Simplified Fusion Power Plant Costing: A General Prognosis and Call for "New Think"

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Abstract

A top-level costing model is developed and used to project the cost of electricity (*COE*) (in mills per kilowatt-hour) expected from conceptual fusion power plants. Application is restricted to magnetic fusion energy (*MFE*) concepts. These costs are estimated parametrically in terms of the mass of the fusion-power-core (*FPC*) heater, the power required to sustain a reacting deuterium-tritium plasma, the heat transport/transfer system that delivers the fusion power to the balance of plant (*BOP*), and the *BOP* needed to convert the fusion heat to electrical power. Although the highly integrated (simplified) cost-estimating relationships (*CERs*) used to express *COE* in terms of *FPC* mass power density (*MPD*) [in kilowatt(electric) per ton] and the engineering gain Q_E (inverse of fraction of gross electric power recirculated to the fusion power plant) apply primarily to *MFE* approaches to fusion power, the costing gauge that results is generally independent of confinement scheme. Unlike other analyses, the approach used here does not require a plasma model for evaluation; this costing gauge simply evaluates a financial model that expresses the *COE* (or unit direct cost [in dollars per watt(electric)]) in terms of *MPD*, Q_E, and a minimum number of top-level (e.g., highly integrated) unit costs or *CERs*. The nonlinear scalings and connectivities between physics, engineering, and financial models (including credits for unique safety features and licensing advantages) must be determined by appropriate (generic or concept-specific) systems models. Results from concept-specific studies are used to assess the practicality of achieving the required combination of physics and engineering needed to assure competitive *COEs* vis-a-vis appropriate combinations of *MPD* and Q_E for the unit costs and *CERs* used. Although highly simplified and intended primarily to provide an easily used economic gauge for *MFE* power plants, a comparison of the predictions of this gauge with the results of modern, detailed, and cost optimized studies of a number of *MFE* approaches indicates the need for change in the direction of the current fusion program and the thinking that is maintaining that direction. Improved economic and operational prospects for *MFE* can be expressed in terms of lineage that begins with higher *MPD* tokamak configurations embodied in the second-stability and spherical torus regimes and moves toward configurations with increased poloidal field domination, reduced externally generated magnetic fields, and further increases in *MPD*. This increase, however, must be attained while maintaining both a safe and environmentally attractive configuration and economic Q_E values. Although scientific progress along a linear extension of the current tokamak database is warranted and necessary, this progress should not occur at the expense of ideas that might lead to an economically and environmentally attractive *MFE* power source that would eventually be pulled into the energy market because of significant cost differentials rather than being pushed into that market by technology advances that may not be recognized as leading to a power plant that is either attractive or needed.

1. Introduction

Although fusion fuels are generally abundant and inexpensive, the fusion reaction of light elements like hydrogen requires that the internuclear Coulomb barrier be overcome before intranuclear forces come into play, nuclear fusion occurs, and energy associated with the resulting mass deficit is released. Since significant energy must be invested to induce an even greater release of fusion energy, a nuclear fusion power plant, at the most rudimentary level, can be described as an energy (power) amplifier. In even more rudimentary terms, the capital and operating costs associated with engineering systems needed to deliver power to induce, sustain, and contain the fusion reaction and to collect and convert the fusion energy release to useful forms must be less by a (financially) acceptable margin than the economic value of the net energy generated. Furthermore, this energy and economic balance must be achieved in a system that exhibits attractive operational, environmental, and safety features. Finally, given the scientific and technological successes needed to assure these conditions, the resulting system must exhibit adequate pull from a market that is both competitive and conservative in its choices of energy generation systems.

Although the scientific progress required to project attractive fusion power plants, in the sense described above, has over the last two decades been enormous;[1] significant advances are required before a steady-state deuterium-tritium (DT) plasma of power plant quality can be achieved. Furthermore, the engineering and materials needed to exploit such a plasma for commercial power production will require decades of development. Although serious designs of the next physics experiments are currently being developed,[2,3] the commercial demonstration (DEMO) resides for the main concept being pursued at least three decades into the future, with an additional two decades as a minimum being required to assess whether commercialization of this fusion approach is deemed economically and environmentally wise; commercial fusion power according to current planning would be available at the earliest no sooner than the year 2050.

The world programs in magnetic fusion energy (*MFE*) research have largely been pulled by scientific successes associated with the tokamak confinement scheme, albeit, many of these significant scientific accomplishments along the road to achieving commercially interesting plasmas have been the result of engineering advances in magnet, plasma-heating, and vacuum technologies. Because of the growing cost of *MFE* research as devices become larger in size, magnetic field, and power consumption; the world fusion program over the last decade has focused primarily on the tokamak confinement scheme, with the greater than $6 billion International Thermonuclear Experimental Reactor[3] (ITER) assuring an almost complete focus on this single confinement system. This focus is occurring when current projections[4,5,6] for a viable commercial tokamak-based commercial power plant are at best uncertain.[7] While the physics of burning DT plasma to be studied in ITER will be of interest to the commercial power plant, in configuration, (pulsed) operational mode, power density, fusion-power-core (*FPC*) materials, and most of the plasma-supporting technologies, ITER has marginal relevance to an attractive commercial product based on the tokamak. Between the dubious commercial reactor projections and the reactor-irrelevant ITER is the DEMO device(s) that must show the way from ITER to a commercial product that, as described earlier, must attract strong market pull; a serious study of this DEMO device is being launched.[8]

The engineering; physics; materials; Environmental, Safety, and Health (*ES&H*); and economic projections associated with devices, like DEMO or the commercial power plant, having a >40-year time horizon are at best uncertain. These uncertainties are driven largely by the scientific and technological extrapolations associated with the wide range of modeling relationships that form the core of complex, cost-based systems codes used to guide the respective conceptual design studies.[4-8] These uncertainties, which add to the usual uncertainties associated with any long-term projection (i.e., resources, energy supply versus demand, and energy production structure of the future), are minimized by use of multidisciplinary teams who in turn apply the most current experimental scalings and theoretical models.[4-6] The connectivity of physics, engineering, *ES&H*, and economics that is quantified by means of a comprehensive systems optimization model, however, can lead to related trade-offs and constraints that may be obscured by the complexities of the (tokamak specific) problem being studied.

With the goal of generating a broader, more generic insight into the elements that may limit the economic viability of an *MFE* commercial power plant, a simplified financial model has been developed and evaluated. This costing model treats the *MFE* reactor as a power amplifier with engineering gain $Q_E = P_{ET}/P_c$ and fusion heater *FPC* mass power density (*MPD*) [in kilowatt(electric) per ton] = P_E/M_{FPC}, where the gross, net, and recirculating electrical powers are P_{ET}, $P_E = P_{ET}(1 - 1/Q_E)$, and $P_c = P_{ET}/Q_E$, respectively, and M_{FPC} is the *FPC* mass (i.e., plasma chamber, blanket, shield, reflector, divertors, plasma heaters, magnets, and primary support structure) (see Nomenclature). The main capital costs are embodied in:

(a) the *FPC*, expressed here on a mass basis

(b) the plasma and overall plant-power requirements, as related to P_c

(c) the primary heat transport/transfer system that connects the *FPC* to the balance of plant (*BOP*)

(d) the *BOP*, scaled in terms of either P_{ET} or $P_{TH} = P_{ET}/\eta_{TH}$, where η_{TH} is a nominal thermal-to-electric conversion efficiency.

This model expresses the economic potential of *MFE* in terms of a cost of electricity (*COE*) (in mills per kilowatt-hour) in an *MPD* versus Q_E phase-space. The model treats the plasma confinement system as a generic entity, with the choice of unit costs and associated cost-estimating relationships (*CERs*) generally reflecting the needs of an *MFE*-based electrical generation plant. A physics / engineering constrained trajectory in this *MPD* - Q_E - *COE* phase space must be charted by a separate, integrated (but simplified) plasma model [9,10,11,12] or use the results of separate, detailed systems models developed for the tokamak fusion reactor [4-7] or other *MFE* confinement schemes.[13,14,15,16,17]

The model reported herein is intended as a gauge with which to indicate directions for competitive *MFE* power plants; it is not a conceptual design tool per se in that unlike either detailed design codes [4-7,18] or simplified variants thereof; [12] the cost-gauge approach is not based directly on plasma physics and/or engineering models; the complexities, interactions, nonlinearities, and connectivities of both are embedded in the highly integrated *MPD* and Q_E parameters and in the trade-offs between these two key parameters in determining the minimum electric generation cost *COE*. While such a simplification precludes this approach from breaking new ground per se, when calibrated and used to compare the results from complete systems models: [4-7, 9-12, 14, 18] the cost gauge model can shed new light on old ground.

The evaluation of cost trade-offs on the basis of a model that lumps all nonlinear interactions between physics, engineering, materials, maintenance schemes (plant availability), etc., into two highly integrated parameters (*MPD* and Q_E and evaluates unit costs like *COE* on the basis of highly integrated unit costs or *CERs* associated with *MPD* and Q_E raises questions about the validity and/or utility of such an approach. Careful selection of the unit costs and/or *CERs* on the basis of predictions from detailed studies, however, combines with the overwhelming import and cost connection of *MPD* and Q_E for many of the massive, relatively inefficient *MFE* power plant concepts being considered to lend credibility in using absolute costs and taking bottom-line results with as much seriousness as given those resulting from complete systems models. Major economic uncertainties related to the plant availability p_f are eliminated in the current analysis by assumption, as this issue is generally treated in the detailed systems studies.[4-7] Additionally, parametric variations can resolve the impact of uncertainties in both p_f and the highly condensed unit costs and/or *CERs* used herein, and such parametric studies will be more meaningful if absolute rather than normalized costs are used.

After briefly describing the generic *MFE* costing model in Section 2, parametric results are given in Section 3, where comparisons are made with the References 4 through 7, 15, and 13 through 17 studies of conceptual tokamak, reversed-field pinch (RFP), spheromak, and stellarator reactors. Section 4 gives a brief discussion leading to the conclusion that higher *MPD* values while maintaining $Q_E \geq 6$ are essential elements for *MFE* power with a future market pull (e.g., cost differential, operational simplification, eased licensing, and enhanced *ES&H* characteristics sufficient for a given concept to be pulled into the marketplace instead of being pushed by ever-increased technological advances alone). Since the current embodiment of the tokamak, or reasonable extrapolations therefrom, does not exhibit these features, a re-evaluation of the direction and emphasis of the present *MFE* program is warranted. The concern that the present direction of a program based totally on the conventional tokamak is leading to an unattractive commercial end product has been expressed elsewhere [7, 19, 20]; the current analysis again emphasizes the need for increased study and research on less-developed confinement concepts that might offer a more economic and operationally satisfactory end product while capitalizing on the significant scientific progress made to date by the tokamak research and development program.

Model

2.A. Overview

Figure 1 depicts the essential elements of an *MFE* power plant and gives a functional breakdown of the key subsystems: the *FPC* heat source, the plasma support systems, the primary heat transport (*PHT*) , and the electric conversion area (*ECA*) comprised primarily of turbine plant equipment (*TPE*), electric plant equipment (*EPE*), and miscellaneous plant equipment (*MPE*). With the inclusion of land and land rights (*LAND*) along with structures and site facilities (*SITE*), these top-level plant components comprise the main cost-accounting structure in a costing system adopted from one developed to assess (early) fission power plants[21] and more recently used to compare a range of advanced fission and fossil energy sources.[22,23] This cost-breakdown structure, as applied to the recently completed Advanced Reactor Innovation and Evaluation Study [4-7] (ARIES) tokamak power plant conceptual designs, is summarized in Table 1.

Detailed physics and engineering models are coupled to *CERs* in a comprehensive parametric systems model[4-6] to optimize design points and to examine a wide range of cost trade-offs by using the cost accounting structure summarized in Table 1. Even though the parametric evaluation extends only down to the second level of costing indicated on Table 2, this evaluation requires detailed plasma (burn, equilibrium, and stability), engineering (magnetics, divertors, blanket/shield neutronics, and thermal-hydraulics mechanics), and materials (compatibility, fabricability, safety, and waste) models to be evaluated under appropriately constrained conditions. These systems constraints (e.g., plasma stability and transport, peak power densities and heat/particle fluxes, maximum coil fields and current densities, maximum thermal and mechanical stresses in key components, and degree of *FPC* openness as dictated by maintenance schemes and allowable magnetic field ripple) then result in optimal costs (*COE*), as dictated indirectly by a balance between the size (mass) of key components and the power needed to sustain the plasma configuration (e.g., plasma current drive, profile control, and active feedback stabilization). These indirect economic balances are driven by constrained physics and engineering and often lead to optimal system characteristics that are nonintuitive.

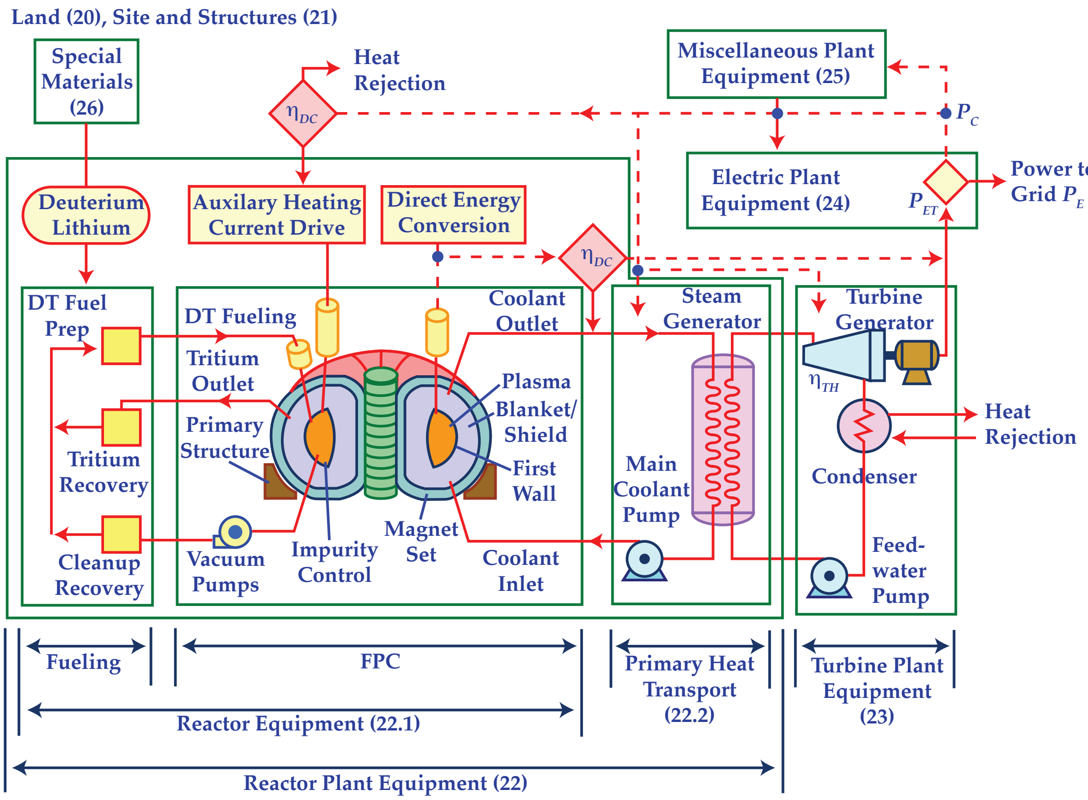

Figure 1 — Fusion power plant layout showing essential systems functionally organized into major cost-account blocks (Table 1).

Ambiguity is added to the problem when safety-related cost credits are awarded certain design choices that otherwise would be more expensive (e.g., lower power density or more expensive material of construction). Finally, when an optimal system emerges to be noncompetitive, as in the case of those tokamak embodiments examined by ARIES (Reference 7), the means by which a more economic system can be obtained is limited and sometimes obscured by these realities of modeling a real system.

Although the credibility of any conceptual fusion power plant design is recognized to rest with the need and ability to couple systematically key physics, engineering, *ES&H*, and costing constraints, the current analysis nevertheless inverts the design-optimization process by evaluating a highly compressed version of Table 1 under the assumption that key costs can be condensed to and expressed as:

(a) A unit mass of *FPC*

(b) A unit power delivered to the *FPC* for plasma sustenance

(c) A unit of thermal power transport/transfer from the *FPC* to the *BOP* for conversion to electricity in the *BOP*

(d) A unit of either thermal or electrical power delivered to an appropriate *BOP* component.

In this way, it is shown that the *COE*, through a small number of well-calibrated assumptions on plant operation and maintenance (*O&M*) and decontamination and decommissioning (*D&D*) costs based on more detailed (concept-specific) studies,[4-7,24] can be expressed in terms of the *FPC MPD* and the engineering gain Q_E. The procedure for fusion power plant optimization is thereby reversed by requiring the plasma configuration and sustainment system to fit an economic region of *MPD* versus Q_E phase-space. Furthermore, the degree to which a specific (optimal) confinement approach (e.g., one of the ARIES concepts) falls short of economic competitiveness with respect to competing energy sources,[7] as well as the potential of other advanced tokamak or non-tokamak approaches for improved economics is quantitatively displayed. The main merit of this inverted evaluation is as a gauge with which to evaluate cost competitiveness on a comparative basis. The approach gives no other information than providing this measure of cost competitiveness; it remains for detailed, cost-based systems models[4-6, 14, 18, 25] to assess the physics, engineering, and operational feasibility of a given *MFE* concept to meet the gauge suggested herein. After describing and evaluating the simplified, *MFE*-related costing algorithm (i.e., through the compressed *CERs* assumed), the results of specific cost-optimized, physics/engineering-constrained design points are intercompared on this costing gauge. A trajectory to more economic regions of the *MPD* - Q_E gauge space can be charted only by relaxing key physics and/or engineering constraints imposed during a given conceptual design study, since these designs as reported are already at or near a position of minimum cost (maximum *MPD* and maximum Q_E) for the constraints imposed; relaxation or circumvention of these physics and engineering constraints generally translates into a need for a "new think" at both physics and engineering levels.

2.B. Approach

The system complexity described by Figure 1 and Table 1 is reduced, while an acceptable level of accuracy needed for quantitative analyses is retained, by introducing the generic DT fusion plant power balance illustrated in Figure 2. As described earlier, the *FPC* is considered a power amplifier that converts the input heating (*HTG*) (and/or current drive) power P_{HTG} to DT fusion power $P_F = P_N + P_\alpha$. The neutron power P_N is multiplied by a factor M_N through exoergic nuclear reactions occurring in the tritium-breeding, heat-recovering blanket. The alpha-particle power P_α combines with P_{HTG} and is collected by the thermal conversion cycle in the form of plasma radiation or transport (e.g., conduction or convection) powers P_{RAD} or P_{TR}, respectively. With the plasma Q-value defined as $Q_p = P_F/P_{HTG}$, the thermal power delivered through the P_{HT} to the *BOP* for conversion to electrical power P_{ET} with overall efficiency η_{TH} is $P_{TH} = P_F(1/Q_p + 0.8M_N + 0.2)$. After recirculating the power P_{HTG}/η_{HTG} to sustain the plasma and the plant auxiliary power $P_{AUX} = f_{Aux}\, P_{ET}$, with $P_c = P_{HTG}/\ \eta_{HTG} + P_{AUX}$, the net electric power $P_E = P_{ET} - P_c$ is delivered for sale to the electrical grid to pay for capital and operating costs. The engineering gain for the system is defined as $Q_E = P_{ET}/P_c$, so the net plant efficiency is $\eta_p = \eta_{TH}\,(1 - 1/Q_E)$; the recirculating power fraction is $\varepsilon = 1/Q_E$.

Table 1A — Summary of Nuclear Cost-Accounting System[21,22] with ARIES Economic Parameters[4-7] Included as Examples

Account	Account Title	I	II	III	IV
20	Land and land rights (LAND) [a]	10.4	10.4	10.4	10.4
21	Structures and site (SITE)	245.2	366.4	333.4	245.3
22	Reactor plant equipment (RPE)	1683.4	1361.8	1356.6	1302.3
22.1.1	First wall, blanket, and reflector	104.5	53.8	8.6	86.7
22.1.2	Shield	515.7	366.4	196.7	406.7
22.1.3	Magnets	436.7	205.8	268.9	222.6
22.1.4	Supplemental heating systems (current drive)	155.2	194.3	529.2	175.7
22.1.5	Primary structure and support	71.4	35.3	50.5	36.5
22.1.6	Reactor vacuum systems	61.5	51.1	11.7	53.1
22.1.7	Power supply, switching, and energy storage	50	55.3	55.3	50
22.1.8	Impurity control	12.3	5.4	8.7	5.6
22.1.9	Direct energy conversion system [b]	N/A	N/A	N/A	N/A
22.1.10	Electron cyclotron resonance heating breakdown system	3.9	4.3	4.3	3.9
22.1	Reactor equipment	1411.3	971.7	1134	1040.9
22.2	Primary heat transport (PHT)	119.2	231.9	68.6	117.3
23	Turbine plant equipment (TPE)	254.5	279.8	323.3	249.3
24	Electric plant equipment (EPE)	101.4	109.5	115	100.1
25	Miscellaneous plant equipment (MPE)	54.7	55.5	58.8	53.8
26	Special materials	0.6	14.8	0.6	0.6

[a] Refer to Figure 1.

[b] Not applicable.

Table 1B — Summary of Nuclear Cost-Accounting System[21,22] with ARIES Economic Parameters[4-7] Included as Examples

Account	Account Title	I	II	III	IV
90	Total direct cost (TDC)	2350.5	2160.3	2198.5	1962.1
91	Construction services and equipment	265.6	259.2	263.8	221.7
92	Home office engineering and services	122.2	112.3	114.3	102
93	Field office engineering and services	122.2	129.6	131.9	102
94	Owner's costs	429.2	399.2	406.2	358.2
96	Project contingency	482.1	516.5	525.6	402.4
97	Interest during construction	623.1	590.9	601.4	520.1
98	Escalation during construction	0	0	0	0
99	Total capital cost	4395	4168.3	4241.9	3668.8
		Constant Dollars [$/W(electrical)]			
[90]	Unit direct cost (UDC)	2.35	2.16	2.2	1.96
[94]	Unit base cost	3.77	3.58	3.64	3.15
[99]	Unit total cost	4.4	4.17	4.24	3.67
		Constant Dollars (mill/kw•h)			
	Capital return	63.8	60.5	61.6	53.3
[40-47, 51]	Operations and maintenance (O&M)	7.5	9.2	9.2	7.5
[50]	First wall / blanket replacement	5	3.6	0.01	6.6
	Decontamination and decommissioning (D&D)	0.3	0.5	0.5	0.3
[02]	Fuel	0.03	0.03	17.5	0.03
	Level of safety assurance (LSA)	1	2	2	1
	Cost of electricity (COE)	76.6	73.8	88.8	67.7
	COE (LSA = 4)	101	84	99	90

Table 2A — Summary of Cost Model Input Parameters

Input	Value
Net electric power, P_E [MW(electrical)] [a]	1000
Plant availability factor, p_f	0.75
Fixed charge rate, *FCR* (1/yr)	0.086
Operating charges as fraction of capital, f_{OM} (1/yr)	0.04
Fuel charge as fraction of capital, *fFUL* (1/yr)	0
D&D charge as fraction of capital, f_{DD}	0.2
IDC as fraction of capital, f_{IDC}	0.96
Constant-dollar cost of money, X_o (1/yr)	0.05
Plant (economic) life, T_{LIF} (yr)	40
Capital recovery factor, *CRF* (X_o, T_{LIF}) (1/yr)	0.0583
FCR for *D&D*, FCR_{DD} (1/yr)	0.0017
Unit-cost ratio, *COE*/*UDC* [mill/kW•h per $/W(electrical)]	32.1
Blanket neutron multiplication, M_N	1.2
Thermal conversion efficiency, η_{TH}	0.4
Wall-plug plasma-heating efficiency, η_{HTG}	0.65
Auxiliary power fraction, f_{AUX}	0.03
Unit cost of *FPC*, UC_{FPC}, f_{AUX}	100
Unit cost of plasma heating, UC_{HTG} ($/W)	2
Unit cost of *SITE*, UC_{SITE} [$/W(electrical)]	0.3
Unit cost of *PHT*,[b] UC_{PHT} [$/W(thermal)]	$0.8/P_{TH}^{0.45}$

Table 2B — Summary of Cost Model Input Parameters

Input	Value
Unit cost of *TPE*, [b] UC_{TPE} [$/W(electrical)]	$0.67/P_{ET}^{0.16}$
Unit cost of *EPE*, [b] UC_{EPE} [$/W(electrical)]	$3.71/P_{ET}^{0.51}$
Unit cost of *MPE*, [b] UC_{MPE} [$/W(electrical)]	$0.87/P_{ET}^{0.41}$
Contingency factor for *FPC*, $CONT_{FPC}$	0.3
Contingency factor for *HTG*, $CONT_{HTG}$	0.2
Contingency factor for *PHT*, $CONT_{PHT}$	0.2
Contingency factor for *BOP*, $CONT_{BOP}$	0.15
Contingency factor for *SITE*, $CONT_{SITE}$	0.1

[a] Base-case value, parametrically varied over a 500- to 1000-MW(electric) range.

[b] Reference 26.

The power balance depicted in Figure 2 introduces one component of the parametric model needed to evaluate *COE* as a function of *MPD* and Q_E. The second part of the model development collapses the cost accounting structure described in Table 1 and Figure 1 into a condensed, more easily managed form while retaining an acceptable level of realism. Figure 3 illustrates this collapsed costing structure that retains the essential elements of the power balance shown in Figure 2. Referring to Table 1, Accounts 20 and 21 are combined into a SITE account, which is assumed to scale in cost linearly with the gross electric power; the unit cost is UC_{SITE}. Table 2 lists these unit costs along with the corresponding contingency factors $CONT_j$, which are subsystem-dependent factors used as a measure of uncertainty in achieving the projected installed cost. The reactor equipment Account 22.1, less the plasma heating/current drive and associated power supplies accounts, is assumed to represent the mass-related *FPC* costs; the corresponding unit cost is UC_{FPC} which is also listed along with the corresponding contingency factor in Table 2. The power required for plasma sustenance is casted in proportion to P_{HTG}/η_{HTG} and scales according to UC_{HTG} and the contingency factor $CONT_{HTG}$. The *PHT* system (Account 22.2) represents the main connection between the *FPC* and the *BOP*; the *PHT* cost is scaled according to UC_{PHT} and the contingency factor $CONT_{PHT}$. The combined *FPC* + *HTG* + *PHT* condensed accounts correspond to the reactor plant equipment (*RPE*) (Account 22) in the full accounting system (Table 1).

The assumption that the *FPC* cost scales linearly with the *FPC* mass is a weakness of the model. The treatment of the *FPC* power as a separate *HTG* category is an attempt to reduce the impact of this assumption. Nevertheless, some *FPC* components considered by a model with higher resolution[4-6, 25] would scale *FPC* subcomponent costs with power, power density, peak heat flux, area, and/or volume. This kind of detail is sacrificed by the current study in favor of a more flexible tool with which to gauge progress toward more economic fusion power plant designs.

The *BOP* is scaled as the sum of the *TPE* (Account 23), the *EPE* (Account 24) and the *MPE* (Account 25) accounts, as is listed in Table 2 along with the respective contingency factors. Unlike the *SITE*, *FPC*, and *HTG* accounts, which are assumed to scale linearly with capacity, the *PHT* and the *BOP* = *TPE* + *EPE* + *MPE* unit costs reflect on an economy of scale[26] not unlike that embedded in the more detailed cost-based systems models.[4-6, 25]

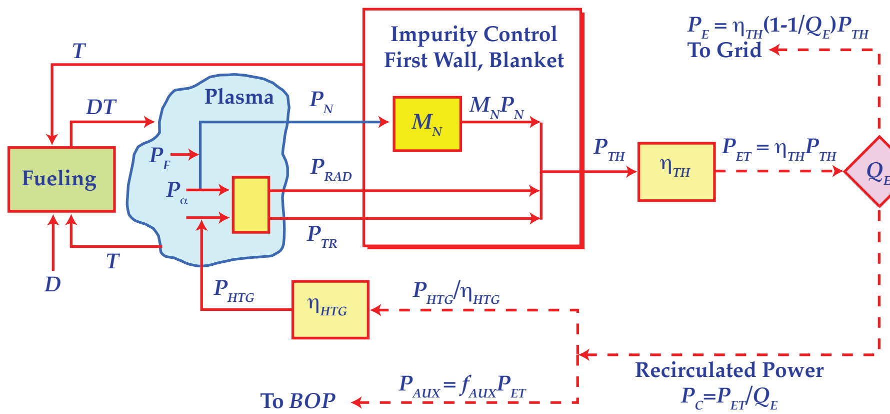

Figure 2 — Simplified energy flows used to model fusion power plant cost.

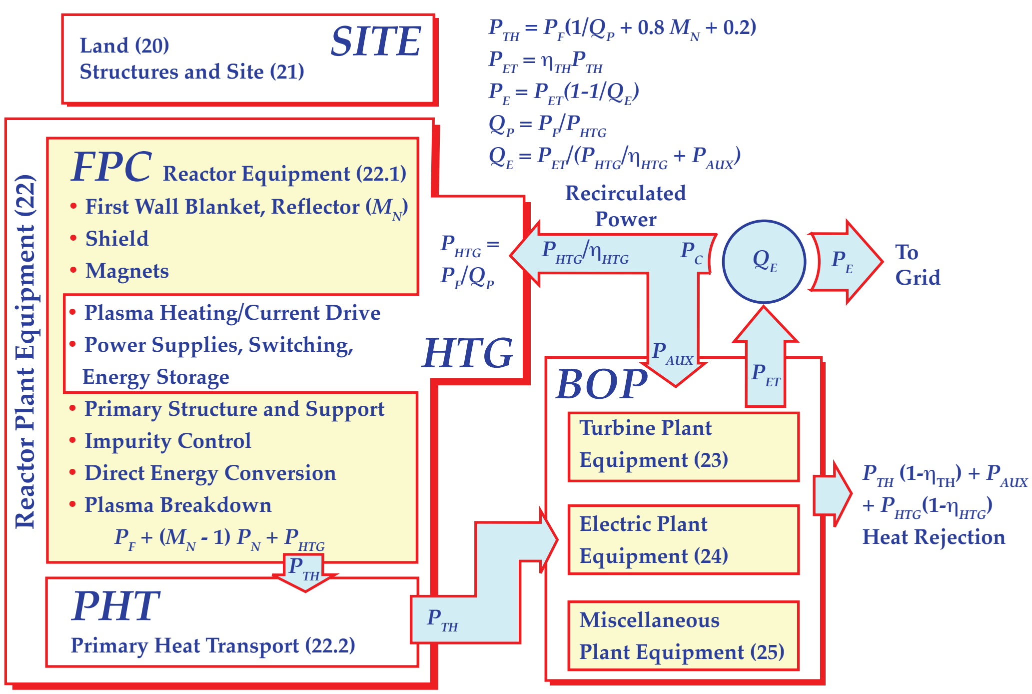

Figure 3 — Condensed fusion power plant costing model and associated power flows (Table 1).

Computation of the *COE* requires that the sum of all annual charges, $AC = FCR(1 + f_{IDC})TDC + OM + FUL + DD$, be divided by the net electric energy sold during a given year, $\sim p_f P_E = p_f(1 - 1/Q_E)P_{ET}$. In this expression, *FCR* is the fixed charge rate [in constant dollars (1/yr)] on the total direct cost (*TDC*) (in million dollars) (including individual contingency factors $CONT_j$), f_{IDC} is an indirect cost (*IDC*) factor that reflects Accounts 91 through 97 in Table 1, FUL(1/yr) is an annual fuel charge (expected to be nearly zero for DT-fueled fusion power plants), and DD(1/yr) is an annual escrow payment made to assure that a fraction f_{DD} of TDC is available for D&D operations at the end of the plant life T_{LIF}. If $CRF(X_o, T_{LIF})$ is the capital recovery factor[22] (1/yr) for a real cost of money X_o (i.e., corrected for inflation), $DD = FCR_{DD}\ TDC$, where $FCR_{DD} = f_{DD}CRF(X_o, T_{LIF})/(1 + X_o)^{**T_{LIF}}$ is an effective FCR for the *D&D* escrow payment.

Defining f_{OM}(1/yr) = OM/TDC, f_{FUL}(1/yr) = FUL/TDC, and the unit direct costs (UDC) [in dollars per watt (electric)] as $UDC = TDC/P_E$, the following expression for COE results:

$$COE = \frac{10^6}{8760}\frac{UDC}{p_f}[FCR(1+f_{IDC}) + f_{CM} + f_{FUL} + FCR_{DD}] \quad (1)$$

Maintaining the generic nature of this model is accomplished by including in the parameter f_{OM} the annual charge associated with first-wall and blanket replacement costs (similar to a fuel charge, but usually accounted separately in the detailed, concept-specific models.[4-6]

If the unit cost for the j'th subsystem is UC_j and the associated contingency factor is $CONT_j$, the TDC is given by:

$$TDC = \sum_{j=1}^{J} UC_j[M_j, P_j](1 + CONT_j) \quad (2)$$

where $[M_j, P_j]$ is either a mass- or power-related capacity appropriate for the subsystem in question. Inserting the specific values of UC_j, as listed in Table 2, into Eq. (2) and defining $UC_j^* = UC_j(1 + CONT_j)$ gives the following expression for UDC:

$$UDC = \frac{UC^*_{FPC}}{MPD} + \frac{1}{\eta_{TH}(1 - 1/Q_E)} \, x \left[\frac{UC^*_{HTG}}{\eta_{HTG}Q_pM} + UC^*_{PHT} + \eta_{TH}(UC^*_{BOP} + UC^*_{SITE})\right] \quad (3)$$

In this expression, $M = 1/Q_p + 0.8M_N + 0.2$, and the plasma Q-value Q_p is related to the engineering gain or Q-value Q_E by the following relationship (Figure 2):

$$\frac{1}{Q_E} = f_{AUX} + \frac{1}{\eta_{HTG}\eta_{TH}Q_pM} \quad (4)$$

The foregoing system of equations allows the dependence of MPD on Q_E to be examined parametrically in goal values of COE and net electric power P_E for the otherwise fixed economic parameters listed in Table 2. These parameters allow the ratio COE/UDC to be computed from Eq. (1) for subsequent use in parametric evaluations of MPD versus Q_E for a range of target or goal COE values. Specification of net electric power P_E allows the gross electric and total thermal powers P_{ET} and P_{TH}, respectively, to be determined for use in the appropriate *CERs*; for a given Q_E, Eq. (4) allows Q_p to be evaluated for use along with a specified COE in Eq. (3) to determine the corresponding MPD value. In this way, the MPD - Q_E trade-offs for a range of specified (goal) COE result. This economic gauge is then used to compare and assess results from detailed conceptual *MFE* reactor studies.

3. Results

The essential elements of the costing-gauge model are embodied in Equations (1) and (3) along with the parameters listed in Table 2. This set of expressions is evaluated parametrically in Figure 4. Figure 4 illustrates the trade-off between FPC costs incurred at low MPD and FPC-related recirculating power costs associated with low-Q_E operation. The MPD - Q_E - COE topology illustrated in Figure 4 is established largely by the parameters listed in Table 2 and the assumptions (accuracy) of highly integrated *CERs* that form the basis of this model, particularly with respect to FPC cost estimates. Generally, the costing gauge given in Figure 4 for the assumptions listed in Table 2 are optimistic, as is seen for the limiting case where $MPD \rightarrow \infty$ and Q_E approaches the limiting value of $1/f_{AUX} = 30$ (i.e., $Q_p \rightarrow \infty$). In this case, COE = 27 mill/kW• h, which, if increased by ~15 to 20% to account for a light water (fission) reactor (LWR) pressure vessel,[27] amounts to ~41 to 42 mill/ kW•h once a 10 mill/kW• h fuel charge is added; advanced fission systems are expected to be in the 45 to 48 mill/ kW• h range for the cost basis used herein.

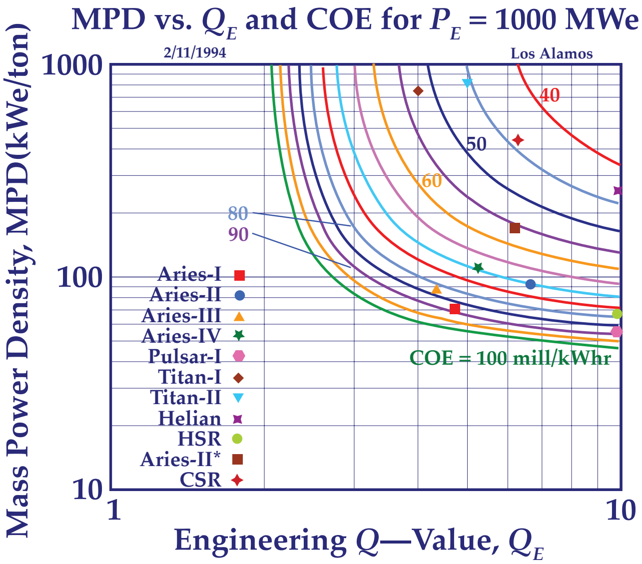

Figure 4 — Parametric dependence of *FPC MPD* on engineering gain and a range of *COE* values for a P_E = 1000 - MW(electric)(net) fusion power plant described by the parameters listed in Table 2. Optimized design points from a number of recent tokamak,[4-6] RFP (Reference 14), and stellerator,[16,17] reactor studies are also shown. All conceptual *MFE* power plant designs are based on a DT fuel with negligible fuel cycle costs, except ARIES-III, which is based on a D-^{3}He fuel, with the Lunar-^{3}He fuel supply contributing -20% ($1.5 million/kg) to the *COE* (References 5 and 7). The design points for ARIES and TITAN generally reside at or near the top of the minimum-*COE* crest in this *MPD* - Q_E gauge space, with movement to regions of reduced COE being possible (particularly for the ARIES designs) only by a significant relaxation in physics, engineering, and/or materials constraints.

As seen from Eq. (1) and Table 2, the ratio *COE*/*UOC* is determined primarily by debt-servicing requirements according to the following proportions:

$FCR(1 + f_{IDC})/f_{OM}/f_{FUL}/FCR_{DD}$ = 0.802 / 0.190 /0.000/ 0.008; based on the Table 2 parameters, the ratio *COE*/*UOC* equals 32.1 mill/kW• h per $/W(electric). This ratio establishes the Figure 4 topology, with Eq. (3) through the subsystem *CERs*, UC_j, determining the *MPO* Q_E - *COE* trade-offs that result. The partitioning of *FPC* and *RPE* = *FPC* + *HTG* + *PHT* direct costs (including individual subsystem contingencies) as a fraction of *TDC* are illustrated in Figures 5 and 6, respectively. In the case of *LWRs*, the fraction of *TDC* given over to the *FPC* equivalent (e.g., Account 22.1) and to the *RPE* (Account 22) amounts,to 15% (Reference 28)[28] and 30 to 34% (References 23 and 28), respectively; the *RPE* fraction of *TDC* for the lower power density gas-turbine modular high-temperature gas-cooled reactor,[29] however, ranges from 49% (steam or indirect cycle) to 56% (direct cycle).

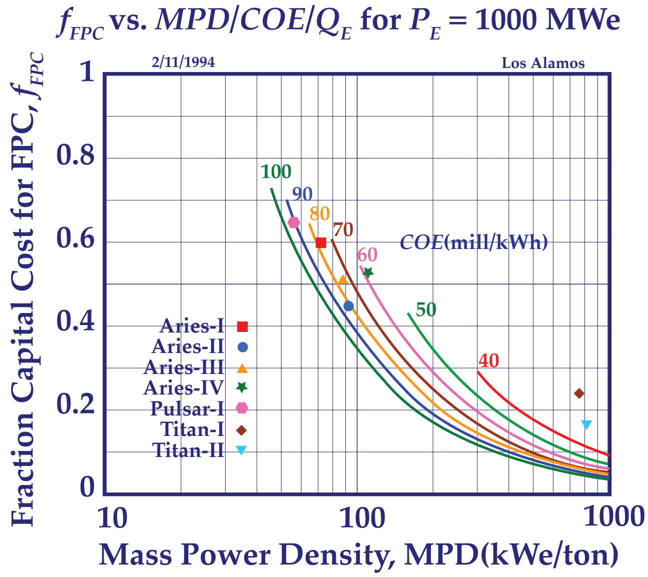

Figure 5 — Parametric dependence of fraction of *TDC* (including contingencies) allocated to the FPC (e.g., reactor equipment Account 22.1, Table 1) on *FPC MPD* and a range of *COE* values for a P_E = 1000 MW(electric)(net) fusion power plant described by the parameters listed in Table 2. Optimized design points from a number of recent tokamak[4-6] and *RFP* (Reference 14) reactor studies are also shown. The design points for ARIES and TITAN generally reside at or near the top of the minimum-*COE* well in this f_{FPC} - *MPD* gauge space, with movement to regions of reduced *COE* and/or f_{FPC} being possible (particularly for the ARIES designs) only by a significant relaxation in physics, engineering, and/or materials constraints.

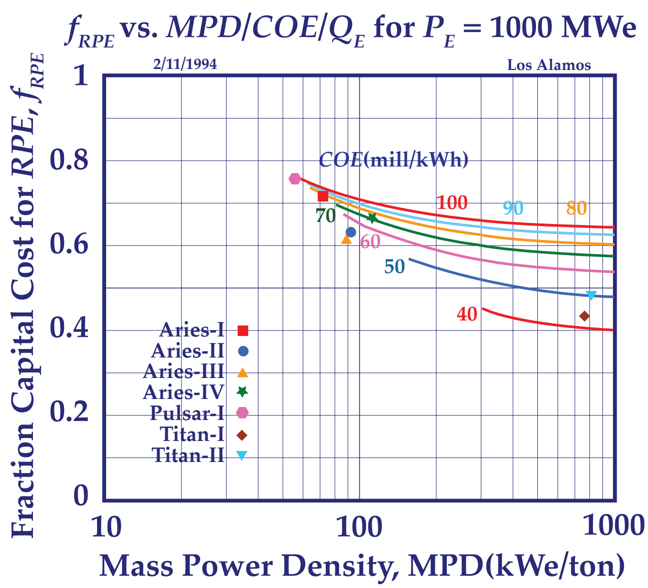

Figure 6 — Parametric dependence of fraction of *TDC* (including contingencies) allocated to the RPE (Account 22.1, Table 1) on *FPC MPD* for a range of COE values for a P_E = 1000 - MW(electric)(net) fusion power plant described by the parameters listed in Table 2. Optimized design points from a number of recent tokamak[4-6] and RFP (Reference 14) reactor studies are also shown. The design points for ARIES and TITAN generally reside at or near the top of the

minimum *COE* well in this f_{RPE} - *MPD* gauge space, with movement to regions of reduced *COE* and/or f_{RPE} being possible (particularly for the ARIES designs) only by a significant relaxation in physics, engineering, and/or materials constraints.

The parametric curves given in Figures 4, 5, and 6 all pertain to a P_E = 1000 - MW(electric)(net) fusion power plant. As seen from Table 2, the *BOP* = *TPE* + *EPE* + *MPE* unit costs use *CERs* that reflect economies of scale. The greater the restriction placed on COE to be competitive, the greater is the need, for a given Q_E, to find plasma/engineering configurations that control *FPC* cost by permitting high-*MPD* designs, as is shown in Figure 4. For an economically constrained *COE*, this need for higher *MPD* systems is relaxed for higher capacity power plants, as is illustrated in Figure 7. The more that the constraint for economic competitiveness is relaxed, the less important is the need to push *FPC* physics and engineering in the direction of high-*MPD* systems. Note that for a specific fusion power plant design[4-7] where physics and engineering combine to determine the *FPC MPD* through heat load, power density, tritium-breeding, magnet shield, divertor geometry, plasma-shaping (stability /equilibrium), plasma heating/ current drive, and peak coil field constraints, an intrinsic *FPC* economy of scale also emerges that is similar to that used for the *BOP*, wherein a doubling of (for example) thermal power results in an *FPC* cost that is somewhat less than doubled.

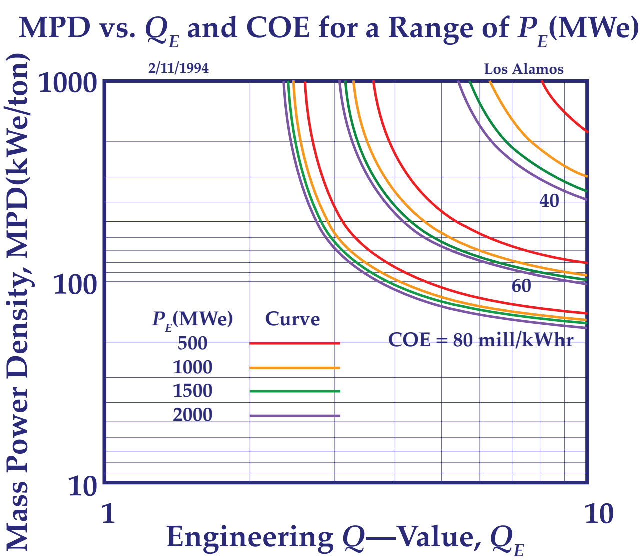

Figure 7 — Parametric dependence of *FPC MPD* on engineering gain for a range of *COE* and P_E values for the fusion power plant described by the parameters listed in Table 2.

The unit cost of the *FPC*, UC_{FPC} represents a highly compressed *CER*. More than any of the key fusion power plant systems, the economics of the *FPC*, as parametrically expressed through *MPD* and UC_{FPC}, is determined by nonlinear dependencies between physics, engineering, and *ES&H* variables and constraints. The array of subsystem *CERs* that comprise UC_{FPC} in actuality scale with areas, volumes, and linear dimensions as well as component mass; note that most *FPC* costs related to plasma heating or current drive power in this cost-gauge model have been pulled out of UC_{FPC} and loaded into costs associated with Q_E. To express the *FPC*-related *CERs* solely on the basis of mass is an approximation; the base-case UC_{FPC} = 100 \$/kg gives reasonable agreement with the more detailed ARIES projects,[4-7] although even the ARIES Systems Code (ASC) evaluates magnet costs on the basis of mass in comparison to more sophisticated procedures. Illustrating the sensitivity shifts in the *MPD*-Q_E regions where competitive *MFE* economics may reside has been accomplished by subjecting UC_{FPC} to a 50% variation above and below the UC_{FPC} = 100 \$/kg base-case value; the results for three *COE* values are shown in Figure 8. As expected, high-*MPD* systems that are constrained to medium-to-high electric generation costs show a relative insensitivity to UC_{FPC}, whereas those systems attempting to achieve low *COE* while limited (by physics and/or technology) to the low-*MPD*, but with the potential to achieve high Q_E, show a significant sensitivity to UC_{FPC} Systems like the high-Q_E stellarator (i.e., no current drive and ignited), for example, may face economic problems if UC_{FPC} is too high for these generally high-aspect-ratio, coil-intensive, low-*MPD* systems, unless plasma confinement efficiencies β are sufficiently high to reduce coil magnetic fields and allow increased coil current densities (e.g., reduced mass).

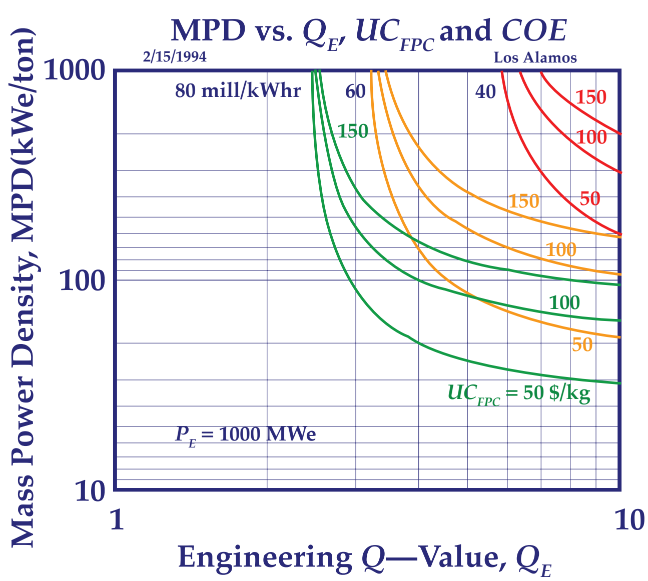

Figure 8 — Parametric dependence of *FPC MPD* on engineering gain for three *COE* values and three *FPC* (composite) unit costs for the fusion power plant described by the parameters listed in Table 2.

Like the detailed studies: [4-7, 9-12] the emphasis is placed in the evaluation of this cost-gauge model on capital costs vis-a-vis MPD, $\mathcal{Q}_E$, and the top-level unit costs and CERs used in Eq. (3); the plant availability factor p_f in Eq. (1) directly and strongly has an impact on *COE*, but in both approaches, this parameter is held fixed (p_f = 0.75 for all cases considered here and elsewhere[4-7, 9-12]). Except for *MFE* systems that push for high neutron wall loading and high-*MPD* values,[13-15] where p_f may be decreased if the fixed-fluence-life first wall and blanket require replacements that occur too frequently, the assumed value for p_f generally represents an area of high uncertainty and optimism, particularly for the large, low-*MPD* systems; compactness, in spite of possible (moderate) reductions in plant availability to accommodate more frequent component replacement (but for the same net electrical energy generation per unit of discarded first wall/blanket mass), may in fact have a greater chance of achieving the p_f values assumed.

Systems models that couple physics and engineering for specific confinement systems [4-6, 9, 10, 14, 15 ,17, 25] determine concept-specific design points or allowable (i.e,. constrained) design trajectories in the *MPD* - $\mathcal{Q}_E$ phase-space described in Figure 4. More generic physics/ engineering systems models have been developed[11] and used,[11,12] but generally these models are of limited value in accurately assessing the physics/ engineering constrained position in the Figure 4 topology where viable power plant designs may reside. Consequently, the economics gauge developed and reported herein is applied only to optimized design points that have been developed in the course of specific, comprehensive design activities; these optimized design points for the ARIES tokamak,[4-7] the TITAN RFP (Reference 14), and the compact spheromak reactor[15] (*CSR*) are included in Figures 4, 5, and 6. Also included is an interim design point for the PULSAR pulsed tokamak reactor study,[30] as well as preliminary estimates for fusion reactors based on stellarator confinement concepts,[16,17] which offer the potential for high-$\mathcal{Q}_E$, steady-state operation. High *MPD* systems have been projected for a (steady-state) spheromak [*MPD* ≈ 1000 kW(electric)/ton, $\mathcal{Q}_E$ > 6.0] compact torus,[15] which together with advanced tokamak configurations and the RFP form a lineage of ever-increasing, poloidal field-dominated (PFD) toroidal confinement schemes with increasing confinement efficiency (i.e., the ratio β of plasma pressure to magnetic field pressure) and reduced coil mass and (operational) interference. Important steps for the tokamak in this relatively unexplored direction include the second stability region [6,7,25] (SSR) and the spherical torus[31,32] tokamaks.

By using the same methodology and physics assumptions reported in Reference 15, the *CSR* was reoptimized[31] by using the ARIES costing model[6] and is included in Figure 4 with differences between the minimum electric generation cost (*COE* ≈ 60 mill/kW• h) and the predictions of the cost-gauge model (Table 2 and Figure 4) being accounted primarily by differences in assumed level of safety assurance (*LSA*) (reflecting safety-related cost) credits [LSA = 1 ⇒ full (~25%) safety-related cost reduction, depending on subsystem; LSA = 4 ⇒ no safety-related cost reduction[4-7]]; the unit costs in Table 2 reflect LSA ≈ 1 to 2, whereas those for the CSR correspond to LSA = 3. A similar statement applies to the TITAN RFP reactor study.[14] Although not shown in Figure 4, the ultra-low-aspect ratio spherical torus tokamak was also subject to a preliminary examination[31] in the context of the *MPD* versus $\mathcal{Q}_E$ trade-off, with the interim result that high *MPD* values appear to be achieved at the expense of high-current-density toroidal field (TF) coil centerposts, high ohmic losses therein, and decreased $\mathcal{Q}_E$; these preliminary results indicate a strong negative coupling for this concept between *MPD* and $\mathcal{Q}_E$ in the search for reduced-cost systems (e.g., upper right-hand corner in Figure 4).

The four ARIES tokamak reactor designs shown in Figures 4, 5, and 6 represent the culmination of nearly four years of work by a large, multidisciplinary team of physicists and engineers. These cost-optimized, physics/ engineering-constrained designs generally reside at or near a minimum-cost region determined largely by *FPC* and recirculating power costs for the physics, engineering, and *ES&H* constraints imposed. These (near) minimum-*COE* ARIES designs have actual *COE* values (Table 1) that expectedly differ from the predictions of the generic and highly compressed costing model used here, but the agreement seen in Figure 4 is reasonable, particularly in view of trade-offs related to safety-related cost credits and the added cost of using reduced activation materials not included in the costing gauge reported here. It is emphasized that each design point included in Figure 4 that is generated from detailed (and generally highly constrained) systems analyses [4-7, 9-12, 14] represents an optimum (or a constrained extremum) in this *MPD* - $\mathcal{Q}_E$ phase-space as (for example[4-7]) the plasma dimensions are varied; no optimum combination of $\mathcal{Q}_E$ and *MPD* exists from the *COE* viewpoint, except to minimize *COE* by maximizing $\mathcal{Q}_E$ and *MPD*, insofar as physics, engineering, materials, and *ES&H* constraints allow. For example, attempts to increase *MPD* for the conventional tokamak power plant generally occur at the expense of reduced $\mathcal{Q}_E$ (e.g., reduced bootstrap current), with the result that *COE* may remain the same or actually decrease. For this example, an optimum design point given in Figure 4 may actually reside at a maximum of a concept-specific curve when plotted in *MPD* versus $\mathcal{Q}_E$ phase-space and be limited from entering regions of lower *COE* by the particular physics and engineering constraints and assumptions imposed by the detailed analyses.

Generally, in spite of a wide range of combined physics, engineering, and materials extrapolations, none of the four (near-minimum *COE*) ARIES conceptual designs would compete economically with other advanced energy sources.[7] Although many of the key features of the high-cost ARIES designs are determined by configurational and material choices made to enhance *ES&H* merits, as well as to qualify for safety related cost reductions, the main driver of high costs projected for ARIES is embedded in a physics base that allows significant bootstrap current drive only at the cost of increased plasma aspect ratio A and reduced confinement efficiency β, both of which increase *FPC* mass and reduce the *MPD* parameter. A post study assessment[7] of ARIES, which was performed outside the ARIES project, concluded that a more aggressive push into the SSR of tokamak confinement, which included both high confinement efficiency ***and*** high Q_E (nearly all plasma currents would be driven by neoclassical, pressure-gradient bootstrap effects), was one possible way to pull the tokamak out of the low-*MPD*, moderate-Q_E regime in which the four ARIES designs depicted in Figure 4 reside. The potential for this direction was illuminated by a post study parametric analysis[7] that started with the SSR ARIES-II design and parametrically (i.e., without guidance from plasma stability/ equilibrium and bootstrap-current computations) varied (increased) the confinement efficiency β. The result of increasing the SSR confinement efficiency from β = 0.034 to 0.080 is designated as ARIES-II* in Figure 4; this direction of (economically) improved tokamak power plants is being pursued under the aegis of ARIES-V (Reference 33), which hopefully will provide a more attractive target for the tokamak DEMO study[8] recently launched by the ARIES team. However, other approaches to economically attractive *MFE* reactors are indicated in Figures 4 through 7, each with unique reactor attributes[19,20] and a level of development immaturity that is similar to that for an ARIES-II*-like SSR tokamak reactor. Exploration of this promising direction for an attractive tokamak power plant is continuing.[33]

4. Discussion

A simplified cost-gauge model has been developed to assess approaches whereby the economic attractiveness of MFE power plants might be improved. This model does not provide a concept-specific reactor design point but instead serves as a post-study diagnostic tool by which a top-level comparison and assessment of detailed conceptual *MFE* reactor studies can be made. This cost-gauge model has intentionally been unencumbered by detail to enhance its use as a scoping tool while simultaneously maintaining a level of realism necessary to provide useful results. The cost-gauge model does not break new ground but instead is intended to shed new light on old ground: In a composite, generic, and simplified sense, why are most past designs of *MFE* power plants so expensive, and what can be done to enhance the economic competitiveness of *MFE* in terms of increased *MPD* and Q_E. It remains for complete systems analyses to address this question in the context of specific MFE approaches, some of which have been included in Figure 4; the cost-gauge model indicates the kind of improvement in *MPD* and Q_E required, with everything else being held fixed.

When viewed generically as a potentially capital intensive power amplifier driven by potentially energy intensive sustainment sources, the economics of an *MFE* power plant can be expressed as a balance between the FPC cost and the cost of providing and recirculating high-technology power to the plasma; the pertinent systems parameters are *MPD* versus Q_E. When applied to the current generation of MFE reactor concepts,[4-6] these two parameters are useful for charting quantitatively directions for improved economics: increased *MPD* while maintaining acceptable values of Q_E in a safe and environmentally benign engineering configuration that can be maintained and reliably operated with high plant availability.

In some ways, early fusion researchers unknowingly may have made a Faustian bargain by introducing strong externally generated magnetic fields to quell instabilities that were destroying any attempt to create and sustain more self-confining plasma configurations. The success in containing and heating present-day plasmas by using high, externally generated magnetic fields, coupled with a natural tendency to extrapolate linearly from a position of success, has led to magnet-dominated *MFE* reactor designs like those projected by the recently completed ARIES series and has resulted in the uncompetitive cost projections summarized in Figure 4. Furthermore, reactor extrapolations of plasma configurations that require strong externally applied magnetic fields must deal with added construction and maintenance problems that exacerbate an already serious cost problem: Factory fabrication becomes impossible, and small-segment *FPC* maintenance may require even larger coils; a single coil replacement could take years; and spares are too expensive to backlog. Finally, Figures 5 and 6 illustrate the dominance of the *FPC* and the related economic lever exerted by fusion physics in determining the overall capital cost of the *MFE* power plant; comparable fission reactor values for f_{FPC} (Figure 5) and f_{RPE} (Figure 6) are 0.15 to 0.20 and 0.30 to 0.35, respectively; decoupling of *MFE* power plant economics from the uncertainties of fusion physics would be highly desirable in the current stage of fusion development for reasons of reduced risk and (possibly) reduced total development cost.

A range of viable alternatives [7,19,20,31-34] to the economic problems and uncertainties projected by this and other fusion reactor studies, all of which reduce the reliance on strong, externally applied magnetic fields, has been identified. These approaches form a lineage [19,20,31] that starts with advanced forms of the tokamak and pushes toward regimes of ever-increasing reliance on plasma self-magnetic fields for confinement; Figure 9 illustrates[19,20,31] this lineage of increasingly *PFD* systems[19]; the impact on cost of reducing significantly the generation of externally applied magnetic field for some of these *PFD* configurations is indicated in Figure 4. Beyond the *PFD* options, departures from the application of thermonuclear plasmas (i.e., non-equilibrium) for power generation are receiving increased attention [24,35,36] as a means to produce simplified, compact, and easily built, maintained, and (ultimately) disposed fusion power plants. It is instructive to note[37] (Figure 9) that in moving from the stellarator through the tokamak(s) and RFP to the spheromak and the field-reversed configuration (*FRC*), the experimenter/design/operator impresses less and less external control on the plasma. While the stellarator configuration fully controls both toroidal and poloidal magnetic fields through engineered systems, the tokamak largely relinquishes external control of the poloidal field. The RFP continues this trend and gives up a large part of the TF control to the plasma as well as that of the poloidal field. The spheromak gives the plasma almost complete freedom to generate the required toroidal and poloidal magnetic fields, with the *FRC* and dense *Z*-pinch requiring only self-generated poloidal fields. While much remains to be learned about the physics required to guide such self-controlled plasmas to stable regimes having confinement properties of reactor interest, the engineering and economic attractiveness (and flexibility) seem to improve significantly with the relinquishing of external control of the magnetic fields required to hold the plasma together.

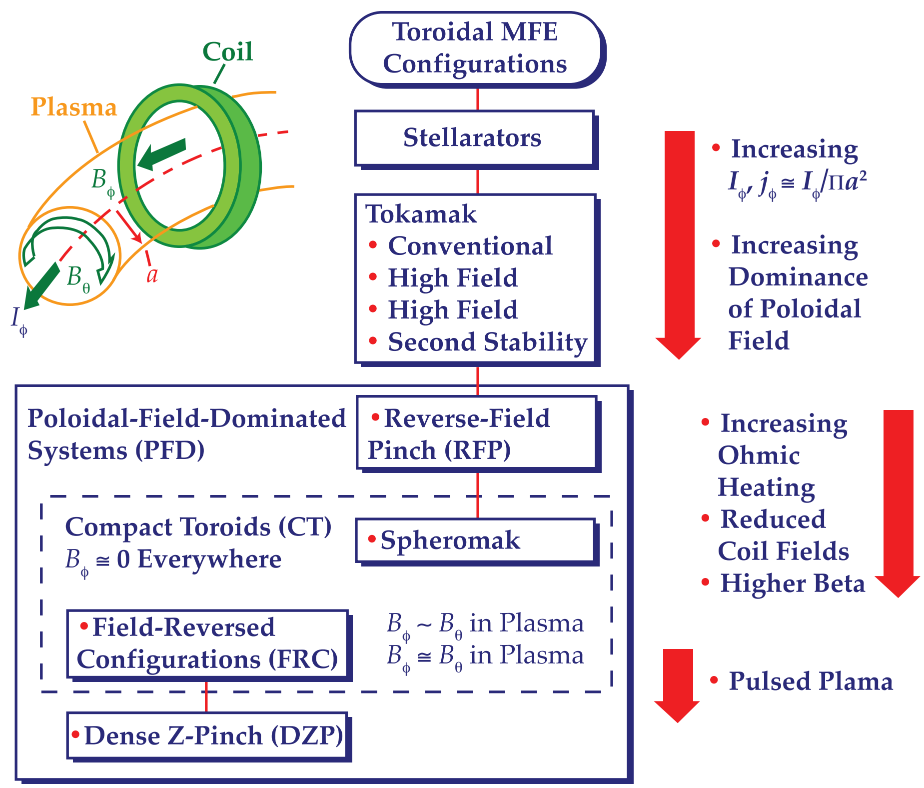

Figure 9 — Spectrum of main *MFE* configurations ordered according to toroidal (axial) current density and domination of poloidal magnetic field; starting with SSR and spherical torus tokamaks. a lineage of *MFE* concepts is identified that reduces reliance on externally applied magnetic fields and the economic and operational problems such fields create for the *MFE* power plant extrapolation.[4-7,25,30]

Whether being a member of the *PFD* magnetically confined family or based on completely new (and sometimes speculative) physics, these smaller, more compact, and simpler approaches to fusion power have as goals and/or offer a number of significantly improved power plant characteristics, a few of which are listed as follows:

1. A potential for compact, high-*MPD FPCs*, which implies unique fabrication and maintenance schemes leading to reduced construction time, increased availability, reduced impact of physics on capital cost, and potential for economic systems with reduced net electric output

2. An ability for highly radiating plasma conditions (without plasma disruption), which implies that plasma heat can be spread uniformly over the first wall, with the divertor plates serving primarily as particle collectors thereby pushing for increased overall *FPC* compactness without requiring heat fluxes beyond limits normally accepted as necessary in fusion

3. A unique combination of plasma sustainment (e.g., magnetic-helicity injection) and more configurationally symbiotic magnetic divertor systems,[15] which implies reduced first-wall heat loads in a compact system while reducing overall system complexity

4. Magnet designs that in terms of current density, mass, and forces are considerably eased, which implies reduced or eliminated TF coils, low-field equilibrium-field coils, leading to a more symmetric, open *FPC* that could operate economically with resistive coils and thinner blanket-shield systems

5. Auxiliary heating or current sustainment systems may not be required, which implies reduced *FPC* complexity, simplified first-wall design, and enhanced compactness.

6. A broad range of power plant advantages related to a potential for single-piece *FPC* maintenance as follows:

   a. factory fabrication of a fully operational unit
   b. fully operational, preservice, nonnuclear *FPC* testing
   c. minimization of electrical, fluid, and vacuum connections in the nuclear environment of the *FPC*
   d. a shortened scheduled maintenance period that implies reduced maintenance time per se along with a reduced restart period with increased restart confidence
   e. standard and/or rapid recovery from unscheduled events related to *FPC* malfunctions.

7. Increased plant availability, which implies *COE* ~ capital/capacity/availability, a major cost impact, particularly if *UDC* = capital/capacity can be held to low values. In fact, the ability to manage repairs on the smaller, more compact systems may be an essential ingredient for achieving in practice the moderate-to-high plant factors ($p_f > 0.75$) assumed in theory by most conceptual *MFE* power plant studies.

8. Accommodation of *FPC* improvements throughout plant life, which implies that *FPC* is not a major cost item; technology and materials advances can be economically and environmentally exploited throughout the plant lifetime.

In summary, although highly simplified and intended primarily to provide a costing gauge for *MFE* power plants, a comparison of the predictions of an *MPD* - $\mathcal{Q}_E$ - *COE* costing gauge with the results of modern, detailed, and cost-optimized studies of a number of *MFE* approaches indicates the need for changes in the direction of the current fusion program and in the thinking that is maintaining that direction. The agreement between the cost-gauge model and the predictions of complete systems studies that wrestle with the nonlinearities and connectivities of the physics, engineering, and financial design space indicates the importance of *MPD* and $\mathcal{Q}_E$ in projecting electric generating costs for the given (calibrated) set of top-level unit costs and *CERs* used herein. Improved economic and operational prospects for *MFE* can be expressed in terms of a lineage that begins with higher-*MPD* tokamak configurations embodied in the SSR and spherical torus configurations and moves toward configurations with increased *PFD*, reduced externally generated magnetic fields, and further increases in *MPD*. Although scientific progress along a linear extension of the current tokamak database is warranted and necessary, particularly as applied to an early resolution of alpha-particle effects in sustained-burn DT plasmas, this progress must not occur at the expense of ideas that might lead to an economically and environmentally attractive *MFE* power source that would eventually be pulled into the energy market because of significant cost differentials rather than being pushed into that market by technology advances that may not be recognized as leading to a power plant that is either attractive or needed.

Nomenclature

A	= plasma aspect ratio, *R/a*
AC	= annual charges ($ million/year)
ARIES	= Advanced Reactor Innovation and Evaluation Study
ASC	= ARIES Systems Code
a	= plasma minor radius (m)
β_{ϕ}	= toroidal (axial) magnetic field (T)
β_{θ}	= poloidal (plasma-encircling) magnetic field (T)
BOP	= balance of plant
CER	= cost-estimating relationship
COE	= cost of electricity (mill/kW• h)
$CONT_j$	= contingency factor *j* = *FPC*, *HTG*, *PHT*, *TPE*, *EPE*, *MPE*, *SITE*

CRF (X_o, T_{LIF})	= capital recovery factor (1/yr)
CSR	= compact spheromak reactor
D&D	= decontamination and decommission (charges)
DT	= deuterium-tritium
EPE	= electric plant equipment
ES&H	= Environmental, Safety, and Health
FCR	= fixed charge rate (constant dollars) (l/yr)
FCR_{DD}	= effective FCR for D&D escrow (l/yr)
FPC	= fusion power core
f_{AUX}	= auxiliary power fraction, P_{Aux}/P_{ET}
f_{DD}	= fraction *TDC* needed for *D&D*
f_{FPC}	= fraction *TOC* devoted to *FPC*
f_{FUL}	= fuel charges as fraction *TOC* (l/yr)
f_{IDC}	= *IDC* as a fraction of *TDC*
f_{OM}	= *O&M* charges as fraction *TDC* (l/yr)
f_{RPE}	= fraction *TDC* devoted to *RPE*
HTG	= supplemental heating
I_ϕ	= toroidal (axial) plasma current (A)
IDC	= interest during construction or indirect charges
$ITER$	= International Thermonuclear Experimental Reactor
j_ϕ	= toroidal plasma current density, $I_\phi/\pi a^2$ (A/m²)
$LAND$	= *LAND* and land rights
LSA	= level of safety assurance reflecting safety-related cost credits; LSA = 1 = full (~25%) safety-related cost reduction, depending on subsystem; LSA = 4 = no safety-related cost reduction[4-7]
LWR	= light water reactor
M	= nominal energy multiplication, $1/Q_E + 0.8M_N + 0.2$
M_c	= coil mass (kg)
M_{FPC}	= *FPC* mass (kg)
M_N	= blanket neutron energy multiplication
MFE	= magnetic fusion energy
MPD	= *FPC* mass power density, P_E/M_{FPC} [kW(electric)/ton]
MPE	= miscellaneous plant equipment
O&M	= operation and maintenance
P_{AUX}	= auxiliary plant power, $f_{AUX}\, P_{ET}$ (MW)
P_c	= recirculating power (current drive plus *BOP* auxiliaries) (MW)
P_E	= net electric power [MW(electric)]
P_{ET}	= total electric power [MW(electric)]
P_F	= fusion power (MW)
P_{HTG}	= current drive or heating power (MW)
P_{TH}	= thermal power [MW(thermal)]
p_f	= plant capacity factor
PF	= poloidal field (coil)
PFD	= poloidal field-dominated
PHT	= primary heat transport
Q_E	= engineering *Q*-value or gain, P_{ET}/P_c
Q_p	= plasma *Q*-value or gain, P_F/P_{CD}
RPE	= reactor plant equipment
$SITE$	= structures and site facilities
SSR	= second stability region
T_{LIF}	= plant financial lifetime (year)
TDC	= total direct cost
TF	= toroidal field (coil)
TPE	= turbine plant equipment
UC_{EPE}	= unit cost of *EPE* [$/W(electric)]
UC_{FPC}	= unit cost of *FPC* ($/kg)
UC_{HTG}	= unit cost of plasma *HTG*, current drive ($/W)
UC_{MPE}	= unit cost of *MPE* ($/kg)
UC_{PHT}	= unit cost of *PHT* [$/W(thermal)]
UC_{SITE}	= unit cost of *SITE* [$/W(electric)]
UC_{TPE}	= unit cost of *TPE* [$/W(electric)]
UC_j	= unit cost of j'th item with contingency
UDC	= unit direct cost [$/W(electric)]
X_o	= real (inflation-free) cost of money (1/yr)
β	= ratio plasma pressure to magnetic field pressure
ε	= recirculating power fraction, $1/Q_E$

η_{HTG} = plasma heating current drive wall-plug efficiency

η_{TH} = thermal conversion efficiency

η_p = net plant efficiency, η_{TH} (1 - ε)

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