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COST ASSESSMENT OF A GENERIC MAGNETIC FUSION REACTOR*

J. Sheffield and R. A. Dory

Oak Ridge National Laboratory
Martin Marietta Energy Systems, Inc.
P. O. Box Y
Oak Ridge, Tennessee 37831

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ABSTRACT

A generic magnetic fusion reactor model is used to determine the conditions under which electricity generation from fusion would be economically viable. The use of a generic model helps to circumvent problems associated with present perceptions of magnetic configurations. It helps also to decouple those limitations set by generic constraints such as nuclear cross sections from those set by the state of development today. The model shows that only moderate advances are required in reactor characteristics over current designs to make an economically attractive magnetic fusion reactor.

INTRODUCTION

Over the past decade numerous articles have been written which discuss the economics of magnetic fusion reactors(1, 2, 3). In some of these articles it is argued that, because fusion reactors with superconducting coils may be somewhat larger than thermal fission reactors, the cost of electricity from them will be prohibitively high. These observations are based upon more or less detailed comparisons between existing fission reactors and fusion reactor designs such as Starfire(4), Mars(5), EBT-R(6), and MSR(7). However, the deployment of fusion is some years away and it is important to decouple the limitations set by generic considerations from those deriving from the state-of-the-art today. On the one hand, advances may be expected which enhance the attractiveness of fusion. On the other hand, the generic constraints such as the neutron attenuation lengths in the shield materials and the tritium breeding and fusion cross sections set ultimate limits on advances. In the generic reactor model it is possible to separate these two facets of magnetic fusion and to show that fusion should be able to take its place beside other energy sources as a viable commercial source of electricity in the 21st century. At the same time the study defines the self-consistent goals for each aspect of magnetic fusion (beta, coil performance, additional heating power, unit costs and availability, etc.) which are required for the development of an attractive reactor.

MODEL

A study of existing reactor designs(4, 5, 6, 7) shows many common features even though the configurations range from toroidal, tokamak(4), EBT(5), stellarator(7), to linear, tandem mirror(5). The common elements are: electrical efficiency $n_e \approx 35\%$; ratio of magnetic field in the plasma to maximum field on the coil $B_p/B_m \lesssim 0.60$ (for the tandem mirror only the center cell is considered here, and this model does not apply to the Reverse Field Pinch for which $B_o/B_m \gtrsim 1.0$); ratio of minimum wall radius to plasma radius ≈ 1.1; neutron gain in the blanket $g_n \approx 1.14$; minimum blanket and shield thickness (under the coils), $\Delta b = 0.45$m, $\Delta s \approx 0.75$m; maximum thickness between the coils $\Delta b = 0.9$m, $\Delta s = 0.80$m; minimum and maximum service gaps between blanket and shield, $\Delta g(\min) = 0.10$m and $\Delta g(\max) = 0.30$m respectively; Dewar radial thickness $\Delta d = 0.10$m; average ratio of secondary coil mass to primary coil mass $f_{cs} \approx 0.40$; ratio of the volume of inter-coil structure to total coil volume $V_{st}/V_{ct} \approx 0.50$. For a tandem mirror, the secondary coil structure is taken to be mirror coils plus end cells and $f_{cs} \approx 0.70(5)$. For a tokamak, the secondary set is the poloidal coils $f_{cs} = 0.40(4)$. For a stellarator, the non-toroidal part of the coil has $f_{cs} \approx 0.20(8)$.

In the generic model, Figure 1, the plasma is non-circular, the primary coil set is taken to be toroidal. This permits us to obtain a simple relationship between the plasma field and the maximum field on the coil $B_p/B_m = (R-1.1a-(\Delta b+\Delta g+\Delta s)_{min} - \Delta d)/R$ where (R) is the plasma major radius and (a) is the minimum plasma minor radius. It is assumed that the plasma is elliptic in cross section

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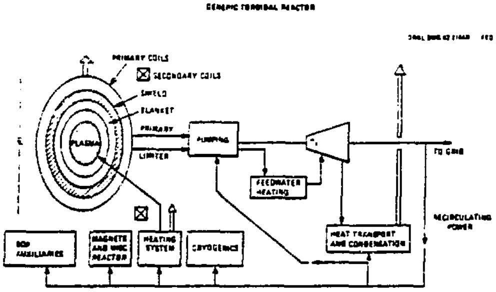

Figure 1

with ellipticity b/a = 2.0. It is assumed that one third of blanket, gap and shield are between the plasma and the primary coil and that this has the minimum thickness. The other two thirds, between the coils has the maximum thickness(8).

The plasma pressure profile is taken to be parabolic and the fusion power is approximated as $P_F = 5P_\alpha = 128\beta_i^2 B_p^4$ Rab (MW) where the average ion beta $\beta_i = \beta/[1+(1+\beta_z/\beta_e)/(\beta_i/\beta_e)]$ the fractional impurity beta $\beta_z/\beta_i = 0.1025$. It is assumed that for a good system T_i may be slightly bigger than T_e thereby, compensating for the fact that $n_i < n_e$, and we take $\beta_i = \beta_e$. The total thermal power is given by $P_t = P_\alpha(1+4(1+g_n))$. The net electric power is given by $P_e = P_t\,\eta_e(1-0.07) - 0.5P_a$, where 7% of the power is recirculated. For the reference reactor calculations, we use an additional power of $P_a = 100\ MW_e$, $P_t = 3893\ MW_t$, $P_e = 1220\ MW_e$. It is assumed that half of the additional power is used for start-up and half is used during the burn phase.

For the superconducting coils we use an algorithm developed in studies for TFCX and INTOR(8) which relates the winding pack current density j_m to the maximum field on the superconducting coils for B_m = 6T to 12T. $j_m = (96-6\,B_m)/(1+(B_m/12)^{1.5})\ MA/m^2$. The denominator allows for the coil structure. The Balance of Plant (BOP) characteristics are taken from the Starfire(4) study.

COSTING MODEL (Constant 1983 dollars)

The Cost of Electricity (COE) is calculated from(9)

$$COE = \frac{(C_C\,F_{CR} + C_F + C_{om})}{(P_e \times 8760 \times f_{av} \times 10^{-3})}\ \text{mills/kW.h}$$

- where $C_C = C_{DO} \times 1.15 \times 1.50 \times 1.10$ is the capital cost of the power station. C_{DO} is the direct cost, the contingency factor is 1.15, the indirect charges are 1.50, this value is based upon studies of fusion and coal plants(9). The tax adjusted, constant dollar interest charge during an 8 year construction period amounts to 10% of the capital cost (9% tax adjusted interest, 6% annual inflation).
- The factor F_{CR} is the annual repayment (similar to a mortgage) which pays off the capital cost during the plant lifetime (30 years). $F_{CR} = 0.10$.
- C_F is the annual fuel charge which in this study includes the annualized cost of the lithium blanket, divertor targets or limiters and replaceable additional heating items as well as the cost of deuterium fuel.
- C_{om} represents the costs of operations and maintenance additional to the fuel costs.
- P_e represents the maximum electric power.
- f_{av} is the plant availability factor at maximum power. It is assumed that $f_{av} = 0.65$.

The direct capital cost is given by

$$C_{DO} = \{\underbrace{683\left(\frac{P_t}{4000}\right)^{0.6}}_{\text{BOP}} + \underbrace{277\left(\frac{V_{ni}}{3900}\right)^{0.67}}_{\text{Reactor Buildings}} + \underbrace{C_{ni}}_{\text{Nuclear Island}}\}\ \text{M\$}$$

The thermal power P_t(MW) and nuclear island volume $V_{ni}(m^3)$ are normalized to Starfire values. The scaling power is based upon typical values for power stations. The cost of the nuclear island is given by

$$C_{ni} = [\underbrace{83\left(\frac{P_t}{4000}\right)^{0.6}}_{\text{steam generators}} + \underbrace{1.2\,(1.4\,V_{pc}\,\rho_c\,\$_c)}_{\text{coils}}$$

$$+ \underbrace{V_{st}\,\rho_{st}\,\$_{st}}_{\text{structure}} + \underbrace{V_s\,\rho_s\,\$_s}_{\text{shield}}]$$

The primary coil volume is obtained from the maximum field B_m and the coil current density algorithm, $\rho_c = 7.9 \times 10^3\ kg/m^3$ $\$_c = 6.7 \times 10^{-5}$ M$/kg. The factor 1.2 allows for redundancy in each coil.

The structure volume $V_{st} = 0.7\ V_{pc}$, $\rho_{st} = 6.0 \times 10^3\ \mathrm{kg/m^3}$, $\$_{st} = 2.5 \times 10^{-5}$ M\$/kg. The shield volume V_s is calculated from the plasma volume, the wall radius and the given blanket, gap and shield radial thicknesses, $\rho_s = 6.4 \times 10^3\ \mathrm{kg/m^3}$, $\$_s = 2.0 \times 10^{-5}$ M\$/kg (the blanket costs appear in the annual fuel costs).

GENERIC REACTOR COE

The model described above has been used to compute the cost of electricity of a wide range of toroidal reactor configurations. The variation of COE with (R/a) and $\langle\beta\rangle$ is shown in Figure 2. The COE is relatively insensitive to changes in R/a over a wide range. The increase in cost at low R/a occurs because it becomes necessary to increase the overall scale of the plasma in order to attain the field B_m in the bore of the torus. At larger aspect ratio, the increase in plasma surface to volume area leads to a larger nuclear island and increased costs. The limitation $B_p/B_m \lesssim 0.6$ eliminates the factor which ameliorates the increase in size at moderate aspect ratios. In Figure 3, the variation of $\langle\beta\rangle$ and average neutron wall loading p_{wn} are shown as a function of the nuclear island mass. It can be seen that lower mass (lower cost) results from improved plasma performance, though at some penalty in wall loading. The plots illustrate the importance of achieving $\langle\beta\rangle = 10\%$ rather than the 5% used in some of the older reactor designs. If higher $\langle\beta\rangle$ is achieved then the most attractive reactor is achieved by lowering the magnetic field rather than by increasing the neutron wall loading. Similar studies were undertaken earlier(10).

COST OF ELECTRICITY CONTOURS (mills/kWh)

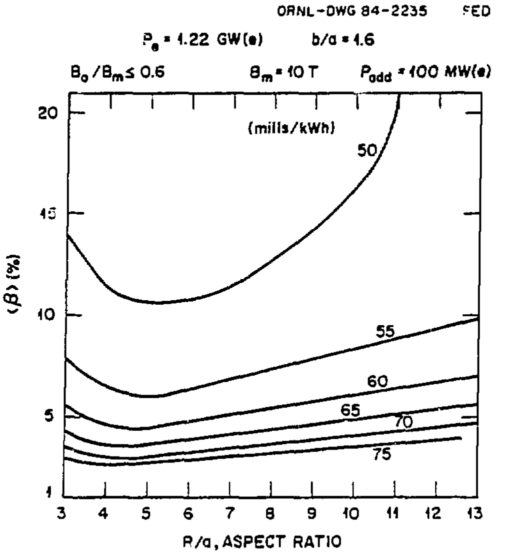

Figure 2

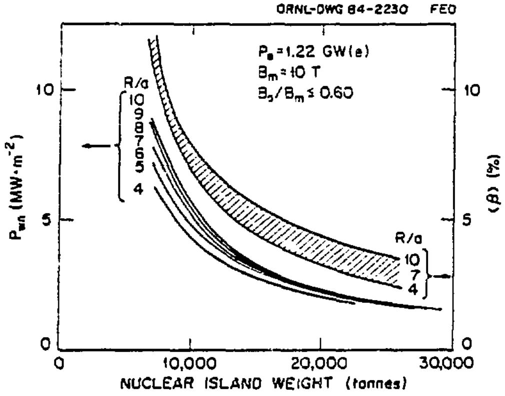

Figure 3

In Figure 4, the dependence of COE on nuclear island weight is shown along with the breakdown of the costing. This plot is similar to those shown by Los Alamos(7, 8).

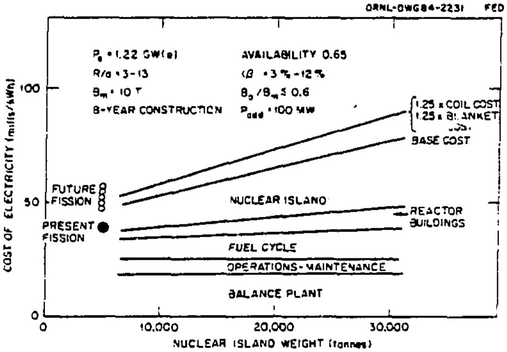

Figure 4

The present fission reactor COE of ~ 45 ± 5 mills/kW.h at the power station are expected to increase by some 20% when the cost of U_3O_8 rises to ~150 \$/lb. in the early 21st century. An interesting feature of the calculations is the insensitivity of fuel costs to reactor size. This is a result of using a fixed neutron fluence (20 MW.yr/m^2)

for blanket and first wall lifetime and a fixed fluence (10 MW.yr/m^2) for targets, limiters and r.f launching structures.

The detailed breakdown of the COE for 1200 MW_e fission(9) and optimized fusion plants operating in the 21st century when the cost of U_3O_8 is ~150 $/lb. isgiven in the Table in mills/kW.h.

	FISSION	FUSION
Operations-Maintenance	6	7
Fuel Cycle	21	10
BOP	17	18
Reactor Buildings	3	4
Nuclear Island	5	13
TOTAL	52	52

It can be seen from this cost model that at this time fusion reactors of mass 10,000 to 15,000 tonnes should be competitive. This mass is somewhat smaller than many present designs(4, 5, 6, 7) but it should be achievable with modest improvements in the magnetic configuration. Developments of the past few years have already indicated routes to such improvements for all of these designs.

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