New Opportunities for Fusion in the 21st Century – Advanced Fuels

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ABSTRACT

It is shown that the long-range goal of the world fusion program can be to generate energy without long-lived radioactive waste and the associated safety problems that accompany today's nuclear power sources. This can ultimately be accomplished through the ^{3}He-based fusion fuel cycles. This paper compares ^{3}He-based fusion fuels with first-generation, D-based fusion fuels and fission. Potential applications of ^{3}He fusion to radioisotope generation, proliferation-resistant electrical power plants, and space propulsion are also discussed.

I. INTRODUCTION

As we move into the 21st century, the need for clean, safe, and economically attractive energy sources becomes more apparent with each passing day. Limits to the long-term use and/or availability of fossil fuels are evident in greenhouse gas accumulations, price fluctuations, and regional tensions. The growth of hydroelectric sources appears to be slowing and energy produced from the fission process has peaked or is stagnant in many of the major energy consuming nations of the world. The development of renewable energy sources such as wind and solar has been promising in many localized areas around the Earth. However, the intermittent nature of renewables and the sheer magnitude of the demands from an increasingly urban society make these sources impractical for more than a small fraction of the global energy needs. Many scientists and engineers have pointed to nuclear fusion as the long-range answer to the world's energy needs. For fusion energy to play a major role, one has to ask the following question, "Why would society support fusion over other options that may be available in the 21st century?"

II. CURRENT VISION OF FUSION POWER PLANTS

The development of fusion energy over the past 50 years has produced some dramatic successes in the area of plasma physics but the progress in the area of commercialization has been disappointingly slow.[1] Scientists are very close to demonstrating energy breakeven conditions in one of the first generation fusion fuel cycles (Eq. 1a), deuterium (D) and tritium (T).[2] The other first generation fuel cycle (DD, Eq. 1b) will require more demanding confinement conditions before it can achieve breakeven.

First Generation

$$D + T \rightarrow {}^0n\ (14.1\ MeV) + {}^4He\ (3.5\ MeV) \qquad (1a)$$

$$D + D \rightarrow {}^0n\ (2.5\ MeV) + {}^3He\ (0.8\ MeV) \quad 50\% \qquad (1b)$$
$$\rightarrow {}^1H\ (3\ MeV) + T\ (1\ MeV) \quad 50\%$$

However, there are huge technological challenges that remain to be addressed before a commercial power plant can even be considered. The fact that 80% of the energy released in the DT reaction (and ~2/3 the energy in the DD reaction) is in the form of neutrons raises a whole host of problems related to neutron damage, radioactive waste, and safety. While it is generally accepted that DT fusion systems should be able to demonstrate energy breakeven, or even a significant gain in the near future, that milestone alone is a long way from demonstrating an economical source of electricity. What remains to be shown is that an integrated power system can be built that solves the public concerns over long-term storage of large amounts of radioactive waste, potential proliferation issues, and public fears of potential releases of radioactivity.

III. A 21st CENTURY VISION OF FUSION

In the long run, we will have to move past first-generation fusion fuels onto the second-generation (D^3He) or even third-generation ($^3He^3He$) fuels such as those shown in Equations 2 and 3 respectively. In this paper, we will discuss only $^3He^3He$ as a third-generation fuel, even though other candidates exist (e.g., $p^{11}B$ and p^6Li), because side or secondary reactions in the other fuels lead to neutron production ($p + {}^{11}B \rightarrow n + {}^{11}C$, ${}^4He + {}^{11}B \rightarrow n + {}^{14}N$, several ${}^6Li + {}^6Li$ reactions, etc.) Finally, we will also limit our analysis to magnetically or electrostatically confined plasmas and not consider inertially confined systems at this time.

Second Generation

$$D + {}^3He \rightarrow p\ (14.7\ MeV) + {}^4He\ (3.7\ MeV) \quad (2)$$

Third Generation

$${}^3He + {}^3He \rightarrow {}^1H + {}^1H + {}^4He\ \ (total\ 12.9\ MeV) \quad (3)$$

On the surface, the reactions in Equations 2 and 3 avoid the production of neutrons or any radioactive atoms. However, in the D^3He plasma, some of the D atoms will fuse with other D atoms, thus producing a small amount of neutrons (Eq. 1b) and tritium. Previous studies[3-12] have shown that the energy carried by the neutrons can amount to 1-5% depending on the confinement approach and fuel mixture (i.e., $^3He/D$ ratio) as shown in Figure 1 for a Maxwellian plasma. The higher $^3He/D$ ratios require higher magnetic fields and better confinement to compensate for reduced power density. This level of reduction can make the difference between a 1-2 full power year (FPY) life of DT reactor first walls or a full reactor life for materials in a D^3He power plant.[1, 6-9] The use of the second-generation fuel may also make the design of a proliferation resistant reactor possible,[13] it greatly reduces the volume and level of nuclear waste, and it substantially reduces the radioactive inventory in the reactor itself.[6-8, 13]

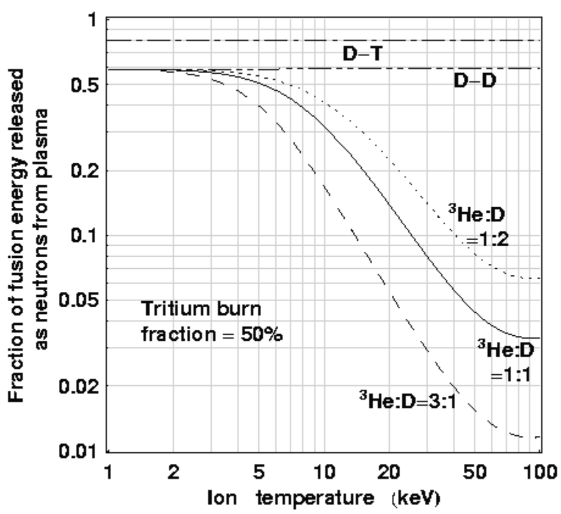

Figure 1. Neutron power fraction for D-T, D-D, and D-^3He fuels in Maxwellian plasmas. Several ratios of ^3He to D density are shown, and burnup of 50% of the D-D produced T is assumed. No blanket multiplication included.

In a limited paper such as this, one cannot develop all the metrics that would allow a quantitative comparison to be made between fission and fusion nuclear power systems. Therefore, an attempt is made in Figure 2 to present a qualitative assessment of concerns about the use of fission energy versus the use of four different fusion fuel cycles. The darker the shading, the more serious the problem is or the harder it is to solve the problem. For example, it is well known that the public has major concerns about the misuse of civilian fission power plants to make weapons grade material. The neutrons generated in the fission process also degrade the ability of the cladding and other structural components to completely isolate the fuel from the coolant and the rest of the power cycle. In addition, the fission process itself generates long-lived radioactive waste and the neutrons from the fission process contribute to that inventory. In the event of an accident, there is legitimate concern about the release of radioactivity into the environment. There is very little tritium in a fission plant (CANDU reactors being the exception) and the physics of a power plant is well established and predictable.

If a DT fusion power plant is used to generate the electricity, the proliferation concerns are reduced but not eliminated. There are four times more neutrons emitted per MeV from DT fusion than from a fission plant. The radiation damage problem is in fact worse in a DT fusion plant because the higher energy neutrons promote more gaseous transmutation products that can embrittle the structural materials. One advantage for fusion compared to fission is that one can choose materials that have shorter half-lives. The generally shorter half-lives not only reduce the difficulty of storing the waste, but because most of the radioactivity is in the solid structural materials, the safety issues associated with the release of isotopes in an accident presents less of a problem. One countervailing factor is that the DT cycle may have as much as 10 kg of highly volatile tritium in the power cycle that could be released in the event of an accident. This is much more tritium than is present in a fission plant. Conversely, the case can be made that the physics requirements for DT confinement are relatively easier than the other fuel cycles (Sec. IV discussion). Finally, because of the need to obtain ^3He from the Lunar surface, the fuel cycle (including resources) would be considered more difficult for the ^3He cycle fuels. The deuterium could easily be obtained from sea water, and the U and Li from terrestrial mines. The requirement for enrichment of U for fission reactors (or the use of processed Pu) and the need to handle liquid Li or other alloys and compounds of Li in order to breed tritium make these fuel cycles more difficult than the DD cycle.

Switching to the DD cycle reduces the radiation damage problem from the 14 MeV neutrons but that cycle does not eliminate the problem because 2.5 MeV neutrons are still quite damaging. The fact that less energy is released per fusion in DD means that there are actually ~3 times more neutrons emitted per MeV in the DD cycle when compared to a DT cycle (or 12 times the number emitted from a fission reactor). The fact that tritium breeding is not required for the DD cycle is

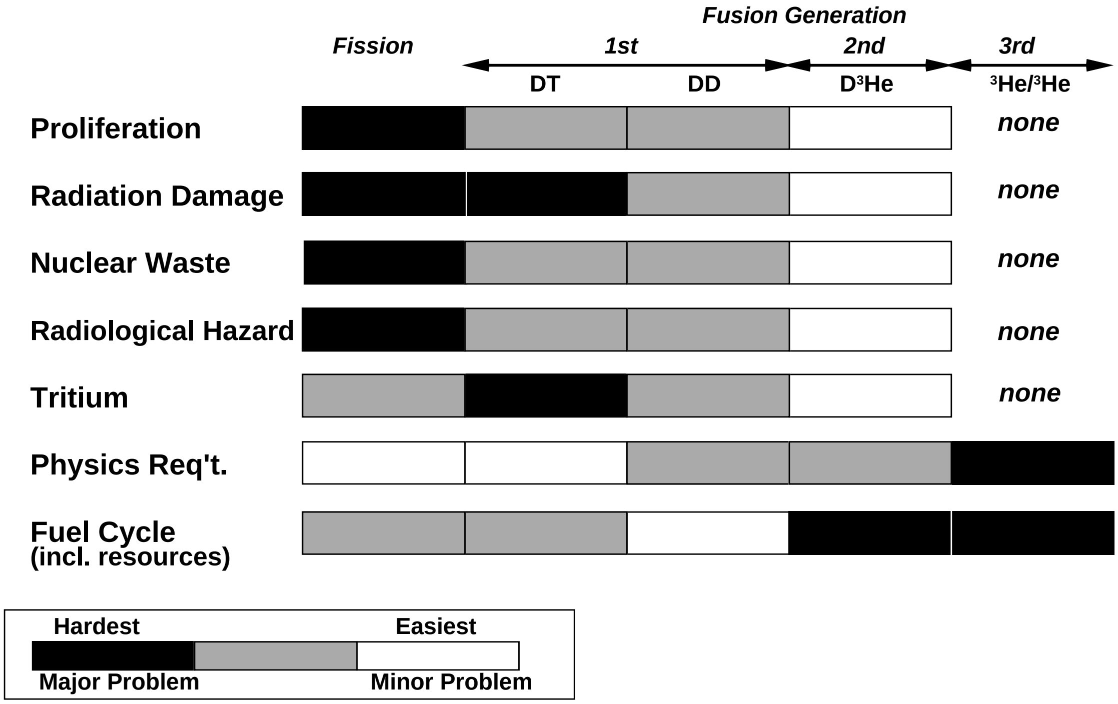

Figure 2. It is clear that a transition from current fission reactors to future first-, second-, and third-generation fusion fuels will greatly alleviate, or even eliminate, some of the most serious concerns over nuclear power. However, these gains are purchased at the cost of solving more difficult plasma physics confinement problems.

countered by the fact that 50% of the DD reactions produce a tritium atom which is either burned up in the plasma (thereby exacerbating the radiation damage problem) or removed and stored somewhere. On the physics side, the required energy and confinement conditions are clearly more demanding for DD than DT (Figure 3).

The low neutron production rate in the D^3He cycle potentially removes the cycle from being a proliferation risk. However, even 1-5% of the energy in neutrons will cause some radiation damage and radioactivity in the surrounding structures. Also, a small amount of tritium will be generated by side DD reactions. The physics requirements for D^3He will be somewhat easier than those for a DD plasma.

If we can eventually control the $^3He^3He$ cycle, the proliferation, radiation damage, nuclear waste, safety, and tritium concerns will be essentially eliminated. However, as shown later in Figure 3, the physics and fuel cycle issues are much harder to solve than for the other three fuel cycles.

IV. BARRIERS TO A MORE ATTRACTIVE FUTURE FOR NUCLEAR FUSION

As one might expect, the enormous promise of the second- and third-generation fuels carries a large price tag. In this case there are two “price tags”, one related to physics and the other to resources. With respect to the first challenge, both the second- and third-generation fuels require higher plasma temperatures and better confinement conditions than the DT cycle. Figure 3 indicates the key physics difficulty faced by the advanced fuels: the charged-particle reactivity, which mainly sustains the plasma, peaks at a lower reactivity and higher plasma temperature than does DT fuel. The higher temperature typically requires better energy confinement in Maxwellian plasmas. It also, along with the higher Z (thus more electrons for plasma neutrality) of advanced fuels, requires good impurity control and higher plasma pressures for the same ion density. Therefore, to maintain the same plasma pressure, advanced fuels probably must be burned in high-beta devices, so that power density can be regained by raising the magnetic field. Fortunately, research into innovative fusion concepts such as the field-reversed configuration, spheromak, spherical torus, and reversed-field pinch have recently shown great progress.[13] DT fusion cores typically reach neutron wall load constraints long before

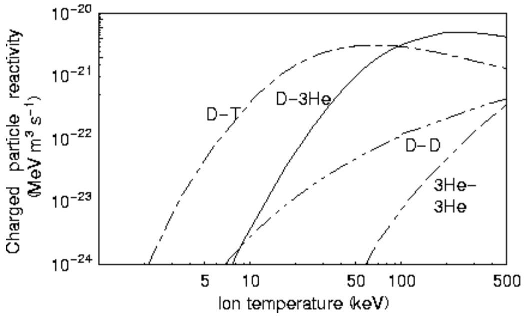

Figure 3. Charged-particle reactivity, $E_Q<\sigma v>$, for selected fusion fuels.

they can take advantage of the full power-density capability of high-beta devices.[13-14] Other concepts, such as inertial electrostatic confinement (IEC) also show promise.[15-16] Achieving the higher energies will not be easy for the ^{3}He-based fuels, but the payoff is so great, the effort is well worth the return.

The great progress of fusion plasma performance must continue for the advanced fuels to become viable, but the progress so far instills confidence that the necessary performance will be achieved.[17] Furthermore, the reduced neutron production of advanced fuels will relax many engineering constraints, and the successful development of high-beta concepts, such as the field-reversed configuration or spherical torus, would allow high-power density D^{3}He operation.[13-14] Fusion development looked at as a whole—balancing physics, engineering, environment, and safety aspects—may in fact require advanced fuels in order to break into the marketplace and could quite possibly leapfrog first-generation fusion fuels altogether. Although prudence dictates continuing the present DT-based fusion research program, the promise of second- and third-generation fuels certainly motivates their active investigation.

The second issue of the ^{3}He based fuel cycles is related to the world reserves of ^{3}He. Currently, most of the ^{3}He reserves come from the decay of tritium used in the U.S. and Russian nuclear weapons programs, or from tritium generated by CANDU reactors in Canada.[18-19] The exact amount is unknown but can be estimated to be on the order of a few 100 kg. Breeding of ^{3}He using DD or other fuels has been investigated for many years[20-21] usually combining a ^{3}He breeder with a "satellite" power plant burning the ^{3}He. The difficulty with such schemes is that the breeder reactor is non-economic and produces substantial neutron-induced radioactivity, plus large quantities of tritium typically must be stored until it decays to ^{3}He, thereby mitigating key advantages of D-^{3}He fuel. Since one kg of ^{3}He burned with D will produce ~10 MW_e-y of electrical energy, it is clear that there is not enough of this advanced fuel on Earth to supply a long lasting economy. All of this changed in 1986 when it was discovered the Earth's Moon contained enormous amounts of ^{3}He as proven by the Apollo program in 1970.[18] The amount of ^{3}He is conservatively calculated to be ≈ 1 million tonnes, enough to satisfy the Earth's electrical needs for a 1000 years or more. Several reviews[22-23] by the space community have shown that it is quite feasible to mine and transport this precious fuel to the Earth. The economic impact of lunar ^{3}He on the cost of electricity is calculated to be ~1 cent/kWh.[24] Taking an even broader perspective, the Solar System's resources of D and ^{3}He dwarf those of Earth. Perhaps in the 21st century, but almost certainly in the 22nd century, humankind will access the ~10^{23} kg of ^{3}He in the gas-giant planet atmospheres—effectively an infinite resource.

V. NEW OPPORTUNITIES FOR FUSION BASED ON ^{3}He FUEL CYCLES

A. Radioisotope Production

Recent studies[25-27] have shown that the second-generation fuel cycle can be used to produce near term (Q<1) commercial products such as radioisotopes at low power levels (Table 1). This early demonstration cannot only generate income for reinvestment in larger fusion facilities but it can also enhance the image of fusion in the eyes of the public at large. IEC devices are well suited to this application.[15-16, 25-27]

Neutron Applications	Detection of Clandestine Materials	PET Isotopes ^{18}F	Medical Isotopes ^{99}Mo
Proton Applications	PET Isotope ^{15}O, ^{11}C, ^{13}N	PET Isotopes- ^{18}F	Medical Isotopes ^{99m}Tc
Neutron or Proton Flux Needed	10^6 to 10^8 particles/cm^2/s	10^8 to 10^{10} particles/cm^2/s	10^{10} to 10^{12} particles/cm^2/s
Fusion Power Level	0.1-10 Watts	10-1,000 Watts	1-100 kWatts

Table 1. Near-term applications of low power fusion devices can be important for Q<1 plasma conditions.

B. Nuclear Proliferation Resistance

One of the major issues facing society today is the proliferation of nuclear weapons. Therefore, let us examine more closely the question of whether an advanced-fuel fusion power plant could be designed to be proliferation resistant and possibly achieve the ultimate goal of being proliferation proof. The first-generation DT and DD fuels both produce copious neutrons, and the large neutron multiplication of fissile fuels makes breeding fissile fuels relatively easy. Successful development of fusion power plants capable of burning the second-generation fuel D^{3}He, however, would greatly reduce the neutron production, potentially to neutron wall loads of ~0.01 MW/m^2 if a modest tradeoff with cost of electricity is allowed. Preliminary versions of such a power plant have been analyzed.[6,12] Some prospective features of a D^3He fusion core (Figure 4) should make either inserting a fissile-fuel breeding module or replacing a D^3He plasma by a DT plasma extremely difficult and thereby easily monitored. The increased D-T neutron and heat flux to sensitive components such as superconducting magnets should prohibit operation of the power plant. These questions have so far received only preliminary consideration, and they obviously will require a substantial effort and detailed analysis for this resolution.

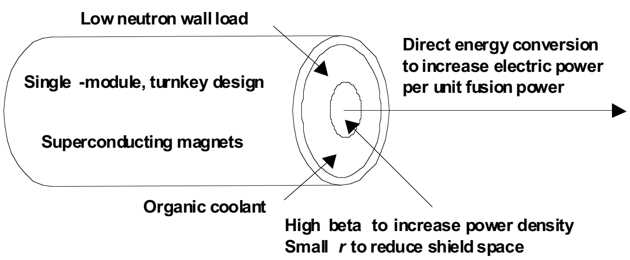

Figure 4. Some prospective features of a proliferation-resistant D^3He fusion core.

C. Space Propulsion

In addition to producing isotopes or electricity for terrestrial use, fusion energy may play an important role in space. As society expands from the Earth to the Moon, orbiting colonies, Mars, and beyond in the 21st century, efficient power sources of >> 1 MW_e will be the enabler. Small electrical power plants for the early settlements will be largely nuclear-based with some solar supplements. As the power needs increase, nuclear systems will become increasingly attractive.

Longer range missions for the exploration and development of the Solar System require propulsion capabilities that D^3He magnetic fusion presently appears able to deliver. Both conceptual design studies[28-31] and generic arguments[32] indicate that space propulsion systems based on D^3He magnetic fusion reactors can provide performance dramatically beyond that of chemical, fission, and DT fusion rockets for long-range missions. D^3He fusion's capabilities include flexibility, a specific power of $>1\ kW_{thrust}/kg_{reactor}$, and exhaust velocities at least an order of magnitude higher than chemical-rocket exhaust velocities. Such capabilities would lead to three-month missions to Mars with the same payload as nine-month chemical missions or greatly increased payloads for longer durations. More distant missions, such as to the outer Solar System or Oort Cloud, show D^3He fusion to even better advantage, because the energy available from the constant-power fusion source scales linearly with the trip time. The mass estimates for D^3He fusion propulsion systems can be made with some confidence, because the masses of the key components—shields, magnets, radiators, and refrigerators—can be calculated with good accuracy.[32] Besides propulsion, fusion energy could also provide power and materials processing capabilities. Three typical applications will be transporting humans and supplies to settlements, accessing the vast resources on asteroids and moons, and enabling scientific outposts analogous to Antarctic bases.[29]

VI. CONCLUSIONS

It is shown that the second- and third-generation ^3He based fusion fuels can go a long way in eliminating some of the concerns that the public may have about nuclear power. The reduction or even elimination of the proliferation issue is a characteristic of these fuel cycles. Equally important from a technological perspective is the reduction or elimination of radiation damage, nuclear waste, and nuclear safety issues. The more difficult plasma confinement issues will have to be addressed in a high-beta device or even in an inertial electrostatic facility. Nevertheless, the enormous payoff to be gained from low or even zero neutron emitting fusion fuels is well worth the challenge.

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