Advanced-Fuel Heat Flux, Power Density and Direct Conversion Issues

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ADVANCED-FUEL HEAT FLUX, POWER DENSITY, AND DIRECT CONVERSION ISSUES

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ABSTRACT

Several key areas are fundamentally different for D-T and advanced-fuel fusion reactors. Although the physics constraints are generally more stringent for advanced fuels, the engineering advantages can dominate when assessing a concept. Assuming that the necessary physics performance can be demonstrated, several alternate fusion configurations would make attractive advanced-fuel fusion power plants. This paper focuses on three areas: surface heat flux, power density, and direct conversion.

I. INTRODUCTION

The question of the feasibility of advanced fuels and direct conversion of fusion energy to electricity has recently been raised in an analysis that is labeled 'generic.'[1] The present paper points out that engineering constraints on advanced-fuel fusion reactors are much less limiting than indicated in Ref. 1, given reasonable expectations for progress in plasma physics. In particular, better energy confinement allows engineering solutions to be put forward for both toroidal and linear reactors. In general, however, linear configurations (tandem mirrors, field-reversed configurations (FRC's), and spheromaks) are more suitable for burning advanced fuels. The focus of this paper will be the key advanced fuel, D-^{3}He.

Except for energies and temperatures, which will be given in keV, SI units will be used.

II. SURFACE HEAT FLUX

Surface heat flux limits are critical for almost all fusion reactor designs, and several engineering solutions have been proposed for dealing with them. For a D-T reactor, the neutron wall load is almost always more constraining than the surface heat flux, and the necessity of breeding tritium in a blanket zone greatly complicates the region closest to the plasma. Thus, D-T tokamak designs usually have first-wall surface heat fluxes of ~0.5 MW/m^2. In advanced-fuel reactors, however, the greater flexibility allows the use of more efficient coolants—such as water or an organic coolant. The real surface-heat-flux limit on the first wall is then closer to divertor values, or ~5 MW/m^2. Figure 1 gives the average divertor heat loads, first-wall heat loads, and neutron wall loads for some major recent commercial tokamak and RFP reactor designs. Other mitigating effects include the reduced total power required when efficient direct conversion is used and the deposition of transport power on expanded end walls in linear geometries.

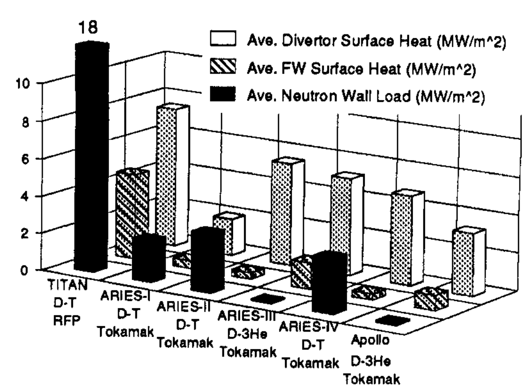

Fig. 1. Average divertor heat load, first-wall heat load, and neutron wall load for some major recent commercial toroidal fusion reactor designs.[2–6]

A. Toroidal Reactors with Direct Conversion

Direct conversion of fusion energy to electricity both decreases the total surface heat load and reduces the fusion power required per unit electric power. For a net efficiency of η, the electric power generated per unit of surface-averaged heat in a D-^{3}He reactor scales approximately as

$$\frac{P_e}{P_h} \simeq \frac{\eta}{1-\eta}, \tag{1}$$

where P_e is the net electric power and P_h is the surface-heat power (radiation and charged particles). This function is plotted in Fig. 2. For example, the improvement in increasing from an all-thermal conversion reactor with a net efficiency of ~40%, to a thermal- and direct-conversion reactor with a net efficiency of ~70% is a factor of 3.5.

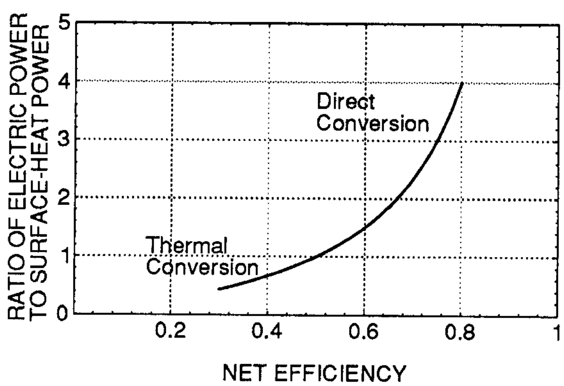

Fig. 2. Ratio of electric power to surface-heat power improves strongly with net electric conversion efficiency.

B. Toroidal Reactors without Direct Conversion

The reduced radiation-shield thickness in a D-^{3}He reactor often leads to a first wall that is at a larger radius, reducing the surface heat flux. Even for the same surface area as a D-T reactor, a reduction in the surface heat can be effected by using overmoded waveguides to carry synchrotron radiation to a *thermal* power conversion system in a chamber outside of the reactor vessel—effectively increasing the total surface area. This is not direct energy conversion, it simply carries power to another chamber. This solution requires a higher $n\tau_E$ value, but it is clearly impossible to claim that we know the limits when tokamak transport remains one of the critical issues of magnetic fusion research.

C. Linear Fusion Reactors

For linear systems, the heat loss channels are qualitatively different from toroids for two reasons: (1) linear fusion reactors are usually high-β devices with much lower magnetic fields, so the synchrotron-radiation power is greatly reduced, and (2) the transport power flows out the ends of the devices and can either be directly converted to electricity or deposited in an end chamber of large surface area. Linear-reactor surface heat fluxes in the fusion core are produced primarily by bremsstrahlung radiation, which will be 25–50% of the fusion power in the D-^{3}He operating temperature range of 45–100 keV. Linear systems are also much more amenable to high-efficiency direct electrostatic conversion than toroids, which reduces the first-wall heat flux even further.

III. POWER DENSITY

The relatively low fusion power density in the plasma is often quoted in arguments against advanced fuels. A much more important parameter, however, is the *engineering* power density (the net electricity per unit mass of the reactor). Factors that typically enhance the engineering power density in advanced-fuel reactors include a reduced blanket and shield thickness, an increased efficiency due to direct conversion, and an increased magnetic field (because the high neutron wall load often causes D-T reactors to optimize at magnetic fields that are well below technological limits).

The fusion power densities in the plasma for D-T and D-^{3}He as a function of ion temperature are shown in Fig. 3. The resulting ignition contours in $n\tau$ versus T space are shown in Fig. 4. The peak plasma fusion power density is a factor of about 75 lower for D-^{3}He, and the minimum $Tn\tau$ product is about a factor of 25 higher. It is important to recognize, however, that:

- The plasma fusion power density results from an extremely simple analysis derived from an exclusively physics-oriented viewpoint; it is a poor measure of the performance and cost of an actual reactor.
- To realize most of the benefits of the D-^{3}He fuel cycle, it is by no means necessary to fit the common (but arbitrary) definition of 'aneutronic' as producing $\lesssim 1\%$ of the fusion power in neutrons. Most toroidal D-^{3}He reactor designs use a 1:1 ^{3}He:D density ratio, generating ~5% of the fusion power in neutrons. This suffices to gain the advantages of direct conversion, a perma-

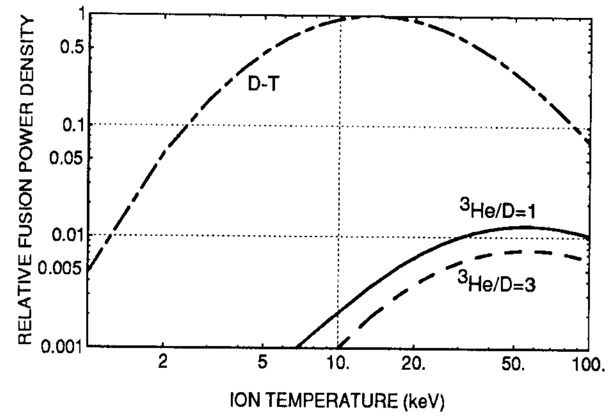

Fig. 3. Fusion power density in the plasma for D-T and D-^{3}He fuels.

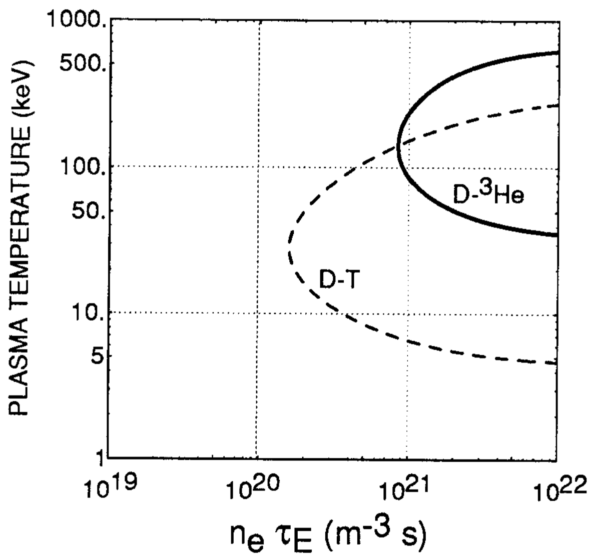

Fig. 4. Ignition contours for D-T and D-^{3}He fuels.

nent first wall, and near-surface radioactive waste disposal—resulting in significant positive impacts on availability, safety, environment, and licensing.

- Neutron production is reduced by operating at higher temperature or higher ^{3}He:D density ratio, although this requires better confinement or higher β.
- The peak plasma fusion power density actually occurs at about a 1:2 ^{3}He:D density ratio, but the increased neutron production is often not worth the slight power-density increase.
- The assumption that the magnetic field and other constraints will be the same for both D-T and D-^{3}He fuels implicitly assumes that the reactor is a tokamak operating at the limits of coil technology. Several concepts—spheromaks, field-reversed configurations, and tandem mirrors, for example—optimize for D-T at a few tesla, which is far below coil-technology limits. These devices are neutron-wall-load limited for D-T operation, and the field can be increased substantially for D-^{3}He to take advantage of the B^4 scaling of plasma power density.

As an example of the trade-offs, Table I shows typical factors contributing to the engineering power density for D-^{3}He compared to D-T in a tandem mirror reactor. The D-^{3}He parameters are extrapolated from the first University of Wisconsin D-^{3}He reactor conceptual designs, 'Ra'[7] and 'SOAR',[8] for the case of a ^{3}He:D density ratio of 1:1 and utilizing both direct and thermal energy conversion. The D-T parameters are based on MINIMARS.[9]

IV. DIRECT CONVERSION

Direct conversion of fusion energy to electricity constitutes a great advantage for advanced fuels—where much of the plasma loss is usually charged particles. Detailed engineering designs of highly efficient direct converters exist, but they work best in linear geometry and are difficult to implement in toroidal geometry.[10]

The tandem mirror would be ideal for electrostatic direct conversion, because the escaping plasma consists of a Maxwellian drifting at a speed corresponding to the energy of the peak electrostatic potential minus the ground potential. The ratio of energy spread to peak energy is ~0.1, leading to efficiencies of ~80% with only a two-stage direct converter,[7,8] using the well-verified theory of Barr and Moir.[11]

Although the field-reversed-configuration and the spheromak have some similarities with toroidal systems, from the viewpoint of direct conversion they should be considered linear devices due to their external magnetic-field geometry. Electrostatic direct conversion can be performed on the plasma flowing out the ends of the device in a manner similar to the tandem mirror, although requiring more stages due to the nearly Maxwellian energy distribution in the scrape-off layer. This requires an expansion of the plasma volume, but this can be done in a separate, relatively inexpensive chamber at the ends of the device, rather than in the fusion core itself. The resulting cost impact is minimal because vacuum chambers are much less expensive than blankets and magnets.

TABLE I.

Gain in Engineering Power Density for a D-^{3}He Thermal-Barrier Tandem-Mirror Reactor Compared to One Fueled with D-T

	D-T	D-^{3}He	D-^{3}He Gain in Effectiveness
Normalized fusion power density in plasma	1	0.013	0.013
Net efficiency (with direct conversion)	0.40	0.77	1.9
Blanket and shield thickness	1.07 m	0.40 m	2.7 (vol.)
Central cell magnetic field	3.1 T	6.4 T	18
TOTAL D-^{3}He GAIN FACTOR			1.2

Because the FRC is expected to have a significant flux of ~14.7 MeV protons escaping along the z axis, a recent D-^{3}He reactor design includes a traveling-wave direct converter for them.[12] Another earlier design used an electrostatic direct converter for these high-energy protons, as did a D-^{3}He tandem-mirror design.[8]

V. CONCLUSIONS

The key feasibility requirement for advanced-fuel fusion reactors is making progress in plasma physics. Given reasonable advances, particularly in energy confinement, engineering solutions exist for the reactor design problems of surface heat, power density, and direct conversion. Progress in tokamak plasma physics would allow the use of advanced fuels, while progress in alternate concepts potentially would lead to very attractive fusion reactors.

ACKNOWLEDGMENTS

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