CRITICAL IMPURITY CONCENTRATIONS
FOR IGNITION OF CATALYZED-
DEUTERIUM FUSION PLASMAS

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ABSTRACT

The maximum concentrations f_{zc} of various impurity species that permit ignition of catalyzed-deuterium fusion plasmas have been calculated. If cyclotron radiation is negligible, the values of f_{zc} at 35 keV, where the fusion power density is maximum, are approximately one-fifth of the values allowed for D-T ignited plasmas at 14 keV. For any impurity species, the allowed f_{zc} decreases nearly linearly with increasing cyclotron radiation loss.

1. INTRODUCTION

Recently there has been renewed interest in the feasibility of toroidal fusion reactors operating in the "catalyzed-deuterium" fuel cycle — that is, where the tritium and helium-3 products of the D-D reactions are burned up at the same rate as produced.^(1,2) The overall cycle can be written

The principal advantages of the catalyzed-D cycle over the D T cycle stem from elimination of the tritium breeding requirement. Great flexibility now exists to design the blanket for minimum long-term activation; the tritium inventory can be reduced by up to two orders of magnitude; and the lithium fire hazard is eliminated. By tailoring the radial profiles of plasma density and temperature, it appears feasible to produce an ignited catalyzed-D plasma in a tokamak of reasonable size, subject to the constraint of relatively low $\bar{\beta}$ = average plasma pressure/magnetic field pressure (e.g., $\bar{\beta} < 0.10$).⁽³⁾

The feasibility of catalyzed-D operation depends most critically on minimization of plasma radiation levels. Cyclotron (or synchrotron) radiation has generally been regarded as the most severe obstacle to "advanced-fuel" reactors,⁽¹⁾ with impurity radiation always neglected. In this paper we present results of the calculations of the maximum allowed impurity concentration $f_z = n_z/n_D$ for attaining ignition, determined from recent coronal equilibrium calculations of impurity radiation and charge state. It is shown that when cyclotron radiation is

negligible, the maximum allowed f_z are a factor of 5 smaller than the values of f_z for ignition in D-T, which have been presented in Ref. (4). Moreover, the allowed f_z decreases approximately linearly with cyclotron radiation power, regardless of the impurity species.

2. MAXIMUM IMPURITY CONCENTRATION FOR IGNITION

The effect of impurity ions on the power balance follows the treatment used previously for D-T.⁽⁴⁾ The steady-state power balance equation for a zero-dimensional model is

$$\frac{\frac{3}{2}(n_e T_e + \sum_{\text{ions}} n_i T_i)}{\tau_E} + n_e n_z L_z + n_e L_H (n_D + 4n_{\text{He}}) + R_{\text{cy}} = P_c \quad (2)$$

where τ_E is the energy confinement time against nonradiative losses such as heat conduction, L_z and L_H are the impurity and deuteron emission rates per ion per free electron, n_D = deuteron density, n_{He} = equilibrium density of ^3He in the bulk plasma, $n_z = f_z n_D$ = impurity ion density, R_{cy} is the cyclotron radiation power density, and P_c is the power deposition of charged fusion-reaction products. The quantity L_z is calculated numerically using sophisticated coronal equilibrium calculations described in detail in Ref. (5).

In a low-beta tokamak plasma, electron temperatures exceeding 20 keV seem possible only in the center of the plasma, and then only in the case of very peaked temperature profiles. For $T_i > 20$ keV, it is probable that T_e will lag T_i somewhat, because of radiation power loss. For high-beta ignited plasmas, on the other hand, one expects that $T_e \approx T_i$. For the present calculations we use a zero-dimensional model with $T_e = T_i$.

The maximum f_z permitted for obtaining ignition, f_{zc} , is found by setting $\tau_E = \infty$ and $R_{cy} = 0$ in Eq. (2) — that is, the plasma power loss is dominated by impurity-ion radiation. Figure 1 shows the critical concentrations f_{cz} for ignition as a function of plasma temperature $T_e = T_i$, for six important impurity species found in toroidal fusion plasmas. (The values of f_{zc} for other impurity species can be found from their atomic numbers by interpolation. In general, radiation loss increases strongly with Z .⁽⁵⁾) The minimum ignition temperature, where the power of charged fusion-reaction products equals the D^+ and $^3He^{++}$ bremsstrahlung loss, is 26 keV. For a given plasma pressure, maximum fusion power density in catalyzed-D is reached at $T_e = T_i = 35$ keV.⁽¹⁾ The corresponding value in D-T is 14 keV. At 35 keV, the f_{zc} -values in catalyzed-D are about 5 times smaller than in D-T at 14 keV (see Fig. 6 of Ref. 4). Thus for catalyzed-D reactors, it is even more imperative that heavy metals not be used as liner or limiter material in the torus.

3. COMPARISON WITH CYCLOTRON RADIATION

The curves of Fig. 1 are applicable only when cyclotron radiation loss can be neglected. The cyclotron radiation power density is⁽⁶⁾

$$R_{cy} = 2.5 \times 10^{-32} \times \left(1 + \frac{T_i}{fT_e}\right) \left(1 + \frac{T_e}{204}\right) \frac{1-\beta}{\beta} n_e^2 T_e^2 K_c, \quad (3)$$

where f is the number of free electrons per ion, and K_c is the fraction of the emitted radiation that is not re-absorbed in the plasma.⁽⁷⁾ In a tokamak plasma, $\bar{\beta}$ (the spatially averaged value)

is likely to be limited to 0.10 or less by MHD instability. The magnitude of K_c is determined by the plasma size and by the vacuum wall reflectivity.⁽⁷⁾ At $\bar{\beta} = 0.10$ and $f_z = 0$, cyclotron radiation together with bremsstrahlung radiation are sufficient to prevent ignition of 35-keV catalyzed-D plasmas for $K_c = 0.0065$, even when $\tau_E = \infty$. We denote by $K_{cmax}(\beta, T_e)$ the maximum value of K_c for ignition, when $f_z = 0$ and $\tau_E = \infty$.

The principal adverse effect of high-Z impurities is enhanced radiation. In the presence of cyclotron radiation, the critical f_z is reduced, so that impurity plus cyclotron radiation losses balance the power density of charged fusion-reaction products:

$$f_z(T_e) = f_{zc}(T_e) \left[1 - \frac{K_c}{K_{cmax}(\beta, T_e)} \right], \quad (4)$$

where f_{zc} is the value shown in Fig. 1. For low-Z impurities, the reduction in fusion power density by depletion of reacting ions is the most important adverse effect. Provided that $\bar{Z}f_z \ll 1$, where $\bar{Z}$ is the average ion charge, the reduction in fusion power density by the depletion effect is nearly linear in f_z , so that Eq. (4) remains approximately valid.

Figure 2 shows the reduction in f_z with increasing K_c/K_{cmax} for various impurity species, calculated from Eq. (1) at $T_e = T_i = 35$ keV (the value giving maximum fusion power density). These curves are independent of β . At $K_c/K_{cmax} = 0.5$, the radiation from the indicated concentration of high-Z impurity equals the cyclotron radiation. For low-Z ions, the impurity-ion radiation, plus the reduction in fusion power by depletion, equal the cyclotron radiation.

In conclusion, even with zero cyclotron loss, the values of f_{zc} are smaller than commonly observed impurity concentrations in present-day tokamak experiments. Hence even more stringent precautions for impurity control must be taken for catalyzed-D operation than for D-T, and impurity-ion radiation must be treated with the same importance as cyclotron radiation in evaluating the designs of high-temperature catalyzed-D reactor plasmas.

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Fig. 1. Maximum allowed impurity concentration for ignition as a function of plasma temperature, assuming zero nonradiative losses and zero cyclotron radiation loss. The atomic number is shown in parentheses.

773705

Fig. 2. Maximum allowed impurity concentration for ignition at 35 keV, as a function of cyclotron radiation loss, assuming zero nonradiative losses. $K_{c \max}$ is the maximum allowed fraction of emitted cyclotron radiation that is not re-absorbed (e.g., $K_{c \max} = 0.0065$ at $\beta = 0.10$).