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A Review of Confinement Requirements for Advanced Fuels

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The energy confinement requirements for burning D-^{3}He, D-D, or P-^{11}B are reviewed, with particular attention to the effects of helium ash accumulation. It is concluded that the DT cycle will lead to the more compact and economic fusion power reactor. The substantially less demanding requirements for ignition in DT (the $n_e \tau_E$ T required for ignition in DT is smaller than that of the nearest advanced fuel, D-^{3}He, by a factor of 50) will allow ignition, or significant fusion gain, in a smaller device; while the higher fusion power density (the fusion power density in DT is higher than that of D-^{3}He by a factor of 100 at the same plasma pressure) allows for a more compact and economic device at fixed fusion power.

KEY WORDS: Confinement requirements; advanced fuels.

1. INTRODUCTION

The great majority of fusion reactor studies are based on the deuterium/tritium (D-T) fuel cycle through the reaction t(d,n)α. This reaction is chosen because it has the largest fusion cross-section (peaking at about five barns) and reaches this maximum cross-section at the lowest energy (~65 keV in the center-of-mass) of any potential fusion fuel. This large cross-section and low center-of-mass energy lead to the lowest confinement requirement for ignition (ignition in D-T requires a confinement triple-product $n\tau_E$ T = 4.9 × 10^{21} keV-s/m^{-3} in the presence of a plausible impurity mix) and the highest fusion power density at fixed plasma pressure. The D-T fuel cycle also presents unique challenges to reactor designers. Two particular issues are the 14 MeV neutrons produced in the t(d,n)α reaction, and the presence of tritium in the fuel cycle. The 14 MeV neutrons damage reactor components (principally the structure of the blanket and shield) thereby limiting their useful lifetime; and activate materials, thereby opening the possibility that D-T fusion reactors will produce large volumes of radioactive wastes. Tritium does not occur in nature, but must be bred through the reaction n(^{6}Li,t)α in a breeding blanket which surrounds the plasma. In situ breeding of tritium can result in large on-site tritium inventories (principally in the blanket and tritium recovery system) raising both safety and nuclear proliferation concerns.

Alternative ("advanced") fuel cycles[(1)] have also been under investigation for many years. Two considerations have motivated these investigations are:

(i) Removing tritium from the fuel cycle in order to simplify the fuel cycle (no tritium breeding), to expand the available fuel supply (the earth's lithium supply limits the ultimate amount of tritium which might be produced by breeding blankets), and/or to address nuclear proliferation concerns.

(ii) Eliminating (or greatly reducing) neutron production in fusion reactors as a means of avoiding (or greatly ameliorating) neutron damage to, and activation of fusion reactor components.

In this paper we compare the performance of three advanced fuel cycles, D-^{3}He [which features the reaction ^{3}He(d,p)α]; "catalyzed DD" [that is, a primary cycle

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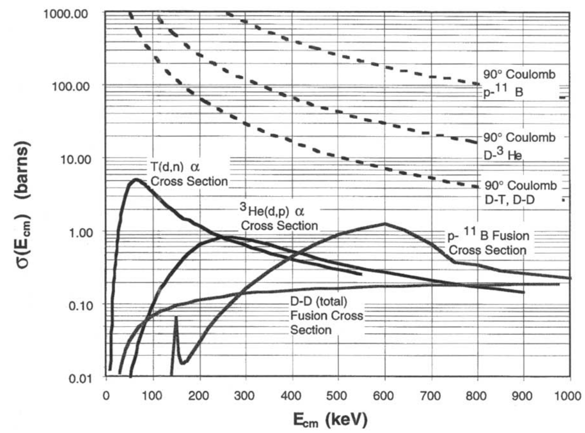

Fig. 1. Fusion cross-sections and effective Coulomb scattering cross-sections for DT and selected advanced fusion fuels.

involving the two reactions d(d,n)^3 He and d(d,p)t together with the secondary reactions t(d,n)α and ^{3}He(d,p)α to consume all t and ^{3}He produced by the primary reactions], and p-^{11}B [which features the reaction ^{11}B(p,α)2α]

The D-^{3}He fuel cycle has the advantage that it produces fewer neutrons than does the D-T fuel cycle. While the principle reaction ^{3}He(d,p)α is aneutronic, neutron production via the side reaction d(d,n)^3 He and the secondary reaction d(t,n)α is unavoidable. The neutrons produced mainly have lower energy [2.45 MeV neutrons from d(d,n)^{3}He reactions as opposed to 14 MeV neutrons from d(t,n)α reactions] so that material damage is reduced relative to the DT fuel cycle. Reactor studies show that the D-^{3}He fuel cycle largely solves the reactor component lifetime issues associated with neutron damage, while neutron activation and the associated production of radioactive waste remains a concern.(2) The D-^{3}He fuel cycle avoids tritium, but does this by replacing it with another exotic isotope, ^{3}He. ^{3}He does not occur on earth in sufficient quantities to support a fusion power industry. However, ^{3}He can be found on the moon,(3) and proponents of the D-^{3}He fuel cycle have suggested that it may be economic to mine ^{3}He on the moon and transport it to earth to fuel a fusion power industry.(4) The D-^{3}He fuel cycle has a higher confinement requirement for ignition (ignition in D-^{3}He requires a confinement triple-product $n\tau_E T = 2.4 \times 10^{23}$ keV-s/m^{-3} in the presence of a plausible impurity mix), and a lower fusion power density at fixed plasma pressure.

The Catalyzed D-D fuel cycle avoids tritium without introducing any exotic isotopes, and thereby holds out the promise of an essentially unlimited supply of fuel for fusion power generation. The catalyzed D-D cycle actually produces more neutrons per unit of fusion power produced than the D-T cycle so that this fuel cycle does not address materials damage and activation concerns. The catalyzed D-D fuel cycle has a still higher confinement requirement for ignition (ignition in catalyzed D-D requires a confinement triple-product $n\tau_E$ T $= 1.1 \times 10^{23}$ keV-s/m^{-3} in the absence of impurities. Ignition in catalyzed DD cannot be achieved with a plausible impurity mix) and still lower fusion power density at fixed plasma pressure.

The p^{11}B fuel cycle avoids exotic isotopes, so that no breeding of fuel is required and the potential fuel supply is essentially unlimited. It is also nearly aneutronic, thus addressing materials damage and much of the materials activation concern. However, there are residual activation issues associated with high energy γ-rays produced via the reaction ^{11}B(p,γ)^{12}C, and with neutron production from the reactions ^{11}B(α,n)^{14}N and ^{11}B(p,n)^{11}C; and safety concerns associated with possible equilibrium inventories of MCi/GW of ^{11}C.(5) More fundamentally, there is the problem that the p-^{11}B fusion reactivity is too low to compete with bremsstrahlung radiation losses, so that ignition (or even high fusion gain) cannot be achieved with this fuel.(6)

2. FUSION CROSS-SECTIONS

Fundamental to any analysis of confinement requirements and fusion power density are the fusion cross sections. These cross sections are shown as a function of the center-of-mass energy in Fig. 1. It is apparent that the t(d,n)α reaction has the largest fusion cross-section. More importantly, the peak in the DT cross section occurs at much lower energy. The maximum of the DT cross section of 5.07 barns occurs at 65 keV in the center of mass. This compares to a maximum of 0.819 barns at 262 keV for D-^{3}He and 1.2 barns at 600 keV for p-^{11}B.(7) The large values of the DT fusion cross section at low energy lead to substantially higher fusion reactivities at fixed plasma pressure.

Figure 1 also shows the effective Coulomb scattering cross section (derived from the rate at which many small angle collisions accumulate to produce a 90° scatter).(8) For energies below 1 MeV the DT fusion cross section is 50 to 100 times smaller than the DT Coulomb scattering cross-section; while this ratio is larger for the advanced fuels. It follows that the rate at which the ion distribution relaxes towards thermal equilibrium (which is governed by averages of the Coulomb cross-section over particle orbits) is large compared to the fusion reaction rate (which involves the same averages over par-

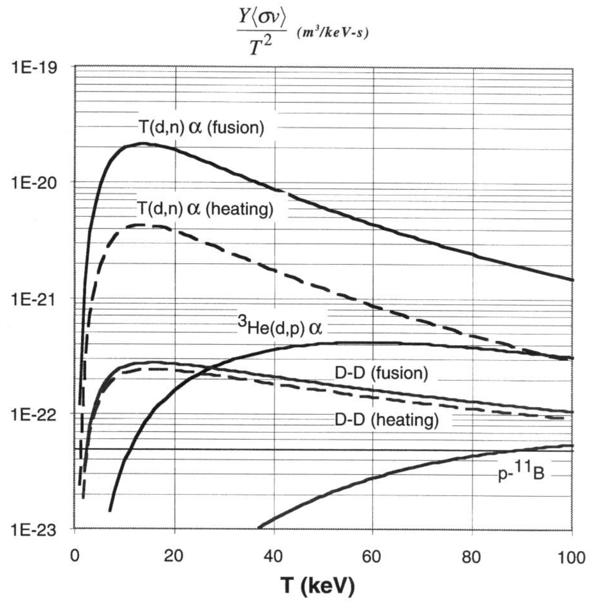

Fig. 2. Specific fusion reactivity, $Y\langle\sigma v\rangle/T^2$, for DT and selected advanced fusion fuels.

ticle orbits of the substantially smaller fusion cross-section). Hence, thermonuclear reactor scenarios [i.e., scenarios in which the electrons and ions both have locally (near) Maxwellian distributions] are greatly favored over nonthermal schemes. Detailed analyses[9,10] of nonthermal reactor schemes[11] generally show that power required to maintain significantly nonthermal ion (or electron) distributions exceeds the fusion power produced by the system under analysis. We note that advanced fusion fuels are less likely candidates for achieving significant gain in nonthermal systems because the ratio of the Coulomb cross sections to the fusion cross section is larger for the advanced fuels. In the remainder of this paper we consider only thermonuclear systems.

3. CONFINEMENT REQUIREMENTS AND FUSION POWER DENSITY

For thermonuclear systems, both the confinement requirement for ignition and the fusion power density at fixed plasma pressure are determined by the fusion rate coefficient, $\langle\sigma v\rangle$, through the specific fusion reactivity, $Y\langle\sigma v\rangle/T^2$, where Y is the appropriate fusion energy release and T is the temperature, which is assumed to be the same for both electrons and ions (we will relax the assumption that $T_e = T_i$ in the next section).

In an ignited system we require that the conducted energy loss/unit volume be less than the fusion heating power/unit volume, or

$$\frac{3/2(1+f_i)n_eT}{\tau_E} < f_1 f_2 n_e^2 Y_{\text{heating}}\langle\sigma v\rangle,$$

where n_e is the electron density; $f_i = n_i/n_e$ is the relative density; $f_1 = n_1/n_e$ and $f_2 = n_2/n_e$ are the relative densities of the two reacting ion species; and Y_{heating} is the energy released in charged particles (and, hence, available for plasma heating) per fusion event. Rearranging terms, we find that the confinement triple-product required for ignition is given by

$$n_e\tau_E T > \frac{3}{2}\left(\frac{1+f_i}{f_1 f_2}\right)\left[\frac{Y_{\text{heating}}\langle\sigma v\rangle}{T^2}\right]^{-1}$$

In magnetically confined plasmas the plasma pressure, $p = (1 + f_i)n_eT$, is generally limited through a limit on $\beta \equiv 2\mu_0 p/B^2$, where B is the magnetic field. Hence, the fusion power density is limited by

$$P_{\text{fusion}} < \frac{\beta^2 B^4}{4\mu_0^2}\frac{f_1 f_2}{(1+f_i)^2}\frac{Y_{\text{total}}\langle\sigma v\rangle}{T^2}$$

where Y_{total} is the total energy released per fusion event (which is larger than Y_{heating} for reactions which produce neutrons).

Fusion power systems require both ignition (or high fusion gain), and high fusion power density. Hence, one must choose an operating point with a high specific fusion reactivity. It is clear from Fig. 2 that DT has a substantial advantage in specific fusion reactivity over the advanced fuels. The nearest competitor is D-^{3}He. The fusion reactivity in DT is maximized by choosing $f_d = f_t = 1/2$; while the fusion reactivity in D-^{3}He is maximized by choosing $f_d = 1/2$ and $f3_{He} = 1/4$. With these choices for the relative densities of fuel ions, the confinement requirement for DT is 18 times lower than that for D-^{3}He; and, the fusion power density for DT is 75 times higher than that of D-^{3}He. This performance advantage of DT over D-^{3}He is further widened if one chooses to operate the D-^{3}He fueled systems lean in deuterium (e.g., $f_d \approx 0.1$ and $f3_{He} \approx 0.4$) in an effort to minimize neutron production rates.

4. BREMSSTRAHLUNG RADIATION PREVENTS IGNITION IN p-^{11}B

Both fusion reactions and bremsstrahlung (which results from electrons scattering on ions) are binary interactions so that both the fusion heating power/unit volume and the bremsstrahlung loss power/unit volume

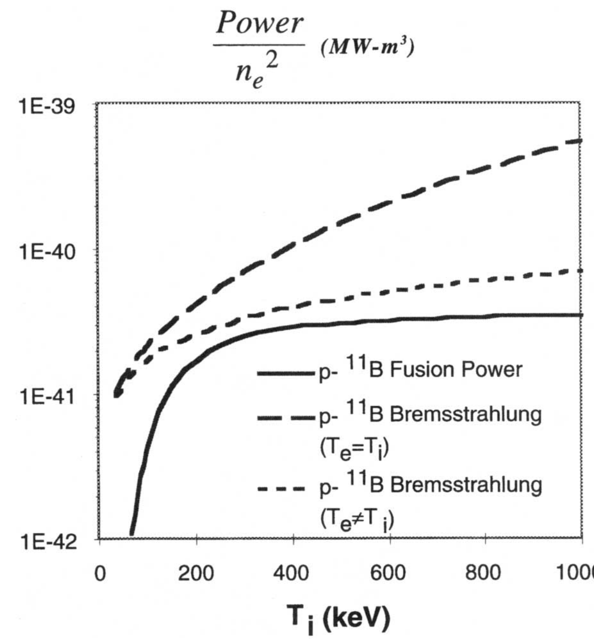

Fig. 3. Comparison between P_{fusion} and P_{brem} for p-^{11}B.

scale as n_e^2. All magnetic confinement systems are optically thin to the multi-keV X-rays generated by bremsstrahlung, so that the bremsstrahlung power is lost from the system thereby reducing the power available for plasma heating. Rider[9] provides a convenient formula for the bremsstrahlung power density,

$$P_{Brem}=1.69\times10^{-32}n_e^2\sqrt{T_e}\left\{Z_{eff}\left[1+0.7936\frac{T_e}{m_ec^2}+1.874\left(\frac{T_e}{m_ec^2}\right)^2\right]+\frac{3}{\sqrt{2}}\frac{T_e}{m_ec^2}\right\}\text{MW/m}^3$$

In Fig. 3 we compare P_{brem} to P_{fusion} for the p-^{11}B fuel cycle. We have taken $f_p = 1/2$ and $f11_B = 1/10$ in order to maximize the p-^{11}B fusion reactivity. The fusion rate coefficient, $\langle\sigma v\rangle$, for p-^{11}B was computed by the author using cross-section data from Becker *et al.*[7] This more recent cross-section data is somewhat more optimistic than previous measurements by Davidson *et al.*,[12] and we were unable to find any tables of p-^{11}B fusion rate coefficients which took account this newer data.

In computing the bremsstrahlung power we first consider a fully thermal system with $T_e = T_j$. The result, shown by the long-dashed line (— — —) is higher than the fusion power density; the fusion power density is closest to the bremsstrahlung power at T = 200 keV, where the bremsstrahlung power is larger than the fusion power by a factor of 2.4.

A more optimistic result can be obtained by following Dawson[6] and employing a two-fluid power balance (so that $T_{ec}T_i$). The p-^{11}B fusion heating power essentially all goes to heating ions at relevant temperatures. We ignore all transport losses, assuming that the only ion loss mechanism is drag on the (colder) electrons; and that the only electron loss mechanism is bremsstrahlung radiation. The electron temperature can then be computed by equating the ion drag power (equal to P_{fusion}) to P_{brem}. This calculation produces the short-dashed (– – –) curve in Fig. 3. The bremsstrahlung power is still greater than the fusion power. The closest approach between P_{fusion} and P_{brem} now occurs at 300 keV, where P_{brem} is larger than P_{fusion} by a factor of 1.3. Hence, auxiliary heating would be required to maintain power balance at this operating point; and the maximum fusion gain that could be achieved, $Q \equiv P_{fusion}/P_{aux}$ is limited to $Q \leq 3$ for p-^{11}B in the absence of any transport losses. This low value of Q even under such optimistic assumptions rules out p-^{11}B as a practical fuel cycle for fusion power reactors.

5. THE LAWSON CONDITION

The Lawson condition[13] for ignition follows from balancing the conduction losses and the bremsstrahlung losses against the fusion heating power to obtain

$$\frac{3/2(1+f_i)n_eT}{\tau_E}-P_{Brem}=f_1f_2n_e^2Y_{heating}\langle\sigma v\rangle$$

Rearranging terms then yields

$$n_e\tau_ET=\frac{\frac{3}{2}\left(\frac{1+f_i}{f_1f_2}\right)}{\frac{Y_{heating}\langle\sigma v\rangle}{T^2}+\frac{P_{Brem}}{n_e^2T^2}}$$

Because $P_{brem}\sim n_e^2$, we find that the value of the confinement triple-product, $n_e\tau_ET$, required for ignition is only a function of T. The $n_e\tau_ET$ required for ignition in D-T, D-^{3}He, and catalyzed D-D is displayed in Fig. 4. In computing the curves in Fig. 4 we have assumed that there are no impurities present; and we have chosen the relative density if each fuel ion species so as to maximize the fusion reactivity ($f_d = f_t = 1/2$ for D-T; f_d = 1/2 and $f3_{He}$ = 1/4 for D-^{3}He; and f_d = 1 for catalyzed D-D).

This log–log version of the Lawson diagram illustrates the great progress that has been made in improving energy confinement in magnetic fusion devices since the

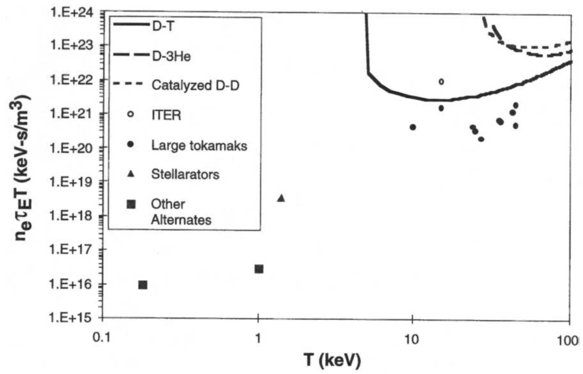

Fig. 4. $n_e\tau_E T$ requirements for ignition in DT and selected advanced fuels in keV-s/m³. Also shown are typical values of $n_e\tau_E T$ achieved experimentally in various magnetic confinement systems.

early 1960's when all magnetic confinement devices had performance similar to the "other alternates"; and shows how close we have come to achieving the conditions required for DT ignition in large tokamaks. Such progress can lead to optimism that substantial further improvements in $n_e\tau_E T$ will soon be forthcoming. However, log–log plots are deceiving. The apparently small gap between our what has been achieved in large tokamaks and what is expected from the ITER design point leads to a substantial increase in size, contributing to the order-of-magnitude increase in the cost of ITER relative to existing large tokamaks. The very substantial cost of an ignition-scale tokamak has driven a crisis in the U.S. magnetic fusion program, and leading to the recent restructuring of the U.S. program.[14]

It is necessary to increase $n_e\tau_E T$ by a further factor of 22 beyond what is required for ignition in D-T in order to achieve ignition in the next most reactive fuel, D-³He. This is similar to the ratio of the $n_e\tau_E T$ expected from ITER to the best that has been achieved in TFTR. Experience in tokamaks suggests that an increase in confinement requirements of this magnitude will lead to an order-of-magnitude increase in cost of the minimum size device capable of ignition in D-³He relative to what would be required for ignition in D–T. We show in the next section that the situation gets worse when impurities and α-ash are considered.

6. IMPURITIES AND α-ASH FURTHER INCREASE $n\tau_E T$ REQUIREMENT

A ubiquitous product of both DT and advanced fusion fuel cycles are fast α-particles. These fast alpha particles thermalize through collisions with plasma electrons and ions, thereby providing the plasma heating required to sustain the fusion burn. A result of this generally beneficial process is the accumulation of thermal alpha particles (α-ash) in the plasma. These alpha particles displace fuel ions, thereby reducing the fusion reactivity at fixed plasma density or pressure. We assume that the rate at which α-ash is removed from plasma, τ^*_{He}, is proportional to the energy confinement time, τ_E, because the same turbulent processes are responsible for the transport of thermal energy and particles. Experience with helium pumping in tokamaks indicates that helium can be transported radially nearly as fast as the thermal energy. However, the α-ash generally recycles several times at the divertor (or limiter) before it can be pumped, so that a relative helium pumping time, τ^*_{He}, in the range 5 to 10 can reasonably be expected. In particular, the ITER design point takes $\tau^*_{He}/\tau_E \approx 10$, which this largely explains why the ITER operating point appears to be above the ignition curve in Fig. 4.

The equilibrium density of α-ash can be estimated as

$$n_\alpha = n_1 n_2 \langle\sigma v\rangle \tau^*_{He}$$

so that the relative density of α-ash,

$$f_\alpha \equiv \frac{n_\alpha}{n_e} = f_1 f_2 \frac{\tau^*_{He}}{\tau_E} \langle\sigma v\rangle n_e \tau_E$$

is independent of density, and can easily be included in a Lawson-type analysis of confinement requirements as a function of temperature.

In Fig. 5 we show the confinement requirements for ignition in D-T, D-³He, and catalyzed D-D corrected for finite helium removal rates (τ^*_{He} = 5 and 10), and for the presence of levels of the trace impurities typical of what is achieved in magnetic confinement experiments. In preparing the data for Fig. 5, we assume one light impurity, carbon, at a relative density n_C/n_e = 1%, and one heavy impurity, iron, at a relative density n_{Fe}/n_e = 0.02%. In a purely hydrogenic plasma this impurity mixture would result in a modest Z_{eff} = 1.43.

The inclusion of impurities and α-ash has a relatively modest impact on the confinement requirements for ignition in DT, with the minimum value of the confinement triple-product increasing from 3.0 × 10²¹keV-s/m³ in the absence of impurities to 4.9 × 10²¹keV-s/m³ at τ^*_{He}/τ_E = 5, and 8.5 × 10²¹keV-s/m³ at τ^*_{He}/τ_E = 10. However, in D-³He the impact is substantial, with the minimum confinement triple-product increasing from 6.7 × 10²²keV-s/m³ in the absence of impurities to 2.4 × 10²³keV-s/m³ at τ^*_{He}/τ_E = 5; while the fusion burn is can-

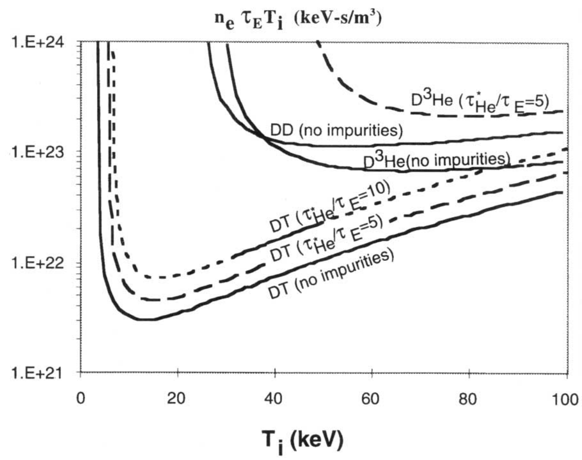

Fig. 5. Confinement triple-product required for ignition in DT and selected advanced fuels in the presence of achievable concentrations of impurities (1% C and 0.02% Fe) and helium ash as determined by the helium pumping efficiency, τ_{He}^*/τ_E.

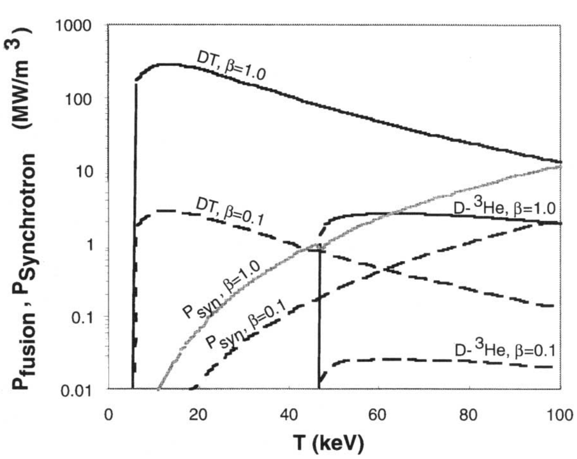

Fig. 6. Fusion heating and synchrotron loss power for DT and D³He.

not be sustained with $\tau_{He}^*/\tau_E > 5$. Ignition in catalyzed D-D, which requires a confinement triple-product of 1.1×10^{23}keV-s/m³ in the absence of impurities, cannot be achieved for relative helium confinement times τ_{He}^*/τ_E above 2.2.

Impurities and α-ash have a larger impact on ignition requirements for advanced fuels because bremsstrahlung is a much more important component in their ignition power-balance at the optimal temperature (that is, the temperature which minimized the confinement triple-product required for ignition). In a pure DT plasma ($f_d = f_t = 1/2$) at the optimal temperature of 14 keV the bremsstrahlung power is only 6.4% of the fusion heating power; while in a pure D-³He plasma ($f_d = 1/2$, $f3_{He} = 1/4$) at the optimal temperature of 68 keV the bremsstrahlung power is 23% of the fusion heating power; and in a pure catalyzed D-D plasma (composed of deuterium plus equilibrium concentrations of tritium and ³He) at the optimal temperature of 54 keV the bremsstrahlung power is 33% of the fusion heating power. The inclusion of impurities and α-ash both reduces the fusion power by displacing fuel ions, and increases the bremsstrahlung power by increasing Z_{eff}.

These effects can be compensated in a D-T fueled reactor by modest improvements in the conducted power loss. At $\tau_{He}^*/\tau_E = 5$ the equilibrium α-ash fractions at the optimal temperature (14 keV) is 5.3% while the fractional power loss from bremsstrahlung has risen to 14%; At $\tau_{He}^*/\tau_E = 10$ the α-ash fraction at the optimal temperature (16 keV) is 16% and the bremsstrahlung loss is 23% of the fusion heating power.

In D-³He at $\tau_{He}^*/\tau_E = 5$ the equilibrium α-ash fraction at the optimal temperature (85 keV) is 12%, and the fractional power loss from bremsstrahlung radiation has risen to 53%. The α-ash fraction rises sharply for $\tau_{He}^*/\tau_E > 5$.

7. SYNCHROTRON RADIATION

Synchrotron radiation is also an important contributor to the power balance for operating points at the high temperatures required by D-³He. Synchrotron radiation is a single-particle effect, so that the radiated power scales with n_e rather than with n_e^2. Hence, it is necessary to specify both the plasma density and temperature to compare the synchrotron power loss to the fusion power. We do this by specifying the both the magnetic field (which is required in any case in computing the synchrotron power) and the value of $\beta = 2\mu_0 p/B^2$. Calculation of the synchrotron power losses is complex, and dependent on the configuration (particularly on ∇B), and on the reflectivity of the wall surrounding the plasma to microwave and far-infrared radiation.[15] We will not attempt to include the synchrotron losses self-consistently in the power balance, but only compare the synchrotron power to the fusion heating power to assess its possible importance in the overall power balance using a formula due to Uckan.[16] We consider the ignited operating points shown in Fig. 5 with $\tau_{He}^*/\tau_E = 5$, assume a magnetic field of 5 T, and a wall reflectivity R = 0.9995. The resulting fusion power density and synchrotron power density, $p_{synchrotron}$ are shown in Fig. 6 for $\beta = 0.1$ and 1.0.

First consider the dashed curve in Fig. 6 corresponding to $\beta = 0.1$. The DT curve peaks at a fusion power density of a few MW/m^3, typical of conceptual designs for tokamak reactors. The synchrotron power at relevant temperatures (10–20 keV) is less than 0.1 MW/m^3, so that synchrotron radiation is not a dominant term in the DT power balance. However, the fusion power density of D-^{3}He is only a few 10's of kW/m^3. When the effects of α-ash are included, the maximum D-^{3}He fusion power density is 107 times smaller than what can be achieved with the same $\tau_{He}*/\tau_E$ in D-T; while at the higher temperatures required for ignition in D-^{3}He the synchrotron loss power has risen to several 100 kW/m^3. Hence, the synchrotron power is expected to be one of the dominant terms in the D-^{3}He power balance at $\beta = 0.1$; in fact, it appears that ignition cannot be achieved in D-^{3}He at such low values of β because the synchrotron loss power greatly exceeds the D-^{3}He fusion power.

The solution to this dilemma suggested by proponents of advanced fuels is to assume that magnetic confinement systems can be developed that can be operated at $\beta \geq 1$. Since the fusion power density rises far more quickly with increases in β than the synchrotron losses, this leads to the more optimistic situation shown by the solid curves in Fig. 6. At $\beta = 1$ the D-^{3}He fusion power density increases by a factor of 100, and is comparable to that of D-T at $\beta = 0.1$; while the synchrotron loss power rises somewhat slower than linearly with β. At $\beta = 1$ the synchrotron loss power remains an important term in the D-^{3}He power balance, but it is now smaller than the fusion power for temperatures in the range 47 keV $< T \leq 63$ keV. With suitable adjustments to the magnetic field and electron temperature it is likely that overall power balance can be achieved without an excessive increase in the $n_e\tau_E T$ requirement beyond 2.4×10^{23}keV-s/m^3 required against bremsstrahlung losses at $\tau^*_{He}/\tau_E = 5$.

However, instead of comparing a $\beta = 1$ D-^{3}He reactor to a $\beta = 0.1$ D-T reactor, we should consider what can be achieved in D-T at $\beta = 1$. Increasing β to 1.0 increases the DT fusion power density to several 100 MW/m^3! While such high fusion power densities might lead to excessive power loading on the first wall, it can still be used to advantage. The higher fusion power density together with the lower ignition requirement can be used to reduce the overall size and/or the magnetic field of a DT reactor relative to what would be required in D-^{3}He thereby reducing the wall loading to acceptable levels and reducing both reactor cost and unit size.

8. CONCLUSIONS

Given the present database, it seems clear that the DT fuel cycle will lead to more compact and economic fusion power reactors. The DT fuel cycle has the least demanding ignition requirements (by a factor of ~50 in $n\tau_E T$ relative to D-^{3}He for an achievable α-pumping efficiency, $\tau^*_{He}/\tau_E = 5$). Efforts to achieve higher values of $n\tau_E T$ in magnetic fusion experiments have been the prime driver towards larger experimental facilities. A fifty-fold increase in the confinement triple-product required for ignition (or high fusion gain) in advanced fuels will inevitably lead to larger and more expensive reactors than that which would be required by the DT fuel cycle. The DT fuel cycle also has the highest fusion power density (by a factor of ~100 relative to D-^{3}He for $\tau^*_{He}/\tau_E = 5$). Fusion power density is a critical parameter in determining both the overall economics of fusion power systems and in determining the smallest practical unit size. The hundred-fold decrease in fusion power density for advanced fuels will inevitably lead to physically larger (and more expensive power) plants which produce less electricity than a DT fueled power plant based on the same confinement system.

Of the advanced fuels considered only D-^{3}He is a plausible alternative to DT. However, synchrotron radiation will clearly be a significantterm (perhaps the dominant term) in the power balance for D-^{3}He. Careful calculations of synchrotron losses should be included in future D-^{3}He conceptual reactor designs. If D-^{3}He is to replace DT as the most plausible fuel cycle for fusion power systems, we will require (i) Very high-β systems (to reduce synchrotron radiation); (ii) Excellent impurity control (better than can be achieved with a high recycling divertor); and (iii) Greatly improved energy confinement ($n_e\tau_E T \geq 2 \times 10^{23}$keV-s/$m^3$). It follows from the first two requirements that neither tokamaks nor stellerators are likely candidate systems for advanced fuel reactors. The best energy confinement that has been achieved in other alternate confinement systems, $n_e\tau_E T$ of a few 10^{16}keV-s/m^3, is nearly seven orders of magnitude below that which is required for ignition in D-^{3}He. Clearly, much work would be required to develop a physics basis for confinement systems suitable for advanced fuels. Finally, we note that High-β, improved impurity control, and improved energy confinement all improve prospects for DT operation in the same device. In judging prospects for advanced fuel reactors we must compare advanced fuel performance to what might be achieved in a DT fueled reactor based on the same underlying confinement scheme, using the same rules to determine β-limits, energy confinement, etc.

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