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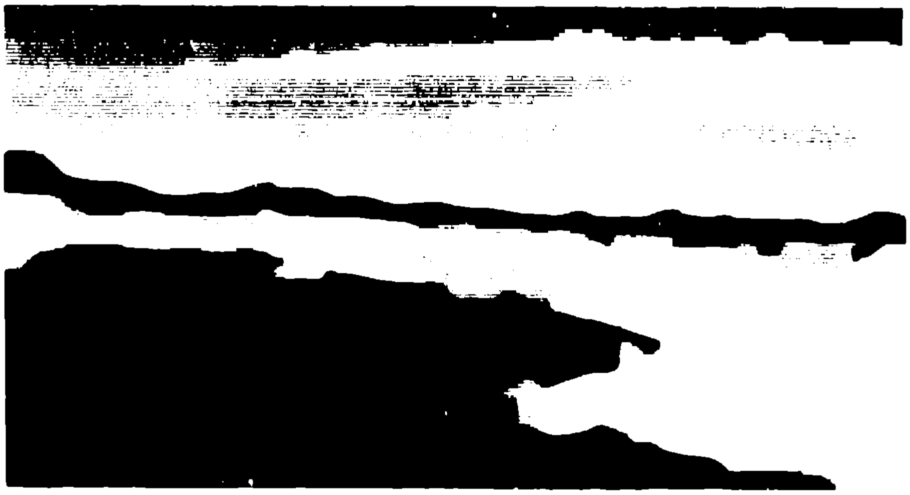

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MAGNETIC FUSION REACTOR ECONOMICS

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ABSTRACT

lmost primordial trend in the conversion and use of ;y is an increased complexity and cost of conversion ms designed to utilize cheaper and more-abundant ; this trend is exemplified by the progression fossil →)n → fusion. The present projections of the latter ate that capital costs of the fusion "burner " far ed any commensurate savings associated with the pest and most-abundant of fuels. These projections est competitive fusion power only if internal costs :iate with the use of fossil or fission fuels emerge to : them either uneconomic, unacceptable, or both with :ct to expensive fusion systems. This "implementation- :fault" plan for fusion is re-examined by identifying in ral terms fusion power-plant embodiments that might)ete favorably under conditions where internal costs ι economic and environmental) of fossil and/or fission ιot as great as is needed to justify the contemporary n for fusion power. Competitive fusion power in this :xt will require a significant broadening of an overly sed program to explore the physics and simbiotic ιologies leading to more compact, simplified, and ient plasma-confinement configurations that reside at ιeart of an attractive fusion power plant.

INTRODUCTION

ιuse the central role of fusion reactors has been as a eyor of electrical energy to commercial and public)rs in competition with other means of electrical power ration, the projected cost of that product [Cost of tricity, COE(1.0 mill/kWeh = 3.6 \$/GJ)] has served as nportant figure-of-merit since the inception of fusion or studies. When possible, environmental and safety ntages suggested for fusion over other long-term gy sources (*e.g.*, nonconventional coal, nuclear fission) been translated into potential economic advantage which to counter the added costs associated with rally massive (low-power-density) and/or power- ιsive (low engineering energy gain) fusion power cores 's) that characterize many designs based on Magnetic on Energy (MFE) concepts. Detailed reactor studies d largely on a range of scientific and technological ιpolations of the tokamak suggest that environmental safety advantages are insufficient to project petitiveness with advance fission systems that are safe, ιsable, publicly acceptable, and operable within a :d fuel cycle [1]. Consequently, two scenarios are :ested to justify continued investment in the present netic-fusion R&D direction: a) advanced fission will achieve the above-mentioned goals while remaining ιomic; b) advanced fission is disallowed for ronmental or safety reasons, and the escalating cost of l fuel and the environmental costs imposed on its use will push the associated COE into and eventually beyond the range presently being projected for tokamak-based fusion power plants.

While waiting for the competition to price itself out of the market within 50-100 years represents one market-penetration plan for fusion, other less-fortuitous scenarios can be envisaged (*e.g.*, fission succeeds, solar photovoltaic/hydrogen competes with both fusion and unconventional fossil). These scenarios suggest a better understanding is needed of the causes that drive upward the cost of (tokamak) fusion power. Means must be found by which these costs can be reduced while assuring an environmentally and publicly acceptable product on a reasonable time schedule and for a reasonable development cost. These cost drivers and the means by which they can be ameliorated are addressed in a context where fission does solve its problems, breakthroughs in solar/hydrogen occur, and/or the real costs of fossil fuel do not escalate out of the range of future competition. While fusion market-penetration studies that accommodate both an escalating competition and (tokamak) concept improvements have been reported [2], the present investigation focuses on concept improvements need in the event that the costs of alternative energy sources do not escalate significantly, in which case new fusion approaches may be required.

DESIRABLE ATTRIBUTES

The "optimal " fusion power plant can be described as follows in terms of flexibility, competitiveness, simplicity, and safety attributes:

- flexibility in (net-electric) power output at acceptable (competitive) cost: total cost, unit costs, development and implementation cost; flexibility in end-product delivered (electricity, process heat, hydrogen, nuclear-waste transmutation, fissile fuel);
- competitive energy-generation costs: acceptable (high) power density, high overall efficiency (high thermal-to-electric conversion, low recirculating power), simplicity of operation and maintenance (reduced and/or combined plasma support functions, few- or single-piece FPC maintenance of the fusion power core), high availability;
- overall design and operational simplicity: steady state, reduced and/or combined plasma support functions, few- or single-piece FPC maintenance, reduced radioactivity (active inventory and waste stream);
- enhanced safety and environmental attributes: inherently or passively safe, reduced radioactivity (active inventory and waste stream), acceptable resource (raw-material) commitment.

Many of these desirable attributes are counteracting and cannot simultaneously be maximized. Additionally, different attributes share common elements (*e.g.*, the elements of reliability, availability, and maintainability contribute not only to the competitiveness attribute, but are important to most of the others also).

The development of commercial MFE power plants that exhibit these attributes can learn much from the experience of U.S. fission power-plant developers. While many of the problems faced today by fission power were not controllable (*e.g.*, cheap fossil fuel and high discount rates, both of which impact a capital-intensive fission power plant that offers primarily a reduced fuel charge), many of these problems have been driven from within the fission-power community [3] and in one form or another can be attributed to: appraisal optimism; premature choice (focus); and cost of complexity. The (commercial) development history of fusion is not sufficient to assess the impact of appraisal optimism (*i.e.*, projecting a surprise-free future and anticipating large savings compared to past projects), but the development history of nuclear fission presents ample cause for concern. An early indication of "appraisal optimism " creeping into MFE projections, even at the preconceptual design level, is the increase in cost projections away from a competitive position reported preliminarily in [4] *versus* subsequent more-detailed and realistic studies [1,5], which in themselves have projected increased cost as the designs evolved. Comparing the complexity of an operating fission power plant with that of a conceptual fusion power plant based on a linear extrapolation of the present leading fusion concept [6] increases cost-of-complexity concerns even more. At the present stage of MFE development, the economic concerns driven by appraisal optimism and system complexity would not be as great had not the choice to focus and reduce opportunities for serious corrective action been made.

DESIRABLE DIRECTIONS

A. *Status*

A change in the direction of fusion development is needed to ameliorate the cost-related concerns discussed in the previous section and summarized quantitatively in [1]. To some extent, these changes are reflect in recent shifts to advanced tokamak physics [7], as embodied primarily in ultra-low-aspect-ratio geometries [8] and plasmas with reversed-shear magnetic-field profiles [9]. Interim projections of advanced tokamaks based on reversed-shear physics indicate [4] COEs close to and possibly below values estimated for the advanced ARIES-II/IV tokamak concepts [1]; Fig. 1 summarizes these ARIES results and makes a comparison with a number of fission and fossil-fuel power plants [10].

As elaborated in [1], "economic competitiveness" is measured against an advanced nuclear power plant that is assumed: a) to be accepted by the customer (utilities, power generators, and ultimately the public); b) to be licensed in an acceptable period of time; and c) to have developed and implemented safe and economic means to close both ends of the nuclear fuel cycle. While a possibility for fusion to exploit opportunities for enhanced public acceptance, reduced licensing burden, generation of a more acceptable (radioactive) waste form, and an economic "closure" of the nuclear fuel cycle, this possibility is a matter of conjecture at this time. Similarly, the competitiveness of fusion with fossil fuel over the next century will depend both on the projected cost of fossil fuels from both conventional and unconventional (*e.g.*, synfuels) sources, as well as the implementation and severity of carbon taxes; estimate of the former have been made as an aide to defining better the fusion economic

Fig. 1. Histogram of Cost-of-Electricity (COE, 1992) values projected for both ARIES [1] and a range of fossil- and fissile fuel power plants [10] of comparable net-electrical capacity, P_E = 1.0-1.2 GWe (PWR = Pressurized-Water Reactor; I = Improved; A = Advanced; MU = Multiple Units; ARIES-I' = first-stability-region tokamak; ARIES-II/IV = second-stability-region tokamak (different blankets); ARIES = second-stability region D-^{3}He tokamak).

window [2], but scarcity-driven fuel-price increases for all ossil fuels remain to be detected [11].

B. *Direction Finders*

1) *Global Energy Assessments:* The COE values used for comparative analyses are derived from technology-based economic assessments, wherein physics and technology constraints are imposed to arrive at a constrained cost optimum for a given set of physics, engineering, materials, and costing assumptions. These analyses yield a discounted COE for comparison with, but in isolation from, other contributors to a regional energy market (Fig. 1). Within a limited scope, however, the cost-benefit analyses reported in [12] has been performed in a global context, wherein the economic impact of fusion on the total mix of available energy-producing technologies is estimated for a given COE assigned to a new technology like fusion. The use of this forced market-equilibrium model [13] to assess the (global) benefit of fusion introduced at a given COE (obtained from a separate technology-based economic assessment of the tokamak-based reactor [6]) gives a view of the impact of COE on the viability of fusion electric power that is broader than that provided by a "one-on-one" comparison of COE (Fig. 1). Fig. 2 displays the (global) incremental Gross National Product, ΔGNP(B$), as a function of the COE assumed for fusion for a range of economic (*e.g.*, discount rate, carbon tax) conditions in a situation where fusion as a new technology impacts the global energy mix through an ability to shift the secondary-energy (*e.g.*, solids, liquids, gases, and electricity [13]) supply curve. Instead of comparing COE values amongst competitive fuels and electricity generators, the global energy/economics/environmental (E^3) model compares net present-value GNP to the cost of developing fusion to generate electrical power at a given COE ascribed to fusion by the technology-based economic assessment (*e.g.*, ARIES). As seen from Fig. 2, the sensitivity of net benefit to fusion COE is strong ($\Delta GNP \sim 1/COE^{2.4-3.9}$, depending on the discount rate and the tax/tariff attached to carbon burning). More recent results from this global E^3 assessments have been reported [14].

2) *Technology-Based Assessments*: Use of the above-described E^3 global model is a logical step after the physics and engineering dependence of COE is assessed using technology-based economic studies like ARIES [1,15]. While cost-base systems models like ASC [15] or SuperCode [16] incorporate all key physics, engineering, and materials models and constraints to arrive at economic optima and to elucidate relevant trade-offs, a simplified "gauge" model can provide valuable guidance for improved economic prospects for MFE. Specifically, a top-level costing model [17] is used to project the cost of electricity on the basis of two highly aggregated reactor parameters: the mass power density, MPD(kWe/tonne), and the engineering energy gain, Q_E. Fig. 3 gives a cost and functional condensation of a generic MFE power plant into Site (SITE), Fusion Power Core (FPC), HeaTinG (HTG), and Balance of Plant (BOP) power-plant "macrosystems". Unit costs for each of these macrosystems

Fig. 2. Net (Global) Value of Fusion, ΔGNP(B$), as a Function of Projected Cost of Electricity, COE(mills/kWeh, 1976) for a Business-as-Usual (BAU) Case and a Carbon Tax (CT) Case under two assumptions of discount rate, x; respective slopes, v, are indicated, where $\Delta GNP \sim COE^{v}$; plotted from values reported in [12].

are used along with the indicated plant energy balance to give [17] the following relationship between COE, MPD, and Q_E:

$$COE = \frac{1}{p_f}\left[\sum_j ACR_j\right]\left[\frac{UC_{FPC}}{MPD} + \frac{1}{\eta_{TH}}\frac{Q_E}{Q_E - 1}\sum_j \xi_j\, UC_j\right], \quad (1)$$

where p_f is the plant availability factor; ACR_j(1/yr) are annual charges related to capital, indirect, Operations and Maintenance (O&M), and Decommissioning and Decontamination (D&D) costs; UC_j are aggregated unit costs associated with macrosystems, η_{TH} is a thermal-to-electric conversion efficiency, and ξ_j is a "Jacobian" that assures all powers are ultimately reduced to electric units. For the typical parameters listed in Table II of [17], Fig. 4

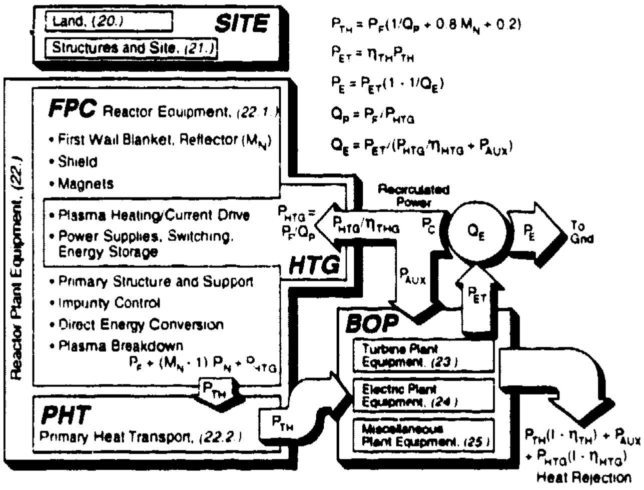

Fig. 3. Condensed MFE Reactor Power Flows and Nuclear Costing Structure. Pj are power. (N = neutron, F = fusion, TH = thermal, ET = total electric, E = net electric, HTG = heating, AUX = plant auxiliary, C = recirculated).

llustrates this dependence of MPD on Q_E for a range of Q_E values. This "gauge" contains no physics, which is provided by concept-specific technology-based assessments, the results from which are also indicated 1,15,18-22].

C. *Directions*

This COE comparison using the MPD *versus* Q_E cost metric suggests directions for improved commercial prospects. Assignment of concept-specific attributes and limitations expressed in the broader terms listed above remain for a more detailed study. While limited in scope, however, the approach and results presented in Fig. 4 serves as one of a number of lodestones with which to guide MFE research along more optimal path to competitive commercialization: high mass power density MPD ≥ 500 kWe/tonne) and high engineering gain (Q_E ≥ 6). The increase of the advanced-tokamak β (*e.g.*, reversed magnetic shear with high bootstrap current, as approximated in Fig. 4 by ARIES-II → ARIES-II*) and an number of poloidal-field-dominated systems (PFDs, high engineering β for nearly self-confined plasma, along with efficient current drive *vis a vis* efficient injection of magnetic helicity, as modeled by the TITAN [16] reversed-field pinch or the CSR [19] spheromak) offer candidate systems.

Fig. 4. Parametric dependence of Mass Power Density, MPD(kWe/tonne) on Engineering Gain, Q_E, showing comparisons between ARIES steady-state tokamaks [1,18]; the PULSAR pulsed tokamak [15]; the TITAN reversed-field pinch [19]; the HELIAC [20] and HSR [21] stellarators; a high-beta ARIES-II* [1]; and the CSR [22] spheromak reactors.

SUMMARY

The price that must be charged by any producer of electrical power to pay for all annual capital, O&M, and fuel charges must be reflected in the bus-bar COE. As seen from Fig. 1, a major part of the cost for an MFE power plant is associated with the intense capital investment required to burn a cheap and abundant fusion fuel. This increase in capital charges needed to utilize fuel with ever increasing resource, in fact, follows the progression fossil → fissile → fusion. For the MFE system on which the world R&D program is now focused, the escalating capital cost is projected to outstrip any potential savings in reduced fuel charge. That increased capital charge has two sources: a) increased cost of the Fusion Power Core reflected in the relatively low MPD values; and b) the increased capital charges associated with an oversized balance-of-plant if the engineering gain is insufficient (*e.g.*, the recirculating power fraction, $1/Q_E$, is too large). Equation (1) and Fig. 4 quantify the related impact on COE.

ither accessed through advanced tokamak physics ,15], PFD systems [19,22], or other less-developed but e compact systems [17,23], the associated iguration and confinement physics must function iotically with the engineering and materials straints imposed by high-power-density operation in a em that is efficient [*e.g.*, both high Q_E and high η_{TH}, ing to high plant efficiency, $\eta_p = (1-1/Qp)\,\eta_{TH}$, as cated on Fig. 3], passive with respect of afterheat ing, and manageable in terms of quality and quantity adioactive waste. The following generic attributes for a competitive system are listed as follows:

- highly radiating plasmas (bulk plasma, edge plasma, or both) to alleviate divertor heat-transfer requirements; the divertor, ideally, should only handle particles;
- high neutron wall loadings (10-20 MW/m^2 DT-fusion neutrons) with the commensurate technology and configurational capability to operate with:
  - high-power-density blankets that more than likely preclude solid tritium breeders and gas cooling;
  - annual changeout of entire first wall and inner-blanket structure;
- material and configurational choices that assure ES&H attributes are maintained·
- all components designed to acceptable engineering criteria at high (but generally more uniform) power density to maintain operational reliability;
- approach 'few'-piece (or ideally, single-piece) maintenance and accrue major benefits related thereto:
  - factory fabrication of (nearly) fully operational FPCs;
  - fully operational pre-service, non-nuclear FPC testing;
  - minimum *in situ* electrical, fluid, vacuum connections during FPC replacement;
  - shortened scheduled maintenance/replacement period;
  - standard and rapid recovery from unscheduled events related to major FPC malfunction;
  - ability to incorporate major physics and technology advances into FPC during life of plant
  - neutron-damage life times that exceed 15 MWyr/m^2.

ile generic in nature and in need of demonstration for cific confinement systems, many of the attributes listed Sec. II should come to fruition if these characteristics of h-MPD, high-Q_E systems can be achieved. Furthermore, se characteristics may allow some of the assumptions g., 75% plant availability) necessary to obtain even the E values listed in Fig. 1 to actually be achieved.

CONCLUSIONS

e focus of these projections and prognoses has been on ion as a provider of electrical energy to improve the ng conditions (*e.g.*, prosperity and security) of a growing world population (1.8%/yr over the period 1989-90; projected [25] to decrease to 1.4%/yr over the period 1990-2020) having hopes of achieving a *per capita* energy utilization comparable to that of North America (NA) plus Western Europe (EUR) [13.8% of the world population and 41.1% of the 8,807 Mtoe (tonne oil equivalent and equal to 42 GJ) energy consumption in 1990; 5.0 toe/capita (NA + EUR) and 7.8 toe/capita (NA), compared to a world-wide average of 1.7 toe/capita]. Electricity, as one of four secondary-energy sources (*i.e.*, gases, liquids, solids, and electricity) accounted for 11.3% (11,607 TWh or 1,325 GWyr) of the secondary energy used in 1990 [23] (ranging from 13.8% in NA to 6.6% in Sub-Sahara Africa), with the linear growth rate of this percentage being ~0.11%/yr.

The energy demand required for a global increase of living standard, as measured by the ratio GNP/capita (18,559 $/capita for NA, 13,403 $/capita for EUR, and 2,144 $/capita for the Rest of the World) [21]), will depend on the efficiency with which energy is utilized (toe/k$ or MJ/$) to achieve and maintain that standard of living, with environmental and other internal costs of each component to the energy spectrum being accounted; if the energy efficiency needed to build an infrastructure required for improved living conditions is increased (*e.g.*, reduced energy intensity, toe/k$) compared to past experiences [25], global energy demands can be significantly reduced, compared to linear projections. Much of this nevertheless significant energy requirement, however, will be non-electric; it seems prudent, therefore, for fusion correspondingly to broaden its end-use spectrum to either directly or indirectly (*i.e.*, in simbiosis) contribute to these future non-electric needs. An expanded niche for fusion may also deal simbiotically with cost and complexity issues related to fusion as an "on-line " producer of electrical power. This broadened role for fusion can become even more important in any future that, through carbon taxes, carbon sequestering, or complete banishment, limits carbon burning.

Magnetic fusion reactor economics have been addressed primarily at a technical level, wherein the least expensive system that meets safety and environmental goals would ultimately enjoy the largest portion of the market. As pointed out in [26], however, straight economics rarely plays a central role in deciding which energy resource to develop. Important quasi- or non-economic considerations that factor into the choices of which energy paths to develop include [26]: a) the political need to control balance of payments, import vulnerability, and energy dependence; b) internal and international pressures related to the environment; c) merits of international cooperation not having direct economic roots; and d) a range of economic/costing biases and/or distortions related to inconsistent/non-uniform assumptions and hidden subsidies. Nevertheless, a more affordable means of meeting energy needs is an important ingredient in presenting an economically, environmentally, and politically manageable solution to the long-term global energy problem; at this early stage of fusion reactor development, the projection of a versatile and economic commercial l-product would go a long way in attracting the attention ìon deserves as a long-term solution global energy needs.

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