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TITLE: MATERIALS NEEDS FOR COMPACT FUSION REACTORS

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MATERIALS NEEDS FOR COMPACT FUSION REACTORS

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The economic prospects for magnetic fusion energy can be dramatically improved if for the same total power output the fusion neutron first-wall (FW) loading and the system power density can be increased by factors of 3-5 and 10-30, respectively. A number of "compact" fusion reactor embodiments have been proposed, all of which would operate with increased FW loadings, would use thin (0.5-0.6 m) blankets, and would confine quasi-steady-state plasma with resistive, water-cooled copper or aluminum coils. Increased system power density (5-15 MWt/m^3 *versus* 0.3-0.5 MW/m^3), considerably reduced physical size of the fusion power core (FPC), and appreciably reduced economic leverage exerted by the FPC and associated physics result. The unique materials requirements anticipated for these compact reactors are outlined against the well documented backdrop provided by similar needs for the mainline approaches. Surprisingly, no single materials need that is unique to the compact systems is identified; crucial uncertainties for the compact approaches must also be addressed by the mainline approaches, particularly for in-vacuum components (FWs, limiters, divertors, etc.).

1. INTRODUCTION

Both the technical and commercial success of magnetic fusion depend on advances in engineering materials operating in an environment of highly non-uniform surface and volumetric power densities. These heat loads will be applied under conditions where the basic engineering material properties of stressed components are being dramatically altered by an intense neutron/gamma-ray/charged-particle irradiation field. The interdependence between plasma physics/engineering, reactor design, and materials science/engineering needed to achieve economic, commercially attractive fusion power has been highlighted by a number of excellent overview papers dealing with first walls[1] (FW), blankets[2] (B), materials needs for specific devices,[3,4] and the worldwide materials programs addressing these needs.[5,6]

Nygren[3] points out that these materials needs have been identified primarily by conceptual design studies, with the more exacting "designs to construct" eventually requiring difficult materials choices, an expanded materials data base, considerably more design detail, and improved estimates of major subsystem performance. Even at the conceptual design level, however, the list of materials performance requirements presents a major challenge for the INTOR/DEMO/COMMERCIAL development sequence. The more compact, higher-power-density fusion approaches propose smaller fusion power cores (FPC, i.e., first-wall/blanket/shield/coils) operating with increased power density and FW neutron and heating loads. The degree to which materials performance requirements are altered by the needs of these compact fusion reactors is addressed qualitatively herein. The rationale, pathway, and generic technology required for the compact reactors have been described recently.[7,8]

After summarizing the reasons for considering systems with material requirements that in some cases may exceed those projected in Refs. 1-4, the generic needs of compact devices are described. Specific compact reactor designs have been suggested[8] for the Reversed-field Pinch (RFP), the Ohmically-Heated Toroidal Experiment (OHTE, an RFP with auxiliary helical windings), and the high-field tokamak. Other candidates for compact reactors have also been identified.[8,9]

Although the materials issues and needs addressed herein are generic, specific quantitative examples are referred to conceptual design results emerging for the compact RFP reactor (CRFPR).[10] Similarly, comparisons with the mainline development sequence are made with the STARFIRE[11] and Culham MkIIB[12] tokamak reactor designs.

2. COMPACT FUSION REACTORS

The dominance in mass and cost of the FPC for most approaches to magnetic fusion[7] has created interest in more compact, higher-power-density systems. The following improved characteristics are being pursued through the compact reactor option.

- FPC mass and volume comparable to alternative nuclear power systems (system power density of 5-15 MWt/m^3, mass utilization of 0.3-0.5 tonne/MWt), which are factors of 10-30 times better than values being projected for most magnetic fusion schemes.
- Reduced sensitivity of unit direct cost (UDC, \$/kWe) to the cost of the reactor plant equipment (RPE/TDC $\lesssim$ 0.3 rather than 0.5-0.8, where TDC is the total direct cost).
- Competitive system costs and cost of electricity (COE, mills/kWeh) using realistic unit materials costs, fabrication/construction times, and development schedules/costs.
- Rapid deployment of small FPCs with the potential for "block" installation and maintenance (i.e., single or few piece FPC), using systems relying on a minimum extension of technology (e.g., resistive rather than superconducting coils, ohmic heating rather than high-frequency rf heating or neutral-beam injection, etc.).

This prescription for economically competitive fusion is not without risks or trade-offs;[7,8] potential for increased recirculating power, reduced thermal conversion efficiency, and reduced plant factor could lead to reduced plant efficiency, increased plant cost, and increased COE. Minimization of these risks will depend on the availability and use of materials and material engineering approaches that differ somewhat from those being suggested and pursued by the mainline programs. These differences are highlighted herein.

Although heuristic arguements can be made to point the way towards improved system economics through higher system power density or lower FPC mass utilization, ultimately detailed parametric studies on specific concepts must establish economically optimum, technologically feasible systems.[10] For the present purposes, however, Fig. 1 continues with the heuristic approach by displaying the system power density *versus* the inverse of the FPC mass utilization; lines of unit slope on Fig. 1 give the average FPC mass density, ρ_{FPC} (tonne/m^3). The system power density for most of the "superconducting" fusion systems displayed on Fig. 1 are at least one order of magnitude below other nuclear power systems. In order to gain an order of magnitude increase in this important parameter, an increase in FW neutron current by 3-5, simultaneously with a decrease by ~2-3 in FW radius, B/S thickness, and coil radius and size, is required.[7] The former change makes stainless steel even less attractive from the heat-transfer viewpoint, whereas the reduced B/S thickness eliminates superconducting coils

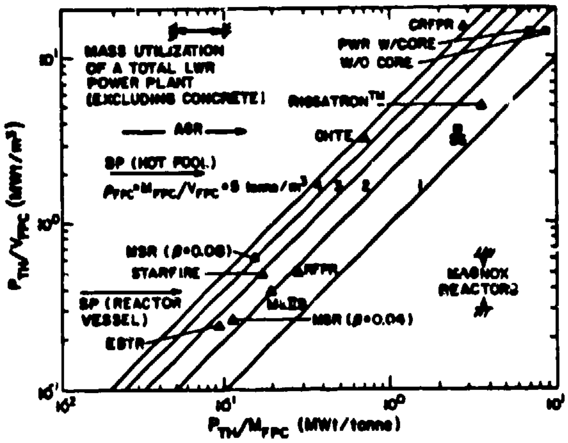

FIGURE 1

Comparison of system power densities being projected for conceptual fusion reactors with a number of fission reactor systems. STARFIRE tokamak (Ref. 11), Culham MkIIB tokamak (Ref. 12), Superconducting Reversed-field Pinch Reactor RFPR (Ref. 13), Modular Stellerator Reactor MSR (Ref. 14), ELMO Bumpy Torus Reactor EBTR (Ref. 15), Magnox Gas-Cooled Reactor (Ref. 16), Super Phenix Liquid-Metal Fast-Breeder Fission Reactor SP (Ref. 17), Advance Gas Reactor AGR (Ref. 18), Compact Reversed-Field Pinch Reactor CRFPR (Ref. 10), Ohmically-Heat Toroidal Experment Reactor OHTE (Ref. 19), High-Field Tokamak Reactor, Riggatron (Ref. 20), Pressurized-Water fission Reactor PWR (Ref. 21), PWR Steam Generator SG (Ref. 21).

from consideration, since neutron fluxes and heat deposition in the coils cannot be kept low in the space available. Hence, the compact systems that emerge (CRFPR, OHTE, Riggatron) use resistive copper-alloy coils with ceramic electrical insulation and generally provide only a thin (0.5-0.6 m) blanket between the FW and the high-radiation-flux, resistive coils. In certain instances, FW (Riggatron) or near-FW (OHTE) actively-driven coils may be necessary.

The compact systems depicted on Fig. 1 would achieve DT ignition by Ohmic dissipation of toroidal plasma currents. Inferred, therefore, is some form of inductive current drive, at least for startup; each system in principle is capable of burn extension by non-inductive means. For those compact reactors with plasma confinement depending in part (i.e., OHTE) or totally (i.e., Riggatron) on strong toroidal fields, the magnet coils may be highly stressed as well as presenting a potentially serious drain on the overall plant efficiency (i.e., increased recirculating power, reduced thermal recovery efficiency, etc.) Generally, the high-heat-flux FWs and other in-vacuum component (IVC) surfaces, thin high-power-density blankets, and resistive exo-blanket (CRFPR) or near-FW (OHTE, Riggatron) resistive coils largely define the differences in materials requirements between the compact and the other magnetic fusion approaches.

Generally, two crucial questions must be answered before the economic attractiveness of compact approaches to fusion power can be fully substantiated.

- can a plasma confinement scheme based either on a mainline, alternative, or a combination thereof be found that will stably confine plasma of the required power density while giving some assurance of long-pulsed or steady-state operation with a recirculating power fraction ≤ 0.15-0.20?
- given the plasma physics inferred from the last issue, can all subelements of the FPC (i.e., IVC, blanket/shield, coils) be made to operate with an acceptable engineered lifetime, both in terms of real time (i.e., maintenance period) and fluence (i.e., total amount of energy generated per mass of FPC consumed)?

The first issue is not within the scope of this paper, but second-stability-region tokamaks, RFP/OHTEs, and spheromaks/field-reversed configurations provide exciting potential on both theoretical and experimental grounds. The second question of FPC lifetime as summarized in Table I, is complex, and centers on the materials theme of this overview. Four major determinants of FPC lifetime are identified in Table I: reactor operating conditions; FPC material properties; component geometry and constraints; and design and failure criteria. By applying similar design and failure criteria to all fusion approaches, and assuming negligible influence of rate on the effects of radiation in changing materials properties (i.e., a fluence effect) the FPC lifetime issue becomes one of reactor operations and component geometry.

Operating in the compact regime significantly influences both reactor operations and geometry (i.e., size). The major change in reactor operating conditions is the increased heat/particle fluxes, but designing to the same failure criteria should eliminate these differences, albeit potentially at a higher cost. The reactor operational flexibility afforded by smaller FPCs, particularly with respect to the last point in Table I listed under component geometry, potentially can offset the added cost of designing for a more highly stressed reactor operating condition in order to assure that each unit mass of FPC delivers the economically necessary amount of energy within its lifetime. This issue of total ("batch") versus partial ("patch") FPC maintenance, although difficult to quantify, is best depicted on Fig. 2, which compares a compact reactor (the CRFPR, the OHTE reactor is of similar size) with both a PWR and the STARFIRE tokamak reactor. In summary, therefore, the key elements of the FPC lifetime issue (Table I) may either a) be common to fusion in general, or b) have a mutually self-concealing impact [i.e., more severe reactor operation in a more favorable reactor geometry (size)].

TABLE I. SUMMARY OF FPC LIFETIME DETERMINANTS[22]

- Reactor Operating Conditions
  - FW neutron loading
    - Volumetric heating
    - damage rates (dpa/yr, He appm/yr, H appm/yr, burnup)
  - Plasma energy rejection
    - particle fluxes to IVC (DT, neutrals, He, impurities)
    - heat fluxes (conduction and radiation)
  - Duty cycle
  - Coolant (kind and temperature/pressure)
- Material Properties
  - thermal (heat capacity, conductivity, expansivity)
  - mechanical (Young's modulus, ultimate and yield stresses, uniform elongation, total elongation, fracture toughness, creep, fatigue, crack growth, swelling)
  - electrical (conductivity)
  - nuclear (alloying constituents, transmutations, gas production, dpa, radioactivity, afterheat).
  - surfaces (sputtering, adsorption, gas recycle, electron emission)
- Component Geometry and Constraint
  - stress and temperature distributions
  - component interactions/interplay
  - size and degree precheck/shakedown allowed, QA, replacement/repair time
- Design and Failure Criteria
  - elastic deformation and elastic instability
  - plastic deformation and plastic instability (incremental collapse/ratchetting)
  - brittle fracture
  - stress rupture/creep deformation
  - high-strain/low-cycle fatigue and creep/fatigue interaction
  - stress corrosion
  - corrosion fatigue
  - swelling and differential volume change
  - undesirable changes in material properties (embrittlement, DBTT, electrical resistivity).

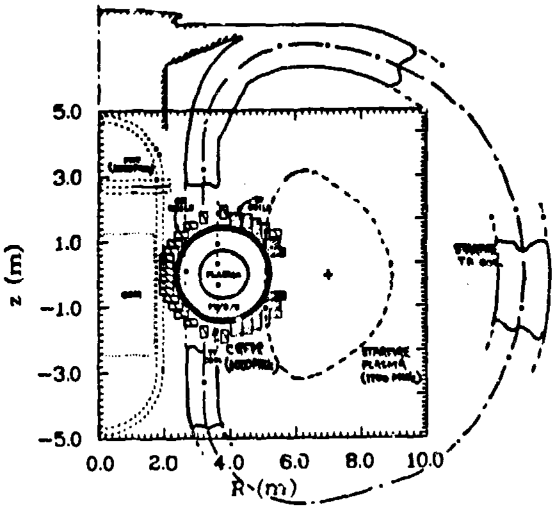

FIGURE 2
Cross sectional comparison of a compact fusion reactor design (CRFPR) with a fission reactor pressure vessel (PWR) and the STARFIRE tokamak reactor.

Although the scope of this overview does not allow a comprehensive assessment of the "compact" *versus* "conventional" systems, Table II nevertheless is included to give a quantitative example of the physics, engineering, and economic differences between two comprehensive tokamak reactor designs[11,12,23] and a compact RFP reactor design.[10] Since the demands on engineering materials performance are primarily generated by the thermal radiation and mechanical (stress) environment created by high-power-density plasma, FW, and blanket operation, the neutronics results[24] from a specific high-power-density FPC is given in Table III. This design also uses a 20-mm-thick copper-alloy FW, which allows some inferences to be made for those compact reactors requiring FW resistive coils. Again, the comparisons and quantitative information given in Figs. 1-2 and Tables II-III are intended to demonstrate the "order-of-magnitude" differences between the compact and more "conventional" approaches to fusion power rather than to emphasize differences between specific conceptual reactor designs.

3. MATERIALS ISSUES/NEEDS

The key materials issues and needs for fusion in general can be divided according to the following three FPC subsystems:

- In-vacuum Components (IVC)[1]
  - first wall
  - limiter
  - divertor
  - coils
  - antennae
  - windows (rf)
- Blanket/Shield (B/S)[2]
  - breeder
  - coolant
  - structure
  - multiplier
  - reflector/moderator
  - tritium barrier
  - ducts (rf, beams, fueling, vacuum, coolants)
- Magnet Coils (C)
  - conductor (superconductor *versus* resistive)
  - insulator (organic *versus* inorganic)
  - structure
  - coolant (He(ℓ) *versus* water)
  - kinds (TF, PF, OH, EF, active feedback, passive shell)

In addition to comprehensive materials needs assessments for these subsystems,[1-4] general reviews of fusion materials needs are available.[25] The technology needs for the compact systems have also been summarized recently.[8] No attempt is made here to repeat or to summarize these reviews and assessments. Instead, based on the general system differences and goals as outlined in Sec. 2. and Table II, differences in materials needs

TABLE II. PLASMA, COSTING AND FPC PARAMETER COMPARISON BETWEEN

FUSION-POWER-CORE (FPC) PERFORMANCE COMPARISONS[(a)]

PARAMETER	STARFIRE[11]	MKIIB[12,23]	CRFPR[10]
Gross thermal power, P_{TH} (MWt)	4000	3261	3389
Blanket energy multiplication, M_N	1.14	1.14	1.10
Thermal conversion efficiency, η_{TH}	0.36	0.37	0.35
Recirculating power fraction, ε	0.167	0.08	0.16
Plant efficiency, $\eta_P = \eta_{TH}(1-\varepsilon)$	0.30	0.34	0.30
Net electrical power, P_E(MWe)	1200.	1200.	1000.
Nominal B/S thickness, Δb(m)	2.5	3.2	0.60
Nominal coil thickness, Δc(m)	1.6		0.45
FPC volume, $V_{FPC}(m^3)$	8110(6630)	8000(4401)	242
First-wall area, $A_w(m^2)$	780	716	112
FPC volume/surface, V_{FPC}/A_w	10.4(8.50)	11.2(6.15)	2.16
System minor radius,			
$r_s = [V_{FPC}/2\pi^2R_T]^{1/2}$ (m)	7.66(6.90)	7.7.(5.77)	1.60
Plasma chamber volume, $V_{PC}(m^3)$	1104(950)	870(836)	42.
First-wall radius, r_w(m)	2.83	2.71	0.73
FW neutron loading, I_w(MW neutron/m^2)	3.6	3.2	19.3
Power density, P_{TH}/V_{FPC} (MWt/m^3)	0.50(0.66)	0.41(0.74)	14.
FPC mass, M_{FPC} (tonne)	23174/16496	17330[(b)]	1160
• FW/B	1374	4700	223
• Shield	13560/6882	3630	---
• Coils	8240	8980	937
Mass utilization M_{FPC}/P_{TH} (tonne/MWt)	3.7/4.1	3.3	0.40
FPC density, M_{FPC}/V_{FPC} (tonne/m^3)	2.86/266	2.17(3.94)	3.6
Area density, $\rho_{FPC}[V_{FPC}/A_{FW}]$(tonne/$m^2$)	29.7	24.3	12.1
FPC cost (M$)	440.1/363.3	719.1[473.9]	43.6
• FW/B	82.4	204.3[13.50]	14.8
• Shield	186.1/109.3	137.2[90.3]	---
• Coils	171.6	377.4[248.6]	30.8
FPC unit cost, c_{FPC}($/kg)	19.0/22.0	41.3[27.3]	37.0
FPC volumetric cost, c_{FPC}(M$/$m^3$)	0.033/0.039	0.16[0.11]	0.20
FPC area cost, (FPC cost)/A_w(M$/$m^2$)	0.66/0.31	1.00[0.66)	0.36
Cost Figures of Merit			
• RPE/TDC	0.36	0.72	0.36
• FPC/TDC	0.26/0.21	0.23	0.06
• (FW/B)/TDC	0.050	0.067	0.017

PLASMA PHYSICS/ENGINEERING PARAMETERS

PARAMETERS	STARFIRE[11]	MKIIB[12,23]	CRFPR[10]
Major radius, R_T(m)	7.0	6.7	3.79
Aspect ratio, A	3.6	3.5	5.3
Plasma elongation, κ	1.6	1.75	1.0
Plasma triangularity, d	0.5	0.	0.
Average plasma minor radius, r_p(m)	2.38	2.51	0.71
Plasma volume, $V_p(m^3)$	781.	834.	57.7
Average beta, ⟨β⟩	0.067	0.092	0.20
Magnetic field at plasma, B_θ(T)	5.8	4.0	0.58(5.2)[(c)]
Safety factor at limiter, q_a	3.1	2.5	0.02
Plasma toroidal current, I_ϕ(MA)	10.1	10.2	18.4
Plasma current density, $I_\phi/\pi r_p^2$(MA/m^2)	0.54	0.51	11.8
Average electron temperature, T_e(keV)	17.3	12.0	20.0
Average ion temperature, T_i(keV)	24.1	12.0	20.0
Average electron density, $n_e(10^{20}/m^3)$	0.81	1.50	3.39
Average fusion power, P_F(MW)	3510.	2992.	3138.
Average plasma power density, P_F/V_p	4.49	3.60	83.2
Average neutron FW loading, I_w(MW/m^2)	3.6	3.2	19.3
Burn-time/off-time	-	20.	[illegible]

FUSION POWER PLANT COST COMPARISON (NORMALIZED TO TDC)

ACCOUNT	STARFIRE[11]	MKIIB[12,23]	CRFPR[7]
20. Land and land rights	0.19	—	0.38
21. Structure and site	20.09	12.48	19.33
22. Reactor plant equipment (RPE)	56.00	72.04	36.04
22.1.1 First-wall/blanket (FW/B)	4.77	6.66	1.71
22.1.2 Shield (S)	10.78	4.47	—
22.1.3 Coil (C)	9.90	12.30	3.56
FPC = FW/B + S + C	23.48	23.43	5.27
23. Turbine plant equipment	14.47	10.88	23.49
24. Electric plant equipment	6.77	3.29	14.02
25. Miscellaneous plant equipment	2.37	1.27	4.84
26. Special materials	0.014	—	0.029
90. Direct Costs (TDC)	100.	100.	100.
99. Total costs	185.2	200.26	173.00
Unit direct cost, UDC ($/kWe)	1439	2536[1685][(a)]	863
Cost of electricity, COE(mills/kWe)	67.0	—	40.7
Net electric power, P_E(MWe)	1200	1200	1000

[(a)] Values in () based on toroidal volume, otherwise volume of central column included. Values to right of / do not include vacuum pumping ducts and ports. Values in [] $/ conversion in 1977 followed by $ inflation from 1977 to 1980; otherwise the conversion/inflation order is reversed.

[(b)] Does not include 33,000 tonne iron core.

[(c)] Poloidal field at plasma edge.

between the mainline and the compact approaches are highlighted. Each of the three FPC major subsystems listed above is treated separately. Materials needs for subsystems outside the FPC are expected to be similar for all approaches and, therefore, are not discussed.

3.1. In-Vacuum Components (IVC)

Table III gives the neutronics response of a "typical" high-heat-flux IVC (i.e., FW) to a fusion neutron FW loading, I_w(MW/m^2). Since I_w typically will be 3-5 times greater for the compact reactor (I_w = 15-20 MW/m^2, and even higher for the Riggatron), the radiative/conductive/convective energy fluxes emanating from the ignited DT plasma, $I_{QW} \le I_w/4$, will be correspondingly increased for similar

TABLE III. NEUTRONIC RESULTS FROM A "CANONICAL" COMPACT REACTOR FPC WITH FW NEUTRON LOADING I_w (MW/m^2)

- First-wall (copper/H_2O)
  - 14.1-MeV neutron current, J_w (n/m^2 s) = $4.43(10)^{17} I_w$
  - Neutron flux, ϕ_w(n/m^2 s) = $4.43(10)^{18} I_w$
  - Total full power year fluence, $\phi_w \tau$ (n/m^2) = $1.40(10)^{26} I_w$
  - Radiation dose rate, R(rad/s)
    - Neutrons, R_n(rads/s) = $8.2(10)^4 I_w$
    - Gamma rays, R_γ(rads/s) = $1.3(10)^5 I_w$
  - dpa/yr = $11 I_w$
  - Helium appm/yr = $31 I_w$
  - Hydrogen appm/yr = $83 I_w$
  - Average transmutation rates
    - Nickel (%/yr) = $0.13 I_w$
    - Zinc (%/yr) = $0.11 I_w$
  - Heat flux, I_{QW} (MW/m^2) $\leq I_w/4$
  - Average power density, Q_w (MW/m^3) = $10 I_w$
- Blanket (Δb = 0.6 m, Li-Pb/B_4C/W)
  - Peak power density, Q_B(MW/m^3) = $13 I_w$
  - Average power density, $\langle Q_B \rangle$ (MW/m^3) = $1.4 I_w$
  - Average dpa/yr = $2.3 I_w$
  - Average helium appm/yr = $26.7 I_w$
  - Average hydrogen appm/yr = $7.7 I_w$
- Exo-blanket coil (copper/H_2O)
  - Peak neutron flux, ϕ_c(n/m^2 s) = $3.4(10)^{16} I_w$
  - Radiation dose rate, R(rad/s)
    - Neutrons, R_n(rads/s) = $1.2(10)^2 I_w$
    - Gamma rays, R_γ(rads/s) = $1.10(10)^3 I_w$
  - Peak dpa/yr = $0.063 I_w$
  - Peak helium appm/yr = $0.027 I_w$
  - Peak hydrogen appm/yr = $0.13 I_w$
  - Average transmutation rates
    - Nickel (%/yr) = $1.1(10)^{-3} I_w$
    - Zinc (%/yr) = $0.5(10)^{-3} I_w$
  - Peak power density, Q_c(MW/m^3) = $0.1 I_w$

plasma conditions (i.e., profiles, edge-plasma parameters, etc.). The power partition between particles *versus* photons, as well as the split of each between FW, limiter, and/or divertor, represents a crucial uncertainty for all fusion devices. The major materials questions for the IVCs are:

- Removal of both surface ($\leq I_w/4$ MW/m^2) and volumetric ($\sim 10 I_w$ MW/m^3) heat loads within acceptable temperature, stress, and critical-heat-flux limits, (i.e., need for materials with high thermal conductivity and high thermal stress parameter, M).
- Sputter erosion and redeposition rates for FW and limiter surfaces.
- Long-term (swelling, creep, embrittlement, alloy charges, etc.) and short-term (thermal conductivity changes, hydrogen permeation and recycle, etc.) radiation effects.

Two limiting cases of uniform heat deposition onto IVCs can be envisaged: a) all energy is incident as radiation from a high-Z_{eff} plasma edge or, b) all energy is convected to IVC surfaces by charge-exchange neutrals and edge-plasma particles. If all energy shed by the plasma appears as a uniform heat load, then IVC structural alloys with thermal transport properties that are better than stainless steel will be required for the compact reactor options. Figure 3 gives the thermal stress parameter $M = 2\sigma_Y(1-\nu)/\alpha E = I_{QW}^{*}\delta$ as a function of FW temperature; M measures the heat flux, I_{QW}^{*}, through a material of thickness δ that will cause yielding by the resulting thermal stress. For the copper-alloy and stainless-steel materials "extrema", Fig. 4 gives the dependence of I_{QW} allowed for a pressurized-water-cooled tube of thickness δ if the sum of the primary (pressure) and secondary (thermal) stress is maintained at the indicated fraction, σ/σ_Y, of the yield stress; constraints relevant to elastic-plastic

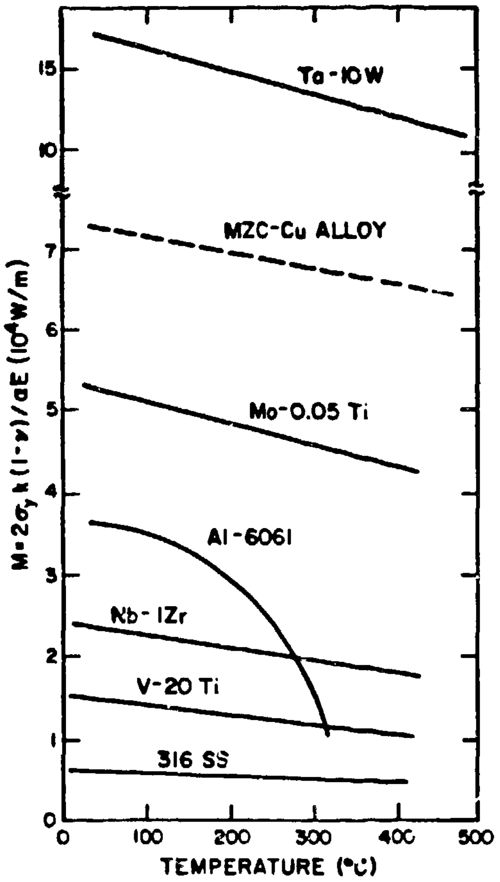

FIGURE 3

Thermal stress parameter as a function of temperature for a range of potential IVC metals.

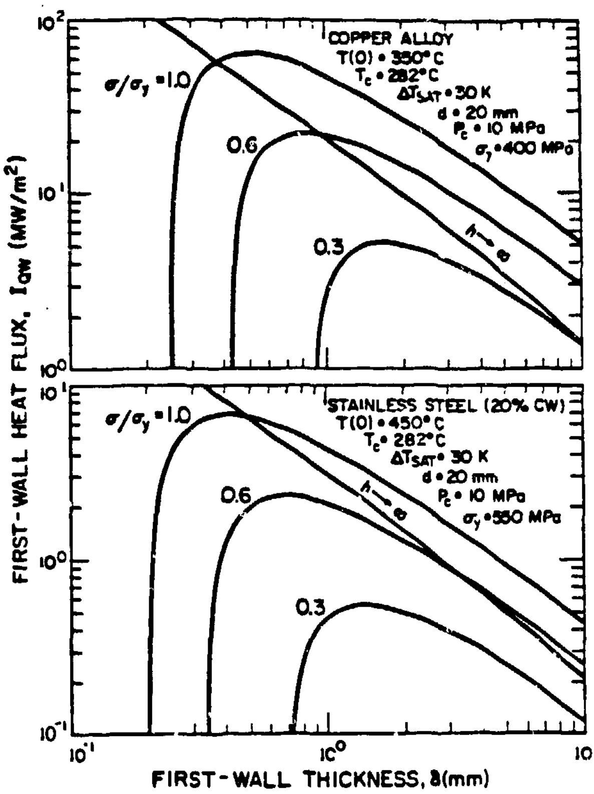

FIGURE 4

Dependence of maximum heat flux, $I_{QW} = I_W/4$, allowed onto a FW coolant tube of thickness δ and cooled with pressurized water for a given primary plus secondary stress level, σ, for both stainless steel and copper alloy under the conditions indicated.

limits, thermal ratchetting, and fatigue-creep limits, can similarly be applied to Fig. 4. The copper alloy achieves a superior performance at a lower operating temperature, which will degrade somewhat the overall thermal performance to an extent determined by the fraction of the fusion energy appearing in the IVC coolant circuit. This important tradeoff between high-heat-flux operation, decreased FPC cost, and derated system performance remains to be comprehensively assessed in terms of a COE figure-of-merit. Indications are, however, that the significant reduction in UDC accompanying the compact option reduces the COE to an extent that exceeds the increase associated with a potentially lower system performance (i.e., reduced plant efficiency, increased recirculating power fraction, and decreased plant factor).

If all the energy rejected by the plasma, on the other hand, is deposited uniformly as energetic particles with an energy, T_E, characteristic of the plasma edge, a particle flux of $4.2(10)^{21}/T_E I_{QW}$ [~$1.4(10)^{23}$ particles/m^2 s for I_{QW} = 5 MW/m^2 and

$T_E = 150$ eV] would result. For a DT sputtering yield of ~0.02 and a FW atomic density of $\sim 8(10)^{28}$ atoms/m^3 (stainless steel), gross erosion rates of ≥ 1 m/yr would result, even if self-sputtering and ion acceleration through electrostatic sheaths were neglected. This problem is worsened if particle and energy fluxes are concentrated onto the IVC surfaces by limiter and/or divertor action. The degree to which this problem will hinder the development of fusion depends on poorly understood edge-plasma processes that are generic to magnetic fusion and not uniquely a compact reactor issue. Potential solutions to this problem are:

- Operate with edge-plasma temperatures below the sputtering threshold (≲ 50 eV).
- Operate with edge-plasma temperature that are well above the sputtering-yield maximum (≳ 1000 eV).
- Establish a high-Z radiating plasma mantle without having the FW supply the high-Z material through large sputtering rates.
- Design for large gross sputtering rates, but assure a nil net erosion rate through careful control of redeposition distribution.

From the viewpoint of FW survivability, these problems are not unique to or more severe for the compact reactors. Aside from differences in basic plasma processes that may result when differences of ~3-4 in average plasma density (Table II) are taken into account, the ratio of particle flux to neutron current incident onto a FW from an ignited DT plasma should be similar for both systems, thereby decoupling somewhat the FW erosion problem from the issue of device compactness; the compact, FPC simply achieves both its neutron (dpa) and erosion (mm) lifetime "fluence" in an expected shorter chronological lifetime, but only after generating a similar total quantity of fusion energy for nominally a similar expenditure of FW/B mass. Issues that relate specifically to device compactness and the expected higher erosion rates, however, are:

- can the compact reactor plasma survive a potentially higher recycle rate and achieve and/or remain ignited?
- depending on the heat load under which any IVC surface must function, the use of thick-walled tubes with an erosion margin designed to extend the sputtering life is generally less attractive for the compact systems because of the higher heat fluxes (Fig. 4).

An estimate of the effects of neutron irradiation on a copper-alloy FW, and possibly on inorganic electrical insulation if FW coils or electrical breaks are required, has been summarized in Ref. 8 and more recently for the FW copper-coil insert proposed for MARS.[26] Transmutation-induced resistivity increases in the FW copper conductor (Table III) and the dimensional stability of both the copper alloy and the proposed MgO or $MgAl_2O_4$ insulation[27] are key concerns for a FW "coil", whether actively driven (i.e., TF coil in Riggatron, R-coil in OHTE) or a passive conducting shell needed to stabilized short-wave length plasma MHD modes. Perkins[28] also points out that for sufficiently high voltages (≳ 700 V) and instantaneous radiation dose rates (≳ 10^4 Gy/s = 10^6 rad/s), thermal runaway through Joule heating can be potentially destructive to electrical insulators; these conditions generally apply near the FW and for relatively high-field, actively driven coils.

A increase of the electrical resistivity by radiation and transmutation effects is also accompanied by a decrease in the thermal conductivity in metals, since both current and heat are carried by electrons. A high-heat-flux FW, therefore, must be designed to operate with increased thermal stress towards the end of life, although thinning of the FW by sputter erosion, if allowed, will tend to counteract the effects of decreased thermal conductivity on the FW stress. If the initially unirradiated material is a solution strengthened copper alloy, however, the decreased electrical and thermal conductivities caused by alloy additions can mask the effects of transmutation product (Ni, Zn) buildup. Although some information on radiation-induced swelling exists for candidate inorganic insulators, similar data for copper alloy are not available at present; fission reactor irradiations of relevant alloys, however, are in progress.[29] Age-hardened copper alloys, such as MZC may over-age or the alloying element may dissolve under irradiation; generally,[29] dispersion hardened alloys may exhibit greater radiation stability in this respect. It is noted that procedures for radiation hardening against high-energy neutrons of steering magnets for the LAMPF[30] and the quadrupole beam transport magnets for FMIT[31] have developed fabrication methods that are directly applicable to the compact fusion reactors (co-extruded Cu/MgO co-axial conductors with internal water cooling); the radiation fields and lifetime fluences for these accelerator applications fall short of fusion FW conditions, however. Lastly, the requirements of the FW coil proposed for the MARS design[32] will satisfy the needs for most compact fusion systems. Generally, the need and potentially high payoff for high-heat-flux alloys in most IVC applications and the role that such alloys may play in shaping the fusion end product has only recently been recognized.[33,34]

3.2. Blanket/Shield (B/S)

The B/S thickness for the compact reactor approaches is reduced to the minimum required for adequate tritium breeding and thermal energy recovery. The minimum-thickness (optimized) B/S, when coupled with the increased FW loading, achieves at least an order of magnitude increase in FPC power density, and a considerable reduction in total cost, as well as providing options for appreciably different installation and maintenance schemes because of reduced FPC mass (Table II). Magnet shielding in the usual sense is not envisaged; instead a thin (0.05-0.10 m) outer region of the 0.5-0.6-m-thick blanket may contain a mixture of B_4C and a dense, high-Z material operated at the blanket temperature and cooled by the primary blanket coolant.

For FW neutron loadings in the 15-20 MW/m^2 range, the local blanket power density becomes comparable with that in the core of an LWR ($\geq$ 200 MWt/m^3), with the average blanket power density being in the range 30-50 MWt/m^3. At the peak and average power densities envisaged for the compact reactors, ceramic breeders cooled by pressurized helium gas or water become less attractive. Because of the low lithium inventory, reduced fire hazard, and unique combination of breeder/coolant/multiplier functions, the low-melting (235°C) lead-lithium eutectic, $Pb_{83}Li_{17}$ (referred to hereinafter as PbLi), has become a popular choice for high-power-density blankets.[7,35-37]

Confinement systems with magnetic topologies that require liquid-metal coolant to flow across magnetic fields[37,38] may be forced either to coat coolant ducts with electrical insulators[35] or to reduce the MHD pressure drop simply by limiting the coolant flow velocity and thereby limit the FW neutron loading.[36] The high power density for the PbLi-cooled CRFPR blanket,[7,37] however, can be achieved with minimal pumping power without recourse to the use of electrically insulated coolant ducts because of the unique, low-field poloidal magnetic topology that characterizes that system. The materials problems related to corrosion (particularly for ceramic coatings), tritium recovery, and tritium barriers for the compact reactors remain similar to those for other systems using similar blankets. The acceleration of stress corrosion cracking by the addition of small amounts of water to these liquid-metal systems remains as a particularly critical concern.

Although rf and neutral-beam ducts are not envisaged for the compact systems so far considered, the task of manifolding and (vacuum) ducting appears to be more exacting. Since the gaseous (DT, He impurities) and coolant throughputs will in magnitude remain unchanged for any fusion power plant of similar power rating, the reduction of the FPC volume by at least an order of magnitude results in ducting and manifolding to regions outside the FPC becoming a more dominant part of the FPC "real estate"; FPC design integration for the compact systems becomes a more challenging exercise.[37]

Lastly, even for the topologically favorable RFP, the MHD pressure drop needed to provide adequate cooling by a liquid metal to the high-heat-flux, high-power-density FW region can easily require excessive MHD pumping power. Either a ceramic coating of the FW coolant channels or a separate pressurized-water coolant circuit will be required. The problems that attend the use of pressurized-water cooling, even in conjunction with the chemically less reactive PbLi, presents some concern. The need to isolate/insulate thermally the lower-temperature FW coolant circuit from the higher-temperature blanket coolant circuit in order to minimize the backflow of high-quality blanket heat into the lower-quality FW heat, however, naturally results in a double, if not triple, containment of the pressurized-water coolant circuit from the liquid-metal circuit.

3.3. Magnet Coils

Most compact reactor embodiments considered to date specify water-cooled copper coils located either at or near the FW, outside the thin (0.5-0.6 m) high-power-density blanket, or both (e.g., main coils outside the blanket, feedback or current-drive coils within the blanket or at the FW). In either case, radiation-resistant inorganic electrical insulation will be required. Either insulator coatings would be plasma-sprayed onto preformed copper conductors, or a powdered insulation (i.e., MgO or $MgAl_2O_4$) would be co-extruded with conductor and coolant tube, the latter method being used in the fabrication of radiation-hardened coils for use in high-energy particle accelerators.[30,31] Under more severe conditions, the FW coil requirement should be similar to the requirements envisaged for the MARS hybrid magnet insert,[26,32] or for the less severe tokamak conditions anticipated at the in-blanket equilibrium-field coils.

The issue of coil radiation life is poorly resolved by the existing data base, but under the conditions listed on Table III, a coil at the FW location exposed to a neutron loading of $I_w = 20\ MW/m^2$ would sustain an $MgAl_2O_4$ swelling rate of 11 volume percent per year and a (peak) copper conductor resistivity increase of 100-200% per year. It is noted that the swelling and mechanical degradation in cubic ceramics like MgO or $MgAl_2O_4$

considerably less than axisymmetric ceramics (i.e., hexagonal Al_2O_3),[27] and that the increased resistivity in 300–400 K copper is related to the transmuted alloy additions rather than intrinsic point-defects. Even under fresh startup conditions, a FW coil can significantly reduce the overall plant efficiency for both the OHTE[19] and the Riggatron[20] reactors; operational lifetimes of only a few months are predicted for I_w = 20 MW/m^2. A strong incentive exists, therefore, to locate these coils outside the FW zone and behind at least $\geq$ 0.1-m of blanket. As shown in Table III, interposition of a 0.6-m-thick PbLi blanket reduces the rate of insulator swelling and conductor resistivity increase by over two orders of magnitude. Such a coil could possibly outlive the FW/B and could be recycled. Generally, however, the incentive to move the coil outside the blanket is not driven by considerations of lifetime and the desire to reduce mass usage (i.e., operating cost), but instead by the need to: a) improve the overall plant thermal efficiency, since the FW coil would operate at a thermodynamically uninteresting temperature, b) to ease the breeding of tritium, although a few 10s of millimeters of copper has a net benefit on tritium breeding because of neutron multiplication, and c) to relieve the overall FPC congestion related to electrical/hydraulic/thermodynamic/tritium-recovery functions. Generally, the engineering development needs from both a systems and a materials viewpoint, even for the high-field FW magnets,[19,20] should be easier and less costly than for the large superconducting magnet designs. Lastly, a potentially significant advantage of compact systems is the facilitated use of efficient (i.e., reduced stored energy, currents, and forces) magnetic divertors because of the close proximity of magnet coils to the plasma, an option available only when thin-blanketed, copper-coiled compact systems are considered.

4. SUMMARY AND CONCLUSIONS

Significant improvements in both the operational and economic prospects for fusion power are promised for systems with power densities an order of magnitude above present projections. These compact reactors will require materials that in some areas differ from the mainline approaches.

The greatest need for materials development rests with the high-heat-flux IVCs (FW, limiters, divertors). Given that IVCs can be designed and operated with 4–5 MW/m^2 heat fluxes, the critical areas reduce to the partition of radiation <u>versus</u> particle flux incident upon IVC surfaces, the associated sputter erosion rate, the reposition processes (location and integrity), and the impact on the overall plasma performance of potentially large transfers of impurities around the system. The problems related to sputter erosion, however, in magnitude and kind, are not unique to compact reactors. Although sputtering rates are expected to be increased for the compact systems, given similar plasma and edge-plasma physics, the amount of FW sputtered per neutron fluence [mm/(MW yr/m^2)] should be independent of the concept and simply becomes a matter of "fluence".

Hence, the potentially unique materials problems for compact systems are related to the need to understand and control the bulk mechanical radiation damage properties of the new FW materials (copper, vanadium, molybdenum alloys) required to deal with the increased heat fluxes. Even then, such materials may be used in pumped limiters and/or divertor plates for the larger superconducting fusion systems.

The compact reactor option narrows the many B/S choices listed in Ref. 2 to a few concepts that can operate at local and average power densities considered economically necessary for other nuclear power systems (Fig. 1). The magnet development required to produce relatively small, radiation-hardened resistive coils appears to be well advanced,[30,31] <u>albeit</u> on a reduced scale. Hence, for both B/S and magnet areas, the materials requirements for the compact options appear no more difficult, and in many respects easier, than the mainline program needs.

In summary, all materials issues for compact reactors are being or can be addressed within the mainline program. A new emphasis, however, must be placed on understanding, creep, fatigue, fatigue-creep interaction, alloy stability, coolant-alloy interaction, etc. for these new high-heat-flux systems. It is in this classical area of materials and systems engineering, as applied to IVC surfaces, that major strides can be made in advancing fusion as a truly competitive energy source.

ACRONYMS

B/S	Blanket and Shield
COE	Cost of Electricity (mills/kWeh)
FPC	Fusion Power Core (FW, B/S, and coils)
IVC	In-Vacuum Components (FW, limiter, divertors, etc).
FW	First Wall
TDC	Total Direct Cost
RPE	Reactor Plant Equipment (Account 22) cost
UDC	Unit Direct Cost ($/kWe)
TFC	Toroidal-Field Coil
PFC	Poloidal-Field Coil
OHC	Ohmic-Heating Coil
EFC	Equilibrium-Field Coil

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