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ECONOMIC ANALYSIS OF ALPHA CHANNELING IN TOKAMAK POWER PLANTS*

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July 1998

FUSION POWER PROGRAM

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1. Introduction

The hot-ion-mode of operation [1] has long been thought to offer optimized performance for long-pulse or steady-state magnetic fusion power plants. This concept was revived in recent years when theoretical considerations suggested that nonthermal fusion alpha particles could be made to channel their power density preferentially to the fuel ions [2,3]. This so-called anomalous alpha particle slowing down can create plasmas with fuel ion temperature T_i somewhat larger than the electron temperature T_e, which puts more of the beta-limited plasma pressure into the useful fuel species (rather than non-reacting electrons). As we show here, this perceived benefit may be negligible or nonexistent for tokamaks with steady state current drive.

It has likewise been argued [2, 3] that alpha channeling could be arranged such that little or no external power would be needed to generate the steady state toroidal current. Under optimistic assumptions we show that such alpha-channeling current drive would moderately improve the economic performance of a first stability tokamak like ARIES-I [4], however a reversed-shear (advanced equilibrium) tokamak would likely not benefit since traditional radio-wave (rf) electron-heating current drive power would already be quite small.

Our treatment of alpha channeling uses the calculational techniques described in [5]. Traditional rf electron-heating current drive power is based on the particular scaling laws, $\gamma_B(\overline{T}_e) = \overline{n}_e I_o R_o / P_{rf}$, developed for both standard and advanced equilibria, including the bootstrap effect and assuming specific density/temperature profiles. The profile-average plasma power balance is computed with the TRAC-II code, including the external power supplied to both electrons and ions. As usual, we calculate the cost of energy (COE), which we consider the primary figure of merit for fusion power. As formulated in Ref. 5, COE is principally a function of mass-power-density, ρ, and Q_E (a measure of the inverse circulating power for external heating). Details of the current drive, power balance, and economic models are provided in [5], and we can summarize the important points as follows. Mass power density is related to the average neutron wall load by ρ = (30kW/tonne)$\cdot W_n$, where W_n is in units of MW/m^2. The plant designs are carried out for net electric power P_E = 1000 MW and a gross electric power $P_{ET} = \eta_T P_T$. The thermal power is $P_T = (0.25 + M_n)\, P_n + P_H$, where we use a blanket neutron energy multiplication factor M_n = 1.207, P_n is the fusion neutron power, and the term $P_H = \phi P_\alpha$ is the external power supplied to beat the plasma. Following the notation in [3], ϕ is the fraction of fusion alpha power (P_α = 0.25Pn) that is injected to sustain plasma operations. The circulating electric power is $P_{ET} - P_E \equiv P_c = (P_H/\eta_{rf}) + f_{AUX}\, P_{ET}$. For plant auxiliaries, coolant pumping, etc., f_{AUX} = 0.05; and the plant thermal and (rf) heating efficiencies are respectively η_T = 0.462 and η_{rf} = 0.62. From these quantities we compute the parameter $Q_E \equiv P_{ET}/P_C$.

The tokamak designs we study are similar to the peaked density plasmas $(n_o / \bar{n} \approx 1.4)$ of Ref. 5, with $Z_{eff} \approx 1.7$; and the first stability "ARIES-I" (AI) and advanced, reverse shear (RS) equilibria are identical to the MHD equilibria in that reference. For comparison with the reference economic tradeoff study of Ref. 5 we also select the peak toroidal magnetic field to be B_M = 13T at the inboard leg of the toroidal coils.

Preliminary investigations into the mechanism for achieving alpha channeling have focussed on the ion Bernstein wave launched into a deuterium-rich plasma [6]. We account for this non-optimal fuel mix by selecting a D/T ratio of 65/35.

Regarding the anomalous alpha slowing down, we adopt the guidelines of Ref. 3 that a fraction $\eta_w = 0.75$ of the virgin alpha power may be transferred to fast fuel ions and that a fraction $\eta_f = 0.84$ of the fast fuel energy is transferred to the thermal fuel population, resulting in alpha-to-fuel-ion energy transfer of $U_{\alpha}/U_0 \equiv \eta_w \eta_f = 0.63$. This anomalous slowing down is imposed as a constant value on all flux surfaces. (Alpha particles are constrained to slow down on their birth flux surface.) In contrast, classical slowing down results in much less fuel heating, $U_{\alpha i}/U_o \approx 0.35$ near the plasma center ($T_{eo} \approx 20$ keV) and decreasing roughly linearly at lower temperatures.

In order to take advantage of anomalous fuel heating and to increase the ratio T_i/T_e we vary the ratio, τ_e/τ_i, of electron-to-ion energy confinement times; specifically, we investigate the benefits of spoiling electron energy confinement [3]. Moreover, we independently survey variations in T_e (or T_i) in order to find the minimum COE [5].

2. Results

A detailed model of alpha channeling does not now exist, so we examine two plausible scenarios which are intended to indicate the range of possible benefits. The first case, which we term "Reactivity Enhancement," is a conservative treatment of current drive which assumes none of the alpha power is utilized to generate current; instead external electron heating power,

$P_{rf} = I_o \bar{n}_e R_o / \gamma_B$, is injected for traditional current drive. Moreover, we posit that another $P_{Hi} = 50$ MW is injected into the plasma ions in order to accomplish the alpha power channeling to the fuel ions. In this operating mode the injected power, $P_H = P_{rf} + P_{Hi}$, depends strongly on the current drive requirements, and the fraction $\phi = P_H/P_\alpha$ varies accordingly. The power balance is not sensitive to the fractional split of external heating between ions and electrons, but this quantity is self-consistently provided as input to the calculation.

The alternative "Current Drive" mode will assume that diversion of the alpha power will provide ample power to somehow generate the plasma current; in this case $P_{rf} = 0$. Despite the large amount of free energy available in the fast alpha population, it strains credibility to imagine that a favorable toroidal current density profile may be achieved in this fashion. So this scenario is an optimistic or "best case" limit. For lack of better guidance [3] we assume that a fraction $\phi = P_H / P_\alpha = P_{Hi} / P_\alpha = 0.25$ of the alpha power is needed to accomplish this feat.

2.1 ARIES-I equilibrium

Consider first the Reactivity Enhancement scenario. Our initial investigation set $\bar{T}_e = 11.0$ keV and varied τ_e/τ_i. By reducing τ_e/τ_i to values less than unity we find $T_i > T_e$, but, unlike conventional wisdom [3,7,8], this does not increase fusion power density. This is because, in our model, there is a large buildup of alpha ash as τ_e/τ_i is reduced. Basically, spoiling the electron confinement forces τ_i to significantly increase, in order to maintain power balance; and the (alpha) particle confinement time, taken to be a multiple of τ_i, likewise increases, which raises the ratio of alpha to fuel ion density (n_α / n_{dt}) and dilutes the fuel. This is seen in Fig. 1, where the plus, x, and circle denote COE for several cases at $\bar{T}_e = 11$ keV and varying τ_e/τ_i. Note the modest decrease in ρ as τ_e/τ_i is reduced. Moreover, the larger $\bar{n}_e$ (due to increased alpha fraction) and larger R_o result in higher P_{rf} and smaller Q_E for these $\tau_e/\tau_i < 1$ designs.

Further calculations at other temperatures and τ_e/τ_i ratios confirms that under our rather reasonable alpha particle confinement rules there is no benefit from spoiling the electron energy confinement.

Next, holding the ratio τ_e/τ_i fixed at unity, we varied the input parameter $\overline{T}_e$. The locus of points, $\overline{T}_e = 9,11,13$, and 16 KeV, in Fig 1 falls along or below the reference design points from [5], i.e. the COE with alpha channeling is not lowered. This can be understood by comparing the two points with $\overline{T}_e = 13$ Kev. The reactivity enhancement with channeling does increase ρ, but the additional P_{Hi}=50 MW reduces Q_E. In both cases the optimum temperature which minimizes the COE is in the range $T_e \approx$ 11-13 KeV.

Under the Current Drive Scenario, $P_{rf} = 0$ by assumption and $P_H/P_\alpha = 0.25$. For all operating temperatures these conditions correspond to $P_{Hi} = 110.4$ MW and $Q_E = 5.17$. Once again it was found that reducing τ_e/τ_i at a fixed $\overline{T}_e$ results in lower ρ and thus a larger COE. Also, with $\tau_e/\tau_i = 1$, it was determined that the maximum ρ, and minimum COE are possible near the operating temperature of $\overline{T}_e \approx 9$ keV ($\overline{T}_i \approx 10$ keV). At this optimal design point the Current Drive operating mode promises a COE ≈ 110 mills/ (kW·h), roughly 15% lower than the most economic reference design result. [As explained in Ref. 5 the COE units are essentially arbitrary, as only the relative difference in COE among various operating modes is significant when comparing fusion power plants.] Note that in an even more optimistic case, in which the Current Drive mode were accomplished with $P_{rf} = 0$ and for which only $P_{Hi} = 50$ MW is needed, the power density ρ would remain the same for these designs, but the COE points would move to $Q_E \approx 8.3$. This represents only a marginal improvement, as in best case ($\overline{T}_e$ = 9 KeV) COE ≈ 105 mills/(kW·h), which is 19% cheaper than the best reference design point.

2.2 Reverse shear equilibrium

By comparing Fig. 1 and 2 it is apparent that the advanced equilibrium offers a lower COE, which is due to the higher beta and lower current drive power required [5]. Alpha channeling was applied to these designs as well.

For the Reactivity Enhancement mode we again found the best performance occurs for $\tau_e/\tau_i \approx 1$. Also, varying the plasma temperature, we conclude that $\overline{T}_e \approx 11$ KeV minimizes the COE. Moreover, Reactivity Enhancement through alpha channeling results in a minimum COE which is actually higher than the COE of the best reference design points. As before, the additional $P_{Hi} = 50$ MW significantly reduces Q_E.

In the Current Drive operating mode ($P_{rf} = 0$, $\phi = 0.25$) the design points all lie along Q_E = 5.17, and in the best case ($\overline{T}_e \approx 9$ keV) the minimum COE is about the same as for the best Reactivity Enhancement design (≈ 80 mills/(kW·h)). If, optimistically, the Current Drive mode were attainable with $P_{Hi} = 50$ MW the best design point would move to $Q_E = 8.3$ and result in COE ≈ 73 mills/(kW·h), a 3% reduction from the minimum COE for the reference design points.

3. Conclusions

For typical first stability tokomaks alpha channeling benefits, in terms of higher fusion reactivity, are largely offset by reductions in Q_E if P_{Hi} = 50MW is required from the circulating power, in addition to the standard P_{rf} required for electron heating current drive. If Current Drive is accomplished with $P_{rf} = 0$, via channeling some alpha power to create a steady state current, then for $\phi \leq 0.25$ ($P_{Hi} \approx$ 110 - 50 MW range) the COE may be as much as 19% lower than for the best operating point without channeling.

For the advanced RS equilibrium alpha channeling appears to provide little opportunity for reducing the COE. This conclusion stems from the very low P_{rf} ($\leq$ 50 MW) needed for standard current drive in these advanced equilibria.

Finally, note in Fig. 2 that the reference RS designs (without alpha channeling) have very attractive COE ($\approx$ 76 mills/(kW·h)), which is much lower than the best AI design of Fig. 1 even with alpha channeling (COE $\approx$ 105 mills/(kW·h)). On this basis we conclude that rf power injection may be more useful for creating advanced (reverse shear) steady state equilibria with carefully tailored current density profiles than for purposes of channeling the fusion alpha power.

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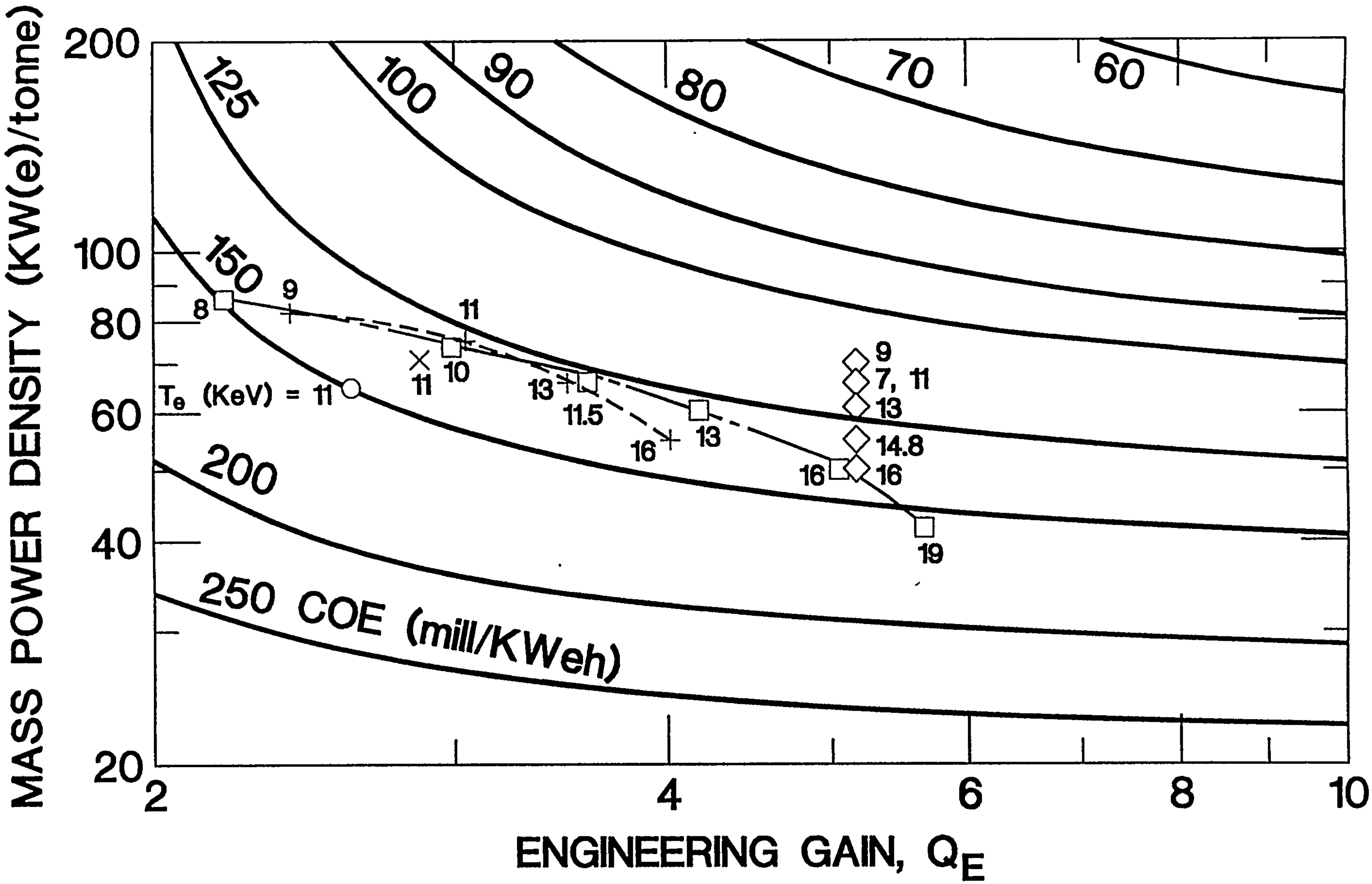
Figure Captions

1. First stability (ARIES-I) equilibrium with peaked density profile, COE parameterized by mass power density and Q_E. Reference points (boxes), without alpha channeling, at various temperatures are from Ref. 5 Reactivity Enhancement designs have τ_e/τ_i =1.0 (plus marks), 0.5 (x), and 0.35 (circle); Current Drive designs have $\tau_e/\tau_i = 1$ and are denoted by diamonds.

2. Advanced, reverse shear, equilibrium with peaked density profile. Symbols are the same as Fig. 1. Uppermost diamond is for T_e=9 keV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80
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10
ENGINEERING GAIN, Q_E
125
100
90
80
70
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150
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250 COE (mill/KWeh)
T_e (KeV) = 11
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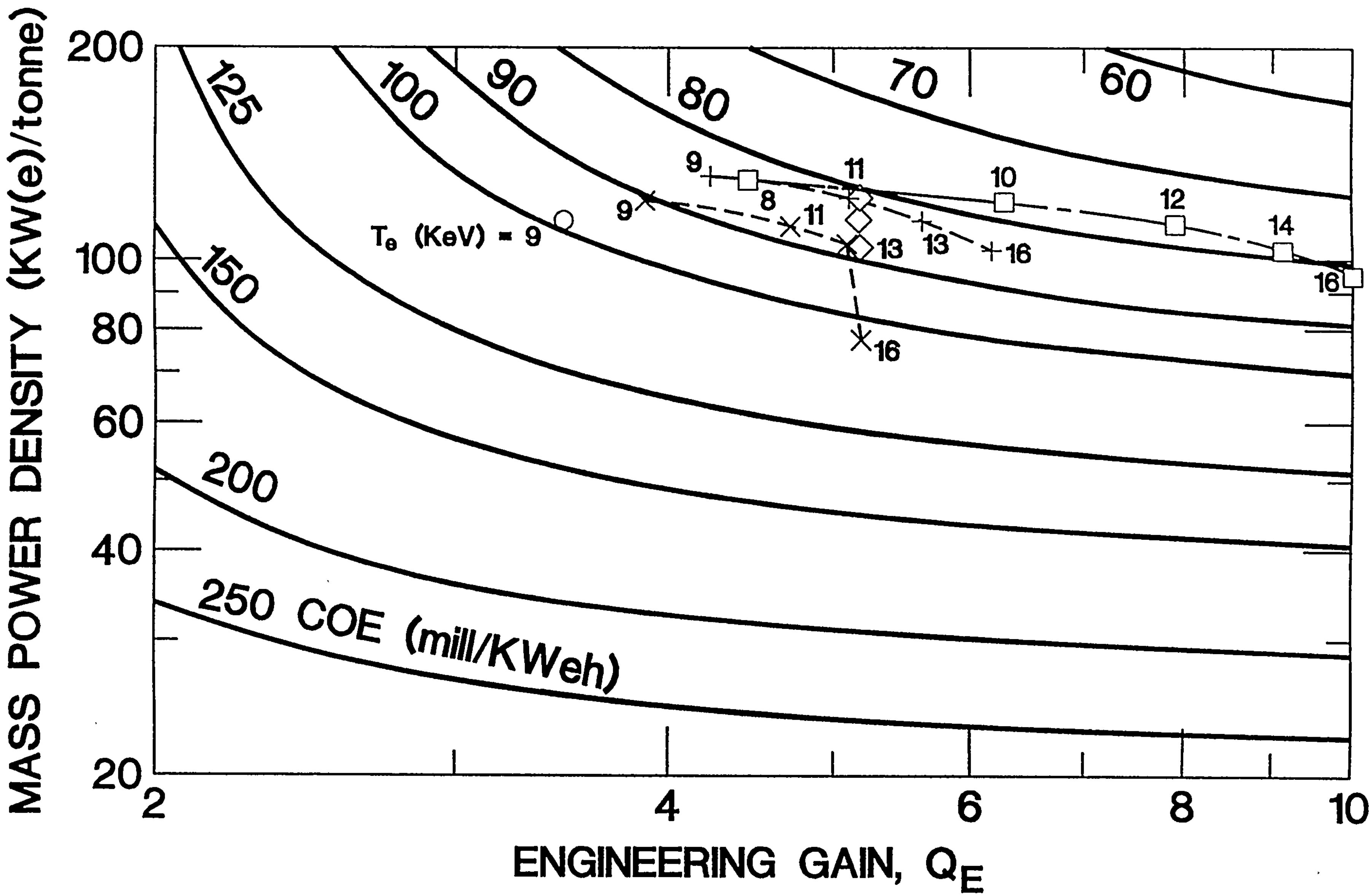
MASS POWER DENSITY (KW(e)/tonne)
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