A Passively Proliferation-Proof Fusion Power Plant

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J.F. Santarius, G.L. Kulcinski, L.A. El-Guebaly

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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J.F. Santarius, G.L. Kulcinski, L.A. El-Guebaly
Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706
(608) 263-1694, santarius@engr.wisc.edu

ABSTRACT

This paper investigates whether a fusion power plant could be designed to be passively proliferation-proof. Even low neutron production rates enable fissile-fuel breeding, so such a fusion reactor must burn neutron-lean fuels. To burn these fuels economically requires a high-power-density fusion concept, and a D-^{3}He field-reversed configuration will be analyzed here. The paper discusses physics and engineering design features that would defeat attempts to modify the reactor to burn the neutron-rich fuels D-T and D-D. These include burning an advanced fusion fuel, utilizing direct energy conversion, minimizing the radius to leave inadequate room for D-T neutron shielding of superconducting magnets, designing a single-module, full-lifetime fusion core requiring no module changeout, and using an organic coolant.

I. INTRODUCTION

Few problems trouble today's world as greatly as the proliferation of nuclear weapons. Power plants utilizing either fission or D-T fusion will generate copious neutrons that could be used to produce weapons-grade fissile material with relatively minor modifications. However, as first suggested in Ref. 1, an alternative exists: fusion utilizing advanced fuels that produce few or no neutrons coupled with innovative confinement concepts that could achieve the high power densities required to burn such fuels. The reactions for key advanced fusion fuels plus D-T and D-D fuels appear in Table 1.

A proliferation-proof fusion reactor must be designed to be extremely difficult to modify for fissile-fuel breeding. Clandestine modifications to produce weapons-grade fissile materials (^{233}U or ^{239}Pu) may include burning D-T fuel and replacing a shield module with a fissile-fuel breeder module during the frequent changeouts of tritium-breeding blankets. The long history of the consideration of fission-fusion hybrid reactors,[2] still an active research topic,[3,4] indicates the ease with which D-T fusion reactors can breed fissile fuel.

Table 1. Key Fusion Fuels.

First generation fuels:

$$D + T \rightarrow n\ (14.07\ \text{MeV}) + {}^4He\ (3.52\ \text{MeV})$$

$$D + D \rightarrow n\ (2.45\ \text{MeV}) + {}^3He\ (0.82\ \text{MeV})\ \{50\%\}$$

$$\rightarrow p\ (3.02\ \text{MeV}) + T\ (1.01\ \text{MeV})\ \{50\%\}$$

Second generation fuel:

$$D + {}^3He \rightarrow p\ (14.68\ \text{MeV}) + {}^4He\ (3.67\ \text{MeV})$$

Third generation fuels:

$${}^3He + {}^3He \rightarrow 2\ p + {}^4He\ (12.86\ \text{MeV})$$

$$p + {}^{11}B \rightarrow 3\ {}^4He\ (8.68\ \text{MeV})$$

What would breeding weapons-grade fissile fuel entail? To approach this problem, assume that a proliferation-proof power plant should defeat potential design modifications that could produce fissile fuel in excess of a critical rate. The value used here, 1 kg/y, would make acquiring a fissile-fuel critical mass a 5-10 year program, significantly vulnerable to discovery. For conversion from fertile to fissile material, the reactions most often considered are ^{232}Th to ^{233}U and ^{238}U to ^{239}Pu.[2,3] The latter will be considered here. The number of neutrons required to convert ^{238}U to 1 kg of ^{239}Pu corresponds to 0.72 MW·a of D-T neutrons or 0.13 MW·a of D-D neutrons. The D-T value implies a neutron wall load of 0.023 MW·a/m^2 for a cylindrical reactor core with a radius of 0.5 m and a length of 10 m. For a 100 MW$_e$ power plant, the corresponding neutron power level in one year would be ~1/200th of the fusion power. If economy of scale leads to larger net electric power levels per reactor, the neutron power fraction must be proportionally smaller. The actual neutron power constraint will be somewhat higher and depend on conversion efficiencies, neutron multiplication in the fissile-fuel breeding module, and extraction efficiency.

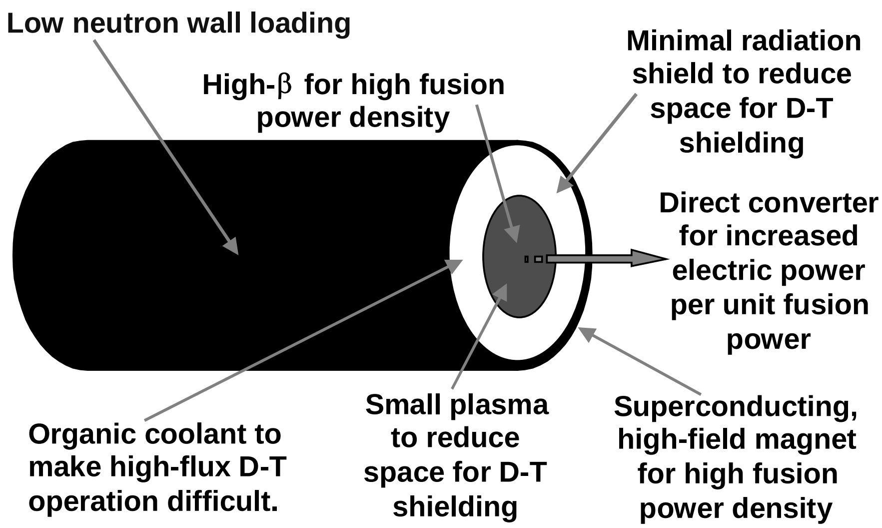

Fig. 1. One potential approach to designing a proliferation-proof D-^{3}He field-reversed configuration power plant.

Many features could combine to create a proliferation-proof fusion power plant, as illustrated schematically in Fig. 1. The most likely solution would burn the advanced fuel D-^{3}He, which requires increased fusion power density, higher plasma temperatures, and better plasma confinement than does D-T fuel.[5] Increased power density would be generated by using (1) a high-β (plasma pressure/magnetic field pressure) concept; (2) a strong magnetic field; and (3) direct conversion of charged-particle energy. Proliferation resistance would stem from (1) high power density coupled with a small radius, thus leaving minimal space for radiation shielding; (2) low neutron wall loading, greatly increasing the time required to produce significant amounts of fissile fuels; (3) use of energy conversion technologies, such as direct conversion and organic coolants, that match advanced fuels well but are poorly suited to D-T fuel; plus (4) full-lifetime shield modules—stemming from the low neutron wall load and making replacement very difficult. Subsequent sections further treat these questions.

II. PHYSICS CONSIDERATIONS

Burning an advanced fusion fuel requires substantial, continued progress in plasma physics, especially in the area of plasma energy confinement. The ignition contours for D-T and D-^{3}He fuels appear in Fig. 2. Particularly beneficial to the present strategy would be the development of the field-reversed configuration (FRC) or another suitable, high-β, innovative confinement concept. The scarcity of ^{3}He on Earth also raises the question of whether the time frame for acquiring the large lunar ^{3}He resource[6,7] will be compatible with fusion power plant needs.

Because a low production rate for fissile fuel would make the design unattractive for creating a nuclear stockpile, the neutron wall load objective is set very low, <0.01 MW/m^2. Such values of the total neutron power would lead to a correspondingly low fissile-fuel breeding capability. Typical D-T reactor neutron wall loads are ~3 MW/m^2. If D-T neutrons constituted 1% of the D-^{3}He fusion power and all were fully utilized, to reach 1 kg ^{239}Pu production per year with a neutron wall load of 0.01 MW/m^2 would necessitate increasing the first-wall surface area above the example given in Section 1 to 72 m^2.

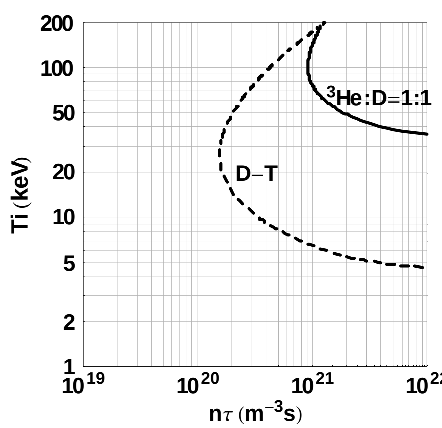

Fig. 2. Ignition contours for D-T and D-^{3}He fuels as a function of plasma temperature, T, and the plasma confinement parameter, nτ (density times energy confinement time).

Achieving a low neutron wall load would be accomplished by operating at a low D to ^{3}He density ratio in order to reduce D-D and secondary D-T neutron production. This reduces the fusion power density, so the design must use a higher magnetic field (B-field) to compensate. Increased power density would derive from using a high-β concept, such as a FRC, which optimizes for D-T operation at B~3 T. The fusion power density in the plasma scales as $\beta^2 B^4$, so the high FRC β (~80-90%) and superconducting magnet technology limits (~20 T) give the resulting D-^{3}He FRC fusion core a power density capacity far exceeding the limits imposed by engineering constraints on surface heat fluxes and neutron wall loads.[1,5] The decreased fusion power density in the plasma for D-^{3}He fuel compared to D-T fuel is shown in Fig. 3. The power density enhancement available by increasing the magnetic field within technological limits appears in Fig. 4.

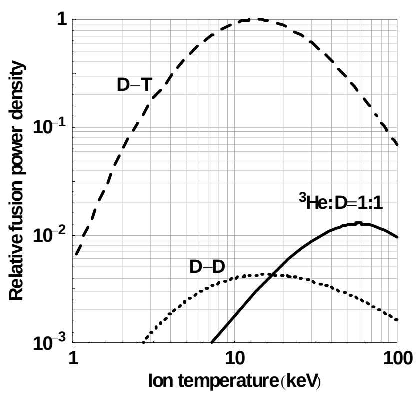

Fig. 3. Fusion power density in the plasma for selected fusion fuels, neglecting impurities and fusion ash.

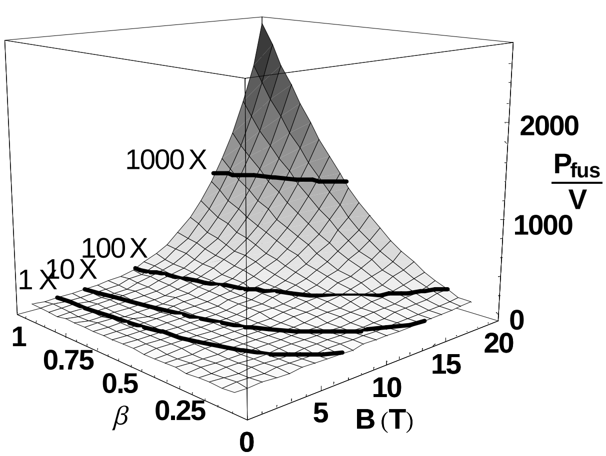

Fig. 4. Relative fusion power density capacity of a D-^{3}He FRC compared with that of a D-T FRC with β=0.85 and B=3 T.

The plasma radius in the fusion core and the relatively small D-^{3}He magnet shielding thickness would be selected to total much less than that required to protect the superconducting magnets from D-T or D-D neutron radiation damage and heating at neutron wall loads relevant to breeding fissile fuels. Although D-T fuel could be burned in this type of fusion core at a greatly reduced fusion power level and neutron wall load, the resulting fissile-fuel breeding should then be excessively slow and inefficient.

The non-proliferation goal could be facilitated by choosing operating parameters such that D-^{3}He plasmas would be macroscopically stable, but D-T plasmas with the same parameters would be macroscopically unstable. For example: (1) the maximum elongation (ratio of axial length to radius) of a D-^{3}He FRC fusion core could be set large and near the stability limits for those plasma parameters, so that reducing the plasma radius for D-T fuel in order to allow a thicker shield would require reducing the length and, thereby, the total neutron production; and (2) large particle orbits contribute significantly to stability in an FRC, so the reactor would rely upon finite gyroradius stabilization by fusion products. This can be a much more important effect for D-^{3}He plasmas than for D-T plasmas, because D-^{3}He protons possess twice the gyroradius of D-^{3}He and D-T alpha particles and carry four times the power for a given total fusion power.

III. ENGINEERING CONSIDERATIONS

Although D-^{3}He fusion requires a more demanding physics development path than does D-T fusion, the reduced neutron flux using D-^{3}He fuel facilitates power-plant engineering and safety, and much of the technology required for D-^{3}He reactors already has been demonstrated.[1] Neutron power fractions for D-T, D-D, and D-^{3}He Maxwellian plasmas appear in Fig. 5. Low neutron wall loads in conceptual D-^{3}He fusion power plants should lead to full-lifetime shields.[8]

Conceptual fusion power plant designs for electricity production almost all contain at least several core modules for easy maintenance. For non-proliferation, however, the best approach may be to design single-unit D-^{3}He fusion power cores that would last the ~30 full-power-year lifetime projected for steels and other structural materials. The low neutron wall loads in extant conceptual D-^{3}He fusion power plants already allow full-lifetime shields.[8] For non-proliferation purposes, therefore, the D-^{3}He fusion power core could be a single module that would have no provision for replacement except for limiters or thin first walls. Modifying such a design for insertion of a fissile-fuel breeding blanket would be extremely difficult.

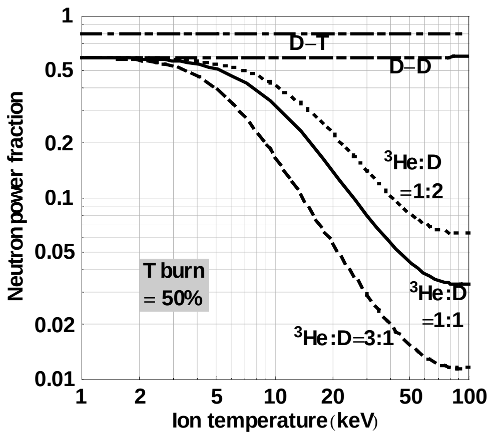

Fig. 5. Neutron power as a fraction of total fusion power for selected fusion fuels.

Highly efficient direct energy conversion could be used on a large fraction of the fusion power produced by D-^{3}He plasmas, because of the reaction's large charged-particle power fraction. This increases the net plant efficiency and reduces both the total fusion power for a given net electric power and the fraction of that power converted by a thermal conversion system. Designs exist for directly converting the energy of fusion products near their birth energy, but only part of this energy is then available to heat and sustain the core plasma.[9] A more feasible approach would be first to allow the fusion products to slow down on the background plasma, and then to directly convert the charged-particle transport losses using the well-demonstrated direct electrostatic converter technology.[10]

At most, 20% of a D-T plasma's fusion power would consist of charged particles potentially available for direct conversion, and the remaining 80% of the power would require a thermal conversion system. In D-^{3}He FRC reactor plasmas, charged particles would carry ~70% of the fusion power, bremsstrahlung radiation would constitute ~30% of the power, neutrons would carry ~1% of the power, and the synchrotron radiation power would be negligible due to the high β and low B field. Burning D-T fuel in the proliferation-proof D-^{3}He power plant would reduce the net electric power generated unless major design modifications to handle much higher thermal powers were undertaken.

For D-^{3}He fuel, where protons carry 80% of the fusion power, as opposed to neutrons carrying the same power fraction for D-T fuel, the natural question arises of whether neutron flux problems simply get replaced by surface heat flux problems. Fortunately, in magnetic geometries like the FRC and spheromak, where a compact magnetic toroid is immersed in a linear external magnetic-field geometry, almost all of the charged-particle transport losses will flow out the ends of the device. There, they can be directly converted or allowed to follow an expanded flux tube until their heat flux reaches manageable levels, as illustrated in Fig. 6. The first wall in a D-^{3}He fusion core must, therefore, deal mostly with bremsstrahlung and synchrotron radiation losses, which will be 25-30% of the fusion power for D-^{3}He. The peaking factor for this heat flux will be small, in contrast to the tokamak and other toroidal configurations. The use of direct conversion, with typically twice the efficiency of thermal cycles, reduces the total fusion power required from the core, further reducing the surface heat flux there.

The possibility of using organic coolants, which match advanced fuels well but produce copious organic tars under the large neutron flux from D-T fuel, also potentially contributes to proliferation resistance. The use of organic coolants in a D-^{3}He tokamak power plant has been considered for the ARIES-III conceptual design and found plausible.[11] For the present design, even lower neutron wall loads than in ARIES-III would be present, increasing the feasibility of using organic coolants.

The power plant would be optimized for non-proliferation, so the cost of electricity (COE) would likely be somewhat higher than for a power plant optimized for minimum COE, particularly if low (~100 MW_e) net electric power levels were utilized.

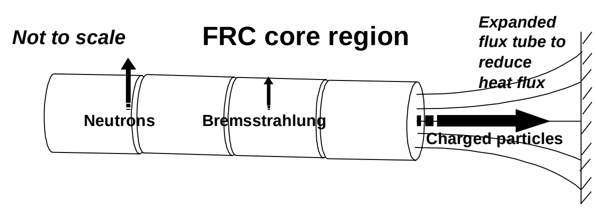

Fig. 6. Power flows in a fusion core with linear geometry for the external magnetic field.

IV. SUMMARY

Preliminary investigations suggest that a fusion power plant burning D-^{3}He fuel could be designed to be proliferation proof. This reactor would be extremely difficult to modify for use with other, neutron-rich fusion fuels, such as D-T and D-D, which produce high neutron power fractions that could be used to breed weapons-grade fissile fuels. The power plant could be exported, yet be easily monitored to prevent nuclear proliferation. Burning an advanced fuel would require substantial, continued progress in plasma physics—particularly better plasma energy confinement and development of the FRC or another suitable high-β innovative confinement concept. The low neutron power fraction of advanced fuels, on the other hand, would facilitate overcoming the engineering and safety obstacles on the present D-T fusion power development path. Exportable, proliferation-proof fusion reactors would greatly ease the nuclear proliferation problem in the future.

ACKNOWLEDGEMENTS

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