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TITLE COMPACT FUSION REACTORS

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ABSTRACT

Compact, high-power-density approaches to fusion power are proposed to improve economic viability though the use of less-advanced technology in systems of considerably reduced scale. The rationale for and the means by which these systems can be achieved are discussed, as are unique technological problems.

I. INTRODUCTION

The engineering development needs for the mainline tokamak have been quantified by detailed conceptual design studies of both first-generation engineering experiments[1,2] and commercial power reactors,[3] while similar studies of the Tandem Mirror Reactor (TMR)[4-6] as well as nearer-term engineering devices[7,8] are being conducted. The status of reactor designs for tokamaks, tandem mirrors, and alternative fusion concepts (AFCs) has been summarized quantitatively,[9,10] and a qualitative assessment of the engineering and technology needs of the major AFCs has been presented recently.[11] The assessment of economic viability for magnetic fusion energy (MFE) provided by these studies can become somewhat convoluted and obscured by the interdependence of complex physics, engineering, and costing/economics. In order to circumvent in part the ambiguity that usually accompanies attempts to combine and interpret results from a large number of relatively independent studies, this paper proceeds on the basis of one simple observation and one straightforward remedy proposed to reduce the implication of that observation. Specifically:

- Observation: most fusion power reactor projections, be they mainline or AFC, indicate a water-heating fusion power core [FPC, i.e., first-wall/blanket/shield/coils (FW/B/S/C)] that is at least an order of magnitude more massive, voluminous, and complex than alternatives.
- Implication: these MFE systems will be appreciably more expensive than alternative, long-term energy sources in spite of a negligible fuel charge.
- Solution: FPCs of considerably higher power density that simultaneously operate with acceptably low recirculating power fractions ($\lesssim$ 0.1-0.2) and reasonable extrapolations of present technology will be required.

Concern over this dominance in FPC mass and cost for many MFE approaches[1-10], therefore, has led to consideration of more compact options.[10-13] This generic category includes the Compact Reversed-Field Pinch Reactor (CRFPR),[12-13] the reactor embodiment of the Ohmically-Heated Toroidal Experiment (OHTE),[14] high-field tokamaks (i.e., Riggatron™)[15-19], and certain subelements of the Compact Toroids (CT, i.e., spheromaks and field-reversed configurations).[20-27] The word "compact" describes approaches that would operate with high engineering or system power density (i.e., total thermal power per unit of FPC volume) and does not necessarily imply small plant capacity. Also, "compact" does not necessarily refer to or limit a specific confinement scheme; just as the Reversed-Field Pinch (RFP) has a viable "conventional" reactor embodiment[28], compact reactor options for the tokamak[15-17], the stellarator/torsatron/heliotron (S/T/H)[29], and certain CT configurations can be envisaged. General characteristics being sought by the compact reactor options are: power densities within the FPC approaching those of light-water fission reactors (i.e., 10-15 MWt/m^3 or 10-30 times greater than for other MFE systems); projected total costs that are relatively insensitive to large changes in unit costs ($/kg) used to estimate FPC and associated reactor plant equipment (RPE) costs, thereby reducing the impact of uncertainties in the associated physics and technology on total cost; considerably reduced FPC size and mass with potential for "block" (i.e., single or few-piece) install-

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ation and maintenance; and the potential for rapid, minimum-cost development and deployment.

The compact option will require the extension of existing technologies to accommodate higher heat and particle fluxes, higher power densities, and, in some instances, higher magnetic fields required to operate FPCs with higher system power densities. Both the advantages and limitations of the compact option, as well as related technological needs, have recently been summarized.[30]

After summarizing in Sec. II. the status of fusion reactor designs in relationship to present and projected near-term experiments, Sec. III. gives a rationale for investigating higher power density options. The pathway to the high-power-density approach is described in Sec. IV. After summarizing a number of recent compact reactor design points in Sec. V., key technology needs are summarized in Sec. VI. Summary conclusions are given in Sec. VII.

II. STATUS

Although the achievement of physics energy breakeven and eventual deuterium-tritium ignition represents major near-term and practically achievable goals, these conditions will be demonstrated in devices containing total plasma kinetic energies that differ significantly from the requirements projected for commercial power reactors. This difference is best illustrated on Fig. 1 by plotting the confinement parameter against the total kinetic energy stored in the plasma. Given steady progress towards achieving improved confinement at reactor-like plasma densities and temperatures, the gap existing between experiments and FED-like devices, as well as between FED-like devices and commercial reactors, translates into a need for significant technology development.

Key plasma, FPC, and power-plant parameters emerging from recent reactor design studies are summarized on Table I. Given continued steady progress, improved plasma confinement leading to plasma ignition appears as a reasonably attainable goal. Extension to the additional 100-1000 fold increase in stored plasma energy required for the commercial reactors summarized in Table I and listed on Fig. 1, however, will require major technological development and attendant costs. Significant reduction in FPC mass utilization, stored plasma and magnetic-field energies, and projected unit costs are possible for the compact systems. These smaller, more compact approaches may lead to a less-costly commercial reactor, while considerably reducing development requirements and costs.

III. RATIONALE

Although the compact approaches reduce the stored plasma energy required for commercial fusion by an order of magnitude, while simultaneously giving enhanced system power density and FPC mass utilization, ultimately, the decision on an optimal system power density must be made on the basis of economics. The direct costs of a fission or fusion reactor is divided into the Reactor-Plant-Equipment (RPE) and the Balance-of-Plant (BOP) costs. The BOP consists of all subsystems outside the secondary containment. The RPE cost for fission reactors is approximately 25% of the plant total direct cost (TDC). Most of the studies summarized on Table I, however, project RPE costs that range from 50 to 75 percent of the TDC. The BOP costs for a fission and fusion plant of the same electrical power output are expected to be approximately the same, although the reactor-building costs for the latter can be greater. Hence, TDC estimates for fusion reactors predict higher values than for fission power plants because of high RPE costs related primarily to expensive (i.e., massive, high-technology) FPCs. This simplified view must be tempered with certain caveats. Fusion reactors capable of significant direct conversion attain higher overall energy conversion efficiencies and, therefore, project smaller BOP costs; the TDC, however, will be smaller only if the cost of the direct energy convertors is sufficiently low. Also, systems with high recirculating power fractions will require larger BOPs and associated costs, even though the FPC mass utilization may be low.

A correlation of the ratio RPE/TDC with the Unit Direct Costs (UDC) for a range of conceptual fusion power plants (Table I) is given in Fig. 2; the dominance of the RPE costs for both mainline and major alternative fusion concepts is indicated. The UDC and the ratio RPE/TDC use nominal values of ~ 900 \$/kWe and 0.25, respectively, in Fig. 2 to normalize the fusion projections to LWRs. The TDC for fusion relative to fission can then be determined under the assumption that the BOP costs for like fusion and fission power plants are nominally equivalent; this curve of $R_{DC} = (UDC)_{FUSION}/(UDC)_{FISSION}$ is also given on Fig. 2. Assuming that the fusion system can expend more on capital investment because of a negligible fuel cost, this tradeoff of fuel for capital cost becomes marginal for R_{DC} values in excess of ~ 1.3 if the fuel cost for fission nominally comprises 1/4-1/3 of the energy cost. Generally, operation in the low-economic-

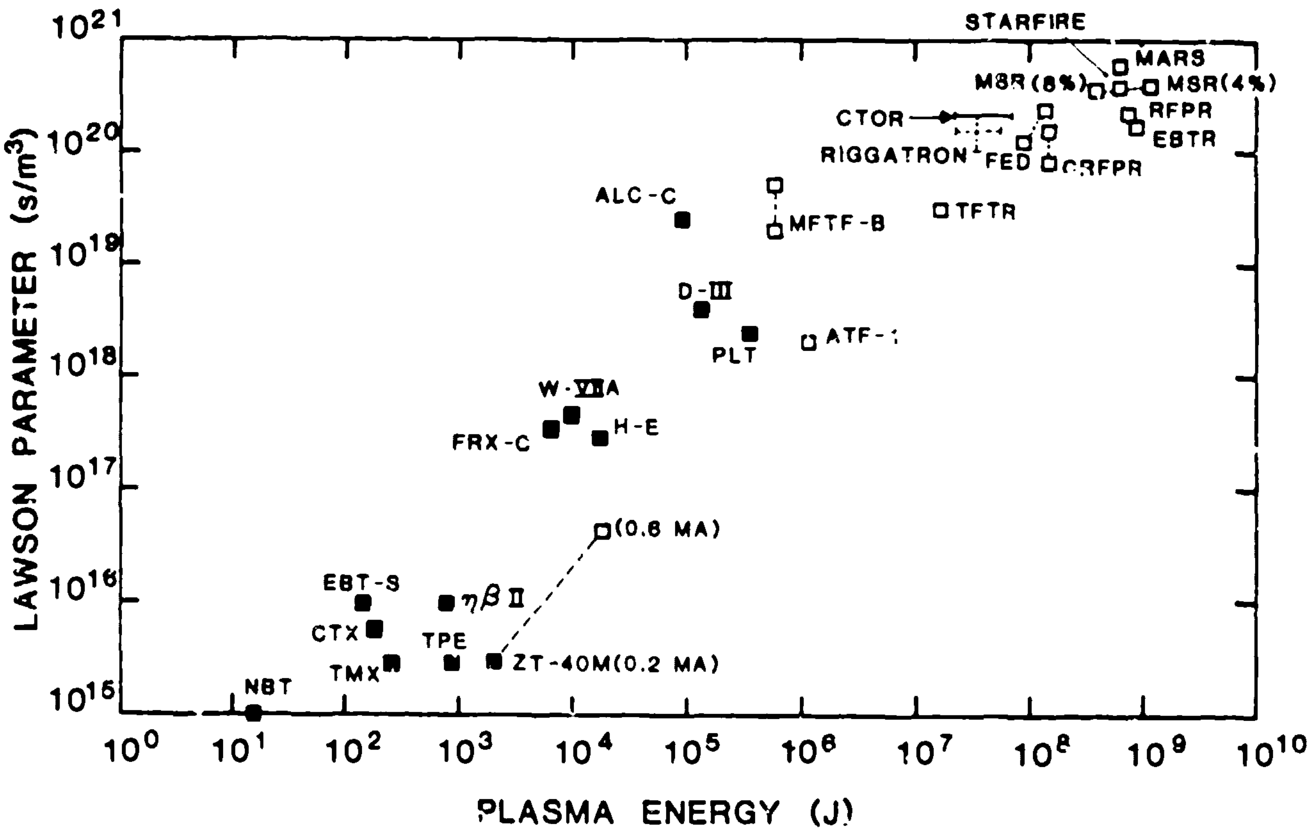

FIG. 1. Achieved, projected, and reactor values of the confinement parameter, $n\tau_E$, plotted versus total kinetic energy stored in the plasma, E_p. Solid points correspond to experimental achievements, and open points are projections. Sources of information: Alcator-C (Ref. 31); Doublet-III (Ref. 32); PLT (Ref. 33); Heliotron-E (Ref. 34); Wendlstein-VIIA (Ref. 35); ZT-40M (Ref. 36); ETA-BETA II (Ref. 37); TPE-1RM (Ref. 38); EBT-S (Ref. 39); NBT (Ref. 40); FRX-C (Ref. 41); CTX (Ref. 42); TMX (Ref. 43).

leverage regime, where RPE/TDC $\lesssim$ 0.3, will require the FPC to be a less dominant component of the TDC. For reasonable unit costs (\$/kg) of fabricated, high-technology components, this criterion can be met only by decreased FPC mass utilization (tonne/MWt) or increased system power density; more compact systems will be required.

The FPC mass utilization for most fusion plants is projected to lie in the range 5-10 tonne/MWt, compared to 0.3 tonne/MWt for LWRs. The mass utilization for the LWR is computed as the mass of the primary containment vessel (less the fuel) divided by the total thermal power. The mass utilization must be used carefully as a comparative measure of system performance; clearly, such comparisons imply a monotonic relationship between mass and cost. Systems with a FPC comprised of large masses of inexpensive coolant (i.e., PbLi) should use mass utilizations that are appropriately compensated (e.g., mass of drained blanket). The mass of an entire fission power plant, exclusive of concrete but including all reinforcing bar, is 10-15 tonne/MWt, which for some fusion reactors is approached by the FPC mass utilization alone. The FPC mass utilizations predicted for a range of commercial fusion reactor designs is shown in Fig. 3; an average FPC unit cost of ~ 30 \$/kg is indicated. Importantly, the total cost of systems with RPE/TDC $\lesssim$ 1/3 (Fig. 2) will be less sensitive to physics and technology uncertainties associated with the assumed plasma performance and FPC operation; both significantly affect plant performance and cost, which in turn can lead to appreciable costing uncertainty and significant under-estimates.[49]

The direct capital cost represents only one component used in estimating the cost of electricity (COE). Figure 4 graphically

TABLE I SUMMARY OF KEY PARAMETERS FOR A RANGE OF DT FUSION REACTOR CONCEPTS

	CONVENTIONAL REACTORS						COMPACT REACTORS		
Device	MSR[44]	STARFIRE[3]	EBTR[45]	RFPR[46]	MARS[47]	PWR[48]	CRFPR[43]	OHTE[14]	RIGGATRON[15]
Design date:	1982(1988)	1980	1980	1979	1982	1980	1983	1983	1982
Plasma radius (m)	0.81(2.25)	2.38	1.0	1.2	0.42	—	0.71	0.66	0.32
Major radius (m)	23.0(27.9)	7.0	35.0	12.7	150.[(a)]	—	3.8	6.32	0.80
Plasma volume (m^3)	298(2788)	781	691	361	83.	—	38.	54.	2.
Average density ($10^{20}/m^3$)	3.64(1.38)	0.81	0.95	2.00	3.0	—	3.4[(e)]	7.0[(f)]	2-30
Temperature (keV)	8.0(8.0)	22	29	15	35	--	20[(e)]	18-23[(f)]	12-20
Plasma energy (GJ)	0.4(1.5)	0.67	0.91	0.81	0.64	—	0.12	0.16	0.03
Field energy (GJ)	109(230)	61.	131.	14.7	—	—	1.5[(g)]	30[(g)]	0.6
Lawson parameter (10^{20} s/m^3)	3.43(3.74)	3.0	1.7	2.0	6.6	—	1.6	1.5	2.0
Average beta	0.08(0.04)	0.067	0.17	0.30	0.40	—	0.20	0.43	0.20
Plasma power density (MW/m^3)	12.4(1.7)	4.5	4.1	7.0	42.5	90	72.4	53.0	500.
Peak magnetic field (T)	11.6(11.2)	11.	10.	3.0	25.0[(b)]	—	8.0[(h)]	13.7[(h)]	16.0[(i)]
Neutron current (MW/m^2)	2.0([illegible])	3.6	1.4	2.7	5.0	—	19.5	14.0	68.4
Thermal power (MWt)	4000(5100)	4033	4028	3000	4536	—	3400.	3200.	1325.
Net power (MWe)	1302(1660)	1200	1214	750	1558[(c)]	1000	1000.	675	355
System power density (MWt/m^3)	0.60(0.30)	0.30	0.26	0.50	—	19.8(7.5)[(d)]	12.0	2.7	5.2
Mass utilization (tonne/MWt)	6.5(8.4)	5.7	~0.85	3.7	5.7[(a)]	0.33	0.36	~1.0	0.28
Thermal conversion efficiency	0.35(0.35)	0.35	0.35	0.30	0.40	0.33	0.35	0.35	0.41
Recirculating power fraction	0.07(0.07)	0.167	0.15	0.17	0.26	—	0.17	0.40	0.33
Net plant efficiency	0.33(0.33)	0.30	0.30	0.25	0.43	—	0.30	0.21	0.27
Unit direct cost ($/kWe)	1265(1482)	1438	1737	1104	~1805	900	875	—	--
Construction time (years)	10(10)	6	5	10	—	8-10	5	—	—
"Then-current" date	1990(1990)	1986	1985	1988	—	1983	1987	—	—
COE (mills/kWeh)	70(78)	67	72	66	—	40	42.5	—	—

(a) Central cell.

(b) Peak field at mirror throat.

(c) Based on 2800 MW of neutron power, which is multiplied in the blanket by 1.37 and an alpha-particle power of 700 MWe (3500 MW fusion power), which is direct converted with an efficiency of 0.5.

(d) Including steam generator volume.

(e) Flat temperature profile, $J_o^2(\alpha r)$ density profile.

(f) Profiles given by $[1-(r/r_p)^2]^\alpha$, where $\alpha = 2$ for $T(a)$ on 0.25 for $n(r)$.

(g) Peak energy in OH coil before plasma startup, reduced to ~ 1 GJ (CRFPR) and ~ 5 GJ (OHTE) thereafter.

(h) Peak field on OH coil during startup, reduced by a factor of 2-3 thereafter.

(i) Peak field at TF coil, fields at OH coil will approach 30 T.

summarizes all major cost components and indicates the combination of these components to determine the COE. Issues that impact on the COE are also shown. The annual fixed charges for conventional and compact fusion reactors will be approximately proportional to the TDC because the indirect capital cost is nominally the same percentage of the TDC for both compact and conventional fusion reactors. Furthermore, the fixed charge rate will be the same unless, for example, the compact reactors require less time to construct and are more amenable to mass production methods. Fuel expenses will be equal for the same fusion power, and operation and maintenance (O&M) costs are expected to be approximately equal for the same plant electrical capacity. The O&M costs will vary if the costs of replacing the FPC differ. Both conventional and compact reactors, however, require replacement of approximately equal masses of material per unit time (~ 200-400 tonne/yr) for the same FW/B lifetime ($MWyr/m^2$). The annual generating cost for a compact fusion reactor, therefore, is expected to be lower than for other approaches to fusion, primarily because of the lower RPE cost. The annual energy output (kWeh/yr) for compact and other fusion reactors of equal capacity may not be equal because the recirculating power fractions and the capacity factors may be different.

Compact fusion reactors clearly must be higher performance devices relative to other fusion approaches because of higher power densities, thermal loads, neutron fluxes, and in some case, higher magnetic fields at the coil. These more "stressed" operating conditions, however, are similar to operating conditions encountered in fission systems, albeit in a more favorable coolant geometry. Furthermore, operating in the compact-reactor regime should not necessarily reduce the plant capacity factor if equal engineering design criteria are used; a higher unit cost for the compact approaches, however, may result.

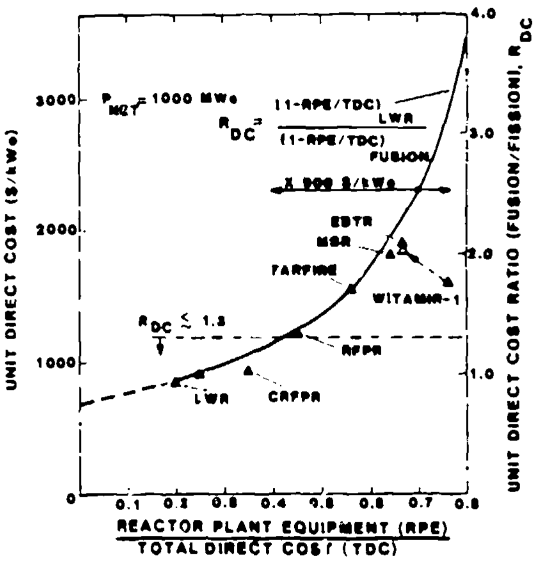

FIG. 2. Plot of UDC versus RPE/TDC for a range of fusion reactor designs. Normalizing these costs to the LWR (UDC ≈ 900 \$/kWe, RPE/TDC ≈ 0.25), the curve of R_{DC} = $(UDC)_{FUSION}/(UDC)_{FISSION}$ is also shown as a function of RPE/TDC under the assumption of nearly equal BOP cost for comparable fusion and fission power plants.

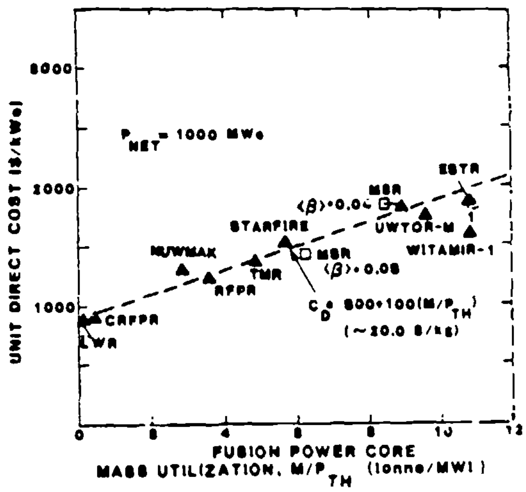

FIG. 3. Correlation of the UDC projected for a number of fusion reactor designs on the FPC mass utilization. The small variations resulting from differences in total power output have been reduced by normalizing all designs to 1000-MWe(net) plant capacity.

Because of the significantly reduced mass utilization, the compact systems can allow "block" maintenance of the FPC, with the attendant potential for relatively rapid FPC change out, replacement, and restart. Nevertheless, a potential exists for a lower plant factor, perhaps diminishing the promise of reduced COE related to reduced TDC and construction time (Fig. 4). Finally, the compact fusion options may offer cost and schedule advantages for the overall development of a usable product for fusion, these advantages also being related to the lesser role played by the FPC and associated support systems in devices leading to the reactor; a bolder research and development program may ensue.

IV. PATHWAY

By focusing on the system power density, P_{TH}/V_c, where P_{TH} is the total useful thermal power and V_c is the FPC volume, the general characteristics for a compact fusion reactor can be estimated. The system power density, expressed in terms of the neutron first-wall loading, $I_w(MW/m^2)$, blanket energy multiplication, M_N, first-wall radius, r_w, blanket/shield thickness, Δb, and nominal coil thickness, δ, is given by

$$\frac{P_{TH}}{V_c} = \frac{2I_w(M_N + 1/4)r_w}{(r_w + \Delta b + \delta)^2} \quad . \qquad (1)$$

Based solely on Euclidian arguments for a toroid that can be approximated by a cylindrical geometry, the maximum system power density occurs for $r_w \simeq \Delta b + \delta$ and equals

$$\left(\frac{P_{TH}}{V_c}\right)_{MAX,I_w,M_N} = \frac{I_w(M_N + 1/4)}{2(\Delta b + \delta)} \quad . \qquad (2)$$

In arriving at this expression, I_w, Δb, and δ are held constant, ignoring the relatively weak interdependence between Δb, I_w, r_w, M_N, and the desire to achieve a given radiation/heating level at the coil position. Within these limitations, Eq. (2) indicates three approaches to increased system power density and decreased FPC mass utilization.

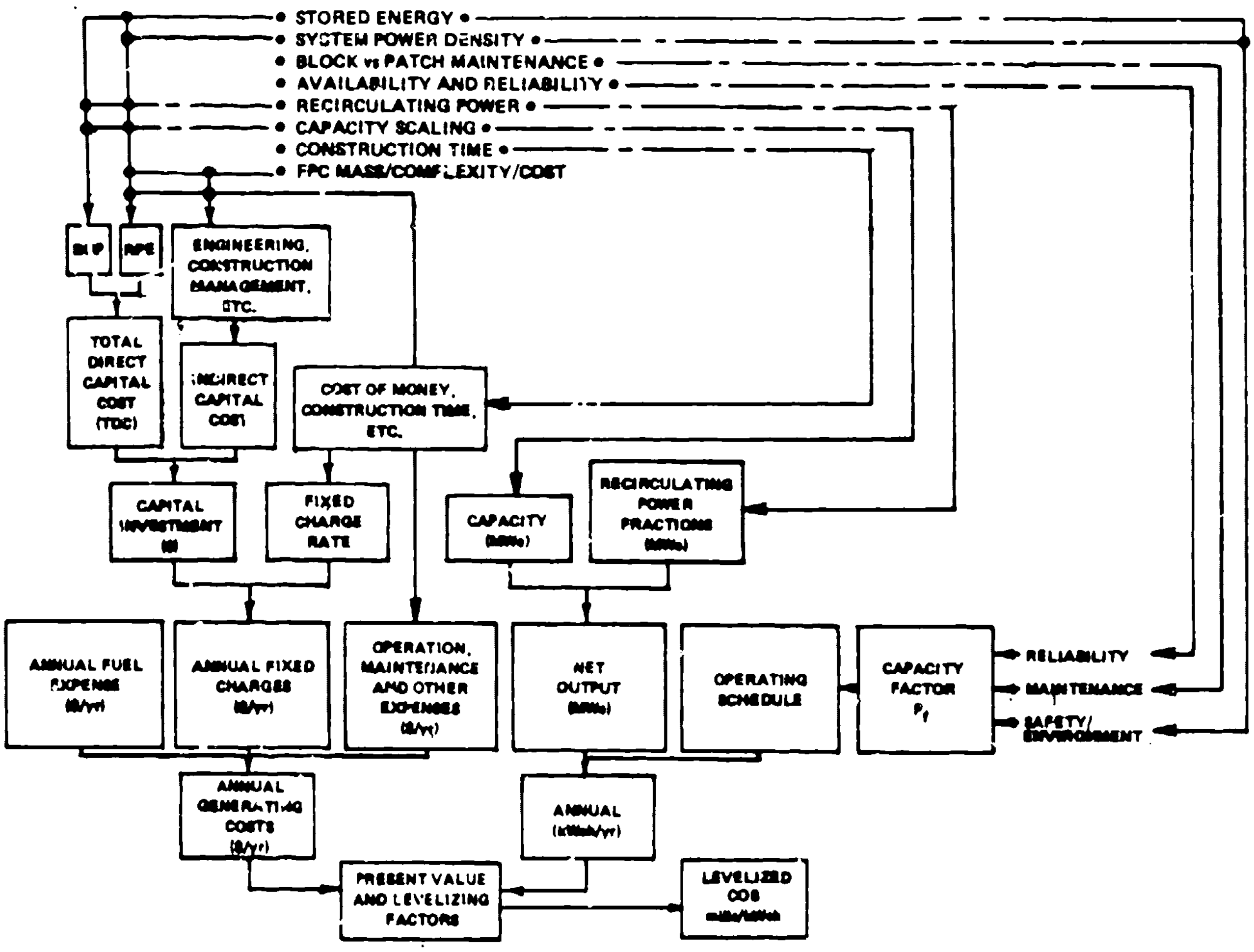

FIG. 4. Logic diagram illustrating the means by which the levelized generating cost of electricity (COE) is computed. Also shown at the top are key influences that may impact the COE when considerations of compactness are taken into account.

- Increase blanket energy multiplication, M_N.
  - real increase: in situ fission
  - virtual increase: in situ fissile-fuel breeding
- Increase fusion neutron first-wall current: $I_w(MW/m^2) \simeq 0.57 r_p \beta^2 B^4$.
- Decrease minor system radius, $r_s \simeq r_w + \Delta b + \delta$, which is achieved through a reduced blanket/shield thickness.

Using Eq. (2) and requiring $(P_{TH}/V_c)_{MAX} \geq (P_{TH}/V_c)^*_{MAX}$, the latter being a reference or design value,

$$\frac{P_{TH}}{2(2\pi)^2(\Delta b + \delta)^2 R_T} \geq (P_{TH}/V_c)^*_{MAX} , \qquad (3)$$

where $r_w \simeq \Delta b + \delta$ and a constraint on total power is implied. For instance, if $P_{TH} \leq 4000$ MWt, requiring that the major radius $R_T \geq r_w + \Delta b + \delta \simeq 2(\Delta b + \delta)$, and specifying that $(P_{TH}/V_c)^*_{MAX} \geq 10$ MW/m^3 together lead to the following constraint

$$(\Delta b + \delta)^3 \leq \frac{P_{TH}}{(P_{TH}/V_c)^*_{MAX}(4\pi)^2} \simeq 2.54 \text{ m}^3 , \qquad (4)$$

or that $\Delta b + \delta \leq 1.36$ m. Clearly, only thin tritium-breeding blankets ($\Delta b \geq 0.6$ m) and resistive magnets ($\delta \leq 1.36 - \Delta b \simeq 0.8$ m) can meet these constraints.

The compact reactor option with $P_{TH}/V_c \geq 10$ MWt/m^3, therefore, is available to MFE approaches that: a) can operate with long-pulsed or steady-state resistive coils while consuming only a small portion ($\lesssim$ 5-10%) of the fusion power, and b) can operate with steady-state first-wall neutron currents given by

$$I_w(\mathrm{MW/m^2}) \simeq \left(\frac{P_{TH}}{V_c}\right)_{MAX} \frac{2(\Delta b + \delta)}{M_N + 1/4}$$

$$\leq \frac{2P_{TH}^{1/3}\,[(P_{TH}/V_c)^*_{MAX}]^{2/3}}{(M_N + 1/4)(4\pi)^{2/3}} \simeq 15\text{-}20\ \mathrm{MW/m^2}\ , \quad (5)$$

where, again, $(P_{TH}/V_c)^*_{MAX} \simeq 10$ MWt/m^3, $P_{TH} \simeq 4000$ MWt, and $M_N = 1.1$ have been used. Hence, fusion neutron first-wall loadings that are 5-10 greater than those being projected for other systems will be required. Furthermore, recalling that $I_w \simeq 0.57\beta^2B^4r_p$ and assuming $r_p \simeq r_w$, the compact reactors must be based on plasmas that are capable of $\beta B^2 \geq 5.1\ T^2$, where B is evaluated at the plasma surface and typically is less by a factor of ~ 2 than the magnetic field at the coil. Generally, improvements in beta and/or coil technologies will be required for many of the approaches listed on Table I in order to significantly enhance the system power density, decrease the mass utilization, and lower the TDC and COE. Simultaneously, these conditions must be achieved in copper-coil systems that do not require a large fraction of the fusion power to recirculated for makeup of Ohmic losses, thereby assuring the cost advantages of less massive FPCs are not seriously eroded by abnormally large BOP costs.

V. OPTIONS

The survey of compact fusion concepts given by Gross in the Ref. 30 workshop encompasses toroidal devices supporting large plasma current density (RFPs, OHTEs, high-field tokamaks), a variety of field-reversed configurations and spheromaks, and other very dense and highly pulsed configurations (i.e., dense Z-pinch, imploding liners, wall-confined systems). Only the first grouping (RFPs, OHTEs, high-field tokamaks) is considered here, these devices sharing common features of Ohmic heating to ignition in a resistive copper-coil system, while focusing specifically on the need for high system power densities. Typical parameters for the CRFPR, OHTE, and Riggatron reactors are also given in Table I.

A. Compact RFP Reactor (CRFPR)[13]

The CRFPR is a toroidal axisymmetric device in which the primary confinement field is poloidal being generated by a toroidal current flowing in the plasma. Although large within the plasma, the toroidal field passes through zero at the plasma edge, reversing direction to a very low value at the magnet coils. The resulting large magnetic shear allows high-β operation and is maintained by intrinsic plasma processes that convert poloidal to toroidal flux, thereby maintaining the reversal. All coils are positioned externally to the blanket, enhancing the ability to breed tritium, providing radiation protection of the exo-blanket coil, and decreasing the recirculating power fraction. The high power density is attained with moderate betas (0.1-0.2) without requiring high fields at the coils, which also substantially reduces the recirculating power fraction. Significantly smaller plant-capacity systems than the 1000-MWe reported in Table I are also possible for the CRFPR, although at a higher unit cost. Central to the achievement of high system power density is the reduction in blanket/shield thickness accompanying the use of normal copper coils. For efficient heat recovery and for adequate tritium breeding, minimum blanket thicknesses of ~ 0.6 m will be required. Although designed for long-pulsed operation, the potential exists for a unique and efficient steady-state current drive[50] for the RFP.

B. Ohmically Heated Toroidal Experiment (OHTE) Reactor[14]

More conservative assumptions with respect to the external control plasma energy losses that accompany the maintenance of toroidal-field reversal near the RFP plasma edge leads to the OHTE. The field reversal and associated magnetic shear at the plasma edge is controlled by actively-driven helical coils positioned near the plasma edge. The high-power-density operation is attained at moderate to high beta, but with higher coil fields than for the RFP without helical windings. To ensure proper field structure these helical coils force larger aspect ratio plasmas, increasing the stored magnetic energy. In addition, this winding produces magnetic flux in opposition to the ohmic heating (OH) winding requiring increased current swings of ~ 25% in the OH set. Since the resistive copper coils are operated near room temperature and are positioned near the first wall, the overall system performance may be reduced in terms of increased recirculating power, reduced plant thermal efficiency, and increased stored energy.

C. Riggatron High-Field Tokamak[15]

The Riggatron is based on a high-field, Ohmically-heated tokamak that uses a high toroidal current density and high toroidal-field copper coils positioned near the first wall. Net energy production is possible in a relatively short burn period from a moderate-beta, Ohmically-heated plasma. The severe thermal-mechanical and radiation environment in which the relatively inexpensive plasma chamber and coil set must operate dictates an approximately one-month life. The overall system performance in terms of plant thermal efficiency and the ability to breed tritium is reduced, since the coils are positioned near the first wall. Unlike the compact RFP and OHTE reactors, the fusion neutron power is recovered in a fixed lithium blanket located outside of the plasma chamber and magnet system. Recovery of Ohmic and neutron heating in the copper coils is also an essential element of the overall Riggatron power balance, which like the OHTE reactor requires a large recirculating power fraction.

D. Other Potential Approaches to Compact Reactors

A number of reactor configurations based on field-reversed[41] or spheromak[42] plasmoids may qualify for the compact, high-power-density option, as previously defined. These Compact Toroids (CT) are generally pulsed systems based either on a translating burning plasmoid or a stationary plasmoid that is subjected to in situ magnetic and/or liner compression. The latter approaches, as embodied in the TRACT[20] or LINUS[21] reactors, offer the potential for system power densities approaching the 5-10 MWt/m^3 range; other CT reactor embodiments also promise significant increases in system power density. The advantages and limitation of a number of CT reactors have been reviewed in Refs. 9 and 25; no attempt is made here to include unique engineering and technology needs of the CT reactors until reactor designs that emphasize the specific goal of high system power density and reduced cost become available. Similar comments apply to the other AFCs.

VI. TECHNOLOGY

The technology requirements for the compact approaches have been summarized[30] relative to the STARFIRE tokamak.[3] This technology assessment has been presented according to major systems that directly impact the FPC (Plasma Engineering Systems, Nuclear Systems, and Magnet Systems); some indications on Remote Maintenance and Safety systems are also given.[30]

Compact reactors would operate at higher plasma densities and, therefore, refueling, impurity control, and ash removal requirements differ. The higher plasma density may also lead to more difficult rf current-drive requirements for steady-state operation. The potential for low-frequency (few kHz) "F-Θ pumping"[50] available to the RFP and OHTE, however, represents an attractive means to drive steady-state plasma currents. The first-wall power loads for compact reactors are higher than for other fusion systems, which also leads to higher blanket power densities. Although the FW/B for the compact systems would operate under more highly stressed conditions, these conditions are considered standard for fission energy sources. The magnetic field requirements for the RFPs can be lower than for most fusion reactor systems, but the fields are considerably higher for the Riggatron. However, the primary difference in magnet technology is reflected by the use of resistive-copper rather than superconducting coils for compact fusion reactors, giving the latter an enormous advantage in terms of development and reliability requirements.

The requirements for the Plasma Engineering Systems should not significantly differ from other fusion systems. Because of the higher first-wall thermal loadings, a heat-flux-concentrating limiter does not appear feasible, and a larger fraction of the first wall will have to serve the limiter function if a divertor is not used. Therefore, the compact option poses more difficult technology requirements related to the first-wall thermal/particle load and blanket (or magnet f Riggatron) power density. A potentially more difficult safety requirement for the compact systems is related primarily to the need for increased emergency-core-cooling capability because of the higher afterheat power density in the FW/B or in the coils in the case of the Riggatron, this enhanced afterheat power density resulting from the higher overall operating blanket power density. The magnet technology requirements are significantly less difficult for the CRFPR and OHTE concepts because of the absence of superconducting magnets and, in the case of the CRFPR, the steady-state magnetic fields are low. Lastly, because of the physical size and mass, block maintenance is possible for compact reactors, wherein the complete FPC is removed external to the reactor cavity, for maintenance and repair operations, with a more rapid replacement by a fresh, pre-tested unit, promising shorter downtimes and more reliable restarts.

VII. SUMMARY AND CONCLUSIONS

In summary, the following characteristics emerge for compact fusion systems.

- The FPC is comparable in mass or volume to comparable heat sources of alternative fission energy sources.
  - system power density: 10-15 MWt/m^3
  - mass utilization: 0.4-0.5 tonne/MWt

- UDC ($/kWe) and COE (mills/kWeh) are less sensitive to large changes in FPC unit costs ($/kg) and related physics and technology.

- Rapid development at reasonable cost may be possible.
  - small system size, flexible (alterable) development path, possible to experiment with technology paths while avoiding large cost and time penalties.
  - no need for long-lead development items that are sufficiently uncertain in themselves as to impact the overall approach (i.e., large superconducting magnets, high-frequency/large-power rf, large-power/ steady-state neutral-beam injectors, remote maintenance of massive structures).

- "Block" installation and maintenance becomes a possibility.
  - off-site mass production of complete FPC.
  - shortened construction times.
  - complete pre-installation thermo-mechnical/electromechanical/vacuum test of FPC.
  - shortened scheduled/unscheduled downtime and higher plant availability.

Generally, the compact options require extended rather than new technologies and project competitive COEs by demanding higher FPC performance while attempting to maintain high plant factors and low recirculating power. Extension of existing technologies are required to accommodate the higher heat fluxes and power densities needed to operate the FPC with enhanced system power density and mass utilization. The major technological challenge, therefore, rests with achieving reliable reactor operation of a more highly "stressed" FPC. In return, a power system emerges in which basic physics and technological unknowns related to the FPC exert considerably reduced economic leverages on the total plant and energy costs. Equally if not more important are the benefits related to more rapid development, installation, and maintenance of FPCs that are at least an order of magnitude less massive and complex than those presently being projected for other MFE approaches.

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