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TITLE CONNECTIONS BETWEEN PHYSICS AND ECONOMICS FOR TOKAMAK FUSION POWER PLANTS

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CONNECTIONS BETWEEN PHYSICS AND ECONOMICS FOR TOKAMAK FUSION POWER PLANTS

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Abstract: A simplified physics, engineering, and costing model of a tokamak fusion reactor is used to examine quantitatively the connection between physics performance and power-plant economics based on a DT-fuelled tokamak reactor. Areas where physics and technology advances are needed and where physics/technology tradeoffs exist for attractive end-products are quantitatively identified.

1. INTRODUCTION

Since growth and extension in the tokamak physics database is still required for commercialization, and since the worldwide tokamak program today is at the threshold for new device design and fabrication,[1,2] as well as extrapolation to devices with more commercial-like features,[3-5] it is useful to examine quantitatively the connection between physics performance and economic competitiveness. The generic fusion reactor model developed by Sheffield, et al.,[6,7] presents an approach of sufficient balance, depth, simplicity, and flexibility for such a study. The Generomak model[7] was modified for use by the Senior Committee on Environment, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM).[8,9] Only the ESECOM "point-of-departure" case is treated here, which is a self-cooled lithium-metal/vanadium-alloy-structure blanket with steel shielding, pumped-limiter impurity control, highly efficient steady-state current drive, and superconducting magnets. The choice of blanket/shield concept, however, impacts many power plant systems and can strongly influence the final cost of energy.[9,10] A more elaborate examination of the range of tokamak options can be found in Ref. 11, which includes the impact of the tokamak Second-Stability Region (SSR),[12] Super-High-Field (SHF) tokamaks,[13] low-aspect ratio Spherical Torus (ST) tokamaks,[14] as well as the direct and conservative application of the existing tokamak database.[15]

2. MODEL

2.1 Fusion-Power-Core Physics and Engineering

The essential physics, engineering, and economic parameters of the Generomak model[6,7] are listed in Table I. The elliptical plasma of elongation $\kappa = b/a$ is assumed to operate at the ballooning-mode stability limits,[16] as expressed below in terms of total beta, β, plasma current, I_ϕ, minor radius, a, and toroidal field at the plasma, B_ϕ

$$\beta = 0.04 I_\phi / a B_\phi , \tag{1}$$

The flux-averaged safety factor is given by

$$q_\psi = C\, B_{\phi c} / B_\theta \frac{(1+\kappa^2)/2}{(1-\epsilon^2)^2} , \tag{2}$$

where the coefficient, $C = 1.1$, limits this fit of numerical results[17] to $\epsilon\beta_\theta \lesssim 0.3$, with β_θ being the poloidal beta and ϵ the inverse aspect ratio. All single-point parameter variations of cost with changes in physics or engineering operating points preserve these dependencies between κ, ϵ, q_ψ, β and $\beta B_\phi a/I_\phi$.

The plasma current, I_ϕ, is assumed to be driven with a fixed efficiency of $I_\phi/P_{CD} = 0.2\ A/W$ delivered to the plasma.[7] This assumption for the basecase parameters represents a significant advancement relative to values achieved by present experimental methods. The normalized current-drive efficiency[18]

$$\gamma = (n_e/10^{20} m^{-3}) I_\phi(A) R_T(m) / P_{CD}(W) \tag{3}$$

for typical basecase parameters is higher than best-achieved experimental values for fast-electron parallel-pushing waves. This issue is examining quantitatively (Sec. 3.3.1).

TABLE I. Generomak Physics/Engineering/Economics Model[7,9]

Plasma Parameters	
Aspect ratio, $A = R_T/a = 1/\epsilon$	[4.0][(a)]
Elongation, $\kappa = b/a$	[2.5]
Safety factor,[(b)] q_ψ	[2.3]
Total beta, $\beta = 0.04\ I_\phi/aB_\phi$	[0.1]
Poloidal field at coil, $B_{\phi c}(T)$	[10]
Plasma ion temperature, $T_i(keV)$[(c)]	10
Ion/electron beta ratio	1.0
Impurity(alpha-particle)/(electron) beta ratio	0.2
Plasma standoff, a_w/a	1.1
Current-drive efficiency, $I_\phi/P_{CD}\ (A/W)$[(c)]	0.2
Engineering Parameters	
Net electric power, $P_E(MWe)$	[1,200]
Thermal-conversion efficiency, η_{TH}[(d)]	0.404
Fusion-power-core dimensions: blanket/gap/shield thickness, $\Delta b/\Delta g(m)/\Delta s(m)$	[0.71]/[0.10]/[0.83]
Ratio of TFC mass to EFC, OHC[(e)] masses	0.25
TFC current density, $j_{\phi c}(MA/m^2)$	$\frac{(96-6B_{\phi c})}{1+(B_{\phi c}-12)^{1.3}}$
Capacity factor, p_f[(f)]	0.65
Neutron Fluence lifetime $(MW \cdot yr/m^2)$	[20.0]
Recirculating power fraction to BOP	0.06
Blanket neutron-energy multiplier, M_N	1.27
Economic Parameters	
Plant lead time/life (yr)	6/30
Indirect cost factor	0.375
Contingency factor	0.15
Construction escalation and interest factor	1.0856
Spare-parts multipliers, blanket/coil/limiter	1.1/1.2/1.2
Cost of money, nominal/constant dollars	0.09/0.0283
Inflation rate (%/yr)	6
Effective tax rate	0.4816
Tax depreciation life (yr), overall/replaceable	10/5
Fixed charge rate, nominal/constant	0.165/0.0844
Unit Material Costs ($/kg)	
· V15Cr5Ti/HT-9/Fe1422	400/50/20
· natural lithium	45
· SC coils/structure	90/25
· current-drive power ($/W)	2.25
Limiter (k$/m²)	60

(a) Basecase parameters in brackets were varied in exploring a range of possibilities.

(b) Flux-definition of safety factor with fitting constant $C = 1.1$ [re. Eq. (2)].

(c) The impact of fixing $\gamma = (n/10^{20}) I_\phi R_T/P_{CD}$ is examined in Sec. 3.3.1, for which a range of temperatures was examined and cost options occur at ~25 keV.

(d) Based on inlet/exit primary coolant temperatures of 573/823 K, 75% of ideal constant-pressure thermal efficiency, and 3% (30 K temperature drop) penalty for IHX.

(e) TFC is toroidal-field coil, EFC is equilibrium-field coil, and OHC is ohmic heating coil.

(f) If $I_W\ (MW/m^2)$ is the neutron wall loading and the radiation lifetime is $I_W\tau\ (MW\ yr/m^2)$, then $p_f = 0.753/[1 + 0.1034\ I_W/(I_W\tau)]$ when $I_W/(I_W\tau) \geq 1.54\ yr^{-1}$. This expression is based on an allowance of 90 days/yr of unscheduled maintenance and 38 days per fusion-power-core (FPC) replacement.

The cost-optimization procedure used[11] gives a cost-optimum confinement time, $\tau_E(OPT)$. The required confinement is then compared with predictions of plasma confinement, $\tau_E(PHYS)$. For the purposes of this study, a global physics scaling based either on Neo-Alcator[19] or H-mode Kaye-Goldston[20] (KG) results is used.

The relationship between current density in the superconducting toroidal-field coil (TFC), $j_{\phi c}(MA/m^2)$, and the field at the windings, $B_{\phi c}(T)$, is given[7] in Table I. The relationship between B_ϕ and $B_{\phi c}$ is given by the usual expression for the major-radial fall-off of magnetic field. With the TFC current density, $j_{\phi c}$, and the FPC geometry determined, the coil masses can be computed.

The Generomak reactor power balance increases the 14.1-MeV fusion-neutron power, P_N, by the blanket energy multiplication, M_N; 30% of the alpha-particle power, P_α, and current-drive power delivered to the plasma, $(1 - f_{CD})P_{CD}$, appears as low-grade heat. The "available" thermal power, $P_{TH} = M_N P_N + 0.7(P_\alpha + f_{CD}P_{CD})$, is converted to the total electrical power, $P_{ET} = \eta_{TH} P_{TH}$, with an efficiency η_{TH} determined by the blanket (i.e., primary loop) inlet and outlet temperatures. Once converted to electrical power, the fraction $f_{AUX} \simeq 0.06$ of P_{ET} is recycled along with P_{CD} back to the power plant, giving a net-electric power equal to $P_E = P_{ET}(1 - f_{AUX}) - P_{CD}$.

2.2 Economics

The basic economic methodology and financial parameters used to determine levelized power costs were derived from the Nuclear Energy Cost Data Base (NECDB).[21] The NECDB methodology was used to calculate the equivalent fixed charge rate (FCR) on capital, where FCR is a factor that multiplies the initial capitalized investment to give the equivalent annual cost of charges related directly to the initial investment. Both nominal (includes inflation) and constant-dollar FCRs are given in Table I. The nominal dollar rate produces levelized costs that include inflation. Even though the constant-dollar FCR is used, the calculations of revenue requirements leading to this rate include inflation and are subsequently adjusted to the constant-dollar rate. The constant-dollar (1986), levelized cost of electricity (COE) is the equivalent annual cost of all cost components divided by the annual electric power production and is expressed as follows:

$$COE(mills/kWeh) = \frac{I \times FCR + C_F + C_{OM}}{P_E \times 8,760 \cdot p_F} , \qquad (4)$$

where I is the initial capitalized investment, C_F is the annual fuel cost, and C_{OM} is the annual operating and maintenance (O&M) cost. In the case of designs evoking high neutron first-wall loading and concomitant frequent blanket replacement, the capacity factor, p_f, is adjusted downward to account for the additional time needed for more frequent FPC changeout [Table I, footnote (f)]; the cost of blanket replacement is treated as a fuel charge. The reference capital cost model, economic scaling, indirect cost factors, etc., are discussed in Refs. 9 and 11.

3. RESULTS

Results only for the optimistic basecase (Table I) are presented here, with the implications for SSR, SHF, ST, or conventional tokamak reactors being given in Ref. 11.

3.1 Optimization of Maximum Coil Field ($B_{\phi c}$)

The TFC field was varied for a given set of plasma physics parameters, and the the minimum-COE point was determined. This procedure was repeated whenever a main physics or engineering parameter was changed from the basecase value. Typical results are expressed on a plot of COE as a function of the fusion-power-core (FPC) mass power density, MPD(kWe/tonne), as is shown in Fig. 1. These curves are typical of this superconducting system and the coil scalings used (Table I). As the magnetic field is increased from a lower value for a fixed beta, the plasma power density and first-wall neutron loading increases, the plasma volume is reduced, and the FPC shrinks in size, mass, and cost for this constant net-electric-power system; the COE decreases rapidly, since in this region the FPC is a main component in the total direct capital cost. As $B_{\phi c}$ increases above ~10-11 T, however, the decreasing TFC current density causes the coil size and mass to increase, which drives a decrease in MPD and a rapid increase in cost; a COE minimum and MPD maximum results. Use of an advanced superconductor capable of higher current density as $B_{\phi c}$ is increased can shift and even broaden this minimum to higher values of MPD and lower COE.[9,11] (Sec. 3.3.4)

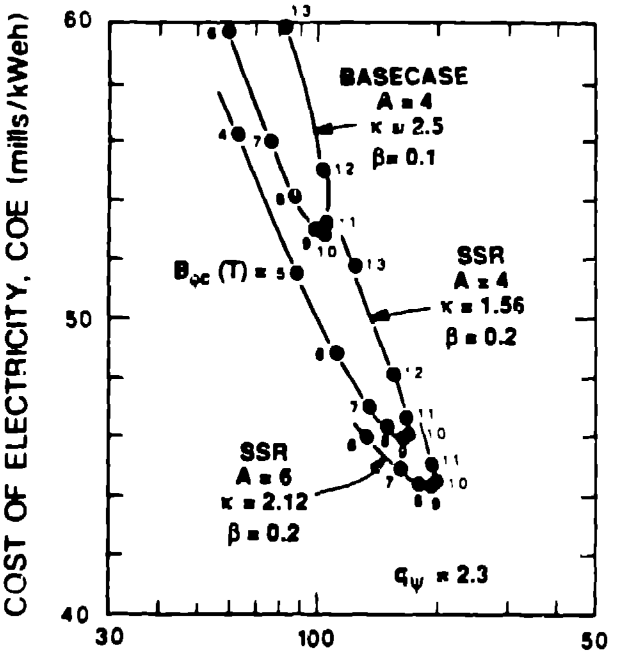

Fig. 1. Dependence of COE on mass power density, MPD(kWe/tonne), for the basecase tokamak and two (β = 0.1, 0.2) SSR tokamak cases.

3.2 Sensitivity to Main Physics Parameters (q_ψ, ϵ, κ, β)

The basecase parameters are considered optimistic, with present experience suggesting $\kappa \lesssim 2.0$ and $q_\psi \gtrsim 3.0$ in order to assure a higher confidence of disruption-free operation. The dependence of COE on β and A is shown on Fig. 2, which also tracks the degree of plasma elongation required [Eqs. (1) and (2)]. The sensitivity of COE on q_ψ for β = 0.1, but constraining A and κ according to Eqs. (1) and (2), is shown on Fig. 3. If the basecase value of κ is decreased from 2.5 to 2.0 with a simultaneous increase in q_ψ from 2.3 to 3.0, while maintaining β at 0.1, a 16.5% increase in COE (52.8→61.5 mills/kWeh) results. The safety factor, q_ψ, may also be increased by a) reducing β, with $q_\psi \simeq 4$ possible for β = 0.057 with a 10% COE penalty, or b) by reducing A, with $q_\psi \simeq 4$ at A = 2.7 with a 13% increase in COE.

3.3 Basecase Single-Point Parameter Variations

3.3.1 Current Drive (I_ϕ/P_{CD}, γ). The simplest single-point parameter variation used to examine the impact of the current-drive efficiency on COE varied I_ϕ/P_{CD}. The impact on COE relative to the basecase is shown on Fig. 4. Efficiencies greater than that assumed for the basecase are achieved with diminishing returns in COE, whereas current-drive efficiencies much below 0.2 A/W portend serious economic consequences. Cases where I_ϕ/P_{CD} was held constant for the typical basecase reactor parameters correspond to a normalized current-drive efficiency of $\gamma \simeq 2.7$ A/m^2W (density in $10^{20}/m^3$ units); this efficiency is

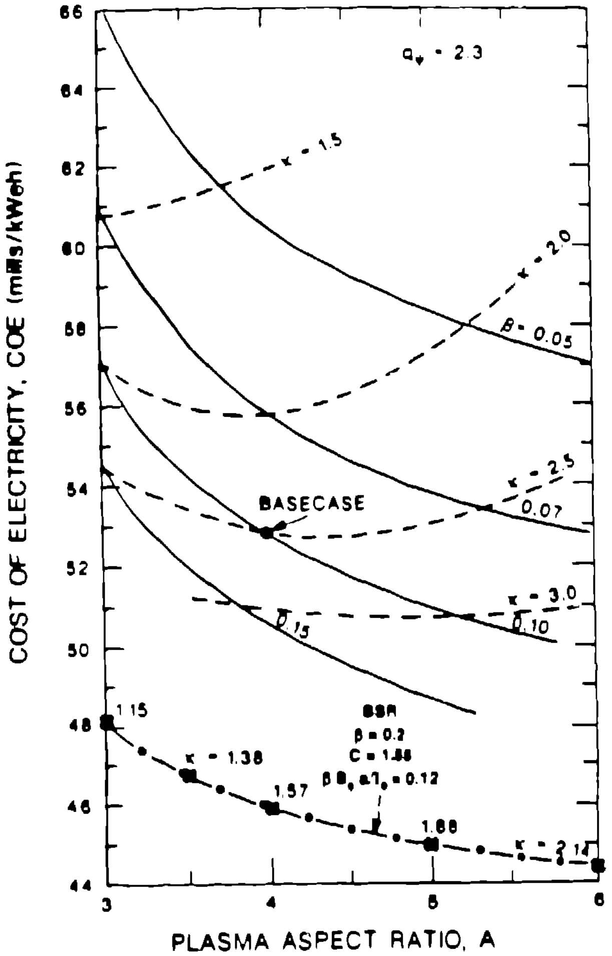

Fig. 2. Dependence of COE on plasma aspect ratio, A, and beta, β, for q_ψ = 2.3 with Eq. (20) enforced. Lines of constant plasma elongation, κ, are also shown. The β = 0.2 SSR tokamak case is also included.

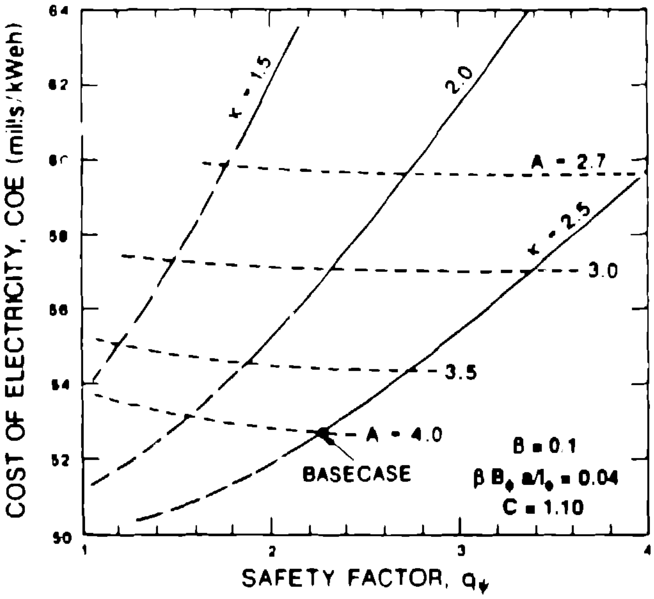

Fig. 3. Dependence of COE on q_ψ for a range of κ and A values that satisfy Eq. (20) with β = 0.1; the basecase tokamak shown.

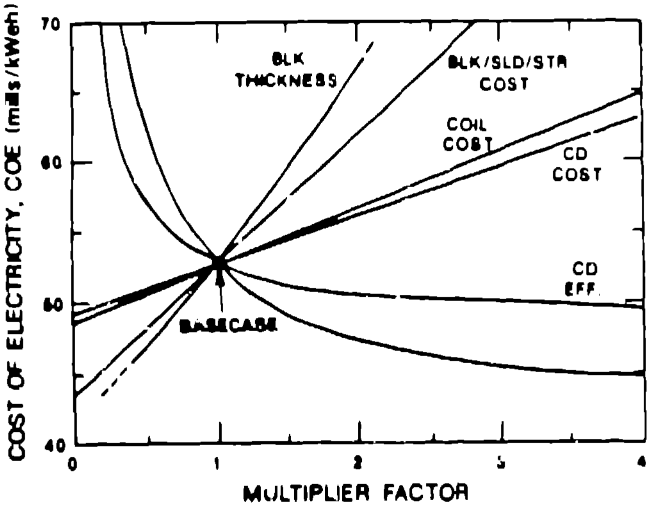

Fig. 4. Sensitivity of COE for the basecase tokamak on stability limits, $\beta B_\phi a/I_\phi$, current-drive efficiency, I_ϕ/P_{CD}, current-drive power costs, coil units costs, blanket shield/structural unit costs, and blanket thickness.

In re-evaluating the current-drive issue for fixed values of γ rather than I_ϕ/P_{CD}, the magnetic field at the TFC was first varied. The minimum-COE design point shifts from $B_{\phi c}$ = 10 T to the range 8-9 T for these constant-γ cases. With $B_{\phi c}$ = 9 T and other basecase parameters retained, both γ and T were varied. A minimum COE for a given γ occurs at $T \simeq 25$ keV.[11] Furthermore, the minimum-COE point shifts towards lower T as γ is increased, this behavior being indicative of the tradeoff between the cost of current-drive and the need to increase power density (i.e., reduce T and increase n) and to reduce FPC size and cost. The COE for the basecase would increase by 42% if γ was limited to ~0.5. Reoptimizing the basecase plasma temperatures (T ~ 25 keV) with γ = 0.5 reduces this COE to within 15% of basecase. Maintaining the basecase COE requires a 25-keV plasma operating with $\gamma \simeq 1.2$, which is about three times better than achieved in present experiments.[18] It is noted that incorporation of bootstrap current can have a dramatic, positive effect.[11]

3.3.2 Magnetic-Field Utilization (β). The COE is found to increase with decreasing beta as ~ $1/\beta^\nu$, where ν is in the range 0.13-0.20; hence, a factor of ~2 reduction in beta for the basecase parameters increases COE by 15%. As expected, a strong COE dependence on beta for the basecase scaling of j_c with B_c (Table I) is shown. These effects of beta variations were obtained by changing κ for fixed A = 4 and q_ψ = 2.3, while keeping constant the Troyon coefficient, $\beta a B_\phi/\mu_0 I_\phi$ = 0.04; the result of varying this latter parameter is reported below.

3.3.3 Stability Limits ($\beta B_\phi a/I_\phi$, κ). The dependence of COE on the Troyon ballooning-mode limit[15] is shown in Fig. 4. Pushing stability-related beta limits beyond the numerical Troyon limits leads only to small reductions in COE, but minor shortfalls in this limit dramatically increases cost. A reduction in the Troyon coefficient from 0.04 to 0.03 with a concomitant reduction in β from 0.10 to 0.075 will increase COE by about 7%. Generally, the tokamak basecase lies optimally at the "knee" in the curve given on Fig. 4.

3.3.4 Advanced Superconducting Magnets. The COE minimum in Fig. 1 for the superconducting tokamak basecase is determined in large part by a balance between a) larger magnetic fields (for the fixed β = 0.1) for increased plasma power density and reduced FPC size and b) the ever-increasing magnet costs caused by decreasing critical current densities and higher conductor fields. A more aggressive coil design has suggested[*] a scaling according to $j_c(MA/m^2) = 35(12/B_{\phi c})^{0.8}[1 + (B_{\phi c}/12)^{1.5}]$. The impact of this more advanced superconductor is shown on Fig. 5 as the curve labelled $SC(a)$, with the minimum-COE design point being 2-3% lower than the basecase and shifting from $B_{\phi c}$ = 10 T to ~11 T. Shown also on Fig. 5 as curve $SC(b)$ is the result of using an even more aggressive magnet design procedure and assumptions.[9] By dividing a given TFC into four subcoils, each operating at ever-increasing value of the critical field, it can be shown (Appendix A, Ref. 9) that the average current density in the winding pack is given by $j_{\phi c}(MA/m^2) = 71\left[1 - (B_{\phi c}/41.6)^2\right]$. Important (~13%) reductions in COE are predicted if the aggressive design proposed in Ref. 9 is adapted. The impact of coil cost alone on COE is shown on Fig. 4 for the basecase.

3.3.5 Economy of Scale. The dependence of COE on net electric power for the tokamak basecase was determined and compared with pressurized-water (fission) reactor (PWR) power costs.[22] These single-point variations did not adjust the magnetic field to hold neutron wall loading constant, which for given beta will give at most a few percent "diffuseness" to the correlations. The economy-of-scale curves are approximately described by exponential functions (COE $\propto 1/P_E^{\nu}$) with ν being 0.49 for the basecase and 0.45 and 0.39, respectively, for the medium- and best-experience PWR cases; the basecase lies between these PWR cases.

3.3.6 Blanket Radiation Lifetime. The radiation lifetime of the first wall and blanket structure, $I_w\tau(MW\,yr/m^2)$, determines the plant factor as well as the operating cost, with 20 $MW\,yr/m^2$ being assumed for the basecase. The sensitivity of COE to $I_w\tau$ is expected to be greatest for those systems that increase I_w and FPC power density to achieve reduced cost. A serious degradation of economic performance for $I_w\tau \lesssim 10\ MW\,yr/m^2$ is found,[11] with an 11% increase in COE at $I_w\tau = 10\ MW\,yr/m^2$.

3.3.7 Blanket Thickness and Unit Cost. The nominal thickness of the Li/Li/V blanket ($\Delta b \simeq 0.71\ m$) was varied for fixed shield ($\Delta s \simeq 0.83\ m$) and gap ($\Delta g \simeq 0.10\ m$) thickness. The results of this single-point variation are shown on Fig. 4. If the blanket/shield/structure, coil, and current-drive power were each "free," the respective decreases in the baseline COE would be 18%, 8%, and 8%. If the blanket unit cost alone were reduced by 50% (from $190 to $95/kg installed), a decrease of 6% in the COE would be expected.

3.3.8 Plant Lead Time. One of the greatest uncertainties in estimating COE for a fusion power plant is the time required to license and construct; this lead time was fixed at six years for the basecase. Results were normalized to give the reference case for a six-year lead time. A one-year change in lead time is estimated to produce about a 3% change in constant-dollar COE. The COE sensitivity to lead time expressed in nominal dollars (including an assumed 6%/yr inflation rate) is approximately 9%/yr if the startup date is changed and the order date remains constant.

3.3.9 Safety Assurance Cost Credits. The generally low neutron wall loading and local power density that characterizes the Li/Li/V tokamak basecase should permit a higher level of safety assurance[9] and the potential for some capital-cost credit associated with eliminated safety systems and reduced usage of more costly nuclear standards. The maximum credit would be obtained if most nuclear-grade restrictions were removed, and the cost credit factors suggested in Ref. 9 were applied. Figure 5 shows the resultant maximum reduction in the basecase COE is 25%. This reduction represents a significant potential savings that must, however, be balanced against the increased capital cost associated with the more-massive (low-power-density) fusion power core.[11]

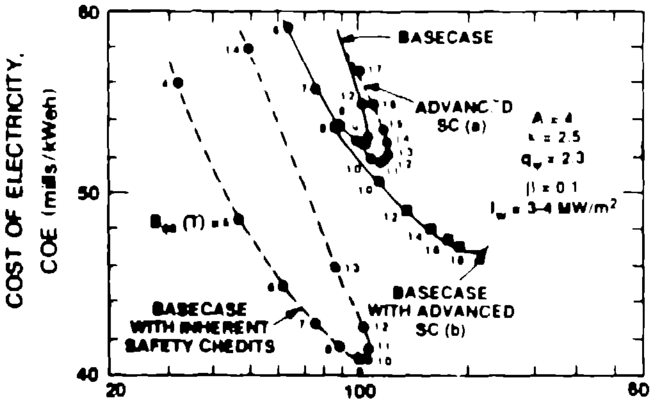

Fig. 5. Impact of superconducting (SC) coil performance on basecase economics, with SC(a) being an advanced design from Ref. 7 and SC(b) being an advanced design from Ref. 9. The impact of apply inherent safety credits to specific accounts is also shown.

TABLE II. Effect of Single-Point Variations/Uncertainties on Basecase Cost[(a)]

	Change (in COE)
Troyon Coefficient, $\beta B_\phi a/I_\phi = .04^{(b)}$	
• Reduced from 0.04 to 0.03 β = .075	-7
• Proportional to $1/\kappa$ $\beta = .04,\ \kappa = 2.5$ $\beta B_\phi a/I_\phi = 0.016$	-30
Plasma Safety Factor, $q_\psi = 2.3^{(b)}$	
• Increase to q_ψ 4	
– Reduce β to .057	+10
– Decrease A to 2.7	+13
Plasma Elongation, $\kappa = 2.5^{(b)}$	
• Reduce elongation to 2 with A = 3	+8
Blanket Radiation Life, 20 MW yr/m² [(b)]	
• Decrease to 10 MW yr/m²	+11
Current Drive Efficiency, $\gamma = 2.7\ A/m^2W\ (I_\phi/P_{CD} = 0.2\ A/W)$	
• Limit γ to 0.5 A/m² W	+42
• Limit γ to 0.5 A/m² W and increase plasma temperature to 25 keV	+14
• Include effect of Bootstrap Current	-8 [(c)]
Basecase with conservative parameters[15]	+38
Eliminate Nuclear Grade Requirements	-25
Coil Current Density, $j_{\phi c} = 20.5\ MA/m^2$ [(b)]	
• Improved aggressive design $j_{\phi c} = 58\ MA/m^2,\ B_{\phi c} = 18\ T$	-13
Plant Lead Time, Y = 6 yr [(b)]	
• Reduce leadtime by 1 yr	-3
Blanket Unit Cost, 190 $/kg [(b,d)]	
• Reduce by 50%	[illegible]
Achieve Second Stability Region	-16

(a) Changes indicated are based on single-point variations from the basecase parameters listed in Table I ($\beta B_\phi a/I_\phi$ = 0.04, β = 0.1, κ = 2.5, A = 4, T = 10 keV, I_ϕ/P_{CD} = 0.2 A/W)

(b) Basecase value

(c) Based on full I_ϕ = 15.7 MA being sustained by bootstrap currents

(d) Installed cost

4. SUMMARY AND CONCLUSIONS

Table II summarizes the impact on COE of changes in the main basecase parameters. The magnitude of these COE changes may not appear significant in comparison with the overall uncertainty in power plant costs. However, the relative cost effects shown in Table II should persist irregardless of the absolute cost. These relative cost differences convey real insights about the economic effects/impacts of these uncertainties. As one example of the impact of these uncertainties, a 10% COE uncertainty is equivalent to a change in annual revenue of ~35 M$/yr for the referenced 1200-MWe power plant. To provide both a contrast and perspective, four other approaches (i.e., SSR, SHF, ST, and conventional) to the tokamak power plant were examined[11] but not described explicitly here. The COE projected for a power plant based on present[15] and yet-to-be-achieved[12] physics spans a range from 44 to 72 mills/kWeh, with an optimistic extrapolation of the present-day database[9,11] predicting a value of ~53 mills/kWeh; this latter value of COE is competitive with alternative energy sources, particularly with advanced fission-power systems. Although not examined directly, the results given on Figs. 4 and 5 give some indication of the impact of recent advances[23,24] in increasing the critical temperature for ceramic superconductor; the major impact of these higher-temperature superconductors would be in (a) operating at higher fields and current densities (Fig. 5) and (b) reducing the thickness of blanket and shield (Fig. 4) because of enhanced radiation tolerance; under the optimistic assumption that both effects are additive, a cost reduction of ~26% in COE could result. In summary, high beta, efficient and economic current-drive schemes, and/or high-performance superconducting magnets represent major leverage issues in dictating the extent to which physics must be pushed to maintain an economic edge for fusion power through the tokamak route.

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