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LA-UR -86-641

CONF-860603--5

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LA-UR--86-641

DE86 007377

TITLE: PROSPECTS FOR IMPROVED FUSION REACTORS

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SUBMITTED TO: Fourth European Nuclear Conference (ENC-86)
Geneva, Switzerland
June 1-6, 1986

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PROSPECTS FOR IMPROVED FUSION REACTORS*

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I. 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 a strong impetus to develop advanced fission breeders and, even more strongly, the exploitation of nuclear fusion. Both fission and fusion systems trade a reduced fuel charge for 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 a capital intensiveness that could override cost savings promised by an inexpensive fuel cycle. Early warnings of these problems appeared,[11-13] and generalized routes to more economically attractive systems have been suggested;[14,15] specific examples have also recently been given.[16,17] Although a direct reduction in the cost (and mass) of the fusion power core (FPC, i.e., plasma chamber, first wall, blanket, shield, coils, and primary structure) most directly reduces the overall cost of fusion power, with the mass power density (MPD, ratio of net electric power to FPC mass, kWe/tonne) being suggested as a figure-of-merit in this respect,[18] other technical, safety/environmental, and institutional issues also enter into the definition of and direction for improved fusion concepts. These latter issues and related tradeoffs are discussed in Sec. II., and a few specific examples are given in Sec. III.

II. DIRECTIONS FOR IMPROVEMENT

A. Cost-Based Issues. The large FPCs projected for early conceptual reactor designs is reflected in a high unit direct (capital) cost, UDC($/kWe), and a high cost of electricity, COE(mills/kWeh). Estimates of these costs reflect uncertainties both in the level of physical performance required of the plasma and in the cost of individual FPC components that support that plasma. Uncertainties of ~ 20-25% in UDC have been estimated, with failure to achieve the design net power, plasma power density, neutron wall loading, and materials performance dramatically influencing UDC and COE;[19] depending on the plant availability factor, p_f, the uncertainty in COE can equal or exceed the uncertainty associated with the UDC. Both UDC and COE, however, remain as meaningful figures-of-merit by which to intercompare fusion concepts as well as comparing fusion with alternative energy sources.

A nuclear power plant can be divided into the Reactor Plant Equipment (RPE, i.e., the FPC, primary heat transport, and support systems) and the Balance of Plant (BOP).[20-22] For fusion power plants using conventional BOPs, the RPE represented $\gtrsim$ 50% of the total direct cost, with the FPC requiring 25-30% of all direct expenditures; these percentages compare to ~ 30% and $\lesssim$ 5%, respectively, for identical accounts in a typical light-water fission reactor.[23] Table I summarizes the major costs[20-22] for a number of earlier fusion power-plant designs, as well as recently improved designs.[24-27] Both the magnitude of and sensitivity to the RPE and (particularly) the FPC costs, as well as required physics and materials performance, point to a key area where the economic prospects of fusion can be increased and the associated time and risks required for commercialization can be decreased: increased FPC power density and decrease FPC size. Increased MPD, however, will have implications for safety,[29] environmental impact, plasma performance,

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*This work was supported under the auspices of USDOE, Office of Fusion Energy

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	UWMAK-I[1,19]	STARFIRE[4]	MARS[10]	CRFPR[25,26]	ATR/ST[24]	CSR[27]	PRV[21]
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	0.10	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	4.68	~5.-6.(c)
23.	Turbine Plant Equipment	15.01	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	0.88	2.37	1.40	3.76	2.82	4.28	4.67
26.	Special Materials	2.65	0.014	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.[28]

(b) Based on 1966 $/kWe and 67 mills/kWeh in 1983 dollars; factor of 1.21 converts back to common-base 1980 costs.[28]

(c) Not explicitely reported in Ref. 23, but the ~ 1000-tonne pressure vessel (including heads) costed at ~ 50 $/kg would give the listed value. Reference 23 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.[28]

development cost and flexibility, as well as end-product cost (i.e., UDC and COE).

For the geometrically optimal case, MPD can be increased by increasing the plasma power density, MPD $\propto I_w/a \propto \beta^2 B^4$, where a(m) is the plasma radius, I_w(MW/m^2) is the neutron wall loading, B is the magnetic field, and β is the efficiency of magnetic-field utilization. Increasing MPD by this route requires increased β, but increased β will either increase the recirculating power if resistive coils are used or increase the magnet cost for either superconducting or resistive-coil FPCs, ultimately increasing the unit FPC costs ($/kg). These tradeoffs, along with others to be mentioned, must be examined in the context of 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, $\chi_E = a^2/4\tau_E$ in plasmas of smaller dimensions (total fusion power, $P_F \propto \chi_E R_T/a$ for $n\tau_E T \propto \beta B^2 a/\chi_E$ 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 MPC can impact costs in other areas, listed 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 walls, limiters) and bulk-heating (blankets) coolants, decreasing thermal-conversion efficiency, η_{TH}, and adding to FPC, RPE, and BOP unit costs.

- Already noted was the possibility for increased recirculating power fraction, ε, if thin blankets and/or resistive coils are utilized to increase MPD; the tradeoff associated with the FPC versus ε tradeoff is strongly dependent upon concept (Sec. III.). 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 following potential improvements beyond the reduction of direct cost:

- Increased FPC operational flexibility related to single- (or fewer-) piece maintenance of the reactor torus resulting in an: ability to sustain and recover from significant FPC breakdowns; ability to conduct significant testing on a fully-assembled FPC prior to nuclear service; 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

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

B. Utility-Based Issues. In addition to capital and life-cycle energy cost, the attractiveness of a new energy source also depends on construction lead-time and financial risks. If a new plant were available to the utility at low overall cost, substitution of new capacity for aged and uneconomic units would be encouraged; this new capacity would create forces to decrease the cost of energy, increasing both demand and the capacity to fulfill it. On the other hand, if large capital outlays combine with long lead-time, as is the case presently in the U.S., the utility will minimize financial risks by constructing short-lead-time, low-capacity ($\lesssim$ 300 MWe) plants, or more likely emphasize conservation, better load-management, extension of existing (aged) plant life, and use of short-term, high-fuel-cost options; in the U.S., these fuel costs are passed to the consumer through the rate base, unlike the time-related costs of delayed construction that directly impact the utility. The optimal size of a power plant from the utility perspective depends largely on the utility structure, with incremental supplies totaling not more than 10% of the total grid being desirable. The appeal of the fusion reactor, like that of fission today,[30] is expected to be sensitive to properties of the reactor such as optimal unit capacity, construction lead-time, plant reliability, and risks of long-term outages.

These utility-based issues strongly, but less-quantitatively, will shape the direction for improved fusion systems. The present trend in the U.S. towards small, short-lead-time power plants may be short-termed, but nevertheless this trend shapes a window for fusion that may be difficult to meet by past conceptual designs.[1-10] 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.

III. SPECIFIC APPROACHES FOR IMPROVEMENT

The main classes of magnetic confinement systems presently under study are shown in Fig. 1.; systems supporting large plasma currents are positioned on the left and those containing little or no plasma current being are positioned on the right. The latter systems are dominated by externally imposed axial or toroidal magnetic fields and, therefore, generally require large superconducting coils. Confinement systems located on the left support more of the plasma pressure by internal plasma currents, are to varying degrees poloidal-field dominated (PFD), and have reduced requirements for externally imposed magnetic fields; the PFD concepts that can utilize resistive coils require minimal blanket/shield thicknesses compared to superconducting

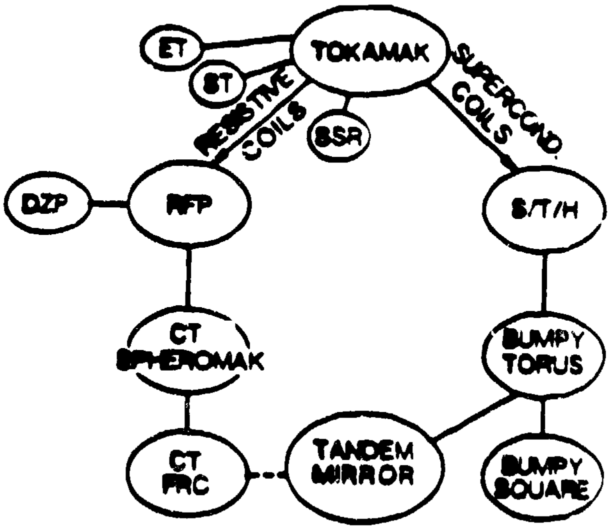

Fig. 1. Options for magnetic fusion. The higher-beta options for the tokamak include the spherical torus, ST[24,31]; the elongated torus, ET[32]; and operation in the second stability region, SSR.[33] The stellarator, torsatron, and heliotron systems are grouped as S/T/H.[7,8,34,35] As for the S/T/H, the bumpy torus[9] can be viewed in terms of plasma confinement on drift surfaces, this usually large system projecting compactness when formed into a square or high-order polyhedron.[36] The reversed-field pinch, RFP[25,26] is the first significant step away from the standard tokamak as a PFD system. The Dense Z-Pinch, DZP,[37] and compact torid (CT) spheromak[27] 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[10,39] embodies characteristics of both FRCs, S/T/Hs, and bumpy tori/squares, including the use of high-field superconducting and resistive coils, drift surfaces, energetic electron rings, and linear central geometry.

systems, and a considerable reduction in the FPC mass and cost is envisaged. The prognoses for improved reactors given herein is based on the RFP, spheromak, and the ST tokamak. Each concept is briefly described in the following sections, with Table II summarizing key reactor parameters. The dependence of COE(constant 1986 dollars) on MPD, neutron wall loading, and net electric power is given for each concept on Fig. 2.

A. Reversed-Field Pinch (RFP). The RFP is emerging as an attractive reactor concept because of encouraging physics results[40,41] and because of inherent properties that promise compact, high-power-density reactors.[25,26] As for the tokamak, the poloidal field, B_θ, is generated by toroidal plasma currents, I_ϕ, but the toroidal field, B_ϕ, within the plasma is comparable to B_θ and decreases through zero to a small negative value (hence, the name RFP) outside the plasma. The RFP engineering features, therefore, are dominated by the need to generate and sustain large poloidal fields, which decrease inversely with distance from the plasma. The resulting high-beta plasma is particularly amenable to confinement by low-field copper-alloy coils that can be separated from the plasma by the minimum thickness (0.5-0.7 m) required for a blanket to breed tritium and to recover the fusion energy efficiently (> 99%); the absence of thick shields required of superconductors considerably reduces the mass of both coil and blanket/shield systems, projecting 1,000-2,000 tonne FPCs rather than 20,000-30,000 tonne units envisaged for superconducting reactors of comparable power output.[4,10] In addition to operating with plasma current densities that are sufficient for ohmic heating the plasma to ignition, considerably simplifying an otherwise major complexity for fusion,

TABLE II
PARAMETER SUMMARY OF
RECENT RESISTIVE-COIL REACTOR DESIGNS PERFORMED AT LOS ALAMOS

	CRFPR[25]		ATR/ST[24]	CSR[27]
	CRFPR(20)	CRFPR(5)		
Net electric power, P_E(MWe)	1000.	1000.	1000.	1000.
Plasma minor dimensions, a/b(m)	0.71	1.42	1.50/4.50	1.12/3.72
Plasma major toroidal radius, R_T(m)	3.90	7.60	2.70	1.89
Aspect ratio, A = R/a	5.5	5.5	1.8	
Plasma volume, V_p(m³)	37.81	302.5	358.	105.2
Average plasma density, n(10^{20}/m³)	6.55	2.3	1.63	2.3
Plasma temperature, T(keV)	10.	10.	15.	20.
Plasma energy, W_p(GJ)	0.12	0.34	0.43	0.23
Field energy, W_B(GJ)	1.7	~5.	16.	1.5
Total thermal power, P_{TH}(MWt)	3,472.	3,609.	3,710.	3,41[illegible]
Recirculating power fraction, $1/Q_E$	0.20	0.22	0.25	0.21
Thermal conversion efficiency, η_{TH}	0.36	0.36	0.36	0.36
Net plant efficiency, $\eta_p = \eta_{TH}(1 - 1/Q_E)$	0.29	0.28	0.27	0.28
Neutron first-wall loading, I_w(MW/m²)	19.0	5.0	5.87	19.8
Plasma power density, P_F/V_p(MW/m³)	70.4	9.6	8.5	26.0
Average beta, β	0.13	0.13	0.291	0.10
Field at plasma, B_θ(T)[(a)]	5.2	3.0	4.77(2.67)	5.0
Field at coil, B_c(T)	3.0-4.0	2.5-3.0	8.0	2.6
Plasma thermal diffusivity, χ_E(m²/s)	0.41	0.54	0.72	0.73
Plasma current, I_ϕ(MA)	18.4	21.6	46.2	47.3
Plasma current density, j_ϕ(MA/m²)	11.6	3.4	2.2	4.3
FPC volume, V_{FPC}(m²)	359.	1,042.	2,120.	321.
FPC mass, M_{FPC}(tonne)	1,117.	~2,000.	6,492.	820.
FPC power density, P_{TH}/V_{FPC}(MWt/m³)	9.7	3.5	1.8	10.7
Mass power density, $1000P_E/M_{FPC}$(kWe/tonne)	895.	~500.	154.	1,200.
FPC unit cost ($/kg)	45.	42.	45.	TBD

(a)Values in parentheses are on-axis vacuum fields, values for CRFPR and CSR correspond to plasma edge, outboard equatorial plane.

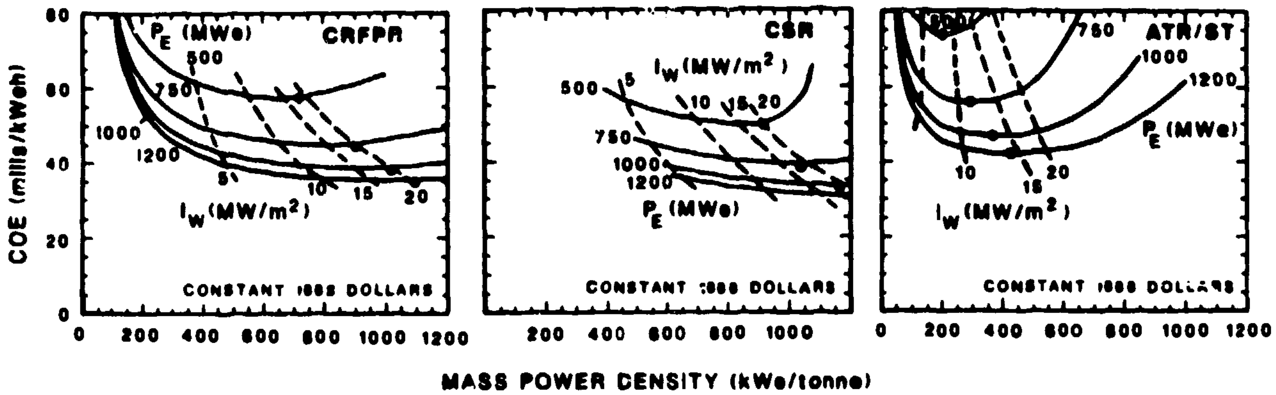

Fig. 2. Dependence of reactor cost on FPC mass power density, neutron wall loading, and net electric power for the RFP, Spheromak (CSR) and spherical torus (ST) reactors.

the close coupling of toroidal and poloidal currents (fields) in the near-minimum-energy RFP plasma[42] promises a unique means to rectify externally applied voltage oscillations and to drive the plasma current with no net change in the poloidal flux linking the torus; the very mechanism that sustains the $q \equiv (B_\phi/B_\theta)(a/R_T) << 1$ RFP configuration promises a means for low-frequency, non-intrusive current drive.[43] Furthermore, sustainment through the dynamo effect can be used to ramp slowly the toroidal current and to create internal toroidal flux. Given the ability to form slowly and then to sustain the RFP configuration, the transport scaling of these high-beta, ohmically heated discharges to the reactor regime become of paramount interest. The observed transport scaling predicts approaches to ignition and burn that emphasize increased plasma current and select plasma size primarily to meet constraints related to heat-transfer and plasma-wall interactions. Plasma performance and the technology of the plasma-wall interaction, however, become linked early into the development of the RFP.

B. Spheromak Compact Torus (CT). A CT is an axisymmetric torus that has no magnet coils, conducting walls, or vacuum surfaces linking the torus. The high-β (0.8-1.0) FRC requires only poloidal field and an elongated (prolate) form for stability. The spheromak is a CT with both B_θ and B_ϕ fields, and, like the RFP, both field components in the oblate spheromak are comparable in magnitude and are generally configured into a near-minimum-energy state.[42] Spheromaks have been generated using magnetized co-axial plasma guns [CTX,[44] BETA-II[45]], combined fast-pulsed Z- and θ-pinch techniques (PS-1),[46] and electrodeless flux-core formation techniques (S-1).[47] Reactor projections have been made for spheromaks formed by flux-core[48] and magnetized-gun[27] techniques.

In addition to the attributes of strong ohmic heating, high beta, and the efficient use of resistive (equilibrium) coils to give a high MPD, the simply connected CT magnetic geometry further reduces the economic impact of the FPC. Formation techniques based on a magnetized co-axial electrode also promise an exo-reactor divertor for impurity control as well as the proper arrangement of electrodes to sustain the configuration with an externally applied dc voltage; dc current drive through electrodes immersed in the plasma scrapeoff may be possible. Hence, toroidal flux emerging from the magnetized-gun electrodes links a small fraction of poloidal flux at the outer flux surfaces, and linked poloidal/toroidal magnetic flux is injected at a rate required to sustain the plasma against resistive decay of the magnetic configuration as well as supplying power losses incurred in the divertor and the edge-plasma regions. Experimental evidence has been reported for such sustainment over ten magnetic-energy decay times.[44] The development of cleaner and more energy-efficient electrode systems, along with improved confinement, represents key areas of research for the spheromak.

C. Spherical Torus (ST) Tokamak. The plasma performance for the tokamak as measured by χ_E, β, and current drive, generally depends strongly on plasma shape (e.g., aspect ratio, $1/\varepsilon = R_T/a$, elongation, κ, triangularity, and indentation) and current profile. For a given value of $q \geq 2$-3, critical beta limits increase with ε or I_ϕ, χ_E tends also to increase with I_ϕ, but high-frequency current drive expectedly becomes more power intensive at high values of I_ϕ. Coupled with the goal to reduce FPC size and cost by reducing the plasma major radius, the ST concept has emerged[31] with $1/\varepsilon = 1.5$-2.0, $I_\phi = 15$-30 MA, $q \simeq 2.5$, and $\beta > 0.2$. The ST reactor embodiment[24] requires all structure except the toroidal-field-coil return conductor to be eliminated from the region inboard of the plasma. Conventional tokamak equilibrium considerations cause a natural plasma elongation of $\kappa = 1.5$-2.0 for these low-aspect-ratio systems, and, although $q \simeq 2.5$ on average, B_θ can be comparable to B_ϕ at the plasma outboard side; high-beta plasmas with reduced toroidal fields result. Significant paramagnetism is also predicted for the equilibrium ST configuration , wherein the on-axis toroidal field can exceed the vacuum field by a factor of ~ 2. A tokamak configuration results that in shape outwardly resembles that of a spheromak with a hard-core conductor, exhibits a paramagnetism like that more strongly operative in RFPs and spheromaks, but is stablized according to traditional tokamak lore ($q > 2$-3). A non-inductive means is needed both to initiate and to drive the large toroidal current; while high-frequency waves may drive current in low-density plasma, the strong paramagnetism makes tempting the postulate that oscillating-field current drive[43] may be applicable to the ST tokamak as well. The ST concept remains to be tested experimentally.[31]

IV. SUMMARY AND CONCLUSIONS

When the projection of power and utility needs, safety and environment issues, and the general cost and time scale for the development of fusion are combined with minimum capital and energy costs needed for the penetration of a future energy market, the direction for improved fusion concepts is determined by complex and other opposing tradeoffs. Comparisons of past fusion reactor projections with those for competitive energy sources, however, show the need to reduce the size and cost of the FPC and associated RPE. Recognizing other constraints, the main thrust of most recent fusion reactor studies has been to increase the reactor MPD. The predictions of competitive fusion for MPD $\geq$ 100-200 kWe/tonne by generic fusion-reactor studies[15] are in line with this trend of improved economics in the sequence: thermal solar → UWMAK-I[1] → STARFIRE[4]/MARS[10] → GENEROMAK[15] → (MINIMARS,[39] ATR/ST,[24] RFP,[25] CSR,[27] other). The concept of MPD is valuable in tracing this improvement as well as the increased physics goals thereby represented. A long list of issues other than MPD, however, enter into the quest for economic fusion. The purpose of fusion-reactor conceptual design studies is to bring these other factors into the overall evaluation of fusion. The MPD, however, remains as one important figure of merit by which to monitor that evaluation.[18]

A number of options exist significantly improving the prospects for commercial fusion power based on the principal tokamak as well as other concepts. 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. Although the tokamak physics database is better developed than that for PFD systems like the RFP or spheromak, the degree to which these advanced tokamaks must extrapolate from that database is not unlike that for the other approaches. Recent advances in these other concepts have been impressive, and the promise is great for development paths that alter considerably the previously assumed trend of ever-escalating device size and cost. A less costly but bolder and more flexible development path to commercial fusion is anticipated for both these PFD systems as well as appropriately tailored variants of the tokamak. The direction for improved fusion systems is multi-faceted, with increased MPD being one of a number of important approaches. The progress represented on the design evolution depicted on Table II, provide a positive indication that fusion is on the right track and ultimately will lead to an economic and environmentally attractive source of long-term energy.

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