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CRITICAL IMPURITY CONCENTRATIONS FOR POWER
MULTIPLICATION IN BEAM-HEATED
TOROIDAL FUSION REACTORS

BY

R. V. JENSEN, D. E. POST, D. L. JASSBY

PLASMA PHYSICS
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86
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CRITICAL IMPURITY CONCENTRATIONS FOR POWER MULTIPLICATION IN
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ABSTRACT

Using the most recent evaluations of power loss by impurity radiation, we have calculated the maximum permitted impurity concentration for several species as a function of Q , the ratio of D-T fusion power to injected beam power. These criteria for maximum impurity concentration must be satisfied before applying the usual $n_e \tau_E$ vs T_i conditions for obtaining a given Q -value. For $Q > 3$, the critical impurity concentration f_{cz} varies as $Z^{-2.2}$ to -2.5 . The tolerable concentration of medium- and high- Z impurities for operation at low Q (≈ 2) can be at least one order of magnitude larger than the concentration allowed for ignition, provided that the plasma temperature is maintained by reacting ion beams.

1. INTRODUCTION

Present tokamak experiments indicate that it will be difficult to avoid at least trace levels of impurity ions in toroidal fusion-reactor plasmas. Line radiation from very small levels of heavy impurities ($n_z/n_i \gtrsim 10^{-3}$) can easily prevent ignition⁽¹⁻³⁾, and can also result in marked reductions in the attainable fusion power multiplication Q of driven reactors.⁽⁴⁻⁵⁾ (Q is defined as the deuteron-triton reaction rate per unit volume, times 17.6 MeV per reaction, divided by the injected power density.) If heavy impurities are avoided completely by using only low- Z elements for components inside the torus, as well as for the first wall coating, then one can expect a considerable population of light impurity ions in the discharge, because of the high sputtering coefficients for deuteron and triton bombardment of low- Z materials.⁽⁶⁾ While radiation from light impurities is relatively unimportant, in a magnetically confined plasma with restricted pressure the additional thermal pressure of the large number of electrons that accompany impurity ions results in a reduction in the reacting-ion population, and hence in fusion power output.

In this work we calculate the maximum tolerable concentrations of six representative impurity species in order to attain given Q -values in the range $Q = 1$ to ∞ . We recall that for D-T reactor applications that make use of the 14-MeV neutrons directly, such as fissile breeding, the minimum economically

useful Q-value is $Q \sim 1$.^(4,7) The minimum useful Q-value for a driven "pure fusion" reactor, assuming 70% injector efficiency and 40% thermal conversion efficiency of the blanket and heat exchanger, is $Q \sim 5$. The most desirable operating mode for a fusion power reactor is at $Q = \infty$, where the plasma temperature is sustained only by the energy deposition of fusion alpha particles; this state is referred to as the equilibrium ignition condition.

Previous work in defining impurity-level criteria for achieving certain fusion reactor goals has been rather limited. Meade⁽¹⁾ illustrated the variation in the $n_e \tau_E$ vs T_i criteria for ignition and for the "Lawson" condition, for several different concentrations of tungsten and molybdenum. Gervids and Kogan⁽²⁾ calculated the maximum impurity concentration that would still allow ignition at arbitrarily large temperature. This maximum concentration tends to occur where the D-T fusion reactivity is maximum — about 65 keV — and where even heavy impurities are almost completely stripped (if $T_e \sim T_i$). However, temperatures in this range are unrealistically large for confinement in toroidal geometry. Jassby⁽⁴⁾ calculated the reduction in attainable Q and in the maximum attainable fusion power density with increasing impurity content of 6-keV tritium plasmas driven by 200-keV deuterium beams. For driven plasmas of given current and varying temperature, Conn and Kesner⁽³⁾ showed how Q is degraded by increasing impurity content of iron and carbon.

In particular, it was found that economically interesting driven power reactors could tolerate several times the impurity content that would prevent ignition.⁽³⁾ Finally, Pistunovich⁽⁵⁾ has presented an expression for the $n_e \tau_E$ -value required to achieve a given Q as a function of temperature and impurity concentration.

The present study employs impurity radiation levels that have been calculated with the most up-to-date coronal-equilibrium treatment, including the best available estimates of electron collisional ionization and excitation, dielectronic and radiative recombination, and line transitions.⁽⁸⁾ (In the case of tungsten, the radiation level is a factor of 4 higher than previous estimates⁽²⁾ at 10 keV.) As discussed in Section 2, the maximum tolerable impurity concentration for a given Q -value between 1 and ∞ is nearly independent of $n_e \tau_E$. (Here τ_E is the energy confinement time against nonradiative losses, such as heat conduction.) This result allows us to derive impurity-concentration versus Q criteria that are approximately valid for any $n_e \tau_E$. Section 3 presents these critical impurity concentrations for a variety of impurity species for the economically practical range of beam-driven operation: $Q = 1$ to ignition, for $7 \leq T_e = T_i \leq 20$ keV. Some other consequences of plasma impurity levels are discussed in Section 4.

Our results are not peculiar to tokamak operation, but in fact are applicable to all closed D-T plasmas driven by reacting ion beams, when the injected beams and fusion alphas are the only significant power inputs to the plasma, and when loss regions in velocity space are unimportant.

2. CALCULATIONAL MODEL

2.1 POWER BALANCE AND Q

Our treatment employs a zero-dimensional model for the plasma. We assume that a single energy confinement time, τ_E , applies to the transport losses of bulk ions and electrons. The power balance per unit volume is then

$$\frac{\frac{3}{2} (n_e T_e + \sum_{\text{ions}} n_i T_i)}{\tau_E} + R = P_b + P_\alpha + P_{OH} \quad (1)$$

where $P_{OH} \propto T_e^{-3/2}$ is the Ohmic power dissipation, P_α is the power deposition of charged fusion-reaction products, P_b is the injected beam power density, and R is the radiation power density. For a D-T plasma, $P_\alpha = 0.20 \times Q P_b$, where $Q = P_f / P_b$ is the fusion power multiplication factor, and it is assumed that all fusion alpha particles are confined in the plasma. For reactor-level conditions, $P_{OH} \ll P_b + P_\alpha$, so that Ohmic power dissipation is neglected in the following. The fusion power density $P_f = P_{TN} + P_{fb}$, where P_{TN} is the thermonuclear

power density and P_{fb} is the fusion power density of beam-target reactions. (4,7)

We consider a D-T plasma with a single impurity species, and define n_i = total hydrogenic ion density, n_z = impurity-ion density, $n_z = f_z n_i$, n_T = triton density = $F n_i$ and n_D = deuteron density = $(1-F)n_i$. If L_z and L_H are the impurity and hydrogenic emission rates per ion per free electron, then $R = n_e n_z L_z + n_e n_i L_H$.

With these definitions, Eq. (1) can be written

$$n_e T_e = \frac{\frac{3}{2} [T_e (1 + f_z \bar{Z}) + T_i (1 + f_z)]}{\frac{A \langle \sigma v \rangle E_f (1-F) F}{1 + f_z \bar{Z}} - f_z L_z - L_H} \quad (2)$$

where $E_f = 17.6$ MeV, $\bar{Z}$ is the mean charge of the impurity ion at temperature T_e , and

$$A = \frac{1 + 0.2Q}{Q - \frac{P_{bf}}{P_b} \frac{F}{1 + f_z \bar{Z}}} \quad (3)$$

A similar expression was obtained in Ref. (5), although the expression given there for L_z significantly underestimates the radiation from high-Z ions.

In the calculations reported here, 200-keV deuterium beams are injected to maintain the plasma temperature, with $Q_b = P_{fb}/P_b$ taken from Fig. 18(b) of Ref. (7). When $7 < T_e < 20$ keV, maximum Q_b is obtained with 200-keV beams,

but the results are relatively insensitive to beam energy in the range 150 to 400 keV. The bulk-plasma composition is taken as 50% D, 50% T for $Q \geq 3$; 65% T, 35% D for $Q = 2$; and 80% T, 20% D for $Q = 1$. (Actually, for $Q \sim 1$ the optimal bulk-plasma composition is 100% T, but it would seem impossible to maintain this value in practice, in the face of intense deuterium beam injection. (9))

The impurity radiation L_Z has been calculated numerically using an "average-ion model". Coronal equilibrium values of the emission were determined from the steady-state solutions of a set of related rate equations which include the effects of electron collisional ionization and excitation, dielectronic and radiative recombination, $\Delta n = 0$ and $\Delta n \neq 0$ line transitions, and bremsstrahlung. The detailed calculational method and the results for a variety of impurity ions are given in Ref. (8). These calculations agree well with all previous work for low and moderate-Z elements. However, the predicted radiation levels for tungsten and other heavy impurities are significantly higher than previous crude estimates for $T_e \gtrsim 10$ keV.

2.2 DEPENDENCE OF $n_e \tau_E$ ON f_Z

As can be seen from Eq. (2), the results presented here are independent of the absolute value of plasma density. Figure 1 shows representative variations of $n_e \tau_E$ with impurity fraction f_Z , for various Q -values. (Similar results of this type have been given in Ref. (8).) If f_{Z1} is the impurity fraction at which $n_e \tau_E$

is twice the value $(n\tau)_0$ for $f_z = 0$, then from Fig. 1 it is evident that $n_e\tau_E = \infty$ when $f_z = f_{zc} \approx 2f_{z1}$. That is, the maximum f_z permitted for obtaining a given Q is relatively insensitive to the attainable value of $n_e\tau_E$; in fact, the variation in permitted f_z from its value at $n_e\tau_E = 2(n\tau)_0$ to its value at $n_e\tau_E = \infty$ is probably of the order of the accuracy of the radiation calculations. Thus to a first approximation, one may take any value of f_z between f_{z1} and f_{zc} as representative of the maximum allowed impurity concentration to attain a given Q , regardless of the $n_e\tau_E$ that is attainable. It is clear then that one can establish a criterion of maximum f_z vs Q that must be satisfied before applying the usual $n_e\tau_E$ vs T_i criterion. In Section 3, the maximum allowed f_z is taken as f_{zc} (corresponding to $n_e\tau_E = \infty$).

3. IMPURITY CONCENTRATION VERSUS Q CRITERIA

3.1 TEMPERATURE RANGE

For a given Q , the permitted levels of impurity content do increase somewhat with $T_e \sim T_i$, because the increase in fusion reactivity with T_i can offset additional radiation loss. But the practical operating range of temperature in low-beta toroidal reactors is likely to be 6 to 20 keV: At $T_e < 6$ keV, it is difficult to attain ignition or even $Q > 1$. At $T_e \geq 20$ keV, synchrotron radiation becomes important. Furthermore, in a magnetically confined plasma with restricted pressure, increasing $T_e \sim T_i$ results in a reduction in plasma density, which eventually

offsets the favorable effect of increasing fusion reactivity on the fusion power density. An adverse behaviour of τ_E with plasma temperature may turn out to apply even further restrictions on $T_e \sim T_i$. In principal, one might ameliorate the adverse effects of higher temperature operation by choosing a regime where $T_i > T_e \gtrsim 20$ keV, but in this work we use $7 \leq T_i = T_e \leq 20$ keV.

3.2 CRITERIA FOR VARIOUS IMPURITY IONS

Figures 2 to 4 show f_{zc} , the maximum permitted f_z , as a function of Q for a variety of impurities with atomic number Z ranging from 6 to 74. The following conclusions are evident from these graphs:

- (1) For light elements, the decrease in f_{zc} with Z for a given Q is due principally to the increase in hydrogenic depletion per impurity ion. Radiation loss is less important.
- (2) For heavy elements, the decrease in f_{zc} with Z is due principally to the increase in radiation emission per impurity ion, when $Q \gtrsim 3$; but the depletion effect is dominant when $Q \sim 1$. At low Q -values, the fusion power production is due almost entirely to beam-target reactions; that is, $Q \approx Q_b$. The radiation itself cannot lower Q_b — that is, the radiation power density from increasing impurity content can be balanced by injecting more beam power. In the absence of impurity-ion depletion, each beam ion produces the same amount of fusion energy, so that

Q_b (and Q) are nearly constant. But the decrease in n_T/n_e that results from the presence of impurity ions does lower Q_b . Because radiation losses do not affect Q_b , it is not surprising that nearly the same fractional contents of molybdenum and tungsten can be tolerated for $Q \sim 1$; the small difference is due to the higher degree of depletion caused by tungsten ions.

When one requires $Q > Q_b$, on the other hand, thermonuclear reactions must contribute significantly to the total fusion power output. Increased radiation loss must be balanced by increased P_b , but fusion power output no longer increases proportionally to P_b . Hence radiation loss alone can lead to a decrease in attainable Q . This effect is responsible for the excessively large drop in f_{cz} for tungsten at $Q \gtrsim 2$. (For example, $Q_b = 1.4$ at 10 keV when $n_T/n_i = 0.65$.)

- (3) For a given T_e and $Q \gtrsim 3$, one has $f_{cz} \propto Z^{-2.2}$ to -2.5 . This result is expected, because the emission rate at a given temperature scales as Z^2 to 3 (8).
- (4) For light elements, f_{cz} decreases by approximately one order of magnitude as Q increases from 1 to 100. For heavy elements, f_{cz} decreases by nearly two orders of magnitude over this range of Q . In all cases, at $Q = 5$, which is approximately the minimum value for a "pure fusion" reactor, f_{cz} is 2 to 3 times the value at $Q = 100$ (which is essentially the same as f_{cz} for ignition).
- (5) With increasing temperature, f_{cz} increases significantly, mainly because of enhanced fusion reactivity. The largest increase takes place for the heavy elements, which "strip out" and have reduced line radiation at higher T_e .

- (6) Low- Q systems can tolerate significant concentrations of heavy impurity ions only if the plasma is driven by reacting ion beams. Figure 3 also shows f_{cz} for 50:50 D-T plasmas heated by some other method (i.e., $P_{fb} = 0$). In the latter case, an increase in radiation loss can be compensated by increasing the power input, but there is no corresponding increase in fusion power output. Hence the allowed f_{cz} is much smaller than in the reacting-beam case. To obtain $Q = 1$, a plasma heated by reacting ion beams can tolerate a factor of 3 larger iron content, or a factor of 16 larger tungsten content than a plasma sustained by some other heat source. (The $n_e \tau_E$ -criterion for achieving $Q \sim 1$ is also greatly reduced for the reacting-ion-beam case.^(7,9)) For $Q \gtrsim 3$, beam-target reactions are less important, so that f_{cz} varies little with heating method.

3.3 MAXIMUM IMPURITY CONCENTRATION

Figures 5 and 6 show f_{cz} for ignition, as a function of Z and T_e respectively. The largest possible value of f_{cz} for ignition, which is sometimes called the 'fatal fraction,' is calculated in Ref. (2), and occurs near the temperature at which the fusion reactivity is maximum, namely 65 keV. The 'fatal fraction' varies at $Z^{-1.6}$; this dependence is relatively weak, because at $T_e \sim 65$ keV all elements except the heaviest are completely stripped. Our results for lower temperature, on the other hand, show that f_{cz} varies nearly as $Z^{-2.5}$ (see Fig. 5). As noted previously, it seems unlikely

that low-beta toroidal reactor plasmas will operate at temperatures exceeding 20 keV, so that our maximum impurity concentrations are much more restrictive than the 'fatal fractions' of Ref. (2), especially for the heavy ions.

(It appears also that the emission levels of Ref. (2) for high-Z ions are greatly underestimated for $T_e \lesssim 15$ keV.)

4. OTHER ASPECTS OF PLASMA IMPURITY LEVELS

4.1 REQUIRED BEAM POWER

While large impurity content can be tolerated at low Q , the beam power required to balance the impurity radiation can be enormous. For example, in a 7-keV plasma with $n_e = 10^{14} \text{ cm}^{-3}$, tungsten impurity concentration $n_z/n_i = 1 \times 10^{-3}$, and $\bar{Z} \approx 50$ ($Z_{\text{eff}} = 3.5$), the radiation power density is about 2 W/cm^3 .⁽⁸⁾ Consequently, 50 MW of injected power would be required to sustain a hot plasma volume of 25 m^3 . Fortunately, even higher levels of power are specified in conceptual designs of low- Q driven tokamaks that are to be used primarily as 14-MeV neutron sources.^(7,10) (Figure 2 shows that $Q \approx 1.5$ for the conditions given.) In fact, radiation loss can be desirable for 'clamping' the plasma temperature when operation is designed specifically for continuous injection of intense neutral beams.

Whether beam injection is to assist fusion alpha particles in sustaining a high- Q plasma with f_z just above the maximum

permitted value for ignition,⁽³⁾ or whether a low-Q impure plasma is to be driven by intense beam injection, the principal concern must be to insure adequate neutral-beam penetration. While early theoretical work had indicated that the penetration length of 200-keV beams may vary inversely with Z_{eff} , the most recent theoretical indications are that penetration is affected only weakly by the impurity-ion content.⁽¹¹⁾

4.2 IMPLICATIONS OF IMPURITY LEVELS IN PRESENT TOKAMAK PLASMAS

Table 1 shows the measured concentrations of oxygen and other impurity species in representative present-day tokamaks. By referring to Fig. 6, it is evident that reactor-sized tokamak plasmas of arbitrarily large $n_e \tau_E$ cannot be ignited at temperatures of around 5 keV, unless the impurity concentrations are no greater than in Alcator,⁽¹²⁾ by far the cleanest of present-day tokamaks. A reactor-sized plasma containing the minimum concentrations of heavy-metal impurities typical of most contemporary tokamaks, together with the usual amounts of oxygen and iron impurities, is unlikely to be capable of ignition at temperatures less than 20 keV — if ignition could be obtained at all. Oxygen can apparently be eliminated by special discharge-cleaning methods.⁽¹²⁾ However, in order to reach ignition at $T_i \sim 10$ keV or less, it seems likely that the influx of sputtered metallic impurities must be controlled either by a magnetic divertor, or by the dense cold plasma blanket technique that is inherent to high-density Alcator operation.

5. CONCLUSIONS

- (1) When designing a driven toroidal reactor to achieve a given Q -value, one must first ensure that the concentration of a given impurity species is unlikely to exceed the critical value f_{cz} for that Q . For example, if a plasma at 10 keV or less is to have a Q -value exceeding 3, tungsten must be eliminated as a limiter material or as armor plating to protect the first wall. The criteria for f_{cz} versus Q , which are given in this paper, are relatively insensitive to the attainable $n_e \tau_E$. Only after these criteria are satisfied can one apply the usual $n_e \tau_E$ vs T_i criterion to determine an operating point.
- (2) To obtain a given $Q \gtrsim 3$ at a given operating temperature, the allowed impurity concentration varies as $Z^{-2.2}$ to -2.5 .
- (3) Low- Q ($\gtrsim 2$) toroidal plasmas driven by reacting ion beams can tolerate a light-impurity concentration a factor of 3 to 5 higher than for ignition, and a heavy-impurity concentration a factor of 10 to 30 larger. If a means of sustaining the plasma other than reacting-ion beams is used, the allowable f_z at low Q is much closer to the ignition value. Hence the direct production of fusion power by the injected beams is a telling advantage of this heating method, even when large $n_e \tau_E$ is attainable.

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REFERENCES

1. MEADE, D. M., Nucl. Fusion 14 (1974) 289.
2. GERVIDS, V. I., KOGAN, V. I., JETP. Lett. 21 (1975) 150.
3. CONN, R. W., KESNER, J., Nucl. Fusion 15 (1975) 775.
4. JASSBY, D. L., Nucl. Fusion 15 (1975) 453.
5. PISTUNOVICH, V. I., Sov. J. Plasma Physics 2 (1976) 3.
6. Proc. Int. Conf. on Surface Effects in Controlled Fusion Devices (San Francisco, 1976), J. Nucl. Materials to be published.
7. JASSBY, D. L., "Neutral-Beam-Driven Tokamak Fusion Reactors," to be published in Nucl. Fusion 17 (1977) No. 2.
8. JENSEN, R. V., POST, D. E., GRASBERGER, W. H., TARTER, C. B., LOKKE, W. A., "Calculations of Impurity Radiation and Its Effects on Tokamak Experiments," Princeton Plasma Physics Lab. Rep. PPPL-1334 (1977).
9. JASSBY, D. L., TOWNER, H. H., Nucl. Fusion 16 (1976) 911.
10. KULCINSKI, G. L., et al., in The Technology of Controlled Nuclear Fusion (Proc. 2nd Top. Mtg., Richland, 1976) 73; ROSE, R. P., et al., in US-USSR Symp. on Fusion-Fission Reactors (Proc. Lawrence Livermore Lab., 1976) 91; JASSBY, D. L., TOWNER, H. H., Nucl. Tech. 31 (1976) 159; ROSE, R. P., et al., "Fusion-Driven Breeder Reactor Design Study," Westinghouse Elec. Corp. Reports WFPS-TME-035, 037 (1976).
11. OLSON, R. E., SALOP, A., "Charge Transfer and Impact Ionization Cross Sections for Various $A^{+q} + H$ Systems," in APS Top. Conf. on Atomic Processes in High-Temperature Plasmas (Knoxville, 1977).

12. APGAR, E., et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 6th Int. Conf. Berchtesgaden, 1976) 1, IAEA, Vienna (1977) 247.

TABLE 1

ESTIMATED IMPURITY LEVELS IN SOME PRESENT-DAY TOKAMAK PLASMAS

	Oxygen n_z/n_i	Min. T_i (keV) for Ignition [†]	Other Species	n_z/n_i	Min. T_i (keV) for Ignition [†]
ALCATOR [*] (a)	2×10^{-3}	4.6	Mo	1×10^{-5}	4.6
ORMAK (b)	2×10^{-2}	6.7	W	1×10^{-3}	20
PLT (c)	1×10^{-2}	5.6	W	1×10^{-3}	20
TFR (d)	3×10^{-2}	7.6	Mo	1×10^{-3}	9.7

* High-density regime.

[†] In reactor-sized plasma with indicated single-species impurity content.

(a) R. R. Parker, Trans. Am. Nucl. Soc. 25 (1977) in press.

(b) L. A. Berry, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 6th Int. Conf., Berchtesgaden, 1976) 1, IAEA, Vienna (1977) 49.

(c) D. Grove, et al., ibid., 21; also E. Hinnoy, private communication (1977).

(d) TFR Group, ibid., 35.

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Fig. 1. $n_e \tau_E$ requirements to achieve various Q-values in D-T as a function of concentration of tungsten or iron impurities. (Q = fusion power/injection power, taking 17.6 MeV per reaction.) In the Q = 2 and 5 cases, the plasma temperature is maintained by 200-keV deuterium beams (plus fusion alpha particles.)

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Fig. 2. Maximum allowed concentrations of various impurity species for attaining given Q -values in a 7-keV D-T plasma. The plasma temperature is maintained by 200-keV deuterium beams. (f_{zc} at $Q = 100$ is indistinguishable from f_{zc} at ignition.)

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Fig. 3. Maximum allowed concentrations of various impurity species for attaining given Q -values in a 10-keV D-T plasma. The solid lines are for plasma heating by 200-keV deuterium beams, while the dashed lines are for any heating method other than reacting beams.

Fig. 4. Maximum allowed concentrations of various impurity species for attaining given Q-values in (a) 15-keV and (b) 20-keV D-T plasmas. The plasma temperature is maintained by 200-keV deuterium beams.

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Fig. 5. Maximum allowed impurity concentration versus Z for ignition at various plasma temperatures ($T_e = T_i$), assuming zero nonradiative losses.

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Fig. 6. Maximum allowed impurity concentration for ignition as a function of plasma temperature, assuming zero nonradiative losses.