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AUTHOR(S): R. A. Krakowski, J. E. Glancy and A. E. Dabiri

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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THE TECHNOLOGY OF COMPACT FUSION-REACTOR CONCEPTS

By

R. A. KRAKOWSKI*, J. E. GLANCY** AND A. E. DABIRI**

ABSTRACT

An identification of future engineering needs of compact, high-power-density approaches to fusion power is presented. After describing a rationale for the compact approach and a number of compact fusion reactors, key technology needs are assessed relative to the similar needs of the conventional tokamak in order to emphasize differences in required technology with respect to the well-documented mainline approaches.

1. INTRODUCTION

The development and eventual commercialization of magnetic fusion energy (MFE) is presently being pursued in the U. S. through two mainline concepts, the tokamak and the tandem mirror, with a number of promising but less developed approaches being funded as alternative fusion concepts (AFCs). The reason for pursuing AFCs is the potential for less expensive reactor systems that may be easier to assemble, operate, and maintain while requiring less development time and dollars; the need for lower technology and better, more flexible operating characteristics (steady-state plasma, use of advanced fuels, easier assembly/maintenance, etc.) are also reasons for pursuing certain AFCs.

The engineering development needs for the mainline tokamak have been quantified by detailed conceptual design studies of both first-generation tokamak engineering experiments[1,2] and commercial power reactors.[3] To a lesser extent, but nevertheless at a significant level of effort and conceptual design detail, are studies of the Tandem Mirror Reactor (TMR)[4-6] as well as nearer-term engineering devices[7,8] based on the tandem mirror confinement principle. Complementing both the tokamak and tandem mirror mainline approaches are the AFCs. The status of reactor designs for tokamaks, tandem mirrors, and AFCs has been summarized quantitatively in a recent review paper[9], and an even more recent status has been reported by an IAEA workshop.[10] A qualitative assessment

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of the engineering and technology needs of the major AFCs has also been presented recently.[11]

A generic category termed "compact"* or high-power-density has been identified[10,11] into which is placed 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, field-reversed configurations, field-reversed mirrors, etc.).[20-27] Concern over the dominance in mass and cost of the fusion power core [i.e., first-wall/blanket/shield/coils (FW/B/S/C)] for many of the "conventional" MFE approaches[1-10] has led recently to serious consideration of the compact option.[13] Fusion-power-core (FPC) power densities approaching those of light-water fission reactors (i.e., 10-30 times greater than for conventional MFE systems), projected costs that are relatively insensitive to large changes in the FPC unit costs ($/kg) and associated physics and technology, considerably reduced size and mass of the FPC with potential for "block" (i.e., single or few-piece) installation and maintenance, and the potential for rapid, minimum-cost development and deployment are general characteristics being sought through the compact reactor options.

It is emphasized that use of the adjective "compact" does not necessarily refer to or limit a specific confinement scheme; just as the Reverse Field Pinch (RFP) has a viable conventional reactor embodiment,[28] it is possible to envisage compact reactor options for the tokamak[15-17] and the stellarator/torsatron/heliotron (S/T/H).[29] If a given AFC is to impact significantly the overall development of MFE, it must lead to a substantially more competitive reactor. Furthermore, this better reactor probably must be achieved on a shorter time schedule and with significantly smaller expenditure of funds. Given steady progress in physics research for certain AFCs, these goals can be met most probably along the compact route. In order for an AFC to have impact as a true option, rather than merely as a backup to the mainline, it must pose a true alternative; for economic reasons discussed in Ref. 13 and summarized in Sec. 2., that alternative may have to be compact.

*The word "compact" is used here to describe explicitly high-power-density fusion power cores and does not necessarily imply small capacity [i.e., MWe(net)]. Although the combination of compactness and smallness in capacity is possible, economies of scale generally dictate higher unit costs (i.e., $/kWe or mills/kWeh) for systems with lower capacity.

The compact option for fusion power will require the extension of existing technologies to accommodate the higher heat flux, power density, and (in some instances) higher magnetic fields required to operate the FPC with system power densities* in the 10–15 MWt/m^3 range rather than in the 0.3–0.5 MWt/m^3 range being predicted for the conventional MFE approaches. After giving a more quantitative rationale for pursuing the compact route in Sec. 2., the three compact fusion reactors used as a basis for this assessment of technology needs are briefly described in Sec. 3. It is noted that the three compact systems used here to identify engineering and technology needs are included in but do not encompass the reactor spectrum considered by Gross' contribution to this workshop; the definition of compactness given above is restrictive and further study remains to be done before the qualifications of the field-reversed configurations, spheromaks, dense Z-pinches, etc. for high-power-density compactness can be properly assessed. Section 4. then gives a quantitative technology assessment for the compact option using only the three aforementioned concepts (RFPs, OHTEs, tokamaks) as an assessment base. Section 5. concludes with a summary and recommendations for engineering/technology development in the area of compact fusion systems. It is emphasized that both the advantages and limitations of the compact option, as well as related technological needs, are only beginning to emerge; much of the technology prognoses presented herein, therefore, must be viewed as initial and is yet to be subjected to examination against a more fully developed data and study base.

2. RATIONALE FOR COMPACT REACTORS

The direct costs of building a fission or fusion reactor can be divided into two major components: the Reactor-Plant-Equipment (RPE) cost and the Balance-of-Plant (BOP) cost. The fusion power core (FPC), which consists primarily of the first wall, blanket, shield, and magnets, can be a major contributor to the RPE cost. Other RPE items include auxiliary heating equipment, vacuum, cryogenic, and tritium systems. The BOP consists of all

*System power density is defined as the ratio of total (useful) thermal power to the volume enclosed by and including the coils (i.e., the FPC volume). Although generally a useful measure of performance for most MFE systems with exo-blanket/shield coils, application to one version of the high-field tokamak (Riggatron), which proposes to locate all coils within the blanket structure, presents an anomaly, although this definition is still used for such systems.

subsystems outside the secondary containment, such as the heat transport system, heat exchangers and steam generators, turbines, electrical generators, auxiliary systems, and buildings.

The RPE cost for fission reactors is approximately 25 percent of the total plant direct cost (TDC), and the BOP accounts for the other 75 percent. Studies of conventional fusion reactors 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.* Hence, estimates of fusion reactor TDC have predicted higher values than for fission power plants because of the expensive RPE costs related primarily to expensive (i.e., massive, high-technology) FPCs. This result that RPE/TDC > 0.5 for most conventional fusion reactors is contrary to the frequent claim that the BOP cost dominate the total plant cost and, therefore, little can be done to reduce the projected costs of fusion power; the summary given in Table I is based on the most recent design studies and indicates the dominance of the RPE costs for both mainline and major alternative fusion concepts. The mass of the FPC per unit of generated thermal power for most conventional fusion plants (i.e., FPC mass utilization) is projected to lie in the range 5-10 tonne/MWt, compared to 0.3 tonne/MWt for a light-water fission reactor.**[13] The RPE for compact reactors is projected to be only ~ 1/3 of the TDC because the FPC and associated support equipment are smaller and less costly than the conventional fusion systems of similar capacity (MWe); the FPC mass utilization is similarly closer to the comparable figure (0.3 tonne/MWt) for fission power. The direct cost of the

*It is noted that fusion reactors capable of direct-energy conversion, such as the TMR, attain higher overall energy conversion efficiencies and, therefore, project smaller BOP costs. The total plant cost (TDC), however, will be smaller only if the cost of the direct energy convertors is sufficiently low. It is also noted that systems with unattractively high recirculating power fractions will require larger BOPs and associated costs; for such systems the RPE/BOP cost ratio will be falsely depressed, not because of low RPE, but because of abnormally high BOP costs.

**The mass utilization for the fission plant is taken 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 infer a monotonic relationship between mass and cost. System which have FPCs that are comprised of large masses of inexpensive and easily replaced/reused coolant (i.e., LiPb) or concrete should use mass utilizations that are appropriately compensated (i.e., mass of drained blanket). It is also noted that the mass of an <u>entire</u> fission power plant, exclusive of concrete but including all reinforcing bar, is 10-15 tonne/MWt, which in some cases is approached by the FPC mass utilization for certain systems.

compact fusion reactor, therefore, is expected to be only slightly higher than the cost of a fission reactor. More importantly, however, the total cost of fusion for systems with RPE/TDC $\leq$ 1/3 will be less sensitive to physics and technology uncertainties associated with the assumed plasma performance and FPC operation; both significantly effect plant performance and cost, which in turn can lead to appreciable costing uncertainty and potential overruns.[30]

A summary of recent results from a number of conventional fusion reactor studies and associated cost estimates is shown in Table I. These findings are compared with results from a recently completed, but preliminary, study of a compact RFP reactor (CRFPR). The cost of a pressurized water reactor (PWR) is also shown. Figure 1 displays graphically the sizes of conventional FPCs relative to the FPC of a compact fusion reactor (CRFPR), again graphically illustrating differences in system power density and FPC mass utilizations reflected by the values given in Table I.

As indicated previously, an important economic incentive for considering compact reactor systems is the lower sensitivity of the TDC to physics and engineering uncertainties associated with all aspects of the FPC. Considerable uncertainty exists in fusion RPE cost estimates; however, much less uncertainty is associated with BOP costs because the associated technology is relatively mature. The uncertainty in cost estimates of conventional fusion systems is much higher than the uncertainty in compact fusion reactor cost estimates. This means that a doubling of the RPE cost for conventional fusion reactor designs would lead to a 50–75 percent increase in the TDC; a similar doubling of RPE for a compact reactor would lead to only a 20 percent increase in the direct capital cost.

The unit direct costs (UDC) summarized in Table I are plotted on Fig. 2 as a function of the ratio RPE/TDC, with nominal values of ~ 900 \$/kWe and 0.25 for UDC and RPE/TDC, respectively, being used to locate the LWRs. Using this LWR point as a normalization, the ratio of TDC for fusion relative to fission can be determined analytically under the assumption that the BOP costs for like fusion and fission power plants are nominally equivalent; the "analytic" curve of $R_{DC} = (UDC)_{FUSION}/(UDC)_{FISSION}$ is also given on Fig. 2. Assuming that the fusion system is allowed to expend more on capital investment in order to take advantage of an ideally zero fuel cost, this tradeoff of fuel for capital cost becomes questionable 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 RPE/TDC $\leq$ 0.3, low-economic-leverage regime 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.

Direct capital cost is only one component used in deriving the overall cost of electricity (COE) from a power plant. Figure 3 presents all the cost components and how these components are combined to determine the COE. 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 reactor types, and the fixed charge rate will be the same unless, for example, the compact reactor takes less time to construct and is more ammenable to mass production methods because of its smaller size. 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 capacity (MWe). The O&M costs will differ if the costs of replacing the FPC are different; however, both conventional and compact reactors require replacement of approximately equal masses of material per unit time (~ 200-400 tonne/y) for the same FW/B lifetime.* The annual generating cost for a compact fusion reactor, therefore, is expected to be lower than for a conventional fusion reactor, primarily because of the lower RPE cost. The annual energy output (kWeh/y) for compact and conventional fusion reactors of equal capacity may not be equal because the recirculating power fractions and the capacity factors may be different. The compact tokamak reactor (Riggatron) and the OHTE reactor may have high recirculating power requirements, because of the first-wall coil position, but the CRFPR has a recirculating power fraction approximately equal to conventional fusion reactors (10-15% half of which supplies the Ohmic losses in the coils and plasma).

Compact fusion reactors are also expected to be higher stress** devices relative to conventional fusion reactors because of higher power densities, thermal loads, and neutron fluxes (and higher magnetic fields at the coil for the Riggatron); however, this more highly stressed operating condition differs

*Although lifetimes of 10-15 MWy/m^2 are projected for low-flux stainless-steel first walls and blankets, transmutation-related resistivity increases in frist-wall coils (Riggatron and OHTE) may reduce lifetimes to 5 MWy/m^2.

**The word "stress" is used here to describe a general performance condition rather than a specific force per unit area.

little from standard operating conditions encountered in fission systems, and, furthermore, operating at the higher stress state should not reduce the capacity factor if equal engineering design criteria are used for compact and conventional reactors. Nevertheless, a potential exists for a lower plant factor relative to conventional low-stress fusion systems, this lower plant factor perhaps cutting into the promise of reduced COE resulting from reduced TDC and construction time; design-specific reliability analyses remain to be performed comparatively on conventional and compact FPCs.

In summary, the annual generating cost for a compact reactor may be significantly lower than that of equal capacity conventional fusion reactors, and the annual energy output can be approximately the same or only slightly lower. This situation couples with the desirably lower economic leverage exerted on the total cost by the RPE cost (wherein lies a majority of all physics and engineering uncertainty) for the compact system to give the primary rationale and promise for the compact approaches. Additionally, the compact fusion option may offer certain cost/schedule advantages related to the overall development of a usable product for fusion, these advantages also being related to the lesser role played by the FW/B/C systems in devices leading to the reactor.

3. DESCRIPTION OF COMPACT REACTORS

The desire to reduce the importance of the fusion power core (FPC), in terms of volume, mass, and finally costs, relative to the remaining components of the RPE and the BOP dictates system power densities that are considerably higher than those projected for conventional fusion reactors (Table I). The survey of compact fusion concepts considered by Gross in this workshop encompasses toroidal devices supporting large plasma current density (RFPs, OHTEs, high-field tokamaks), a variety of field-reversed configurations and spheromaks, as well as other very dense and highly pulsed configurations (i.e., dense Z-pinch, imploding liners, wall-confined systems). On the basis of the goals and arguments developed in the previous sections, however, only the first grouping (RFPs, OHTEs, high-field tokamaks) have been considered as models for the engineering and technology assessment presented herein. These compact devices can generally be classified as toroids using resistive coils to provide high-density tokamak, OHTE, or RFP confinement. All such devices generally rely on significant Ohmic heating to achieve ignition. Typical parameters for the CRFPR, OHTE, and Riggatron reactors are given in Table II. These reactor designs are generally characterized by the following features:

- High system power densit y
- Low FPC mass utilization
- Significantly lower ratio of RPE/TDC costs
- High first-wall neutron loading
- High blanket power density
- Little or no passive radiation shield for the magnets

The increases in plasma power density, neutron first-wall loading, and blanket power density* that accompany any attempt to maintain a given total power output at an enhanced engineering power density represent both potential benefits and deficits. The economic tradeoff between the benefits of high-power-density operation (i.e., reduced system mass, size, and cost) and the potential liabilities of increased recirculating power and reduced first-wall/blanket chronological life (i.e., potential for reduced plant efficiency, availability, and reliability) remains to be fully assessed in the context of a complete conceptual design for the three concepts summarized in Table II; the situation remains even less resolved for the other less developed, but perhaps more promising, AFCs cited by Gross' survey paper.

3.1. COMPACT RFP REACTOR (CRFPR)

The CRFPR is a toroidal axisymmetric device in which the primary confinement field is poloidal and is generated by a toroidal current flowing in the plasma. Unlike the OHTE and Riggatron reactors, all magnetic coils in the CRFPR are positioned externally to the blanket, increasing the ability to breed tritium, providing enhanced 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. Figure 4 shows a

*The blanket power density in the Riggatron high-field tokamak, however, is low since the blanket is far removed from the first-wall and coil systems.

schematic cross section of the 1000-MWe(net) reactor with the specifications given in Table II; significantly smaller capacity systems are also possible for the CRFPR. 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 recovery of sensible heat and for adequate tritium breeding, minimum blanket thicknesses ranging from 0.5 to 0.6 m will be required. Such a "model" blanket design is described and used in Sec. 4.2.7. to give a generic example of key radiation effects anticipated for these high-wall-loading FPCs.

3.2. OHMICALLY HEATED TOROIDAL EXPERIMENT (OHTE) REACTOR

More conservative assumptions with respect to the external control of potentially large energy losses that may accompany the maintenance of toroidal-field reversal near the RFP plasma edge leads to the OHTE approach.[14] The OHTE controls the field reversal and associated magnetic shear at the plasma edge by actively-driven helical coils positioned near the plasma edge. The high-power-density operation is attained at moderate to high beta with modest coil fields. Since the resistive copper coils are operated near room temperature and are positioned near the first wall, the overall system performance in terms of plant thermal efficiency is reduced. Figure 5 shows a commercial OHTE reactor.[14] Five OHTE reactor types have been described in Ref. 14; the specifications of a commercial electric power plant, which is sized for 900-MWe(net) output, are shown in Table II.

3.3. RIGGATRON

This reactor 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[15] 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 FPC must operate dictates a FPC life of approximately one month. Figure 6 shows a Riggatron reactor with the specifications given in Table II. The plasma chamber and the water-cooled copper magnets would be small because of the increased plasma density and the assumed beta. The overall system performance in terms of plant thermal efficiency and the ability to breed tritium is greatly reduced, since the coils are positioned near the first wall. The short-lived (30 days) FPC would operate in clusters of two or more fusion modules, with one, or perhaps two, additional stand-by modules and a rapid "plug-in" capability promising high plant reliability/availability without in situ remote maintenance. The fusion neutron power is recovered in a fixed lithium blanket located outside of the magnet system. Recovery of Ohmic and neutron heating in the copper coils is also an essential element of the overall power balance.

3.4. OTHER POTENTIAL APPROACHES TO COMPACT REACTORS

A number of reactor configurations based on field-reversed or spheromak plasmoids may qualify for the compact, high-power-density option. 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. Only the latter approaches, as embodied in the TRACT[20] or LINUS[21] reactors, appear to offer the potential for system power densities approaching the 10-15 MWt/m^3 range, although the other CT reactor embodiments still promise significant increases in system power density relative to the more conventional mainline and AFC systems. 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 become available that emphasize the goal of high system power density; the potential for high-power-density operation for certain of the CT configurations, however, should be recognized. Similar comments apply to the other AFC reviewed for this workshop by Gross.

4. COMPACT REACTOR TECHNOLOGY REQUIREMENTS

4.1. OVERVIEW AND SUMMARY

Table III summarizes compact reactor parameters that differ significantly from conventional tokamak (STARFIRE) parameters and that impact projected technology requirements. These design differences result primarily because of:

- Increased plasma power density, which is proportional to β^2B^4, where B is the confining magnetic field at the plasma and β is the ratio of average plasma pressure to magnetic field pressure at the plasma surface.
- Increased first-wall neutron current (15-20 MW/m^2) and surface heat flux (4-5 MWt/m^2, maximum, for uniform heat deposition onto the first wall).
- Increased peak ($\gtrsim$ 100 MWt/m^3) and average ($\gtrsim$ 30 MWt/m^3) power density within a tritium-breeding blanket.
- Increased radiation and heat fluxes at resistive magnet coils in systems designed to operate at most with only a thin heat-recovering/tritium-breeding blanket placed between the coil and the plasma.

Key parameters for the three compact reactors being considered here are presented in Table III according to three major systems that comprise the FPC: Plasma Engineering Systems, Nuclear Systems, and Magnet Systems. Compact reactors would operate at higher plasma densities and, therefore, refueling, impurity control, and ash removal requirements may be more demanding. The higher plasma density may also lead to more difficult rf current-drive requirements for steady-state operation. The potential for low-frequency "F-Θ pumping"[36] that is unique to the RFP confinement, however, represents a potentially new and attractive means to drive steady-state current; F-Θ pumping, however, remains to be tested experimentally. The first-wall power loads for compact reactors are higher than for conventional systems, which also leads to higher blanket power densities. It is noted that although the FW/B for the compact systems would operate under more highly stressed conditions, compared to the conventional fusion systems, the compact options are simply attempting to approach operating conditions that are considered standard for fission energy sources. The magnetic field requirements for the CRFPR and OHTE are lower than for STARFIRE tokamak reactor, 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.

Table IV gives a summary assessment, indicating where technology requirements for compact reactors are more difficult (+), less difficult (-), or nominally the same (0) as for a conventional (steady-state) tokamak. The requirements for the Plasma Engineering Systems do not significantly differ between long-pulsed and steady-state operation except possibly for ash removal and impurity control; fueling should be similar for a 30-100 s burn as for a truly steady-state burn, but the latter mode may require a magnetic divertor for ash removal and impurity control. Because of the higher first-wall thermal loadings, a heat-flux-concentrating limiter does not appear to be possible, and the first-wall may have to serve the limiter function if a divertor is not used. For pulsed operation, therefore, the only areas where the compact option poses more difficult technology requirements are related to the first-wall thermal/particle load and blanket (or magnet for 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 TF and OH coil set in the case of the Riggatron, this enhanced afterheat power density resulting from the higher overall operating blanket power density. The technology requirments in the magnet area 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, the maintenance procedure envisaged for the compact reactors, because of their physical size and mass, makes possible consideration of "block" maintenance, wherein the complete FPC is removed for maintenance and repair operations external to the reactor cavity, with a more rapid replacement by a fresh, pre-tested unit promising shorter downtimes and more reliable restarts.

Another perspective on the differences and similarities in technology requirements for conventional and compact fusion reactors can be developed using the results of a recent Electric Power Research Institute (EPRI) study.[37] This EPRI study polled fusion technology experts on and generated a ranking of technology issues for different reactor concepts. Table V reports results from the EPRI study for two conventional fusion reactor designs (STARFIRE tokamak[3] and the conventional RFP reactor[28]) and two compact fusion reactors (the Riggatron tokamak[15] and the OHTE[14] reactors). The CRFPR design was not available for inclusion in the EPRI study. Technology issues receiving equal "scores" using the EPRI methodology are grouped together in Table V. Many similarities can be identified, while at the same time the ranking indicates soma differences. The conventional reactors both rate magnet reliability as one of the highest priorities, whereas this issue is not identified for the compact options. Radiation resistance of magnet electrical insulators was rated by the EPRI study as priorities for both compact reactors, whereas this item either is not included in the priority list or is located at a low priority for conventional reactors. The radiation resistance of magnet material (copper alloy) ranks high for the compact reactors and low for the conventional reactors. The degree of remote maintenance is an important issue for conventional reactors but does not appear as an issue for compact reactors because the entire FPC is replaced (e.g., block maintenance). However, the removal of large components is perceived to be of equally high importance for both reactor options. First-wall neutron fluence, heat/mechanical loads, erosion, and fatigue are of the highest priority for compact reactors; these items are also ranked at high priority for conventional reactors, even though the first-wall loads are lower, since the conventional systems require a larger chronological life. Magnet shielding ranks moderately high as a critical issue for conventional reactors but is not an issue at all for compact reactors. The same observation applies to supplemental heating for the STARFIRE tokamak reactor. Critical issues for the compact reactor that do not simultaneously appear for the conventional reactors could not be identified.

In summary, the EPRI study ranks the first wall as first priority for the Riggatron and third priority for the OHTE. The authors of this report would rank the first-wall erosion control as first priority for all concepts, including the CRFPR; the effective cooling of a high-power-density, breeding blanket is ranked by the authors as a close second, except for Riggatron, which because of its inverted configuration operates with a relatively low-power-density blanket (Fig. 6). Radiation-related, life-limiting effects on the FW/B remains an important overall technology issue for all fusion concepts. The following subsection provides a more detailed assessment for each major fusion technology system associated with the FPC.

4.2. TECHNOLOGY REQUIREMENTS FOR MAJOR REACTOR SUBSYSTEMS

4.2.1. PLASMA ENGINEERING SYSTEMS

The higher plasma density envisaged for the compact systems will impact most Plasma Engineering Systems. All three compact approaches listed on Table II rely on significant Ohmic heating by toroidal plasma currents. The high-field tokamak in addition may require auxiliary (adiabatic compressional and/or rf) heating to achieve ignition. The high plasma density makes rf current drive more difficult, although low-frequency "F-Θ pumping" of current in

RFP-like plasmas[36] should not be strongly affected by the higher plasma density. Plasma-ash, impurity, and fueling control remain as uncertainties in the higher density regime. Dense gas blankets and/or magnetic divertors are being considered and may be required even for long-pulsed operation, particularly for first-wall protection against sputtering. The OHTE, of course, would operate with a natural magnetic divertor. The first-wall/plasma interaction and associated sputter erosion, rather than high-heat transfer rates <u>per se</u>[38], represents the key plasma engineering issue for the CRFPR and OHTE compact options; for the Riggatron the physical heat fluxes will be considerably larger. The introduction of high-Z first-wall impurities into the plasma represents a potentially greater problem for the compact systems, since low-Z material coatings (e.g., Be) may be more limited by the higher first-wall heat fluxes. The severity of this limitation, however, depends on yet-to-be-resolved systems and plasma processes related to divertors and dense gas blankets as well as innovative first-wall mechanical design.[39,40]

Pellet refueling and vacuum requirements for compact and conventional reactors appear to be similar. A pellet ablation scaling law that shows good agreement with experiment[41] indicates that the fuel pellet lifetime, r_p/v, where r_p is the plasma radius and v is the pellet velocity, is only weakly dependent on average plasma density ($\propto 1/n^{1/3}$). Even for the same injection velocity, therefore, the decreased plasma radius for the compact systems more than compensates for the increased plasma density; similar or less stringent requirements on pellet velocity are indicated. Since the plasma particle out-flux for a given ignition condition is proportional to the total power, systems with a similar capacity will require the same total fueling rate. Hence, the pellet injection frequency and radius should be the same as for the conventional systems. In addition, the total vacuum and/or divertor pumping speeds will be similar for both compact and conventional systems, although, like the primary coolant ducting to the FPC (Sec. 4.2.2.), the vacuum ducting may become a more dominant feature relative to the FPC size for the compact approaches; approaches that place the FPC or a portion thereof within a vacuum envelop represent an exception to this concern. A more difficult "real estate" problem in the immediate vicinity of the FPC for the compact options generally is envisaged, however.

4.2.2. NUCLEAR SYSTEMS

The increased surface heat flux and volumetric power density at the first wall and within the tritium breeding blanket for the compact option represents a major impact on the technology requirements for the nuclear systems. Preliminary computations[38] find no serious thermomechanical problem under long-pulsed operation for a CRFPR using a high-strength copper alloy at the first wall that is cooled by high-pressure water ($\lesssim 10^6$ pulses, 4-5 MW/m^2 heat flux, $\gtrsim$ 30-s burn, one-year operating life). The results of another study[39] of copper first walls for compact reactors indicates that the creep-rupture strength related to coolant pressure may be an important limitation on the first-wall operating life. Increases in the first-wall thickness required to support high coolant pressure are limited by the high thermal stress that occurs in thick materials, as has been quantified in Ref. 38. A careful and more detailed study is required to optimize first-wall designs that operate with high thermal loads, particularly with respect to radiation-induced degradation of thermal-mechanical properties of solution-strengthened copper alloys. Use of primary candidate alloy stainless steel (PCASS) at the first wall generally does not appear possible for the compact reactors. It is noted that heat fluxes of the magnitude envisaged for the compact reactors are required of the STARFIRE pumped limiter,[3] which itself has an area that may approximate that of the entire first wall of a comparable compact reactor.

As indicated by Fig. 7, heat fluxes anticipated for a range of other fusion applications do not differ appreciably from the (divertorless) first-wall heat fluxes projected for the CRFPR and OHTE reactor. Also shown in Fig. 7 are the heat fluxes for other non-fusion processes occurring in nature and industry, again illustrating that the OHTE and CRFPR requirements are moderate extrapolation of existing technology and that the Riggatron would operate with heat fluxes that have been attained in other areas of high technology. Although first-wall heat transfer appears to present no insurmountable engineering problems, as noted above, the questions of sputtering, non-uniform energy deposition, and bulk radiation effects all present serious uncertainties for compact and conventional reactor approaches alike; this central issue is closely related to the projected engineering/technology needs for both the plasma engineering system (i.e., dense gas blankets, refueling, divertors, etc.) and the magnet systems (divertors).

The peak blanket power density projected for most compact fusion reactors is comparable to the power density in a light-water reactor (LWR) fission core and about 1/4 that expected in a liquid-metal fast-breeder fission reactor. The average power densities are a factor of 6-7 lower than the peak values, but remain six times higher than for conventional (STARFIRE) fusion systems. It is noted however, that the local power density within the beryllium neutron multiplier of the STARFIRE blanket[3] is within a factor of 2-3 of the peak power density within the compact reactor blanket. The compatibility of solid tritium breeders with this local power density presents a question related primarily to uncertainties in thermophysical properties of the solid breeder. Solely for the purposes of establishing perspective, Fig. 8 gives a range of power densities in a number of existing engineering systems. The LiPb-cooled blanket proposed[14] for the OHTE appears particularly attractive for the compact fusion reactor applications, especially for the relatively low-field RFP geometry, where MHD-pumping losses can be considerably reduced. A fully-optimized design of such a thin, tritium-breeding, energy-efficient blanket has been made for the CRFPR and is used in Sec. 4.2.7. as a quantitative example of expected radiation effects in a "model" compact reactor blanket. Generally, the impact on the technology required of the nuclear systems will uniformly be greater for the compact reactor approaches, although for certain compact confinement schemes[14,15] the impact of the magnet systems on the blanket design and overall plant efficiency will also be significant.

Although acceptable thermohydraulic designs of a high-power-density blanket can be made, the exo-blanket coolant ducting required to deliver the same total power from a considerably smaller blanket system may be comparable to the blanket system <u>per se</u> and, hence, may contribute a greater portion to the FPC mass and cost than for the conventional options; more detailed designs are required to resolve this issue, however. For systems like the Riggatron, however, where the blanket is located outside the coil set, this issue of ducting coolant to and from a high-power-density blanket appears not as crucial. Lastly, although the compact systems would operate under higher stressed conditions relative to conventional fusion (but not necessarily with respect to more conventional energy systems in general), the same safety margins would be built into the compact systems, possibly at a somewhat higher cost, to assure an overall plant availability and reliability that are commensurate with economic power plant operation. Detailed FPC reliability analyses, based on generally unavailable radiation effects information, remain to be performed in order to relate the overall FPC stress state to failure probability (frequency), which in turn should be coupled to studies of maintenance/repair/replacement times to determine the total plant availability. This remains an important area of future work.

4.2.3. MAGNET SYSTEMS

The magnet requirements for the three compact approaches listed in Table II differ widely. For those systems requiring large toroidal (tokamak) or helical (OHTE, perhaps high-beta stellarators) fields, resistive coils positioned at or near the first wall may be required when force and/or plasma inductive-coupling considerations are taken into account. For these cases of relatively cool coils positioned near the first wall (i.e., OHTE and Riggatron reactors), the system energy balance can be seriously degraded. The dominance of poloidal field for plasma pressure containment in the self-reversed RFP, on the other hand, allows the use of exo-blanket coils operating with low fields, small amounts of stored energy, and Ohmic losses that can be made a small fraction of the total fusion power. For all compact reactor cases, however, these resistive coils must operate in high neutron and gamma-ray radiation fluxes, requiring the use of inorganic (e.g., powdered $MgAl_2O_4$ or MgO) electrical insulation and relatively low-temperature alloyed copper (or aluminum) conductors that are water cooled. In addition to insulator damage, radiation-induced changes in copper resistivity and neutron-induced swelling of both conductor and insulator must be better quantified (Sec. 4.2.7.). Although the toroidal-field coils dominate the compact tokamak magnet system, the Ohmic-heating/poloidal/equilibrium coils dominate the CRFPR design, and the first-wall helical coils dominate the OHTE reactor, the questions of divertor coils and feedback/position-control coils remain to be resolved for all compact concepts. Generally, the use of poloidal divertor coils in these high-current devices appears to be unattractive because of the high currents and associated Ohmic losses incurred within these divertor coils. The coil design and lifetime prognoses for the high-field systems (i.e., Riggatron) is further complicated by the need for additional inner-coil structural support (e.g., stainless steel). Generally, the engineering requirements of high-radiation-flux copper-coil design and operation for most compact reactor approaches should be similar to requirements of hybrid magnets for the TMR design[6] or tokamak designs requiring equilibrium-field coils positioned near the plasma; even for the high-field coils, however, the engineering development needs are judged to be considerably reduced from those required of the large superconducting coils envisaged for the conventional fusion reactors.

For those compact systems that propose a long-pulsed operation, the method adopted for power/energy transfer and storage (PETS) can present an important cost issue that depends intimately on key physics issues related to plasma startup, volt-second requirements, and plasma processes occurring during approach to ignition. Ideally, transfer times and total energy requirements that are most suitable for direct drive from the electrical grid would be preferable. The greatest demand on magnet and PETS systems occurs during plasma startup, a demand that will be strongly determined by as yet poorly understood, fundamental plasma processes occurring during the startup transient. The amount of flux-drive required for long-pulsed operation or current-drive power needed for steady-state operation is also closely related to the degree to which the resistivity of the burning plasma is anomalous; anomaly factors in excess of approximately ten at burn conditions can seriously degrade the overall plant performance in terms of PETS cost and added recirculating power requirements. Anomalously large energy losses incurred during the startup phase when the stable magnetics configuration is established within the plasma will also impact the degree to which the first wall is thermally stressed as ignition is attained. For both the CRFPR and OHTE systems, field reversal per se would be achieved in a low-temperature/low-density plasma with the expenditure of only a small fraction of the initial investment of magnetic field energy; the subsequent current rampup and ignition would be achieved on a longer time scale to minimize the startup power and perhaps to allow more realistic considerations of drawing a significant portion of the startup energy directly from the electrical grid.

4.2.4. REMOTE MAINTENANCE SYSTEMS

A major goal of the compact approaches is to achieve FPC mass utilizations within or below the range of 0.3-1.0 tonne/MWt. At the lower limit, a 4000-MWt power plant would be driven by an FPC that weighs less than 1500 tonne. This mass is equivalent to at most a few of the many toroidal-field coils envisaged for some of the more conventional MFE approaches. In the case of the Riggatron the first wall and coil set are surrounded by a fixed blanket structure, the former replaceable unit weighing only 25 tonne (Table III). It is, therefore, conceivable that the entire FPC could be replaced as a single or at most a few units during scheduled maintenance period (annually for the CRFPR, every four months for the OHTE, and monthly for the Riggatron). Typically, the complete FW/B/S system for this approximately 1000-MWe power plant would weigh 200-400 tonne, and at the 15-20 MW/m^2 first-wall neutron loading would be subject to annual replacement. This annual replacement rate generally is comparable to that for the conventional fusion systems, which on the average would replace only a fraction of a larger FW/B mass each year. These mass replacement rates, of course, do not include the mass of coolant or the recycle of key blanket components (i.e., multipliers, shields, etc.). Both conventional and compact approaches to MFE would essentially "burn" FW/B systems at comparable rates (200-400 tonne/y for an approximately 4000-MWt plant) and, therefore, would be subjected to similar operating costs. Equally if not more importantly, a more rapid and reliable FW/B replacement scheme based on block maintenance approaches could enhance overall plant availability, which in turn can counteract potentially lower operational reliability that may be associated with these higher-performance systems. The concept of block maintenance, wherein the entire FPC or at least the FW/B/S is replaced as a single unit, offers a new and innovative maintenance approach for both scheduled and unscheduled outages. As noted in Sec. 4.2.2., however, the exo-blanket coolant ducting for most compact systems will become a more dominant feature of the FPC, and the impact of this dominance on the overall maintenance scheme remains to be evaluated by detailed conceptual engineering designs.

4.2.5. OTHER SUBSYSTEMS AND ISSUES

4.2.5.1. Diagnostics, I/C, and Environment

Technology R&D needs in the area of diagnostics and instrumentation/control (I/C) systems are not fully understood, even for the conventional approaches to MFE. In terms of total rate of radionuclide generation, little difference is expected between conventional and compact approaches. The quality of this radionuclide production, as measured by the post-shutdown decay and biological hazard potential, depends primarily on material selection and not directly on the compact versus conventional issue. For a given tritium solubility in a Li-Pb blanket, the compact systems are expected to operate with reduced inventories of "vulnerable" tritium. Although the compact device will store considerably less magnetic energy in a resistive rather than a superconducting magnet set, the density of radionuclide generation and the related nuclear afterheat problem will scale with the increased system power density. Given that each unit mass of FW/B will generate similar amounts of total energy for both approaches, the structural radwaste problem is expected to be similar for both conventional and compact approaches.

4.2.5.2. MFE Development

The major goal of the MFE program is to achieve economic commercial fusion power by the shortest, least-costly development path. This path may be optimized by using the unique characteristics and advantages of the compact fusion approaches that generally require the extension of existing engineering technologies rather than the development of new ones. More rapid-paced, higher-risk development appears to be more ammenable to MFE approaches that represent modest technological extensions of systems that have the flexibility associated with smallness in size, stored energy, and total R&D costs. Most compact systems provide such a high-risk/high-payoff opportunity. The savings in R&D time and dollars allowed by integrating technology development needed for the generation of technological data bases through the major experimental confinement devices should allow a more rapid development of the compact option.

Lastly, it is recognized that the plasma performance for most AFCs, as measured by plasma temperature, confinement time, Lawson parameter, or Lawson parameter times temperature, is below the corresponding measures for the tokamak mainline. Nevertheless, for those AFCs that scale to the reactor regime by increasing current rather than size, or that rely on well-proven heating schemes (i.e., Ohmic heating, compressional heating, or both) significant improvement in plasma performance is expected to occur at a considerably enhanced pace when compared to past experience that relied primarily on size scaling and the development of exotic heating methods. In short, time scales that are considerably less than decades are anticipated for significant, "reactor-like" plasma performance for most AFCs that promise a compact reactor option.

4.2.6. PULSED VERSUS STEADY-STATE OPERATION

Like the mainline tokamak, most systems being considered for the compact reactor option intrinsically would operate in a long-pulsed mode. The thermal power delivered to the blanket, the primary coolant, and the turbine, as well as the electrical energy generated by the turbine/generator systems, however, would always be steady ... e; only the plasma, and to some extent the first wall, would be cycled in ... g-pulsed system. Furthermore, careful tailoring of the startup/burn/ ... st cycle can significantly minimize the first-wall temperature cycle and extend considerably the low-cycle fatique life. A high-beta S/T/H (e.g., heliac[29]), however, would be intrinsically steady state, although crucial and interrelated geometric, stability/equilibrium, and beta issues remain to be resolved. A high-duty-cycle, long-pulsed operating mode for RFPs, OHTEs, and high-field tokamaks can be made to resemble closely a truly steady-state operation, particularly if the startup/shutdown schedules are engineered to minimize thermal transients both at the first wall and within the blanket. Generally, for long-pulsed systems that minimize thermal cycling and related transients the dwell or off-time should be minimized, which in turn will influence the rate at which the OH coils are back-biased and will also determine the means by which pumpout is achieved. Like the tokamak,[3] steady-state current drive for both RFPs and OHTEs can also be proposed.[36] Although this current drive for the RFP should require only low-frequency oscillations of the toroidal and poloidal field circuits rather than high-frequency rf, this F-θ current drive remains to be experimentally demonstrated.

Generally, the attraction of "steady-state operation" must be weighed against the added engineering/technology/physics development needed to achieve this goal. In addition to new and often difficult requirements of steady-state current drive for those devices requiring toroidal currents to be sustained inductively beyond approximately 100 s, the issue of active refueling and impurity/ash control contributes to the uncertainty of that approach. Embracing inherently steady-state confinement schemes (EBT/NBT, S/T/H, TMR) brings equally serious uncertainties of beta/stability/equilibrium (EBT/NBT, S/T/H), applicability or compatibility of the magnetic divertor (EBT), and overall system efficiency (EBT/NBT electron ring losses, TMR end losses). Superposed onto those uncertainties is the tendency of any closed-field-line steady-state plasma to establish radial electric fields that may enhance the trapping of helium ash and possibly impurities, thereby necessitating periodic (approximately 30 s) plasma shutdown for ash purge. Lastly, efficient plasma operation in relatively small compact systems may bring advantages that subjugate the issue of long-pulsed versus steady-state reactor operation, particularly if fatigue problems can be further reduced through better control of the total burn cycle; the tradeoffs must be more clearly understood before establishing a priority for the many future engineering needs of MFE, only one of which being a desire for steady-state plasma operation.

4.2.7. ANTICIPATED FPC RADIATION EFFECTS AND INFLUENCE ON SYSTEM PERFORMANCE

The previous discussions of technology needs for compact fusion reactors have necessarily been qualitative because of the generic approach adopted by this study, as well as a general absence of quantitative design and/or experimental information. A LiPb blanket design has been proposed for the CRFPR; this FPC layout, however, uses a 20-mm-thick copper first wall and exo-blanket coils. The results of neutronic computations based on this ~ 0.6-m-thick "model" blanket are representative of systems that have either first-wall or exo-blanket coils. This blanket is shown schematically in Fig. 9, with the "second wall" being PCASS and the "third wall" being a 0.1-m-thick region of a B_4C/W composite.

Table VI summarizes for this model FPC the key neutronic responses per unit of first-wall neutron loading as well as responses that would be typical of a 20 MW/m^2 first-wall neutron loading. These results can be used to project the FPC performance in terms of pacing (materials) technology issues if sufficient radiation effects information were available. Present understanding, however, permits only the generation of implications. For instance, the swelling of candidate electrical insulators,[42] MgO and $MgAl_2O_4$, has been measured after near-room-temperature irradiation to fluences of $2.1(10)^{26}$ n/m^2 and neutron energies above 0.1 MeV (2.8 and 0.8 v/o, respectively). For a first-wall neutron loading of 20 MW/m^2, extrapolation of this data would predict swelling of 11 v/o per year for $MgAl_2O_4$, at the first wall, if no saturation occurred. For the same material and first-wall flux, interposition of a 0.6-m-thick blanket would reduce the predicted swelling to 0.09 v/o per year. A tendency toward saturation is likely, however, and would greatly decrease the high fluence swelling while possibly increasing this value somewhat at low fluence. In addition, the electrical conductivity of many inorganic electrical insulators is increased by roughly an order of magnitude for every order of magnitude increase in dose rate. For the relatively low-voltage applications envisaged, however, the increased leakage current and Ohmic loss should be tolerable in most cases, although more detailed coil designs are required to assess fully this potential problem.

Increases in the electrical resistivity of first-wall or exo-blanket copper coils is anticipated from the introduction of point lattice defects (i.e., vacancies and interstitials), dislocations, voids, transmutation-induced impurities, and magnetoresistivity effects. The contribution of point defects to the enhanced electrical resistivity of copper is expected to saturate at ~ 0.0034 μΩ-m at 300 K.[43] This contribution to the increased resistivity will saturate at a considerably lower value at elevated temperatures because of the reduction in point defect content. Since the starting resistivity is ~ 0.02-0.04 μΩ-m, the effect of point defects on increased resisitivity should be quite small.

A high dislocation density in the copper conductor may result from plastic deformation or from the formation of radiation-induced dislocation loops. However, even for a density of 10^{16} dislocations/m^2, which is unlikely to be sustained at operating first-wall temperatures, the resistivity would be increased by only a few percent.[44] The resistivity contribution from this source, therefore, is expected to be insignificant. Furthermore, voids or large defect aggregates should not have an important effect on resistivity. Similarly, the resistivity contribution from magnetoresistivity for fields in the range 2-3 T and temperatures of 400-600 K is estimated to be a few percent at most and more likely will be less than one percent.

The high 14-MeV neutron first-wall flux will generate a significant concentration of metallic impurities through (n,2n) reactions. Similarly, transmutation of exo-blanket coil conductor will also occur at a reduced level. Both Ni and Zn impurities will be generated (Table VI). Assuming the formation of only the former element, which will have the greater effect on the electrical resistivity, the predicted resistivity increase will be slightly exaggerated. The rate of impurity formation would be 2.6% per year at the first wall and is reduced to 0.022% per year outside a 0.6-m-thick blanket for a first-wall neutron loading of 20 MW/m^2. Using two sets of data for Cu-Ni alloy,[45] the respective (average) resistivity increases at a first-wall or exo-blanket coil would be 100-200% per year and 0.7-1.4% per year, respectively. Both the insulator swelling and transmutation-related resistivity increases in a first-wall copper coil will require coil changeouts more frequently than once a year (3 times a year for OHTE and 12 times a year for Riggatron). The dramatic decrease in radiation effects when a ~ 0.6-m-thick blanket is interposed between the plasma and coil points to significant benefits of locating even a thin (0.10-0.15 m) neutron absorbing/moderating region between the plasma and the coil; the OHTE reactor design in fact is pursuing this approach.

Since thermal conduction in copper takes place primarily by the motion of electrons, an increase in electrical resistivity will also result in a decrease in thermal conductivity. To a first approximation the changes in electrical and thermal resistivities may be assumed to be proportional[46] (Wiedemann-Franz law). Consequently, changes in the thermal properties of a copper first wall are expected over the lifetime, perhaps leading to higher temperatures, greater thermal gradients, and increased stresses as end-of-life is approached.

Electrolytic tough-pitch copper (standard electrical wire grade) contains Cu_2O. Heating of this metal in hydrogen above ~ 775 K results in internal formation of steam which causes embrittlement.[47] Maximum first-wall temperatures envisaged for most compact systems, therefore, are sufficiently low to avoid this problem in the presence of molecular hydrogen. The presence of atomic hydrogen isotopes at the first-wall surface and the presence of transmutation-induced hydrogen within the lattice (Table VI), however, may result in embrittlement at the operating temperature. It may be desirable to specify oxygen-free high-conductivity (OFHC) copper for this application, although this would not be fully consistent with the use of a solution-hardened, high-strength copper alloy.

Irradiation-induced swelling of copper occurs in the temperature range between ~ 500 and 825 K, depending on the bombarding particle, damage rate, damage level, and gas content of the metal.[48] For "gassy" copper subjected to neutron irradiation at damage rates of $6(10)^{-7}$ DPA/s (18.3 DPA/y), the swelling range is shifted to ~ 500-775 K, with a maximum occurring at 625 K. The initial neutron-induced swelling rate at 775 K corresponds to ~ 0.4 v/o per DPA.[47] A copper first wall may have a high gas content because of transmutation-induced H and He and is expected to suffer a damage rate that is greater than the above value. A high initial swelling rate, therefore, is indicated, but saturation may occur, and the effects of alloying on swelling is not known. Possible constraint by the stainless steel structure backing the copper first wall may also be considered. Temperature differences between inner and outer first-wall surfaces will also result in a variation of the swelling rate through the thickness. Some variation may also result from different displacement and gas generation rates at inner and outer surfaces. These separate effects remain to be integrated into a composite estimate of first-wall life based on a detailed engineering design. Ultimately, reliable materials models of an integrated nature must be used to set the first-wall operating temperature. Generally, little or no data are available on the effect of alloying, the effect of neutron fluence (above ~ 1 DPA), or the effect of temperature except on pure copper at < 1 DPA.

Irradiation damage often results in strengthening and embrittlement of metals as a consequence of microstructural changes. Copper is strengthened by irradiation, at least up to 400 K,[47], and, although experimental results showing embrittlement or decreased stress-rupture lifetime for this metal is not available, these effects are likely consequences of the formation of a damage microstructure. At temperatures below approximately half the melting point and in fast neutron fluxes greater than 10^{17} n/m^{2}s, metals typically show an enhanced creep rate compared to that observed for the unirradiated material.[49] This enhanced creep results from the generation of point defects during irradiation. Since a copper first wall must desirably operate from 0.40 to 0.45 times the melting temperature in a high fast neutron flux, accelerated creep can be expected. The interaction of enhanced creep and embrittlement processes in a high-radiation-flux first wall is largely unknown, however, particularly for solution-hardened alloys.

Generally, the radiation responses of both alloyed copper conductor and candidate electrical insulator are poorly known, potential problems can be envisaged that limit both the life and performance of first-wall and exo-blanket coils, and similar problems can be envisaged for copper-alloy first walls. Although operation of first-wall coils with a life that is comparable to that projected for a PCASS blanket (i.e., 10-15 MWy/m^2) seems improbable, addition of even 0.10-0.15 m of blanket between coil and plasma promises significant improvement. Furthermore, it is expected that a copper-alloy high-heat-flux first wall may have to operate at temperatures that are below the blanket coolant, thereby reducing the overall plant thermal efficiency. The impact on overall plant efficiency of both first-wall temperature and thickness, as well as the influence of the average blanket temperature and whether or not an intermediate heat exchanger (IHX) is used between the blanket and the steam generator is illustrated in Fig. 10; the tradeoff of η_{TH} with these key system variables is clearly illustrated. Generally, considerably more work is required to define a fully-optimized FPC design that operates reliably at high power density while assuring that each major FPC component (i.e., FW/B/C) simultaneously achieves an acceptable end-of-life exposure before replacement. Lastly, it is again emphasized that both conventional and compact reactors ideally would consume nominally the same FW/B mass, and for the FW/B mass throughputs being considered for compact fusion the major impact on COE is through reduced availability (i.e., scheduled downtime) rather than increased operating cost.

5. SUMMARY AND CONCLUSIONS

The assessment presented above is summarized in Table VII. Although Figs. 7 and 8 attempt to place the engineering needs of compact fusion in perspective with actual and projected reality, the nature of a technology assessment of the generic class of compact systems precludes a more quantitative comparison to reality without becoming device specific. An attempt to add a quantitative flavor to this assessment, however, was made in Sec. 4.2.7. by adding a specfic FPC example. On the basis of this qualitative assessment, however, no surprises arise with respect to the key areas of engineering needed for the compact approaches relative to the better defined needs of the conventional mainline tokamak. Specifically, the future engineering needs of both mainline and compact approaches lies primarily in the following areas.

- Plasma engineering (auxiliary and/or startup heating, impurity/ash/fuel control, current drive <u>versus</u> long-pulsed operation).
- First-wall/limiter systems (transient thermal effects, sputtering, radiation effects, tritium permeation/retention/recycle, end-of-life mechanism(s) and lifetime, maximum operating temperature and overall plant efficiency).

- Blanket/shield (materials compatibility, radiation damage, solid-breeder properties <u>versus</u> liquid-metal breeder containment).
- Magnets (thermomechanical/electromechanical properties, radiation effects to conductors and insulators, reliability, maximum fields and hybrid magnets, size/modularity).
- Remote maintenance (better definition of maintenance scheme and downtime, need for less massive modules, quantify relative merits of block <u>versus</u> batch maintenance FPC reliability analysis).

The basic difference between the conventional and compact approaches is that the latter extends directly existing technologies while newer and sometimes exotic technologies are required for the former approach. The compact systems, however, are more highly "stressed", although it must be recognized that in terms of heat fluxes and power densities the compact option is only attempting to retrieve for MFE a level of system performance that is already achieved and deemed necessary for fission power. Furthermore, application of similar engineering design criteria to the more highly stressed compact systems should retain acceptable plant reliability/availability, albeit potentially at a somewhat increased cost.

The ability of any MFE concept to project to the compact regime will depend on the fulfillment of future engineering needs that may not automatically emerge from D&T programs put in place to support the more conventinal approaches. Nevertheless, the conventional mainline approaches are expected to supply important engineering information for the compact options in the area of high-heat-flux first walls (pumped limiters for tokamaks, direct convertor surfaces for tandem mirrors, neutral-beam dumps, rf tube electrodes, etc.), and radiation-resistent resistive coils (equilibrium coils for tokamaks, high-field hybrid magnets for the tandem mirror axicells), as well as pulsed power/energy transfer and storage (tokamak startup). All these requirements are considered to represent long-term development items for the mainline approaches, however, whereas many of the related engineering problems for the compact options must be addressed experimentally on a much shorter time scale; in terms of heat fluxes, power densities, and mechanical stress levels, the compact options generally force development of devices to operate nearer to anticipated reactor conditions than do the more conventional approaches. For these reasons many of the extended technologies required by the compact systems will have to be developed in the course of understanding the fundamental physics of the respective approaches. If a single important future engineering need can be identified from this survey it would call for a concerted effort to understand the degree to which existing technologies can be extended to accomodate the needs of the compact option, compared to the reduction or elimination of the need for more advanced technologies required of the conventional MFE approaches.

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Table I. Summary of Key Parameters for a Number of Recent MFE Reactor Studies

Device	Thermal Cycle Efficiency η_{TH}	Overall Efficiency(a) $\eta_p = \eta_{TH}(1-\epsilon)$	Net Electric (MWe) $P_E = \eta_p P_{TH}$	Quoted Unit Direct Cost (1980,$/kWe)	Unit Direct Cost Normalized to P_E = 1000 MWe (1980,$/kWe)(b)	$\frac{RPE}{TDC}$(c)	System Power(d) Density (MWt/m^3)	Mass(e) Utilization (tonne/MWt)
STARFIRE[3]	0.35	0.30	1,200	1,440	1,550	0.56	0.3	3.9
WITAMIR-I[5]	0.42	0.39	1,530	1,350	1,600	0.76	0.24	11.0
EBTR[31]	0.35	0.30	1,214	1,740	1,880	0.68	0.24	10.8
MSR[32]	0.35	0.32	1,530	1,550	1,840	0.65	0.26	9.0
RFPR[33]	0.30	0.25	750	1,320	1,180	0.45	0.50	3.7
CRFPR[13]	0.35	0.30	1,000	900	500	0.35	15.0	0.37
PWR[34,35]	0.33	0.30	1,000	900	900	0.25	15–20	0.33

(a) ϵ is the recirculating power fraction.

(b) Differences due to economy of scale removed: [$/kWe 1000 MWe] = [Reported $/kWe] $[P_E(MWe)/1000]^{0.4}$

(c) Ratio of Reactor Plant Equipment (RPE) costs (Account 22) to the Total Direct Cost (TDC).

(d) Ratio of total thermal power to the volume enclosed by and including the coils, where exo-blanket/shield coils are presumed.

(e) Ratio of the FPC mass (FW/B/S/C) to the total thermal power, where the coolant ducting, piping, and manifolding are either not included, are presumed small in mass compared to the FPC, or are located outside the FPC.

Table II. Summary of Key Parameters for Compact High-Power-Density Toroidal Fusion Reactors

	STARFIRE[3]	CRFPR[13]	OHTE[(f)14]	RIGGATRON[15]
Plasma radius (m)	2.38	0.71	0.67	0.32
Major radius (m)	7.0	4.3	5.91	0.80
Plasma volume (m^3)	781.	42.7	52.1	2.0
Average density ($10^{20}/m^3$)	0.8	3.4	10.0[(g)]	20–30
Average temperature (keV)	22	20[(a)]	5–6[(g)]	12–20
Average beta	0.067	0.20[(l)]	0.43[(l)]	0.20
Plasma power density (MW/m^3)	4.5	72.4	64.0	500.
Plasma current (MA)	10.1	18.5	12.4	3–4
Plasma current density (MA/m^2)	0.57	11.7	8.8	7.2–9.6
Magnetic field (T)	5.8	3.3[(b)]	11.2[(h)]	10.–16.[(m)]
Neutron current (MW/m^2)	3.6	19.5	19.5	58.4
Thermal power[(c)] (MWt)	4033.	3350.	2740.	1225.
Net power (MWe)	1200.	1000.	904.	355.
System power density[(d)] (MWt/m^3)	0.30	15.0	3.2	5.2[(k)]
Mass utilization[(e)] (tonne/MWt)	3.9	0.37	1.45[(j)]	0.28
Thermal conversion efficiency	0.35	0.35	0.40	0.41
Recirculating power fraction	0.167	0.15	0.35	0.33
Net plant efficiency	0.30	0.30	0.24	0.27

(a) Flat temperature profile, $J_0^2(\alpha r)$ density profile.

(b) Peak fields at toroidal field coil.

(c) Total useful thermal power.

(d) Based on volume enclosed by and including the coils and total thermal power.

(e) Based on total thermal power and total mass of FW/B/S/C.

(f) Ref. 14, electrical power plant.

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

(h) Peak fields at Ohmic-heating coil during initiation of discharge.

(i) Total fusion power is 3795 MWt.

(j) Of the 5500 tonne for FW/B/S/C, this particularly heavy (LiPb) blanket weighs 3200 tonne. An unusual heavy OH coil is also used to minimize losses during startup.

(k) The power density within volume defined only by the Riggatron coil set is 160 MWt/m^3.

(l) Poloidal betas evaluated at the plasma radius, which nearly equals the total beta.

(m) [illegible]

Table III. Summary of Parameters Used to Assess Technology R&D Needs for Compact Reactors Relative to STARFIRE

	CONVENTIONAL	COMPACT		
	STARFIRE[3]	CRFPR[13]	OHTE[14]	Riggatron[15]
Plasma Engineering Systems				
• Average density ($10^{20}/m^3$)	0.8	3.4	10.0	20–30
• Plasma current (MA)	10.1	18.5	12.4	3–4
• Plasma current density (MA/m^2)	0.5	11.7	8.8	7.2–9.6
Nuclear Systems				
• Limiters (MW/m^2)	5.0	NR[a]	NR[a]	NR[a]
• First-wall thermal loading (MW/m^2)	0.9	4–5	5	20–50
• Blanket				
– Average/peak power density (MW/m^3)	4.5/60.	28/260	27/120	3/18
– Breeder	solid	liquid	liquid	liquid
Magnet Systems				
• TF coil (T)	11.1(SC)[b]	3.3(N)[c]	4(N)	10–16(N)
• OH coil (T)	8(SC)	2.6(N)	11.2(N)	30(N)
• Energy storage (GJ)	61(11)[d]	1.65	9	0.6
Remote Maintenance				
• mass of unit replaced (tonne)	65[e]	436[f]	164[h]	25[i]
• Annual mass usage (tonne/y)	260[e]	276[g]	492[h]	900[i]
Safety				
• afterheat (MW/m^3)[j]	2	12	10	--[k]

(a) NR = not required in the sense that concentration of an already high first-wall heat flux onto an extended limiter is not advisable; the first-wall *per se* would serve as a limiter.

(b) SC = superconducting.

(c) N = normal magnet.

(d) 11 GJ stored in the OH and equilibrium coil sets.

(e) Mass of largest unit replaced is 65 tonne, 16.7% of FW/B is changed each year, which gives an annual rate of about 260 tonne/y. Accounting for material recycle, the actual mass usage is 140–150 tonne/y.

(f) Includes mass of drained LiPb blanket (277 tonne total; 31 tonne FW(Cu), 23 tonne structure (PCASS), 223 tonne B_4C/W/PCASS third wall) plus mass of TF coils (159 tonne).

(g) Annual mass replaced related to FW/B. If B_4C/W/PCASS third wall recycled, FW/B mass usage amounts only to 54 tonne/y. If the TF coils (159 tonne) must be recycled, the annual mass usage would be 213 tonne/y.

(h) FW and helical coil changes every 4 months giving mass usage of 492 tonne/y. This change out period is dictated by the neutron transmutation rate in the first-wall copper coil and the associated increase in electrical resistivity. More recent OHTE reactor designs extend this FW coil life and total system efficiency by interposing a 0.10–0.15 m thick semi-blanket between the coil and the plasma.

(i) This unit is changed every 30 days. About 3 such units comprise a plant of 1000 MWe (net), given an annual mass usage of 900 tonne/y.

(j) Values at t = 0 after plasma shutdown and assumes afterheat proportional to blanket power density.

(k) Same as for conventional systems for the blanket, much higher in coils, but yet to be determined.

Table IV. Compact Reactor Technology R&D Needs Evaluated Relative to STARFIRE Projections(a)

	Steady-State		Long-Pulsed		
	CRFPR[13]	OHTE[14]	CRFPR[13]	OHTE[14]	Riggatron[15]
Plasma Engineering Systems					
• Current drive	+(?)	+(?)	NR	NR	NR
• Auxiliary heating(b)	NR	NR	NR	NR	NR
• Ash removal/impurity control	0	0	-	-	-
• Fueling	0	0	0	0	0
Nuclear Systems					
• Divertor(c)	(?)	-	(?)	-	(?)
• First-wall (limiter)(c)	+	+	++	++	++
• Blanket					
- Thermohydraulics	+	+	+	+	-
- Breeding	0	+	0	+	++
• Magnet radiation shield(d)	NR	NR	NR	NR	NR
Magnet System					
• TF coil	-	-(e)	-	-(e)	0
• OH coil	-	-	-	-	0
• Power/energy transfer and storage	-	-	-	-	-
Remote Maintenance	←Different→ (block vs. patch)		←Different→ (block vs. patch)		
Safety and Environmental Systems(f)	0	0	0	0	0

(a)NR = not required, (-) = less difficult, (0) = similar, and (+) = more difficult than STARFIRE.

(b)A small quantity of auxiliary heating might be needed to reduce startup losses for ignition.

(c)Conventional limiters that concentrate heat flux are not considered for most compact options operating already at high first-wall heat loads. Generally, the entire first wall must be considered a "limiter". The use of a magnetic divertor is generally considered desirable for these systems.

(d)Most compact systems use copper magnets that at most are shielded by the high-temperature breeding blanket. Passive, room-temperature radiation/thermal shield *per se* of the kind needed to protect superconducting magnets is not envisaged for the compact systems.

(e)The toroidal field for OHTE would be generated by a first-wall helical coil operating continuously at 4 T using normal copper conductor. This is judged to make the "TF-coil" requirements for OHTE somewhat more difficult than for CRFPR, but easier than the baseline STARFIRE case.

(f)Afterheat power density is higher for compact systems, presenting a more serious loss-of-coolant-accident concern.

Table V. Ranking of Critical Technology Issues for Conventional and Compact Fusion Reactors from Ref. 37

	CONVENTIONAL		COMPACT	
	STARFIRE	RFP	RIGGATRON	OHTE
1.	Magnet Reliability First-Wall Coating Application Impurity Control Performance Degree of Remote Maintenance	First Wall - fluence limit - fatigue heat/mechanical loads Magnetic Reliability Current/Time Switching Steam Generator Tritium Permeation I&C	First Wall - fatigue - heat/mechanical loads	Impurity Control Performance
2.	Tritium Inventory	First Wall Erosion Rate Tritium Inventory	First Wall - fluence - erosion Breeder Safety Magnet Insulators	First Wall - fluence - heat/mechanical load Magnet Insulator Steam Generator Tritium Permeation Fueling Maintenance-Removal of Large Components
3.	First-Wall Fluence Limit Tritium Breeding Ratio Magnet Field Strength Magnet Plasma Control Maintenance-Removal of Large Components	Breeder Safety Tritium Breeding Ratio Coolant/Breeder Compatibility Degree of Remote Maintenance Maintenance-Removal of Large Components	I&C	First-Wall Erosion Rate Tritium Inventory Magnet Radiation Damage Divertor Plate Life
4.	Shield Cost/Effectiveness Supplemental Heating Power Level, Frequency, Efficiency, Cost Fuel Handling and Storage I&C	Shielding Cost/Effectiveness Shielding Neutron Streaming Magnet Plasma Control Magnet Cost Vacuum Pump Size Power Supply Fueling	Power Supplies Coolant/Breeder Compatibility Maintenance-Removal of Large Components	Magnet Structure Power Supply
5.	First-Wall Erosion Rate Multiplier Energy Multiplication Magnet Cost Vacuum Seal Vacuum Pump Reliability	Magnet Field Strength Magnet Radiation Damage Magnet Structure Primary Structure Size/Cost	Magnet - field strength - radiation damage - structure Radioactive Waste Fuel Handling	First-Wall Fatigue Breeder Safety Magnet - field strength - plasma control - cost Radioactive Waste Fuel Handling
6.	Shielding-Neutron Streaming Magnet Radiation Damage Magnet Structural Compatibility Supplemental Heating Primary Structure Size/Cost Vacuum Pump Size	Reflector Magnet Insulator Magnet Coil Alignment Vacuum Seals Electrical Energy Storage Cryogenics Radioactive Waste Fuel Handling	Magnet Cost Vacuum Pump Reliability Electrical Energy Storage Steam Generator Tritium Permeation I&C Degree of Remote Maintenance	Multiplier Resources Tritium Breeding Ratio Electrical Energy Storage Degree of Remote Maintenance

Table VI. Implications of Compact Reactor for A "Model" FW/B/C

	VALUE FOR $I_W = 20\ MW/m^2$
• FIRST WALL (Cu/H_2O)	
- 14.1-MeV neutron current, $J_w(n/m^2s) = 4.43(10)^{17} I_w$	$8.8(10)^{18}$
- Neutron flux, $\phi_w(n/m^2s) \simeq 4.43(10)^{18}\ I_w$	$8.8(10)^{19}$
- Total FPY[(a)] fluence, $\phi_w\tau(n/m^2) = 1.40(10)^{26} I_w$	$2.8(10)^{27}$
- Radiation dose rate, R(rad/s)	
neutrons, $R_n(rad/s) = 8.2(10)^4\ I_w$	$1.6(10)^6$
gamma ray, $R_\gamma(rad/s) = 1.3(10)^5\ I_w$	$2.6(10)^6$
- DPA/y $\simeq$ 11 I_w	220.
- He appm/y $\simeq$ 31 I_w	620.
- H appm/y $\simeq$ 93 I_w	1860.
- Average transmutation rates	
Ni(%/y) = 0.13 I_w	2.6
Zn(%/y) = 0.11 I_w	2.2
- Heat flux, $I_Q(MW/m^2) \lesssim I_w/4$	5.
- Average power density, $Q_w(MW/m^3) \simeq 10\ I_w$	200.
• BLANKET (Δb = 0.6 m, $LiPb/B_4C/W$)	
- Peak power density, $Q_B(MW/m^3) = 13\ I_w$	260. (in LiPb coolant)
- Average power density, $\langle Q_B \rangle(MW/m^3) = 1.4\ I_w$	28.
- Average DPA/y = 2.3 I_w	46.
- Average He appm/y = 26.7 I_w	534.
- Average H appm/y = 7.7 I_w	154.
• EXO-BLANKET COIL (Cu/H_2O)	
- Peak neutron flux, $\phi_c(n/m^2s) = 3.4(10)^{16}\ I_w$	$6.8(10)^{17}$
- Radiation dose rate, R(rad/s)	
neutrons, $R_n(rad/s) = 1.2(10)^2\ I_w$	$2.5(10)^3$
gramma rays, $R_\gamma(rad/s) = 1.1(10)^3\ I_w$	$2.2(10)^4$
- Peak DPA/y = 0.063 I_w	12.6
- Peak He appm/y = 0.027 I_w	0.54
- Peak H appm/y = 0.13 I_w	2.6
- Average transmutation rates	
Ni(%/y) = $1.1(10)^{-3}\ I_w$	0.022
Zn(%/y) = $0.5(10)^{-3}\ I_w$	0.010
- Peak power density, $Q_c(MW/m^3) = 0.1\ I_w$	2.0(nuclear)
	0.8(Ohmic)

(a) FPY = Full-power year.

(b) For CRFPR fully-cost-optimized design.[13]

Table VII. Summary of Compact Reactor Technology Requirements

Plasma Engineering Systems

- Operate with high toroidal current density ($\geq$ 10 MA/m^2) in a dense plasma to achieve DT ignition by Ohmic heating alone, possibly with auxiliary-heating boost or plasma preconditioning in order to minimize volt-second consumption while attaining ignition.
- Understand means to provide fueling, impurity/ash control, and steady-state current drive in dense plasma.
- Plasma edge control, dense gas blanket, isolation of plasma from FW.
- Examine potential of compact options for confinement systems that operate with currentless plasma.

Nuclear Systems

- High heat-flux (3-5 MW/m^2) FW and high-power-density breeding blanket (100 MWt/m^3 peak, 50 MWt/m^3 average) precludes use of PCASS at the FW and solid tritium breeders within the blanket.
- Control/understand FW sputter erosion through use of magnetic divertor, dense gas blankets, and/or tailoring of plasma edge conditions.
- Interrelationship between FW temperature, FW life-limiting mechanisms, maximum blanket temperature, blanket thickness, and overall plant efficiency needs better resolution.
- Single/few-piece FW/B/S construction for purposes of "block" maintenance requires careful resolution, particularly with respect to coolant and vacuum ducting.
- Better resolve tradeoff between reduced inner coil shield thickness and increased biological and exo-FPC equipment radiation shielding.
- Better resolve interrelationships between overall system stress, reliability, and availability.

Magnet Systems

- Very high-field (30 T) resistive OH coils required by Ohmically-heated compact tokamak reactor (Riggatron).
- Most compact systems require resistive coils to operate in high radiation field. Need exists to understand response of such coils (conductor and insulation) and life-limiting mechanisms (swelling, resistivity change, structural integrity, etc.).

- Certain compact options successfully tradeoff higher recirculating power and BOP cost for reduced shield and coil costs; this tradeoff requires additional study.

Remote Maintenance

- The basic maintenance approach differs considerably from the conventional mainline and AFC concepts; total "block" maintenance of the FW/B/S (200-400 tonne) is proposed. The merits of "block" versus "patch" maintenance require further examination.

- The topology of coolant and vacuum ducts, the size of which should not change for a given total power output, and the FPC, which is decreased in volume by a factor of 10-30, must be resolved and reconciled with the "block" maintenance approach.

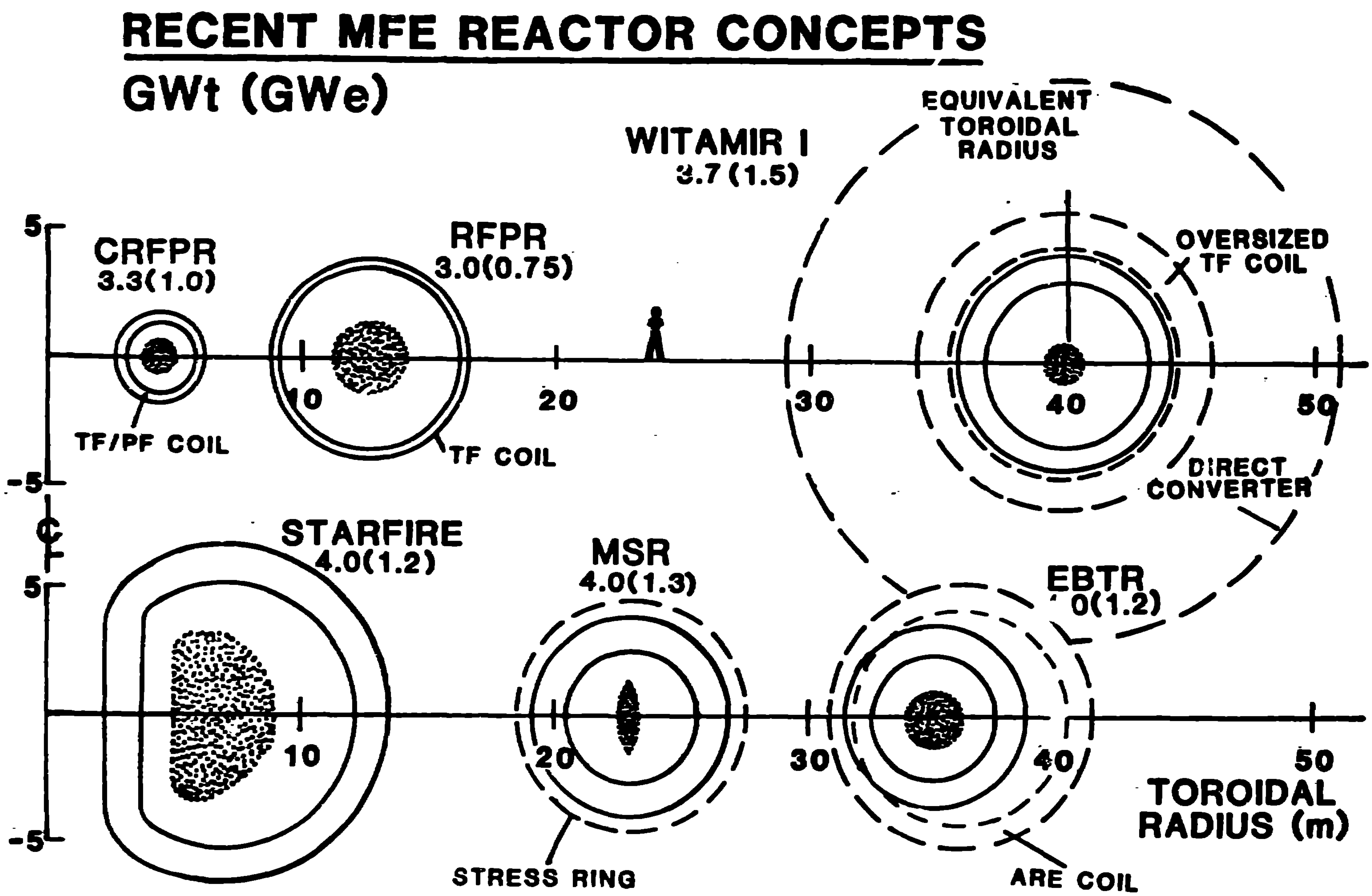


Fig. 1. Graphical display of relative sizes of fusion power cores (FPCs) for the concept listed in Table I.

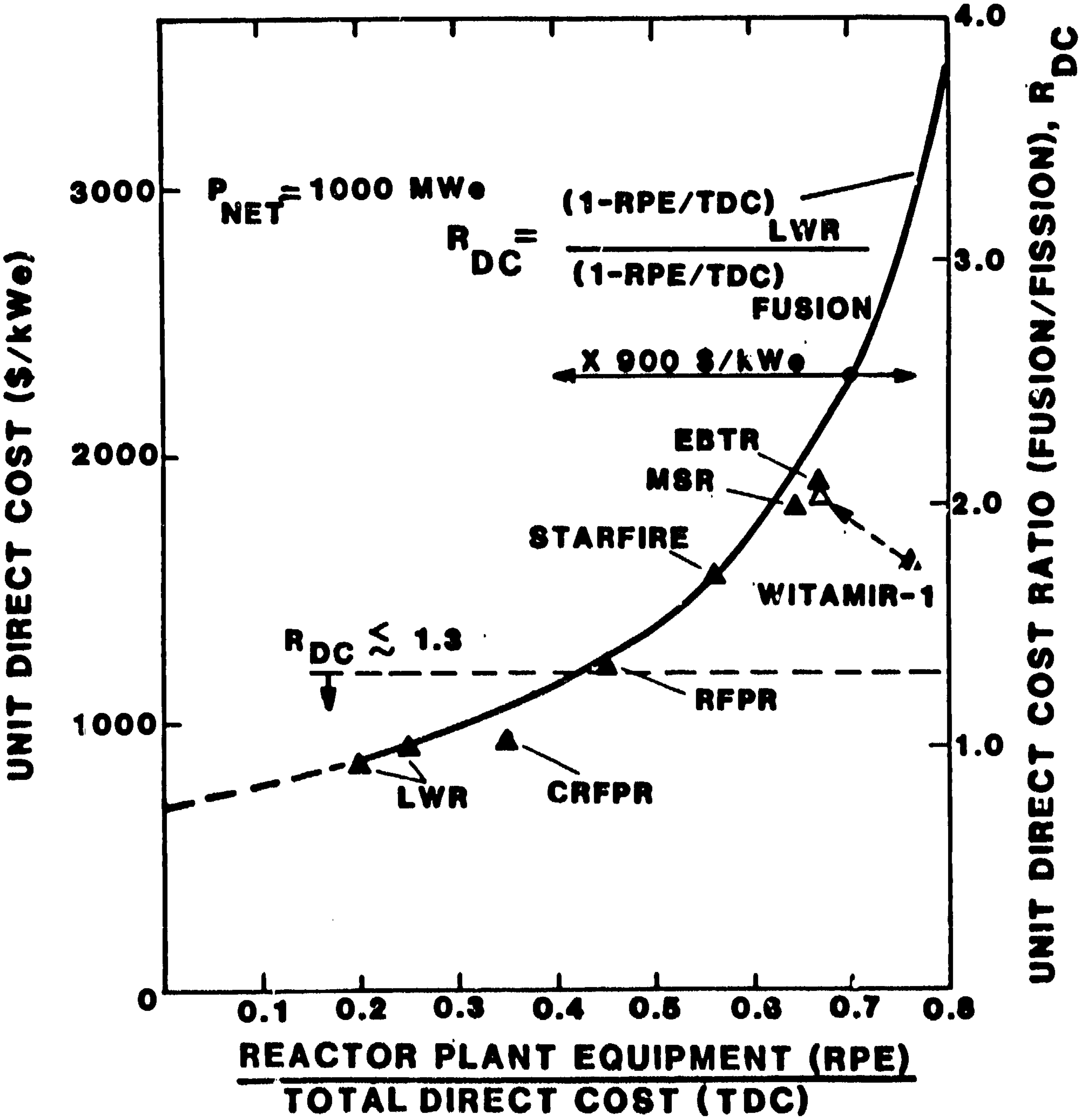


Fig. 2. Plot of UDC versus RPE/TDC data from Table I for a range of fusion reactor designs. Normalizing these costs to the LWR (UDC = 900 $/kWe, RPE/TDC = 0.25), the "analytic" curve of $R_{DC} = (UDC)_{FUSION}/(UDC)_{FISSION}$ is also shown as a function of RPE/TDC under the assumption of nearly equal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

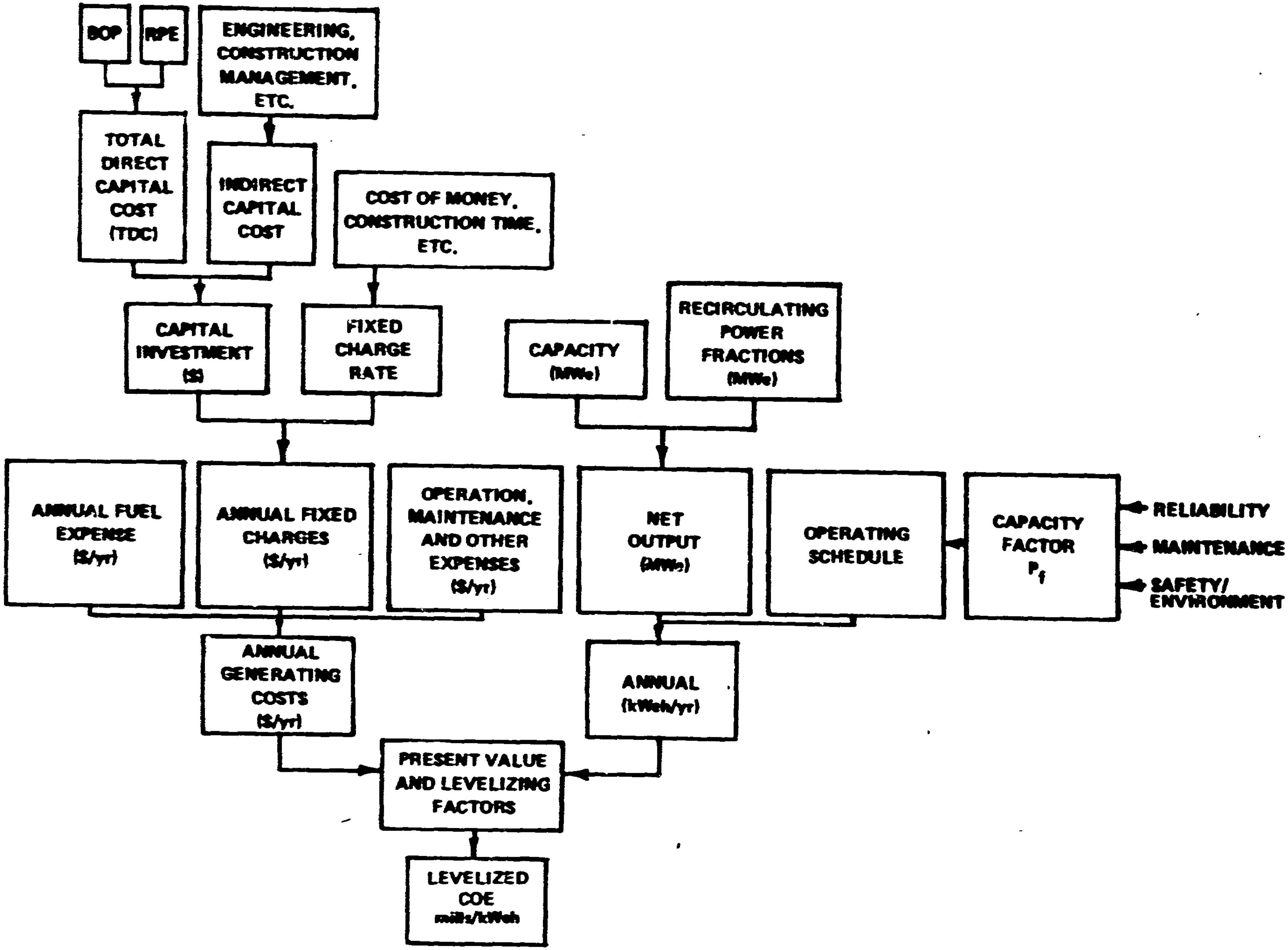


Fig. 3. Logic diagram illustrating the means by which the levelized generating cost of electricity (COE) is computed.

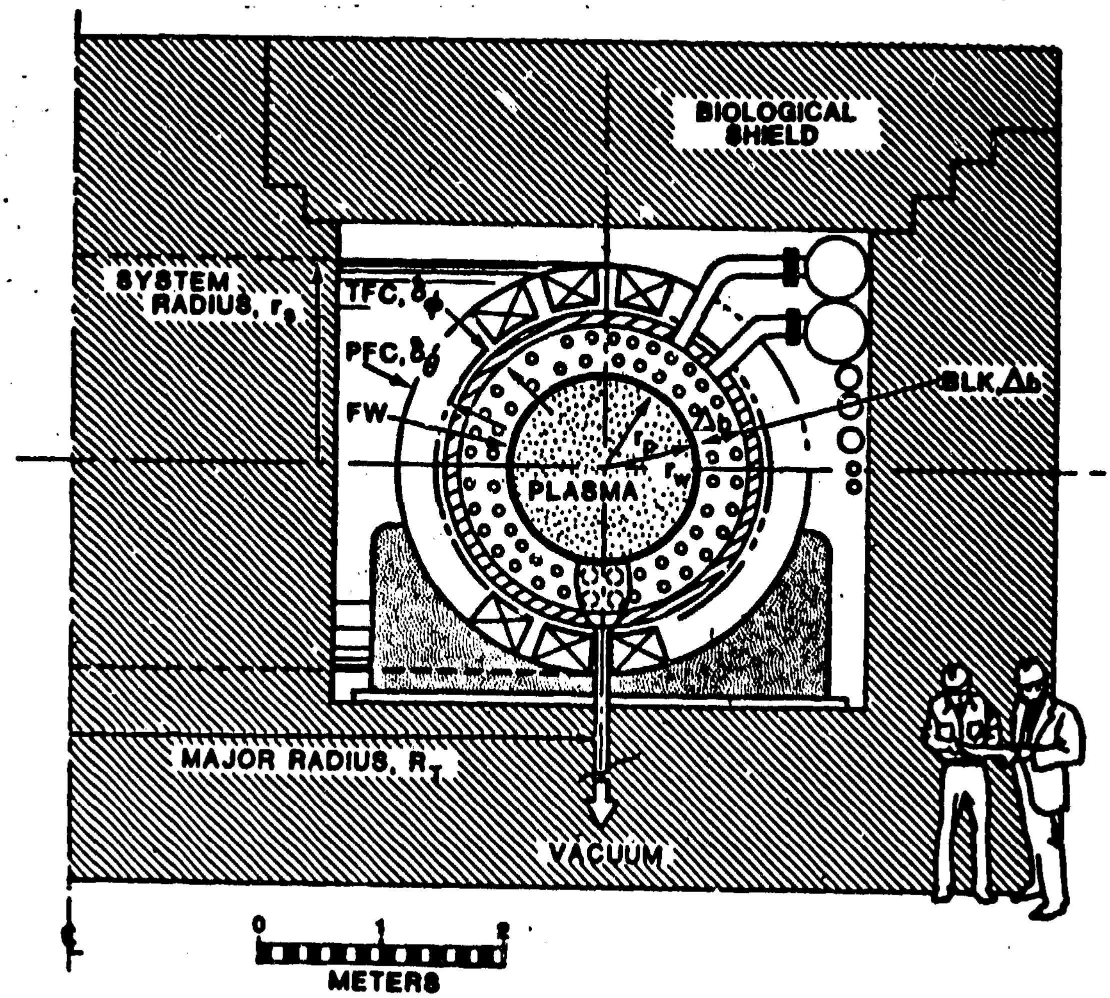
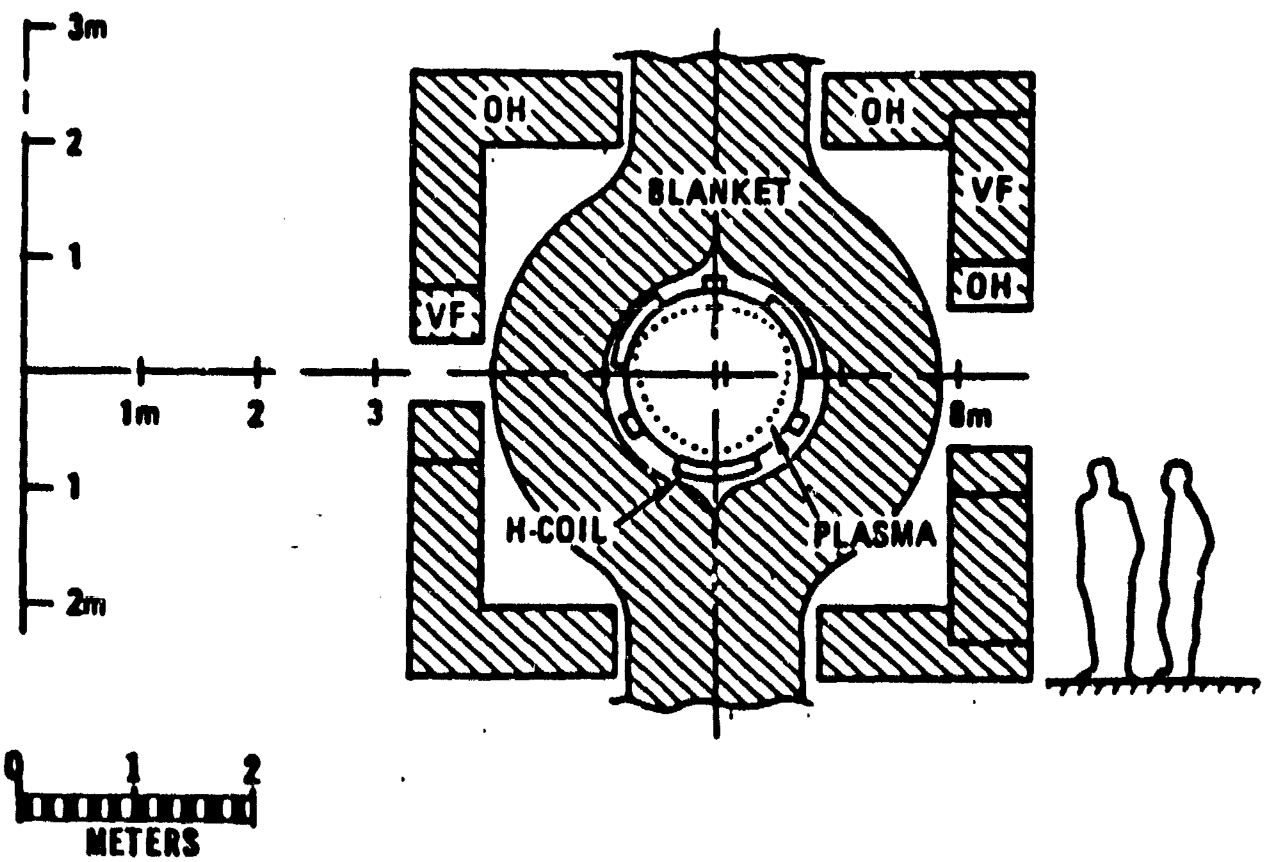


Fig. 4. Compact RFP Reactor Configuration (1000 MWe).



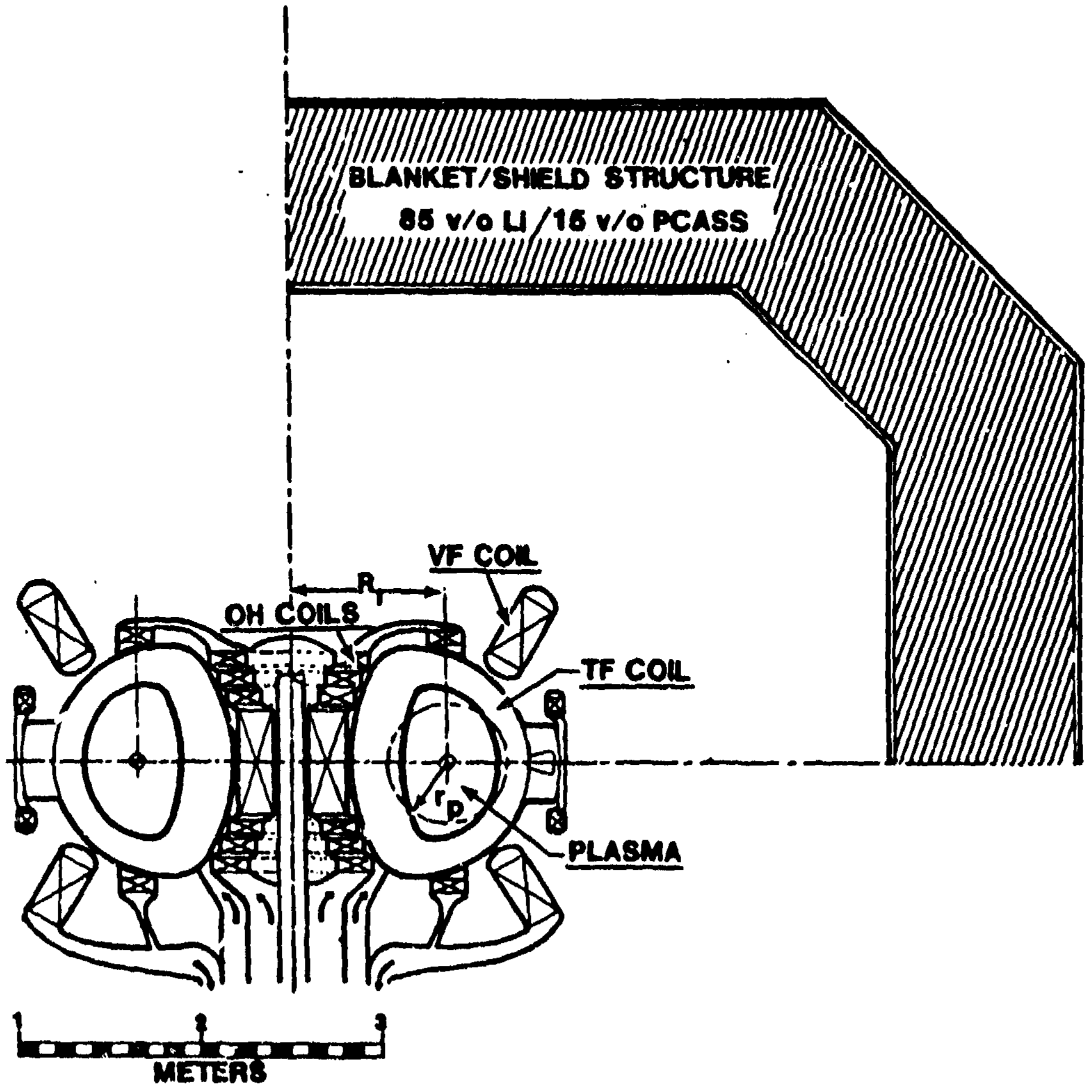


Fig. 6. Riggatron high-field tokamak Reactor configuration (355 MWe).

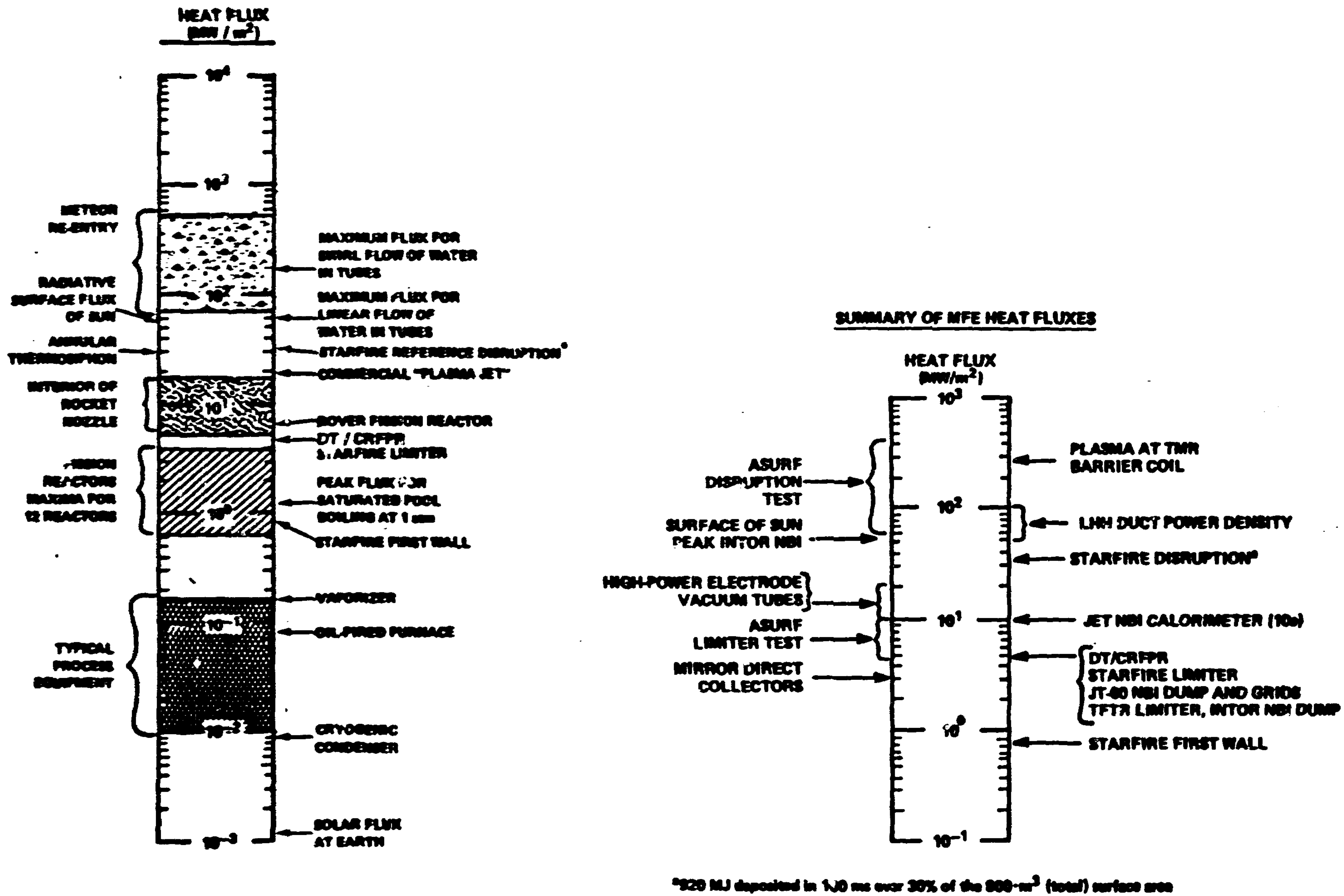


Fig. 7. Range of surface heat fluxes encountered in natural, general engineering, and MFE systems.

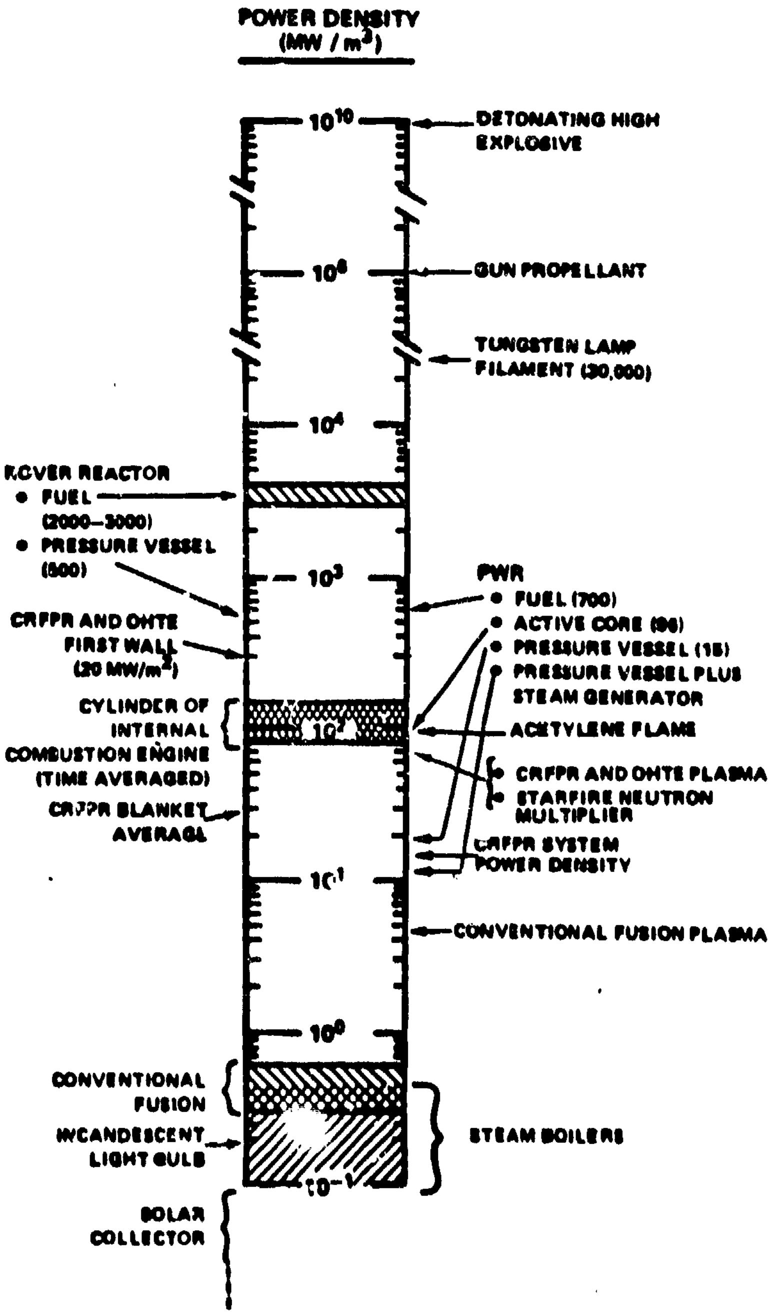


Fig. 8. Range of power densities encountered in a variety of natural, general engineering, and MFE systems.

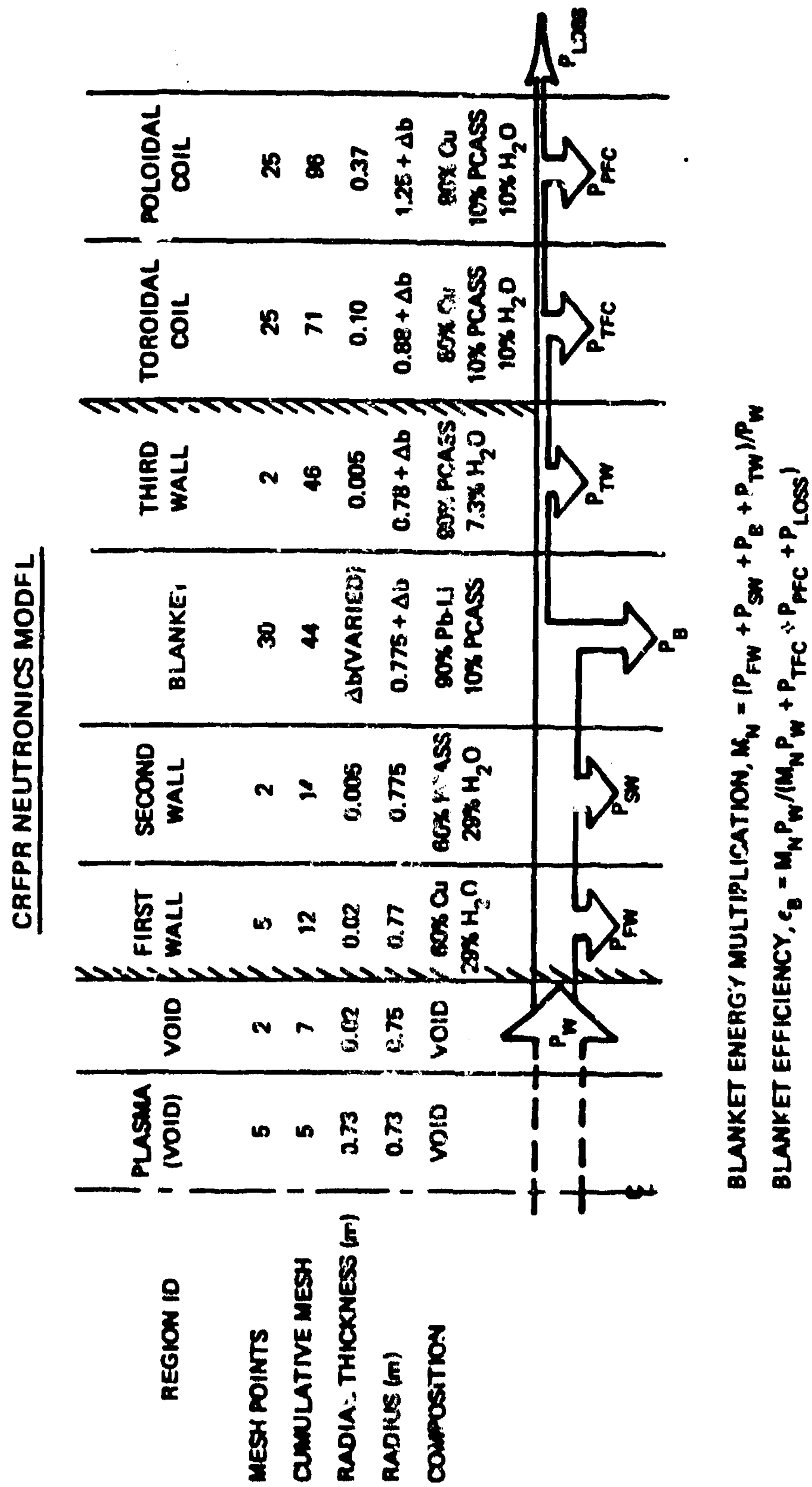


Fig. 9. Schematic diagram of "model" blanket used to examine neutronic and radiation-damage responses of a typical FPC envisaged for a compact fusion reactor.

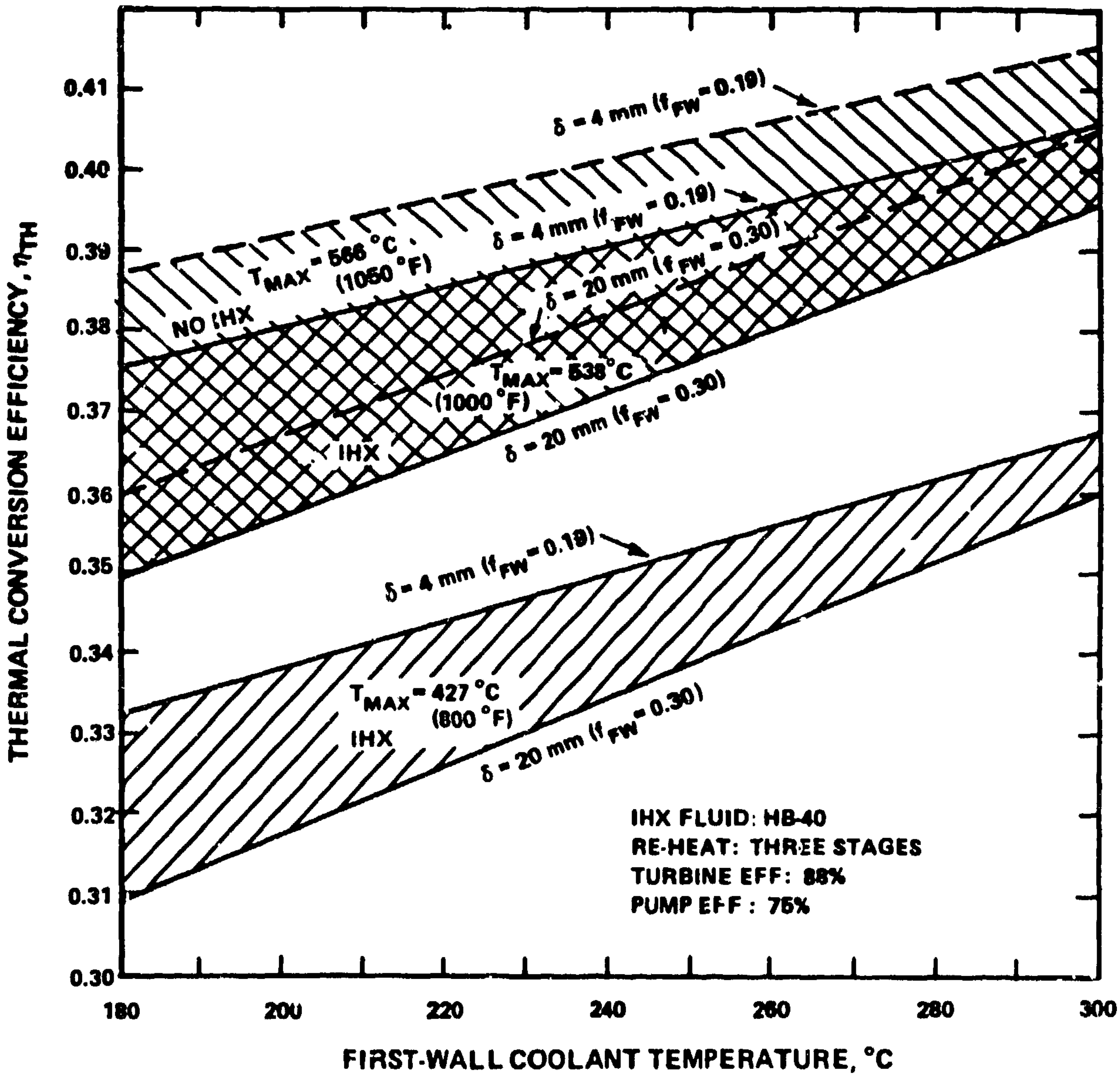


Fig. 10. Dependence of plant thermal efficiency on first-wall coolant temperature, blanket temperature, first-wall thickness (δ, with f_{FW} equal to the fraction of total fusion energy delivered to first wall), and use of an intermediate heat exchanger (IHX).