mines which has had the effect of establishing a market price for this commodity.[15]

The Bureau of Mines estimates annually the reserves of helium contained in the natural gas wells of the USA.[16] These estimates increased nearly 230% from 1980 to 1982 as the newly discovered helium-bearing wells of the Riley Ridge field in Wyoming were added to the reserve. The Bureau of Mines classifies natural gas wells according to their helium content as: > 0.3, 0.29-0.10, and < 0.10 vol% He. In order to evaluate the total reserves of the U.S. the helium in proved and potential resources of natural gas must also be included. Potential natural gas resources are defined as: "probable" - supply associated with existing fields; "possible" - outside of existing fields but in similar productive formations; and "speculative" - undiscovered natural gas deposits that may occur in a favorable geological setting. The potential helium content in each of the natural gas reservoirs was combined with the estimates of the gas reservoirs, giving the potential He-3 reserves, Table 1. In addition to these North American reserves, some helium, 8 x 10^6 m^3/yr, is derived from natural gas wells in Poland and the USSR.

D. Atmospheric Helium

The earth's atmospheric helium budget represents a steady-state between the outgassing of helium derived from the earth plus several extraterrestrial sources and the escape of helium from the stratosphere.[8] The helium concentration in the atmosphere has been recently measured with high precision from samples collected at 12 locations in the USA,[17] giving a value of 5.2204 ± .0041 ppm (vol) and a He-3/He-4 isotopic ratio of 1.393×10^{-6}. When these values are combined with the weight of the total atmosphere the quantity of He-3 is calculated to be 4000 tonnes.

POTENTIAL PRODUCTION OF HE-3

Review of Table 1 indicates that potentially large quantities of He-3 exist in the terrestrial environment. On the other hand, Table 2 shows that the presently accessible He-3 is a dilute constituent of other gases. In most cases, the He-3 would be economically recovered only as a by-product during the utilization of the host gas. The present-day utilization of the host gases has been surveyed in order to determine their potential for He-3 production.

Table 2. He-3 Content of Various Terrestrial Gases

	Volume Fraction He-3
Atmosphere	7.3×10^{-12}
Helium-rich (> 0.3%) Natural Gas	$(4.2 \text{ to } 6.7) \times 10^{-10}$
Subduction Zone Natural Gas	$(1.4 \text{ to } 8.8) \times 10^{-10}$

The most direct source of He-3 would be to isotopically separate it from the helium sold by the Bureau of Mines. In 1987 the U.S. production capacity of helium totaled 76×10^6 m^3 (STP)/yr. The total He-3 in these gases, at an isotopic ratio of 0.2 ppm, would be ~ 2 kg/yr if it were separated at 100% efficiency. These sales increase slowly each year.

The atmospheric source of He-3 is large, well-mixed and available worldwide. Its potential production would probably be coupled with existing commercial plants for the liquefaction of air. In the USA during 1985, such plants produced 20×10^9 m^3 (STP) of nitrogen. Because of the low abundance of He-3 in air, the total He-3 production potential from this source would be only 20 g/yr. Worldwide such production would be < 0.1 kg/yr of He-3.

For potentially larger amounts of He-3, the utilization of natural gas must be considered. For instance in the USA during 1983, 500×10^9 m^3 of natural gas was used. Approximately, 4% of this gas came from wells containing an estimated 10^8 m^3 of helium, comprising ~ 3 kg of He-3; however, all of the helium was vented.

Local communities along the Western Rim of the Pacific Ocean are using natural gases derived from tectonic plate subduction zones which contain helium with high He-3 isotopic ratios. The production rates from these reservoirs has not been assessed for this report, but is probably small at this time, < 1 kg/yr of He-3.

DISCUSSION

The nuclear reaction in a d/He-3 fusion power plant produces 19 MW_tyr of thermal energy or 10 MW_tyr of electric energy per kg of He-3. In order to operate a reasonably sized fusion demonstration power plant, the operator would require several 10's of kg of He-3 per year.

The most readily accessible resource is the 30 kg of He-3 contained in the helium storage field of the U.S. Bureau of Mines. The assurance of a continuous supply of He-3 depends, however, upon an on-going program for the separation of helium from natural gas. If such a program were revived in the USA, ~ 6 kg of He-3 per year would be derived from all sources (Table 3). In order to increase the production of He-3, the proportion of the natural gas wells containing helium could be increased. More attractive, however, would be the utilization of new gas wells containing significant amounts of He-3, in order to supply new energy uses. For instance, the electrical power generation capacity in the USA is predicted to increase[18] by 20% by the year 2000. If all of the fuel for these plants were supplied by natural gas, containing

Table 3. Potential He-3 Production Scenarios

Separation from Various Gases	kg (He-3)/yr Present	kg (He-3)/yr By Year 2000
Helium in Storage	0	2
Helium Production	2	3
Natural Gas Usage(a) (USA)	3	15
Subduction Zone Gas Usage(a)	< 1	5
	6	25

(a) No helium is presently recovered from these sources.

high helium content and the He-3 were separated, an additional 12 kg/yr of He-3 would be available.

Similar new energy demands could also be considered worldwide by the increased use of natural gas containing He-3. For instance, locations along the Western Pacific which are sited near potential subduction zone gas wells could utilize or export the natural gas both as a fuel and as a source of He-3. As a result, up to 25 kg/yr of He-3 could be produced by the year 2000, supplying several d/He-3 fusion power demonstration plants worldwide (Table 3).

The substitution of natural gas for coal has been proposed as a means of reducing atmospheric effluents such as SO_2, CO_2 and particulate material. The combustion of methane produces 40% less CO_2 than coal for the same energy release. If the association between increased atmospheric CO_2 and the corresponding warming of the earth becomes more firmly established, then, such CO_2 reduction scenarios will be required.

In summary, this report has described several large, terrestrial resources of He-3. The rate of production of these reservoirs is tied closely, however, to the utilization of natural gas. A scenario to increase natural gas usage is suggested. The feasibility and cost of separation of the helium from the natural gas and the isotopic separation of the He-3 from the He-4, have not been discussed. Such studies are in progress and will be reported subsequently.

ACKNOWLEDGEMENT

Support provided by the Wisconsin Electric Utilities Research Foundation and Fusion Power Associates.

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