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**STARLITE FIGURES OF MERIT FOR TOKAMAK CURRENT
DRIVE - ECONOMIC ANALYSIS OF PULSED AND STEADY STATE
POWER PLANTS WITH VARIOUS ENGINEERING AND PHYSICS
PERFORMANCE PARAMETERS**

by

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Starlite Figures of Merit for Tokamak Current Drive - Economic Analysis of Pulsed and Steady State Power Plants with Various Engineering and Physics Performance Parameters

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ABSTRACT

The physics efficiency of current drive ($\gamma_B \propto n_e I_0 R_0 / P_{CD}$), including the bootstrap effect, needs to exceed certain goals in order to provide economical steady state operation compared to pulsed power plants. The goal for γ_B depends not only on engineering performance of the current drive system, but also on normalized beta and the effective safety factor of the achievable MHD equilibrium.

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1. Introduction

It is well known that pulsed, ohmic operation of a tokamak power plant would impose serious engineering penalties associated with mechanical and thermal fatigue, as well as increased costs for power supplies and thermal energy storage. Yet, steady state operation requires continuous circulating power to the current drive system, which reduces the plant net efficiency. A cost-benefit analysis of these issues was presented in a study of Ehst et al. [1]. Since publication of Ref. 1 our understanding of tokamak power plant physics and engineering has matured in several respects. As part of the Starlite project we revisit these issues and correct several deficiencies in Ref. 1. For example, we now feel confident that both pulsed and steady tokamaks will benefit from the naturally occurring bootstrap current; today we also have better confidence in predicting the plasma stability limits which figure so prominently in power plant economics. Likewise, the Pulsar study [2] suggested cost savings for a pulsed tokamak power plant are possible by the use of thermal storage in the radiation shielding.

As a result of this present investigation we can identify several figures of merit which affect the relative attractiveness of pulsed or steady state power plant operation. Three are plasma physics parameters: normalized beta (β_N), effective safety factor (q_*), and the bootstrap-aided current drive efficiency (γ_B). The requisite performance in the physics area is a function of two engineering parameters: the electric-to-plasma current drive power efficiency (η_{cd}), and the capital cost of the current drive system (c_{cd}). The results presented here should guide the fusion research community in focusing on the levels of performance needed in both physics and engineering in order to make a steady state power plant more attractive than a pulsed tokamak. A data base assessment and extrapolations in our expectations for these five figures of merit will follow in other publications.

2. Engineering Figures of Merit

For simplification we isolate the design features which have the largest impact on cost variability when comparing power plants; the focus of this study is thus on the costs associated with the large magnets and also with maintaining

the toroidal current in the plasma. As in Ref. 1, two separate machines are considered, one being a pulsed tokamak and the other a steady-state device. Both have similar parameters (aspect ratio, A ; major radius, R_0 ; plasma temperature and density; fusion power, P_f ; average neutron wall load, W_n ; thermal efficiency, η_{th} ; see the appendix for a detailed description of both tokamaks).

Although we consider varying stability limits for plasma beta (β) we keep the fusion power constant by adjusting the toroidal field strength such that $\beta^2 B_0^4 = \text{constant}$, where B_0 is the vacuum field at R_0 . Power supply requirements for pulsed tokamaks and current drive costs for steady state also vary with B_0 since the equilibrium toroidal current, I_0 , is a function of B_0 . As discussed in the appendix, all capital costs are normalized to the STARFIRE direct cost [5] (\$2062 M in 1983 dollars). Comparison among design choices is then based on a normalized cost of energy (NCOE) which accounts for variations in P_{net} , the net electric output of the power plant.

After establishing similar performance and costs for most subsystems of both the pulsed and steady state tokamaks, two engineering parameters emerge as dominating the economic comparison of these machines. One, the engineering current drive efficiency, η_{cd} , is the ratio of plasma power absorbed for steady state current drive to the input electric power to the current drive hardware. The other, the normalized unit cost, c_{cd} , of the current drive power delivered to the plasma is defined and discussed in the appendix. As we will show, both of these are prominent figures of merit for steady state operation—large η_{cd} and low c_{cd} improve the economic appeal of steady state. However, the goals for η_{cd} and c_{cd} will depend on achievements in the discipline of tokamak plasma physics.

3. Physics Figures of Merit

The toroidal current I_0 in a tokamak equilibrium is a crucial parameter because larger I_0 generally maximizes the stable beta and energy confinement time while smaller I_0 usually reduces the current drive power and cost. A useful normalized measure of the (inverse) current, which we take as the first physics figure of merit, is

$$q_* \equiv \frac{2\pi R_o B_o S}{\mu_o A^2 I_o}, \quad (1)$$

where $S \equiv (1 + \kappa^2)/2$. Here κ is the elongation of the limiter flux surface (or 95% of the poloidal flux for a diverted plasma), and $\sqrt{S}$ is an approximation to the shape factor, the poloidal perimeter of the outermost flux surface divided by $(2\pi R_o / A)$.

Neoclassical theory [8] indicates that the bootstrap current fraction of the total current increases with poloidal beta, which we define as

$$\beta_p \equiv \frac{8\pi^2 R_o^2 \bar{p} S}{\mu_o A^2 I_o^2},$$

where $\bar{p}$ is the volume-averaged pressure. This dimensionless ratio becomes the Shafranov poloidal beta [9] if $\sqrt{S}$ is replaced with the exact, numerically computed shape factor. For a fixed toroidal field strength, fusion power increases with (toroidal) beta, the ratio of kinetic to magnetic pressure,

$$\beta \equiv 2\mu_o \bar{p} / B_o^2.$$

Combining the last three algebraic expressions, we find the ratio of toroidal to poloidal beta, at fixed geometry, is a simple function of the normalized current, $(A\beta)/S = q_*^{-2} (\beta_p/A)$. This relationship is shown in Fig. 1.

A second plasma figure of merit is the normalized beta, or "Troyon coefficient," a ratio of average pressure (or beta) to the toroidal current,

$$\beta_N \equiv \beta / [(\mu_o I_o / 40\pi) / (B_o R_o / A)]. \quad (2)$$

Since current drive becomes less attractive at large I_o it is clearly advantageous to operate at the largest possible β_N consistent with plasma stability. Generally there are two stability limits, imposed by ideal magnetohydrodynamics (MHD), associated with the two physics parameters: $q_* \gtrsim 2$ (external kink mode) and β_N is limited as a complicated function of the pressure and safety factor profiles, as

well as other conditions. In Fig. 1 these two forbidden regions are shown, with typical possible limits, $\beta_N \leq 3.5$ or $\beta_N \leq 4.5$, indicated. The Troyon limit is a hyperbola found by expressing Eq. (2) in terms of q_* ,

$$\frac{A\beta}{S} \leq \frac{\beta_N}{20q_*} \quad (3)$$

or, equivalently,

$$\left(\frac{A\beta}{S} \right) \left(\frac{\beta_p}{A} \right) \leq (\beta_N / 20)^2 .$$

The third physics figure of merit is the bootstrap-assisted current drive efficiency,

$$\gamma_B = (\bar{n}_e / 10^{20} \text{ m}^{-3}) (I_o / A) (R_o / m) / (P_{CD} / W) \quad (4)$$

where P_{CD} is the heating power launched into the plasma, $\bar{n}_e$ is the volume averaged electron density, and I_o includes the bootstrap current. When the bootstrap fraction is large (high β_p) it is necessary to explicitly compute γ_B from the self-consistent MHD equilibrium with bootstrap plus noninductive current drive.

In order to summarize, thus far we have identified two engineering and three physics parameters which dominate the economic comparison of pulsed and steady state tokamaks:

η_{cd}	electric-to-current drive power efficiency
C_{cd}	unit cost of current drive system
γ_B	bootstrap assisted current drive efficiency
β_N	normalized beta (Troyon coefficient)
q_*	effective safety factor

Of these, the first four are true figures of merit in that extreme values will improve the power plant economics. The influence of q_* is more complicated, and its optimum value will depend on the other four parameters, as we will show.

4. Pulsed Power Plant - Cost of Energy with Cyclic Operation

We fix particular physics parameters for the pulsed tokamak. When Ref. 1 was published there was still considerable debate whether the tokamak plasma electric resistance is Spitzer (classical) or neoclassical, so the resistance was left as an independent variable. Now there is increasing evidence [10] that resistance is neoclassical, so we use this value ($R_{NC} = 5.9 \text{ n}\Omega$ for plasma parameters in the appendix and with electron temperature profiles typical of ohmic equilibria [2]). Likewise today there is increasing confidence that the neoclassical bootstrap current is in good agreement with theory, [8,10] so credit can be taken for the bootstrap effect in the form of a reduced loop voltage to maintain I_0 . For a variety of ohmic power plant equilibria [2] we compute a bootstrap fraction in the range 0.37 to 0.51, depending weakly on density and pressure profiles, impurity content, etc. For simplicity we fix the bootstrap fraction at 0.45 for the pulsed power plant.

The final fixed physics parameter for the pulsed tokamak is q_* ; we select $q_* = 2.4$. As shown by Eq. (3), the highest beta occurs for the maximum ratio of β_N/q_* . Inspection of Fig. 2 reveals that, for a variety of MHD-stable ohmic

equilibria, this ratio maximizes at $q_* \cong 2.4$ (with, apparently, $\beta_N \lesssim 3.0$). Since ohmic current is easily generated (with trivial circulating power) there is little to lose and much to gain by operating an ohmic tokamak at the highest current (lowest q_*) which maximizes beta.

The one remaining variable for the pulsed power plant is the physics parameter, β_N . Early tokamak designs used unrealistically high values, like $\beta_N = 7.5$ for STARFIRE [5]; while the previous burn cycle study [1,3] had $\beta_N = 5.2$. As shown in Fig. 2, more recent calculations for ohmic equilibria suggest $\beta_N \cong 3.0$, at best. Moreover, avoidance of disruptions and other MHD phenomena might dictate even lower β_N . Hence, the value of β_N is left as an input variable in our analysis.

Figure 3 shows the results for pulsed tokamaks. As an illustration of the method used to create this figure, consider an ohmic power plant with $\beta_N = 3.5$. From Eq. (3) we find $\beta = 0.0324$ for the pulsed power plant when $q_* = 2.4$. The power balance calculation in the TRAC code indicates $B_0 = 7.68$ T is needed to support the requisite plasma pressure and fusion power ($P_f = 3900$ MW), and, from Eq. (1), we infer that $I_0 = 14.2$ MA for this equilibrium. For the fixed transformer (OHC) flux, assuming 45% bootstrap fraction, the neoclassical plasma resistance results in a fusion burn of $t_f = 7950$ s and a lifetime of $N_f = 1.25 \times 10^5$ fusion burn cycles. The duty factor is nearly unity and the net electric power is $P_{net} = 1459$ MW. However, such a large cycle lifetime requires considerable structural reinforcement of the magnets (cf. Figs. 1, 2, 4 of Ref. 1), which is a significant cost item. For the relatively modest magnets in Ref. 1 ($B_0 = 5.64$ T and maximum field $B_M = 9.81$ T with a toroidal field coil (TFC) stored energy $U_{TF} = 58$ GJ) the magnets and power supplies represent a normalized capital cost of 0.23 (i.e., 23% of the total direct cost of a power plant like STARFIRE) when $N_f = 1.25 \times 10^5$; however, in the present case ($B_0 = 7.68$ T, $B_M = 13.36$ T, $U_{TF} = 108$ GJ) these costs become 0.43 in normalized units. Adding the fixed cost accounts (0.96 normalized units) to the cyclic-dependent cost, the total direct capital cost, in normalized units, becomes $NDCC = 1.39$, as indicated on the dotted curve in Fig. 3. Note in the figure how the power plant cost drops inversely with β_N , due to the smaller costs associated with lower current (fewer cycles, less fatigue) and lower magnetic fields (cheaper magnets). Nevertheless, compared to the idealized STARFIRE power plant (a steady state tokamak) there

is always a capital cost increment for pulsed operation due to power supplies, the OHC system, minimal structural fatigue reinforcement, and some thermal storage costs. Next, in order to compare pulsed operation with steady state, the NCOE is calculated as

$$\text{NCOE} = \text{NDCC}/(P_{\text{net}}/1604 \text{ MW}) , \quad (5)$$

in which we include the factor representing the limiting case (ideal, "free" current drive) net power for the steady state power plant discussed in the next section. The variation of NCOE vs. β_N is the solid curve in Fig. 3.

5. Steady State Power Plant - Cost of Energy with Noninductive Current Drive

In addition to the several engineering features which are kept fixed for all steady state power plant variations (see the appendix), we explicitly consider the two variables, η_{cd} and c_{cd} . The current driver efficiency is a crucial parameter which enters the determination of net electric power as

$$P_{\text{net}} = 1604 \text{ MW} - (\eta_{\text{cd}}^{-1} - \eta_{\text{th}}) P_{\text{CD}} .$$

The variable capital cost associated with the current drive system is assessed only for heating power in excess of 75 MW, as both pulsed and steady state include 75 MW for ignition as a fixed cost account.

Unlike for the pulsed power plant, it is appropriate to leave q_* as a variable for the driven power plant. For fixed β_N there is a tradeoff between current driver cost and TFC cost as q_* varies [11]. Moreover, the freedom to tailor current density profiles with noninductive drive permits enhanced MHD stability in theory, so the achievable β_N value is another variable which strongly enters the economics. The ratio (β_N/q_*) determines beta by Eq. (3), and, as with the pulsed power plant, the steady state power plant has a variable cost associated with the TFC magnetic field: since $\beta^2 B_0^4 = \text{constant}$ in this study, the TFC stored energy varies as $U_{\text{TF}} \propto B_0^2 \propto (q_*/\beta_N)$. The actual cost of the magnet system is based on the detailed design in Ref. 1 and scaled linearly with stored energy.

For the steady state power plant the current drive power is found by combining Eqs. (1) and (4), $P_{CD} = (5 \times 10^{-14} \bar{n}_e R_o^2 S B_o) / (A^2 q_* \gamma_B)$, in SI units. Recall that for fixed P_f and plasma pressure, $B_o \propto \beta^{-1/2}$; using Eq. (3), this latter relationship can be expressed as $B_o = 9.63 \sqrt{q_* / \beta_N}$, where the coefficient (in units of Wb/m²) is specific to the steady state power plant described in the appendix. Using also the values of $\bar{n}_e$, S , and (R_o/A) for this power plant the current drive expression can be written

$$P_{CD} = \frac{615.8 \times 10^6}{\gamma_B \sqrt{q_* \beta_N}}. \quad (6)$$

This relation, in SI units, gives the variation of P_{CD} with the three physics parameters, but only for the particular steady state tokamak under investigation. Nevertheless, the parameters here, $R_o = 7.0$ m, $A = 3.6$, $\bar{n}_e = 1.9 \times 10^{20}$ m⁻³, etc., are reasonably similar to those expected in the future for any steady state power plant.

Due to the number of variables (five parameters in this study) affecting steady state economics the calculation of NCOE must be done in several steps. First, P_{net} , given by Fig. 4, is found; second, the NDCC is inferred by scaling the results in Fig. 5 to the appropriate (β_N/q_*) , as follows. Defining the value of capital cost at $(\beta_N/q_*) = 0.5$ (reading from the ordinate of Fig. 5) to be NDCC*, the actual capital cost is

$$NDCC = NDCC^* - [0.7948 - 0.3974 (q_* / \beta_N)]. \quad (7)$$

This expression accounts for the variability of the TFC cost [1] as a function of plasma beta. Then, the final NCOE is found, as before, from Eq. (5).

In order to provide an example of this economic analysis, consider a steady state power plant with $\beta_N = 3.5$, $q_* = 5.0$, $\gamma_B = 1.5$, $\eta_{cd} = 0.65$ and $c_{cd} = 0.0015/\text{MW}$. The current drive power [by Eq. (6)] is $P_{CD} = 98.1$ MW, and $P_{net} = 1488$ MW; this net power is easily taken directly from the curves in Fig. 4. For the given value of c_{cd} we find from Fig. 5 that the NDCC* = 1.67, but from Eq. (7) we infer that the actual NDCC = 1.44. (Note in Fig. 5 that slightly larger

values on the abscissa, viz. $\gamma_B \sqrt{q_*} \beta_N \geq 8.21$, have no current drive cost penalty, as $P_{CD} < 75$ MW, which is the fixed cost item needed for ignition.) To place the various cost accounts in perspective we note that the fixed capital cost ("balance of plant," including 75 MW of auxiliary heating power) is 0.84 in normalized units, and for our example the TFC cost is 0.57 units (very large due to the low $\beta = 0.017$) while the current driver is 0.03 units $[c_{cd} \times (P_{CD} - 75 \text{ MW})]$. Finally, using Eq. (5), we calculate for this example $NCOE = 1.55$.

6. Applications - Cost Comparisons

a. **ARIES I - Poloidal Beta (q_*) Variation**

The example in Sec. 5 illustrated an extreme case in which the current driver cost was trivial compared to the TFC cost; it usually happens that the NDCC minimizes at a lower q_* value at which the TFC cost drops significantly with only a modest increase in current driver cost. This tradeoff was explored in the ARIES I study [12]; the relevant parameters, also given in Ref. 11, are reproduced in Table I. The sequence of three equilibria falls along a hyperbola in Fig. 1 at $\beta_N = 3.0$ and has at one extreme the standard driven (SD) steady state option with axis safety factor, q_a , near one (highest beta, lowest bootstrap fraction, with $\beta_p = 2.0$) and also includes the ARIES I design choice (AI) with $q_a = 1.6$ (lower beta, higher bootstrap fraction, with $\beta_p = 3.27$). The table shows the decrease in P_{CD} with increasing q_* and the opposite trend for B_0 (and, hence, the TFC cost). Although the cost analysis in Sec. 5 strictly applies to a specific tokamak size, geometry, and plasma parameters, the cost trends are expected to apply also to similar machines, such as in Table I. The cost analysis in the table follows directly from Figs. 4 and 5 with Eqs. (5) and (7), using, from Ref. 12, $\eta_{cd} = 0.71$. Also, the ARIES I current driver has a direct cost of \$104 M/97 MW in 1988 dollars [12]; if this is increased by 21.4% to 1994 dollars and divided by \$2982 M [6], the normalized unit cost is $c_{cd} = 0.00044/\text{MW}$, as used in the table. The minimum in NCOE at $q_* = 3.8$ confirms the advantage of the ARIES I design choice compared to the standard driven tokamak.

b. Pulsed vs. Steady State at Constant β_N

Also lying on a hyperbola at similar β_N values in Fig. 1 are the steady state ARIES I equilibrium and a standard, ohmically driven (SOH) equilibrium. The cost comparison for these designs is made in Table II where, for definiteness, we have chosen the engineering and physics parameters for two specific tokamaks: the ARIES I' configuration of Ref. 13 and the PULSAR II design [2]. It is difficult to explicitly compare pulsed and steady operation for such disparate designs as these: PULSAR II has vanadium structure, Li coolant/breeder, low neutron wall load and $\eta_{th} = 0.46$ while ARIES I' has SiC structure, He coolant, solid breeder, high wall load and $\eta_{th} = 0.49$. The lesson of our cost analysis is, however, independent of these details; despite its lower beta (higher q_*) and higher toroidal field the ARIES I' offers a lower NCOE than the pulsed machine at higher beta and lower q_* . This is likewise reflected in the actual COE reported [13, 2] when further normalized to the same "Level of Safety Assurance" (LSA = 1; e.g., assuming both designs offer the same inherent safety and environmental features). The actual COE advantage reported in Table II for ARIES I' (76.6 vs. 90.4 mill/kWh) is larger than the NCOE advantage, probably because the two designs vary to a somewhat larger degree in η_{th} and W_n compared to the two tokamaks in our cost analysis (appendix).

c. Pulsed vs. Steady State at Constant β

The benefits of steady state operation are increased if current profile control achieves higher β_N as well as higher q_* compared to pulsed operation. Consider the standard ohmic power plant and the ARIES II design point in Fig. 1. These two points, which are exemplified by the PULSAR II and ARIES II parameters [13,2] in Table III, have β_N/q_* roughly equal, but $\sqrt{\beta_N q_*}$ is substantially larger for the driven tokamak. While both tokamaks have similar beta and magnetic field strength, the current is small and the current drive power is modest for ARIES II ($P_{CD} = 66.1$ MW). ARIES II achieves current profile control with combined fast wave and lower hybrid current drive with an overall $\eta_{cd} = 0.50$. Reference to Fig. 5 shows that the NDCC is insensitive to the c_{cd} since the product $\gamma_B \sqrt{\beta_N q_*}$ is so large. The analysis shows, by comparing Tables II and III, that the NCOE relative advantage of ARIES II exceeds that of

ARIES I when compared to a pulsed power plant. Again the actual COE differences quoted in Ref. 13 and 2 (here expressed for $LSA = 2$) exceeds that of our calculated NCOE; no doubt this is due to the large disparity in W_n values for Pulsar II and ARIES II.

d. Performance with Reversed-Shear Equilibrium

Recent Starlite modelling has developed MHD stable reverse shear (RS) power plant equilibria at $A = 4.5$ for which $\beta_N = 4.30$, $q_* = 2.22$ and the self-consistent bootstrap plus fast wave driven (FWCD) plasma achieves $\gamma_B = 1.73$ at $\bar{T}_e = 14$ keV. For such a steady state power plant we feel that $\eta_{cd} = 0.75$ and $c_{cd} = 0.0005/\text{MW}$ are reasonable expectations for these attractive (low frequency ~ 80 MHz) FWCD systems. These parameters result in $NCOE = 1.13$, this being smaller than even the ARIES II result. The RS power plant has $\gamma_B \sqrt{\beta_N q_*}$ adequately large to approach the limiting values of P_{net} and $NDCC^*$ in Figs. 4 and 5, but its β_N/q_* (and, hence, β) value is larger than for the ARIES II design, resulting in a lower NDCC.

7. Conclusions

The present cost analysis is specific to two particular tokamaks which share common engineering features (Li coolant, vanadium structure, $\eta_{th} = 0.357$, TFC structure, etc.) but have different plasma physics performance. One could, for example, compare pulsed and steady state at the same $\beta_N = 3.0$ and $q_* = 2.4$; for the current drive engineering parameters in Tables I and II it is apparent that the pulsed power plant is more economical if $\gamma_B = 0.59$, due to the large P_{CD} cost component. In fact, for this example it is necessary to achieve $\gamma_B \lesssim 0.8$ for the steady state power plant to be more attractive, in rough agreement with the earlier findings in Ref. 1.

A true advantage of noninductive current drive is that a variety of MHD equilibria are possible. Evidence of this is in Table I, where it is shown that the flexibility of operating at high q_* enables operation at $\gamma_B \geq 1.0$; the NCOE for steady state at large q_* may be sufficiently low compared to pulsed (see Table II) that these regimes, with $\gamma_B > 1$, are attractive design goals for fusion research [14]. Further advantages accrue if current drive permits operation at

higher $\sqrt{\beta_N q_*}$ while maintaining a substantial beta ($\propto \beta_N/q_*$), as expected in the second stability regime; Table III shows the large NCOE advantage of steady state in such a case.

Examination of our results yields a broadly stated conclusion with respect to the γ_B goal of tokamak current drive research. That is, for aggressive engineering (e.g., $\eta_{cd} = 0.75$ and $c_{cd} = 0.0005$) we find an advanced tokamak equilibrium (e.g., reverse shear at $\beta_N = 4.8$ and $q_* = 2.4$) can be operated more economically in steady state than in a pulsed mode, provided $\gamma_B \gtrsim 0.45$. More modest engineering parameters (e.g., $\eta_{cd} = 0.45$ and $c_{cd} = 0.001$) and a conservative physics operating regime (like ARIES I with $\beta_N = 3.0$ and $q_* = 3.8$) would result in a more economical steady state power plant only if $\gamma_B \gtrsim 1.7$.

In summary, pulsed operation (Fig. 3) may be compared to steady state, once η_{cd} and c_{cd} are specified, by use of Figs. 4 and 5 and Eqs. (7) and (5). Our model for the steady state power plant breaks down when $P_{net} \rightarrow 0$ (i.e., low $\gamma_B \sqrt{\beta_N q_*}$ values), but the cost comparison appears to reproduce the relative COE for realistic design points [2,12,13] in the range of values actually expected for γ_B , β_N , and q_* .

Appendix

Following the method in Ref. 1 we select two different tokamaks for study. Although plasma beta, toroidal current, and toroidal magnetic field are allowed to vary for each machine, the size, geometry, and plasma pressure and fusion power are fixed for each tokamak. Given in detail in Table I of Ref. 3, the two tokamaks' description may be briefly summarized as follows. The pulsed power plant has an aspect ratio $A = 4.0$, major radius $R_0 = 8.0$ m, average electron and ion temperature of $\bar{T}_e = 10$ keV and $\bar{T}_i = 11$ keV, average electron density of $\bar{n}_e = 2.0 \times 10^{20} \text{ m}^{-3}$, effective charge $Z_{eff} = 1.7$, fusion power of $P_f = 3900$ MW, and an average neutron wall load $W_n = 3.5 \text{ MW/m}^2$. The steady state power plant has $A = 3.6$, $R_0 = 7.0$ m, $\bar{T}_e = 12$ keV, $\bar{T}_i = 14$ keV, $\bar{n}_e = 1.9 \times 10^{20} \text{ m}^{-3}$, $Z_{eff} = 1.8$, $P_f = 4230$ MW, and $W_n = 4.4 \text{ MW/m}^2$. Both tokamaks have noncircular plasmas and are taken to have the same engineering design for the blanket (inboard scrapeoff/blanket/shield radial build $\Delta^i = 1.4$ m, energy

multiplication $M_n = 1.14$, thermal-to-electric gross power efficiency $\eta_{th} = 0.357$ etc.).

In addition to these fixed parameters some other design choices were made for the pulsed power plant. The OHC has a maximum field of 10 T and is wound with the coils inboard of the support cylinder [1], providing 465 V-s of flux. Mechanical fatigue in magnets is one cost driver, the lifetime cycles being determined from the inductive current period and assuming 1×10^9 s of total operation (40 y of plant life at 80% availability). The "startup" volt-seconds, needed to ramp the toroidal current up from zero, is small compared to the available flux for "burn" volt-seconds, so the inductive pulse length for fusion burn, t_f , essentially varies inversely with I_0 . Fatigue in the TFC structure, a major issue for a pulsed power plant, is based on the detailed model in Ref. 1, where it is shown that a "double swing" operating mode minimizes the costs of cyclic fatigue. Likewise our results assume the long-term cost algorithm for the TFC, which duplicates the capital costs for STARFIRE (invoking the usual economies from an aggressive development program and learning curves). The motor-generator-flywheel and SCR power handling network for the pulsed coils are also large cost accounts for pulsed systems; but the present study includes only a rather modest cost penalty for thermal storage, compared to Ref. 1, since the nuclear shield stores thermal energy during the fusion pulse. Despite varying burn lengths, as I_0 is varied in our study, the duty factor is always large, so the net electric power remains nearly constant, $P_{net} \cong 1460$ MW.

In both tokamaks the fusion power is computed with the TRAC code, which uses two dimensional MHD equilibria and performs a profile-average power balance. Since we keep plasma temperatures, density, and fusion power fixed, we allow for different stability limits to plasmas beta (β) by varying the toroidal field strength, i.e.

$$\beta^2 B_0^4 = \text{constant}.$$

Our calculations are extensions of the numerical results in Ref. 1 and 3. Thus, at constant safety factor, we vary the toroidal current proportionally as $I_0 \propto B_0$, where B_0 is the vacuum field at R_0 . Magnet and power supply costs are a large fraction of a power plant capital cost, and, for simplicity, we scale this cost

account to be proportional to the toroidal field coil (TFC) stored energy, which varies only as B_0^2 , since the size and TFC geometry is held fixed [4]. Mechanical fatigue is a strong cost driver for the pulsed tokamak's magnets, which is an issue thoroughly explored in Ref. 1. Hence our magnet costs are also functions of the lifetime number of burn cycles for the pulsed power plant [which in turn depends on I_0 and the burn volt-seconds available from the ohmic heating coil (OHC)]; the magnet costs in this study are based on the structural stress analysis performed in Ref. 1. All costs in this study are normalized to the direct capital cost of the STARFIRE tokamak [5] power plant (\$2062 M in 1983 dollars [6]).

The performance discriminator between various power plant options is a normalized cost of energy –"NCOE"– which, in view of the complex nature of tokamak design space, should be taken to have arbitrary units. Our emphasis is only to assess relative differences in the NCOE versus the achievable physics and engineering figures of merit.

A drawback of our approach is that the net electric power, P_{net} , is not a constant, especially for the steady state power plant. For fixed P_f it is evident that P_{net} varies, for example, due to varying circulating current drive power if γ_B is varied. Future studies can avoid this bias due to changing "economy of scale" by systematically comparing costs at a constant net power.

Performance comparison of operating modes depends on many design choices, and our results do not consider every variable. For example, the thermal efficiency has a minor quantitative effect on our results; however, the value selected, $\eta_{\text{th}} \cong 0.36$, is a reasonable fraction, which was determined by a comprehensive engineering analysis in the STARFIRE project [5]. The somewhat different neutron wall loads for the two tokamaks is another issue which obviously affects capital costs, but small differences between pulsed and steady state tokamaks (3.5 MW/m² vs. 4.4 MW/m²) would seem to be inevitable. In this study the pulsed power plant has the lower W_n due to the a priori decision to select a larger A and bigger major radius in order to accommodate an adequately large OHC to achieve long-pulse, high duty factor operation.

There remain two principal engineering parameters which dominate the economic assessment. One, the engineering current drive efficiency, η_{cd} , is the input plasma heating power for steady-state operation divided by the circulating electric power to the overall current drive plant. Future current drive systems are optimistically projected [7] to range from a high of $\eta_{cd} \gtrsim 0.80$ for MeV - neutral beams and low frequency (ICRF) wave launchers to a low of $\eta_{cd} \approx 0.50$ for high frequency wave drivers. The other engineering parameter, the unit capital cost of the current drive system, is important if large amounts of plasma heating power are needed. The unit cost per megawatt of power launched into the torus is normalized to the STARFIRE direct cost. Two illustrations will suffice to illustrate this definition of c_{cd} . A daisy-chain arrangement of low gain crossed-field-amplifiers provided STARFIRE with a low cost lower hybrid current drive (LHCD) system [5] which, in 1983 dollars, cost \$71.7 M and launched 90 MW of plasma heating power; for this LHCD design we would specify $c_{cd} = (\$71.7 \text{ M}/90 \text{ MW})/\$2062 \text{ M} = 0.00039/\text{MW}$ as the normalized unit cost. As another example, the cost survey in Ref. 7 predicted advanced negative-ion neutral beam current drive (NBCD) systems might cost, in 1989 dollars, \$3.0 M/MW; escalating to 1994 dollars [6], the normalized unit cost would be $c_{cd} = (1.162 \times \$3.0 \text{ M/MW})/\$2982 \text{ M} = 0.00117/\text{MW}$.

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References

- [1] D.A. Ehst, J.N. Brooks, K. Evans Jr., S. Kim, Nucl. Eng. Design/Fusion 2 (1985) 319; and ibid., Nucl. Eng. and Design/Fusion 3 (1985) 113 (erratum).
- [2] F. Najmabadi, et al., "The Pulsar Tokamak Reactor Final Report," to be published.
- [3] D.A. Ehst, et al., Nucl. Eng. and Design/Fusion 2 (1985) 305.

- [4] Magnet mass is certainly strongly correlated with stored energy [see F.C. Moon, J. Appl. Physics 53 (1982) and a recent update, J. Schwartz, J. Fus. Energy 11 (1992) 19], increasing somewhat less than linearly. Costs are difficult to predict for large future tokamaks, but over the range considered in this work it is not unreasonable to assume a linear relation between cost and stored energy.
- [5] C.C. Baker, et al., Nucl. Eng. Des. 63 (1981) 199; C.C. Baker, et al., Argonne Nat. Lab. Rep. ANL/FPP/80-1 (1980).
- [6] Consistency requires the current drive system to be costed in the same dollars as the power plant direct capital cost. In years other than 1983 appropriate price deflator factors must be used. Although fusion equipment and fission plant costs escalate at different rates from the general U.S. inflation rate, we suggest the STARFIRE direct cost in 1994 dollars would be $1.4461 \times \$2062 \text{ M} = \2982 M .
- [7] D.A. Ehst, in Radio-frequency power in plasmas, 8th Top. Conf., Irvine, CA (1989), AIP Conference Proc. 190, R. McWilliams, ed., p393.
- [8] S.P. Hirshman, D.J. Sigmar, Nucl. Fusion 21 (1981) 1079; M.C. Zarnstorff, et al., Phys. Rev. Lett. 60 (1988) 1306.
- [9] M.-Y. Hsiao, D.A. Ehst, K. Evans Jr., Nucl. Fusion 29 (1989) 49.
- [10] S.H. Batha, presented at US-Japan Workshop on Bootstrap Current in Tokamaks and Stellarators, Lake Lanier Islands (GA), November 1994; C.B. Forest, K. Kupfer, P. Politzer, et al., presented at same conference.
- [11] D.A. Ehst, K. Evans Jr., M. Klasky, Phys. Rev. Lett. 64 (1990) 1891.
- [12] F. Najmabadi, et al., "The ARIES-I Tokamak Reactor Study Final Report," UCLA-PPG-1323 (1991).

- [13] R.A. Krakowski, C.G. Bathke, R.L. Miller, K.A. Werley, Los Alamos National Laboratory Rep. LA-UR-93-4217 (1993); ibid., Fusion Technology 26 (1994) 1111.
- [14] P-H. Rebut, D. Boucher, C. Gormezano, B.E. Keen, M.L. Watkins, Plasma Phys. and Contr. Fusion 35 (1993), Supplement A, pA3.

Table I MHD Parameters and Cost Comparison for Steady State Power Plants at Constant $\beta_N = 3.0$ and Varying q_* : $R_o = 6.0$ m, $A = 6$, $S = 2.86$, $\bar{n}_e = 1.9 \times 10^{20} \text{ m}^{-3}$, $\bar{T}_e = 16 \text{ keV}$; $\eta_{cd} = 0.71$, $c_{cd} = 0.00044/\text{MW}$.

q_*	2.35	3.84	5.1
I_o (MA)	11.3	8.81	7.58
β (%)	3.23	1.98	1.51
B_o (T)	10.5	13.4	15.3
β_p	2.00	3.27	4.40
P_{CD} (MW)	223.	97.7	46.8
γ^B	0.59	1.05	1.99
P_{net} (Fig. 4)	1150.	1420.	1520.
NDCC* (Fig. 5)	1.78	1.68	1.63
NDCC (scaled to β_N/q_*)	1.30	1.39	1.51
NCOE	1.81	1.58	1.60

Table II Physics Parameters and Cost Comparison for Steady State and Pulsed Power Plants at Similar β_N and Different q_* ; $\eta_{cd} = 0.71$, $c_{cd} = .00044/\text{MW}$, $\gamma_B = 1.05$.

	Pulsar II	ARIES I'
R_o (m)	7.91	7.64
A	4.0	4.5
I_o (MA)	13.4	10.9
β (%)	2.8	1.9
B_o (T)	7.31	10.6
W_n (MW/m ²)	1.32	2.06
COE@LSA = 1 (mill/kWh)	90.4	76.6
q_*	2.40	3.29
β_N	3.0	3.2
NCOE	1.59	1.46

Table III Physics Parameters and Cost Comparison for Steady State and Pulsed Power Plants at Similar (β_N/q_*) and Different $\sqrt{\beta_N q_*}$; $\eta_{cd} = 0.50$, $c_{cd} = 0.001/\text{MW}$, $\gamma_B = 1.36$.

	Pulsar II	ARIES II
R_o (m)	7.91	5.60
A	4.0	4.0
I_o (MA)	13.4	6.43
β (%)	2.8	3.4
B_o (T)	7.31	7.97
W_n (MW/m ²)	1.32	2.90
COE@LSA = 2 (mill//kWh)	105.5	73.8
q_*	2.40	4.60
β_N	3.0	5.9
NCOE	1.59	1.27

Fig. 1 Equilibrium and stability diagram for tokamaks.

Fig. 2 Maximum normalized beta for ideal stability vs. effective safety factor for several temperature profiles and aspect ratios.

Fig. 3 Economics of pulsed power plants with $q_{star} = 2.4$ and 8-m major radius at $A = 4.0$, effective $Z = 1.7$, and neutron wall load = 3.5 MW/m^2 .

Fig. 4 Net power of steady state tokamaks with noninductive current drive and 7-m major radius at aspect ratio = 3.6, neutron wall load = 4.4 MW/m² vs. driver electrical efficiency.

Fig. 5 Normalized direct capital cost with steady state current drive, 7-m major radius, $A = 3.6$, wall load = 4.4 MW/m^2 vs. normalized driver cost; for $\beta_N/q_* = 0.5$.

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