LA-UR- 94-738
c.1

LA-UR- 94-738

February 18, 1994

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

Author(s): Robert A. Krakowski

Submitted to: Technical Note to Fusion Technology

DO NOT CIRCULATE

PERMANENT RETENTION

Los Alamos
NATIONAL LABORATORY

TABLE OF CONTENTS

SIMPLIFIED FUSION POWER-PLANT COSTING: A GENERAL PROGNOSIS AND CALL FOR "NEW THINK"†

R. A. Krakowski
February 18, 1994

ABSTRACT

A top-level costing model is developed and used to project the cost of electricity, COE(mill/kWh), expected from a fusion power plant. These costs are estimated parametrically in terms of the mass of the fusion-power-core "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, and the balance of plant 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 fusion-power-core mass power density, MPD(kWe/tonne), and the engineering gain, Q_E, apply primarily to Magnetic-Fusion-Energy (MFE) approaches to fusion power, the "costing gauge" that results is generally independent of confinement scheme. 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 à vis* appropriate combinations of MPD and Q_E for the unit costs and CERs used. Although highly simplified and intended primarily to provide a costing 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 changes in the direction of the present 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 (SSR) and spherical-torus (ST) regimes and moves towards configurations with increased poloidal-field domination (PFD), reduced externally generated magnetic fields, and further increases in MPD. Although scientific progress along a linear extension of the present tokamak data base is warranted and necessary, this progress should not ocurr 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 (*e.g.*, too complex, unreliable, costly).

†Work resulted from projects supported by US DOE, Office of Fusion Energy.

I. INTRODUCTION

Although fusion fuels are generally abundant and inexpensive, the fusion reaction of light elements like hydrogen requires that the inter-nuclear Coulomb barrier be overcome before intra-nuclear 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 power 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 presently 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 the fusion approach being pursued is deemed economically and environmentally wise; commercial fusion power according to present planning at the earliest would be available 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 >6-B$ ITER[3] (International Thermonuclear Experimental Reactor) assuring an almost complete focus onto this single confinement system. This focus is occurring when present projections[4–6] for a viable commercial tokamak-based commercial power plant is at best uncertain[7,8]. 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 the an attractive commercial end-product. 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 above, must attract strong "market pull"; a serious study of this DEMO device is about to be launched[9].

The engineering, physics, materials, ES&H (Environmental, Safety, and Health), 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[4-9]. These uncertainties, which add to the usual uncertainties associated with any long-term projection (*i.e.*, resources, energy supply *versus* demand, energy-production structure of the future, *etc.*), are minimized by use of multi-disciplinary teams who in turn apply the most current experimental scalings and theoretical models[4-6]. The interconnectivity of physics, engineering, ES&H, and economics that is quantified by means of a comprehensive systems optimization model, however, can lead to related tradeoffs 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 highly simplified 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 Mass Power Density, $MPD(kWe/tonne) = M_{FPC}/P_E$, where the gross, net, recirculating electrical powers are P_{ET}, $P_E = P_{ET}(1 - 1/Q_E)$, and P_c, respectively, and M_{FPC} is the FPC mass (*i.e.*, plasma chamber, blanket, shield, reflector, divertors, plasma heaters, magnets, and primary support structure). 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); and 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(mill/kWh), in a $MPD versus Q_E$ "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 power plant. A physics/engineering-constrained "trajectory" in this $MPD - Q_E - COE$ phase space must be generated by a separate, integrated (but simplified) plasma model[10-13] or use the results of separate, detailed systems models developed for the tokamak fusion reactor[4-7] or other MFE confinement schemes[14-18]. The model reported herein is a gauge to indicate directions for competitive MFE power plants; it is not a conceptual design tool *per se*.

After briefly describing the generic MFE costing model in Sec. II., parametric results are given in Sec. III., where comparisons are made with the Refs. 4-6, Ref. 7, and Refs. 14-18 studies of conceptual tokamak, Reversed-Field-Pinch (RFP), and stellerator reactors. Section IV. gives a brief conclusion that higher MPD values while maintaining $Q_E > 6$ are essential elements for MFE power with a future "market pull" (*e.g.*, cost differential, operational simplification, eased licensing, enhanced ES&H characteristics, *etc.* sufficient for concept to be "pulled" into the market place, instead of being "pushed" by ever increased technological advances alone). Since the present embodiment of the tokamak, or reasonable extrapolations therefrom, does no 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[8,19,20]; the present 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 R&D program.

II. MODEL

A. Overview

Figure 1 depicts the essential elements of an MFE power plant and gives a functional breakdown of key subsystems: Fusion-Power-Core (FPC) heat source; plasma support systems; Primary Heat Transport (PHT); and 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 along with Sites and Structures, these top-level plant components comprise the main cost-accounting structure in a costing system adopted from one developed to assess fission power plants[24] and more recently used to compare a range of advanced fission and fossil energy sources[25,26]. This cost-breakdown structure, as applied to the recently completed ARIES (Advanced Reactor Innovation and Evaluation Study[4–6]) tokamak power-plant conceptual designs, is summarized in Table I.

Detailed physics and engineering models are coupled to Cost-Estimating Relationships (CERs) in a comprehensive parametric systems model[4–6] to optimize design points and to examine a wide range of cost tradeoffs using the cost-accounting structure summarized in Table I. Even though the parametric evaluation extends only down to the second level of costing indicated on Table II, this evaluation requires detail plasma (burn, equilibrium, stability), engineering (magnetics, divertors, blanket/shield neutronics and thermal-hydraulics-mechanics), and materials (compatibility, fabricability, safety, 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, degree of FPC openness as dictated by maintenance schemes and allowable magnetic-field ripple, *etc.*) then result in optimal COE costs as dictated indirectly by a balance between the size (mass) of key components and the power needed to sustain the plasma configuration. These indirect economic balances are driven by constrained physics and engineering and often lead to optimal system characteristics that are non-intuitive. 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 non-competitive, as in the case of ARIES[7,8], the means by which a more economic system can be obtained is limited and sometimes obscured by these realities of modeling a "real" system.

Recognizing that the credibility of any conceptual fusion power-plant design rests with the need and ability to couple systematically key physics, engineering, ES&H, and costing constraints, the present analysis nevertheless inverts the design-optimization process by evaluating a highly compressed version of Table I 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; or 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 Operating and Maintenance (O&M) and Decontamination and Decommissioning (D&D) costs based on more detailed (concept-specific) studies[4–8,15], can be expressed in terms of the FPC mass power density, MPD(kWe/tonne), 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 confinement approach (*e.g.*, one of the ARIES concepts) fall short of economic competitiveness with respect to competing energy sources, 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[4-6,27] 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 (*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, 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.

B. Approach

In reducing the system complexity represented by Fig. 1 and Table I, while retaining an acceptable level of accuracy needed for quantitative analyses, the generic DT fusion plant power balance illustrated in Fig. 2 is introduced. As described earlier, the fusion plasma is considered a power amplifier that converts the input heating (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 α-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 PHT 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. 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 $\epsilon = 1/Q_E$.

The power balance depicted in Fig. 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 I and Fig. 1 into a condensed, more easily managed form, while retaining an acceptable level of realism. Figure 3 illustrated this collapsed costing structure that retains the essential elements of the plant power balance shown in Fig. 2. Referring to Table I, 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 $UC_{SITE}(\$/We)$.

Table II lists these unit costs, along with the corresponding contingency factors, $CONT_j$. The Reactor Equipment Account 22.1. less the plasma-heating/current-drive and associated power-supplies accounts, are assumed to represent the mass-related FPC costs; the corresponding unit cost is $UC_{FPC}(\$/kg)$, which is also listed along with the corresponding contingency factor on Table II. The power required for plasma sustenance is costed in proportion to P_{HTG}/η_{HTG} and scales according to $UC_{HTG}(\$/W)$. The Primary Heat Transport system (PHT, Account 22.2.) represents the main connection between the FPC and the BOP; the PHT cost is scaled according to $UC_{PHT}(\$/Wt)$ 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 I).

The assumption that the FPC cost scales linearly with FPC mass is a weakness of the model. The treatment of 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[4-6,27] would scale FPC subcomponent costs with power, power density, peak heat flux, area, and/or volume. This kind of detail is sacrificed by the present study in favor of a more flexible tool with which to gauge progress towards more economic fusion power-plant designs.

The BOP is scaled as the sum of the Turbine-Plant-Equipment (TPE, Account 23.), the Electric-Plant-Equipment (EPE, Account 24.) and the Miscellaneous-Plant-Equipment (MPE, Account 25.) accounts, as is listed in Table II, 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 an an economy of scale[23] not unlike that embedded in the more detailed cost-based systems models[4-6].

Computation of the COE requires that the sum of all annual charges, $AC(M\$/yr) = FCR(1 + f_{IDC})TDC + OM + FUL + DD$ 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, $FCR(1/yr)$ is the Fixed Charge Rate on the Total Direct Cost (TDC, including individual contingency factors, $CONT_j$), f_{IDC} is an InDirect Cost factor that reflects Accounts 91.-97. on Table I, $FUL(1/yr)$ 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 $TDC(M\$)$ 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[24] for a real cost of money $X_o(1/yr)$ (*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 fixed charge rate for the D&D escrow payment.

Defining $f_{OM}(1/yr) = OM/TDC$, $f_{FUL}(1/yr) = FUL/TDC$, and the Unit Direct Cost as $UDC(\$/We) = TDC/P_E$, the following expression for COE results:

$$COE(mill/kWh) = \frac{10^6}{8760}\frac{UDC}{p_f}\Big[FCR(1 + f_{IDC}) + f_{OM} + f_{FUL} + FCR_{DD}\Big]. \quad (1)$$

To maintain the generic nature of this model, 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]) is included in the parameter f_{OM}. If the unit cost for the j^{th} subsystem is UC_j and the associated contingency factor is $CONT_j$, the Total Direct Cost is given by

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

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 II, into Eq. (2) and defining $UC_j^* = UC_j(1 + CONT_j)$ gives the following expression for UDC:

$$UDC(\$/We) = \frac{UC_{FPC}^*}{MPD} + \frac{1}{\eta_{TH}(1 - 1/Q_E)}\left[\frac{UC_{HTG}^*}{\eta_{HTG} Q_p M} + UC_{PHT}^* + \eta_{TH}(UC_{BOP}^* + UC_{SITE}^*)\right]. \tag{3}$$

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 (Fig. 2):

$$\frac{1}{Q_E} = f_{AUX} + \frac{1}{\eta_{HTG}\eta_{TH} Q_p M}. \tag{4}$$

The above 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 II. 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 COEs. 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 $MPD - Q_E$ tradeoffs for a range of specified (goal) COEs result. This economic gauge is then used to compare and assess results from detailed conceptual MFE reactor studies.

III. RESULTS

The essential elements of the "costing-gauge" model are embodied in Eqs. (1) and (3), along with the parameters listed in Table II. This set of expressions is evaluated parametrically in Fig. 4. This figure illustrates the tradeoff 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 Fig. 4 is established largely by the parameters listed in Table II and the assumptions (accuracy) of highly integrated CERs that form the basis of this model, particularly with respect of FPC cost estimates. Generally, the costing gauge given on Fig. 4 for the assumptions listed in Table II are optimistic, as seen for the limiting case where $MPD \rightarrow \infty$ and Q_E approaches the limiting value of $1/f_{AUX} \approx 30$ (*i.e.*, $Q_p \rightarrow \infty$). In this case $COE = 27 mill/kWh$, which, if increased by $\sim$ 15-20% to account for an Light-Water (fission) Reactor (LWR) pressure vessel, amounts to $\sim$ 41-42 mill/kWh once an 10-mill/kWh fuel charge is added; advanced fission systems are expected to be in the range 45-48 mills/kWh[36].

As seen from Eq. (1) and Table II, the ratio COE/UDC is determined primarily by debt-servicing requirements: $FCR(1 + f_{IDC})/f_{OM}/f_{FUL}/FCR_{DD} =$ 0.802/0.190/0.000/0.008; based on the Table-II parameters, the ratio COE/UDC equals 32.1 (mill/kWh)/($/We). This ratio establishes the Fig. 4 topology, with Eq. (3) through the subsystem CERs, UC_j, determining the $MPD - Q_E - COE$ tradeoffs that result. The partitionings of FPC and RPE = FPC + HTG + PHT direct costs (including individual subsystem contingencies) as a fraction of TDC are illustrated in Figs. 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%[28] and 30-34%[26,28], respectively; the RPE fraction of TDC for the lower-power-density Gas-Turbine Modular High-Temperature Gas-cooled Reactor (GT-MHTGR)[29], however, ranges from 49% (steam or indirect cycle) to 56% (direct cycle).

The parametric curves given on Figs. 4-6 all pertain to a $P_E = 1000 - MWe(net)$ fusion power plant. As seen from Table II, 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 Fig. 4. For an economically constrained COE, this need for higher-MPD systems is relaxed for higher-capacity power plants, as is illustrated in Fig. 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. It should be noted that for a specific fusion power-plant design[4-7] where physics and engineering combine to determine the fusion-power-core MPD through heat-load, power-density, tritium-breeding, magnet-shield, divertor-geometry, plasma-shaping (stability/equilibrium), plasma-heating/CD, 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 a FPC cost that is somewhat less than doubled.

Systems models that couple physics and engineering for specific confinement systems[4-6,10,11,15,16,19,27] are required to determine concept-specific design points or allowable (*i.e.*, constrained) design trajectories in the $MPD - Q_E$ "phase space" described on Fig. 4. More generic physics/engineering systems models have been developed[12] and used[12,13], but generally are of limited value in accurately assessing the physics/engineering-constrained position on the Fig. 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] and the TITAN Reversed-Field-Pinch (RFP)[15] are included on Figs. 4-7. Also included is an interim design point for the on-going PULSAR pulsed tokamak reactor study[30], as well as preliminary estimates for fusion reactors based on stellarator confinement concepts[17,18], which offer the potential for high-Q_E, steady-state operation. Although not included, very high MPD systems have been projected for a (steady-state) spheromak ($MPD \approx 1000 kWe/tonne, Q_E > 6.0$) compact torus[16], 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 (SSR)[6,27] and the Spherical-Torus (ST)[31] tokamaks.

The four ARIES tokamak reactor designs shown on Figs. 4-7 represent the culmination of nearly four-years work by a large, multi-disciplinary 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 COEs (Table I) that expectedly differ from the the predictions of the generic and highly compressed costing model used here, but the agreement seen on Fig. 4 is reasonable, particularly in view of tradeoffs related to safety-related cost credits and the added cost of using reduced-activating materials are not included in the costing gauge reported here. 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[7,8]. 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 qualifying for safety-related cost reductions, the main driver of high costs projected for ARIES is embedded in a physics base that allowed 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 of ARIES[7,8], performed outside the ARIES project, concluded that a more aggressive push into the SSR of tokamak confinement, wherein both high confinement efficiency *and* high-Q_E (nearly all plasma currents would be driven by neo-classical, 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 on Fig. 4 are mired. 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 (increase) the confinement efficiency, β. The result of increasing the SSR confinement efficiency from $\beta = 0.034$ to 0.080 is designated as ARIES-II* on Fig. 4; this direction of (economically) improved tokamak power plants is being pursued under the aegis of ARIES-V[32], which hopefully will provide a more attractive target for the tokamak DEMO study[9] about to be launched by the ARIES team. However, other approaches to economically attractive MFE reactors are indicated on Figs. 4-7, each with unique reactor attributes[20,21] and a level of development immaturity that is similar to that for an ARIES-II*-like SSR tokamak reactor.

II. CONCLUSIONS

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 kept unencumbered by detail to enhance its use as a scoping tool, while simultaneously maintaining a level of realism necessary to provide useful results. 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 $MPD(kWe/tonne)$ *versus* Q_E. These two parameters, when applied to the present generation of MFE reactor concepts[4−6], 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 way, 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 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 suggested in Fig. 4. Furthermore, reactor extrapolations of plasma configurations that require strong externally applied magnetic fields must deal with added construction and maintenance problems that exacerbates an already serious cost problem: factory fabrication becomes impossible, small-segment FPC maintenance may require even larger coils; a single coil replacement could take years; and spares are too expensive to backlog. Finally, Figs. 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} (Fig. 5) and f_{RPE} (Fig. 6) are 0.15-0.20 and 0.30-0.35, respectively; more decoupling of MFE power-plant economics from the uncertainties of fusion physics would be highly desirable in the present stage of fusion development for reasons of reduced risk and (possibly) reduced total development cost.

A range of viable alternatives[7,20,21,31,33,34] to the economic problems and uncertainties projected by this and other fusion-reactor studies have been identified, all of which reduce the reliance on strong, externally applied magnetic fields. These approaches form a lineage[20,31] that starts with advanced forms of the tokamak and pushes towards regimes of ever-increasing reliance on plasma self-magnetic-fields for confinement; Fig. 8 illustrates[20,21] this lineage of increasingly Poloidal-Field-Dominated (PFD) systems[20]; the impact on cost of reducing significantly the generation of externally applied magnetic field for some of this PFD configurations has been indicated on Fig. 4. Beyond the PFD options, departures from the application of thermonuclear plasmas (*i.e.*, non-equilibrium) for power generation are receiving increased attention[22,34,35] as means to produce simplified; compact; and easily built, maintained, and (ultimately) disposed fusion power plants. Whether 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 below:

- Potential for compact, high-mass-power-density fusion power cores $\Rightarrow$ unique fabrication and maintenance schemes leading to reduced construction time, increased availability, reduced impact of physics on capital cost, potential for economic systems with reduced net-electric output.
- Ability for highly radiating plasma conditions (without plasma disruption) $\Rightarrow$ plasma heat can be spread uniformly over first wall, with divertor plates serving primarily as particle collectors, thereby pushing for increased overall FPC compactness without pushing heat fluxes beyond limits normally accepted as necessary in fusion.
- Unique combination of plasma sustainment (*e.g.*, magnetic-helicity injection) and more configurationally symbiotic magnetic divertor systems[16] $\Rightarrow$ reduced first-wall heat loads in a compact system while reducing overall system complexity.
- Magnet designs that in terms of current density, mass, and forces are considerably eased $\Rightarrow$ reduced or eliminated toroidal-field 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.
- No auxiliary heating or current sustainment systems required $\Rightarrow$ reduced FPC complexity, simplified first-wall design, enhanced compactness.
- Broad range of power-plant advantages related to potential for single-piece FPC maintenance:
  - $\Rightarrow$ factory fabrication of an fully operational unit;
  - $\Rightarrow$ fully operational, non-nuclear FPC testing;
  - $\Rightarrow$ minimize electrical, fluid, and vacuum connections in the nuclear environment of the fusion power core;
  - $\Rightarrow$ shortened scheduled maintenance period, implying reduced maintenance time *per se* along with reduced restart period with increased restart confidence;
  - $\Rightarrow$ standard and/or rapid recovery from unscheduled events related to FPC malfunctions;
- Increased plant availability $\Rightarrow$ COE $\sim$ capital/capacity/availability, a major cost impact, particularly if UDC($/We) = capital/capacity can be held low.
- Accommodate FPC improvements throughout plant life $\Rightarrow$ FPC is not a major cost item, technology and materials advances can be economically and environmentally exploited throughout the plant lifetime.

Although highly simplified and intended primarily to provide a costing gauge for MFE power plants, a comparison of the predictions of an $MPD - Q_E - COE$ 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 present 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 (SSR) and spherical-torus (ST) regimes and moves towards configurations with increased polidal-field domination (PFD), reduced externally generated magnetic fields, and further increases in MPD. Although scientific progress along a linear extension of the present tokamak data base 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 (*e.g.*, too complex, unreliable, costly).

REFERENCES

1. J. C. Cordey, R. J. Goldston, and R. J. Parker, Physics Today, 45(1), 22-30 (January 1992).
2. G. H. Neilson, *et al.*, "Design of a Superconducting Steady State Advanced Tokamak," Proc. 17th Symp. on Fus. Technol.: 1992, 2, 1636 (1993).
3. J. Doggett, *et al.*, "ITER Tokamak Device," ITER Documentation Series No. 25, IAEA, Vienna (1991).
4. The ARIES Team, "The ARIES-I Tokamak Reactor Study Final Report," University of California at Los Angeles report UCLA-PPG-1323 (1991).
5. The ARIES Team, "The ARIES-III Tokamak Reactor Study Final Report," University of California at Los Angeles report UCLA-PPG-1384 (to be published, 1994).
6. The ARIES Team, "The ARIES-II and ARIES-IV Tokamak Reactor Study Final Report," University of California at Los Angeles report UCLA-PPG-1461 (to be published, 1994).
7. R. A. Krakowski, C. G. Bathke, R. L. Miller, and K. A. Werley, "Lessons Learned from the Tokamak Advanced Reactor Innovations and Evaluation Study (ARIES)," Los Alamos National Laboratory document LA-UR-93-4217 (December 8, 1993).
8. R. A. Krakowski, C. G. Bathke, R. L. Miller, and K. A. Werley, "Lessons Learned from the Tokamak Advanced Reactor Innovations and Evaluation Study (ARIES)," Proc. 11th Topical Meeting on the Technology of Fusion Energy, New Orleans, LA (June 19-23, 1994).
9. R. W. Conn, F. Najmabadi, S. Sharafat, K. R. Schultz, and R. A. Krakowski, "The Requirements of a Fusion Demonstration Reactor and the STARLITE Study," University of California at Los Angeles report UCLA-PPG-1394 (February 1992).
10. L. Bromberg, R. A. Krakowski, E. T. Cheng, D. R. Cohn, C. G. Bathke, and R. LeClaire, "Commercial Reactors with Resistive Magnets," Proc. 14th IEEE/NPSS Sypm. on Fusion Engineering, 2, 1016 (September 30 - October 3, 1991).
11. R. A. Krakowski, R. L. Miller, and C. G. Bathke, "A Cost-Based Systems Analysis of Long-Pulsed *versus* Steady-State Tokamak Reactors," Proc. 14th IEEE/NPSS Sypm. on Fusion Engineering, 2, 1119 (September 30 - October 3, 1991).
12. J. Sheffield, R. A. Dory, S. M. Cohn, J. G. Delene, D. E. T. F. Ashby, W. T. Reiersen, "Cost Assessment of a Generic Magnetic Fusion Reactor," Fusion Technology, 9(3), 199-259 (1986).
13. J. P. Holdren, *et al.*, "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy," Lawrence Livermore National Laboratory report UCRL-53766 (September 25, 1989).
14. R. L. Hagenson, R. A. Krakowski, C. G. Bathke, R. L. Miller, M. J. Embrechts, N. J. Schnurr, M. E. Battat, R. J. LaBauve, and J. W. Davidson, "Compact Reversed-Field Pinch Reactors (CRFPR): Preliminary Engineering Considerations," Los Alamos National Laboratory report LA-10200-MS (August 1984).
15. F. Najmabadi, *et. al.*, "The TITAN Reversed-Field-Pinch Fusion Reactor Study," University of California at Los Angeles report UCLA-PPG-1200 (1990).
16. R. L. Hagenson and R. A. Krakowski, "The Spheromak as a Compact Fusion Reactor," Los Alamos National Laboratory report LA-10908-MS (March 1987).

17. G. Grieger *et al.*, "Modular Stellarator Reactors and Plans for Wendelstein 7-X," Fusion Technology **17**, 169 (1991).
18. J. F. Lyon, K. Gulec, R. L. Miller, and L. El-Guebaly, "Status of the U. S. Stellarator Reactor Study," Proc. IAEA Technical Committee Meeting and Workshop on Fusion Design and Technology V, UCLA (September 13-17, 1993) (to be published).
19. R. L. Miller ,"Advanced Stellarator Power Plants," Proc. 11th Topical Meeting on the Technology of Fusion Energy, New Orleans, LA (June 19-23, 1994).
20. C. G. Bathke, R. A. Krakowski, R. L. Miller, "A Need for Non-Tokamak Approaches to Magnetic Fusion Energy," Proc 17th Symp. of Fusion Technol., **2**, 1663 (Rome, Italy, September 14-18, 1992).
21. R. A. Krakowski, "Progress in Commercial Magnetic Fusion Energy Reactor Designs," Fusion Technology, 20(9), 121-143 (1991).
22. L. J. Perkins, D. E. Balwin, J. H. Hammer, C. W. Hartman, D. L. Morgan, S. W. Haney, J. L. Eddleman, "Novel Thermonuclear and Non-Thermonuclear Fusion: Concepts and Reactor Potential," Proc. 11th Topical Meeting on the Technology of Fusion Energy, New Orleans, LA (June 19-23, 1994).
23. R. L. Miller, W. R. Spears, R. Hancox, and R. A. Krakowski, "Comparison of EURATOM and U.S. Estimates of Fusion Reactor Costs," Fusion Technology, 19(3,2A), 813 (1991).
24. "Guide for the Economic Evaluation of Nuclear Plant Designs," Nuclear Utilities Services report NUS-531 (January 1963).
25. J. G. Delene and C. R. Hudson II, "Cost Estimate Guidelines for Advanced Nuclear Power Technologies," Oak Ridge National Laboratory report ORNL/TM-10071/R3 (1993).
26. J. G. Delene, K. A. Williams, and B. H. Shapiro, "Nuclear Energy Cost Data Base," US DOE report DOE/NE-0095 (September 1988).
27. C. G. Bathke, "A Systems Analysis of the ARIES Tokamak Reactors" Proc 17th Symp. of Fusion Technol., **2**, 1658 (Rome, Italy, September 14-18, 1992).
28. United Engineers and Constructors, Inc., "1000-MWe Central Station Power Plants Investment Cost Study," United States Atomic Energy Commission report WASH-1230 (June 1972).
29. G. Pause, "Economic Evaluation of MHTGR-GT ," Trans. Amer. Nucl. Soc., **69**, 342 (November 1993).
30. C. G. Bathke,"A Comparison of Steady-State ARIES and Pulsed PULSAR Tokamak Power Plants," Proc. 11th Topical Meeting on the Technology of Fusion Energy, New Orleans, LA (June 19-23, 1994).
31. Y-K.M. Peng and D. J. Strickler, "Features of Spherical Torus Plasmas," Nucl. Fus., **26**, 769-777 (1986).
32. S. Jardin, personal communication, Princeton Plasma Physics Laboratory (1994).
33. J. Sheffield, "The Physics of Magnetic Fusion Reactors," Rev. Mod. Phys. (to be published).
34. R. W. Bussard, "Some Physics Considerations of Magnetic Inertial-Electrostatic Confinement: A New Concept for Spherical Converging-Flow Fusion," Fus. Technol., 19(5), 273-299 (1991).
35. R. L. Hirsch (Chairman), "Report of the 1992 EPRI Fusion Panel," Electric Power Research Institute report EPRI-TR-101849 (November 1992).

36. J. D. Delene, "Updated Comparison of Economics of Fusion Reactors with Advanced Fission Reactors," Fus. Technol., 19(3), 807 (May 1991).

NOMENCLATURE

Symbol	Definition
A	Plasma aspect ratio, R/a
a(m)	Plasma minor radius
AC(M$/yr)	Annual charges
ARIES	Advanced Reactor Innovations and Innovations Study
ASC	ARIES Systems Code
B_ϕ(T)	Toroidal (axial) magnetic field
B_θ(T)	Poloidal (plasma-encircling) magnetic field
BOP	Balance of Plant
CD	Current Drive
CER	Cost-Estimating Relationship
COE (mill/kWh)	Cost of Electricity
$CONT_j$	Contingency factor, j = FPC,HTG,PHT,TPE,EPE,MPE,SITE
$CRF(X_o, T_{LIF})$(1/yr)	Capital Recovery Factor
DT	Deuterium-Tritium
D&D	Decontamination and Decommission (charges)
DZP	Dense Z-Pinch
ECRH	Electron Cyclotron Resonance Heating
EPE	Electric Plant Equipment
ES&H	Environmental, Safety, and Health
ES	Energy Storage
f_{AUX}	Auxiliary power fraction, P_{AUX}/P_{ET}
f_{DD}	Fraction TDC needed for D&D
f_{FUL}(1/yr)	Fuel charges as fraction TDC
f_{FPC}	Fraction TDC devoted to FPC
f_{IDC}	Indirect charges as a fraction of TDC
f_{OM}(1/yr)	O&M charges as fraction TDC
f_{RPE}	Fraction TDC devoted to RPE
FCR(1/yr)	Fixed Charge Rate (Constant Dollars)
FCR_{DD}(1/yr)	Effective Fixed Charge Rate for D&D escrow
FPC	Fusion Power Core
FSR	First Stability Region
FW/B/R	First Wall, Blanket, and Reflector
FW/B/R REP	FW/B/R REPlacement
MHTGR-GT	Modular High-Temperature Gas-cooled Reactor, Gas Turbine
HTG/CD	supplemental-heating and CD systems
I_ϕ(A)	Toroidal (axial) plasma current
IDC	Interest During Construction or InDirect Charges
j_ϕ(A/m^2)	Toroidal plasma current density, $I_\phi/\pi a^2$
LWR	Light-Water Reactor
ITER	International Thermonuclear Experimental Reactor
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.[4–8]

NOMENCLATURE (continued)

Symbol	Definition
M_c (kg)	Coil mass
M_{FPC} (kg)	FPC mass
M_N	Blanket neutron-energy multiplication
M	Nominal energy multiplication, $1/Q_E + 0.8M_N + 0.2$
MFE	Magnetic Fusion Energy
MPE	Miscellaneous Plant Equipment
MPD (kWe/tonne)	FPC Mass Power Density, P_E/M_{FPC}
NA	Not Applicable
O&M	Operation and Maintenance
P_{AUX} (MW)	Auxiliary plant power, $f_{AUX}P_{ET}$
P_c (MW)	Recirculating power (current-drive plus BOP auxiliaries)
P_{HTG} (MW)	Current-drive or heating power
P_E (MW)	Net-electric power
P_{ET} (MW)	Total electric power
P_F (MW)	Fusion power
p_f	Plant capacity factor
PF	Poloidal Field (coil)
PFD	Poloidal-Field Dominated
PHT	Primary Heat Transport
PS	Power Supply, switching, and energy storage
P_{TH} (MW)	Thermal power
PWR	Pressurized Water Reactor
Q_E	Enginering Q-value or gain, P_{ET}/P_c
Q_p	Plasma Q-value or gain, P_F/P_{CD}
R(m)	Plasma major radius
R&D	Research and Development
RPE	Reactor Plant Equipment
SITE	structures and site facilities
SM	Special Materials
SSF	structures and site facilities
SSR	Second Stability Region
STH	Stellerator/Torsatron/Heliotron
STR	primary STRucture and support
T_{LIF}(yr)	Plant financial lifetime
TF	Toroidal field (coil)
TPX	Tokamak Physics eXperiment
TPE	Turbine Plant Equipment

NOMENCLATURE (continued)

Symbol	Definition
UBC ($/We)	Unit Base Cost
UDC ($/We)	Unit Direct Cost
US DOE	United States Department of Energy
UC_{FPC}($/kg)	Unit cost of FPC
UC_{HTG}($/W)	Unit cost of plasma HTG, CD
UC_{PHT}($/Wt)	Unit cost of PHT
UC_{TPE}($/We)	Unit cost of TPE
UC_{EPE}($/We)	Unit cost of EPE
UC_{MPE}($/kg)	Unit cost of MPE
UC_{SITE}($/We)	Unit cost of SITE
UC_j^*	Unit cost of j^{th} item with contingency
UTC ($/We)	Unit Total Cost
VAC	reactor VACuum systems
X_o(1/yr)	real (inflation-free) cost of money
β	Ratio plasma pressure to magnetic-field pressure
ϵ	Recirculating power fraction, $1/Q_E$
η_{HTG}	Plasma heating (CD) "wall-plug" efficiency
η_{TH}	Thermal conversion efficiency
η_p	Net plant efficiency, $\eta_{TH}(1-\epsilon)$

TABLE I. Summary of Nuclear Cost Accounting System[24,25] with ARIES Economic Parameters[4-8] Included as Examples

Acct. No.	Account Title	ARIES I′	II	III′	IV
		Million		Dollars	
20.	Land and Land Rights	10.4	10.4	10.4	10.4
21.	Structures and Site Facilities	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 (CD)	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 ES	50.0	55.3	55.3	50.0
22.1.8	Impurity control	12.3	5.4	8.7	5.6
22.1.9	Direct energy conversion system	N/A	N/A	N/A	N/A
22.1.10	ECRH breakdown system	3.9	4.3	4.3	3.9
22.1	Reactor equipment	1411.3	971.7	1134.0	1040.9
22.2	Primary Heat Transport (PHT)	119.2	231.9	68.6	117.3
23.	Turbine Plane Equipment (TPE)	254.5	279.8	323.3	249.3
24.	Electric Plane Equipment (EPE)	101.4	109.5	115.0	100.1
25.	Miscellaneous Plant Equipment (MPE)	54.7	55.5	58.8	53.8
26.	Special Materials (SM)	0.6	14.8	0.6	0.6
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	102.0
93.	Field Office Engineering and Services	122.2	129.6	131.9	102.0
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 (IDC)	623.1	590.9	601.4	520.1
98.	Escalation During Construction (EDC)	0.	0.	0.	0.
99.	Total Capital Cost (TC)	4395.0	4168.3	4241.9	3668.8
		$/We	Constant		Dollars
[90]	Unit Direct Cost, UDC	2.35	2.16	2.20	1.96
[94]	Unit Base Cost, UBC	3.77	3.58	3.64	3.15
[99]	Unit Total Cost, UTC	4.40	4.17	4.24	3.67
		mill/kWh	Constant		dollars
	Capital return	63.8	60.5	61.6	53.3
[40-47,51]	O&M	7.5	9.2	9.2	7.5
[50]	First-wall/blanket replacement	5.0	3.6	0.01	6.6
	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
	Cost of Electricity, COE(LSA = 4)	101.	84.	99.	90.

TABLE II. Summary of Cost Model Input Parameters

input	value
Net-electric power, $P_E(MWe)^{(a)}$	1000.
Plant availability factor, p_f	0.75
Fixed charge rate, $FCR(1/yr)$	0.0860
Operating charge as fraction of capital, $f_{OM}(1/yr)$	0.0400
Fuel charge as fraction of capital, $f_{FUL}(1/yr)$	0.0
D&D charge as fraction of capital, f_{DD}	0.20
Indirect charge 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
Fixed charge rate for D&D, $FCR_{DD}(1/yr)$	0.0017
Unit-cost ratio, $COE/UDC((mill/kWh)/(\$/We))$	32.1
Blanket neutron multiplication, M_N	1.20
Thermal-conversion efficiency, η_{TH}	0.40
"Wall-plug" plasma heating efficiency, η_{HTG}	0.65
Auxiliary power fraction, f_{AUX}	0.03
Unit cost of FPC, $UC_{FPC}(\$/kg)$	100.
Unit cost of plasma heating, $UC_{HTG}(\$/W)$	2.0
Unit cost of site, $UC_{SITE}(\$/We)$	0.30
Unit cost of PHT$^{(b)}$, $UC_{PHT}(\$/Wt)$	$0.80/P_{TH}^{0.45}$
Unit cost of TPE$^{(b)}$, $UC_{TPE}(\$/We)$	$0.67/P_{ET}^{0.16}$
Unit cost of EPE$^{(b)}$, $UC_{EPE}(\$/We)$	$3.71/P_{ET}^{0.51}$
Unit cost of MPE$^{(b)}$, $UC_{MPE}(\$/We)$	$0.87/P_{ET}^{0.41}$
Contingency factor for FPC, $CONT_{FPC}$	0.30
Contingency factor for HTG, $CONT_{HTG}$	0.20
Contingency factor for PHT, $CONT_{PHT}$	0.20
Contingency factor for BOP, $CONT_{BOP}$	0.15
Contingency factor for site, $CONT_{SITE}$	0.10

$^{(a)}$ base-case value, parametrically varied over range 500-1000 MWe.

$^{(b)}$ Reference 23.

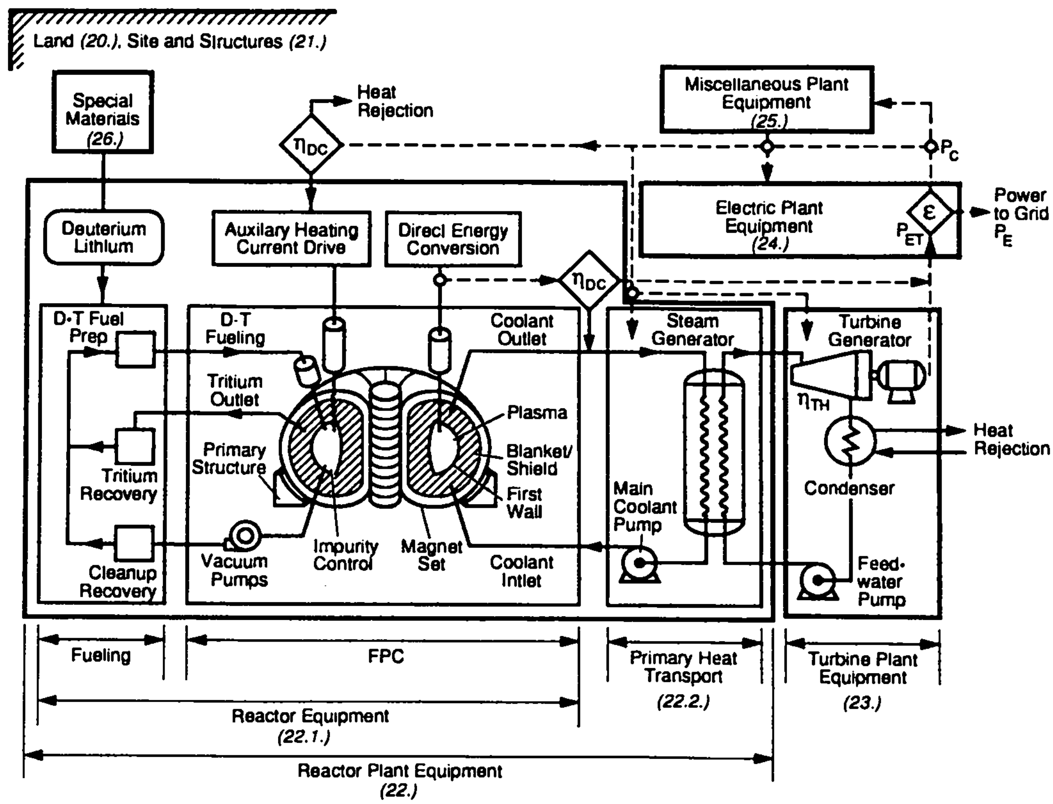

Fig. 1. Fusion power-plant layout showing essential systems functionally organized into major cost-account blocks (Table I).

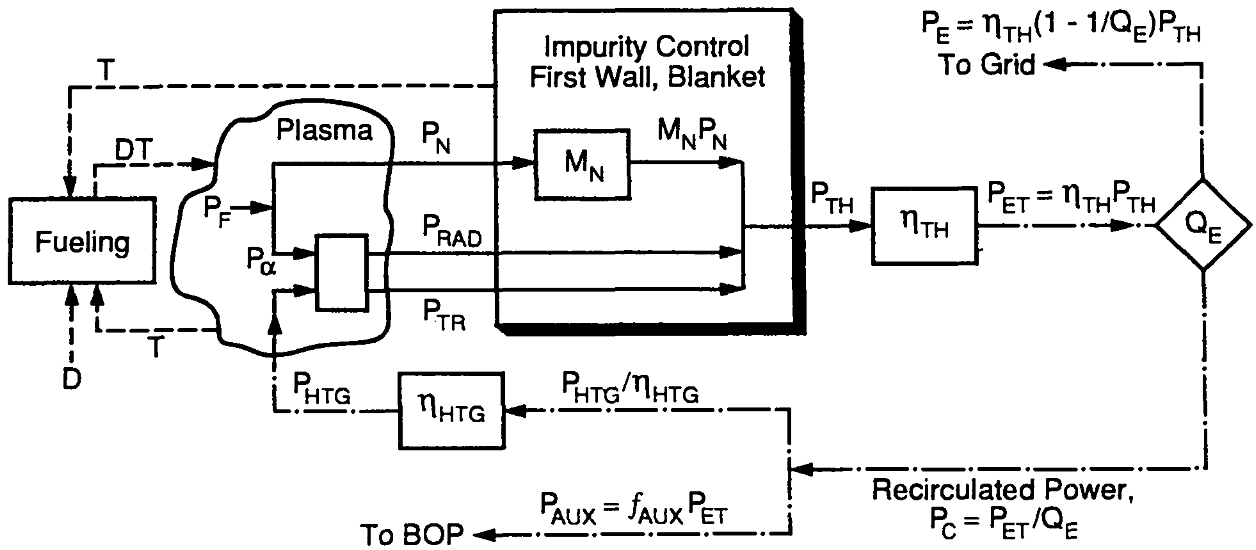

Fig. 2. Simplified energy flows used to model fusion power-plant cost.

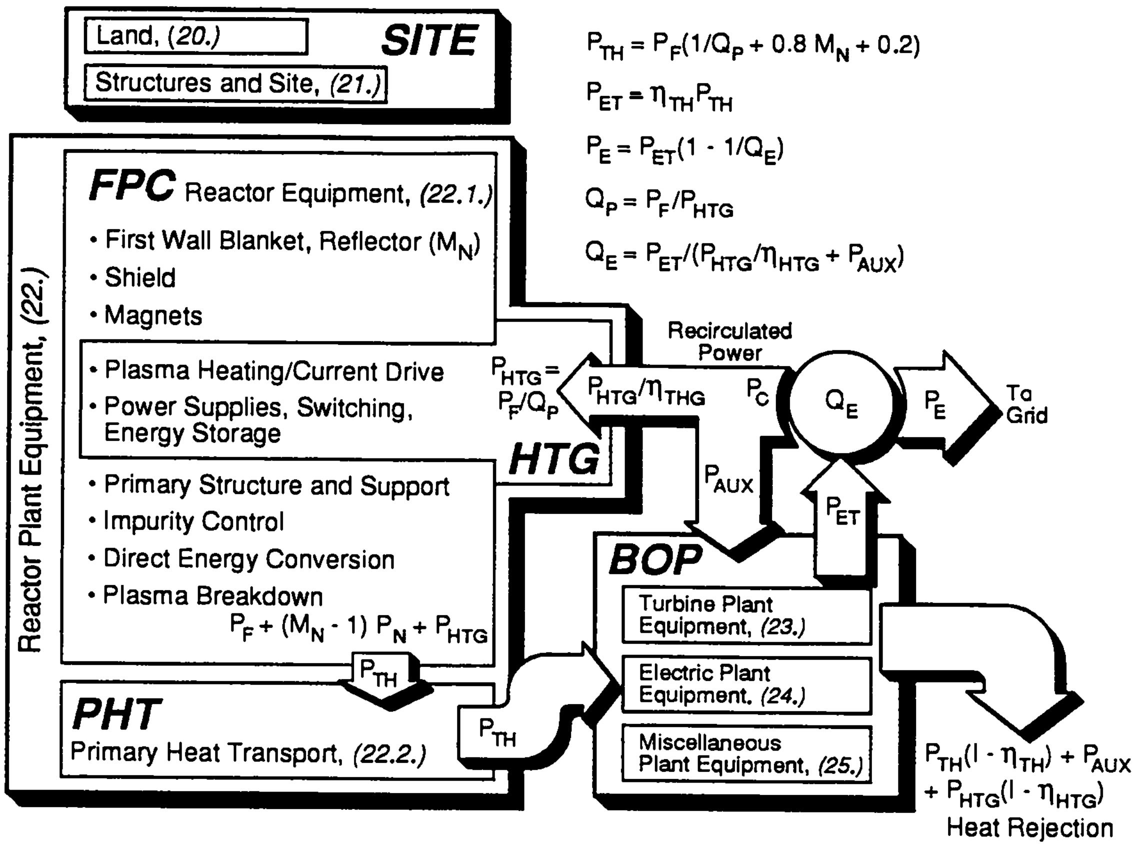

Fig. 3. Condensed fusion power-plant costing model and associated power flows (Table I)

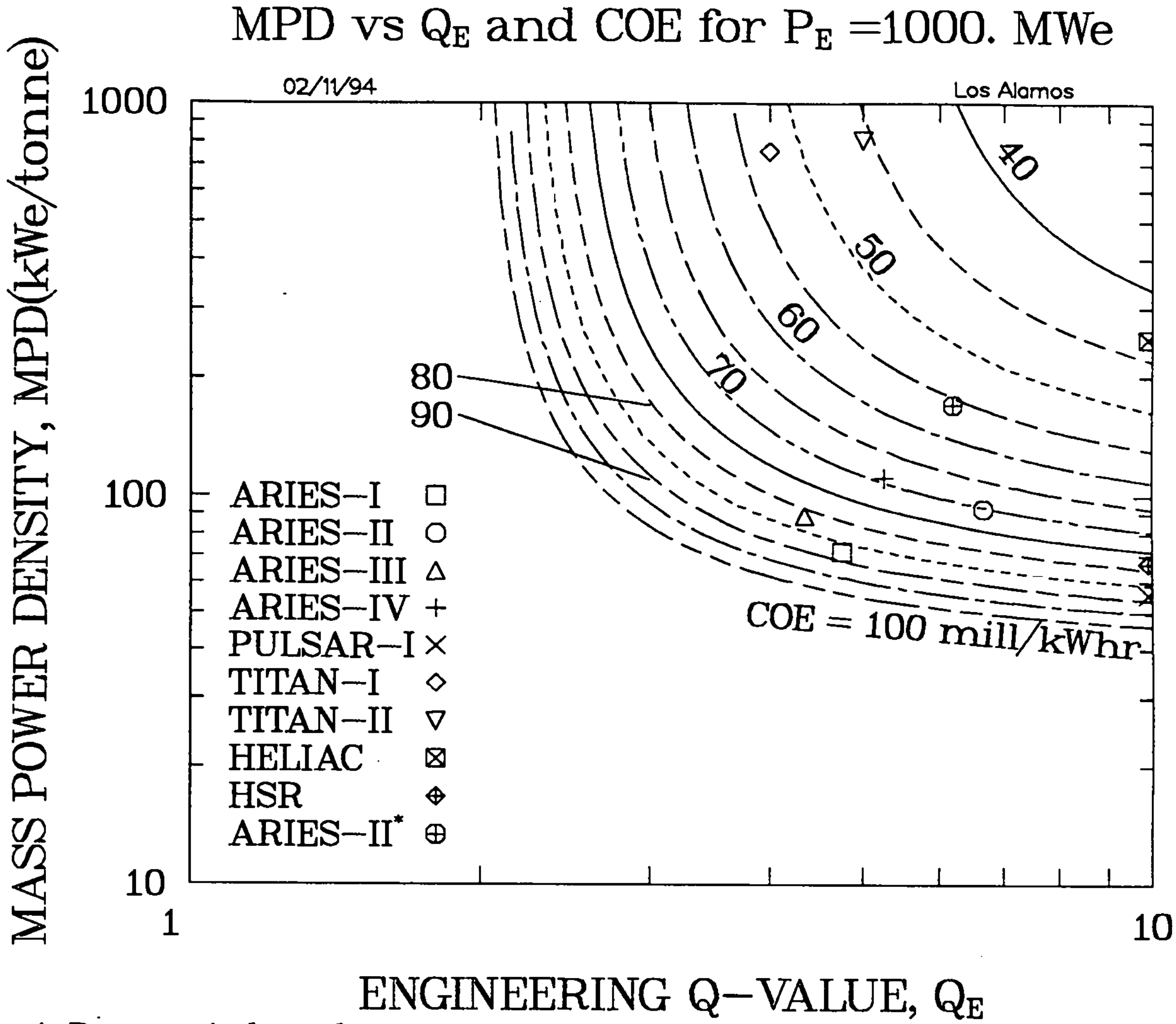

Fig. 4. Parametric dependence of FPC mass power density on engineering gain and a range of COE values for a $P_E = 1000 - MWe(net)$ fusion power plant described by the parameters listed in Table II; shown also are optimized design points from a number of recent tokamak[4–6], reversed-field-pinch[15], and stellerator[17,18] reactor studies. All conceptual MFE power-plant designs are based on a DT fuel with negligable fuel-cycle costs, except ARIES-III, which is based on a D-^{3}He fuel, with the Lunar-^{3}He fuel supply contributing $\sim 20\,\%$ (1.5M$/kg) to the COE[5,7]. The design points for ARIES and TITAN generally reside at or near the top of 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 significant relaxation in physics, engineering, and/or materials constraints.

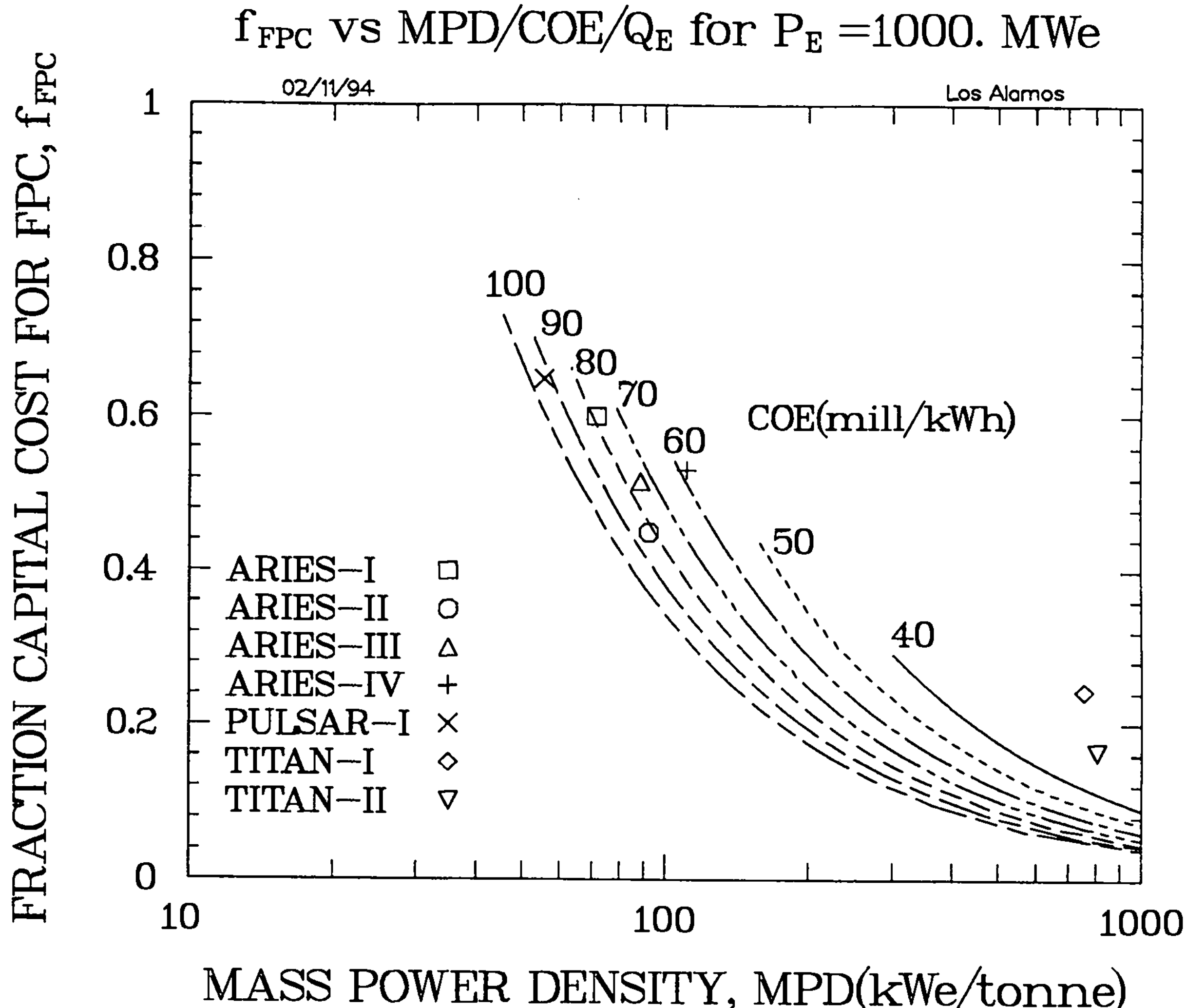

Fig. 5. Parametric dependence of fraction of total direct cost (including contingencies) allocated to the fusion power core (*e.g.*, Reactor Equipment Account 22.1., Table I) on FPC mass power density and a range of COE values for a $P_E = 1000 - MWe(net)$ fusion power plant described by the parameters listed in Table II; shown also are optimized design points from a number of recent tokamak[4–6] and reversed-field-pinch[15] reactor studies. The design points for ARIES and TITAN generally reside at or near the top of 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 significant relaxation in physics, engineering, and/or materials constraints.

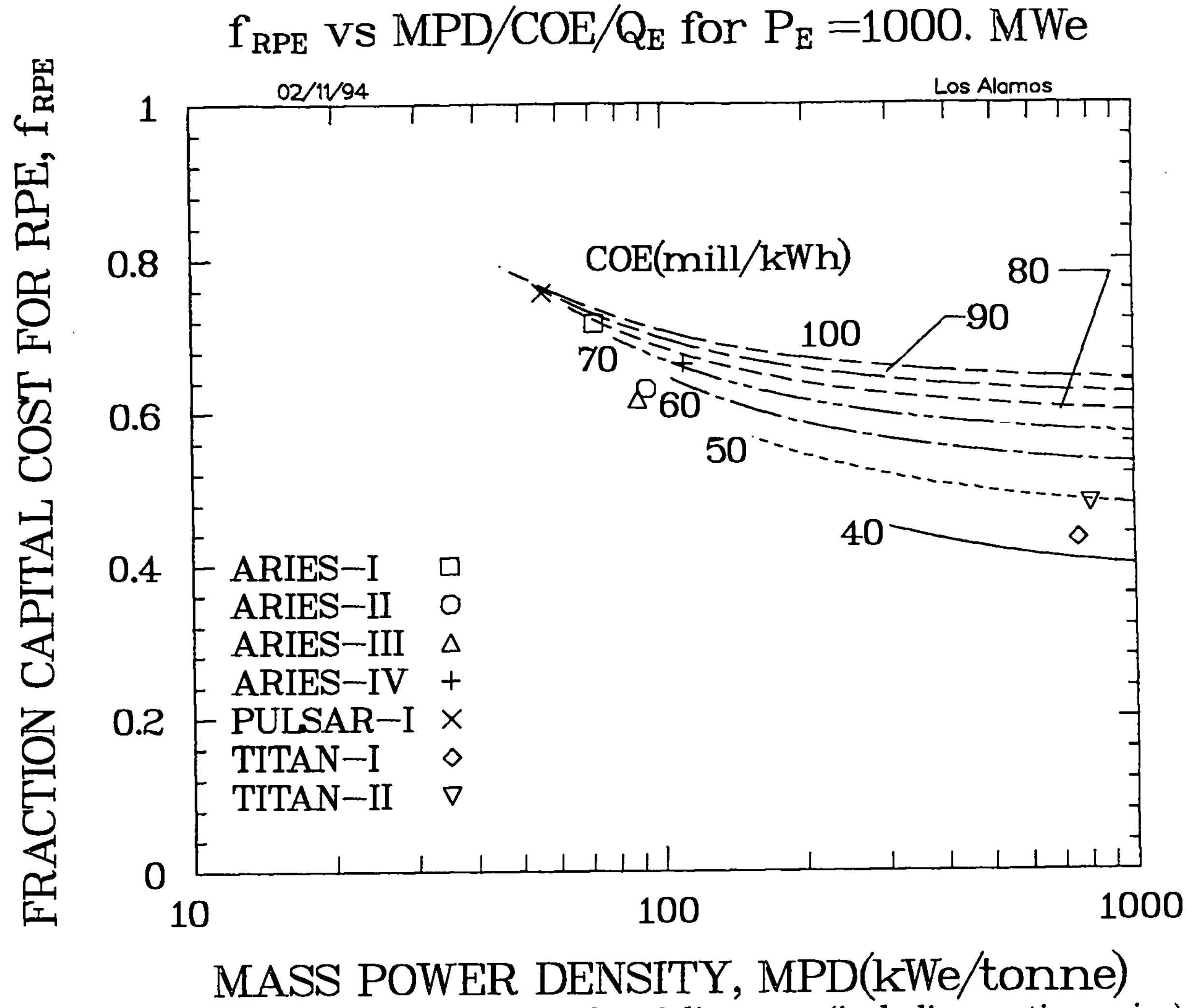

Fig. 6. Parametric dependence of fraction of total direct cost (including contingencies) allocated to the Reactor Plant Equipment (Account 22.1., Table I) on FPC mass power density for a range of COE values for a $P_E = 1000 - MWe(net)$ fusion power plant described by the parameters listed in Table II; shown also are optimized design points from a number of recent tokamak[4–6] and reversed-field-pinch[15] reactor studies. The design points for ARIES and TITAN generally reside at or near the top of 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 significant relaxation in physics, engineering, and/or materials constraints.

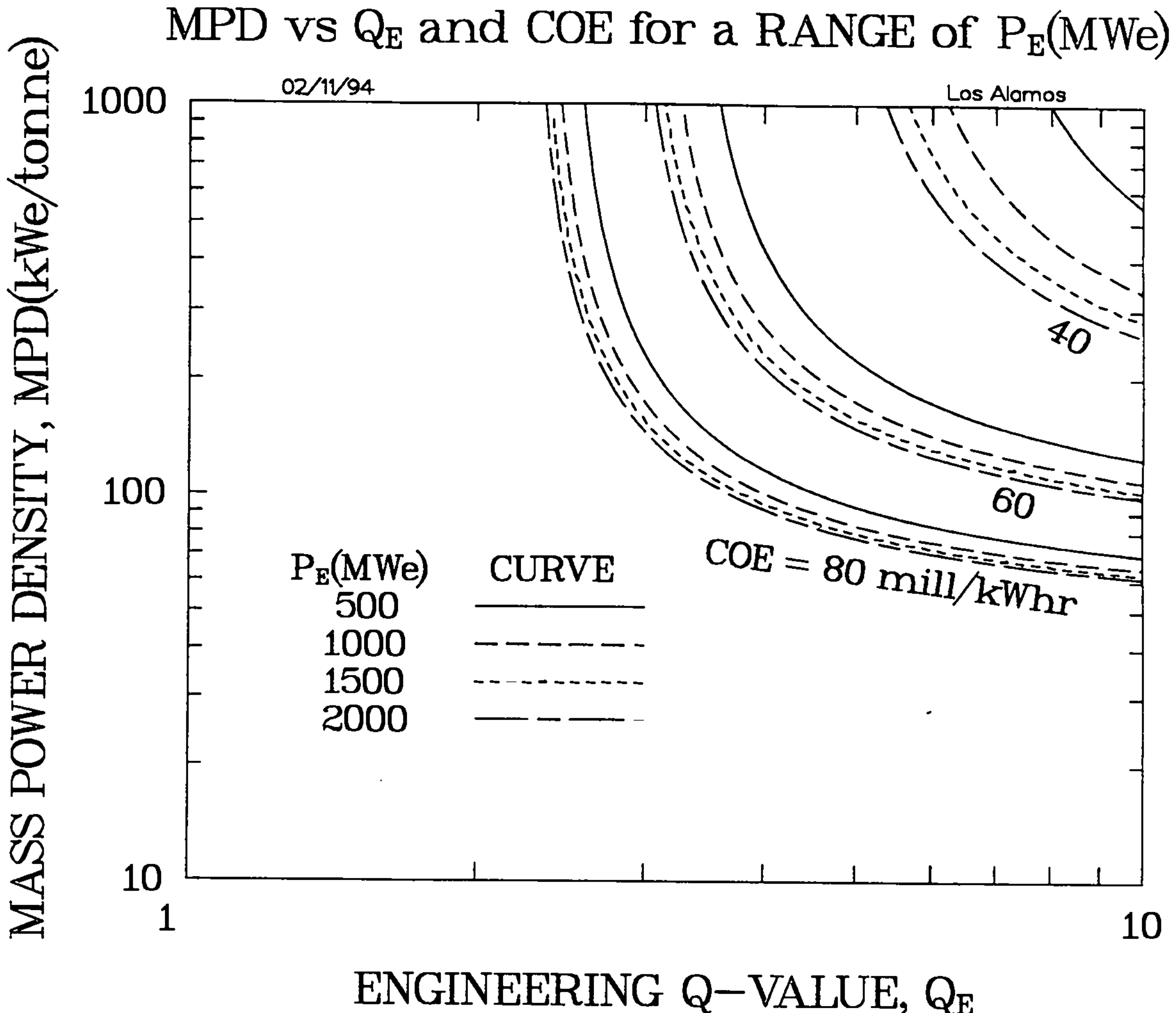

Fig. 7. Parametric dependence of FPC mass power density on engineering gain for a range of COE and P_E values for the fusion power plant described by the parameters listed in Table II.

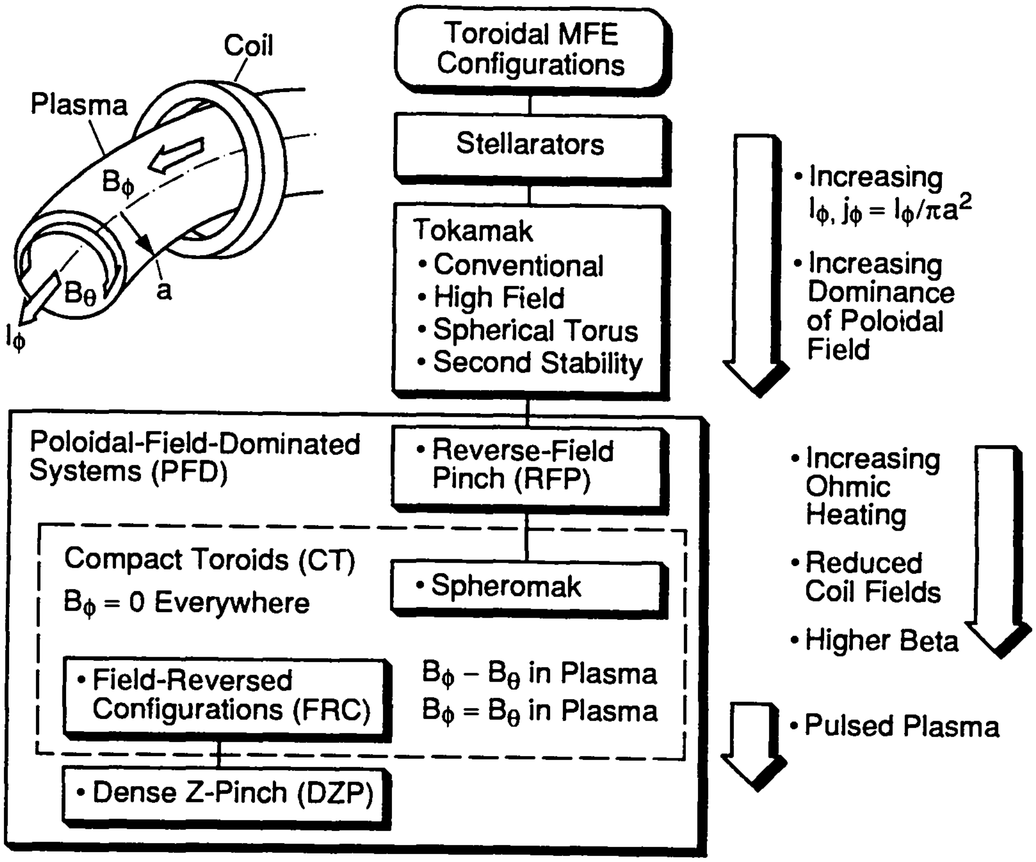

Fig. 8. Spectrum of main MFE configurations ordered according to toroidal (axial) current density and domination of poloidal magnetic field; starting with SSR and ST tokamaks, a lineage of MFE concepts is identified that reduce reliance on externally applied magnetic fields and the economic and operational problems such fields create for the MFEpower-plant extrapolation.