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HIGH-POWER-DENSITY APPROACHES TO MAGNETIC FUSION ENERGY: PROBLEMS AND PROMISE OF COMPACT REVERSED-FIELD PINCH REACTORS (CRFPR)*

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If the costing assumptions upon which the positive assessment of conventional large superconducting fusion reactors are based proves overly optimistic, approaches that promise considerably increased system power density and reduced mass utilization will be required. These more compact reactor embodiments generally must operate with reduced shield thickness and resistive magnets. Because of the unique magnetic topology associated with the Reversed-Field Pinch (RFP), the compact reactor embodiment for this approach is particularly attractive from the view point of low-field resistive coils operating with Ohmic losses that can be made small relative to the fusion power. The RFP, therefore, is used as one example of a high-power-density (HPD) approach to magnetic fusion energy. A comprehensive system model is described and applied to select a unique, cost-optimized design point that will be used for a subsequent conceptual engineering design of the Compact RFP Reactor (CRFPR). This cost-optimized CRFPR design serves as an example of a HPD fusion reactor that would operate with system power densities and mass utilizations that are comparable to fission power plants, these measures of system performance being an order of magnitude more favorable than the conventional approaches to magnetic fusion energy (MFE).

1. Introduction

This study deals with unconventional[1] approaches to achieve high-power-density (HPD) magnetic fusion energy (MFE). A conventional magnetic fusion system would operate with a relatively low engineering power density (0.3-0.5 MWt/m^3), would use large superconducting coils, and, in order to maintain a total power output below ~ 4000 MWt for characteristically large plasma volumes ($500-1000^3$), would operate with a DT fusion neutron first-wall loading in the range 1.0-3.0 MW/m^2. Engineering power density, P_{TH}/V_c, is defined as the ratio of total (useful) thermal power, P_{TH}, to the total volume, V_c, enclosed by and including the coils. For first-wall/blanket/shield/coil (FW/B/S/C) or "fusion-power-core" systems typically being considered for DT-fueled fusion reactors, engineering power densities in the range 0.3-0.5 MWt/m^3 translate into a "mass utilization" of 5-10 tonne/MWt, where the mass is that of the FW/B/S/C. The STARFIRE tokamak[2], the Tandem Mirror Reactor (TMR)[3], the Elmo Bumpy Torus Reactor (EBTR)[4], superconducting versions of the Reversed-Field Pinch Reactor (RFPR)[5,6], and the range of reactor

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configurations being projected for the stellarator/torsatron/heliotron (S/T/H) confinement systems[7]) represent the conventional fusion reactors.

In order to approach engineering power densities and mass utilizations similar to those for light-water fission reactors (~ 5–10 MWt/m^3, 0.3–0.4 tonne/MWt, based on pressure-vessel mass or volume) while maintaining a ~ 4000-MWt upper limit on total power generation, the non-productive volume associated with radiation shielding for superconducting coils must be eliminated. Resistive coils are required, these coils being separated from the plasma by at most a thin (~ 0.4–0.5 m), heat-recovering/tritium-breeding blanket. An increase in plasma power density, neutron first-wall loading, and blanket power density, however, accompanies any attempt to maintain a given total power output at an enhanced engineering power density. An economic tradeoff between the benefits of HPD operation and the potential liabilities of increased recirculating power, higher coil stresses in some cases, and reduced FW/B chronological life, however, exists and remains to be fully resolved.

As discussed in the following section, a number of compact toroidal systems, using resistive coils in conjunction with either thin blankets or a first-wall coil position, are being considered for HPD MFE applications. The RFP represents one such approach, its HPD reactor embodiment being termed the Compact RFP Reactor (CRFPR). The key results from a recent study of the CRFPR[8]) are reported here. After describing the background and rationale in Sec. 2., the methodology used to evaluate this HPD approach is given in Sec. 3. The details of the parametric systems model and associated physics/engineering/costing models used to examine key system tradeoffs is found in ref. 8, as are detailed parametric results. Key results are given in Sec. 4. along with a reactor design point suggested for detail conceptual engineering design. General conclusions, problems, and recommendations for future work are found in Sec. 5.

2. Background and rationale

Over the past decade and to varying levels of detail and design realism, numerous conceptual design studies of a wide range of magnetic fusion reactors have been reported[9]). The assessment of the complex interrelationship between physics, technology, and power-plant operability is generally posed in terms of some measure of economic and environmental acceptability with respect to existing or projected energy alternatives. The degree to which a given fusion approach is deemed "acceptable" is judged on the basis of an economic assessment, using as a measure either cost-of-electricity (COE, mills/kWeh) or unit direct cost (UDC,$/kWe), with constraints on net electric power (i.e., measures of network compatibility and maximized economies-of-scale) being simultaneously imposed. Because of differences in optimism assumed for projected physics, anticipated technology development, and costing, predictions ranging from highly favorable[2]) to cautiously pessimistic[9]) can emerge. More general concerns of this nature have also been expressed recently[10]).

If the present state of toroidal fusion reactor projections could be adequately summarized by a simplified parameter list, a synopsis similar to that given on Table I might result. In accordance with the discussion given in Sec. 1., the Modular Stellarator Reactor (MSR)[11]), STARFIRE[12]), EBTR[4]), and RFPR[5,6]) are conventional systems. Where appropriate, comparable parameters for a pressurized-water (fission) reactor (PWR)[12,13]) are also included on Table I. Results for the fully cost-optimized CRFPR[8]) are also shown. The cost of each fusion concept given on Table I has been estimated by applying a common and self-consistent costing methodology to a generally uniform cost data base[14]).

The future competitiveness of MFE, as measured by COE, depends to some extent on the cost escalation of alternatives[2,4,8]). Table I indicates that the conventional systems are economically competitive with fossil and fission alternatives on the basis of "then-current" values of COE in spite of relatively low engineering power densities and high mass utilizations. In addition to the escalating costs of fossil and fissile energy sources and the negligible fuel cost projected for fusion, MFE holds a competitive position, because a relatively optimistic cost data base has been adopted. Added optimism is injected by the assumption of relatively short construction times (~ 5-6 years), as well as the use of low annual rates of interest during construction (IDC) and escalation during construction (EDC). If this optimism proves unwarranted, the MFE option may require more efficient use of volume and mass of the fusion power core per unit power output in order to maintain the competitive position reflected in Table I.

By eliminating time-related components of the system cost, the question of unit costs related to

FW/B/S/C systems is most clearly addressed by plotting the basic unit direct cost (i.e., before the application of indirect costs, IDC, and EDC) as a function of mass utilization, M/P_{TH} (tonne/MWt), where M is the FW/B/S/C or fusion-power-core mass. This correlation is shown in fig. 1 for the fusion concepts given on Table I. Included on fig. 1 is the Light-Water-Reactor (LWR), the mass utilization being computed on the basis of the pressure vessel mass and the UDC also excluding time-related costs. Points for the NUWMAK tokamak[15]), the Tandem-Mirror Reactor (TMR)[16]), and the reactor embodiment for the Ohmically-Heated Toroidal Experiment (OHTE)[17]) are also included. The spread in OHTE parameters results when the mass of an unusually heavy LiPb blanket is not included; the OHTE/A pertains to the results reported in ref. 17, and the OHTE/B adjusts this design point to require operation with a reduced recirculating power that is similar to that of the CRFPR[8]). It is emphasized that the mass utilization refers only to the fusion power core, and the incremental cost above the $M/P_{TH} \to 0$ intercept represents an added cost that is unique to MFE because of a less efficient use of mass and volume within the fusion power core. The resulting incremental COE needed to pay the price of this incremental UDC and higher mass utilization, of course, must not exceed the savings in fuel cost generally anticipated for MFE.

It is also emphasized that meaningful correlations of the kind shown in fig. 1 occur only for design points that are each fairly well optimized within obvious constraints of acceptable recirculating power fractions (i.e., below 0.10-0.15), total power[8]), and use of a relatively uniform cost data base. Furthermore, no implication is made that correlations of the kind given in fig. 1 are universally predictive or represent the full picture, although such correlations are valuable in pointing out optimal design directions.

A linear fit to these fairly independent results given on fig. 1 indicates an average FW/B/S/C unit cost of ~ 24 \$/kg; the effect of doubling this unit cost is also shown. Adding the typical 23% increase related to indirect costs, as well as the time-related cost of IDC and EDC for a given construction period, gives increases in UDC by a factor of 1.73 and 2.44, respectively, for 5 and 10-y construction times[14]). Furthermore, if the application of indirect cost, IDC, and EDC is biased more heavily against systems with higher mass utilization, fusion power systems would rapidly be forced to higher-performance designs ($M/P_{TH} \lesssim 1$ tonne/MWt), lest the cost of the fusion power core dominace the total plant cost. In achieving a higher performance fusion system, operating and maintenance costs must not increase to a point where the COE is driven beyond the range already indicated on Table I. Hence, operation with inevitably higher first-wall loadings and more frequent FW/B changeout must continue to preserve, if not enhance, the economically attractive plant factor and overall system reliability for the smaller, more compact, but higher performance systems.

On the basis of the foregoing arguments, a number of HPD fusion approaches are being considered for use as ignition, engineering-testing, or compact-reactor devices[18]). These devices can generally be classified as toroids using resistive coils to provide higher-density tokamak[19-22]) or RFP[8,17]) confinement. All HPD devices examined to date rely on significant Ohmic heating to achieve ignition, with the high-field tokamaks also requiring compressional and/or radio-frequency heating to varying degrees. Power reactor embodiments have been suggested for the tokamak (Riggatron)[9,19]), the OHTE[17]), and the CRFPR[8]). Both the Riggatron and the OHTE reactors would require relatively cool (i.e., $\lesssim$ 300-400 K), actively-driven copper coils positioned at or near the first wall; the overall system performance in terms of plant thermal efficiency, the ability to breed tritium, and cost (i.e., OHTE/A in fig. 1), is therefore reduced for configurations that require first-wall coils.

The RFP, on the other hand, represents an ideal limit[8]), in that plasma confinement is provided primarily by poloidal magnetic fields generated by toroidal plasma currents, and the total plasma beta value is expected to be high ($\gtrsim$ 0.1-0.2). Although a thin passive copper shell may be required at the first wall, this first-wall shell would operate at or near the blanket temperature ($\gtrsim$ 500-600 K), thereby enhancing the prospects for high overall thermal efficiency. Since evidence for or against the need for active control of RFP field reversal is not yet available, the present study is based on the direct extension of the experimentally observed[23]) "dynamo effect" to the reactor regime. On long time scales active feedback may be required to replace wall stabilization provided by the shell. The copper-alloy first wall may also be desirable solely from a thermo-hydraulic viewpoint in order to transmit the higher heat fluxes expected of any compact, HPD system[24-26]. Lastly, the RFP promises high plasma power density without requiring high fields at the exo-blanket coils.

3. Approach and methodology

The CRFPR study reported in ref. 8 surveys potential reactor design points using a methodology developed to predict those systems with the lowest cost. The COE serves as an object function to be optimized. Engineering and other indirect costs are computed as a fixed fraction of direct costs along with the time-related costs of IDC and EDC. These time-related costs depend principally on construction time, which is expected to be a function of plant capacity[27] and complexity. The total cost is used to compute a COE that is a function of the total plant output, the economy of scale being built into the cost data base[2,4,8].

The computational algorithm specifies ensembles of reactor designs lying on trajectories of constant engineering power densities, P_{TH}/V_c, and net-electric powers, P_E. This algorithm is depicted in fig. 2. The specified values of P_{TH}/V_c and P_E are subsequently subjected to parametric variation. A parametric evaluation is performed for a range of plasma radii, r_p, in search of the minimum-cost system having the specified values of P_{TH}/V_c and P_E for the burn physics and fixed engineering parameters indicated. For a stationary plasma burn and a given RFP magnetic-field configuration and plasma profiles[8], the plasma power output is determined for a specific energy confinement time, τ_E, or corresponding density, as required by the plasma energy balance and related ignition condition. A specific transport scaling law for τ_E is generally imposed, although from the viewpoint of determining a minimum-cost system a physics scaling law <u>per se</u> is not needed[8].

Referring to fig. 2, the first-wall neutron loading, I_w, plasma current, I_ϕ, and total thermal power per unit major radius, P_{TH}/R_T, can be computed for a given blanket neutron energy multiplication, M_N, having defined the plasma parameters for a given r_p. The constraints of fixed P_E and P_{TH}/V_c are then imposed. Using the specified P_E, the total thermal power, P_{TH}, is estimated from $P_{TH} = P_E/\eta_{TH}(1-\varepsilon)$, where the recirculating power fraction, ε, equals the inverse of the engineering Q-value, Q_E, and the thermal-conversion efficiency is η_{TH}. Since Q_E depends in large part on the level of Ohmic losses in coils and plasma, which in turn depend on unspecified system dimensions, Q_E must first be estimated and the converging iteration indicated on fig. 2 followed. The major radius, R_T, is then estimated, since guesses for both P_{TH} and P_{TH}/R_T are available. Finally, the system (minor) radius, $r_s = r_w + \Delta b + \Delta$ (which includes the addition of a fixed blanket thickness, Δb, and coil thicknesses, Δ, to the first-wall radius, $r_w = r_p/x$) is determined from $r_s^2 = P_{TH}/[2\pi^2 R_T (P_{TH}/V_c)]$, using the previously specified engineering power density, P_{TH}/V_c.

The system minor radius is then defined for the particular first-wall radius of interest. Specifying Δb establishes a unique total thickness of coils, $\Delta = \delta_\phi + \delta_\theta$, which is partitioned between the toroidal-field coil (TFC) thickness, δ_ϕ, and poloidal-field coil (PFC) thickness, δ_θ, by enforcing equal coil current densities. Ohmic losses in both coil sets can then be calculated, and a complete reactor energy balance is performed[8]). An updated value for $\varepsilon = 1/Q_E$, which includes makeup power for Ohmic losses in both plasma and coils, is then used to obtain a more accurate estimate for P_{TH}. The iteration shown on fig. 2 continues as the reactor dimensions are adjusted to achieve the specified values of P_E and P_{TH}/V_c for the assumed physics and engineering parameters. When a dimensionally self-consistent reactor system emerges for a given P_E and P_{TH}/V_c, a complete economic analysis is performed at the specific value of r_p.

As the process describe above is repeated for a range of r_p values, while maintaining fixed values of P_E and P_{TH}/V_c, a cost minimum and a Q_E maximum in r_p results when resistive coils are used. Small values of r_p leads to poor coupling of the magnetic field between the plasma and PFCs, resulting in large coil currents for a given plasma current. Large values of r_p, on the other hand, require thin coils (i.e., specifying P_{TH}/V_c fixes r_s, and increasing r_p for a fixed Δb requires that $\Delta = \delta_\phi + \delta_\theta$ decrease), and high current densities, and increased Ohmic heating in the coils result; the value of Q_E diminishes and the COE increases for a fixed P_E. Hence, for either small or large r_p the recirculating power fraction is increased, and a minimum COE is found at a unique plasma radius. If superconducting instead of resistive coils are used[8]), the coil current density is also fixed, which also specifies a unique value for r_p. In either case, a value of r_p for minimum COE is determined for the specified values of P_E and P_{TH}/V_c, as well as other fixed physics and engineering quantities[6]).

The cost-optimized values of r_p that result from the above-described procedure are determined for a range of P_E and P_{TH}/V_c values. A grid composed of lines of constant P_E and P_{TH}/V_c is generated in a space defined by minimum COE versus r_p, an example of which is shown in fig. 3. Shifts and distortions of this mesh are then examined as heretofore fixed parameters (e.g., beta, plasma profiles, transport, DT versus DD fuel, first-wall lifetime, blanket thickness, normal versus superconducting coils, etc.) are varied. Every point on this grid represents a cost-minimized system, although further minimization is possible as fixed constraints are relaxed. The base-case design point indicated on fig. 3 was adopted to illustrate sensitivity to a wide range of physics and engineering parameters[8]).

An even finer distillation of these cost-optimized results occurs[8]) when the coefficient in the transport scaling law assumed to arrive at fig. 3, $\tau_E = Cf(n,r_p,T)$, is varied to determine the value of $\tau_E = \tau_E(OPT)$ at a given r_p for which the COE is further minimized. That such an optimum confinement time exists at each r_p is clear; if τ_E is too large, the system power density is too low, increasing costs, while reduced τ_E and increased power density ultimately lead to excessive magnetic fields and/or first-wall loadings, which in turn are reflected by higher system costs. Rather than establishing the $\tau_E(OPT)$ versus r_p relationship directly by iteration in both plasma density and radius, a specific (i.e., Alcator, $C = \tau_E/nr_p^2$) transport scaling is imposed. Varying the coefficient C produces loci of such COE minima, which are used to construct the curve $COE(MIN)|_{\tau_E(OPT)}$ versus r_p. This latter relationship is independent of the assumed physics scaling. The desired curve $COE(MIN)|_{\tau_E(OPT)}$ versus r_p itself gives a cost minimum; the resultant minimum-cost point is termed the "fully cost-optimized" design point. This procedure is discussed quantitatively in ref. 8.

Reference 8 describes in detail each of four essential elements (magnetics, plasma, engineering, and costing) that comprise the RFP systems model. Analytic Bessel-function profiles[8,28,29]) are used to approximate stable RFP profiles. Each reactor design is constrained to operate on the Taylor[29]) minimum-energy diagram. The steady-state burn model requires a $J_0^2(\alpha r)$ pressure profile, although results for both flat and $J_0(\alpha r)$ temperature profiles are determined. Time-dependent, multi-species simulation codes are used to verify the minimum-COE design points emerging from the parametric systems codes[8]). The engineering energy-balance model specifies a fixed 7% recirculating power for auxiliary plant power needs; the algorithm described in fig. 2 is used to size the TFC and PFC sets, from which the Ohmic losses and associated recirculating power fraction are computed. The economic guidelines given in ref. 14 are used to assure uniformity and enhancement of intercomparisons. All parametric results given in ref. 8 are presented in a form similar to fig. 3, although only the final results are reported here.

4. Summary results

As previously noted, at each plasma radius an optimal plasma confinement time, τ_E(OPT), is found that yields a minimum COE. The trajectory of τ_E(OPT) versus r_p depends on the system economics and is independent of the assumed plasma transport scaling. The resultant trajectory of reactor designs operating at τ_E(OPT) exhibits itself a unique COE minimum for both the DT- and DD-fueled systems, as is shown in fig. 4 for both DT and catalyzed-DD fuels. These curves are valid for both flat and $J_o(\alpha r)$ temperature profiles at the indicated average plasma temperatures, with the $J_o^2(\alpha r)$ Bessel-function-model pressure profiles being assumed for each case.

The key physics and engineering parameters for the fully cost-optimized DT/CRFPR and DD/CFFPR designs indicated on fig. 4 are summarized in Table II. Both temperature profiles lead to essentially the same reactor designs with the respective differences in plasma parameter being shown parenthetically on Table II.

Although the constraints of the present paper does not allow the full reporting of all important sensitivity studies, the dependence of COE on β_θ is particularly noteworthy. This dependence is shown in fig. 5 for the base-case design shown in fig. 3 and used in ref. 8 as a point of departure for all sensitivity studies. In addition to illustrating the β_θ sensitivity, the fully cost-optimized designs for both the DT and catalyzed-DD designs (Table II) are also shown on fig. 5. Because of the ability of the RFP to maintain high confining magnetic fields at the plasma without excessively stressing the PFCs and TFCs, low-beta operation is possible while maintaining the plasma power density ($\sim\beta_\theta^2 B_\theta^4$) at the level required for low-cost, HPD operation.

5. Conclusions

In terms of both engineering volume (V_c = 223 m^3) and total mass of the fusion power core (1243 tonne), the DT/CRFPR fusion power core is comparable to only a few of the many toroidal-field coils being proposed for certain conventional fusion approaches generating the same total power (Table I). Consequently, the system power density (15 MWt/m^3) and mass utilization (0.37 tonne/MWt) are more than an order of magnitude better than for the more conventional approaches, including earilier (superconducting) RFPR designs[5,6].

The fundamental conclusions for the DT/CRFPR design(s) are:

- Optimal system power density of $P_{TH}/V_c \simeq 15$ MWt/m^3 or (fusion-power-core) mass utilization of $M/P_{TH} \sim 0.4$ tonne/MWt can be achieved.
- Economically optimal energy confinement time for both flat and $J_o(\alpha r)$ temperature profiles scales as $\tau_E(OPT) \simeq 0.28 r_p^{1/2}$.
- Poloidal betas $\beta_\theta \gtrsim 0.1$ are certainly adequate, and even β_θ as low as ~ 0.05 still promise acceptable economics.
- Power recirculated to normal coils is less than 10% of P_{ET} even for $\beta_\theta = 0.1$; no incentive could be identified to impose advanced technologies and operational uncertainties associated with superconducting coils.
- Unique, minimum-cost CRFPRs are identified for $R_T/r_s \simeq 2.5$-3.0, $r_p \simeq 0.6$-0.8 m, and $\tau_E \sim 0.25$ s, systems that would require at most $\sim 20\%$ of Alcator transport scaling.

Similarly, the fundamental conclusions generated for the DD/CRFPR designs are:

- An intrinsic factor ($\beta^2 B^4$) of ~ 25 less power density is expected for DD fuel than for DT fuel. The change from DT- to DD-fuel operation at similar power densities requires: $n\tau$ increased by 20, n increased by 3-4, I_ϕ increased by 2.0, T increased by ~ 2, and τ_E increased by 5.0-7.0.
- The optimal power density is somewhat reduced and the mass utilization is somewhat increased from the DT/CRFPR ($P_{TH}/V_c \simeq 10$ MWt/m^3, $M/P_{TH} \simeq 0.7$ tonne/MWt).
- Economically optimal energy confinement times are identified and are given by

$$\tau_E \simeq 2.3\, r_p^{1/2} \; [T \propto \text{constant}]$$
$$\simeq 1.5\, r_p^{1/2} \; [T \propto J_o(\alpha r)]$$

- Poloidal betas of ~ 0.2 are adequate, which give a system that is approximately equivalent to DT-fuel operation with $\beta_\theta = 0.04$
- Power recirculated to normal coils is below 20% of total electric power; the incentive to embrace superconducting technologies remains weak unless $\beta_\theta \lesssim 0.2$.

- Minimum-cost DD/CRFPRs have dimensions similar to DT/CRFPRs, with $\tau_E \approx 1.2$-1.8 s, the magnitude of which is predicted by ~ 30-70% of Alcator scaling. The total energy confinement time, which includes (Bremsstrahlung) radiation losses, is expected to be less than 30% of these values.
- For the same system power density as the DT/CRFPR, the DD/CRFPR must deal with first-wall heat fluxes that are increased by a factor of ~ 2.8.

Perhaps the most promising composite result of this study is the resiliency of the RFP approach to maintaining conservatively promising cost projections within realistic physics and technology constraints as parameters related to key uncertainties/unknowns are varied[8]).

This study has generated and/or quantified a number of key engineering issues that serve to define the future course of HPD MFE studies in general and of the CRFPR approach in particular. The more important of these issues are summarized below.

- High-heat flux walls (~4-5 MW/m^2) and HPD [~100 MW/m^3(peak)] breeding blankets for DT operation.
- Plasma/wall interactions, effectiveness of dense-gas-blankets for first-wall protection, refueling; need for magnetic divertor; vacuum exhaust.
- Establish a firmer basis for steady-state operation and/or better quantify engineering impact of long-pulsed operation using realistic startup scenario.
- Better resolution of magnet design from viewpoint of equilibrium, startup, burn sustenance, and quench with emphasis on coil energy losses and general aspects of coil support and maintainability.
- Radiation effects to room-temperature copper coil and (inorganic) electrical insulators that are protected only by a thin ($\Delta b \approx 0.4$-0.5 m) heat-recovering/tritium-breeding blanket.

Obviously, if HPD MFE is to be proposed as one means to solve potential economic and operational problems, the task of heat recovery at high power density must be addressed. Preliminary computations and design related to the surface heat flux problem[26]) find no serious thermomechanical problem with the use of a high-strength copper alloy first wall that is cooled by high-pressure water and operated for $\lesssim 10^6$ pulses (i.e., one year $I_w \approx 15$–20 MW/m^2 operation for a ~ 30-s burn period), excluding unresolved radiation effects. The peak blanket power density (~ 100 MW/m^3) is comparable to the centerline power density in a LWR fission core, although the compatibility of solid tritium breeders with this power density is in question, this uncertainty depending primarily on poorly resolved high-temperature thermophysical properties of the ceramic tritium breeders. The use of the catalyzed-DD fuel cycle will considerably reduce this latter problem, the blanket being reduced essentially to an all-metal pressure vessel that is water cooled; the surface heat flux would be substantially increased, however. A spectrum of volumetric power densities and surface heat fluxes, showing both conventional and HPD fusion, is illustrated on fig. 6 in order to give some perspective to this central problem. The LiPb-cooled blanket proposed for the OHTE[17]) appears particularly attractive for the HPD MFE systems, especially for the RFP geometry, where MHD-pumping losses can be considerably reduced.

Although the potential for steady-state RFP operation has been suggested[35]) and would eliminate low-cycle fatigue problems that may limit FW/B life[26]), the RFP can operate efficiently in a long-pulsed operating mode; typically ~ 0.5 s of full-power operation is required to regenerate all magnetic-field energy transferred to the DT/CRFPR, and long-pulsed burns of $\gtrsim$ 30-s duration will more than justify ignoring this setup/startup energy requirement. The added physics, engireering, and cost constraints associated with a steady-state current drive and impurity control, however, must eventually be weighted in the context of the systems model described herein and against the costs of long-pulsed operation.

Radiation effects to first-wall and magnet copper alloy and the impact on long-term operation of the CRFPR remain as a key technological issue to be studied beyond the scoping level presented in ref. 6. The fabrication of the coil set according to a design that fully reflects its magnetics (current drive, equilibrium, etc.) functions, its electrical insulation needs, and its mechanical support in a maintainable configuration presents another area of future study and development. These and other engineering technology areas remain as topics for future conceptual engineering design activities.

In summary, 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 liabilities. The present assessment of the economic tradeoff between the benefits of HPD operation (i.e., reduced system mass, size, and cost) and the potential liabilities of increased recirculating power and reduced first-wall/blanket chronological life is promising. In addition, compact systems may demonstrate a more rapid FW/B replacement approach that could enhance overall plant availability, inspite of the requirement of more frequent changeouts. Even more difficult to quantify but of immense importance are the potentially shorter construction times and less total Capital investment associated with HPD systems. It is this potential for total (block) system maintenance, appreciably lowered total capital cost, flexibility for moderate to high total net power, and considerably reduced construction and maintenance time that gives the strongest impetus for further study of the HPD MFE approaches.

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TABLE I

SUMMARY OF KEY PARAMETERS FOR A RANGE OF
TOROIDAL DT FUSION REACTOR CONCEPTS

PARAMETER	DESIGN DATE: DEVICE:	1981 MSR	1980 STARFIRE	1980 EBTR	1978 RFPR	1980 PWR	1981-82 CRFPR
Plasma radius (m)		2.11	2.38	1.0	1.2		0.71
Major radius (m)		23.24	7.0	35.0	12.7		4.3
Plasma volume (m^3)		2050	781	691	564		42.7
Average density ($10^{20}/m^3$)		1.50	0.81	0.95	2.00		3.4
Temperature (keV)		8.0	22	29	15-20		20
Lawson parameter (10^{20} s/m^3)		3.7	3.0	1.7	2.0		0.79
Average beta		0.04	0.067	0.17	0.30		0.20
Plasma power density (MW/m^3)		2.35	4.50	4.13	4.50	90	72.4
Magnetic field (T)		6.0	5.8	5.0/2.25	3.0		3.3
Neutron current (MW/m^2)		1.3	3.6	1.4	2.7		19.5
Thermal power (MWt)		4800	4033	4028	3000		3350
Net power (MWe)		1530	1200	1214	750	1000	1000
System power density (MWt/m^3)		0.26	0.30	0.24	0.50	19.8	15
Mass utilization (tonne/MWt)		9	3.94	10.85	3.7	0.22	0.37
Thermal conversion efficiency		0.35	0.35	0.35	0.30	0.33	0.35
Recirculating power fraction		0.08	0.167	0.15	0.17		0.14
Net plant efficiency		0.32	0.30	0.30	0.25		0.30
COE (mills/kWeh)		94(1991)	67(1986)	72(1985)	66(1988)	40(1983)	41(1986)
Unit direct cost (\$/kWe)[a]		1547	1438	1737	1104	900	863
Construction time (years)		10	6	5	10	8-10	5

[a] Based on total direct cost before application of indirect cost (~ 23%), interest during construction (IDC), and escalation during construction (EDC).

TABLE II

PARAMETER SUMMARY FOR INTERIM 1000-MWe CRFPR DESIGNS

	FULLY COST-OPTIMIZED		DEGRADED
	DT[a]	DD[a]	DD[b]
First-wall radius, r_w (m)	0.75	0.60	0.62
Major radius, R_T (m)	4.3	4.4	14.9
Minor system radius, r_s (m)	1.6	2.1	2.32
Toroidal-coil mass (tonne)	159	403	2430
Poloidal-coil mass (tonne)	729	1960	7860
First-wall/blanket mass (tonne)	356	304	1060
Mass utilization, M/P_{TH} (tonne/MWt)	0.37	0.70	3.0
Plasma temperature, T(keV)	20.0(10.0)	35.0(20.0)	20.0
Plasma density, $n(10^{20}/m^3)$	3.4(6.7)	13.0(20.9)	11.0
Energy confinement time, τ_E(s)	0.23	1.8(1.18)	2.2
Alcator coefficient, $\tau_E/nr_p^2(10^{-21}$ s m)	1.37(0.76)	4.3(1.75)	6.0
Toroidal plasma current, I_ϕ (MA)	18.5	36.8	27.4
Poloidal field at plasma, B_θ (T)	5.2	13.0	9.4
Poloidal coil field, $B_{\theta c}$ (T)	2.6	4.4	2.9
Initial toroidal-coil field, $B_{\phi o}$ (T)	3.3	8.5	6.0
Poloidal-coil energy, $W_{B\theta}$ (GJ)	1.11	6.2	12.0
Toroidal coil energy, $W_{B\phi}$ (GJ)	0.54	3.0	6.4
Magnetic energy recovery time, τ^* (s)	0.49	2.4	4.8
Total thermal power, P_{TH} (MWt)	3350	3820	3820
Engineering power density, P_{TH}/V_c (MW/m^3)	15.0	10.0	2.4
Recirculating power fraction, $\epsilon = 1/Q_E$	0.147	0.25	0.25
Ohmic Q-value, $Q_T = P_{TH}/(P_{OHM} + P_{TR})$	37.1	15.8	15.8
Neutron wall loading, I_w (MW/m^2)	19.5	10.6	3.0
Unit total cost, UTC ($/kWe)	1490	1810	2605
Cost of electricity, COE (mills/kWeh)	40.7	47.2	67.2

[a] $T(r) = $ CONST $(T(r) = J_0(\alpha r))$.

[b] Power density of DD/CRFPR degraded until the first-wall surface heat flux is equal to the fully cost-optimized DT/CRFPR (4.87 MW/m^2).

FIGURE CAPTIONS

Fig. 1. Dependence of unit direct cost (UDC) on fusion-power-core mass utilization for a range at fusion reactor designs. The effect of doubling the unit cost of the fusion power core from the nominal 24 \$/kg is also shown. The UDC includes only total direct cost prior to the application of indirect cost, IDC, and EDC.

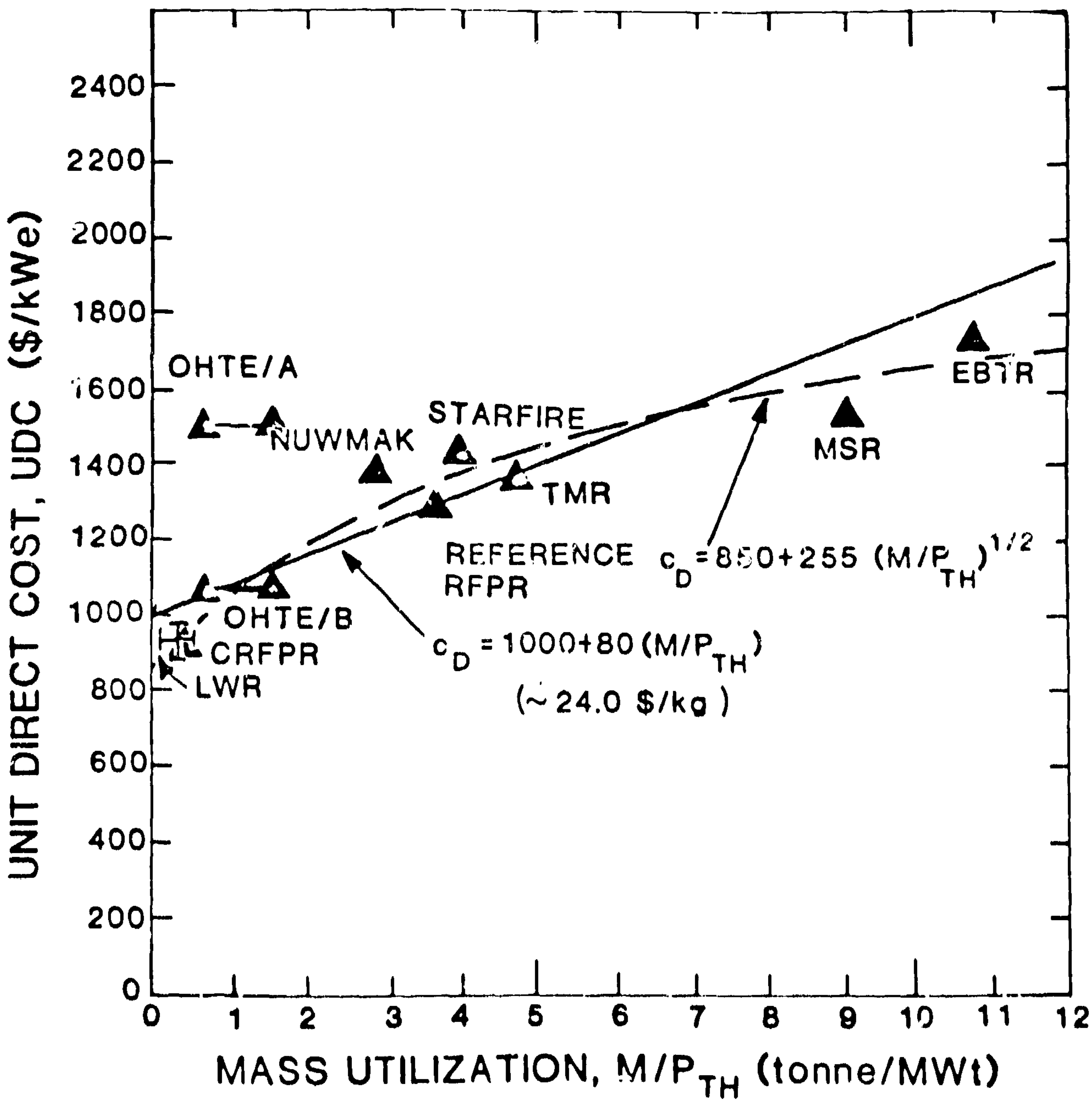
Fig. 2. Calculational algorithm used to determine minimum-cost CRFPR design points.

Fig. 3. Dependence of COE on r_p, P_{TH}/V_c, and P_E for all cost-optimized cases prior to optimization with respect to transport. The indicated base case is used in ref. 8 for sensitivity studies.

Fig. 4. Dependence of cost-optimized confinement time, τ_E(OPT), on plasma radius for both DT and catalyzed-DD fuel cycles. Shown also is the COE dependence for each case, which for both fuels is independent of temperature profile, as is the τ_E(OPT) curve for DT operation.

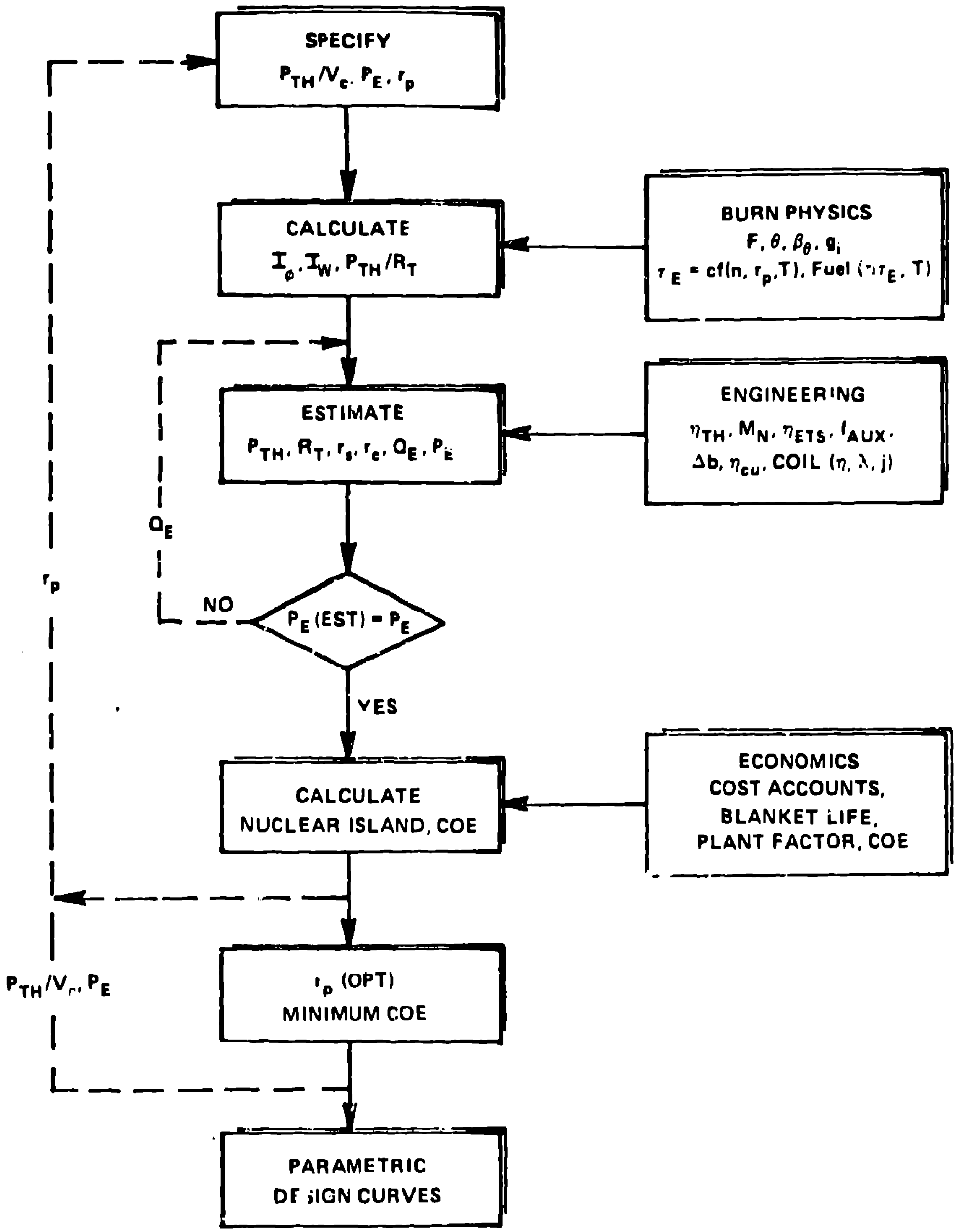
Fig. 5. Dependence of the minimum COE values on the value of β_θ. The DT base case is indicated on Fig. 3, and the fully cost-optimized cases are given in Table II.

Fig. 6. Spectrum of power densities and heat fluxes showing position of both conventional and HPD MFE approaches, relative to fission power and other commercial and physical processes.



UNIT DIRECT COST, UDC ($/kWe)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
OHTE/A
NUWMAK
STARFIRE
TMR
EBTR
MSR
REFERENCE
RFPR
OHTE/B
CRFPR
LWR
$c_D = 850 + 255\ (M/P_{TH})^{1/2}$
$c_D = 1000 + 80\ (M/P_{TH})$
(~ 24.0 $/kg)
0
1
2
3
4
5
6
7
8
9
10
11
12
MASS UTILIZATION, M/P_{TH} (tonne/MWt)

Figure 2



3/82CTR2323

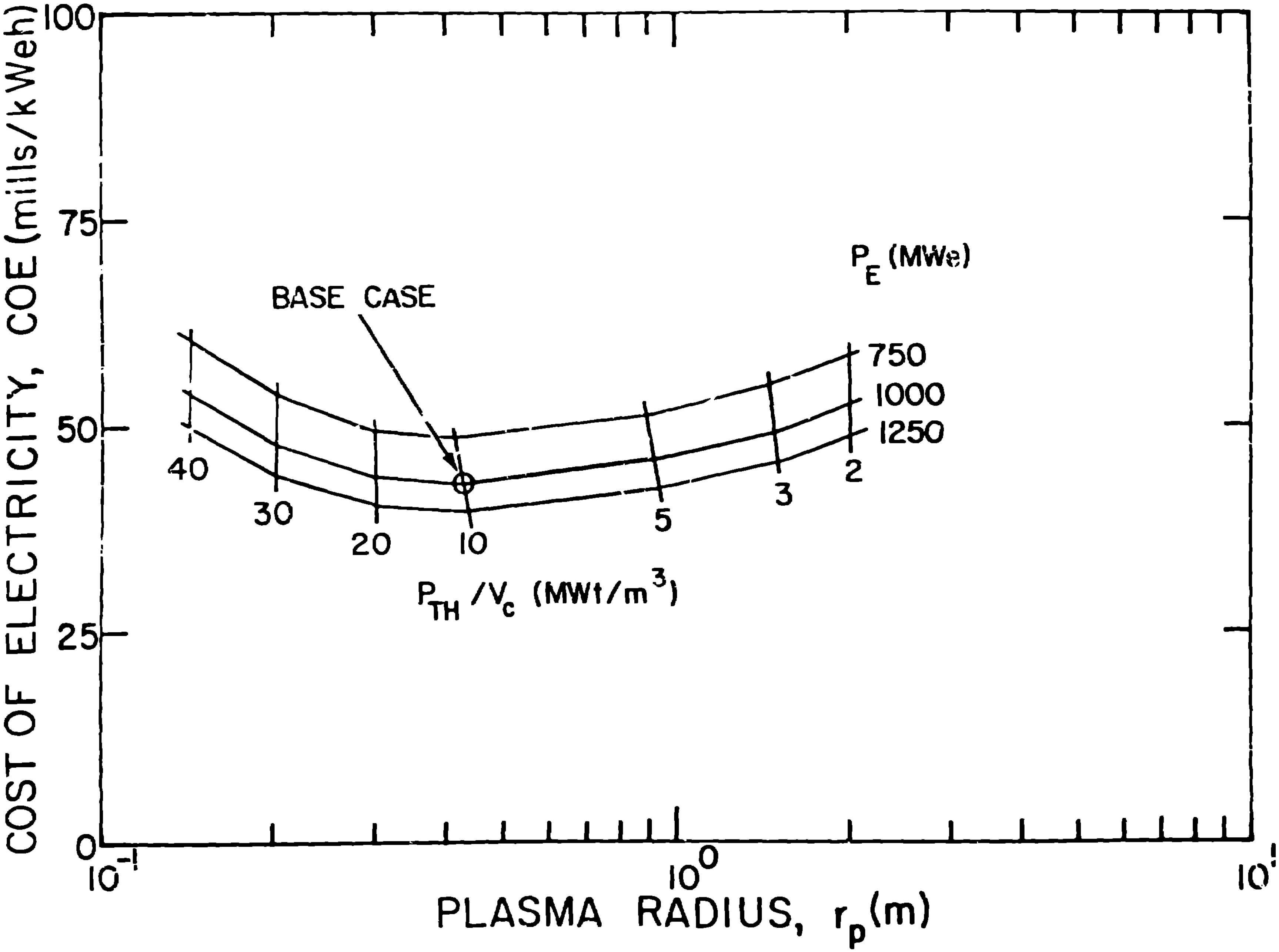
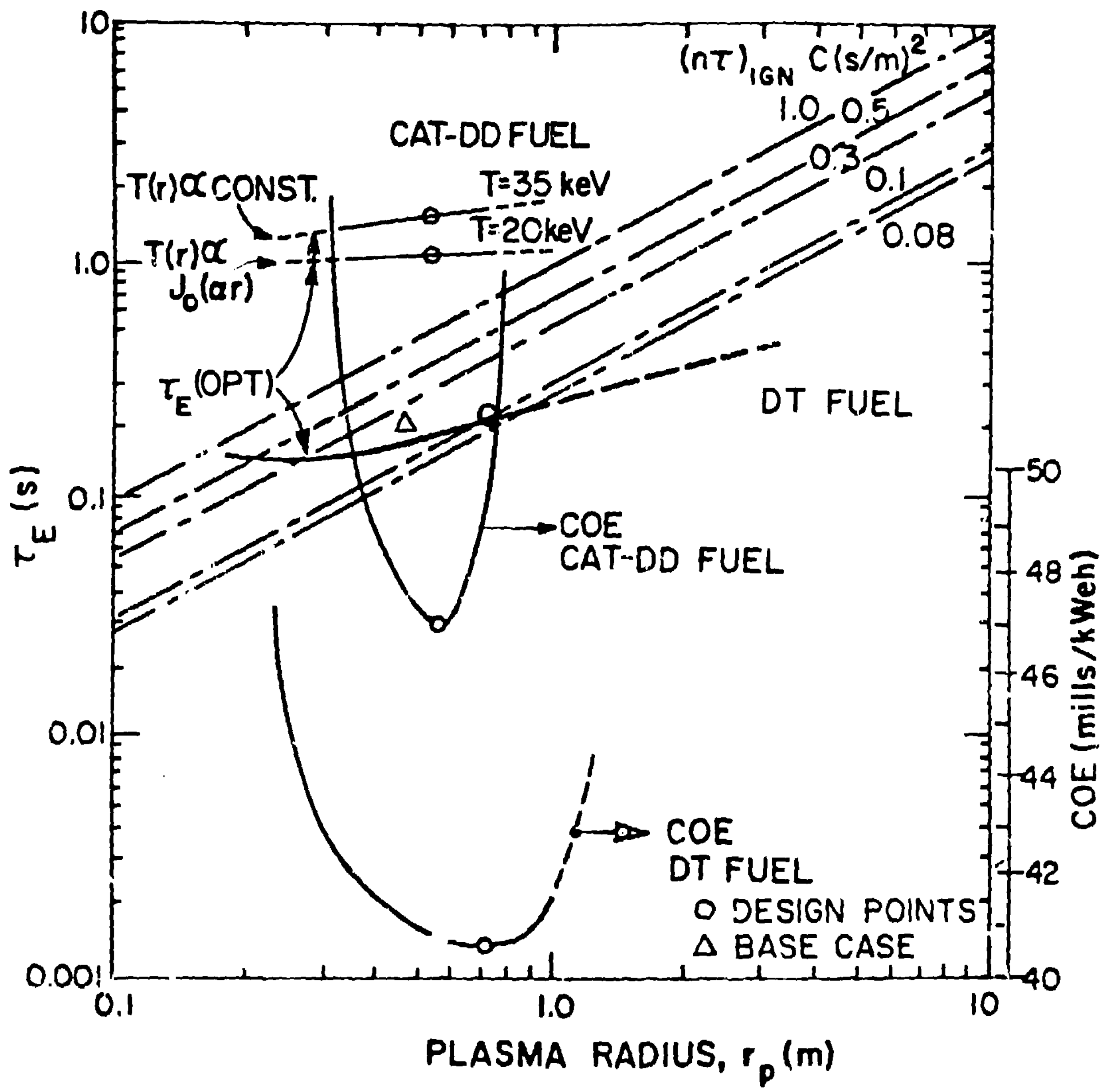
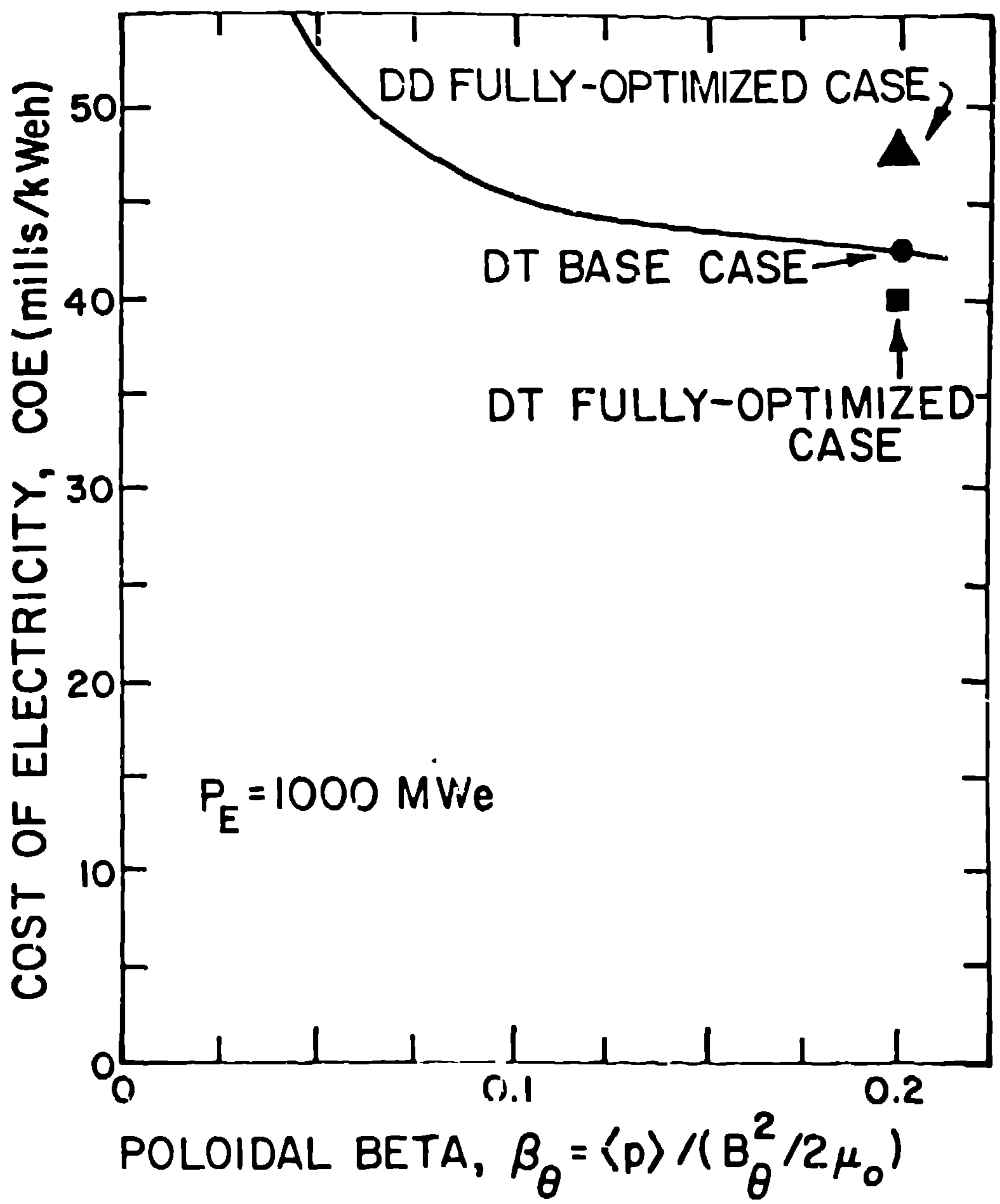


Figure 3

3/82CTR2345



3/82CTR2384A


DD FULLY-OPTIMIZED CASE
DT BASE CASE
DT FULLY-OPTIMIZED CASE
$P_E = 1000$ MWe
COST OF ELECTRICITY, COE (mills/kWeh)
0
10
20
30
40
50
0
0.1
0.2
POLOIDAL BETA, $\beta_\theta = \langle p \rangle / (B_\theta^2 / 2\mu_o)$

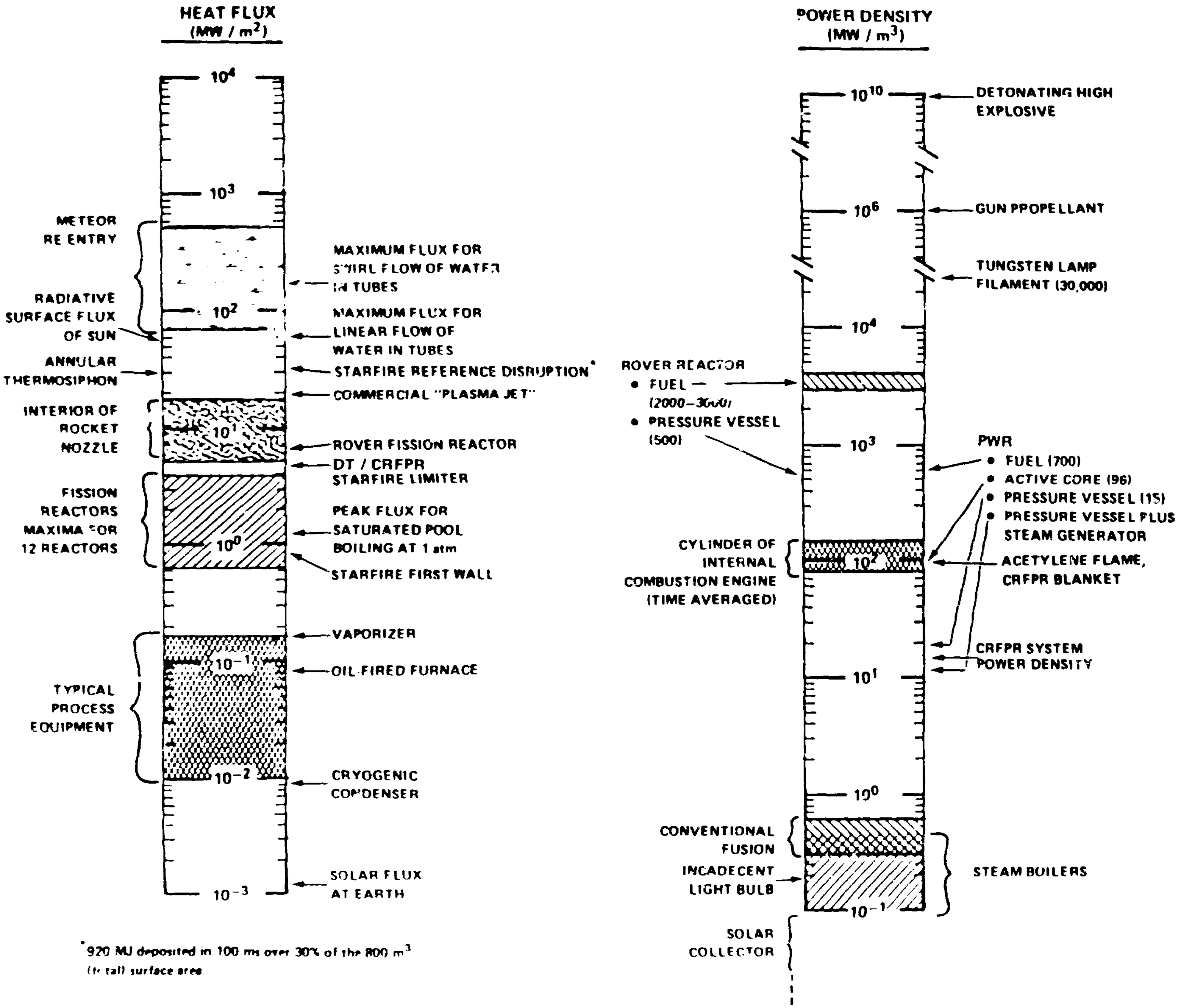

HEAT FLUX
(MW / m²)
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
METEOR RE ENTRY
RADIATIVE SURFACE FLUX OF SUN
ANNULAR THERMOSIPHON
INTERIOR OF ROCKET NOZZLE
FISSION REACTORS MAXIMA FOR 12 REACTORS
TYPICAL PROCESS EQUIPMENT
MAXIMUM FLUX FOR SWIRL FLOW OF WATER IN TUBES
MAXIMUM FLUX FOR LINEAR FLOW OF WATER IN TUBES
STARFIRE REFERENCE DISRUPTION*
COMMERCIAL "PLASMA JET"
ROVER FISSION REACTOR
DT / CRFPR
STARFIRE LIMITER
PEAK FLUX FOR SATURATED POOL BOILING AT 1 atm
STARFIRE FIRST WALL
VAPORIZER
OIL-FIRED FURNACE
CRYOGENIC CONDENSER
SOLAR FLUX AT EARTH
*920 MJ deposited in 100 ms over 30% of the 800 m³ (total) surface area
POWER DENSITY
(MW / m³)
10¹⁰
10⁶
10⁴
10³
10²
10¹
10⁰
10⁻¹
DETONATING HIGH EXPLOSIVE
GUN PROPELLANT
TUNGSTEN LAMP FILAMENT (30,000)
ROVER REACTOR
• FUEL (2000–3000)
• PRESSURE VESSEL (500)
PWR
• FUEL (700)
• ACTIVE CORE (96)
• PRESSURE VESSEL (15)
• PRESSURE VESSEL PLUS STEAM GENERATOR
CYLINDER OF INTERNAL COMBUSTION ENGINE (TIME AVERAGED)
ACETYLENE FLAME, CRFPR BLANKET
CRFPR SYSTEM POWER DENSITY
CONVENTIONAL FUSION
INCADECENT LIGHT BULB
STEAM BOILERS
SOLAR COLLECTOR

Figure 6