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TITLE: A COMPACT APPROACH TO FUSION POWER REACTORS

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A COMPACT APPROACH TO FUSION POWER REACTORS

ABSTRACT

The potential of the Reversed-Field Pinch (RFP) for development into an efficient, compact, copper-coil fusion reactor has been quantified by comprehensive parametric tradeoff studies. These compact systems promise to be competitive in size, power density, and cost to alternative energy sources. Conceptual engineering designs that largely substantiate these promising results have since been completed. This 1000-MWe(net) design is described along with a detailed rationale and physics/technology assessment for the compact approach to fusion.

I. STUDY RATIONALE AND DESIGN BASIS

The difficulties encountered by large nuclear systems in penetrating the US electrical-power market can be attributed to causes generally related to insufficient standardization. Recent approaches based on small fission reactors [1,2] have been suggested as solutions. In particular, factory (off-site) fabrication and quality control methods result in systems that follow economic learning curves, reducing costs as unit production numbers increase and avoiding one-of-a-kind system costs. Plant standardization minimizes site-specific licensing procedures, which are further alleviated by a nuclear system that is better isolated, reduced in volume, and fabricated/tested under more controllable conditions. Finally, systems of lower total cost greatly improve the financial condition for the electric utility [3] even though the unit costs ($/kWe) may be greater.

The aforementioned problems are expected [4-6] to be exacerbated for fusion power systems projecting an end product that may be considerably larger in size and lower in fusion-power-core (FPC, i.e., plasma chamber, first wall, blanket, shield, and coils) power density. Even using tenth-of-a-kind costing (i.e., developed learning curves, mass production, etc.), these fusion plants will have 1.5-2 times greater capital costs; more realistic one-of-a-kind costs can easily lead to capital costs that are at least 2-3 times greater than present fission systems. A competitive fusion system would seek to increase the power density of the nuclear source subject to realistic physics, engineering, materials, and safety constraints. Several fusion systems have been identified [7] that potentially lead to more compact, higher-power-density options, including resistive-coil tokamaks and compact toroids, with the Compact Reversed-Field Pinch Reactor (CRFPR) design [6] being summarized here.

II. REACTOR DESIGN POINT

The efficient heating and confinement of plasma by the RFP (high beta, low fields at coils, ohmic heating) permits a thin blanket/shield (~ 0.6-0.7 m) and resistive (copper-alloy) coils, both being essential for significant increases in FPC power density. The cost of electricity (COE) for a complete range [6] of cost optimized designs is depicted in Fig. 1. The implications of decreasing the first-wall loading, I_w, net electric power, P_E, and system size (r_p, with the minimum-COE designs insensitive to aspect ratio) are shown as constrained by the experimentally derived confinement scaling, $\tau_E \propto I_\varphi^\nu r_p^2 f(\beta_\vartheta)$, $\nu = 1$-1.5, and $f(\beta_\vartheta) = (0.13/\beta_\vartheta)^2 \leq 1$, where the beta dependence is presumed analogous to neutral-beam-heated tokamaks [6]. The minimum-COE base case chosen for a conceptual design study is elaborated in Table I and illustrated in Fig. 2. Although the increase in COE resulting from increased physical size and reduced FPC power density is not great for the parameter range examined in Fig. 1, the goal to investigate technology limits and to maintain a single- or few-piece FPC maintenance scheme resulted in operation at the shallow COE minimum for P_E = 1000 MWe.

III. REACTOR OPERATION

The time-dependent plasma engineering model [6] is driven by the poloidal-field-coil circuit (PFC) which is divided into an Ohmic-Heating-Coil (OHC) set used to drive flux and the Equilibrium-Field-Coil (EFC) set. Precharging the OHC to 33.5 MA-turns in 16.3 s by a 1.0-kV, 350-MWe grid source provides _in situ_ energy storage, which is then resistively decayed while operating the OHC and EFC in parallel, driving the plasma current, I_φ, to 12 MA in 1.2 s. Reapplying the grid source establishes I_φ/OHC/EFC currents of 18.4/21.3/11.0 MA-turns, respectively, in 8 s. The RFP configuration [$\vartheta = B_\vartheta(r_p)/\langle B_\varphi\rangle = 1.55$, $F = B_\varphi(r_p)/\langle B_\varphi\rangle = -0.12$] results at ~ 12 % of the full plasma current as the toroidal field coil (TFC) varies $B_\varphi(r_p)$ from 0.4 to -0.4 T. Supplying the bulk of the internal toroidal flux, $\varphi = \pi r_p^2\langle B_\varphi\rangle$, from the PFC circuit _via_ the experimentally observed "dynamo effect" minimizes the TFC system requirements. Calculating one-dimensional plasma equilibria based on experimentally derived plasma profiles [force-free currents, $T(r) \propto n(r) \propto J_0(\mu r)$], integrating all plasma properties over the cross section, and following the energetic particles by a Fokker-Planck formalism models the plasma response. Taking the electron conduction, $\tau_{ce} = 5(10)^{-8} I_\varphi r_p^2 (0.13/\beta_\vartheta)^2$ for $\beta_\vartheta \geq 0.13$, and particle, $\tau_{pi} = 4\tau_{ce}$, confinement times, the initial (1-mtorr) filling density is increased to the final value by a fueling rate held below 1.3 n_i/τ_{pi}. Ignition is reached by ohmic heating in 6 s; the scaling $\tau_{ce} \propto 1/\beta_\vartheta^2$ saturates the ignited 10-keV burn at $\beta_\vartheta = 0.23$, which includes pressure from superthermal particles.

The sustenance of I_φ against resistive decay by in-phase oscillation of the TFC and PFC circuits ("F-ϑ pumping") is proposed [6]. Reversed-field-pinch experiments demonstrate a remarkable coupling between these circuits as the plasma preferentially maintains a constant average magnetic helicity, $K = \int A{\times}B \, dV_p$, and operates within a narrow range of specific ϑ and F values. Current-drive parameters include 50-Hz fractional toroidal flux swings of $\delta\varphi/\varphi = 0.01$ and toroidal current swings of $\delta I_\varphi/\langle I_\varphi\rangle = 0.004$. If the OHC current were driven to zero upon achieving steady state, the 73 MWe consumed by that coil set would be available for use by the current drive and to supply the plasma resistive dissipation (25.3 MWe).

IV. FUSION-POWER-CORE (FPC) INTEGRATION

The FPC engineering design and integration concentrated on the in-vacuum components (IVCs: first-wall, limiter, vacuum pumping), blanket/shield neutronics and thermohydraulics, and the magnet systems. Uniformily radiating 90 % of the 5 MW/m^2 charged-particle and ohmic powers, the remaining particle-transport loss is delivered to a toroidal array of 24 poloidal pumped limiters operating at a peak local heat flux of 6.0 MW/m^2 and contributing to 40 % of the first-wall area. Because $B_\varphi << B_\vartheta$ at the plasma edge, poloidal pumped limiters or toroidal-field divertors [8] are preferable impurity-control schemes for the RFP. The 112-m^2 first-wall area is comparable to the 62-m^2 limiter area for STARFIRE [9], which is designed to withstand a surface-heat flux of 4 MW/m^2. A high-strength copper alloy is proposed for the first-wall/limiter surface and provides a sufficient engineering design margin contingent upon two predominant uncertainties: a) sputtering effects which invoke the use of low-Z coatings [9] and high plasma-edge temperatures, and b) radiation damage effects incurred during the structural lifetime (15 MWyr/m^2 for the Table I design, values as low as ~ 5 MWyr/m^2 being allowed by economics). Separate pressurized-water coolant loops are used for the limiter and first wall, with the first-wall coolant returning in the blanket structural (HT-9 ferritic alloy) "second wall" to satisfy corrosion-related temperature constraints.

The high peak power density in the blanket (250 MWt/m^3, comparable to that in a fission reactor core) necessitates a liquid-metal coolant/breeder. A 0.6-m-thick flowing $Pb_{83}Li_{17}$ (90 % ^6Li) blanket has a tritium breeding ratio of 1.03 and multiplies the 14.1-MeV neutron energy by 1.28. These two-dimensional neutronics calculations [6] quantify tradeoffs incurred because of design choices that: a) place water-coolant manifolds near the first-wall region, and b) specify first-wall/conducting-shell thicknesses in excess of 5 mm. Surrounding the blanket is a neutron reflecting shield consisting of 90 % stainless steel (316) and 10 % H_2O, which also serves a structural function for the FPC. The combinations of first-wall/second-wall thickness, manifold/header placement, breeder enrichment, and shield albedo enhancement combine in a multi-dimensional geometry to provide an important optimization for this desirably thin blanket/shield system; higher breeding margins are achieved by modest increases in the blanket thickness [6].

Surrounding this blanket/shield structure are 24, 0.075-m thick, TFCs producing a maximum toroidal field of 0.6-0.7 T at the windings. The PFC system is located outside the TFC set and is divided into a 20-coil 100-turn OHC system (394 tonnes) and a 12-coil 80-turn EFC system (404 tonnes). All coils use water-cooled copper-alloy conductors that are insulated with powdered or plasma-sprayed MgO or $MgAl_2O_3$. The maximum conductor resistivity increase (from Ni and Zn transmutation products) and (MgO) insulator swelling are expected to be 0.7-1.4 % and 0.09 v/o per annum, respectively, indicating a lifetime for these coils far exceeding that for the first-wall/blanket/shield system.

Annual replacement of the 45.2-tonne first-wall/blanket system (17.9 kg/MWtyr or 20,000 MWtd/tonne) for the design lifetime (15 $MWyr/m^2$) increments the COE by less than 1 % for a fabricated material cost of \$50/kg. The performance of the copper-alloy first-wall/limiter components represent the greatest uncertainty resulting from degradation of thermal properties, buildup of transmutation products, and sputtering. Penalties reflected by increased COE do not become excessive if I_w exceeds $\sim$ 5 MW/m^2, requiring a lifetime of $\geq$ 5 $MWyr/m^2$ as derived from the comprehensive model relating first-wall loading, FPC lifetime, maintenance requirements, and plant availability (Fig. 1).

The isometric view in Fig. 2 shows access at the outboard equatorial plane for all coolants, vacuum, and electrical lines. Both pressurized-water and PbLi coolant ducts are sized to assure critical limits on water flow velocity (~ 10 m/s), PbLi pressure (1.1 MPa), and pumping power (1.3 % of the gross electric power) are satisfied. The top half of the PFC set (400-tonne total) would be lifted in two sections, exposing the off-site manufactured and pretested 300-tonne first-wall/-blanket/ shield/TFC unit for replacement as a single assembly during the annual maintenance period. The FPC replacement time compared to the time to replace a smaller segment of a larger, low-power-density torus is an important unresolved tradeoff.

V. CONCLUSIONS

The physics and engineering characteristics of key FPC engineering systems have been broadly described, quantified, and integrated for a high-wall-loading, compact RFP reactor. The RFP is one of a class of approaches that can confine high-beta plasma without excessive toroidal magnetic fields at external conductors. Hence, efficient, resistive-coil systems are possible with a FPC mass and volume reduced by factors in excess of 20 when compared with superconducting systems of similar power rating; both reduced cost and single-piece FPC maintenance of a factory-produced system become possible. Furthermore, unique and highly efficient plasma heating and steady state current-drive systems that are inherent to the RFP may be possible. Although this study stressed impurity control by high-wall-coverage (poloidal) pumped limiters, the ability to use closely coupled resistive coils allows serious consideration and enhanced practicality of (toroidal-field) magnetic divertors. Lastly, although this study stressed the minimum-cost, 1000-MWe(net), ~ 20-MW/m^2(neutrons) design (Fig. 1), comprehensive parametric studies show acceptable cost penalties for lower-wall-loading FPCs [5-10 MW/m^2(neutrons)] of nominally the same physical size, operating with reduced power density, delivering reduced total power, but nevertheless projecting a competitive system. This robustness allows the use of alloys based on metals other than copper while still projecting a significantly improved end product. Maintenance of the regenerative RFP dynamo at higher plasma pressures while retaining the already reactor-relevant beta with increasing current is central to achieving this competitive end product. The radiation response and lifetime of the copper-alloy first-wall and limiter systems, control of wall erosion and plasma impurities, and a quantitative understanding of FPC reliability and replacement times, all as they affect plant availability and COE, represent areas where technology development is needed. The RFP, nevertheless, presents a robust plasma confinement system capable of providing a range of reactor systems that are compact in both physical size and/or net power output while assuring acceptable cost and engineering feasibility for a range of assumed physics (beta, transport) performance.

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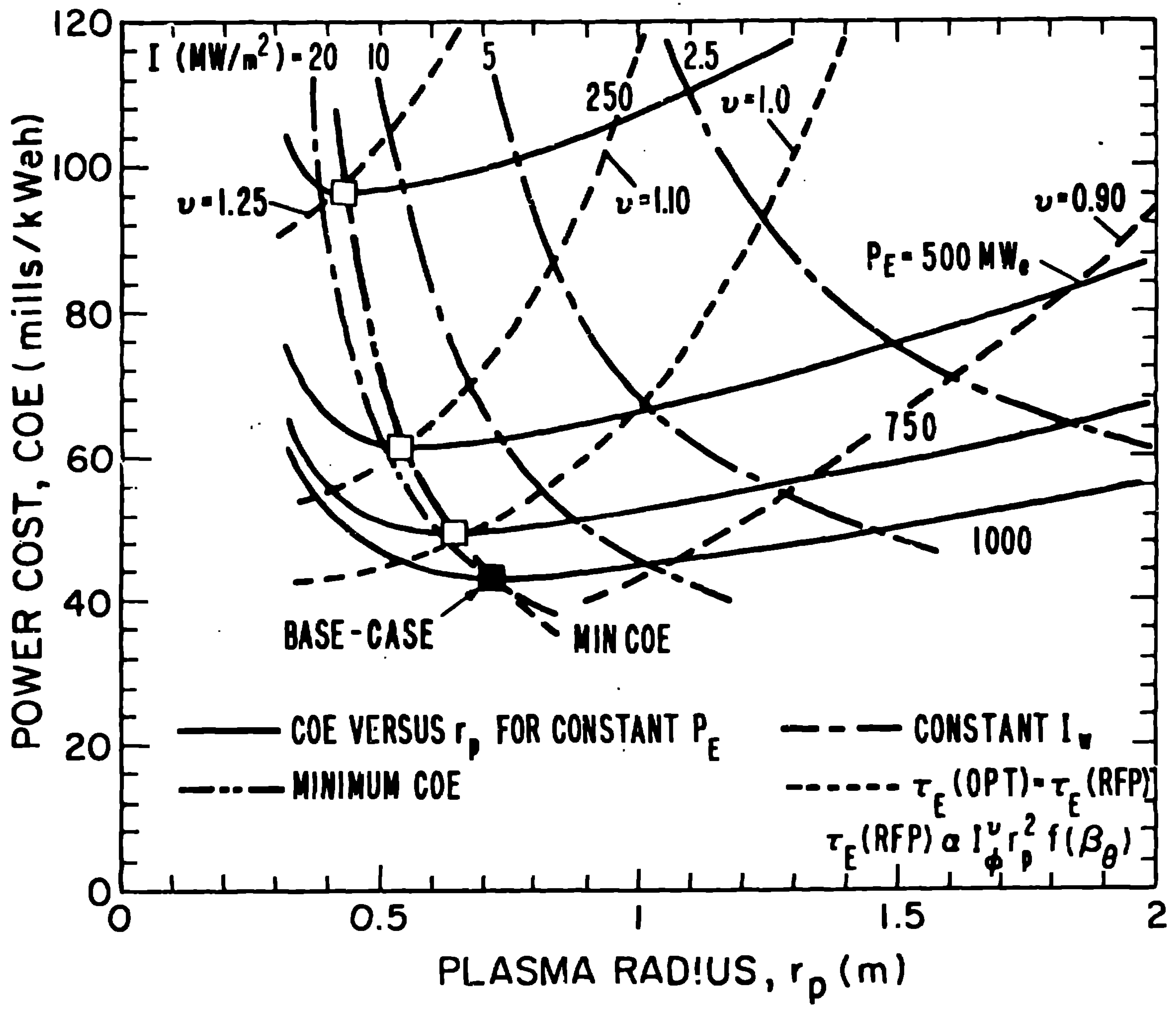
TABLE I
KEY CRFPR PLASMA AND ENGINEERING PARAMETERS

Overall system	
Net electric power (MWe)	1000.
Gross electric power (MWe)	1227.
Total thermal power (MWt)	3365.
Gross power-conversion efficiency (%)	36.5
Overall plant availability (%)[a]	75.
Major radius (m)	3.8
Plasma radius (average) (m)	0.71
Neutron-wall loading (MW/m^2)	19.5
First wall/blanket/shield/TFC mass (tonne)	307.
Maximum OHC field burn/startup (T)	4.5/9.2
Toroidal plasma current (MA)	18.4
Field at plasma edge/axis (T)	5.2/9.5
Average poloidal/total beta	0.23/0.12
Average DT density ($10^{20}/m^3$)	6.6
Average DT ion temperature (keV)	10.0
In-Vacuum Components (First-wall/limiter)	
Material	Cu alloy
Heat flux (MW/m^2)	5.0/6.0
Coolant tube thickness (mm)	1.0/0.8
Coolant (inlet/outlet) (K)	(463/537)/(463/545)
Flow rate (kg/s)	4899./1311.
Pump power (MWe)	1.85/0.94
Blanket and Shield	
Blanket coolant/breeder	$Pb_{83}Li_{17}$ (90 % ^6Li)
Thickness (m)	0.6
Tritium breeding/energy multiplication	1.03/1.28
Inlet/outlet temperature (K)	623./773.
Flow rate (kg/s)	72,840.
Pumping power (MWe)	13.2
Structure	HT-9(ferritic alloy)
Structural shield construction (v/o)	90 % 316SS/10 % H_2O
Structural shield thickness (m)	0.1
Magnet Coils	
Material (v/o)	70% Cu/20% 316SS/10% H_2O MgO or $MgAl_2O_3$ (25 kV)
Total TFC/OHC/EFC mass (tonne)	72.8/394./404.
OHC/EFC turns ratio	100./80.
OHC/EFC lead current during burn (MA)	0.213/0.135
Inductive/Resistive startup flux (Wb)	220/26
TFC/OHC/EFC dissipated power (MWe)[b]	12.6/73.0/53.5

(a) Annual down time is a minimum of 60 (unscheduled) plus 28 (scheduled) days, with each scheduled changeout of the first-wall/blanket/shield/TFC unit requiring 28 days, giving a plant availability that decreases with increasing first-wall loadings.

(b) OHC power available for current-drive subsystem during burn.

Fig. 1. Dependence of COE on r_p for a range of P_E values. Also shown are lines of constant first-wall neutron loading, I_w. The locus of points where the confinement time dictated by economics equals a range of possible RFP physics confinement-time scalings of the form $\tau_E(\mathrm{RFP}) \propto I_\varphi^\nu r_p^2 f(\beta)$ is also shown for a range of current exponents, ν, where $f(\beta_\vartheta) = (0.13/\beta_\vartheta)^2 \leq 1$ and $\beta_\vartheta = 0.2$. Key system parameters for the 1000-MWe(net) base case are given on Table I.



POWER COST, COE (mills/kWeh)
PLASMA RADIUS, r_p (m)
120
100
80
60
40
20
0
0
0.5
1
1.5
2
I (MW/m^2) = 20
10
5
2.5
250
750
1000
ν = 1.25
ν = 1.10
ν = 1.0
ν = 0.90
P_E = 500 MW$_e$
BASE-CASE
MIN COE
COE VERSUS r_p FOR CONSTANT P_E
CONSTANT I_w
MINIMUM COE
τ_E(OPT) = τ_E(RFP)
τ_E(RFP) α $I_\phi^\nu r_p^2 f(\beta_\theta)$

Fig. 2. Isometric view of the TRFPR fusion power core showing one of the 24 integral sectors that together constitute the single toroidal FPC unit (plasma chamber/ first wall/blanket/shield/toroidal-field coil).

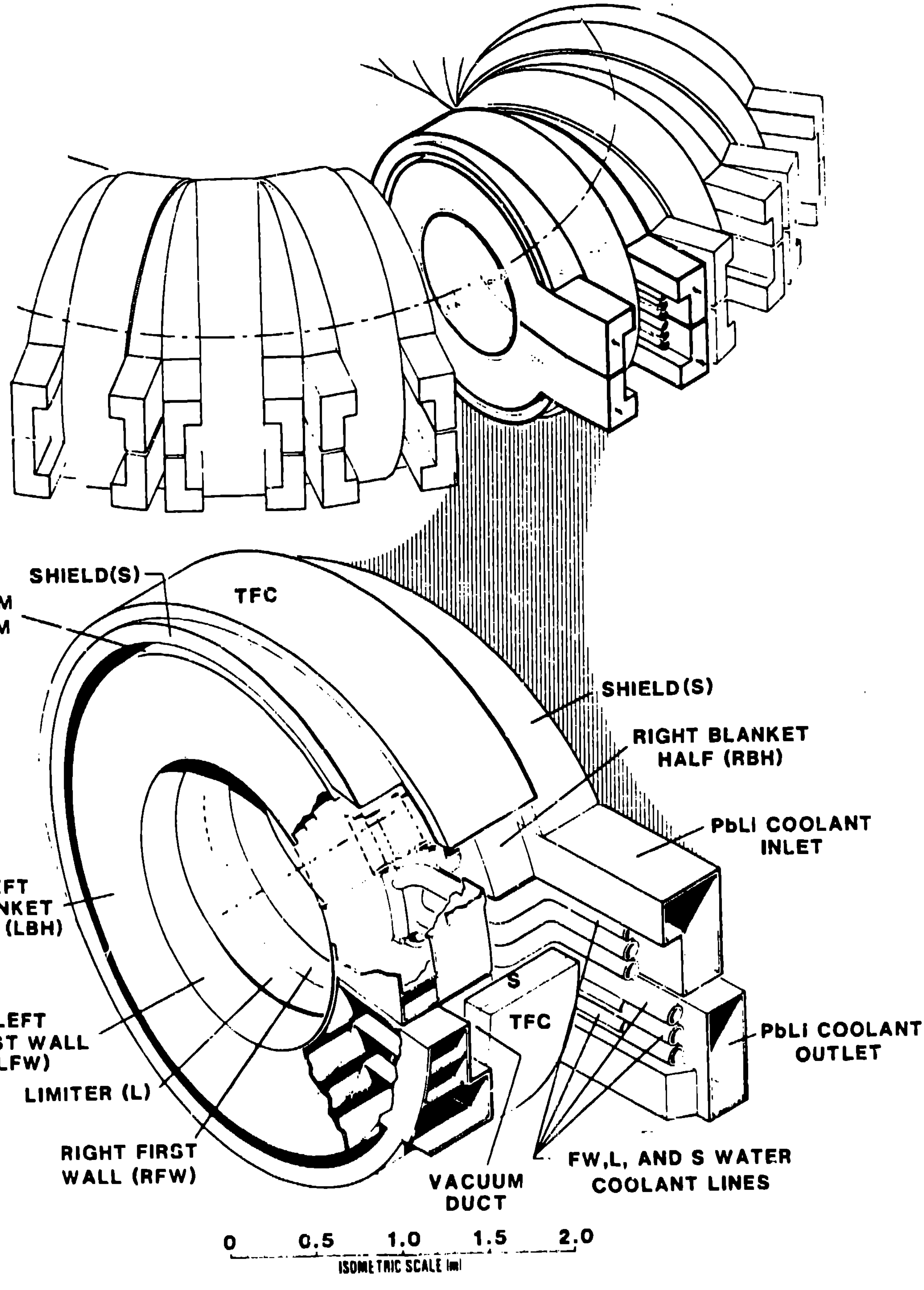

SHIELD(S)
VACUUM
PLENUM
TFC
SHIELD(S)
RIGHT BLANKET
HALF (RBH)
PbLi COOLANT
INLET
LEFT
BLANKET
HALF (LBH)
S
TFC
PbLi COOLANT
OUTLET
LEFT
FIRST WALL
(LFW)
LIMITER (L)
RIGHT FIRST
WALL (RFW)
VACUUM
DUCT
FW,L, AND S WATER
COOLANT LINES
0 0.5 1.0 1.5 2.0
ISOMETRIC SCALE (m)

Figure Captions

Figure 1. Dependence of COE on r_p for a range of P_E values. Also shown are lines of constant first-wall neutron loading, I_w. The locus of points where the confinement time dictated by economics equals a range of possible RFP physics confinement-time scalings of the form $\tau_E(RFP) \propto I_\varphi^\nu r_p^2 f(\beta)$ is also shown for a range of current exponents, ν, where $f(\beta_\theta) = (0.13/\beta_\theta)^2 \leq 1$ and $\beta_\theta = 0.2$. Key system parameters for the 1000-MWe(net) base case are given on Table I.

Figure 2. Isometric view of the CRFPR fusion power core showing one of the 24 integral sectors that together constitute the single toroidal FPC unit (plasma chamber/first wall/blanket/shield/toroidal-field coil).