Transition to Environmentally Acceptable Fuels in the 21st Century

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Abstract

The D/^{3}He fusion fuel cycle merits consideration because of its benign environmental impact and the possibility of utilizing the large lunar ^{3}He resource in the 21st century. Preconceptual designs of low beta, low aspect ratio tokamaks have been studied. Sufficient terrestrial sources of ^{3}He are available to operate fusion research and power demonstration programs through the year 2020.

Introduction

One of the worldwide challenges in the 21st century will be to provide a safe and secure energy supply for the 9-10 billion anticipated inhabitants. This task is even more demanding when it is realized that the environmental impact of the present fossil fuels, namely coal, oil and natural gas, must be reduced rather than allowed to expand to meet the needs of the increasing population. Without this regard for the environment the air and water supplies in even the remote corners of the world will be adversely affected.

In order to meet these challenges, greater reliance will need to be placed upon safe and clean nuclear energy resources, both fission and fusion. The safe operation of well-designed nuclear fission electrical power plants has been demonstrated and their reliability will continue to be improved; however, the site selection for the storage of the radioactive fission products will be an on-going process. At this time nuclear fusion energy is in its infancy and its advocates are working diligently to develop its full potential while at the same time minimizing its environmental effects.

The worldwide fusion research community has concentrated on the development of the DT fuel cycle for a commercial power source. This fuel cycle has two significant disadvantages, namely (1) 80% of the energy released is in the form of energetic neutrons, and (2) there is a need to breed, control and contain the radioactive fuel, tritium. In a full size fusion power plant the tritium inventory could be 100 million curies and will require considerable safety features to contain this elusive gas. The 14 MeV neutrons will cause radiation damage in the structural materials nearest the plasma so that these components will need to be replaced routinely every 2-3 years. In addition, the neutrons cause nuclear transformations in the structural components and generate radioactive isotopes which must be safely contained in the event of an accident and buried in deep repositories at the end-of-life. Because of these detrimental aspects of the DT fuel cycle, alternative fusion fuel cycles are being considered.

The D/^{3}He fusion fuel has been considered as a safer and perhaps more economical fuel cycle. The fusion reaction, D + ^{3}He = p(14.7 MeV) + ^{4}He(3.7 MeV), involves neither a radioactive fuel nor fusion product. Some neutrons are produced by D-D side reactions but can be adjusted by the fuel mixture and temperature. The ignition temperature for this reaction is roughly 3 times and the $n\tau T$ product is ~ 10 times that for DT fuel. While these requirements are significant, it should be noted that $n\tau T$ values have increased in tokamaks by a factor of 20,000 during the past 20 years and that an additional factor of 10 may be achieved near the turn of the century in experimental confinement devices.

As a result of growing international environmental concerns and the potential availability of a large resource of ^{3}He, estimated at a million tonnes residing on the lunar surface, we have initiated a series of studies on D/^{3}He fueled tokamaks in order to determine their feasibility, economics and safety benefits. Our studies build upon previous studies of D/^{3}He fueled toroidal and mirror confinement systems, including papers presented at this conference. Some results of our reactor study, called Apollo [1], are presented in this paper as well as the near and long-term availability of ^{3}He fuel supplies.

Tokamak Design Study

The tokamak was chosen for study because it is the world's leading confinement concept. Design of a commercial D/^{3}He tokamak will require extrapolation from present day temperatures to $T \gtrsim 60$ keV and $n\tau$ values to $\sim 60 \times 10^{14}$ s·cm^{-3} Based upon this information the following decisions had to be made before the study could progress:

(a) Operational Beta Regime: The key features of the low beta (1st stability) and high beta (2nd stability) regimes are compared in Table 1. The low beta case was selected for the initial study.

(b) Power Output: 1200 MWe power was selected to be compatible with the ESECOM study [2].

(c) Magnetic Field: It was reasonably assumed that toroidal field coils up to 20 tesla would be available within the next decade.

(d) Neutron Wall Loading: The neutron wall loading was limited to 0.1 MW/m^2 so that all structural components would last the lifetime of the reactor, and result in low afterheat and low-level radioactive waste.

(e) Energy Conversion: Much of the thermal energy of the plasma is converted to synchrotron radiation. Rectennas are used to convert this radiation directly to electrical power. The utilization of the remaining thermal power for the generation of electrical power was decided ultimately on the basis of the cost of electricity.

Two cases were analyzed, namely (1) energy conversion by microwave and thermal energy conversion, and (2) microwave conversion only, both for 20 tesla magnets and 9% beta. In both cases the plasma current is very high, 60 and 80 MA, respectively, as well as the average ion temperature, 57 and 71 keV. The synchrotron power was increased from 1001 MW for the two-mode energy conversion to 1663 MW for the microwave only option. Although the net efficiency of the two-mode energy conversion case was 54% and only 41% for the microwave only case, the COE was actually lower for the latter case, e.g., 41.1 as compared to 43.7 mills/kWh. This surprising result indicates that the cost of the thermal energy conversion system is high compared to the additional electrical power it generates. This result could change based upon other assumptions, such as the cost of waste thermal energy rejection.

Table 1

Key Features of Low and High Aspect Ratio Tokamaks

Plasma Configuration	Main Advantages	Main Disadvantages
Low Beta (1st Stability) Low Aspect Ratio	• Builds on current world program	• High plasma current
	• High synchrotron fraction	• High magnetic field
High Beta (2nd Stability) High Aspect Ratio	• Low magnetic field	• Unconfirmed physics
	• Low plasma current	• Larger device
		• Low synchrotron fraction

Near-Term Fusion Power Development

In order to develop fusion power based upon a ^3He lunar mining enterprise by the middle of the 21st century, a transition period will be needed during which a significant quantity of terrestrial supplied ^3He will be required for fusion research and development. The potential electrical power generated by D/^3He is ~ 10 MWyr per kg of ^3He; hence, a resource of 10 kg/yr or more will be required for a reasonable sized power plant. The principal ^3He resource is associated with decay of tritium created in the nuclear weapons programs of the major military powers. In addition, the Ontario Hydro Electric Utility has commissioned a separation facility to remove tritium from the deuterated water used as a moderator in their CANDU nuclear power plants [3]. This facility is designed to separate ~ 2.4 kg/yr of tritium. After several years of operation, the accumulated tritium will decay to ^3He at a rate of 2-3 kg/yr. Current uses of ^3He consume ~ 1 kg per year, as a neutron absorber and for low temperature physics experiments.

A survey [4] of the terrestrial resources of ^3He, their inventories and potential production rates indicates that ^3He is associated as a dilute component of terrestrial gaseous reservoirs. Each of the natural resources has a characteristic $^3He/^4He$ isotopic ratio, which together with the helium content of the resource determines the size of the ^3He reserve. The content of ^3He in the atmosphere is 4,000 tonnes but recovery of the resource is judged to be infeasible compared to the recovery of ^3He from gas wells. The potential reserve in the U.S. crustal natural gas wells is ~ 0.7 tonne of ^3He while up to 25,000 tonnes may exist in the subduction zone gas wells, worldwide. Recovery of even a small percentage of this latter resource could provide adequate ^3He resources for decades. An even larger reservoir exists in the earth's mantle as indicated by gases emitting from volcanoes; however, exploratory studies to tap this resource have been unrewarding.

The most exploitable natural resource of ^3He thus appears to be natural gas wells containing fairly high concentrations of helium. Helium from gas wells in the U.S. was separated and stored at government expense between 1925 and 1973. Approximately 30 kg of ^3He can be recovered from this stored helium. Helium-rich gas wells in the U.S. contribute about 4% to the current U.S. production of natural gas and would yield about 3 to 4 kg of ^3He/yr if the helium were separated from the gas.

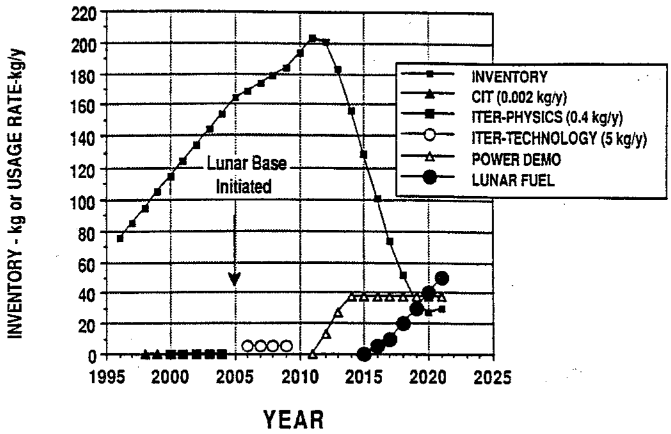

Figure 1. Terrestrial ^3He Availability During D/^3He Fusion Research and Power Demonstration Projects.

An assessment was made to determine if these terrestrial ^3He resources would be sufficient to develop a reliable D/^3He fusion reactor, Figure 1. For this assessment the ^3He stockpile was assumed to be 15 kg in the year 1990. This inventory for fusion research was assumed to increase at the constant rate of 10 kg/yr of ^3He from the combination of terrestrial resources described previously. The fusion reactor research schedule assumed the fueling with ^3He of the Compact Ignition Torus (CIT) beginning in 1998, with a D/^3He fusion power of 80 MW but very low availability, ~ 2500 s/yr. The CIT is followed in year 2000 by the start-up of the International Tokamak Experimental Reactor (ITER) which will need a Plasma Physics Experimental Program for about three years. With minor modifications to the ITER machine, which was designed for D/T fuel, the experiments may generate ~ 80 MW of fusion power in the D/^3He cycle [5] requiring ~ 0.4 kg/yr of ^3He. If these experiments are successful, the machine will be shut down for two years in order to make modifications required to optimize the D/^3He fuel. These modifications require increases in both the toroidal magnetic field strength and the current inductively coupled to the plasma. In addition, rectennas will be installed to test the concept of direct energy conversion and high heat flux components within the plasma chamber and the divertor will be tested for efficient thermal energy removal. The ITER machine in this phase will generate ~ 290 MW of fusion power [6], requiring ~ 5 kg/yr of ^3He at 30% availability for four years.

Following a successful program in the ITER device, a Power Demonstration Reactor (PDR) can be commissioned in the year 2011 to determine the economics of the D/^3He

fuel cycle for electrical power production at high annual availability. Such an aggressive schedule is possible because long-term development programs are not needed to determine the effects of high neutron fluences to reactor components or the need to develop reliable tritium breeders as required in the D/T fuel cycle. In this power demonstration mode the reactor will produce 1000 MW of fusion power and produce > 500 MWe because of the high efficiency of the direct energy conversion equipment. The stockpile of ^{3}He on-hand at the start of the PDR phase is sufficient for ~ 8 years of operation.

During the time scale of the fusion experimental programs, a permanently manned lunar base may be established [7] in the year 2005. This base could be gradually increased in manpower and equipment so that an industry for the collection of ^{3}He could be initiated by 2015. One kg of the lunar ^{3}He could arrive at the PDR by the year 2017 and increase yearly up to 30 kg/yr by 2021. The PDR could continue to operate indefinitely with this fuel supply, supplemented by the 10 kg/yr of ^{3}He from terrestrial resources.

Lunar ^{3}He Abundance

The current cosmological theories concerning nucleosynthesis of ^{3}He propose that it originated from two sources, namely, (1) formation during the first ten minutes following the "big-bang" creation event when ^{2}H, ^{3}He, ^{4}He and ^{7}Li were created, and (2) as a result of protium burning in the stars [8]. The primordial abundance of the ^{3}He/^{4}He ratio has been determined from astrophysical observation to be ~ 1.40 x 10^{-4}. This isotopic ratio probably existed in the pre-solar nebulae from which the planets of our solar system were formed, including our earth and moon.

This primordial ratio of ^{3}He/^{4}He has been modified by the accumulation of α-particles from the decay of U and Th and by the burning of protium in the sun's interior which produces ^{3}He and ^{4}He. This helium is emitted from the surface of the sun along magnetic field lines as a constituent of the solar wind. This solar wind has impinged upon the lunar surface for a period of ~ 4 billion years. It does not penetrate the atmosphere of the earth because of the geomagnetic magnetosphere which protects the earth.

During space flight probes beyond the earth's magnetosphere, the composition of the solar wind was analyzed. Although protons dominate this flux, the helium particles in the "wind," which travel at an average velocity of 450 km/s, have a flux of 6 x 10^{10} atom/m^2•s; containing a high ^{3}He/^{4}He ratio, ~ 480 appm. The high ^{3}He composition relative to the primordial composition is apparently due to the nuclear reaction D(p,γ)^{3}He, which occurs in the high gravitational field of the sun.

The lunar surface has been found to serve as a collector for the solar wind particles. Samples of lunar soil returned by the American Apollo astronauts and analyses by the Russian Luna probes confirm that the lunar soil contains helium with an isotopic ratio nearly that of the solar wind [8].

The characteristic of the lunar soil (regolith) that makes it an effective helium collector is its extremely fine grain size; over 80% by weight of the soil is between 8 to 125 μm. This fine grain size is due to constant meteorite 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 helium-to-soil-weight ratio. Also, the solar wind helium appears to be concentrated in ilmenite granules, a $FeTiO_3$ ore that comprises up to 10% of the maria soils. To calculate the potential quantity of lunar ^{3}He, an average ^{4}He concentration of 30 ppm was taken for the maria surface to a depth of 5 m, and an average ^{4}He concentration of 7 ppm was taken for the highland regions to a depth of 10 m. The lunar surface, 38 x 10^6 km^2, was assumed to be 20% maria and 80% highlands. The potential ^{3}He associated with the lunar surface soil is therefore conservatively estimated as 1.1 x 10^9 kg. This inventory represents < 1% of the ^{3}He that has impacted the lunar surface for the past 4 billion years (assuming a constant solar wind).

Lunar Mobile Miner: The average maria regolith contains ~ 10 mg ^{3}He per tonne of soil (mass ratio ~ 10^{-8}); consequently, a large amount of soil must be processed to obtain a significant quantity of ^{3}He [9]. For this reason a mobile miner [10] has been proposed which would excavate the regolith to a depth of 3 m, by means of a bucketwheel excavator, beneficiating the soil to retain < 50 μm particles and then heating the soil in an enclosed oven to liberate the solar wind gases. The collected gases would be sent to a central processing facility and the spent regolith would be ejected from the rear of the miner. The miner would excavate a trench 11 m wide at a forward speed of 23 m/hr, excavating 1260 tonnes/hr. One miner, operating only during the lunar daylight, would cover an area of 1 km^2/yr and produce ~ 33 kg/yr of ^3He.

Gas Evolution: The beneficiated soil of < 50 μm size range contains ~ 80% of the He in the bulk soil although its weight is reduced by 55%. It is delivered to the vacuum degassing furnace for heating to ~ 700°C where ≥ 80% of the He is evolved. During the lunar daylight hours solar energy is utilized for the thermal power requirements. With an estimated heat capacity of 1.0 kJ/°C·kg, the total thermal power required is 4.5 x 10^4 GJ/kg of ^3He. After degassing the soil, nearly 85% of this thermal energy is captured to preheat the next batch so that the solar collectors need to supply only 12.3 MW of thermal power.

Isotopic Separation: It will be necessary to separate ^3He from the helium recovered from the lunar regolith. A combination of "superleak" separation and cryogenic distillation, both of which require liquefying the entire quantity of recovered helium, is suggested. This requirement coincides with the need to liquefy the helium for transportation. Superleak separation utilizes the unique property of ^4He that it has a negligible viscosity at temperatures below 2.1 K allowing it to pass through channels that block all other liquids. The ^4He can thus be separated from a liquid mixture of ^3He and ^4He by a very fine filter such as tightly packed jeweller's rouge. This method works well up to a few percent ^3He in ^4He, after which the partially enriched ^3He is better enriched by cryogenic distillation. Enrichments of 99.99% ^3He are readily obtained in this manner. This separation can be conducted on the lunar surface or on earth, depending upon the need for the ^4He.

Transportation: An unmanned earth/moon transportation vehicle of the same size as the present space shuttle is capable of transporting a payload of 20 tonnes of liquid ^3He. This amount of ^3He when delivered to earth and used in a D/^3He fusion reactor could supply the present annual use of electrical power for the U.S. In the early stages of lunar helium mining, the ^3He could be shipped as part of other earth/moon payloads or the unseparated helium could be shipped for terrestrial use of both the ^3He and ^4He.

Conclusions

(1) The major attraction of the D/^3He fuel cycle is the reduction in number of neutrons/unit of energy released.

(2) The D/^3He fuel cycle provides a low number of neutrons, high power conversion efficiency, and inherently safe fusion power.

(3) The lunar ^3He resource is sufficient for 5000 years of the projected world energy usage.

(4) Sufficient terrestrial ^3He sources exist to span the period from present research facilities to operation of the first power plant.

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