THE FEASIBILITY OF USING D-^{3}HE AND D-D FUSION FUELS

P.E. Stott

Association Euratom-CEA,
Centre de Cadarache, 13108 Saint Paul lez Durance, France

A careful study of the conditions required to burn D-^{3}He and D-D fuels in a fusion reactor, with realistic models for bremsstrahling and synchrotron radiation losses, shows that the low reactivity of D-^{3}He and D-D fusion reactions severely restricts the choice of fuel mixtures that can be brought to ignition and requires very low levels of impurities and alpha particle ash, with plasma temperature, density, beta and energy confinement time that are far beyond the capability of any known magnetic confinement system. The fuel mixtures of D-^{3}He and D-D that can be brought to ignition produce large fluxes of neutrons and there are serious problems with fuel cycles and reserves.
PACS: 28.52.Cx

INTRODUCTION

The favourite candidate fuel for a fusion reactor is deuterium and tritium (D-T) — it has the largest cross-section of all the fusion reactions and it burns at the lowest temperature. The D-T cycle has two principal disadvantages: (i) it produces neutrons that need shielding and will damage and activate the reactor structure, (ii) breeding tritium requires the extra complexity, cost and radial space for a lithium blanket. The aneutronic D-^{3}He reaction is usually thought to be the solution to these problems and the D-D reaction is seen as the ultimate, inexhaustible source of fusion energy.

The fusion reactions between D, ^{3}He and T are well known:

$$D + D \rightarrow n(2.45MeV) + {}^3He(0.817MeV)$$
$$D + D \rightarrow p(3.02MeV) + T(1.01MeV)$$
$$D + {}^3He \rightarrow p(14.68MeV) + {}^4He(3.67MeV)$$
$$D + T \rightarrow n(14.1MeV) + {}^4He(3.5MeV)$$

All of these reactions have to be considered — a reactor fueled with a mixture of D and ^{3}He cannot be free from parasitic D-D reactions and one fueled with D-D produces ^{3}He and T as intermediate reaction products of the 1st and 2nd (D-D) reactions:

a) if the ^{3}He and T intermediate products remain in the reactor, they will burn with more D via the 3rd and 4th reactions. The complete chain is known as the *fully-catalysed D-D reaction*,

b) if the ^{3}He and T are removed[1] after giving their kinetic energy to heat the plasma but before they burn with further D, this is known as the *uncatalysed D-D reaction*. In principle the extracted ^{3}He together with the ^{3}He produced by β decay of the extracted T could be used to fuel a separate D-^{3}He reactor — a series of "breeder" (D-D) and "satelite" (D-^{3}He) reactors. However it is virtually impossible to ignite the uncatalysed D-D reaction (or one where only the T is retained and burned *in situ* — all the "prompt" ^{3}He has to be retained and burned in the D-D breeder. This allows the following scenarios,

c) all of the prompt ^{3}He burns in the D-D reactor but all of the T is extracted — this we will call it the *^{3}He single-catalysed D-D reaction*. The stored T β decays to ^{3}He to be used as fuel either in a separate D-^{3}He reactor or in step (d),

d) the ^{3}He produced by β decay of the stored T is returned to enhance the ^{3}He concentration in the breeder reactor. Long term fuel equilibrium will be reached after many decades when the rate of ^{3}He production by β decay from the stockpile of stored T equals the rate of T production — then there will be effectively twice the amount of ^{3}He to burn. We refer to this as the *^{3}He double-catalysed D-D reaction*.

In this paper we summarise the main conclusions of a carefull study[1] of the plasma conditions that would be required to burn D-^{3}He and D-D fuels in a fusion reactor taking into account realistic models for losses by bremsstrahling and synchrotron radiation.

IGNITION REQUIREMENTS FOR D-^{3}HE AND D-D AND FUEL MIXTURES

The plasma conditions required for ignition in a mixture of D and ^{3}He are calculated using a zero-dimensional model that takes into account radial profiles of density and temperature. The relative fuel concentration n_{He}/n_D is specified explicitly for scenarios with an external supply of ^{3}He, or implicitly for scenarios using the self supply of ^{3}He and T produced via the primary D-D reactions.

Impurities and helium ash have a major impact on fuel dilution and bremmstrahlung radiation loss. We use as a benchmark concentrations (10% ^{4}He, 2% Be and 0.16% Ar) that were taken for the ITER-98 study and also calculate the ^{4}He ash concentration self-consistently in terms of the ratio of effective alpha particle confinement time τ_α^* to the energy confinement time τ_E. Typically D-T requires $\tau_\alpha^*/\tau_E < 15$ for ignition[2] but D-^{3}He requires $\tau_\alpha^*/\tau_E < 3$ and the ^{3}He-catalysed D-D reactions need $\tau_\alpha^*/\tau_E \approx 1$.

The optimum core plasma temperature for burning these fuel mixtures is around 70 keV. Lower temperatures are inaccessible due to bremsstrahung, and higher temperatures are ruled out by synchrotron loss, The ratio of bremsstrahlung loss to fusion heating power is plotted in Figure 1. It is immediately clear that bremsstrahlung

[1] We do not discuss in detail the selective removal of the intermediate ^{3}He and T fusion products — this has been proposed and discussed by other authors and it is claimed that it could be accomplished without adversely affecting confinement of the thermal plasma. Note however it has not been demonstrated experimentally and would add to the technical complexity of the reactor.

radiates all the fusion power for a plasma with the ITER-98 impurity concentrations. With half of the ITER-98 impurities $F_b > 0.6$. The optimum fuel mixture is D:^{3}He (70:30). At higher concentration of ^{3}He, the relative bremsstrahlung loss increases due to Z_{eff} and to fuel dilution — so that $F_b \approx 0.8$ for a D:^{3}He (50:50) fuel mix with half the ITER-98 impurities. Bremsstrahlung loss exceeds the fusion heating in ^{3}He-rich fuel mixtures, typically $F_b > 1$ for D:^{3}He (<25:>75) fuel concentrations even in a plasma with no impurities or ^{4}He ash. This rules out the "D-lean" mixtures, typically D:^{3}He(15:85), that have been advocated as a means of realising the aneutronic potential of D-^{3}He fuel by reducing the parasitic D-D reactions. Also bremsstrahlung loss exceeds fusion heating in plasmas with very low ^{3}He concentration and especially those with zero ^{3}He. In particular this eliminates both the uncatalysed D-D reaction (even with no impurities) and the T-catalysed D-D reaction (with only a small amount of impurity). Thus schemes that seek to remove all of the prompt ^{3}He from a D-D breeder to fuel a satellite D-^{3}He reactor also fail.

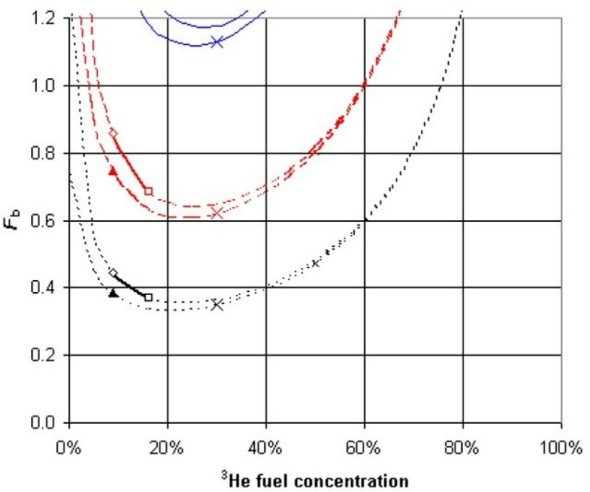

Fig.1. Power loss by bremsstrahlung relative to fusion heating power versus the ^{3}He fuel concentration $n_{He}/(n_{He} + n_D)$ in a D-^{3}He fuel mixture at central temperature of 70 keV. The solid lines have 10% ^{4}He, 2% Be and 0.16% Ar impurities, the dashed lines have 5% ^{4}He, 1% Be and 0.08% Ar and the dotted lines have no impurities. The lower of each pair of curves (with solid points) has T retention, crosses indicate the D-^{3}He reaction with $n_{He}/(n_{He} + n_D)$ = 0.3 and 0.5 respectively and triangles indicate the fully-catalysed D-D reaction. The upper of each pair of curves (with open points) has T removal, diamonds indicate the ^{3}He single-catalysed and squares the double-catalysed D-D reactions. The thicker section of the line between these points indicates the range of ^{3}He concentrations accessable with self generation of ^{3}He from the D-D reaction (including ^{3}He from β decay of T)

Synchrotron radiation is an important loss mechanism in high temperature plasmas. We use expressions given by Albajar *et al* [3, 4] that are based on a statistical fit to an exhaustive set of numerical calculations of the absorption coefficients for arbitrary density and temperature profiles in toroidal geometry with elongated cross section. The fraction of power lost by synchrotron radiation increases strongly with temperature — but at fixed temperature it is minimised by high β.

REACTORS FUELED WITH D-^{3}HE

Values of τ_E for ignition (Q = 100) of the optimum D:^{3}He (70:30) fuel mixture are plotted against central β in Figure 2 for 70 keV central temperature with a = 3 m and B = 6 T. Impurity concentrations are 1% Be and 0.08% Ar (corresponding to ½ of the ITER98 values) with the ^{4}He ash calculated self-consistently for τ_α^*/τ_E = 2 and 3.

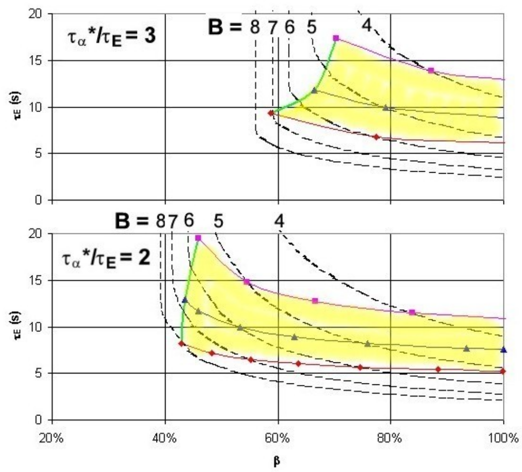

Fig.2. Transport energy confinement time τ_E plotted against central β for ^{3}He fuel concentration $n_{He}/(n_{He} + n_D)$ = 30% with advanced temperature profile, central T = 70 keV, plasma radius a = 3 m and impurity concentration 1% Be and 0.08% Ar with τ_α^*/τ_E = 2 and τ_α^*/τ_E = 3. The magnetic field B is in steps of 1 T over the range 4 to 8 T (the dashed curves). The solid curves are lines of constant wall power flux (and thus roughly constant plasma density) at P_w = 1.25 MWm^{-2} with n ≈ 2.75x10^{20} m^{-3} (line with square points), 2.5 MWm^{-2} and 4x10^{20} m^{-3} (triangles), 5 MWm^{-2} and 5.8x10^{20} m^{-3} (diamonds). The effective operating range indicated by the shaded region lies between the low β limit and β = 100% and within the limits 1.25 < P_w < 5 MWm^{-2}

Note that there is a critical lower value of β below which ignition becomes impossible when the combined loss by synchrotron and bremsstrahlung radiation exceeds the fusion heating. The β limits set constraints on the effective range of B for given values of plasma density and average power flux at the first wall P_w.

The coresponding operating space in terms of tokamak confinement factor H versus the line-average electron density normalised to the Greenwald limit n_L/n_G is plotted in Figure 3. The lowest values of H and n_L/n_G are at the low β limit (and the highest value of τ_E) due to the strong B dependence in the empirical tokamak scalings. The low β limits correspond to $\beta_N \approx 11$ for τ_α^*/τ_E = 2 and $\beta_N \approx 16$ for τ_α^*/τ_E = 3.

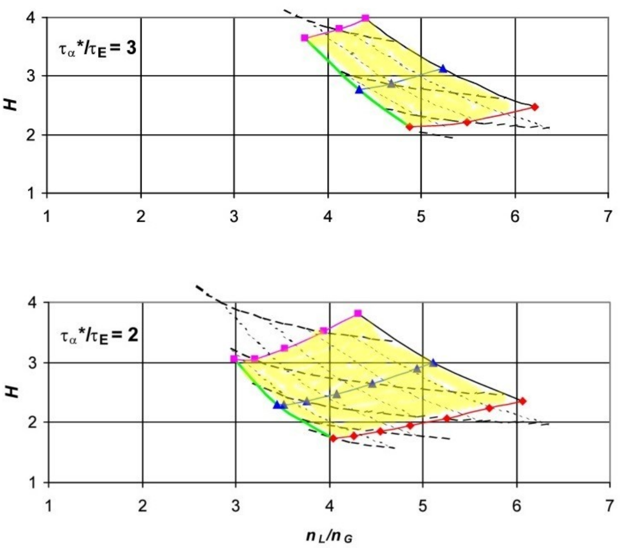

Fig. 3. Confinement factor H *plotted against the line-average electron density normalised to the Greenwald limit* n_L/n_G *for* $\tau_\alpha^*/\tau_E = 2$ *and* $\tau_\alpha^*/\tau_E = 3$. *Plasma parameters and symbols are the same as in figure 2. The shaded region is bounded by* $1.25 < P_w < 5$ *MWm*$^{-2}$. *The upper limit of central* $\beta = 100\%$ ($\beta_{av} \approx 33\%$ *and* $\beta_N \approx 25$) *is indicated by a thick black line. The low* β *limits, indicted by a thick green line, correspond to the limits in figure 2 at central* $\beta \approx 45\%$ ($\beta_{av} \approx 15\%$ *and* $\beta_N \approx 11$) *for* $\tau_\alpha^*/\tau_E = 2$ *and central* $\beta \approx 65\%$ ($\beta_{av} \approx 22\%$ *and* $\beta_N \approx 16$) *for* $\tau_\alpha^*/\tau_E = 3$. *The dotted lines are contours of central* β *at intervals of 10%* ($\Delta\beta_{av} \approx 3.3\%$ *and* $\Delta\beta_N \approx 2.5$). *The dashed lines indicate magnetic field* B *at intervals of 1 T*

D-D REACTORS

Reactor scenarios based on a D-D fuel cycle have the obvious attraction of not relying on external supplies of ^{3}He — and reserves of D are essentially limitless. However burning D-D requires even more demanding conditions than D-^{3}He and these fusion reactions are extremely sensitive to impurities. As noted already, bremsstrahlung loss even in pure plasma rules out the uncatalysed and the T-catalysed D-D reactions leaving the following potential routes for burning D-D fuels:

(1) a "breeder/burner" cycle. The breeder stage would use the ^{3}He single-catalysed D-D reaction with all of the "prompt" ^{3}He left to burn *in situ* so that $n_{He}/(n_{He} + n_D) \approx 8\%$. All of the T would be removed, put into store and allowed to β decay into ^{3}He to be used as fuel in a second stage — either a D-^{3}He reactor with $n_{He}/(n_{He} + n_D) \approx 30\%$ as discussed already or (2),

(2) a ^{3}He double-catalysed D-D reactor that is "kick-started" using an existing stock of ^{3}He until (in the long term) the T to ^{3}He decay cycle becomes self-sustaining to maintain $n_{He}/(n_{He} + n_D) \approx 15\%$,

(3) a fully-catalysed D-D reactor, with all intermediate fusion products left to burn *in situ* with the primary D-D fuel.

In Figure 4, values of the confinement parameter H are plotted against the line-average electron density normalised to the Greenwald limit n_L/n_G for the ^{3}He single-catalysed and double catalysed D-D reactions. (The fully catalysed case falls between the two and has been left out for clarity). These points show the optimum values of H and n_L/n_G for a range of plasma minor radii 4 m < a < 2 m and for average wall power flux in the range 1.25 MWm^{-2} to 5 MWm^{-2}.

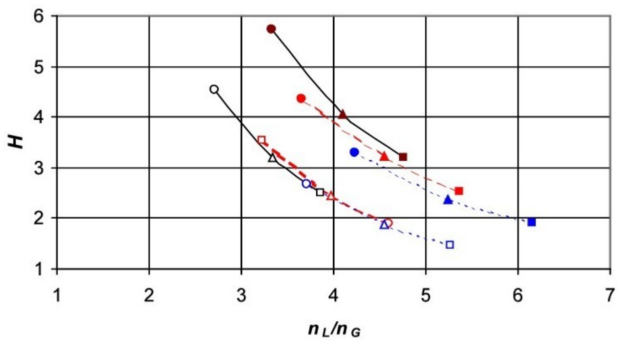

Fig. 4. H *versus* n_L/n_G *for the* ^{3}*He single-catalysed D-D reaction (curves with solid points — impurities are 0.5% Be and 0.04% Ar) and the double-catalysed D-D reaction (curves with open points — impurities are 1% Be and 0.08% Ar). Both reactions have* $\tau_\alpha^*/\tau_E = 1$ *and central temperature 70 keV. Solid lines are 1.25 MWm*$^{-2}$, *dashed lines are 2.5 MWm*$^{-2}$, *dotted lines are 5 MWm*$^{-2}$. *Circles* a *= 2 m, triangles* a *= 3 m, squares* a *= 4 m*

The ^{3}He single-catalysed D-D reaction would be the essential first step in the cycle to manufacture ^{3}He fuel from D. But this is extremely sensitive to alpha ash retention and impurities — ignition requires $\tau_\alpha^*/\tau_E \approx 1$ with maximum impurities Be ≈ 0.5% and Ar ≈ 0.04% (thus only ¼ of ITER-98) and typically $H \approx 4$ and $n_L/n_G \approx 4$. The sensitivity to alpha ash is illustrated in Figure 5 — even with zero levels of other impurities, this reaction requires $\tau_\alpha^*/\tau_E < 2.5$. The double-catalysed reaction is slightly more robust and could operate at $H \approx 3$ and $n_L/n_G \approx 3.5$ with Be ≈ 1% and Ar ≈ 0.08% (thus ½ of ITER-98) and $\tau_\alpha^*/\tau_E \approx 1$.

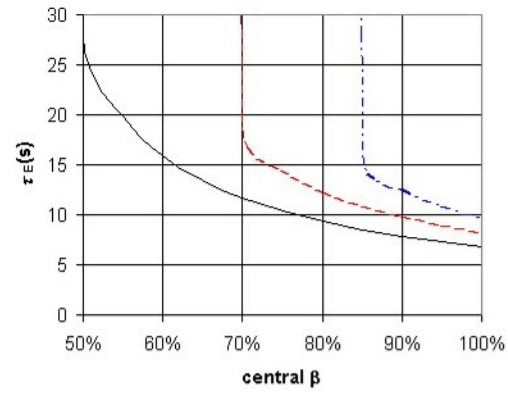

Fig. 5. τ_E *versus* β *for the* ^{3}*He single-catalysed D-D reaction with* <u>*zero*</u> *impurities for* $\tau_\alpha^*/\tau_E \approx 1$ *(solid line), 2(dashed line) and 2.5 (dashed-dotted) demonstrating the extreme sensitivity to alpha ash*

Operation of the single-catalysed D-D reaction in a driven mode at $Q = 10$ has also been studied but is not discussed here due to lack of space. This mode does not give a substantial reduction in the required parameters nor does it significantly relax the limits on impurities.

NEUTRONS

A full discussion of the relative activation and neutron damage is outside the scope of this paper, but Figure 6 shows that none of the accessable reactions is aneutronic — a D-^{3}He reactor would produce about 40% of the neutrons of a D-T reactor of similar power output (half of these would be 2.4 MeV and half would be 14 MeV). The single catalysed reaction produces about 85% (all 2.4 MeV) neutrons compared to D-T and the double-catalysed reaction about 50% (all 2.4 MeV).

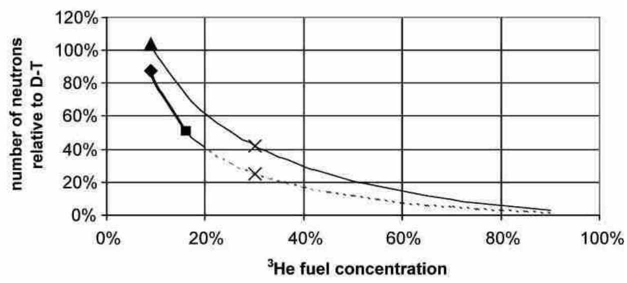

Fig. 6. Total number of neutrons (2.4 + 14.1 MeV) for D-^{3}He and D-D fuel mixtures relative to a D-T reactor of the same fusion power. The solid line indicates T retained and burned, the dotted line has T removed

FUEL REQUIREMENTS AND RESOURCES

Overall world energy consumption today is equivalent to about 3x10^8 TJ (3x10^{20} J) per year. Demand for energy continues to grow steadlily — it is predicted to double by the year 2050 and double again, thus reaching more than 10^9 TJ, by 2100. A network of D-^{3}He fusion power stations with the capacity to generate 10^8 TJ(e) per year (thus 10% of 2100 world energy) would consume about 500 tonnes of ^{3}He per year. There is no significant terrestrial reserve of ^{3}He — the only prospects are lunar mining or manufacture via the D-D reaction. The Moon's surface has accumulated ^{3}He by exposure to the solar wind but the concentration of ^{3}He in the lunar surface is so low that a tonne of lunar rock contains less energy than a tonne of coal. Fusion based on lunar ^{3}He would require the mining of 6x10^{10} tonnes (60,000 million tonnes) of lunar rock each year to supply 10^8 TJ per year — roughly 20 times present-day worldwide coal production — and an order of magnitude more would be required for fusion to supply all the world's energy in 2100. Such an enterprise would be enormously expensive and, with the difficulty of burning the fuel, it is difficult to see that this route would be competitive ecomonically. Nor would the Moon be an inexhaustible source of fusion energy — lunar reserves of ^{3}He would be exhausted in a few hundred years at 10^9 TJ per year.

The alternative route to ^{3}He production, from D-D, introduces other problems. Large tritium stockpiles would be needed to start-up and maintain a self-sustaining network of ^{3}He double-catalysed D-D reactors — about 4000 tonnes of T for 10^8 TJ per year, 40,000 tonnes for 10^9 TJ per year. Such quantities of tritium are many orders of magnitude larger than the amounts that have been produced in fission reactors. The manufacture and long term storage of tritium on such a massive scale clearly poses enormous risks of accidental release or diversion into weapons systems. It would be hard to find acceptance in present day society and fusion[1] certainly would loose one of its significant advantages over fission. Even if these risks of tritium storage and inventory could be accepted, there are serious operational and commercial penalties to consider due to the long delay between T production and decay to ^{3}He — the supply of ^{3}He fuel will lag well behind the demand both for a single power station and a complete network. For example, there will be a 20 year delay before the supply of ^{3}He reaches 66% of the tritium production rate — 50 years for it to approach steady-state. Operationally, it is difficult to see how substantial energy production can be started-up on a realistic time scale.

With ignition almost impossible for a ^{3}He single-catalysed D-D reactor, the only option seem to be to inherit a stockpile of ^{3}He from lunar mining or from T over-production by an earlier generation of D-T reactors. But the later scenario presupposes that D-T fusion will already be well established with solutions to the problems of neutron damage and radioactive waste disposal already in place and begs the obvious question — if these problems are solved, why then switch to a more difficult fuel cycle? Proposals[5] that the T production rate could be increased by adding a Li blanket to the D-D breeder seem to be adding one of the main arguments against D-T onto the already long list of problems with D-D.

CONCLUSIONS

Burning mixtures of D and ^{3}He fuels in a fusion reactor would be extremely difficult requiring much higher plasma temperature, density, beta and energy confinement time than a comparable D-T reactor. A fuel mixture of 30% ^{3}He and 70% D has the lowest requirements in terms of $n_e\tau_E$ and τ_E. This fuel mixture is sensitive to impurities and helium ash, with an upper limit on impurities typically half of that assumed for ITER with D-T and requiring $\tau_\alpha^*/\tau_E \approx 2$. In terms of the tokamak scalings the minimum requiremenst are typically $H > 3$, $n_L/n_G > 3$ and $\beta_N \approx 11$.

One of the main attractions held out for D-^{3}He has been the prospect of no neutrons, but the so-called D-lean fuel mixtures that have been advocated to reduce the number of neutrons cannot reach ignition due to the effects of fuel dilution and bremmsstrahlung loss. The optimum fuel mixture (30% ^{3}He: 70% D) would produce substantial numbers of 14 and 2.4 MeV neutrons with the total neutron flux reduced by only a factor 3 compared to a D-T reactor producing the same fusion power. The 14 MeV neutrons can be avoided only by T extraction cycles but this brings the extra complexity and risks of storing large quantities of T storage until it decays into ^{3}He. The fully catalised D-D reaction offers no appreciable reduction in neutrons compared to D-T.

Even if all the problems with D-^{3}He can be overcome, the barrier would be the lack of a credible and sustainable

[1] Although D-T fusion reactors would have to manufacture and burn large quantities of tritium (about 500 tonnes per year for 10^8 TJ(e)), the cycle time between manufacture and burning T would be much shorter with a much smaller quantity held in store.

source of ^{3}He fuel. We have therefore looked at various schemes to manufacture ^{3}He from D-D — in particular scenarios where all the intermediate T is extracted from a D-D reactor and stored until it decays to ^{3}He that can be used as fuel. In principle such a fuel cycle could be self-sustainable but it has a very long start up time and requires the safe storage of very large quantitities of T. However the basic breeder stage of this cycle (which we call the ^{3}He single-catalysed D-D reaction) requires plasma conditions that are far beyond the capability of any known magnetic confinement system and, in particular, has severe limits on impurity concentrations (typically Be and Ar concentrations less than one quarter of those assumed for ITER) and on alpha particle ash ($\tau_\alpha^*/\tau_E \approx 1$). This seems to rule out the possibility of breeding ^{3}He in one reactor and burning it in another. Perhaps one day far into the future these fuels will be brought to yield their potential, but the difficulties are so great and the benefits seem to be so marginal that, at the present time, these D-^{3}He and D-D fuels cannot be thought of as alternatives to D-T.

REFERENCES

1. P.E. Stott, submitted to PPCF
2. D. Reiter, G.H. Wolf and H. Kever//*Nuclear Fusion (30)*. 1990, p.2141
3. F. Albajar, J. Johner and G. Granata//*Nuclear Fusion* (*41)*. 2001, p.665
4. F. Albajar, M. Bornatici and F. Engelmann// *Nuclear Fusion (42)*. 2002, p.670
5. V.I. Khvesyuk and A.Yu. Chirkov//*Plasma Physics Control. Fusion (44).* 2002, p.235

О ВОЗМОЖНОСТИ ИСПОЛЬЗОВАНИЯ D-^{3}He и D-D ТОПЛИВ В РЕАКЦИЯХ СИНТЕЗА

П. Стотт

Тщательные исследования условий, необходимых для горения D-^{3}He и D-D топлив в реакторе синтеза, использовавшие реалистические модели описания тормозного и синхротронного излучения, показывают, что низкая реактивность реакций D-^{3}He и D-D резко ограничивает выбор горючих смесей , которые могут быть подожжены, а также требует очень низкого уровня примесей и гелиевой золы при значениях температуры и плотности плазмы, параметра бета и времени удержания энергии, значительно превышающих возможности любой из известных систем магнитного удержания. Смесь горючих D-^{3}He и D-D, которая может быть доведена до горения, создаёт большие потоки нейтронов, а также существуют серьёзные проблемы с циклом горючих и их резервами.

ПРО МОЖЛИВОСТІ ВИКОРИСТАННЯ D-^{3}He і D-D ПАЛИВ У РЕАКЦІЯХ СИНТЕЗУ

П. Стотт

Ретельні дослідження умов, необхідних для горіння D-^{3}He і D-D палив у реакторі синтезу, що використовували реалістичні моделі опису гальмівного і синхротронного випромінювання, показують, що низька реактивність реакцій D-^{3}He і D-D різко обмежує вибір паливних сумішей , котрі можуть бути підпалені, а також вимагає дуже низького рівня домішок і гелієвої золи при значеннях температури і щільності плазми, параметру бета і часу утримання енергії, значно перевищуючих можливості кожної з відомих систем магнітного утримання. Суміш пальних D-^{3}He і D-D, що може бути доведена до горіння, створює великі потоки нейтронів, а також існують серйозні проблеми з циклом пальних і їх резервів.