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AUTHOR(S): R. A. Krakowski, R. L. Miller, and
J. G. Delene (Oak Ridge National Laboratory)

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Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DIRECTIONS FOR IMPROVED FUSION REACTORS*

R. A. Krakowski, J. G. Delene**, R. L. Miller
Los Alamos National Laboratory, Los Alamos, NM 87545 USA

ABSTRACT
Conceptual fusion reactor studies over the past 10-15 years have projected systems that may be too large, complex, and costly to be of commercial interest. One main direction for improved fusion reactors points towards smaller, higher-power-density approaches. First-order economic issues (i.e., unit direct cost and cost of electricity) are used to support the need for more compact fusion reactors. A generic fusion physics/engineering/costing model is used to provide a quantitative basis for these arguments for specific fusion concepts.

1. INTRODUCTION

Ideally, a new energy source must be capable of displacing old energy sources while providing both economic opportunities and enhanced environmental benefits. The attraction of an essentially unlimited fuel supply has generated the impetus to develop advanced fission breeders and, even more strongly, to exploit nuclear fusion. Both fission and fusion systems trade off a reduced fuel cost with a more capital-intensive plant needed to utilize a cheaper and more abundant fuel. Results from early conceptual designs of fusion power plants,[1-10] however, indicated that these systems may be so capital intensive as to override any inherent cost savings promised by an inexpensive fuel cycle. Early warnings of these problems appeared,[11-13] but until recently specific solutions to this growing concern were few. Generalized routes have recently been suggested by which fusion could be made more economically attractive.[14,15] Specific examples for improved fusion reactors also have recently been reported.[16,17]

The generally recognized problems of large size, technological complexity, and correspondingly high cost of a magnetic fusion power plant strongly suggest directions of improvement. Although a direct reduction in the mass (and cost) of the fusion power core (FPC, i.e., plasma chamber, first wall, blanket, shield, coils, and primary structure) most directly reduces the cost of fusion power, with the mass power density (MPD, ratio of net electric power to FPC mass, kWe/tonne) being suggested as a good figure-of-merit in this respect,[18] other technical, safety/environmental, and institutional issues also enter into the definition and direction of improved fusion concepts. After discussing these latter issues and related tradeoffs in Sec. 2., specific examples, comparisons, and tradeoffs are given in Sec. 3. using the generic fusion reactor model described in Ref. 15. Section 4. gives a brief summary and conclusions.

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**Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA

2. DIRECTIONS FOR IMPROVEMENT

The large FPCs projected for early conceptual reactor designs are reflected in a high capital cost, usually expressed as a unit direct cost, UDC($/kWe), and a high cost of electricity, COE(mills/kWeh). The major components of the total direct cost are conveniently divided into two major cost categories:[19-21] Reactor Plant Equipment (RPE, which includes the FPC under the Reactor Equipment Account) and the Balance of Plant (BOP). For fusion power plants invoking more-or-less conventional BOPs (i.e., steam-based conversion systems with gross conversion efficiencies of $\eta_{TH} = 0.35$-0.40), the RPE alone represented $\geq 50\%$ of the total direct cost, with the FPC requiring 25-30% of all direct expenditures; these percentages compare to ~ 30% and $\leq 5\%$, respectively, for identical RPE and FPC accounts in a typical light-water fission reactor.[22] Table I summarizes the major costs for a number of earlier fusion power-plant designs, as well as recently improved designs based either on innovative approaches to the tokamak[23] or extensions from non-tokamak concepts[24-26]; a normalized comparison to the pressure-water fission reactor, PWR[22], is also included. Fig. 1 gives a series of FPC cross-sections being projected for the designs listed on Table I,

TABLE I

COMPARISON OF CONSTANT-DOLLAR COSTS NORMALIZED AS PERCENTAGE OF TOTAL DIRECT COST FOR A RANGE OF CONCEPTUAL FUSION REACTORS (1980 DOLLARS, a factor 1.348 takes these costs to 1986)

	ACCOUNT Reference	UWMAK-I [1]	STARFIRE [4]	MARS [10]	CRFPR [24,25]	ATR/ST [25]	CSR [26]	PRW [22]
20.	Land and Land Rights	0.11	0.19	0.21	0.30	0.22	0.34	--
21.	Structure and Site Facilities	13.11	20.09	10.56	24.41	18.58	27.00	22.34
22.	Reactor Plant Equipment (RPE)	53.82	56.00	64.15	37.31	51.29	30.43	34.01
	22.1.1. First Wall/Blanket	6.95	4.77	3.01	0.95	2.98	1.90	--
	22.1.2. Shield	3.88	10.78	3.17	0.19	1.12	--	--
	22.1.3. Coils	17.82	9.90	20.84	3.09	11.03	2.78	--
	FPC	28.65	25.48	27.02	4.23	15.13	4.58	~5.-6.(d)
23.	Turbine Plant Equipment	16.01	14.47	11.63	20.17	16.16	22.81	24.99
24.	Electric Plant Equipment	13.40	6.77	6.76	10.17	8.01	12.41	8.56
25.	Misc. Plant Equipment	0.38	2.37	1.40	3.76	2.82	4.28	4.67
26.	Special Materials	2.65	0.01	5.28	3.89	2.91	2.72	5.33
90.	Total Direct Costs (TDC)	100.	100.	100.	100.	100.	100.	100.
99.	Total Costs	154.25	185.23	138.10	136.28	138.87	136.28	158.93
	Unit Direct Cost, UDC($/kWe)	1150.(a)	1439.	1633.(b)	1112.	1485.	977.8	562.(d)
	Cost of Elec., COE(mills/kWeh)	36.1(a)	35.1	38.3(b)	27.9	37.8	24.6	--
	Unit FPC costs, c_{FPC}($/kg)	7.	19.	25.	42.	45.	53.	40-50
	Net Electric Power, P_E(MWe)	1437.	1200.	1202.	1000.	1000.	1000.	1139.

(a) Originally reported as 742 $/kWe and 23.3 mills/kWeh in 1974 dollars; a factor of 1.55 converts to common-base 1980 costs.[27]

(b) Based on 196[illegible] $/kWe and 46 mills/kWeh in 1983 dollars; factor of 1.21 converts back to common-base 1980 costs.[27]

(c) Not explicitely reported in Ref. [22], but the ~ 1000-tonne pressure vessel (including heads) costed at ~ 50 $/kg would give the listed value. Reference [22] reports the Nuclear Steam Supply System (NSSS) cost is 20.49% of the total direct cost.

(d) Originally reported in 1984 dollars, a factor of 1.25 converts to common-base 1980 costs.[27]

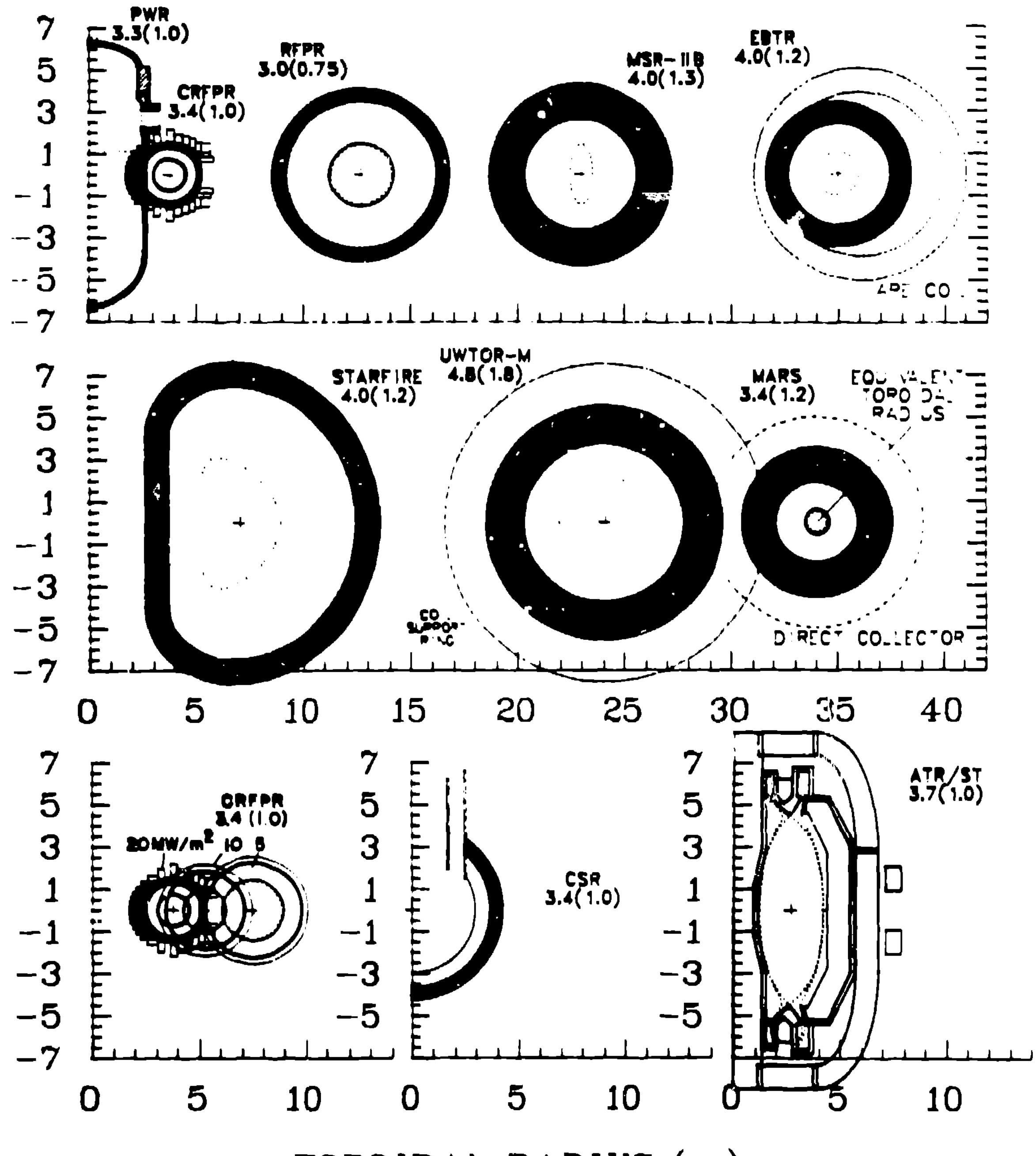

Fig. 1. Cross-section of FPCs for a range of fusion reactors, including the RFP, spheromak, and ST concepts summarized on Table I.

as well as others. Both the magnitude of and sensitivity to the RPE and (particularly) the FPC costs, as well as required (extrapolated) physics and materials performances related thereto, point to a key area where the economic prospects for fusion can be increased and the associated time and risks required for commercialization can be decreased: increased FPC power density and decreased FPC size (mass, cost, and complexity). This approach to an improved fusion reactor, however, is not without technical and economic compromises. Specifically, increased MPD will have implications for safety (i.e., nuclear afterheat power density and degree of inherent safety[28]), environmental impact (character and quantity of radioactive waste), plasma performance (efficiencies of plasma energy confinement, $\chi_E \simeq a^2/4\tau_E$, and magnetic-field utilization, β), development cost and flexibility (both time and funding), as well as end-product cost (i.e., UDC and COE).

A highly simplified but informative costing model[29] relates COE, UDC, MPD, and neutron wall loading, I_w(MW/m²), to predict that COE $\simeq \lambda(F + c_{FPC}/MPD)/8.76$, where λ is an effective pay rate (0.3-0.4 yr⁻¹), the bulk of the direct costs not directly related to the FPC are included in F($/kWe), and c_{FPC}($/tonne) is the average unit cost associated with the FPC. Reduction in COE up to a point, therefore, can be achieved by increasing MPD. The MPD in turn can be increased by increasing the plasma power density, because MPD $\propto I_w/a \propto \beta^2 B^4$ and the plasma power density is P_F/V_p(MW/m³) $\simeq 1.2\beta^2 B^4$. Increasing MPD by this route requires increased efficiency of magnetic-field utilization (i.e., β), but increased magnetic field, B, will either increase the recirculating power (i.e., ε) if resistive coils are used or increase the magnet cost for either superconducting or resistive-coil FPCs. These tradeoffs, along with others to be mentioned, must be examined in the context of the physics for a specific confinement scheme and a self-consistent reactor design. Designs that promote higher power density plasmas while limiting the total power will require better plasma confinement efficiency, χ_E, in plasmas of smaller dimensions (total fusion power, $P_F \propto \chi_E R_T/a^2$ for $n\tau_E T$ nominally constant). In addition to placing more demands on physics through increased β and decreased χ_E, the achievement of direct cost reductions and insensitivity to FPC physics and technology through increased MPD can also have impact on costs in areas other than those noted above. Adverse impacts are summarized as follows:

- Increased I_w leads to increased nuclear-afterheat power density, decreasing the degree of inherent safety and possibly adding costs associated with plant safety systems.

- Increased I_w may be accompanied by increased heat flux, perhaps requiring special high-heat-flux materials, adding to FPC unit cost and possibly limiting materials choices, particularly as related to reductions in long-term radioactivity generation.

- Increased I_w may require separate surface (first wall, limiter) and bulk-heating (blanket) coolants, decreasing η_{TH} and adding to FPC, RPE, and BOP unit costs.

- Increased recirculating power fraction, ε, may result if thin blankets and/or resistive coils are utilized to increase MPD; the tradeoff associated with FPC versus ε is strongly dependent on concept. Increased ε will also lead to increased BOP thermal ratings and associated costs.

On the other side of the ledger, however, smaller higher-power-density FPCs offer the potential for a number of improvements beyond the reduction of direct cost. Improvements envisaged for MPD beyond the COE-based threshold are listed as follows:

- Increased FPC operational flexibility
  - single- (or fewer-) piece maintenance of the reactor torus
  - ability to sustain and recover from significant FPC breakdowns
  - ability to conduct significant testing on a fully assembled FPC prior to nuclear service to increase operational reliability
  - ability to incorporate innovation and improve FPC throughout plant life
- Reduced impact of physics and technology uncertainties on overall cost of fusion power
- More rapid development of "learning curves," more closely coupled feedback to developing experience base, early assembly of reliability database

These advantages, although not directly reflected in present costing models, nevertheless, combine to promise a generally less expensive, bolder, and faster development path towards a competitive fusion end-product.

In assessing the prospects and means for improved fusion, an emphasis has been placed on cost estimates as well as less-quantitative assessments of complexity as related to plant availability and overall operational risk. In addition to capital and life-cycle energy cost, however, the attractiveness of a new energy source depends strongly on construction lead-times and financial risks related both to protracted construction and licensing periods and to capital-cost overruns. Although more difficult to quantify, these highly variable forces are expected to shape strongly the direction for improved fusion systems. The present trend[30] in the U.S. towards small, short-lead-time power systems may present a target for fusion that is difficult to meet by present concepts, as more advanced, economic fission systems are proposed. The long-range nature of fusion power, however, makes reasonable the focus on improvements in UDC and COE rather than the issues of small capacity and utility acceptance based on present-day financial pressures and energy demands. Nevertheless, the role of fusion eventually will be more strongly shaped by and must be cognizant of these utility issues, particularly as they relate to capacity, complexity, reliability, and licensibility.

3. SPECIFIC APPROACHES

Figure 2 depicts the main classes of magnetic confinement systems presently under worldwide study. This diagram emphasizes approximate relationships between concepts, with systems supporting large plasma currents positioned on the left and those containing little or no plasma current being positioned on the right. The latter systems, including the present vision of the tokamak and the tandem mirror, are dominated by large, externally imposed axial or toroidal magnetic fields and, therefore, considerations of overall plant efficiency generally lead to the use of large superconducting coils. Confinement systems located on the left side of Fig. 2 support more of the plasma pressure by internal plasma currents, are to varying degrees poloidal-field dominated (PFD), have reduced requirements for externally imposed magnetic fields, and to varying degrees can operate with efficient resistive coils; these PFD concepts can be designed with reduced coil shielding compared to superconducting systems, and a considerable reduction in the FPC mass, size, and complexity is envisaged. The possible disadvantages of the PFD systems are the need to sustain plasma currents, the need for a conducting shell near the plasma, and a physics database that is not as well developed compared to the tokamak. To varying degrees, the advanced tokamaks (i.e., ST and ET in Fig. 2) can also exhibit PFD-like characteristics, with the efficient use of resistive copper coils to confine higher-beta, higher-power-density plasmas also promising reductions in FPC size, mass, complexity, and cost. Qualitative comparisons of the PFD approaches to improved fusion systems based on separate studies have been reported.[16,29] The approximate but generic model described in Ref. 15 can provide a self-consistent, quantitative intercomparison and sense of direction. Improvements possible for both a superconducting tokamak and a resistive-coil RFP have been examined using this model,[15] which is discussed below.

3.1. Description of Model. A detailed description of the physics, engineering, and costing models for the generic fusion reactor model can be found elsewhere,[15,40] with the essential features being given in Table II for both the improved tokamak and the RFP variants. Table II illustrates both basecase and varied parameters. A Troyon-Gruber beta limit[41] was applied to the superconducting tokamak, and a nominally fixed (poloidal) beta limit, which is observed experimentally,[42] was applied to the resistive-coil RFP reactor. Both systems invoked pumped-limiter impurity control and steady-state current drive, with the adjustments being made for expected differences in current-drive efficiencies and costs; lower-hybrid current drive was specified for the tokamak, and oscillating-field current drive[43] was selected for the RFP. Although identical costs were used for blanket, shield, structure, and limiter unit costs (Table IIC), adjustments were made in the coil unit costs to reflect differences between high-field superconducting coils and low-field resistive-copper coils. Similarly, differences in current-drive efficiencies and costs (technologies) between tokamaks and RFPs may justify adjustments in this area (Table IIB). In examining cost and design-point tradeoffs for both tokamak and RFP cases, the toroidal field at the coil was selected, and for a given net power output [1200 MWe(net) for the basecase] the TFCs were appropriately sized and costed using the current-density constraints expressed in Table II. The "secondary" poloidal-field coils (PFCs) were taken as a factor times the TFC mass,[15] which for the tokamak is ~ 0.25 and for the PFC-dominated RFP is ~ 10. The unit costs and the general costing methodology[15] are more severe than that assumed for the early designs summarized on Table I. Even with this more stringent (realistic)

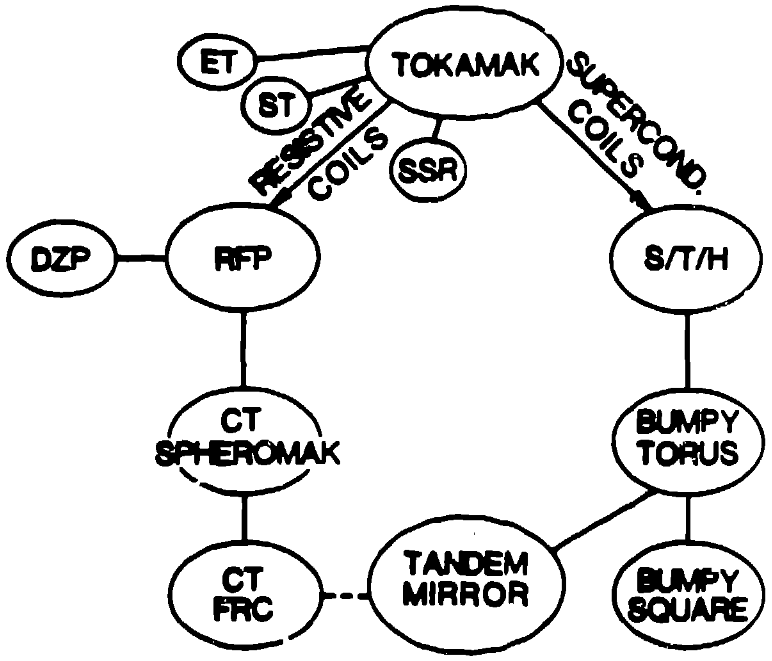

Fig. 2. Options for magnetic fusion. The higher-beta options for the tokamak include the spherical torus, ST[24,31]; the elongated torus, ET[32]; and operation in the second stability region, SSR.[33] The stellarator, torsatron, and heliotron systems are designated as S/T/H.[7,8,34,35] The usually large bumpy torus[36] projects compactness when formed into a square or high-order polyhedron.[36] The reversed-field pinch, RFP[24,25] is the first significant step away from the "conventional" tokamak as a PFD system. The Dense Z-Pinch, DZP,[37] and compact torid (CT) spheromak[26] have no toroidal or axial field outside the plasma. The field-reversed configuration, FRC,[38] is a CT with no toroidal field, either inside or outside the plasma. The tandem mirror[20,39] embodies characteristics of both FRCs, S/T/Hs, and bumpy tori/squares, including the use of high-field superconducting and resistive coils, energetic electron rings, and linear central geometry.

costing model, it will be shown that conditions can be identified where fusion is competitive with alternative energy sources.

3.2. Comparative Results. Figure 3 gives the COE as a function of MPD. The curve for the tokamak labeled $\beta = 0.1$ is typical of the COE minimization shown for this superconducting system and the scaling used (Table II). As the magnetic field at the TFC is increased for a fixed beta, the plasma power density increases, the plasma and FPC size shrinks as the net electric power is maintained constant, and the COE decreases; a decreasing plasma current and cost of current drive also contributes to this decrease in COE as the TFC field is initially increased. For TFC fields above ~ 10-11 T, however, the decreasing TFC current density (Table IIB) causes the coil size to increase, which in turn drives a rapid increase in FPC cost and the observed minimum in

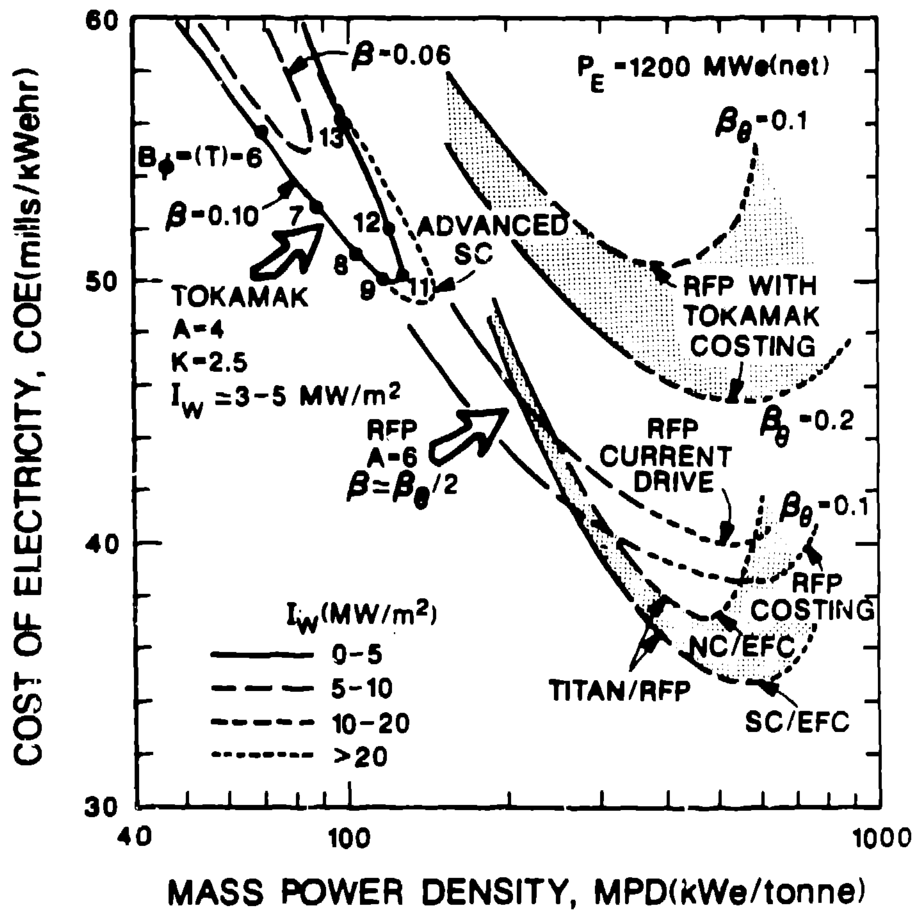

Fig. 3. Correlation of energy costs with FPC mass power density for a range of tokamak and RFP physics and costing assumptions.

COE. Use of an advanced (higher critical current density) superconducting can shift this minimum to lower COE somewhat and higher MPD, as is shown on Fig. 3. The impact of decreased beta (increased q_ψ, Table IIA), is also shown in Fig. 3. Increased plasma elongation, κ, and decreased aspect ratio, A, can in principle give large values of β,[31] but, for the current-drive efficiencies and costs used, the added cost for such high-current (low aspect ratio) tokamaks load to more costly systems than those displayed in Fig. 3. Generally, the β = 0.1 tokamak curve on Fig. 3 represents an optimal "compact" superconducting tokamak for TFC fields in the range 10-11 T. Detailed conceptual design of this advanced system, however, remains to be done.

Figure 3 also summarizes results for the resistive-coil RFP, which also shows a COE minimum but for different reasons and of a different character than that described for the tokamak. Using a cost database

TABLE IIA. GENEROMAK PLASMA PARAMETERS[(a)]

	TOKAMAK	RFP
Aspect ratio, $A = R_T/a$	[4.]	[6.]
Elongation, $\kappa = b/a$	[2.5]	1.0
Safety factor, $q_\psi = (2.75/5.)(B_\phi/B_\theta A)(1 + \kappa^2)/(1 - 1/A^2)^2$	[2.268]	~0.02
Beta		
• Total, β	$0.04I_\phi/aB_\phi$ [0.1]	$\beta_\theta/2$ [0.1]
• Poloidal, β_θ	$<1.$	[0.2]
• Ion/electron beta ratio	1.0	1.0
• Impurity (alpha-particle)/ electron beta ratio	0.2	0.2
Plasma standoff, a_w/a	1.1	1.1
Reversal parameter, $F = B_\phi(a)/\langle B_\phi \rangle$	~1.0	-0.12
Pinch parameter, $\Theta = B_\theta(a)/\langle B_\phi \rangle$	1/qA	1.60
Current drive efficiency (A/W)	0.2	[0.4]
Plasma current, I_ϕ(MA)	$\dfrac{2.75B_\phi a(1 + \kappa^2)}{q_\psi A(1 - 1/A^2)^2}$	$5B_\phi a(\Theta/F)$
Fraction of alpha-particle power to limiter	0.8	0.8

(a)Parameters in brackets varied, with values given being for basecase.

that is identical to that used for the tokamak, the minimum COEs are comparable, but occur at higher MPD and correspondingly smaller FPCs and higher neutron wall loading. As for the superconducting tokamak case, increasing TFC field generates each constant-beta curve shown for the RFP in Fig. 3, and COE diminishes as both plasma and FPC decreases for a fixed total output. Unlike the tokamak case, the neutron wall loading increases rapidly along a given RFP curve as a constant net-electric power is maintained, with blanket burnup, increased TFC Joule losses, and eventually decreased plant availability because of more frequent changeouts causing the COE to increase at high MPD. Hence, whereas increased capital cost is responsible for both sides of the COE minimum for the superconducting tokamak, the resistive-coil RFP exhibits a COE minimum for reasons of capital cost at low MPD and for reasons of operational cost at high MPD. Selecting $\beta_\theta \simeq 0.1$ as the RFP basecase, Fig. 3 also shows the impact of a) use of current-drive efficiencies and costs (Table IIB) estimated as more appropriate for the RFP, and b) use of coil unit costs more appropriate for a low-field, resistive systems. The curve on Fig. 3 labeled "RFP costing" represents the RFP basecase. Along this RFP basecase curve the neutron wall loading can vary substantially; holding the neutron wall loading below 10-20 MW/m^2 disallows access to the COE minimum, but the range 5-10 MW/m^2 can be quite close to the optimal COE. Shown also in Fig. 3 are results from a detailed, RFP-specific systems code[44] that performs a wide range of subsystem optimizations; the general agreement with much simpler Ref. 15 model is surprisingly good, although differences in sensitivities and neutron wall loading versus MPD are noted, these differences resulting

TABLE IIB. GENEROMAK ENGINEERING PARAMETERS

	TOKAMAK	RFP
Net electric power, P_E(MWe)	[1,200.]	[1,200.]
Thermal conversion efficiency, η_{TH}	0.42	0.42
Fusion-Power-Core dimensions		
• blanket thickness, Δb(m)	0.45	0.45
• blanket/shield gap, Δg(m)	0.10	0.10
• shield thickness, Δs(m)	0.75	0.10
Ratio of TFC mass to masses of other coils (EFC,OHC)	0.25	10.
TFC current density, j_{TFC}(MA/m²)	$\frac{(96 - 6B_{\phi c})}{1 + (B_{\phi c}/12)^{1.5}}$	[10.][(a)]
Availability		
• plant, p_f	0.65	0.65[(b)]
• auxiliary (current-drive) power	0.325	0.325
Smear densities (tonne/m³)		
• blanket	2.3	2.3
• shield	7.0	7.0
• coils	7.9	7.9
• structure	6.0	6.0
Structural volume fraction of coil	0.50	0.50
Fluence lifetime (MWyr/m²)		
• limiter (heat)	10.	10.
• blanket and auxiliary heating (neutrons)	[25.]	[25.]
Recirculating power fraction to BOP	0.07	0.07
Blanket neutron-energy gain, M_N	1.14	1.14
Number of blanket modules/section	6.	6.
Number of TFC sectors	20.	20.

(a)Resistive copper alloy, value reported corresponds to a COE minimum.
(b)If I_w(MW/m²) is the neutron wall loading, and the radiation lifetime is $I_w\tau$(MWyr/m²), then $p_f = 0.7534/[1 + 0.1034 I_w/(I_w\tau)]$ when $I_w/(I_w\tau) > 1.54$ yr⁻¹. This expression is based on 90 days/yr of unscheduled maintenance and 38 days per FPC changeout.

from the more exact treatment of coil masses and power requirements in the Ref. [44] study.

The dependence of COE on net electric power for both the tokamak and RFP basecases is shown on Fig. 4 in order to illustrate the competitiveness of both fusion approaches with fossil (coal) and fission (pressurized-water reactors). The STARFIRE prediction[4] of 1980 is also shown (a factor of 1.348 was used to take the 1980-dollar costs to 1986), as is the STARFIRE designs evaluated by the costing algorithm and database[15] listed on Table II.

The generally favorable economic position of both tokamak and RFP fusion systems shown on Fig. 4 must be evaluated against the simplified model used[15] and the key variables held constant. The value of beta ($\beta \approx 0.1$), blanket lifetime (25 MWyr/m²), and cost of current drive are main physics, technology, and economic uncertainties. The economic

TABLE IIC. GENEROMAK ECONOMIC/COST PARAMETERS

	TOKAMAK	RFP
Unit costs		
• blanket ($/kg)[(a)]	113.	113.
• shield ($/kg)	20.	20.
• coil ($/kg)	90.	[50.]
• structure ($/kg)	25.6	25.6
• limiter (k$/m²)[(a)]	60.0	60.0
• auxiliary (current-drive) power ($/W)[(a)]	2.25	[0.50]
• O&M costs $x(P_{EL}/1200)^{0.5}$(mills/kWeh)	8.87	8.87
Nominal fixed-charge rate, f_{CR}(1/yr)	0.167	0.167
Constant-dollar fixed-charge rate, f_{CRO}(1/yr)	0.0856	0.0856
Ratio of constant-dollar to overnite costs, f_{CAPO}[(b)]	0.7525	0.7525
Construction time, Y(yr)	6.	6.
Plant life, L(yr)	30.	30.
Tax-adjusted interest rate, X(1/yr)	0.09	0.09
Inflation and escalation rate, E(1/yr)	0.06	0.06
Effective tax rate, T(1/yr)	0.4816	0.4816
Contingency factor (of total direct cost)	1.15	1.15
Indirect cost factor (of constant-dollar direct cost), f_{IND}[(c)]	0.3750	0.3750
Spare multipliers (SPF)		
• blanket[(a)]	1.1	1.1
• coils	1.2	1.2
• limiters[(a)]	1.2	1.2
Annual cost for waste handling (mills/kWeh)	1.0	1.0

(a)Present worth and depreciation according to tax rate, T, tax-adjusted interest rate X, and escalation/inflation rate E, assuming an effective 4-year life. All costs are referred to the year 1986.
(b)$[1.084 + 0.55 (E - 0.09) + 0.38 (X - 0.09)]^{Y+0.61}/(1 + E)^{Y}$.
(c)$f_{IND} = 1 + 0.5Y/8$.

impact of these three variables for both tokamak and RFP basecases is illustrated in Fig. 5. Generally, the RFP is less sensitive to shortfalls in beta; lower beta, however, is penalized primarily by the need to drive more plasma current, albeit potentially at a greater efficiency and possibly at a lower unit cost. Both tokamak and RFP costs appear to be relatively insensitive to blanket lifetimes above ~ 10 MWyr/m², but the RFP shows a more rapid deterioration of this position if higher, but less-costly, neutron-wall-loading designs are chosen. The cost of current drive is important for both tokamak and RFP designs.

4. SUMMARY AND CONCLUSIONS

Comparison of past fusion reactor projections with those for competitive energy sources show the clear need to reduce the size and cost of the FPC and associated cost of the Reactor Plant Equipment account. The MPD for the pioneering UWMAK-I(1974)[1] tokamak reactor design was 20 kWe/tonne; this design gives reasonable values of COE only because of the low FPC unit costs (9.5 $/kg in 1986 dollars). The STARFIRE tokamak design projected[4] an MPD of ~ 40-50 kWe/tonne, as did

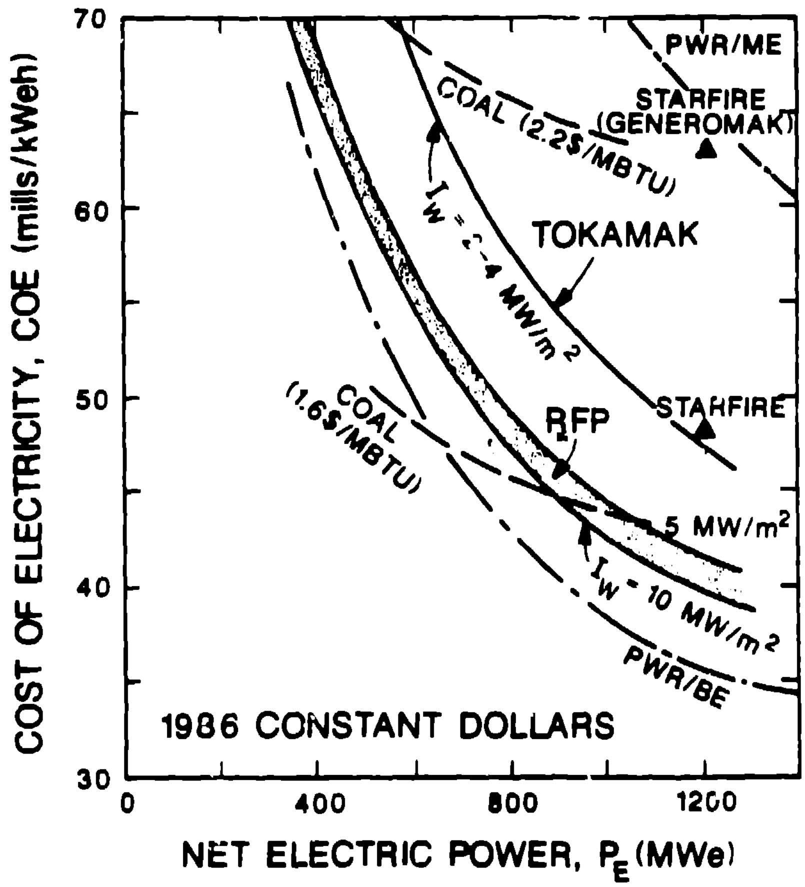

Fig. 4. Dependence of levelized-1986 COE on net electric power for both tokamak and RFP basecases, and a comparison with fossil fuel (coal), medium-experience fission (PWR/ME), and best experience fission (PWR/BE).

MARS,[10] with commensurate increases in economic credibility as competitive COE values were again reported, but now for unit costs that reflect more advanced technologies. The predictions of competitive fusion for MPD $\geq$ 100-200 kWe/tonne both by generic fusion-reactor studies[15] as well as the more specific studies reported here are in line with this trend of improved economics in the sequence: UWMAK-I[1] → STARFIRE[4]/MARS[10] → GENEROMAK[15] → (MINIMARS,[39] ATR/ST,[23] RFP,[24] CSR,[26] ?) while using an even more realistic unit cost database. Factors other than MPD enter into the equation for fusion with an economic edge, some being generic (e.g., coil current densities, materials radiation life, inherent safety, radwaste, etc.) and some being device specific (end-cell/central-cell coupling in tandem mirrors, confinement efficiency versus magnet requirements in PFD systems, plasma beta and current level in driven tokamaks, etc.). The MPD, however, remains as one important figure of merit by which to monitor progress.

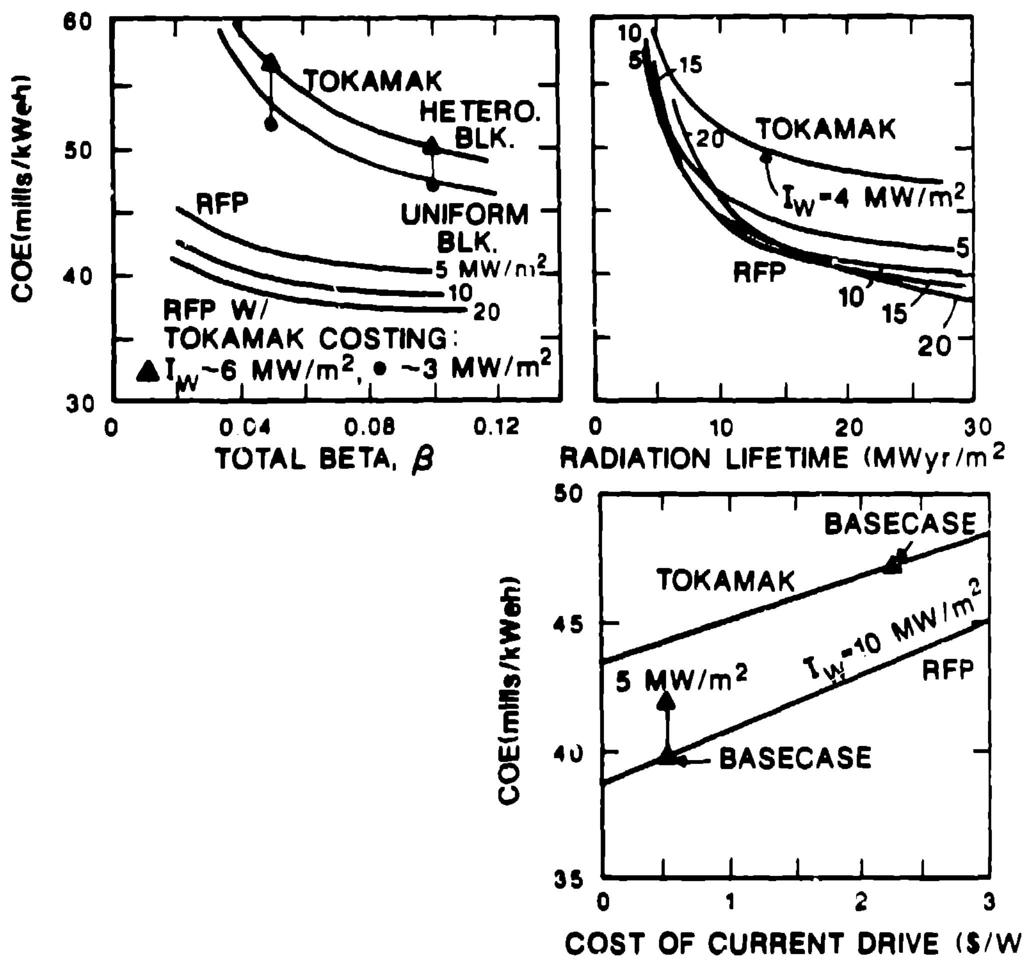

Fig. 5. Sensitivity of tokamak and RFP basecase (1200 MWe) COEs to variations in total beta, β, blanket radiation lifetime, $I_w\tau$(MWyr/m²), current-drive cost, and neutron wall loadings, I_w(MW/m²).

A number of options and opportunities exist for significant improvement in the prospects for commercial fusion power based on the principal tokamak as well as other concepts. The inter-relationships among the options are becoming clearer as physics understanding develops. One important direction for significant improvement is towards systems that assume more of the task of plasma confinement, heating, and sustainment through self-generated fields rather than by imposing these functions exclusively on complex and costly engineering systems that surround a low-power-density plasma. Systems that are dominated by poloidal field offer unique promise to reduce coil and, hence, FPC size, and to some degree may include tokamak variants. The evolution of the more compact systems that result using stringent costing methods point to strong potential for economically competitive fusion systems for reasonable extrapolations from the present physics database.

More detailed analyses of physics and technology constraints and the associated tradeoffs related to development cost and time, end-product operational and cost issues, and general safety and resource concerns are required to define both the attractiveness and competitiveness of fusion power. Hence, in addition to increased MPD and reduced COE, the pursuit of improved fusion reactors to varying degrees must:

- Consider the potential for reduced total power output and associated capital investment, with the possibility of multiplexing a number of smaller FPCs to drive a larger total site electrical capacity.

- Emphasize and/or enhance passive safety (against a loss of coolant) through inherent FPC design characteristics, with maintaining an MPD of economic interest.

- Stress long-pulsed or steady-state plasma operation while addressing related issues of plasma current drive, heating, fueling, and impurity/ash control.

- Simplify the FPC design in terms of reduced fields, stresses, and stored (magnetic) energy while using advanced materials and/or fabrication techniques only where clear-cut advantages are perceived.

- Maintain a high overall plant efficiency by utilizing direct energy conversion (when possible), high coolant fluid temperatures, and minimum power recirculated to the FPC and associated support systems (i.e., coils, current drive, plasma heaters, coolant pumps).

- Emphasize physically small modular FPCs that assure a flexible development path and ultimately factory (off-site) fabrication, full non-nuclear FPC pre-testing, and single- or few-piece FPC maintenance and repair.

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