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ABSTRACT

The need to find safe, clean, and affordable energy for use on the Earth and in Space in the 21st century has driven scientists and engineers to consider innovative sources. One of the most attractive long-range sources is fusion energy and it is shown that the D^{3}He or ^{3}He^{3}He fuel cycles have great advantages over those presently pursued. An experimental demonstration of a steady-state D^{3}He fusion plasma is discussed along with one approach to bridge the gap between present day research and large-scale deployment of fusion power plants. Economically, the development of the lunar ^{3}He resources will have a great influence on the ability of future generations to explore our Solar System as well as to maintain a quality life on the Earth.

INTRODUCTION

One of the greatest challenges facing society in the 21st century is the development of a safe, environmentally friendly, economical, and long lasting supply of energy. This need is driven by the expected doubling of the World's population in the next 50 years [1], and the drive for the under-developed nations of the Earth to improve their standard of living. Increased energy needs in 2050, of perhaps two to three times the present demand (Figure 1) will severely strain the existing fossil fuel resources and could result in unacceptable modification of the weather through the so-called greenhouse gas effect. Furthermore, regional imbalances in fossil energy reserves between nations could result in political instabilities that might even provoke armed confrontations as governments try to satisfy the aspirations of their citizens.

Many solutions have been proposed to address this coming crisis but one scenario that can meet all of the criteria outlined above is the expanded use of nuclear energy. This option now is used to provide ≈ 20% of the world's electricity from fission reactors [2] and could provide even more if the problems of public acceptance could be overcome. If the fission option is not pursued in the future, the use of fusion to provide electricity [3] and/or liquid and gaseous fuels through a coupling with the production of hydrogen has been proposed [4].

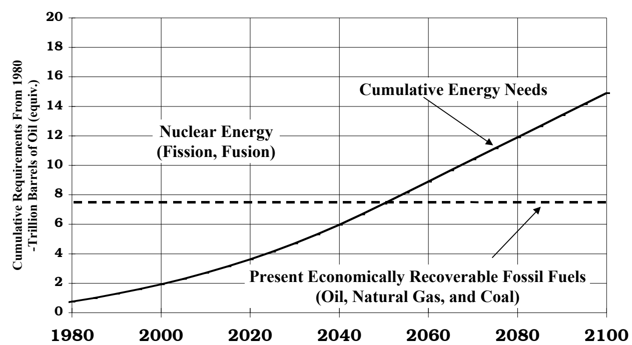

Figure 1. The expected demand for energy in 2050 will exceed the current estimate of the World's economically recoverable reserves of oil, natural gas, and coal by the middle of the 21st century. While new reserves will undoubtedly be added in the next 50 years, sometime in the next 100 years the World will have to turn to other, non-carbon based fuels to support the expected 10-12 billion people at today's, or slightly higher, standards of living. Nuclear energy, either in the form of fission or fusion, could supply that energy.

While the use of fusion energy has many attractive features over those of the fission option, it still suffers from the effects of handling large numbers of neutrons [80% of the energy released in the deuterium (D) tritium (T) fusion reaction comes in the form of neutrons, see Table 1]. The neutrons cause considerable amounts of radioactive waste to be formed and the unavoidable radiation damage to the structural components can greatly reduce the operating performance and safety attributes of fusion.

Fortunately, it was recognized nearly 40 years ago that many of the disadvantages of the DT fusion cycle could be ameliorated by the use of the D-^{3}He cycle [5]. Although this fuel cycle requires higher operating temperatures and better confinement properties than the DT cycle, the great reduction in the number of neutrons more than offsets those disadvantages. Only ≈ 1-5% of the energy of the D-^{3}He reaction comes from neutrons (stemming from side DD reactions) and there are no neutrons whatsoever emitted in the ^{3}He-^{3}He reaction (Table 1).

Fusion Fuel	**Fusion Reaction Products**	**T @ Peak Plasma Power Density-keV**	**Approx. % Energy Released in Neutrons**
D and T	neutrons and ^{4}He	14	80
D and D	neutrons, T, ^{3}He and ^{4}He	16	50
D and ^{3}He	H and ^{4}He	58	1-5
^{3}He and ^{3}He	H and ^{4}He	≈200	none

Table 1. The description of fusion reactor fuels can be broken up into the first-generation (DT and DD), second-generation (D^{3}He) and third-generation (^{3}He-^{3}He) fuels. The second- and third-generation ^{3}He fuels represent the ultimate future of fusion energy because of the low level of neutron production.

While scientists are currently developing methods to effectively "burn" the second- and third-generation fuels; the problem of the source of ^{3}He reserves has become an issue. Note that it takes ≈ 1 tonne of ^{3}He to produce 10,000 MW_e-y from a second-generation fusion power plant. The only known terrestrial reserves of ^{3}He are associated with the decay of tritium in thermonuclear weapons and those reserves are only 100-200 kg [6].

Fortunately, it was recognized in 1986 that there were enormous supplies (≈ 1,000,000 metric tonnes) of ^{3}He on the Moon and that the methods to extract and transport this valuable resource to the Earth exist today [6]. On the other hand, it will be some time before the ultimate second or third generation fusion power plants are built and tested. This realization has led scientists and engineers at the University of Wisconsin to address the possibilities of earlier uses for ^{3}He. It is the purpose of this paper to address those nearer term applications and suggest a development path to the ultimate realization of clean, safe, and economical fusion energy in the 21st century.

ONE EXAMPLE OF A NEAR TERM APPLICATION OF D^{3}HE FUSION

To answer the question "What does the D^{3}He fusion reaction produce that might be of value even though net energy is not produced?" one has to examine the nuclear reaction in more detail:

$$^{2}H + ^{3}He \rightarrow ^{1}H\ (14.7\ MeV) + ^{4}He\ (3.7\ MeV) \qquad (1)$$

The reaction products include a 14.7 MeV proton and a 3.7 MeV helium atom. The most valuable product appears to be the 14.7 MeV proton that can react with a variety of elements to produce valuable diagnostic or therapeutic medical isotopes [7-10]. While no immediately economic applications of the 3.7 MeV alpha particle have been identified at this time, one should not rule out future uses.

Within the emerging field of medical isotopes the use of positron emission tomography (PET) appears to be one of the most attractive. The demand for PET isotopes has been exploding in the past 10 years and now is approaching the $100 million per year level [11]. This technique relies on the fact that these isotopes emit positrons which, when combined with local electrons, release two 0.511 MeV gamma rays. Using coincidence-counting techniques, one can uniquely identify the location at which the PET isotopes are located. When the PET isotopes are attached to molecules that are preferentially attracted to certain organs or abnormalities (e.g., cancers) in humans, an accurate map of the target can be obtained.

Two features of the PET applications are particularly important to the use of the D^{3}He fusion fuel cycle:

1) PET isotopes are usually formed by (p, n) reactions on the parent isotope. The energy at which these reactions take place is in the 10-20 MeV range. Such high-energy protons can be produced in a high-energy proton accelerator or a D^{3}He fusion reaction (see Eq. 1).

2) To reduce the radiation exposure to the patient, short half-life PET isotopes are used. However, there is a conflict between the efficiency associated with PET isotope production in an accelerator facility and the need to have the patient close to the accelerator so that the short-lived isotopes do not

decay away before they can be delivered. If a small, portable D^3He device can be made, then the geographical area that can be served will greatly expand allowing more people to profit from such a PET analysis.

Recognizing the implications of the features above, scientists and engineers at the University of Wisconsin began to develop a fusion device, based on the D^3He fuel cycle, about five years ago [12-13]. In the next section, we will discuss the progress of that research.

CURRENT EXPERIMENTAL DEMONSTRATION OF THE D^3He FUSION FUEL CYCLE

For reasons outlined in previous papers, we have chosen to demonstrate the usefulness of the D^3He fusion fuel cycle in a device that relies on electrostatic confinement of the plasma as opposed to the traditional electromagnetic or inertial confinement schemes. This is not a new concept; the inertial electrostatic confinement (IEC) device was first proposed by Farnsworth [14], the inventor of television. The operation of an IEC device with DD and DT was first demonstrated by Hirsch [15]. Because of the higher energies needed to cause the D and ^3He to fuse, this concept is much more effective at providing high-energy ions than the tokamak or laser driven devices around the world that utilize the DT fuel.

A schematic of the Wisconsin IEC facility [16] is shown in Figure 2 and a photo of the device operating at steady state is given in Figure 3. The basic idea of this approach is to surround an inner cathode charged to a negative potential of 50 kV or more with a larger spherical mesh globe that is positively charged. By mechanisms described elsewhere [16-17], positively charged fuel ions are formed around the outer grid and accelerated inward by the large negative potential. When the inward streaming ions meet energetic ions from the opposite direction they can fuse, releasing energy or scatter and "climb" the potential hill on the other side and return to the center of the device. Obviously, the deeper the potential-well, the higher the energy of the colliding ions and the higher the fusion rate.

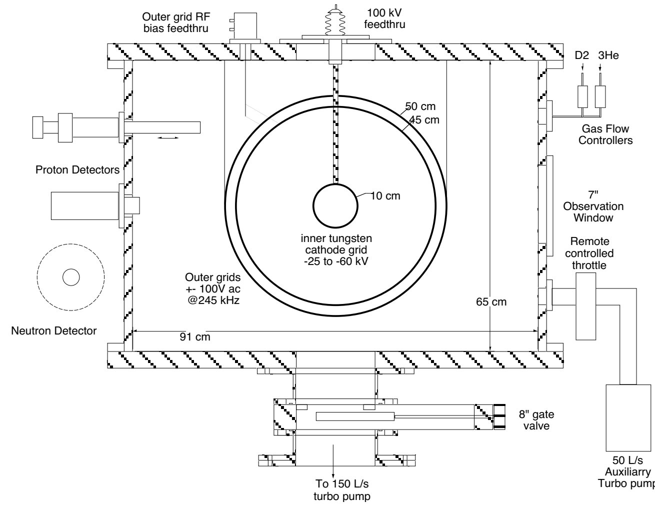

Figure 2. A schematic of the University of Wisconsin IEC device [16] shows the 10-cm diameter inner cathode surrounded by a 50-cm diameter anode. The inner cathode is negatively charged up to 75 kV which attracts the positively charged D^+ and $^3He^+$ (and $^3He^{++}$) formed at the anode by energetic electrons.

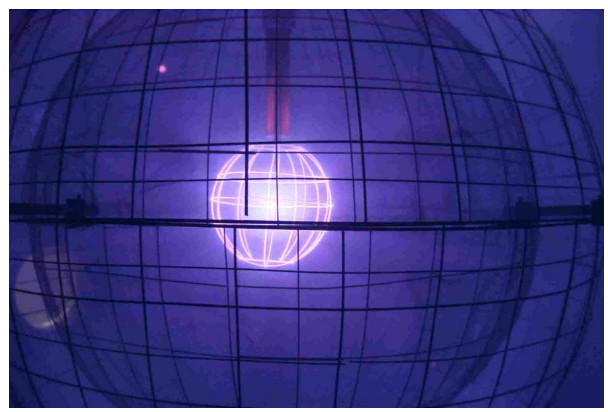

Figure 3. Photograph of a D-^3He plasma in the center of the Wisconsin IEC device. Currently fusion rates of nearly 3 x 10^6 per second at 55 kV and 60 mA current have been achieved.

Initially, the IEC device at Wisconsin was used to study the physics associated with electrostatic confinement. In those studies a DD fuel was used and steady-state fusion reaction rates of $\approx$ 1 x 10^8 per second have been produced to date [16]. In late 1998, our attention switched to the D^3He cycle and an example of the progress made over the past two years is shown in Figure 4. The steady-state reaction rate has been increased nearly by a factor of 1,000 over that time. Use of higher accelerating potentials and more efficient cathode design should boost the fusion rate to levels where PET isotopes such as ^{15}O and ^{18}F can be made for commercial distribution [7-10]. It is hoped that the experience gained with the near-term devices will lead us into the next phase where electricity production can be investigated.

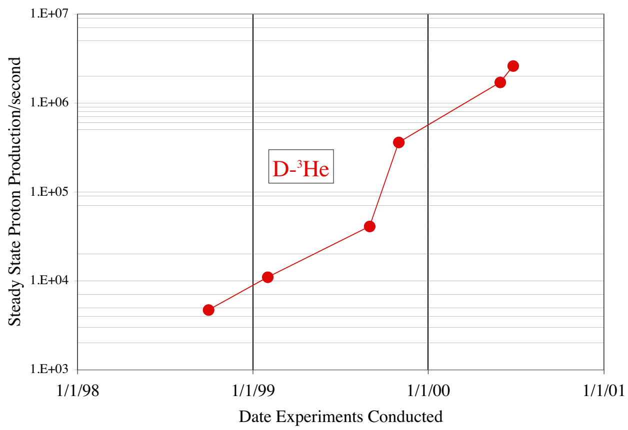

Figure 4. Progress in the steady-state production of D^3He fusion has been rapid as more is learned about the physics of IEC plasmas.

FUTURE APPLICATIONS OF ^{3}He BASED FUSION CYCLES

The ultimate goal of the fusion research programs around the world is to provide a source of electricity that can meet the clean, affordable and long lasting criteria discussed earlier. The question that is often asked of this program is "How does one get from the research phase into a working power plant?" Scientists and engineers around the world have performed many fusion power plant studies over the past 30 years [18-20], however, the path between the near-term research and ultimate use is not so clearly portrayed. Fortunately, there appears to be a path between the present and the future for the use of second-generation fuels. A schematic of one such approach is displayed in Figure 5. This figure summarizes a three-phase plan that could lead to the utilization of second and third generation fusion fuels for the benefit of the society. The first phase envisions near-term commercial applications of fusion products even when much more energy is put into the device than could be extracted in the form of useful energy (i.e., the ratio of output energy to input energy, Q, is << 1.) The second phase occurs shortly after breakeven (Q = 1) is achieved and where small fusion devices could compete in environments where traditional energy sources cannot be used (e.g., space power, remote electric stations in the Antarctic, etc.). The third stage would begin after operating experience was gained with smaller fusion power sources and ^{3}He sources are well developed for space propulsion [21-22] or other high Q operation.

Phase 1 – Near-Term Applications, Q << 1
- Medical Isotopes
- Environmental Restoration
- National Defense

Phase 2 – Unique Applications, Q = 1-5
- All of Phase 1
- Space Power
- Remote Electricity Stations

Phase 3 – Major Energy Source, Q > 10
- All of Phases 1 and 2
- Clean, Safe and Economical Electric Power Plants
- Production of Hydrogen
- Space Propulsion

Figure 5. The development of the right fusion concept should lead to near-term as well as long-term benefits to society.

ECONOMIC VALUE OF LUNAR ^{3}He RESOURCES

A rough measure of the economic value of ^{3}He to society can be obtained by calculating its energy equivalence. Assuming the thermal and kinetic energy released by the D-^{3}He reaction can be converted directly to electricity at 60% (by direct electrostatic conversion), then the energy in one tonne of ^{3}He, burned with 0.67 tonnes of deuterium, can produce ≈ 10,000 MW_e-y. To produce the same amount of electricity with oil (at a conversion efficiency of 40%) would require over 130,000,000 barrels of oil. If a barrel of oil costs $20, than 1 tonne of ^{3}He is worth ≈ $2.6 billion (or about $1 million per pound). This number can be scaled up or down depending on the current cost of energy but the point remains that ^{3}He is perhaps the only material on the Moon, or for that matter in Space, that could justify the cost to bring it to the Earth.

How much ^{3}He would be needed on the Earth? In 1999, the United States alone generated ≈ 420,000 MW_ey of electricity [23]. This amount of electricity could have been generated by ≈ 40 tonnes of ^{3}He (worth ~$100 billion). Since the U.S. generates roughly one quarter of the world's electricity now, the maximum demand for the Earth could be in the range of several hundred tonnes/year.

It has also been observed that the byproducts from the mining of ^{3}He can have a significant influence on the support of life in space and could drastically reduce the cost of space settlements [24-25]. It has been shown that for every tonne of ^{3}He mined, significant amounts of hydrogen, water, nitrogen and carbon compounds are formed. A partial list of those important elements and compounds is given in Table 2. Clearly, the ^{3}He mine of the future could provide the basic ingredients for growing food, as well as providing for the water needs of thousands of people on the Moon [26]. There would even be enough left to supply missions to other parts of the solar system and the Moon could easily become the "Hudson Bay store" of Space.

Element or Compound	Tonnes of Product per Tonne of ^{3}He Produced
Hydrogen	6,100
Water	3,300
Nitrogen	500
Carbon Dioxide	1,700
Carbon Monoxide	1,900
Methane	1,600
Helium-3	1
Helium-4	3,100

Table 2. There are over 18,000 tonnes of valuable life support materials produced for every tonne of ^{3}He mined from the Moon [6, 24].

A final observation can be made as to where ^{3}He resources might fit in the long-range picture of in-situ resource utilization. Previous analyses at the University of Wisconsin have assessed how the resources from the Moon might affect future generations as they push out into space. The conclusions are summarized in Table 3.

The lunar resources are divided into energy and all others for the sake of discussion. It is clear from the preceding discussion that ^{3}He can provide an important energy source on Earth in the 21st century. It is also recognized that solar energy collected on the Moon can be converted to microwaves and sent to the Earth for electrical generation [27]. Both of these energy sources are suitable for use in orbiting space stations as well as on the Moon itself. In addition, the H_2 and O_2 byproducts of ^{3}He generation will be very useful in fuel cells.

There is probably no other lunar resource that could be profitably used on Earth (except for souvenirs). However, the volatile byproducts of ^{3}He mining will be invaluable for life support in Space as well as on the Moon. The metals (Fe, Ti, Al, etc.) can be used for a variety of structural, electrical, and manufacturing purposes. Finally, the regolith will be important as radiation shielding materials to guard against solar and cosmic radiation.

	Energy	**Volatiles, Metals, and Minerals**
On the Earth	• ^{3}He • Microwaves from solar power	• Probably none
In Space	• ^{3}He • Microwaves from solar power • H_2-O_2 fuel cells	• Volatiles (H_2, N_2, O_2, H_2O, CO_2) • Al, Fe, Ti, etc. • Regolith
On the Moon	• ^{3}He • Solar Energy • H_2-O_2 fuel cells	• Volatiles (H_2, N_2, O_2, H_2O, CO_2) • Al, Fe, Ti, etc. • Regolith

Table 3. Lunar resources can have a major impact on future generations regardless of their location in the Solar System

CONCLUSIONS

The use of ^{3}He from the lunar surface can ameliorate future energy shortages or environmental disasters on the Earth if this valuable isotope is used in second or third-generation fusion power plants. Even before net generation of electricity is demonstrated, near term applications of D^{3}He fusion can be used to generate capital for R&D into larger systems and provide a valuable product to the medical community. The economic attraction of ^{3}He is so large that it is, so far, the only known material in space that could be transported to the Earth for profit.

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