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ABSTRACT

The optimal plasma conditions for maximizing fusion power density P_f in a beam-driven D-T tokamak reactor (TCT) are considered. Given $T_e = T_i$ and fixed total plasma pressure, there is an optimal $n_e \tau_E$ for maximizing P_f, viz. $n_e \tau_E = 4 \times 10^{12}$ to $2 \times 10^{13} \mathrm{cm}^{-3} \mathrm{sec}$ for $T_e = 3 - 15$ keV and 200-keV D beams. The corresponding $\overline{\Gamma}$ = (beam pressure/bulk-plasma pressure) is 0.96 to 0.70. P_{fmax} increases as T_e is reduced and can be an order of magnitude larger than the maximum P_f of a thermal reactor of the same beta, at any temperature. A lower practical limit to T_e may be set by requiring a minimum beam power multiplication Q_b. For the purpose of fissile breeding, the minimum $Q_b \sim 0.6$, requiring $T_e \gtrsim 3$ keV if $Z = 1$.

The optimal operating conditions of a TCT for obtaining P_{fmax} are considerably different from those for enhancing Q_b. Maximizing P_f requires

restricting both T_e and $n_e\tau_E$, maintaining a bulk plasma markedly enriched in tritium, and spoiling confinement of fusion alphas. Considerable impurity content can be tolerated without seriously degrading P_{fmax}, and high-Z impurity radiation may be useful for regulating τ_E.

1.0 INTRODUCTION

In the two-energy-component tokamak reactor (TCT), the energy content of a relatively cold tritium plasma is maintained against transport and radiation loss by beams of energetic deuterons that undergo fusion reactions with the bulk tritons while thermalizing [1]. It appears that energy "break-even" in a TCT (or in any beam-heated reactor) can be attained with far less stringent plasma performance than in other fusion reactor schemes. Increasing the energy gain significantly beyond the break-even level, however, requires considerably better plasma confinement and somewhat higher plasma temperature [2], and thus considerable improvements in plasma stability and purity. On the other hand a TCT plasma with approximate energy break-even is characterized by an extremely high fusion power density even at relatively low plasma temperature, and may be successful as an economic breeder of fissile material even when operating with an overall electrical energy deficit. For this application, the most important system parameter is fusion power density, or neutron production rate, rather than power multiplication.

The purpose of this work is to determine the optimal plasma conditions for maximizing fusion power density P_f in the TCT, in order to optimize the total neutron flux for a given size device. The minimum value of fusion power multiplication Q required for economic operation as a fissile breeder is discussed in Section 2. Optimization of the plasma conditions for obtaining the ideal maximum P_f is considered in Section 3; the important principles of maximizing P_f are summarized in Section 3.9. These operating conditions are contrasted in detail with those for maximizing Q. The effects of substantial impurity content on P_f and Q as well as the roles of impurity radiation and scattering are discussed in Section 4.

2.0 FUSION POWER DENSITY VERSUS POWER MULTIPLICATION

2.1 MINIMUM Q FOR FISSILE BREEDING

A potential practical application of the TCT is the breeding of fissile material. A fusion reactor that supplies fissile fuel to a system of fission plants may operate with an overall power multiplication Q_E somewhat less than unity, since a certain fraction of the electrical output of the fission system may be diverted to sustain the fusion breeder. The power flow in the fusion-fission cycle is shown schematically in Fig. 1. In calculating the minimum power gain, we use the definitions:

$$Q_E = \frac{P_{out}}{P_{in}} , \tag{1}$$

$$Q_b = \frac{P_f}{P_b} , \tag{2}$$

$$b = \frac{P_b}{P_{in}} , \tag{3}$$

$$P_{out} = \eta(1 + dQ_b)\, P_b , \tag{4}$$

where P_{in} and P_{out} are the electric power consumption and production respectively of the fusion reactor, per unit volume of the plasma; P_b is the neutral-beam injection power density, the only significant external energy source for the plasma (ohmic heating is negligible at reactor temperatures); P_f is the fusion power density, at 17.6 MeV per D-T reaction; Q_b is the fusion power gain of the injected beams; η is the energy conversion efficiency of the fusion plant; d is the enhancement of the total fusion energy by the blanket reactions.

The net power consumption must satisfy the inequality

$$P_{in} - P_{out} \leq \alpha M_f P_f \tag{5}$$

where M_f is the ratio to 17.6 MeV of the electrical energy produced in the symbiotic fission reactors per fusion reaction in the breeder, and α is the fraction of the electrical output of the fission reactor system that can be used to sustain the fusion breeder that provides make-up fuel.

Combining Eqs. (1) to (5), we find that

$$Q_b \geq \frac{1 - \eta b}{b(\eta d + \alpha M_f)} \tag{6}$$

and

$$Q_E \geq \eta b + \frac{\eta d(1 - \eta b)}{\eta d + \alpha M_f} \quad . \tag{7}$$

For illustrative purposes, we consider near-breeder reactors that operate on the U-Th cycle (such as the CANDU reactors [3]); then $M_f \approx 35$. According to Lewis [4], the electrical feedback parameter α may be as large as 0.04, while η may be taken as 0.40 [5]. Blanket reactions can result in a wide range of energy multiplication, depending on the proportions of Li^6, Li^7, Be, Th, etc., but in the absence of fission reactions, d is in the range 1.0 to 1.8 [6]. Using these parameters, Q_b and the corresponding Q_E are plotted in Fig. 2 as a function of b. Evidently, Q_b is rather insensitive to blanket energy multiplication and may be less than unity when $P_b > 0.45\,P_{in}$, as would be the case for a high-power-density reactor with injected beams derived from negative ion sources, and with superconducting toroidal coils. In principle, high energy neutral beams can be produced with overall efficiency of 85% [7]; allowing 20% of P_{in} for the tokamak electrical systems, then $b \leq 0.68$ and $Q_b \gtrsim 0.60$. The corresponding electric power multiplication is $Q_E \gtrsim 0.50$, for $d = 1.3$ or 22.9 MeV per fusion reaction. (In using the value $M_f = 35$, we have assumed that each fusion neutron breeds one atom of U-233. It may be necessary to include a thin neutron multiplying blanket in order to achieve adequate breeding ratios of both U-233 and tritium, unless the latter can be bred elsewhere.)

2.2 THE ROLE OF POWER MULTIPLICATION

The two economic restrictions on fusion breeders are that the net power consumption be sufficiently small, as discussed in Section 2.1, and that the rate of production of fissile material be sufficiently large so that the capital cost of the breeder can be recovered in a reasonable time (~10 years). If Q_b is increased beyond the minimal level shown in Fig. 2(a), the economic advantage tends to be small, since the electrical output of the symbiotic fission reactors can be some two orders of magnitude larger than that of the breeder that maintains their fissile inventory [3]. The principal benefit of increasing Q_b is that the neutron output can be enhanced for a given capital investment in neutral beam facilities.

On the other hand, it may well be desirable to arrange the plasma conditions so that an increase in neutron production is possible with increased beam injection, but with a somewhat smaller Q_b. The reason is simply that if the entire plant is an economic neutron producer, then since the cost of the beam injectors is less than that of the total plant cost, it follows that additional injectors must increase the economic value of the operation; at the same time the value of Q_b is of secondary importance, as long as it does not fall below the levels shown in Fig. 2(a).

If the optimal economic strategy is to maximize the neutron flux for a given size device, then the preferred plasma parameters and methods of operation are very different from those required to maximize the power multiplication Q_E. In a beam-heated reactor, Q_E is increased by improving the plasma confinement, increasing the proportion of D in the bulk plasma, and allowing a larger fraction of the fusion power output to come from bulk-plasma reactions [2]. An increase in $n_e \tau_E$ allows a reduction in P_b, so that the relatively small thermal fusion power can approach and eventually surpass the injected beam power. This procedure, however, is not optimal as far as increasing the neutron flux is concerned. As shown in Section 3, at moderate temperatures the fusion power production of a thermal reactor is substantially less than that of a TCT with nearly equal beam and bulk-plasma pressures; to meet the latter condition without raising the plasma temperature requires that the energy confinement time τ_E remain relatively small, viz. $n_e\tau_E$ in the range $0.5 - 2\times 10^{13} cm^{-3} sec$. If the plasma exhibits a tendency toward larger values of $n_e\tau_E$, then one must take steps to spoil the confinement. Thus for applications such as fissile breeding, which place a premium on neutron production alone, one may arrive at substantially different conclusions about the usefulness of various reactor configurations, than if one is primarily interested in optimizing power multiplication.

3.0 MAXIMIZING FUSION POWER DENSITY

In this report a zero-dimension spatial model is used in order to facilitate comparison with other results. Of course, this model is easily extended to include practical radial profiles; the values of density and temperature used in this report would represent radially-averaged values for those cases. At any rate the average plasma pressure allowed in a tokamak does not depend on the radial profiles, but only on toroidal field B_t, plasma aspect ratio A, and the rotational transform at the limiter, q.

3.1 TEMPERATURE DEPENDENCE OF POWER MULTIPLICATION

In this section we briefly summarize the basics of TCT operation [1]. Energetic deuterons injected into a relatively low-temperature tritium plasma lose energy by Coulomb collisions with the bulk-plasma electrons and ions. While thermalizing, the deuterons produce Q_b times their injected energy in fusion reactions. In order to maximize Q_b, the injection energy W_o must be somewhat above the energy of maximum fusion reactivity (~125 keV). For $T_e > 4.4$ keV and $W_o \approx 150$ keV, $Q_b > 1$, and Q_b can be as large as 3 for $T_e \to \infty$ (Fig. 3). The energy multiplication factor Q_b is given by the relation

$$Q_b = \frac{\int_0^{\tau_s} n_T \sigma(v) v E_f \, dt}{W_o} \tag{8}$$

where τ_s is the "slowing-down" or thermalizing time of the fast deuterons, $\sigma(v)$ is the fusion cross-section, $E_f = 17.6$ MeV, and n_T is the triton target density. Although Q_b can be increased by raising T_e, the latter tends to be limited by the maximum allowed beta of the plasma, and by the possibility of τ_E rapidly decreasing at large T_e (because of trapped-particle instabilities [8]). At $T_e \gtrsim 15$ keV the fusion production rate of a thermal D-T plasma (but not heated by beams) becomes comparable to that of a TCT, so that at high temperatures it may be appropriate to combine characteristics of both techniques. In this work we shall limit our considerations to plasmas of $T_e \lesssim 15$ keV, and thus $Q_b < 2$, but we note that the peak T_e

in a tokamak is about twice the average T_e, to which our calculations apply. Actually Q_b can be further increased for the same T_e by making use of "energy-clamping" techniques [2,9], which are briefly discussed in Section 3.8.

The results of Fig. 3 apply to plasmas with ion temperature $T_i = 0$. In practice $T_i \approx T_e$, because roughly half the beam energy is given up to the bulk ions [10], while the electron-ion equilibration time tends to be comparable to τ_E. For finite T_i the results of Fig. 3 are significantly modified at $W_o < 100$ keV, but are only slightly altered at $W_o \gtrsim 150$ keV, which is the range of interest in this work [11]. The plasma density enters the calculation of Q_b only through $\ln \Lambda$ factors, so that the values of Q_b tend to increase by approximately 5% per decade of electron density n_e.

3.2 OPTIMAL CONFINEMENT TIME

In addition to the requirements on T_e and W_o shown in Fig. 3, there are two other conditions for TCT operation that concern the confinement times of the fast deuterons and the bulk plasma. First, the lifetime τ_h of the fast ions must be greater than τ_s, in order that the full power gain Q_b be realized. Second, in order that Q_b define the fusion gain of the entire beam-plasma system, all the energy loss of the bulk plasma must be made up by the injected beams; that is

$$P_b = I_b W_o = \frac{(3/2)(n_T T_i + n_e T_e)}{\tau_E} \qquad (9)$$

where I_b is the injection current, and τ_E is the energy confinement time of the bulk plasma. τ_E takes into account all energy loss channels, including particle transport, charge-exchange, and radiation. (We neglect ohmic heating, which tends to be insignificant for $T_e \gtrsim 3$ keV in a large device, and alpha-particle heating, which we consider in Section 3.7. At the large power densities required here, hydrogenic bremsstrahlung is negligible. The effect of impurity radiation is considered in Section 4.2.)

Since $I_b = n_b/\tau_s$, where n_b is the beam-ion density, Eq. (9) leads to the definition

$$\bar{\Gamma} = \frac{\text{suprathermal-ion energy density}}{\text{bulk-plasma energy density}}$$

$$= \frac{n_b \bar{W}_b}{(3/2)(n_T T_i + n_e T_e)} = \frac{\tau_s}{\tau_E} \frac{\bar{W}_b}{W_o} \tag{10}$$

where the average beam energy $\bar{W}_b \approx (1/2) W_o$. (The exact expression for $\bar{W}_b$ is given later; note that previous references [1,2] have defined a quantity Γ in terms of $n_b W_o$.) In principle, τ_E can be made arbitrarily small, with no reduction in T_e, simply by increasing I_b. In the absence of a pressure limitation on the plasma, this increase in I_b would always result in an increase in P_f. However, there are two factors that lead to an optimal value τ_E, and thus a maximum in P_f:

(i) The plasma pressure is limited to the maximum allowed by MHD equilibrium, that is,

$$p = (n_T T_i + n_e T_e)(1 + \bar{\Gamma}) \le \frac{1}{8\pi} \frac{B_t^2}{q^2 A} \quad . \tag{11}$$

For MHD-stable operation, q cannot drop below about 2.5. Hence, an increase in $\overline{\Gamma}$ necessarily leads to a decrease in n_e and target density n_T.

(ii) Charge neutrality requires that

$$n_e = n_T + n_b . \qquad (12)$$

Hence large beam densities appreciably reduce n_T/n_e.

These are two other important consideration that tend to restrict the maximum injection current:

(iii) Large values of $\overline{\Gamma}$ may lead to the onset of instabilities, although recent stability analysis [12] indicate that systems with $\overline{\Gamma} \sim 1$ should be stable, at least for tangential injection.

(iv) Since the fast-ion lifetime τ_h must be at least as large as τ_s, when $\overline{\Gamma} \gtrsim 1$ τ_h must be appreciably longer than τ_E. This situation seems to be the case in present-day tokamaks [8], and will probably always be true if an appreciable part of the plasma energy loss is due to radiation or diffusion by electrostatic instabilities [12].

The remainder of this section is devoted to finding the optimal $\overline{\Gamma}$ for maximum P_f, in accordance with points (i) and (ii) above. For the present we neglect impurities, the pressure of fusion alphas, and the buildup of deuterons in the bulk plasma. The constant-pressure restriction is

$$p = (n_e + n_T)T_e + \frac{2}{3} n_b \overline{W}_b = \text{constant} \tag{13}$$

where we take $T_i = T_e$ and assume an isotropic steady-state suprathermal ion velocity distribution, such as resulting from injection of beams both tangential and perpendicular to the toroidal current. The steady-state fast-ion energy distribution is [12].

$$f(W) = \frac{W^{1/2}}{W^{3/2} + W_c^{3/2}}, \quad W \leq W_o \quad \text{and} \tag{14}$$

where the "critical energy" W_c is that at which the electron and bulk-ion drags are equal [10]; for D on T and $n_T = n_e$, $W_c = 14.2\, T_e$. The derivation of Eq. (14) assumes that W_c and $W_o >> T_e = T_i$. Using Eq. (14), we get

$$\overline{W}_b = \frac{\int_0^{W_o} W f(W)\, dW}{\int_0^{W_o} f(W)\, dW} = \frac{(3/2)\, G_e\, W_o}{\ln\, [1 + (W_o/W_c)^{3/2}]} \tag{15}$$

where G_e is the fraction of the injected beam energy that goes directly to the electrons, and depends only on W_o/W_c [10]. Figure 4 shows $\overline{W}_b$ as a function of T_e and W_o. For maximum Q_b, W_o should be in the range 150 - 250 keV (Fig. 3). In order to get adequate beam penetration [13], the choice of W_o must be partly determined by the product $\overline{n}_e a$, where a is the plasma radius.

Using Eqs. (9), (12) and (13), we find that

$$P_f = \frac{Q_b}{\tau_s}\frac{W_o}{n_{eo}}\left(1 - \frac{n_T}{n_e}\right)\left(\frac{p}{(2/3)\,[1 - (n_T/n_e)]\overline{W}_b + [1 + (n_T/n_e)]\,T_e}\right)^2 \tag{16}$$

where τ_s is now calculated at n_{eo} (which is arbitrary). The curves in Fig. 3 were derived assuming $n_T = n_e$, but in fact both Q_b and τ_s depend on n_T/n_e. One can easily show that $Q_b/\tau_s \approx (Q_{bo}/\tau_{so})(n_T/n_e)$, where Q_{bo} and τ_{so} are calculated for $n_T/n_e = 1$. Once W_o and T_e are chosen, the optimal value of n_T/n_e is found by maximizing P_f. Then n_b/n_e, n_e, and $\overline{\Gamma}$ are found from Eqs. (12), (13), and (10) respectively. τ_E is calculated from Eq. (9), using $I_b = n_b/\tau_s$ and $T_i = T_e$. Results are shown in Figs. 5, 6, and 7 for $p = 0.655$ J/cm^3, corresponding to $B_t = 60$ kG, $A = 3.5$, $q = 2.5$. (The aspect ratio cannot be lowered below 3.5 in a relatively small reactor, such as appropriate for a breeder, because of the blanket thickness. For $B_t = 60$ kG on axis, the maximum field at the inner coil wall is about 150 kG, or considerably less than the critical field for NbSn.)

Perhaps the most interesting result is that P_f is nearly inversely proportional to T_e. This behavior can be seen qualitatively using Eq. (13), with $\overline{\Gamma} \sim 1$:

$$P_f \propto n_b n_T \sim \frac{p^2}{4T_e\overline{W}_b} \tag{17}$$

where we have ignored changes in the average fusion reactivity ($\overline{W}_b$ changes with T_e), and have taken $n_T \approx n_e$. Since $P_f \propto p^2$, it is advantageous to work at the highest possible beta, as in a thermonuclear reactor.

The minimum T_e is limited to 3 - 5 keV, because of the criterion, discussed in Section 2.1, that $Q_b \gtrsim 0.6$. Thus the optimal values of $\overline{\Gamma}$ lie in the range 0.7 - 0.9, or somewhat larger than the values normally required for a power multiplying device [2]. (Note that in Ref. [2], the quantity Γ is defined in terms of W_o, rather than $\overline{W}_b$; the ratio $\overline{\Gamma}/\Gamma$ is given in Fig. 4.)

Another important result is that for maximum P_f, τ_E must be a factor 1.3 - 2 times smaller than $\tau_s \lesssim \tau_h$. But as shown in Fig. 8, P_f is not very sensitive to τ_E/τ_s, as long as $\tau_E < \tau_s$. In view of present experiments, it seems likely that for a device of practical size, i.e., $a > 100$ cm, τ_h will be at least as large as the values of τ_s in Fig. 6, viz. 40 - 300 msec. Since τ_E may be comparable to τ_h, at least at low T_e, measures will probably have to be taken to decrease τ_E by a significant factor. Possible means of accomplishing this, such as enhanced radiation and the degradation of plasma stability, will be discussed in later sections.

3.3 PREFERRED OPERATING TEMPERATURE

In a high power-density TCT, the cost of the beam injectors is likely to be of the same magnitude as the cost of the tokamak facilities. Thus the cost-effectiveness of the breeder plant may be taken approximately as the total neutron production rate times the neutron output per injected ion, a quantity which is measured by P_fQ_b. As shown in Fig. 9, P_fQ_b has an extended maximum at T_e = 2 - 8 keV. If long-pulse, high duty-factor operation is precluded by impurity buildup, for example, it might appear that one should operate at very small T_e, where P_{fmax} is largest. But there are several practical reasons for preferring the range T_e = 5 - 10 keV:

(i) There may be some economic advantage to have Q_b larger than the minimum of Fig. 2(a) (for example, to reduce the injector cost).

(ii) As shown in Fig. 9, P_b increases extremely rapidly at small T_e, so that a substantial fraction of the vacuum wall area might have to be taken up by neutral-beam apertures.

(iii) The large values of n_e required to maximize P_f at low T_e makes beam penetration difficult unless the plasma radius is very small, or unless W_o is considerably larger than 200 keV. But Q_b decreases at larger W_o (Fig. 3).

(iv) The large densities at low T_e may lower the Alfvén velocity below the beam velocity, thus exciting Alfvén instabilities [12].

As a compromise between these disadvantages of low-T_e operation and the need for large P_f, $T_e = 6$ keV seems to be a desirable operating point. The corresponding plasma parameters are listed in Table 1. If the plasma radius is 1 m, then the confinement time predicted by trapped-ion scaling [8] for $Z = 1$ is about $50\,\tau_E$, while the "Bohm diffusion" time is about $0.1\,\tau_E$.

3.4 COMPARISON WITH A THERMONUCLEAR REACTOR AND Q_f VERSUS P_f

Figure 10 compares the maximum P_f in a TCT with P_f for a 50:50 D-T reactor in which all fusion energy is produced by bulk-plasma reactions (i.e., a one-energy-component plasma). The plasma pressure in the latter is the same as the total pressure in the TCT

TABLE 1. PREFERRED OPERATING PARAMETERS FOR B_t = 60 kG, β_p = A = 3.5, q = 2.5, W_o = 200 keV.

$T_e = T_i$	6.0 keV
n_e	$2.0 \times 10^{14} cm^{-3}$
$\tau_h = \tau_s$	83 msec
τ_E	48 msec
$n_e \tau_E$	$9.5 \times 10^{12} cm^{-3} sec$
$\bar{\Gamma}$	0.84
P_f	13.6 W/cm^3
Q_b	1.24
Q_E	0.70 for b = 0.68, d = 1.3

case. While τ_E in the TCT case must be the value shown in Fig. 6, τ_E in the thermonuclear plasma is somewhat arbitrary, but if the thermonuclear plasma is heated by injected (nonreacting) beams, its τ_E must be sufficiently large so that the beam pressure is negligible. If we further specify that the fusion power gain in both cases be at least 0.60 , then the minimum values of $n_e\tau_E$ are those shown in Fig. 11. For the one-component plasma, we have found $n_e\tau_E$ from

$$Q = 0.60 = \frac{(1/4)n_e^2 \overline{\sigma v} E_f}{3n_e T_e/\tau_E} \tag{18}$$

For the two-component case, $Q_b > 0.8$ for the temperature range shown (cf. Fig. 5). For larger values of T_e , the two cases have similar $n_e\tau_E$ and P_f . For the preferred TCT case given in Table 1 (T_e = 6 keV), P_f is a factor of 4 larger than the maximum P_f attainable with the one-component plasma at any temperature. In the optimal temperature range for the latter (12 - 15 keV), the required $n_e\tau_E$ for $Q = 1.2$ is a factor of 5 larger than in the TCT case. In the event that large plasma temperatures cannot be attained, the superiority of the "pure" TCT as a neutron producer is even more striking.

As mentioned earlier, the total fusion gain Q_f of a TCT can be raised beyond the values shown in Fig. 3 by increasing $n_e\tau_E$ as well as the proportion of D in the bulk plasma, so that a larger fraction of the fusion energy comes from thermonuclear reactions [2]. Then neglecting alpha particles, we have

$$Q_f = \frac{n_D n_T \overline{\sigma v} E_f + Q_b P_b}{P_b} \tag{19}$$

where P_b is given by Eq. (9), with n_T replaced by $n_i = n_T + n_D$, where n_D is the bulk-deuteron density; Q_b is still given by Eq. (8). For each value of $n_e\tau_E$, there is an optimal value of n_T/n_i for maximizing Q_f. Figure 12 shows maximum Q_f and the corresponding n_T/n_i for $T_e = T_i = 8$ keV. The contribution to P_f from the beam is given by Eq. (16), with n_T again replaced by n_i. Evidently maximum P_f is attained for an $n_e\tau_E$ that allows only small Q_f. As $n_e\tau_E$ increases and n_D/n_T approaches 1, P_f goes over to the one-component value shown in Fig. 10.

Figure 13 shows Q_f vs P_f for a number of plasma temperatures. Each point on a constant-T_e curve corresponds to a particular value of $n_e\tau_E$, with n_T/n_i optimized to give maximum Q_f. The maximum values of P_f are attained at $n_e\tau_E$ corresponding to the right-hand extremities of the curves. The important features of these curves are the following:

(i) The largest values of P_f are attained at low values of Q_f, reflecting the greater fusion reactivity of "pure" TCT operation.

(ii) The initial rise of P_f with $n_e\tau_E$ is due to the increase in target density as $\overline{\Gamma}$ is reduced.

(iii) At low T_e, the thermonuclear reaction rate is so small that substantial $n_e\tau_E$ is required before n_T/n_i can be reduced. The reduction in P_f as $n_e\tau_E$ is increased is due to reduction in beam density.

(iv) The curves for $T_e > 12$ keV, if plotted, would cross the 12 keV curve, since maximum P_f for one-component operation is attained here.

Figures 12 and 13 clearly demonstrate that the plasma conditions for maximum P_f are markedly different from those for maximum Q_f. In maximizing neutron production, the most important confinement role of the tokamak is adequate confinement of the fast deuterons. The plasma throughput must be sufficient to carry away the energy deposited by the fast ions without undergoing a temperature increase, and in this respect the device is analogous to proposed gas-target neutron sources [14], where the gas ($n \sim 10^{19} cm^{-3}$) flows rapidly through the beam interaction region in order to dissipate the beam energy. In fact, the latter system is the logical extension of the low-T_e extremes of Figs. 5 and 6, where enormous P_f can be attained at small $n_e \tau_E$, provided that Q_b is unimportant, and when beam penetration of the large target density is feasible. In the two-component mirror [15], the bulk plasma is again a flowing target, with no axial confinement, while the energetic ions are confined by magnetic mirrors.

3.5 TCT WITH 50:50 D-T BULK PLASMA

For economic operation, a tokamak operated primarily as a neutron producer must have a large duty factor. Because of the finite time required for current buildup at the beginning of the discharge, and vacuum purging at the end, discharge times of at least 10 sec are essential. The question then arises as to whether the plasma density is to be maintained by neutral particle recycling, or by pellet injection. Even if $\tau_h \approx \tau_s$, so that the deuterons exit from the plasma as soon as they slow down, it is inevitable that if recycling is permitted, D will build up in the plasma — even past the 50% level. Since $\tau_s \sim 100$ msec, and $n_b/n_e \sim 0.1$, in 10 sec about 10 times as many deuterons will have been introduced to the system as there are tritons in the plasma. Thus if the bulk plasma is to remain essentially tritium, neutral recycling must be avoided, presumably by means of a divertor that captures all diffusing plasma ions. At the same time, the bulk plasma must be replenished by injection of tritium pellets. Even if diffusing ions are not captured and removed from the plasma chamber, it may be possible to maintain an essentially 100% T plasma by vigorous pellet injection, since the beta limitation on the plasma would force ejection of electrons and inwardly diffusing ions. (In fact, pellet injection is a possible means of limiting τ_E.)

If neutral recycling is unavoidable then one must resort to using both T and D beams, maintaining a plasma composition of 50:50 D-T, and taking advantage of beam-plasma, bulk-plasma, and beam-beam fusion reactions. For T on D, Q_b is about 80% of the value for D on T [16], with the corresponding W_o about 1.5 times the value for D on T. In that case, both Q_b and P_f (from beam-plasma reactions) will be approximately 0.5 the values for the 100%-T bulk-plasma case. The contribution to P_f from beam-beam interactions is significant, since n_b/n_e can be substantial (Fig. 7) and the relative velocity between D and T beam ions, if injected oppositely, can be large even for ions that have lost most of their energy.

Figure 14 shows the contribution to fusion power density of the three types of reactions. As before, $n_e\tau_E$ has been chosen to maximize P_{fb}, the contribution to P_f from beam-plasma reactions. In calculating the thermal contribution, n_e is taken from Fig. 6 and n_i/n_e from Fig. 7. The contribution to P_f from beam-beam reactions is given approximately by $0.8\,P_{fb}\,n_b/n_i$. Evidently contributions from both beam-beam and thermal reactions are negligible for $T_e \lesssim 8$ keV, and even at higher T_e the beam-plasma reactions are dominant. At $T_e = 2$ keV, the total P_f is 49% of the "pure TCT" value, but the ratio increases steadily to 65% at 10 keV and 81% at 16 keV.

The total P_f can probably be increased slightly by altering $n_e\tau_E$ from the optimal value for P_{fb}. Thus the fusion power density of the TCT will not be drastically reduced by a mixed composition of the bulk plasma, but the minimum Q_b requirement may demand operation at $T_e \gtrsim 6$ keV.

It is worth emphasizing that for long-duration discharges, refueling of the plasma can probably be accomplished by the beams together with neutral recycling; the importance of the latter is greatly reduced if $\tau_p >> \tau_E$.

3.6 FURTHER INCREASES IN BETA

As noted earlier, P_f is approximately proportional to p^2, so that the use of plasmas (and coils) of noncircular minor cross-section [17] would be advantageous, provided that the stability of such plasmas can be verified. Thus with a vertical elongation of the plasma by a factor of 1.5, p could be increased by a factor of 1.6 (for the same q), leading to an increase in P_f of a factor of 2.6 . However, there are two pitfalls to this procedure (cf. Section 3.3):

(i) If n_e is significantly increased, beam penetration will not be adequate unless the plasma radius is very small. But the minimum thickness of the blanket, and the sizeable wall area that must be taken up by beam apertures, indicate that economic operation is not possible for $a \lesssim 75$ cm.

(ii) Large n_e may lower the Alfvén velocity below the beam velocity, thus exciting Alfvén instabilities [12].

Alternatively, T_e rather than n_e could be increased, although the increase in P_f would be smaller. Finally, one could operate at the same p with a much smaller B_t , but the savings in machine cost are likely to be rather minor in a reactor with one-half or more of the cost accounted for by beam injectors.

To achieve good MHD stability affording the largest possible τ_E , present experiments indicate [8] that one should operate at $q(a) > 3$. But in order to maximize P_f , we have seen that τ_E probably needs to be degraded from the values likely to be attainable in plasmas with $a > 100$ cm , so that the MHD activity occurring at $q(a) = 2.5$, for example, may actually be welcome. In this paper we have taken $q(a) = 2.5$ as "standard," but in larger devices where we require the same τ_E , and where the current distribution is flatter, it may be possible to operate at $q(a) = 2.0$. Since $P_f \propto q^{-4}$, a factor of 2 increase in P_f would be attainable, or a 20% smaller B_t could be used for the same P_f .

3.7 THE EFFECT OF ALPHA-PARTICLE RETENTION

In previous sections we have assumed that the alphas resulting from D-T fusions immediately escape from the plasma. In fact the plasma current in a practical neutron producer (I > 2 MA) will be quite adequate for retaining most of the alphas [18], so that their effect on P_f must be taken into account. The energy balance equation is now

$$P_b = \frac{3}{2} \frac{(n_T T_i + n_e T_e)}{\tau_E} - P_\alpha \tag{20}$$

where $P_\alpha = 0.20\, Q_b P_b$, while the pressure equation becomes

$$p = (n_e + n_T) T_e + \frac{2}{3} n_b \overline{W}_b \left(1 + \frac{n_\alpha \overline{W}_\alpha}{n_b \overline{W}_b}\right) = \text{constant} . \tag{21}$$

The ratio of alpha pressure to beam pressure is

$$\frac{n_\alpha \overline{W}_\alpha}{n_b \overline{W}_b} = 0.20 Q_b \frac{\tau_{s\alpha}}{\tau_{sb}} \frac{\overline{W}_\alpha}{W_\alpha} \frac{W_b}{\overline{W}_b} . \tag{22}$$

This quantity (divided by $0.20\, Q_b$) is plotted in Fig. 15. In the temperature range of interest, $T_e = 5 - 10$ keV, the ratio of alpha to beam pressure is approximately $0.20\, Q_b$. Thus to maintain the plasma temperature, P_b must be reduced by a factor of $1.2\, Q_b$ (Eq. 20), and the corresponding reduction in beam pressure will closely compensate for the increase in alpha pressure (Eq. 21). Then $(n_e + n_T) \simeq$ constant , but to preserve charge neutrality, n_e must decrease and n_T must increase by the amount $0.10\, Q_b n_{bo}$, where n_{bo} is the beam density in the absence of alphas. (The effect of the alphas on charge neutrality is negligible.) The net result is that

$$P_f \propto n_T n_b$$
$$= n_{bo} n_{To} (1 + 0.20Q_b)^{-1} (1 + 0.10Q_b n_{bo}/n_{To}) \quad . \qquad (23)$$

Thus if all alphas are retained, in the temperature range of interest P_f will be reduced by about 20% (although Q_b is essentially unchanged).

The alpha loss rate can be markedly enhanced by creating a loss cone via ripple in B_t [19]. However, this measure might also lead to loss of beam ions if they scatter appreciably before slowing down, which will be the case for $Z \gtrsim 3$. (Actually, such a technique might be useful in minimizing dilution of the triton target plasma; if the deuterons escape with $W \lesssim 50$ keV , little fusion energy will be lost.) In a practical reactor, the beam injectors will attempt to concentrate the deuterons in the central region of the discharge, while the alphas will be distributed fairly uniformly because of their large orbits. If the field ripple can be localized to the outer region of the plasma, then only alphas should be lost, and the reduction in maximum P_f can probably be limited to 10%. In the case of a TCT with a 50:50 D-T bulk plasma, the reduction in P_f will be even less because of the smaller Q_b of this plasma.

For a D-T bulk plasma with substantial $n_e\tau_E$, alpha energy deposition allows P_b to be further reduced, thus increasing Q_f until at sufficiently large $n_e\tau_E$ ignition is attained ($P_b = 0$) [2];

P_f is then somewhat smaller then the one-component values (e.g., see Fig. 10), since the alpha pressure forces a reduction in $n_D = n_T$. Thus retaining alphas is desirable for maximizing Q_f, but necessarily leads to a reduction in P_f.

3.8 ENERGY CLAMPING

Techniques are known by which the energy of suprathermal ions can be sustained for appreciable periods [2,9], so that injected deuterons, for example, may be kept near the optimal energy for fusion reactivity. Of the various techniques, toroidal-electric-field clamping and "wobble" clamping methods seem possible candidates for the present application. But for E_t clamping to be effective, all the deuterons must be injected in the same direction, which might seriously damage the plasma equilibrium. Thus a "wobble" technique such as rigid displacement of the plasma column at the ion transit frequency around the torus [9] would seem to be necessary.

Although energy-clamping is capable of almost doubling Q_b, for this purpose a clamping period $\tau_c >> \tau_s$ is required (unless one can utilize decompression [9]). But if we are not particularly concerned with increasing Q_b, then even with τ_c considerably less than τ_s the probability of fusion for each ion is enhanced. Application of clamping would result in $\overline{W}_b$ being larger than the values given in Fig. 4. However, n_b can be reduced only slightly, since beam power loss increases only slightly with increasing W in the range 50 - 200 keV. Thus $(n_e + n_T)$ must be reduced [cf. Eq. (13)], and the resultant decrease in target density must be offset by the increase in $\overline{\sigma v}$ due to energy clamping. Although an increase in P_f is not necessarily attained, the same P_f is obtained with a smaller injection capacity. Thus we are exchanging beam injectors for volt-seconds in the ohmic-heating circuit, in the case of E_t clamping, or stored energy in the vertical field circuit, in the case of "wobble" clamping. Since the basic goal is to exchange electrical energy for neutron production at the lowest possible capital cost, the advantage of energy clamping therefore depends on the relative cost of the additional electrical components compared to the beam injectors eliminated.

On the other hand, any "bootstrap clamping" method, by which the bulk plasma transfers some of its thermal energy back to the beam ions [9], would be desirable. One plasma-clamping effect that may lead to a 5 - 10% increase in neutron production is the classical scattering of injected ions to higher energies by the thermal motion of bulk-plasma particles [12].

3.9 PRINCIPLES OF MAXIMIZING FUSION POWER DENSITY

The optimal operating conditions of a TCT for obtaining maximum P_f are summarized in the following:

(1) The plasma pressure p should be as large as possible, so that B_t should be as large as practical, and q may be reduced until the resulting MHD activity lowers $n_e\tau_E$ below the optimal value.

(2) For a given p and T_e, $\overline{\Gamma}$ has an optimal value (Fig. 5) which thereby fixes optimal values of n_e, τ_E and n_T/n_e (Figs. 6 and 7). The optimal τ_E is 0.5 to 0.8 times the desired fast-ion lifetime (Fig. 8).

(3) Alpha confinement should be reduced as far as possible without losing energetic beam ions in the process.

(4) The optimal T_e increases with the minimum required Q_b (Fig. 5), but if low Q_b and high n_e can be tolerated, smaller T_e gives the largest P_f.

(5) Energy clamping is desirable only if the cost of the electrical components required for clamping is less than that of the injectors eliminated.

(6) Dilution of the tritium bulk plasma by neutral recycling of deuterons should be avoided, either by capture of diffusing ions in a divertor or by vigorous injection of tritium pellets.

In a large device, special measures may have to be taken to reduce τ_E to the optimal value:

(1) Reduction in q, provided that the resultant MHD activity does not lead to loss of beam ions before they slow down.

(2) Addition of high-Z impurities to enhance radiation loss. This possibility is discussed in Section 4.

(3) At large T_e, synchrotron radiation loss could be important.

(4) Introduction of asymmetry in the magnetic field configuration.

(5) Vigorous pellet injection, effectively increasing the specific heat of the bulk plasma.

4.0 THE ROLE OF IMPURITY IONS

4.1 EFFECT OF IMPURITY CONTENT ON P_f AND Q_b

The presence of impurity ions forces a reduction in the triton-target density, because the impurity charge must be neutralized under the restriction of constant total plasma pressure. This depletion of tritons adversely affects P_f and Q_b, but impurity radiation may be welcome for regulating τ_E (cf. Section 4.2). In this section we consider how the results of Section 3 are modified by the inclusion in the plasma of a single impurity specie of charge Z_I and density n_I. In the following we treat a steady-state impurity population, with all energy losses involved in impurity radiation accounted for in τ_E. The impurity ions can be expected to exist in good thermal equilibrium with the tritons and electrons. Then the relevant equations for calculating P_f are

$$P_b = \frac{n_b W_o}{\tau_s} = \frac{(3/2)(n_T + n_I + n_e)T_e}{\tau_E} \quad , \tag{24}$$

$$n_e = n_T + n_b + Z_I n_I \quad , \tag{25}$$

$$p = (n_T + n_I + n_e)T_e + \frac{2}{3} n_b \overline{W}_b = \text{constant} \ . \tag{26}$$

$\overline{W}_b$ is calculated from Eq. (15), using [10]

$$W_c = 14.8\, T_e M_D \left(\frac{1}{M_T} \frac{n_T}{n_e} + \frac{Z_I}{M_I} \frac{Z_I n_I}{n_e} \right)^{2/3} \tag{27}$$

where M_D, M_T, and M_I are the atomic masses of the deuteron, triton, and impurity ions, respectively. For a given impurity ion, Z_I/M_I depends on T_e, n_e, and the ion lifetime, τ_I. From ionization-rate calculations [20] in the range $T_e = 3 - 15$ keV, it appears that Z_I/M_I can be represented approximately as follows:

$Z_I \leq 20$	$Z_I/M_I \approx 0.50$
$20 < Z_I \leq 35$	≈ 0.45
$35 < Z_I \leq 50$	≈ 0.40
$Z_I > 50$	≈ 0.35 .

The fusion power density is now

$$P_f = Q_b P_b \approx \frac{Q_{bo}}{\tau_{so}} \frac{W_o}{n_{eo}} \frac{n_T}{n_e} \left(1 - \frac{n_T}{n_e} - \frac{Z_I n_I}{n_e}\right) n_e^2 \tag{28}$$

where

$$n_e = \frac{p}{(2/3)[1 - (n_T/n_e) - (Z_I n_I/n_e)]\bar{W}_b + [1 + (n_T/n_e) + (n_I/n_e)]T_e} . \tag{29}$$

As in Eq. (16), τ_{so} is calculated at n_{eo}, and both Q_{bo} and τ_{so} are evaluated for $n_T/n_e = 1$.

The impurity concentration is often expressed in terms of an "effective Z," where

$$Z_{eff} = \frac{n_T + n_b + n_I Z_I^2}{n_e} . \tag{30}$$

Hence

$$\frac{n_I}{n_e} = \frac{Z_{eff} - 1}{Z_I(Z_I - 1)} \ . \tag{31}$$

For given values of Z_I and Z_{eff}, the optimal value of n_T/n_e is found as before by maximizing P_f. The corresponding n_b/n_e, n_e, and τ_E are found from Eqs. (25), (29), and (24), respectively. $\bar{\Gamma}$ is found from

$$\bar{\Gamma} = \frac{n_b \bar{W}_b}{(3/2)(n_T + n_I + n_e)T_e} \ . \tag{32}$$

The maximum values of P_f are given in Fig. 16 for $T_e = T_i = 6.0$ keV, a preferred operating temperature when $Z = 1$ (cf. Table 1). The corresponding values of Q_b are given in Fig. 17. Evidently P_{fmax} is reduced by a smaller factor than the reduction in Q_b, for a given impurity content. For example, if $Z_{eff} = 7$ in fully-ionized iron ($Z_I = 26$), P_{fmax} is reduced by 17% while Q_b is reduced by 30%. The difference in the reduction factors is explained by the fact that the beam slowing-down time decreases with increasing Z_{eff}, so that a larger beam current can be injected for the same total p, thus tending to maintain P_f while Q_b drops. One can roughly characterize the situation by stating that the addition of impurities gives almost the same fusion power output at the cost of a smaller Q_b, thus requiring a larger investment in beam injector capacity.

It is evident from Fig. 16 that stringent impurity control is unnecessary in a TCT whose main purpose is neutron production at low Q. Even for $Z_{eff} = 10$ caused by ions sputtered from the vacuum wall (steel or niobium), the reduction in P_f is at most 30%, while at 6 keV Q_b is still above the desired minimum level for a fissile breeder of 0.6. However, as discussed in the next section, impurity radiation must not reduce τ_E appreciably below the optimal value. One adverse effect of a large impurity content is that the mean-free-path for ionization of a neutral beam with $W_o \gtrsim 200$ keV may decrease significantly with increasing Z_{eff}. Thus higher beam energies may be required for adequate penetration, resulting in smaller Q_b (cf. Fig. 3).

4.2 USE OF IMPURITY RADIATION TO REGULATE τ_E

The optimal τ_E for maximizing P_f is about half the required beam-ion lifetime ($\sim\tau_s$), but a large plasma may be characterized by an $n_e\tau_E$ considerably greater than the optimal value. While the particle lifetime τ_p and thus τ_E can be reduced by decreasing q or degrading the magnetic symmetry, there exists the possibility that these measures may also damage the beam confinement. One way to decrease τ_E without affecting τ_h or τ_p is the enhancement of radiation by introduction of high-Z impurities. The concomitant reduction in Q_b may be warranted by the increase in P_f as τ_E is lowered toward the optimal value.

The power losses associated with impurities are (1) enhanced bremsstrahlung; (2) line radiation; (3) recombination radiation; (4) energy required for stripping electrons, including excitation; (5) heating of the stripped electrons. The relation between τ_p and τ_E is

$$\frac{\tau_E}{\tau_p} = 1 - \frac{P_{rad}}{P_b} \qquad (33)$$

where P_{rad} is the total power density associated with impurity loss, and P_b is the injected beam power density. Here we assume that τ_p is the same as the heat conduction loss time.

Bremsstrahlung radiation power is given by

$$P_{brem} = 5.8 \times 10^{-31} n_e^2 T_e^{1/2} Z_{eff} \tag{34}$$

where T_e is in keV. P_{brem} tends to be many times smaller than line radiation from partially stripped ions that hold at least three electrons. The latter is given approximately by [20,21]

$$P_L \approx 1.5 \times 10^{-26} \frac{n_I}{n_e} n_e^2 \tag{35}$$

where n_I/n_e is given by Eq. (31). Recombination radiation is important only for completely stripped ions, and is smaller than line radiation for $Z < 40$. For $T_e < 15$ keV and $n_e \tau_I < 2 \times 10^{13} cm^{-3}$, ions with $Z > 40$ will never be completely stripped [20], so that line radiation is always dominant.

The sum of the ionization energies required for stripping tends to be a small fraction of the excitation radiation loss during the stripping process [21]. The excitation power loss during ionization of incoming impurity ions is similar to P_L, provided that at least three electrons remain. This effect is important, since for high-Z impurities, the time required for the maximum ionization appropriate to the local T_e may approach

τ_I [20]. Heating of the stripped electrons is a factor already taken into account provided that $\tau_I \gtrsim \tau_p$, as seems likely.

Thus all radiation loss can be essentially accounted for by Eqs. (34) and (35). For low-Z ions that are completely stripped, recombination radiation power is smaller than P_L, but Eq. (35) reasonably describes radiation loss during the ionization process. Figure 18 shows the ratio of $P_{rad} = P_{brem} + P_L$ to the beam power density required to maintain the plasma temperature at 6.0 keV, when τ_E is the value that allows maximum P_f, given in Fig. 16; the plasma contains a single impurity of charge Z_I and concentration Z_{eff}. (Although the impurity ions may actually exist in various degrees of ionization, P_L depends only on the impurity density.) If, for example, τ_p is just equal to the minimum required beam confinement time ($\approx \tau_s$), τ_E can be reduced to the optimal value if $P_{rad}/P_b \approx 0.4$ (cf. Fig. 8). This reduction in τ_E occurs with $Z_{eff} = 5$ in iron or $Z_{eff} = 9$ in niobium, which will be 38 times ionized at 6 keV. Of course, in the absence of impurities, P_f may be equally as large when $\tau_E/\tau_p = 1$, but this example shows that a large impurity content may in fact have no effect on P_f (although it does lower Q_b).

For large plasmas where τ_p may be much greater than τ_s, P_f may be only a fraction of its maximum value unless τ_E is drastically reduced. If for example, $\tau_s/\tau_p = 0.3$, so that $P_f/P_{fmax} \approx 0.4$ when $Z = 1$ (cf. Fig. 8), addition of argon in the amount $Z_{eff} = 5$ will allow P_f to increase by about 80%, while Q_b is decreased by 30%. Here we have assumed that the sum of excitation and recombination radiation in argon ($Z = 18$) is comparable to P_L; the same result can be attained with $Z_{eff} = 8$ in iron. This beneficial effect of a large impurity concentration is in sharp contrast to the case of an ignition-type reactor, since $Z_{eff} \sim 10$ in tungsten, for example, completely prevents ignition at any temperature [22].

4.3 EFFECT OF IMPURITY SCATTERING

For $Z_{eff} > 1$, beam ions injected tangentially are scattered through 90° before slowing down. If $Z_{eff} >> 1$, suprathermal ions will undergo trapping and detrapping in banana orbits, and these orbits may eventually diffuse across the plasma. The radial diffusion time τ_D is

$$\frac{\tau_D}{\tau_s} \approx \left(\frac{a}{\Delta}\right)^2 \frac{\tau_{scat}}{\tau_s} \frac{1}{Z_{eff}} \tag{36}$$

where Δ is the gyroradius in the poloidal field and τ_{scat} is the 90° scattering time for $Z_{eff} = 1$. If $T_e = 6.0$ keV, $\tau_{scat}/\tau_s \approx 0.4$ for 200 keV deuterons, while 3.5 MeV alphas do not significantly scatter until they have lost at least 90% of their energy. At higher T_e, scattering is more important. For a given ion, Δ is determined by I/a, which is fixed once B_t, A and q are specified. For our "standard" parameters of $B_t = 60$ kG, $A = 3.5$, $q = 2.5$, Δ is 8 cm for 200 keV D, and 24 cm for 3.5 MeV alphas.

On inserting these numbers into Eq. (36), it appears that banana diffusion is not an important loss mechanism when $a \gtrsim 100$ cm, even for $Z_{eff} = 10$. But if $a \sim 50$ cm, $Z_{eff} \sim 10$ could be effective in ejecting D ions before they completely thermalize and dilute the background plasma, while scattering would also reduce the alpha pressure (cf. Section 3.7). Therefore this aspect of impurity concentration appears to be favorable.

5.0 CONCLUSIONS

This paper has determined how to optimize the plasma parameters of a two-component tokamak reactor for attaining maximum fusion power density P_f (i.e., maximum neutron production rate per unit volume). The optimal operating conditions are rather lenient compared to those normally required for net power-producing reactors (including TCT's). The ideal maximum P_f increases monotonically with decreasing T_e, but if beam power multiplication $Q_b \sim 1$ is desired, the preferred range of operation is $T_e = 5 - 8$ keV. Here the optimal $n_e \tau_E$ is 8×10^{12} to $1.5 \times 10^{13} \text{cm}^{-3}\text{sec}$, while the corresponding beam pressure is 0.8 to 0.9 times the bulk-plasma pressure. For our "standard" parameters of $B_t = 60$ kG, $A = 3.5$, $q = 2.5$, $W_o = 200$ keV, 100% T plasma, and total $\beta_p = A$ (i.e., $p = 0.655 \text{ J/cm}^3$), P_f in the range 10 - 20 W/cm^3 is attainable with $Q_b \sim 1$. These values of P_f are 3 to 6 times larger than available in a thermal (one-energy component) reactor at any temperature, for the same beta; the latter also requires a much larger $n_e \tau_E$ for power gain $Q \sim 1$. Even with a bulk-plasma composition of 50:50 D-T, the TCT affords a P_f considerably larger than does a thermal reactor.

The plasma conditions for maximizing P_f are strikingly different from those for maximizing Q. Enhancing Q demands a larger

$n_e\tau_E$, a reduction in the tritium enrichment of the bulk plasma, and an increase in $T_e = T_i$. Attaining the largest Q-values demands the retention of all D-T alphas. For maximizing P_f, on the other hand, ejection of alphas from the plasma is preferred, because the alpha contribution to p limits the beam injection power. In sum, except for values of $n_e\tau_E$ below the optimal for P_f, increasing Q necessarily leads to a reduction in P_f.

The presence of impurity ions has a significantly smaller effect on P_f than on Q_b. For TCT applications where some reduction in Q_b can be tolerated, Z_{eff} as large as 10 can be sustained in the case of high-Z ions. For larger plasmas with particle lifetimes many times the beam slowing-down time, radiation from high-Z impurities can be effective in reducing τ_E toward the optimal value, thus allowing a substantial increase in P_f. In any event the large values of P_f attainable may permit economic operation even for relatively short pulses — terminated before a significant buildup in impurity level can occur.

For TCT operation as a fissile breeder in conjunction with fission reactors of high conversion ratio, $Q_b \gtrsim 0.6$ appears to be adequate. For this application the TCT operating under optimal conditions for P_f seems decidedly superior to other proposed fusion reactors. The required values of T_e, $n_e\tau_E$, and Z_{eff} are not far from those expected in the next generation of tokamak devices ($I \gtrsim 1$ MA). Present experiments and theoretical analysis indicate that the required suprathermal-ion pressures can be attained with no loss of stability. The chief technological problem, as far as the plasma-beams system is concerned, would seem to be the development of highly efficient 200-keV neutral beams.

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APPENDIX A: NEUTRAL-BEAM ACCESS AREA

In order to realize the large values of P_f theoretically attainable in a TCT, enormous injection currents are required. Figure 9 shows that at $T_e = T_i = 6.0$ keV, for example, $P_b = 11\ W/cm^3$. Thus a plasma of $a = 1$ m, $R = 3.5$ m, and $\bar{T}_e = 6$ keV requires a total injected power of 770 MW, or a total injected current of 3850 A at $W_o = 200$ keV. One limitation to the beam flux is that impact ionization by gas in the beam line may result in energetic ions hitting the wall and producing intolerable gas buildup [23], but with a beam line diameter $\gtrsim 50$ cm and suitable pumping techniques, injection current densities as large as 0.2 A/cm^2 seem feasible at 200 keV. Injection of <u>ions</u> with at least comparable intensity may also be possible with the use of magnetic guide fields in a divertor [24]. Thus the total area of the beam apertures should be at least $1.9 \times 10^4\ cm^2$. Assuming that the vacuum wall is just 10 cm from the edge of the plasma, the area required for admitting the beams is only 1.3% of the total wall area. The percentage of the wall taken up by beam apertures increases linearly with plasma radius, but this percentage remains small for any conceivable TCT operated at maximum P_f, provided that $T_e \gtrsim 5$ keV. The addition of certain impurity control devices, such as a divertor, would increase the wall radius, thus making the fractional area devoted to beam admission even smaller.

REFERENCES

[1] DAWSON, J. M., FURTH, H. P., and TENNEY, F. H., Phys. Rev. Lett. 26 (1971) 1156; POWELL, F., California Research and Development Company Report No. LWS-24920 (1953) unpublished.

[2] FURTH, H. P. and JASSBY, D. L., Phys. Rev. Lett. 32 (1974) 1176.

[3] FRASER, J. S., HOFFMANN, C. R. J., and TUNNICLIFFE, P. R., Atomic Energy of Canada Limited Report AECL-4658 (1973).

[4] LEWIS, W. B., IEEE Trans. Nuclear Science NS-16 (1969) 28-35.

[5] MILLS, R. G., Princeton Plasma Physics Laboratory Report MATT-1050 (1974).

[6] LEE, J. D., Symposium on Thermonuclear Fusion Reactor Design, Lubbock, Texas, 2-5 June 1970, pp. 98-140.

[7] HOVINGH, J. and MOIR, R. W., Lawrence Livermore Laboratory Report UCRL-51419 (July 1973).

[8] DEAN, S. O., et al., Status and Objectives of Tokamak Systems for Fusion Research, USAEC Report WASH-1295 (July 1974).

[9] JASSBY, D. L. and FURTH, H. P., Princeton Plasma Physics Laboratory Report MATT-1048 (May 1974).

[10] STIX, T. H., Plasma Physics 14 (1972) 367.

[11] TOWNER, H., et al., Sixteenth Annual Plasma Physics Meeting of the American Physical Society, Albuquerque, New Mexico, 28 - 31 October 1974.

[12] BERK, H. L., et al., Fifth Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Tokyo, 1974), paper CN-33/G2-3 (to be published).

[13] ROME, J. A., CALLEN, J. D., and CLARKE, J. F., Nuc. Fus. 14 (1974) 141.

[14] LIDSKY, L. M. and COLOMBANT, D., IEEE Trans. Nuclear Science NS-14 (1967) 945.

[15] POST, R. F., et al., Phys. Rev. Lett. 31 (1973) 280.

[16] TENNEY, F. H., private communication.

[17] Third International Symposium on Toroidal Plasma Confinement, (Garching, Germany, 1973), papers B5, B17-I, F2-I.

[18] MCALEES, D. G. and FORSEN, H. K., Bull. Am. Phys. Soc. 18 (1973) 1305; TENNEY, F. H., TANG, K. K., and JASSBY, D. L., Sixteenth Annual Plasma Physics Meeting of the American Physical Society, Albuquerque, New Mexico, 28 - 31 October 1974.

[19] ANDERSON, O. A. and FURTH, H. P., Nuc. Fus. 12 (1972) 207.

[20] HINNOV, E., Princeton Plasma Physics Laboratory Report MATT-777 (September 1970).

[21] POST, R. F., Plasma Physics 3 (1961) 273.

[22] MEADE, D. M., Nuc. Fus. 14 (1974) 289.

[23] SWEETMAN, D. R. and RIVIERE, A. C., private communication.

[24] HAMILTON, G. W. and OSHER, J. E., Lawrence Livermore Laboratory Report UCRL-74096 (August 1972).

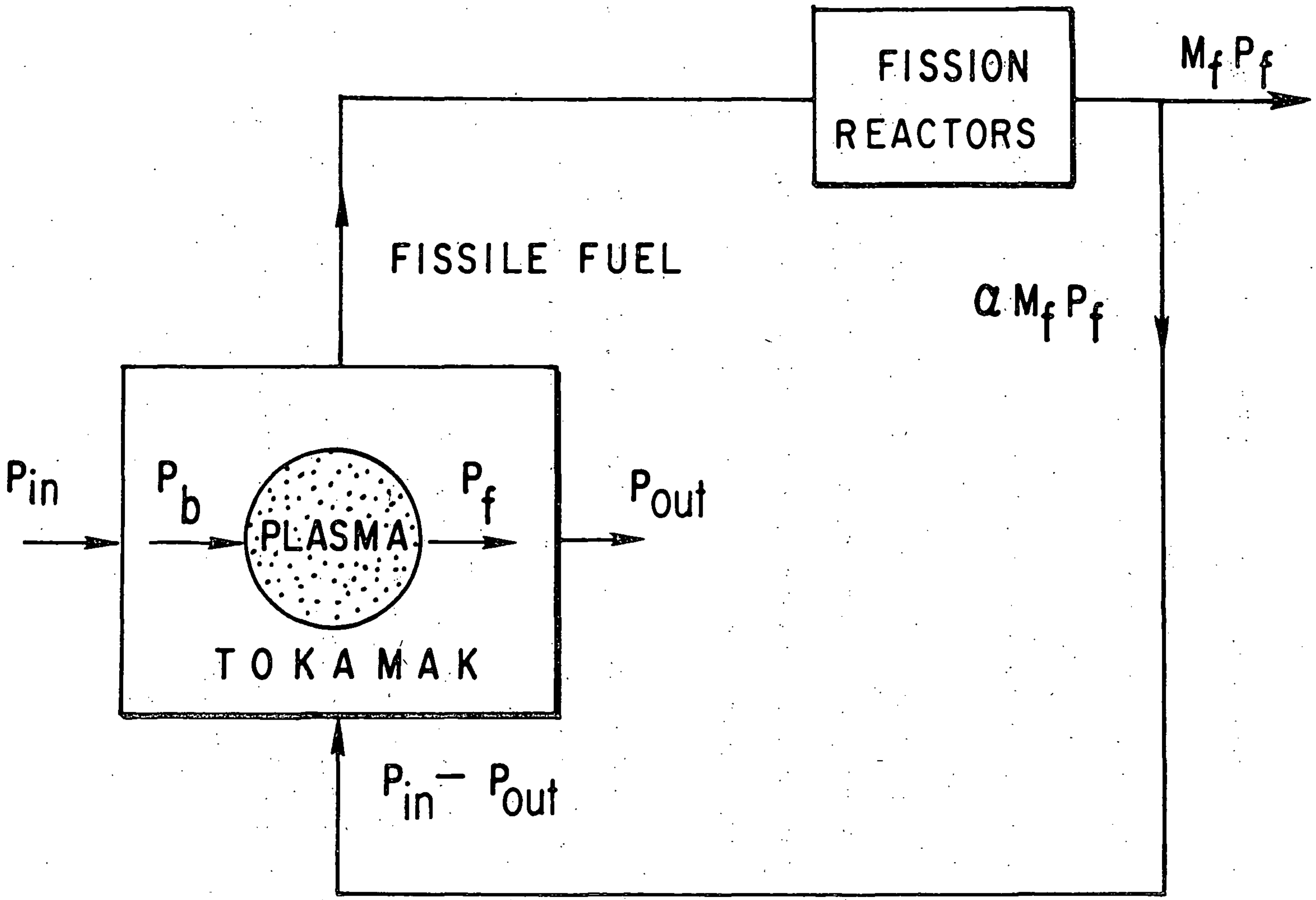

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Figure 1. Power flow in fusion-fission cycle. P_b is the injection power density, and P_f is the fusion power density.

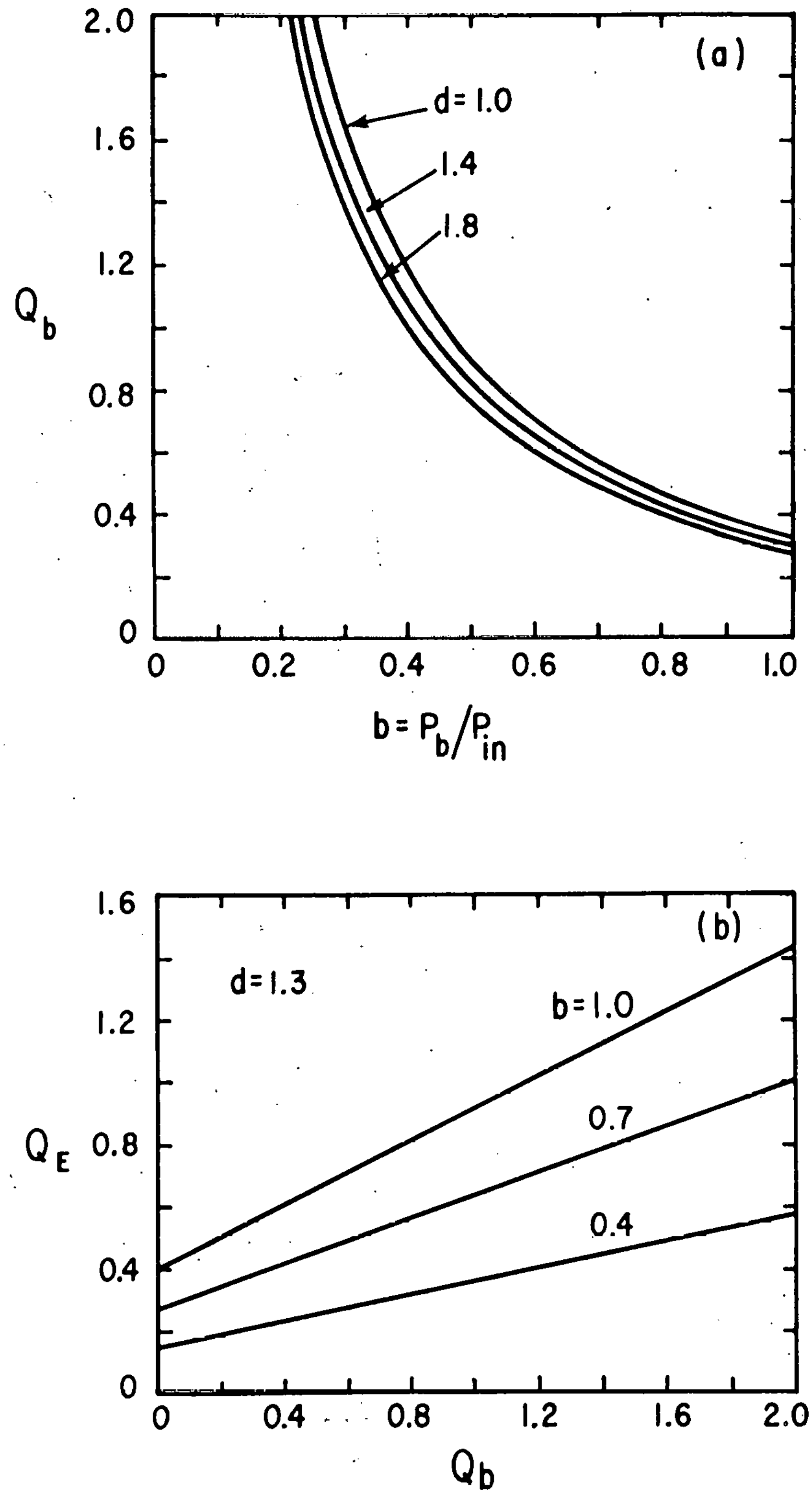

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Figure 2. (a) Minimum required fusion power gain Q_b of injected D beams in a TCT fissile breeder, as a function of the fraction b of input power to the breeder that resides in the beams. These results assume that 4% of the electrical output of the U-Th symbiotic fission plants can be diverted to sustain U-233 breeders. d is the enhancement of fusion energy by the blanket reactions. (b) Overall electric power gain of the fusion breeder, for d = 1.3 .

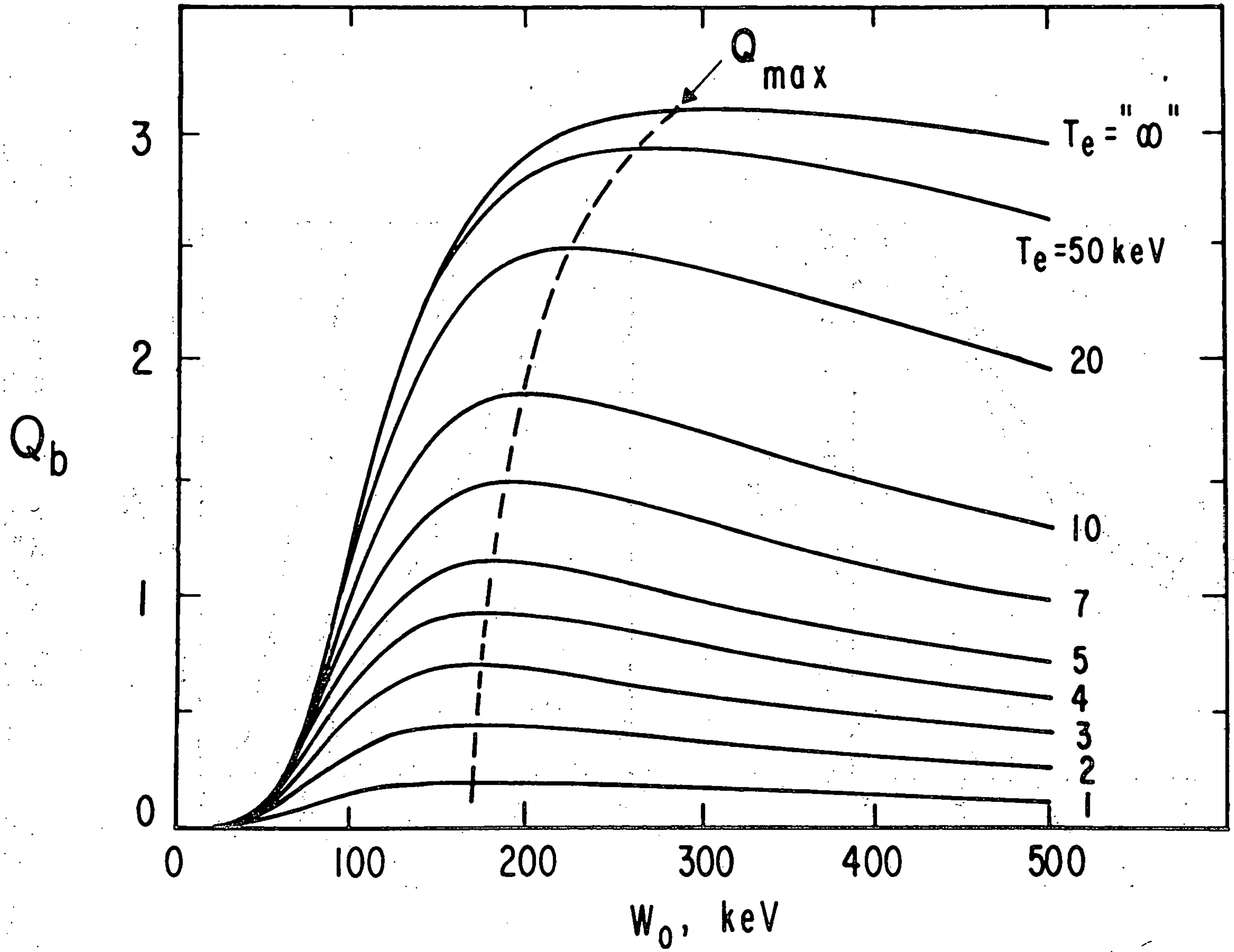

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Figure 3. Fusion power gain Q_b as a function of deuteron injection energy W_o for various values of T_e in a cold-triton target plasma, assuming $n_T = n_e$ (i.e., beam density is neglected). The $\ln \Lambda$ factors are calculated at $n_e = 3 \times 10^{13} cm^{-3}$. (From Ref. 1.)

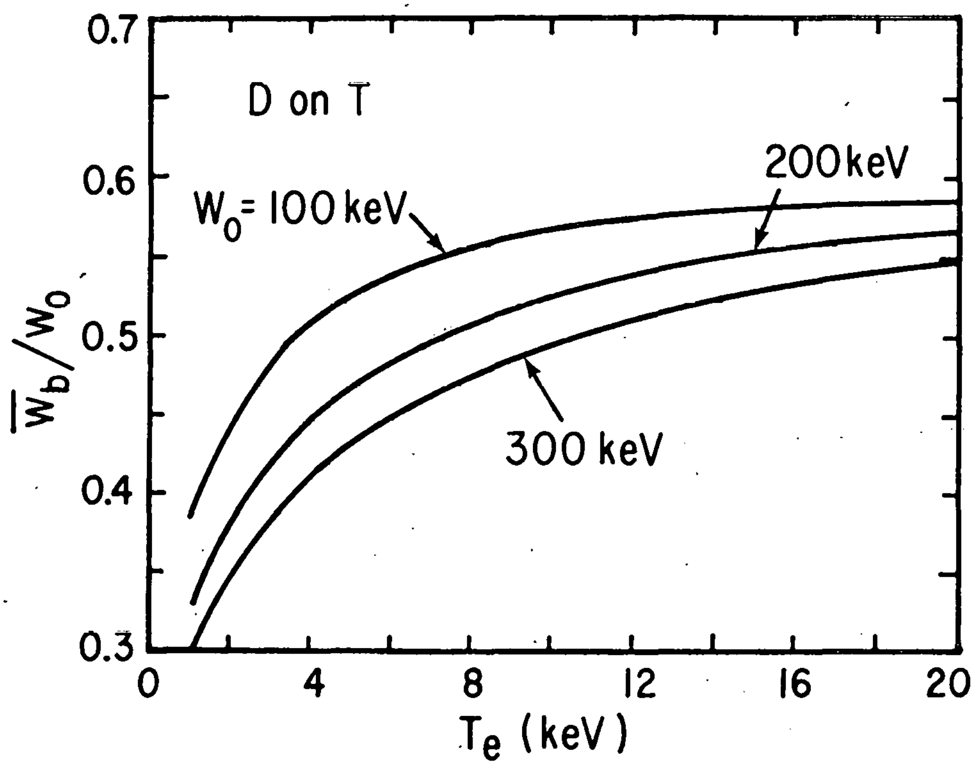

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Figure 4. Average energy $\overline{W}_b$ of suprathermal deuterons injected at energy W_o into a tritium plasma of electron temperature T_e, with $T_i = 0$ and $n_T = n_e$.

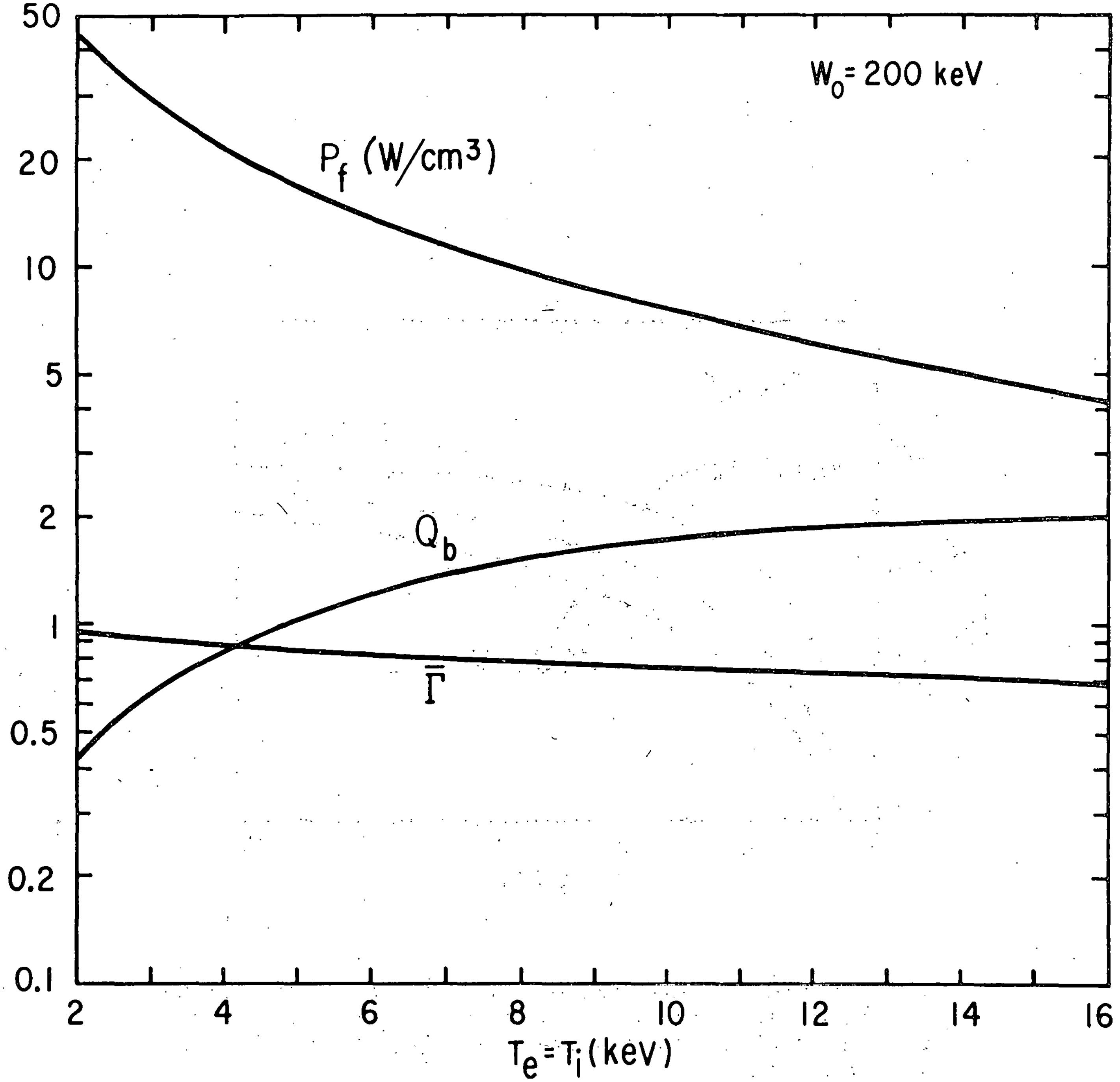

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Figure 5. Maximum attainable fusion power density for 200-keV deuterons injected into a triton-target plasma at T_e, with total plasma pressure = 0.655 J/cm^3, corresponding to B_t = 60 kG, β_p = A = 3.5, q = 2.5. $\bar{\Gamma}$ = beam pressure/bulk-plasma pressure and Q_b = effective fusion power multiplication. Alpha-particle effects are neglected.

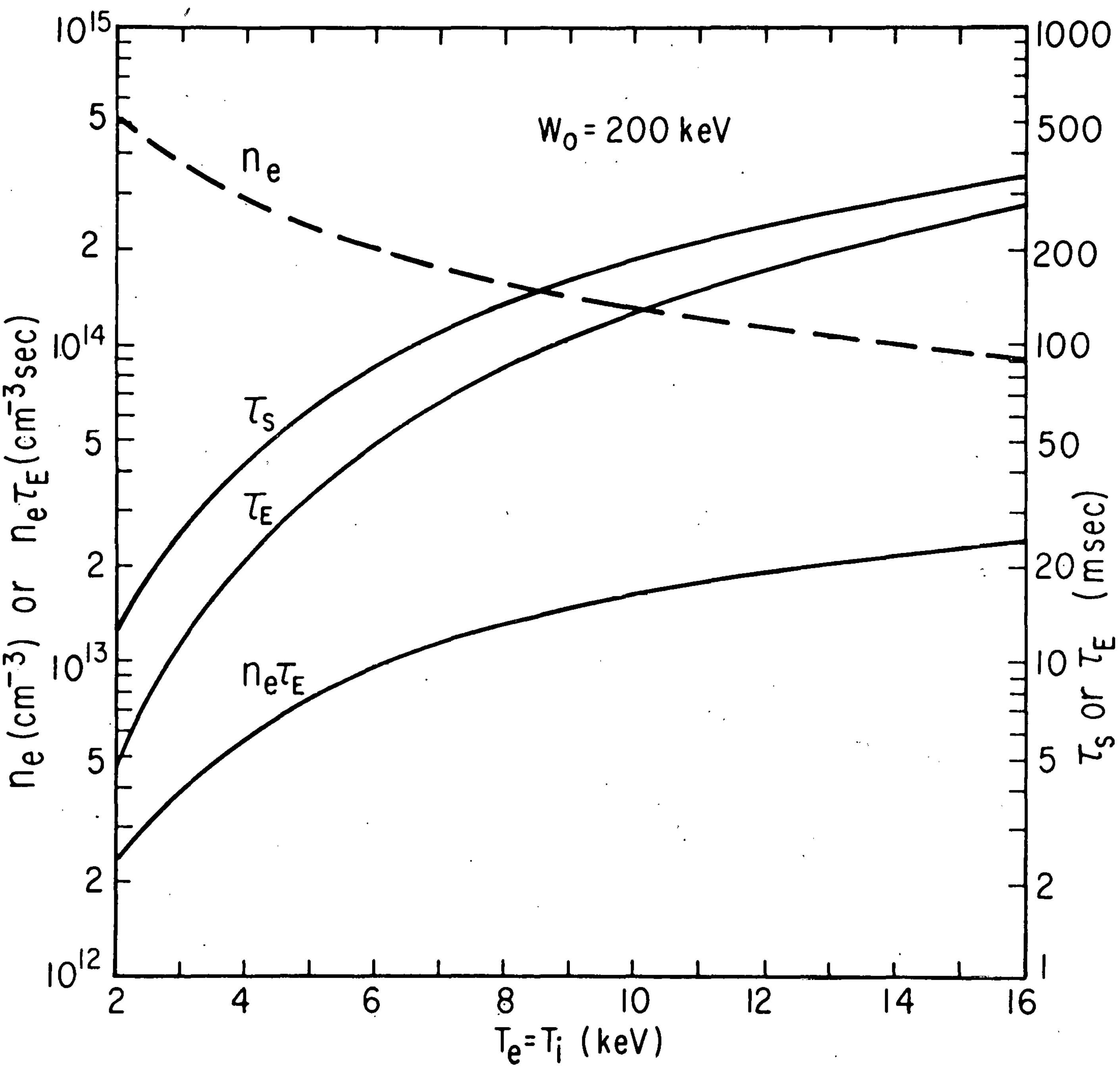

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Figure 6. Values of n_e, τ_s and τ_E for maximum P_f. Same conditions as Fig. 5. Radiation loss is included in τ_E.

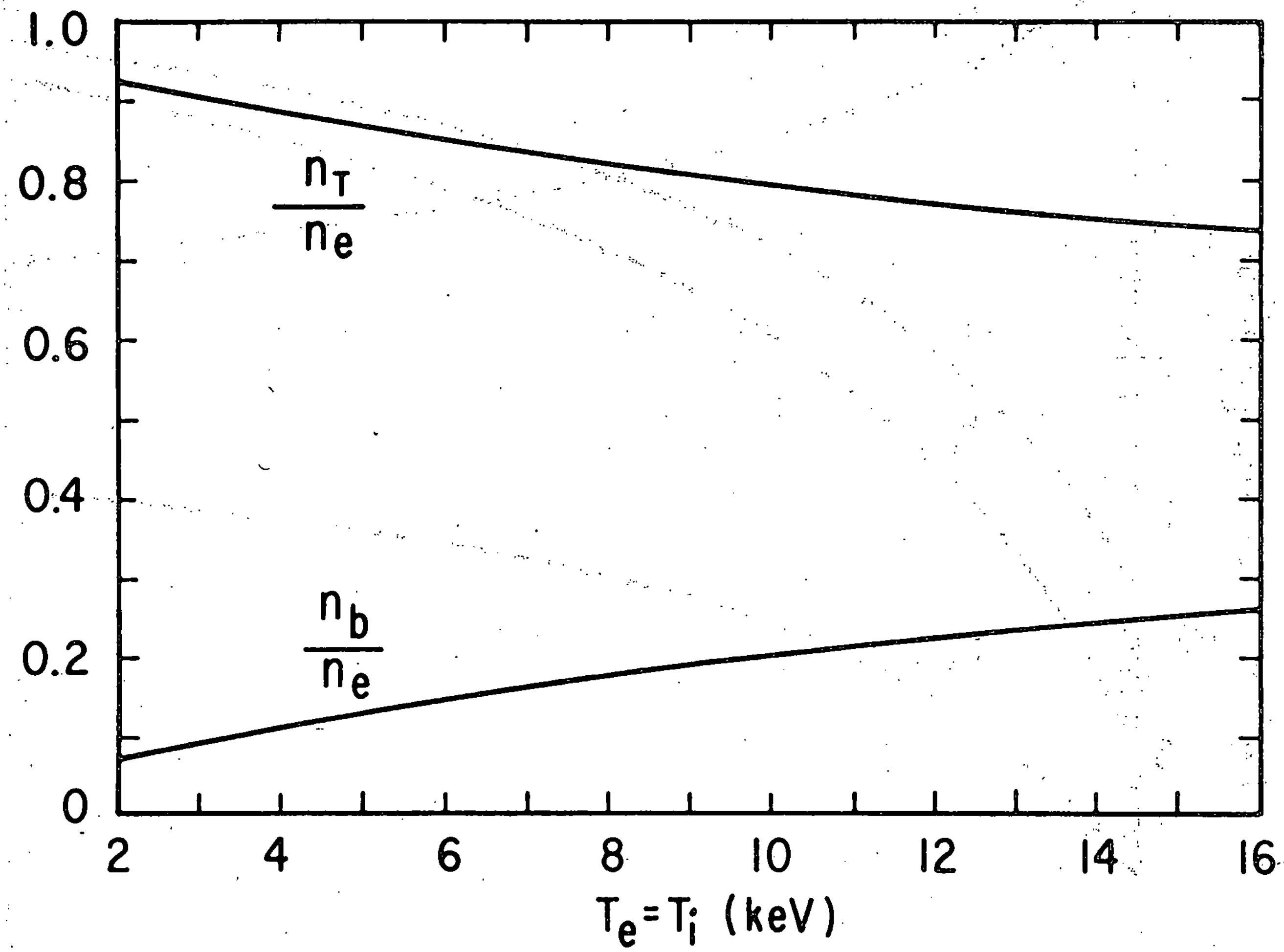

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Figure 7. Values of n_T/n_e and n_b/n_e for maximum P_f. Same conditions as Fig. 5.

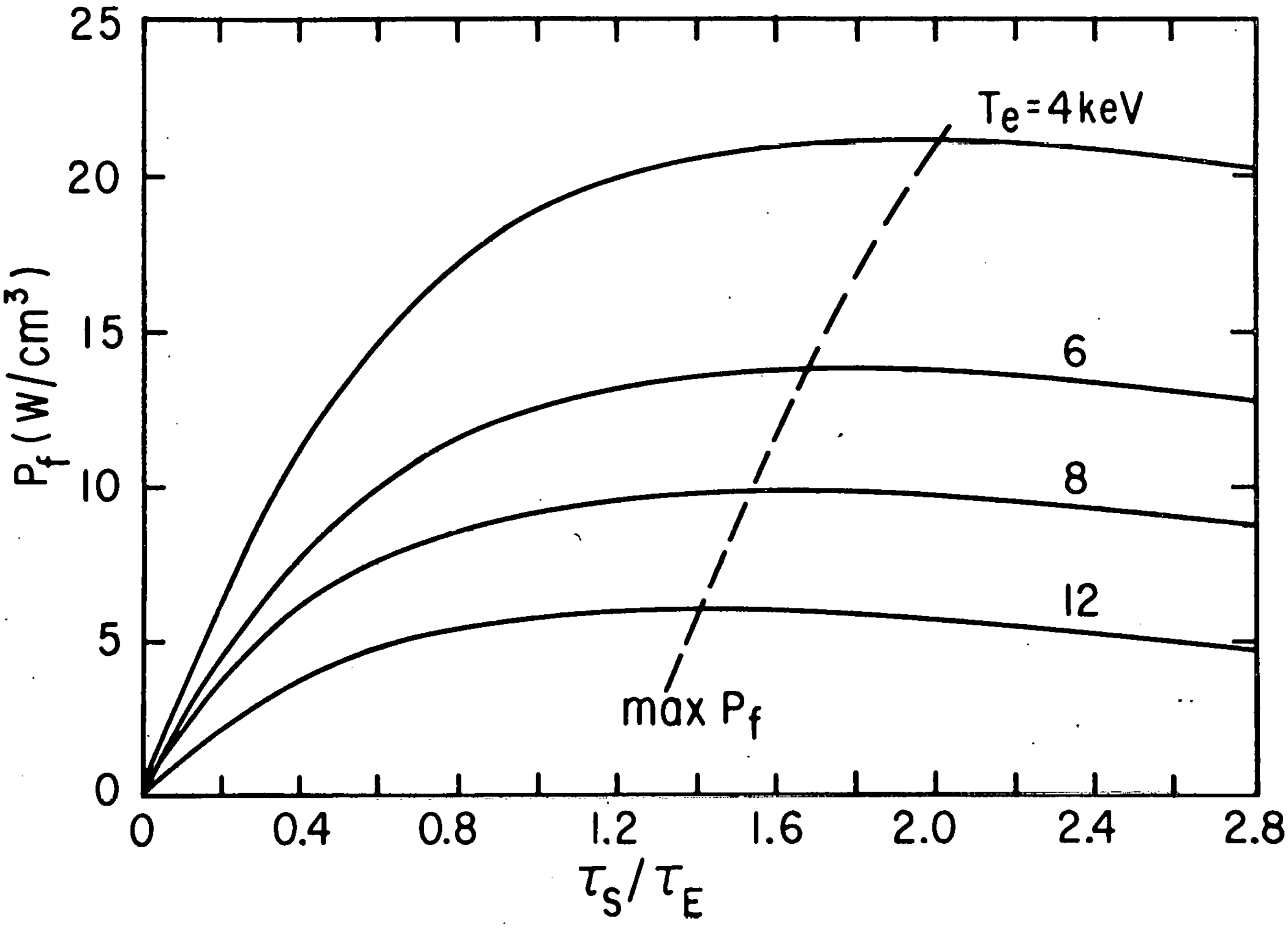

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Figure 8. Fusion power density versus plasma energy confinement time τ_E, for a triton-target plasma heated by 200-keV D beams, with $p = 0.655\ J/cm^3$. τ_s is the beam slowing-down time.

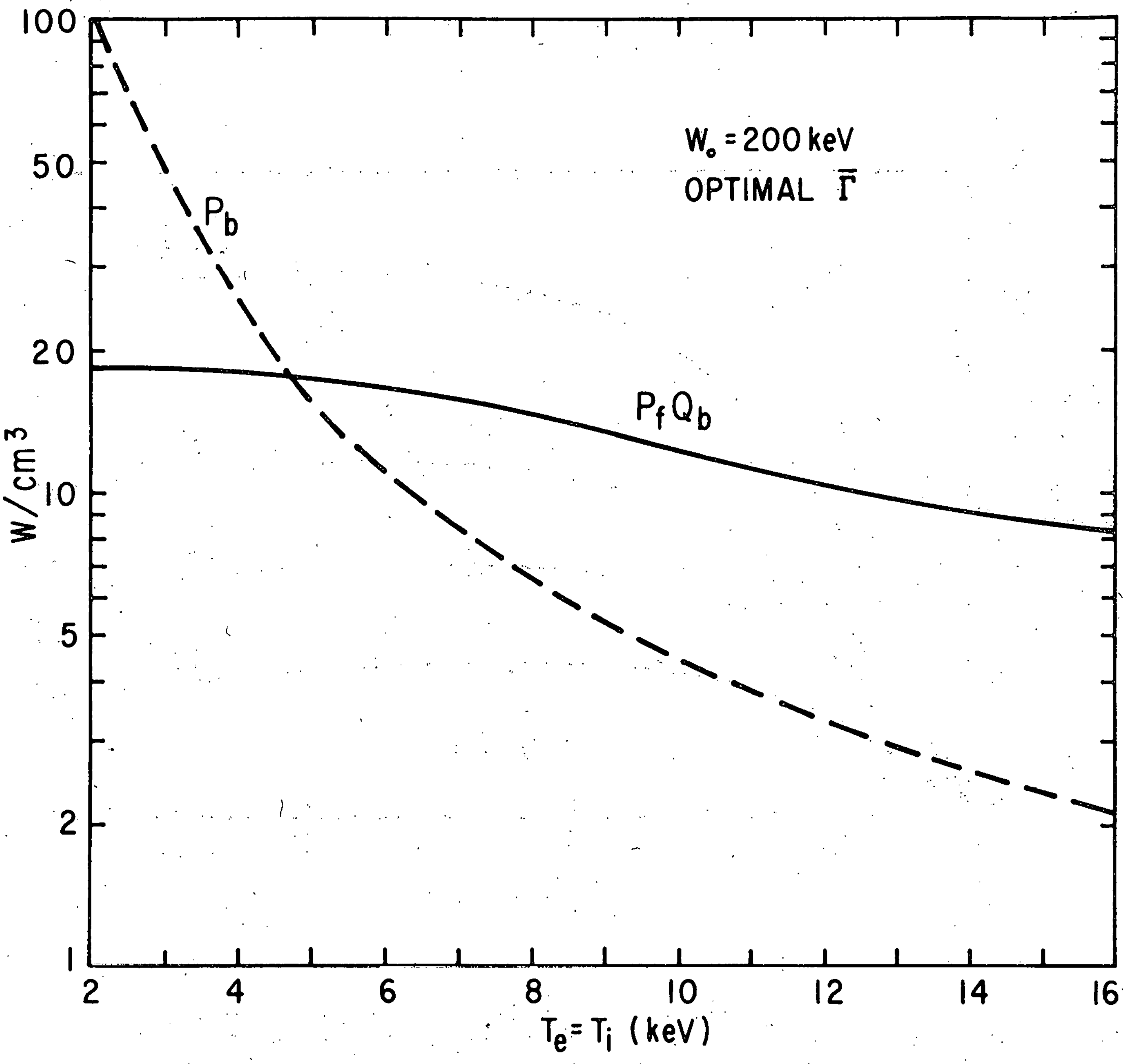

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Figure 9. Injection power P_b required for maximum P_f. P_fQ_b is a measure of cost-effectiveness.

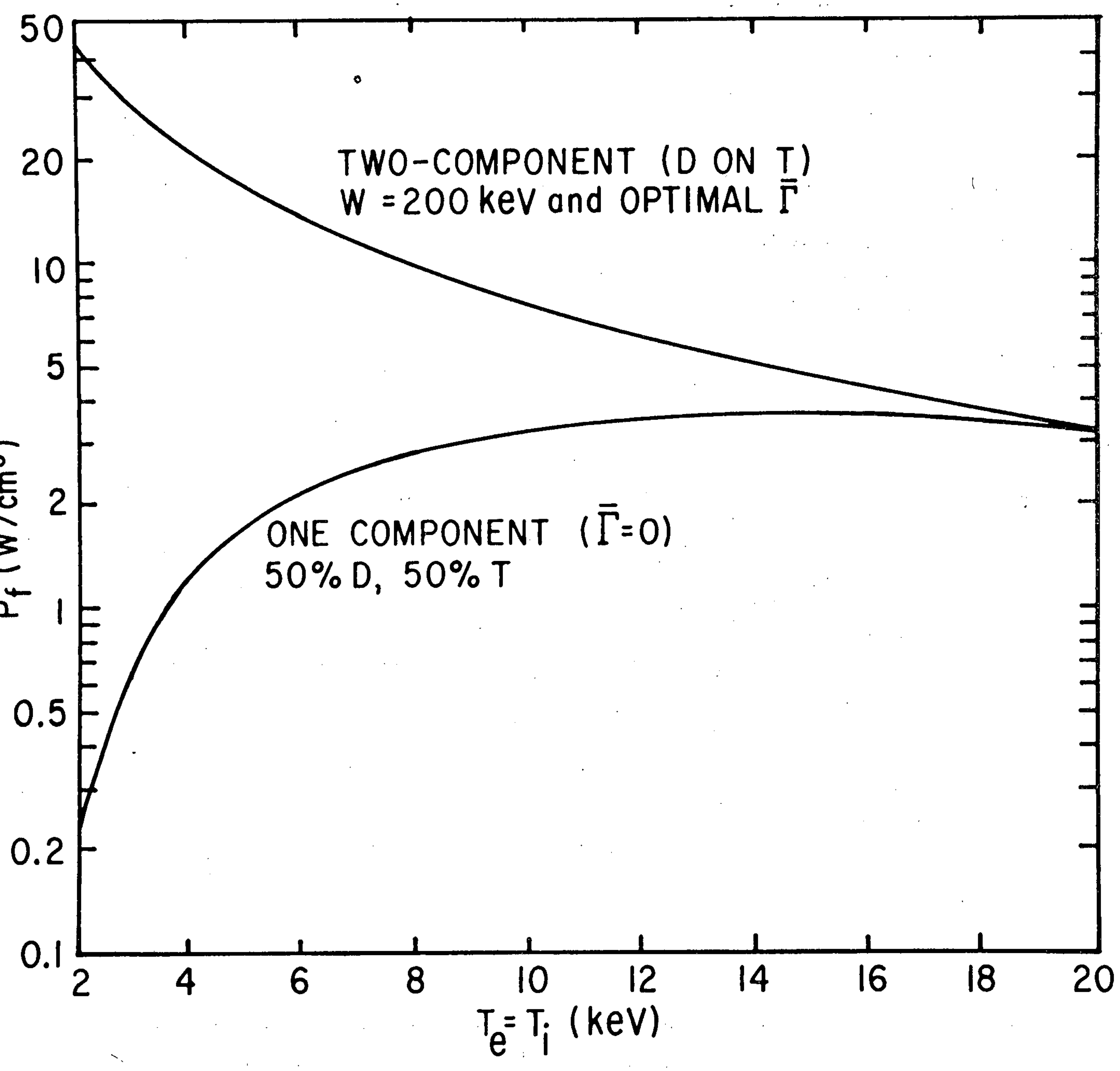

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Figure 10. Comparison of fusion power density for a two-energy-component plasma with optimal $\bar{\Gamma}$ (cf. Fig. 5), and a 50% D, 50% T thermal plasma ($\bar{\Gamma}$ = 0). In each case, total plasma pressure = 0.655 J/cm^3, corresponding to B_t = 60 kG, β_p = A = 3.5, q = 2.5. Alpha-particle effects are neglected.

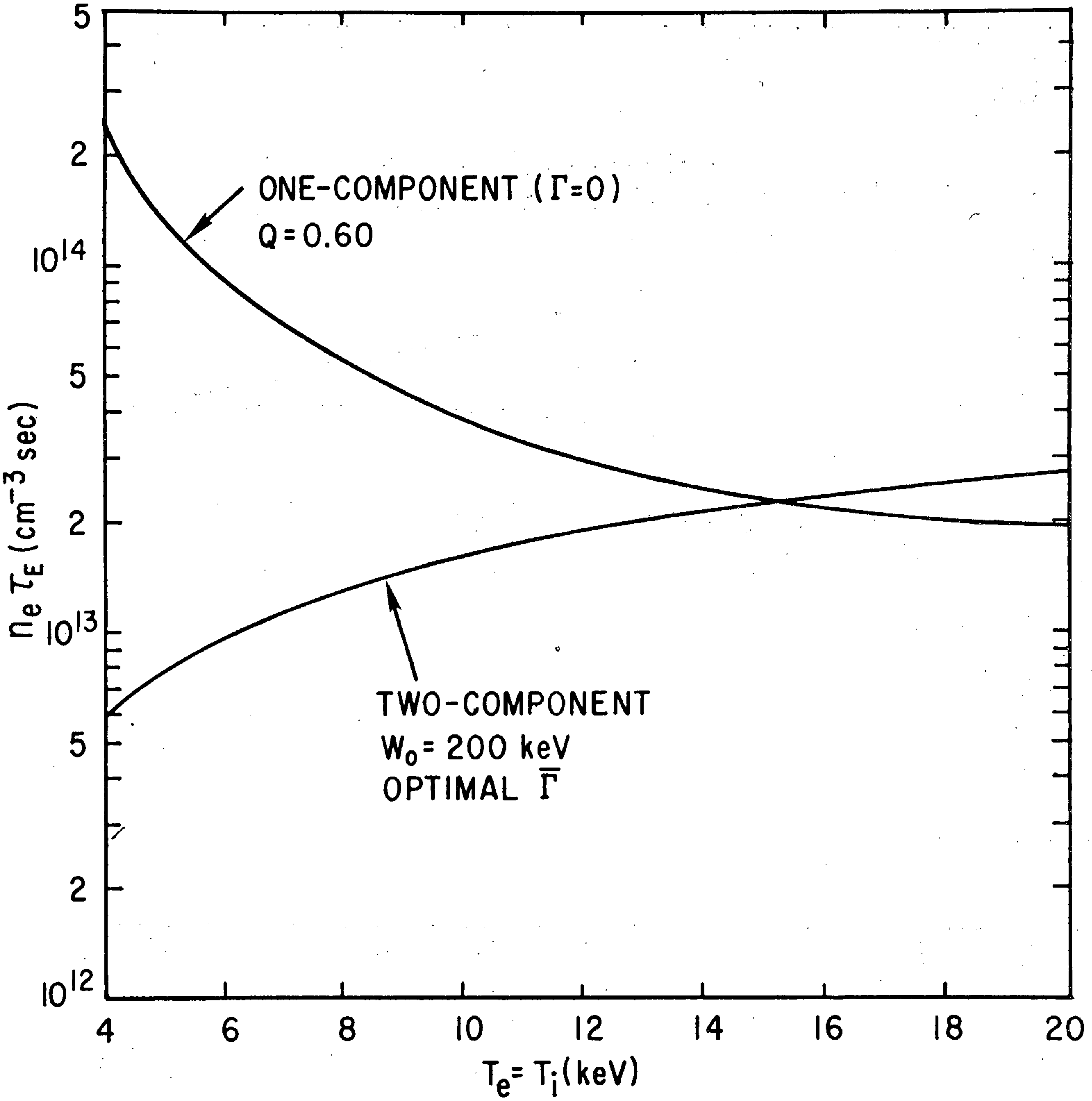

Figure 11. Minimum $n_e \tau_E$ for a one-component 50% D, 50% T plasma with Q = 0.60. The $n_e \tau_E$ for the two-component case is chosen for maximum P_f. Radiation loss is included in τ_E. Alpha-particle effects are neglected.

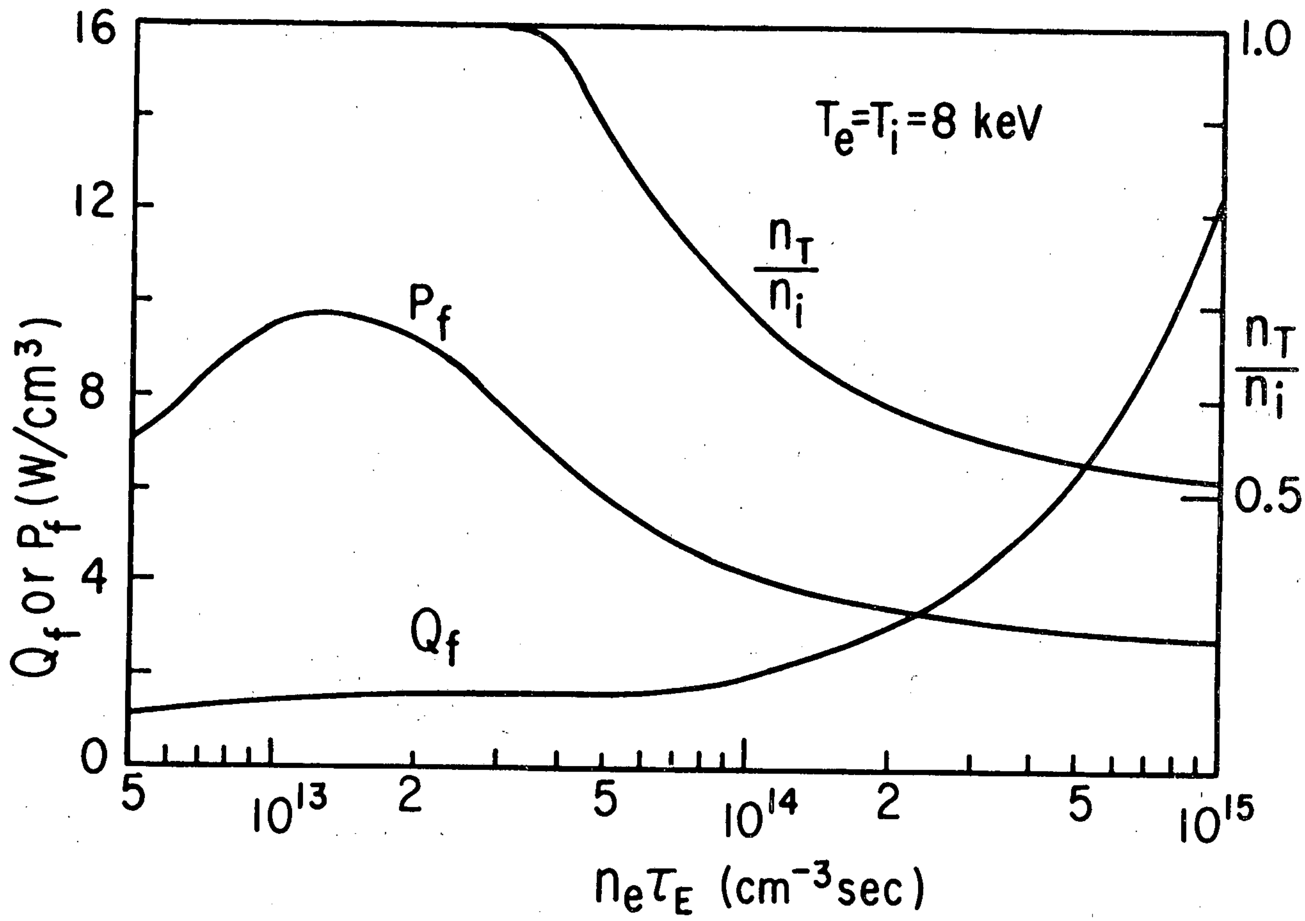

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Figure 12. Dependence of P_f and Q_f on $n_e\tau_E$ for an 8-keV D-T plasma heated by 200-keV D beams. Maximum Q_f is attained for the plasma composition given by n_T/n_i, where n_i is the bulk-ion density. $p = 0.655$ J/cm^3. Radiation loss is included in τ_E. Alpha-particle effects are neglected.

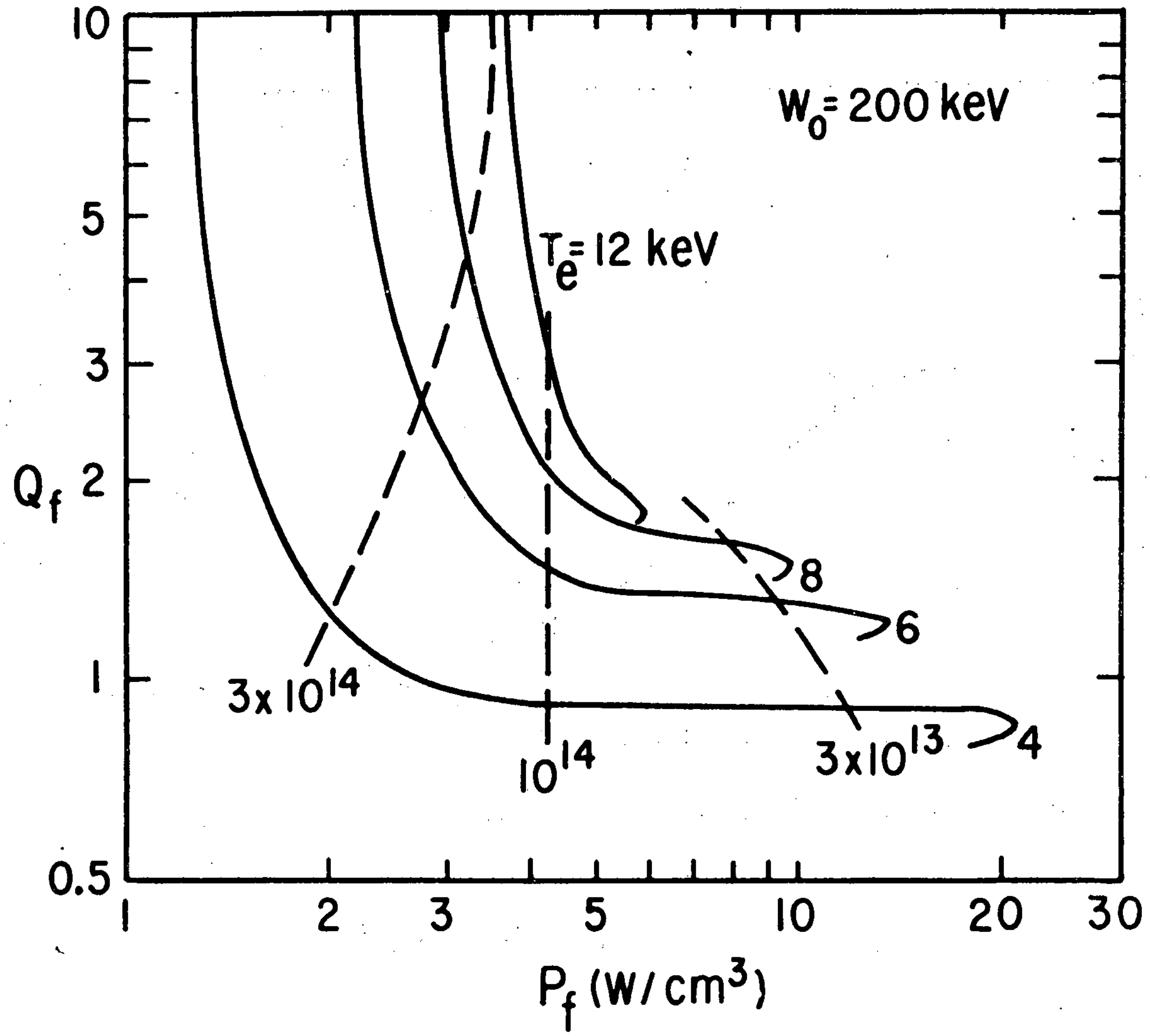

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Figure 13. Q_f versus P_f for a D-T plasma with $T_e = T_i$ heated by 200-keV D beams. For each $n_e\tau_E$, the D-T composition of the background plasma is adjusted for maximum Q_f. For each T_e there is a maximum in P_f, while Q_f increases monotonically with $n_e\tau_E$. The dashed curves are contours of constant $n_e\tau_E$ ($cm^{-3}sec$). $p = 0.655$ J/cm^3.

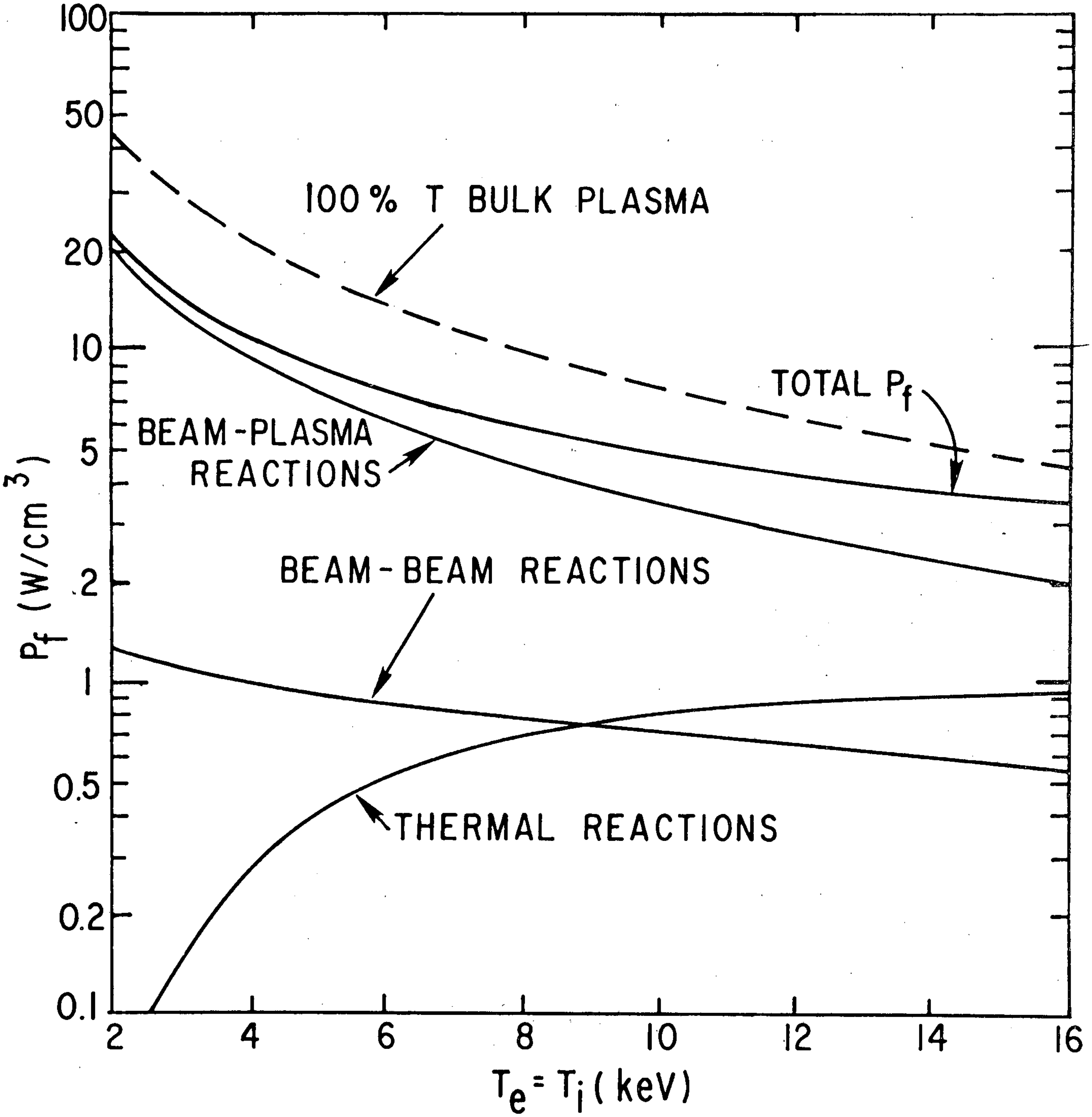

Figure 14. Contributions to P_f from beam-plasma, beam-beam, and thermal fusion reactions in a 50:50 D-T plasma heated by equal number densities of 200-keV D beams and 300-keV T beams. The dashed curve is for a 100% T bulk plasma heated by 200-keV D beams. Total plasma pressure = 0.655 J/cm^3. In each case, $\overline{\Gamma}$ is chosen to optimize P_f from beam-plasma reactions.

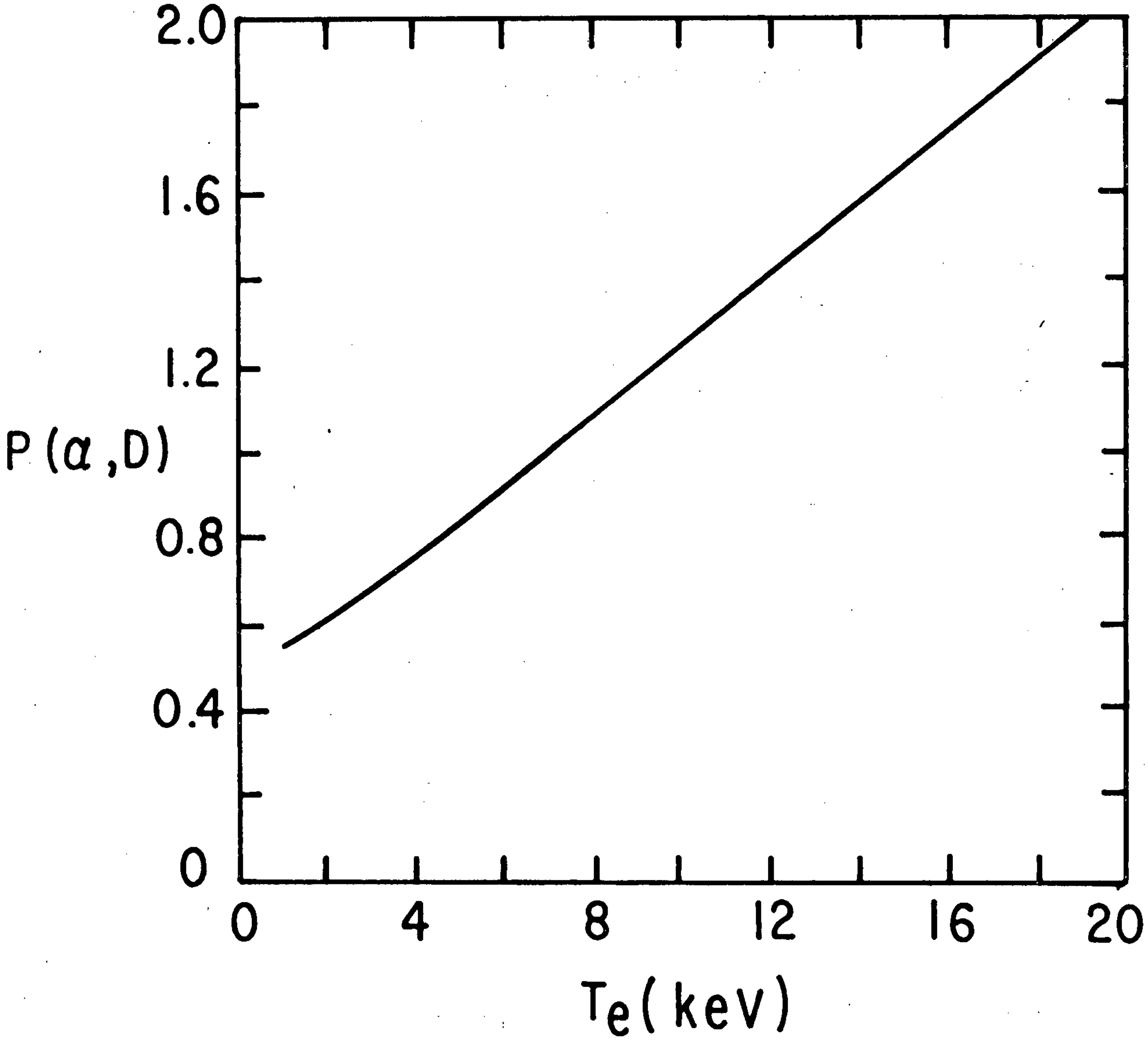

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Figure 15. $P(\alpha, D) \times 0.2\,Q_b$ is the ratio of alpha energy density to beam energy density in a TCT with 200-keV D beams and a tritium-target plasma, assuming that all fusion alphas are confined.

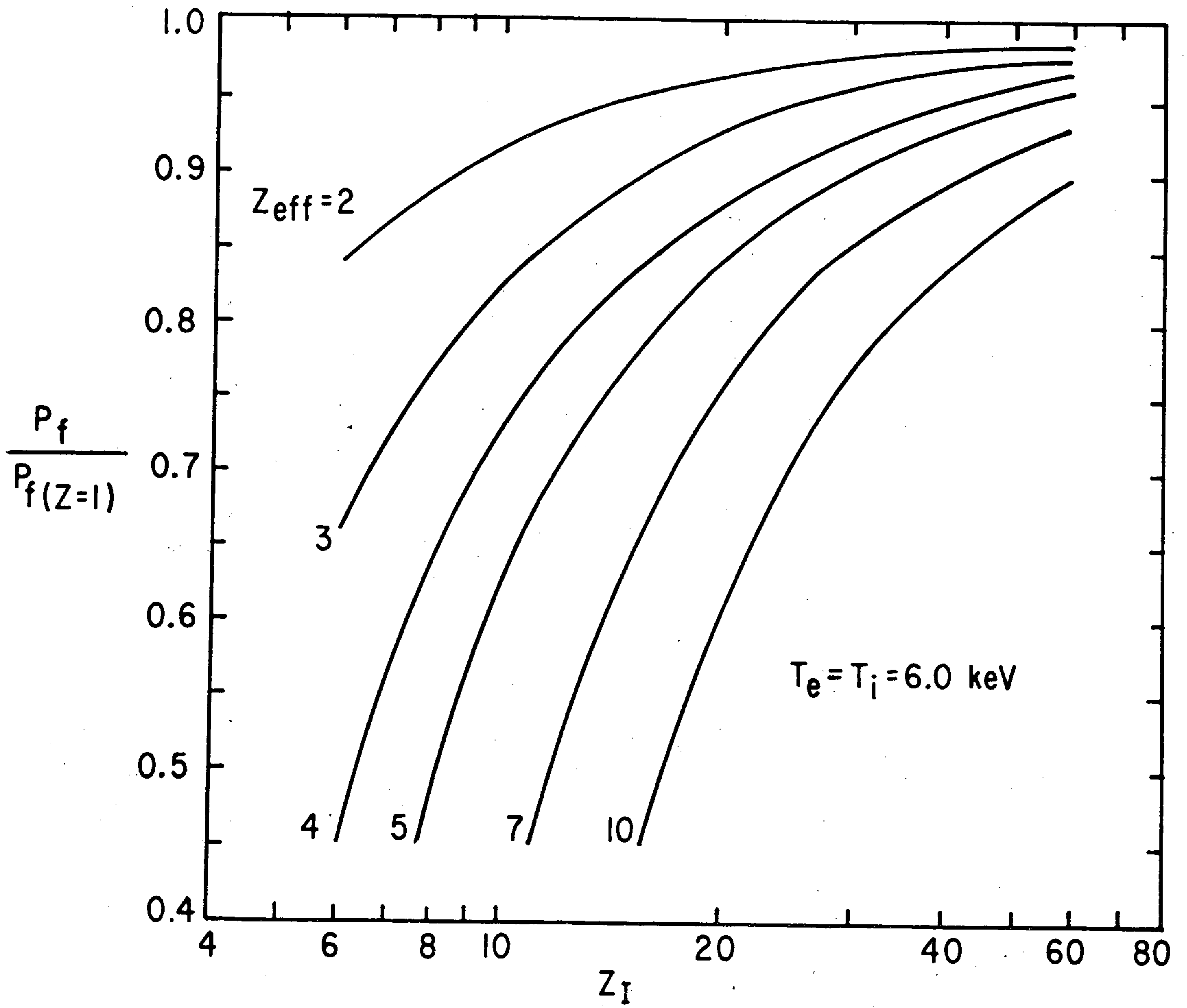

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Figure 16. Maximum fusion power density for 200-keV deuterons injected into a 6-keV triton-target plasma, containing a single impurity specie of charge Z_I with concentration Z_{eff}. p = 0.655 J/cm^3. $P_{f(Z=1)}$ = 13.6 W/cm^3.

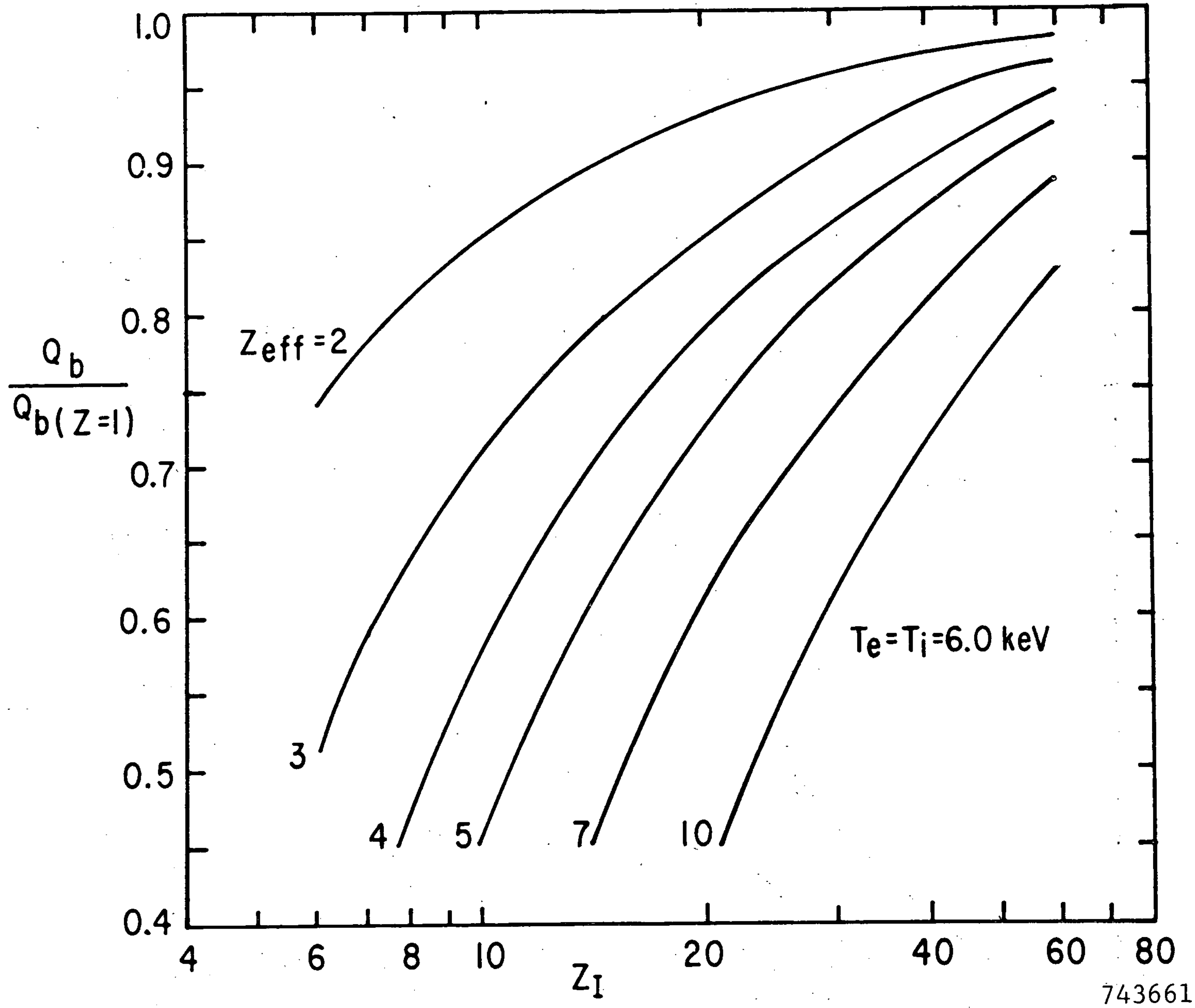

Figure 17. Fusion power multiplication for 200-keV deuterons injected into a 6-keV triton-target plasma, containing a single impurity specie of charge Z_I with concentration Z_{eff}. $p = 0.655$ J/cm^3. $\overline{T}$ is optimized for maximum P_f, given in Fig. 16. $Q_{b(Z=1)} = 1.24$.

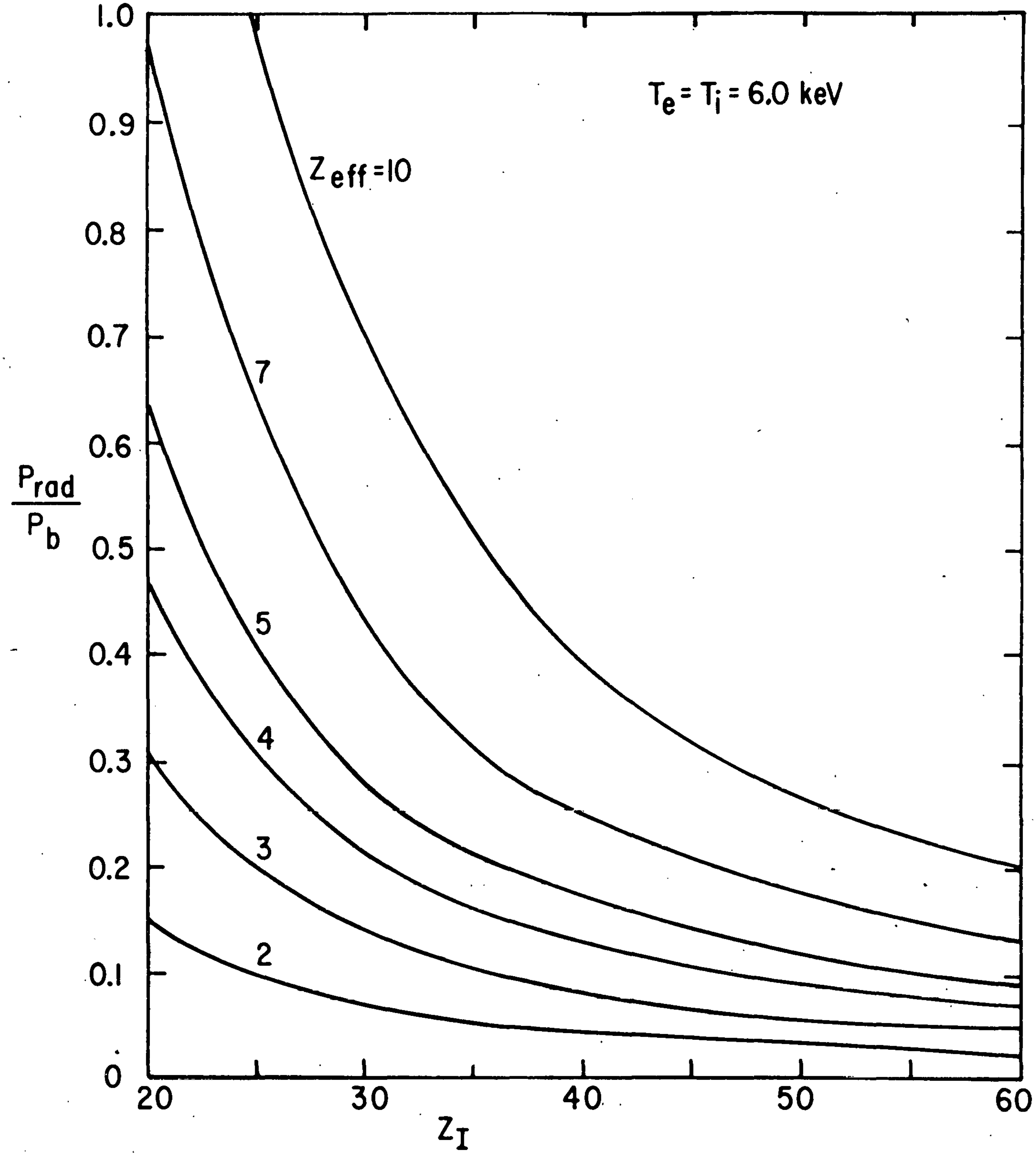

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Figure 18. Fraction of injected beam power balanced by bremsstrahlung and line radiation from a single impurity specie of charge Z_I with concentration Z_{eff}. W_o = 200 keV, $T_e = T_i$ = 6 keV, p = 0.655 J/cm^3. $\overline{\Gamma}$ is optimized for maximum P_f, given in Fig. 16.

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