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Parametric Design Study of Tandem Mirror Fusion Reactors

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Abstract

The parametric design study of the tandem mirror reactor (TMR) is described. The results of this study illustrate the variation of reactor characteristics with changes in the independent design parameters, reveal the set of design parameters which minimizes the cost of the reactor, and show the sensitivity of the optimized design to physics and technological uncertainties. The total direct capital cost of an optimized 1000 MWe TMR is estimated to be $1000/kWe. The direct capital cost of a 2000 MWe plant is less than $1000/kWe.

Introduction

The physics principles of the tandem mirror have been described by Fowler and Logan [1]. Briefly, the configuration consists of three mirror cells in tandem, wherein mirror confinement in the end cells is used to establish electrostatic potentials which provide end stoppering for the ions in the much larger central cell. The improved confinement of the fusion plasma in the central cell allows reactor designs with large values of Q (fusion power/trapped injected power) ~ 5 or more. The mechanical design features of a tandem mirror reactor (TMR) are described in Reference 2. This paper describes the parametric design [illegible] of the [illegible] which have been carried out at Lawrence Livermore Lab- oratory.

[illegible] of the Analytic Model

[illegible]

[illegible]

[illegible] the center cell [illegible]

[illegible] the central cell.

The equations of the [illegible] model can be [illegible] solved in a number of different ways. In the first analytic model we found it most convenient to specify the plug injection energy, the plug [illegible], the mirror ratio between the plugs and central cell, the [illegible] in the plugs and in the central cell, and the central cell ion [illegible]. The [illegible] of the [illegible], [illegible] parameters [illegible], the plasma volume ratio between the central cell and plugs; and 8.

Reactor Design

Next, the specification of a single magnetic field strength (namely the plug central field) allows calculation of all the plasma densities and the fusion power density in the central cell. Then, specification of the blanket energy multiplication factor M and various efficiencies (thermal conversion, direct conversion, and neutral beam injection) allows calculation of power flows. At this point, the power quantities are only relative because an absolute power level has not been selected.

Finally, specification of a single dimension or power quantity (we usually choose to specify the net electric power) allows complete design of the reactor. The dimensions of the cylindrical central cell plasma and the approximately spherical plug plasmas are completely determined by the central cell to plugs volume ratio, the fusion power density of the central cell, the desired total fusion power, and the requirement for magnetic flux conservation throughout the machine.

The plug magnets are designed to provide the specified magnetic field and to be large enough to contain the plug plasmas. The scaling laws for the plug magnets were derived from the point design described in Reference 2.

The central cell design begins at the cylindrical first wall (5 alpha radii away from the plasma) and proceeds outward through the blanket, shield, magnet, support structure, handling and maintenance equipment and finally the reactor building. The scaling laws for the central cell were derived from the point design described in Reference 1. In all cases the blanket and shield thicknesses were held constant at 75 and 80 cm, respectively. Thus, the primary variables in the central cell design are the length, first wall radius, and magnetic field strength. The plant design is completed by the sizing of the injectors, direct converters, and the thermal conversion system.

Cost Estimate

Estimates of direct capital costs are made for all elements of the power plant, permitting a final estimate of the cost of power.

The central cell cost tends to be the dominant cost and is therefore the most carefully estimated. It is broken down into separate cost estimates for the blanket, shield, vacuum vessel, solenoidal coils, coil restraining structure, cell cage, main support structure, the crane-transporter under each central cell module, and the central cell portion of the reactor building. The scaling laws for these costs were derived from the point design described in Reference 1. The blanket is costed on a per unit mass basis using $11/kg for the stainless steel structure and $5/kg for the neutron moderator and tritium breeding material.* (Unless otherwise stated, all component costs include fabrication and installation.) The shield consists of stainless steel at

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*The $5/kg estimate was made [illegible] lithium [illegible], one of the proposed breeding materials. [illegible] approximately [illegible] estimate to be [illegible].

\$11/kg, lead cement at \$1/kg, and borated carbon at \$5.50/kg. The vacuum vessel is stainless steel at \$14/kg. The superconducting solenoidal coil is always at a low magnetic field strength (2.4 tesla in the Reference Design) and is conservatively sized for an overall current density of 1200 A/cm^2. The conductor density is taken to be that of copper and is costed at \$6.60/kg. The cost of winding the coil is separately calculated at \$.0011/Am. The coil restraining structure and coil case are stainless steel at \$14/kg. The main support structure is steel at \$11/kg. The cost for the crawler-transporter is assumed to scale linearly with the mass of the central cell module, and is normalized to an estimate of \$600,000 for a 4 m long module weighing 1.2 X 10^6 kg. Finally, the cost of that part of reactor building which encloses the central cell is assumed to scale linearly with the central cell length and with the square of the central cell outer radius, and is normalized to an estimate of 25 million dollars for L_c = 100 m and r_{outer} = 6.5 m.

The plug cost is broken down into separate cost estimates for the plug coils, coil restraining structures, coil refrigerators, and the plug portion of the reactor building. A plug coil set consists of a cryogenic aluminum Yin Yang inside a superconducting solenoidal pair. The solenoidal pair is designed with an overall current density of 2000 A/cm^2 and is costed at \$.0010/Am plus \$.0011/Am for winding. The stainless steel restraining structure for the solenoidal is costed at \$22/kg. The cryogenic aluminum Yin Yang, consisting of pure aluminum conductor and aluminum alloy internal structure, is costed at \$22/kg plus \$.0023/Am for winding. The mass of a stainless steel external restraining clamp is estimated using a previous tandem mirror reactor study[14] and is costed at $12/kg. The estimated cost of the refrigeration to remove the neutron dissipation from the cryogenic aluminum coil is based on a refrigerator input power of [illegible] W per watt removed. (This refrigerator input power, [illegible] in the reference design, is also subtracted from the gross electric power of the plant when calculating the net electric power.) Finally, the cost of that part of the reactor building which encloses the plasma is assumed to scale with the square of the central cell outer radius, and is normalized to an estimate of [illegible] million dollars for r_{outer} = [illegible] m.

The thermal conversion system is costed at $[illegible] per kW of thermal power handled by the thermal converter. This cost includes the blanket coolant loop, the direct converter coolant loop, steam generators, turbine-generators, steam condensers, all steam and water piping, cooling towers, and the turbine hall building.

The direct conversion system is costed at $[illegible] per kW of charged particle power entering the direct converter. This cost includes the direct converter vacuum tank, the collector elements, the electrical conditioning equipment, and the thermal panels for the radiative cooling of collector elements.

The injection system is costed at $[illegible] per kW of electrical power input to the injectors. This cost includes the injectors themselves as well as their power supplies. (The effect of a higher injection system cost will also be discussed.)

The reactor systems discussed above do not include all of the systems considered in the cost estimate for our previous Standard Mirror reactor study(4). Systems not explicitly included are the cryopump vacuum system for the injectors and direct converters, the refrigeration system for the cryopumps and the superconducting coils, the plant electrical equipment, instrumentation and controls, the tritium handling system, miscellaneous buildings, and site improvements. Our preliminary estimate for the cost of these systems (which we label Other) for a 1000 MWe TMR is 210 million dollars.

As an economic figure of merit, we add all the above direct capital costs* and divide by the net electric power to obtain the direct capital cost per unit of installed capacity ($/kWe). We have used the minimization of this figure of merit to optimize the design of the TMR. (In our Standard Mirror reactor study(4) we pointed out a deficiency of the $/kWe figure of merit, namely that designs with higher first wall neutron loadings are not properly penalized for their more frequent outages for blanket maintenance. For that reason we used the cost of net electrical energy (mills/kWhr) as the economic figure of merit in Reference 4. We will adopt this method for future analytic models of the TMR. We suspect that our results will be about the same since the first wall loading of the optimized TMR Reference Design is only 2.1 MW/m^2 (vs. 3.1 for our Standard Mirror reactor).)

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*It must be emphasized that the estimated costs are direct capital costs only, and that no indirect costs have been added. In our Standard Mirror reactor study(4) we estimated indirect costs (indirect field costs, engineering services, contingency, interest during construction, and general office costs) to be 1.48 times the direct capital costs.

Results of the Analytic Model

Input for the Reference Design

We chose to specify a net electric power of 1000 MWe for the [illegible] Reference Design. (Lower and higher power levels will be discussed [illegible].) Other input parameters [illegible] specified [illegible] Reference Design are given below:

[illegible]	
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

[illegible]

[illegible]

Figure 3, where we plot $/kWe vs the three parameters. The minimum cost of $1350/kWe occurs for the values,

Injection energy = [illegible] MeV

Central cell ion temperature = [illegible] keV

[illegible] in central cell R_{VAV} = [illegible]

We choose this minimum cost design as the TMR Reference Design.

Also shown in Figure 3 are the variations of two derived figures of merit, the recirculating power fraction (defined as the gross electrical power minus the net electrical power, divided by the gross electrical power) and the first wall neutron loading. The optimization [illegible] trade-off between recirculating power and central cell power density (high first wall neutron loading). Note that moving off-optimum results in a "good" change in one figure of merit and a "bad" change in the other.

[illegible] in Figure 3 [illegible] indicate a [illegible] minimum cost the range of injection energy considered. [illegible] performance of the TMR [illegible] injection energy of [illegible] energies. Figure 4 shows [illegible] TMR [illegible] range of injection energy. [illegible] the [illegible] TMR [illegible]. At 500 keV injection energy, [illegible] dropped [illegible] power [illegible]. At [illegible] [illegible] [illegible] [illegible] temperature, [illegible] injection energy [illegible] and the [illegible] changed [illegible] and [illegible]

Description of the Reference Design

The [illegible] parameters of the [illegible] Reference [illegible] given in Table [illegible] characteristics [illegible] given in Table [illegible] given in Table [illegible] the Reference Design.

[illegible] and Costs

Figure [illegible] shows the [illegible] net power outputs ranging from 150 to 2000 MWe. The results plotted [illegible] present designs which have not been reoptimized, [illegible] the same injection energy, [illegible] temperature, and [illegible] the Reference Design. Re-optimization of the [illegible] for temperature, [illegible] and the injection energy for the 150 MWe and 2000 MWe cases was found to have almost no effect on the costs shown in the figures. The second graph in Figure [illegible] shows that the cost [illegible] with increasing power for two reasons: a decrease in the recirculating power fraction and an increase in first wall loading. The optimized 2000 MWe [illegible] has a [illegible] first wall [illegible] structure.

[illegible] Tritium Injection

[illegible] tritium beam injection is assumed for the Reference De- sign. There is a potential advantage to tritium injection, however, [illegible] the Reference Design with tritium [illegible] [illegible] and found [illegible] a slight [illegible] [illegible] [illegible] [illegible] We expected [illegible] increased [illegible] [illegible] However, the recirculating power fraction increased only a small amount [illegible] because the neutral beam trapping fraction increased to 0.95. Finally, the first wall neutron loading increased [illegible] MW/m² because the smaller plasma radius resulted in a [illegible] [illegible] [illegible]

Reoptimization of the tritium injection case would result in the recovery of some of the increased wall loading for a lower recirculating power fraction. However, the potential for improvement is not great. For this reason and because of the added complications of handling tritium in the high energy injectors (for which we received no additional credit), we discarded the tritium option.

Variation of Central Cell β

The Reference Design value of central cell beta, β_c, was [illegible], and the central cell plasma was assumed to obey the "long, thin" [illegible], i.e.,

$$B_{plasma} = B_{vacuum} \sqrt{1 - \beta_c}$$

[illegible] indicate that the central cell plasma may [illegible] as high as [illegible]. Figure 7 shows the cost of optimized [illegible] and the temperature and [illegible] to central cell mirror ratio [illegible] the cost of an optimized [illegible]. This [illegible] is [illegible] from the Reference Design [illegible] the central cell length [illegible] and the first wall [illegible] for [illegible]. The [illegible] and the first wall [illegible].

Variation of β Plug

The Reference Design value of plug beta, β_p, was [illegible], and the [illegible] was assumed [illegible] "long, thin" [illegible] for [illegible] i.e.,

$$B_{p,plasma} = B_{p,vacuum} \sqrt{1 - \beta_p} [illegible]$$

[illegible] the plasma [illegible] [illegible] indicate that S_ψ in the range of 1 to 2 may be possible. Figure 6 shows the cost of optimized (central cell ion temperature and plug to central cell mirror ratio) 1000 MWe TMR's as a function of S_ψ. It can be seen that there is an optimum value of S_ψ = 1.2, for which the reactor cost is reduced to $1100/kWe. This reactor is much more compact than the Reference Design: L_c is 91 m and the first wall radius is only 0.7 m. The recirculating power fraction is reduced to 0.18 and the first wall neutron loading is a high (probably too high) 7.7 MW/m^2. This latter effect occurs because the optimum plug to central cell mirror ratio is only 1.5 (vs 2.0 for the Reference Design), which results in a high central cell ion density (5.1 × 10^{14} cm^{-3}). This optimum design for high S_ψ would probably change if we adopted the mills/kWh minimization method, including the costs of blanket maintenance.

Variation of f_α

For the Reference Design we assumed that f_α, the fraction of alpha particles adiabatically confined, was unity. While this appears possible, it also appears that their confinement could be intentionally spoiled by a redesign of the plug to central cell transition region. In this event, alpha heating would be reduced, but at the same time the reduced alpha pressure in the central cell would permit a higher central cell fuel density. We investigated the design of a 1000 MWe TMR with f_α = 0.5, and found that reoptimization (injection energy, central cell ion temperature, and plug to central cell mirror ratio) yielded a cost of $1670/kWe, 7% higher than the Reference Design. The loss of alpha heat

[illegible]

[illegible]

[illegible] from the Reference Design [illegible]. First, we note that these [illegible] to reduce the [illegible] field from the Reference Design value [illegible]

Selection of Plug Mirror Ratio

The overall mirror ratio of the plug cells, $R_{m,plug}$, was chosen [illegible] for the Reference Design. A plug mirror ratio this low, together with a maximum allowable magnetic field strength, permits either a high confining field in the central cell (high fusion power density) or a high ratio of field (and thus density) between the plugs and central cell (good central cell confinement). The low plug mirror ratio was chosen in the expectation that these gains were more important than better plug confinement. Figure 6 shows the predicted cost of [illegible] central cell ion temperature and plug to central cell mirror ratios [illegible]

$R_{c,plug}$ for a constant value of the plug mirror field [illegible] means that as $R_{c,plug}$ is increased from its Reference [illegible], the minimum magnetic field strength of the center [illegible] from its Reference Design value of [illegible] [illegible] minimum mirror ratio exists at about $R_{c,plug}$ [illegible] the Reference Design value. However, the [illegible] minimum [illegible] % less than [illegible]

[illegible] Energy Multiplication

[illegible] the blanket energy multiplication factor, M, [illegible] for the [illegible] 1000 MWe TMR's [illegible] as a function of M. The [illegible] is seen to be quite [illegible] range [illegible] M.

The Effect of a Beryllium Blanket

Based on our conceptual design of a Standard Mirror Fusion Reactor[12], we predict that an M of 1.1 to 1.9 could be achieved in TMR with a beryllium-bearing blanket, which would cost about 2.x times as much as the non-beryllium blanket. We investigated the use of a beryllium blanket in the 1000 MWe TMR, and found that with reoptimization (central cell ion temperature and plug to central cell mirror ratio), a beryllium-bearing TMR would be 9% less expensive at M = 1.7 and 6% less expensive at M = 1.9. [illegible] of these reactors would be considerably shorter than the Reference Design (L_c = 67 m for M = 1.7; L_c = 59 m for M = 1.9).

Variation of Conversion Efficiencies

The Reference Design values for conversion efficiencies are 0.4 for the thermal converter (including the direct converter bottoming cycle), 0.6 for the direct converter, and 0.8 for the injector system. (Recent work on the injector system indicates that 0.7 may be a more accurate estimate of the injector system efficiency.) Figure 5 shows the percentage change in the predicted cost of 1000 MWe RRS's (without reoptimization) as a function of the three efficiencies. It is seen that for a given percentage point change in efficiency, the change in cost [illegible] the same for changes in the thermal efficiency as for [illegible] changes in the direct converter efficiency.

As [illegible] from their Reference Design values. For a 5 percentage point [illegible] in the efficiencies, the predicted cost [illegible] 1000 MWe RRS [illegible]

[illegible] Cost

[illegible] Reference Design [illegible] ion temperature and plug to center cell mirror ratios from the TMR was an 11% increase in the predicted reactor cost. Thus, it is quite important to resolve the question of injector cost.

Electron Heating

Direct heating of electrons in the TMR is an attractive idea because it would reduce the required neutral beam injection energy in the end cells. We have investigated the effect of electron heating where we have assumed that the electrical efficiency of such heating as well as the cost per unit power is the same as for the neutral beam injectors. Figure 7 shows the optimum neutral beam energy and the predicted cost of optimized TMR reactors as functions of f_e, the fraction of the [illegible] heating that goes directly to the electrons. For our Reference design with neutral beam injection only, f_e = 0. There is an optimum value of f_e near 0.75 for which the cost of the reactor is reduced to [illegible]/kWe. The neutral beam injection energy for this optimized reactor is [illegible] keV.

Concluding Remarks

[illegible]

[illegible]

[illegible]

Table I

Plasma Parameters — TMR Reference Design

Injection energy	1.2 MeV
Average plug ion energy, E_p	575 keV
Electron temperature, T_e	42 keV
Central cell ion temperature, T_c	30 keV
Electron potential, ϕ_e	263 keV
Central cell ion potential, ϕ_c	88 keV
Plug β	1.0
Central cell β	0.7
Plug particle nτ	$2.5 \times 10^{14}\ \frac{s}{cm^3}$
Central cell particle nτ	7.7×10^{14}
Plugs to central cell plasma volume ratio	500
Plug to central cell ion density ratio	7.96
$\langle\sigma v\rangle_{DT}$	$6.66 \times 10^{-16} \frac{cm^3}{s}$
Plug ion density, n_p	$8.57 \times 10^{14} cm^{-3}$
Central cell ion density, n_c	1.08×10^{14}
Plug plasma radius, r_p	0.48 m
Central cell plasma radius, r_c	1.22 m
Fusion power density	$5.61\ \frac{W}{cm^3}$
First wall neutron loading, P_N	$2.00\ \frac{MW}{m^2}$
Q	6.01

TABLE [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Table [illegible]

Power Flow Quantities - [illegible] Reference Design

Electric input power to injectors		[illegible] MW
Injected neutral beam power		[illegible]
Trapped neutral beam power		[illegible]
Fusion power		[illegible]
Thermal power into blanket		[illegible]
Thermal power out of blanket		[illegible]
[illegible] power [illegible]		[illegible]
[illegible]		[illegible]
Thermal power [illegible] converted		[illegible]
[illegible] power [illegible] converted		[illegible]
[illegible] power		[illegible]
[illegible] power		[illegible]
[illegible] power		[illegible]
[illegible]	[illegible]	
[illegible]	[illegible]	

Table 4

Cost Breakdown - TMR Reference Design

		Cost	% of total
Central Cell			
Blanket		$114 M	8.92
Shield		62	4.8
Vacuum vessel		11	0.9
Coil		44	3.4
Coil structure		21	1.6
Main structure		51	4.0
Crawler-transporter		22	1.7
	Subtotal	$316 M	24.77
Plug cells		$171 M	13.37
Reactor building		44	3.4
Injector system		147	11.5
Direct conversion system		134	10.5
Thermal conversion system		199	15.5
Other		270	21.1
	Total	$1,281 M	100%

References

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2. W. S. Neef, "Mechanical Design Aspects of a Tandem Mirror Fusion Reactor", these transactions, also LLL Report UCRL-79634, April 1977.

3. F. H. Coensgen, "TMR Major Project Proposal" (Appendix B-Tandem Mirror Reactor Scaling by B. G. Logan), LLL Report LLL-Prop-148, January 1977.

4. G. A. Carlson and R. W. Moir, "Mirror Machine Reactors", Proceedings of the 2nd ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, September 1976, also LLL Report UCRL-78148, September 1976.

Acknowledgement

The author wishes to thank Co-op student Elizabeth Carrick for the many computer calculations she performed in support of this work.

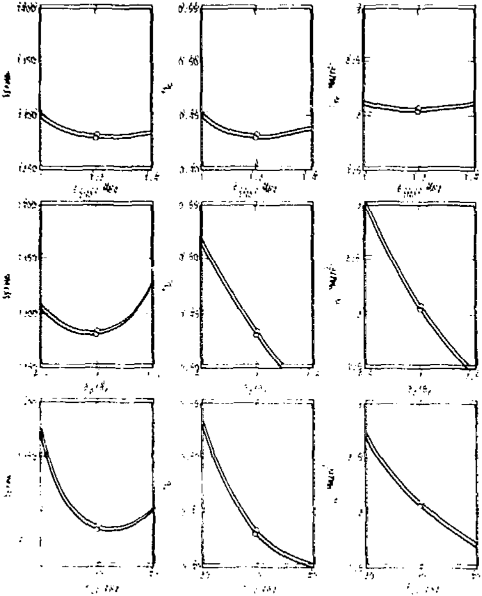

Figure 1

Optimization of the 1000 MWe FBR

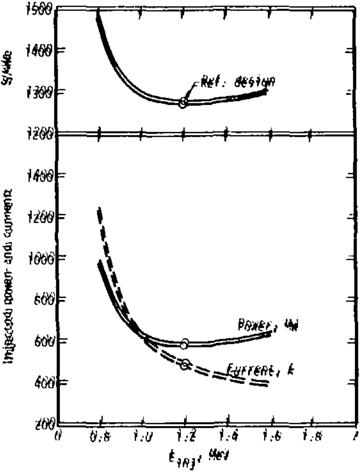

Figure 2

[illegible] Cost vs Injection Energy

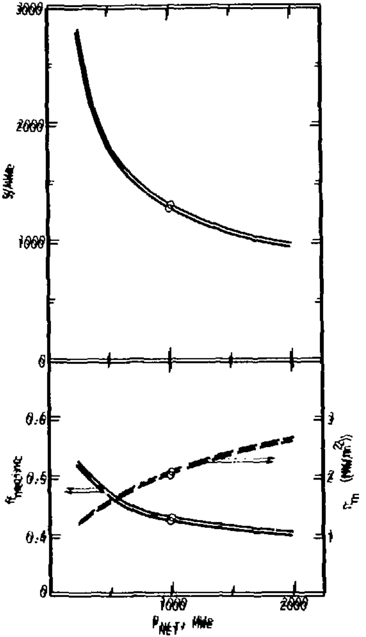

Figure 3

TMR Cost vs Power Output

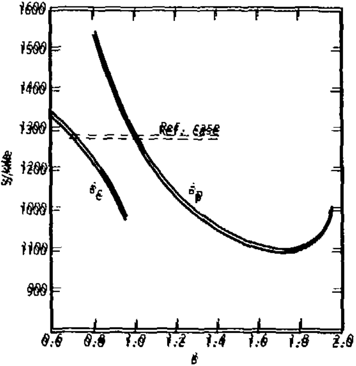

Figure 4

TMR Cost vs Beta

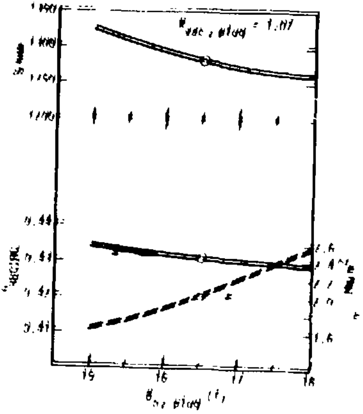

Figure 5

[illegible] Cost vs Plug Field Strength

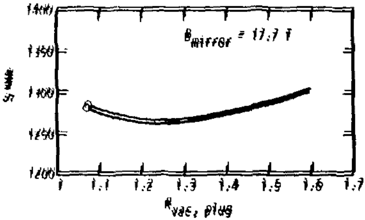

Figure 6

TMR Cost vs Plug Mirror Ratio

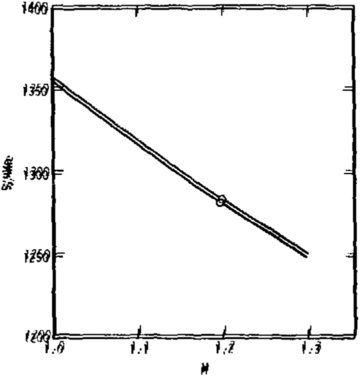

Figure 7

TWR Cost vs Blanket Multiplication

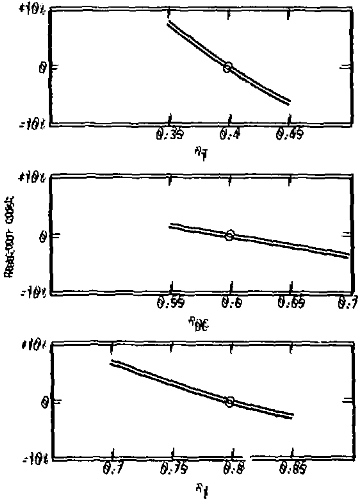

Figure 8

TMR Cost vs Energy Conversion Efficiencies

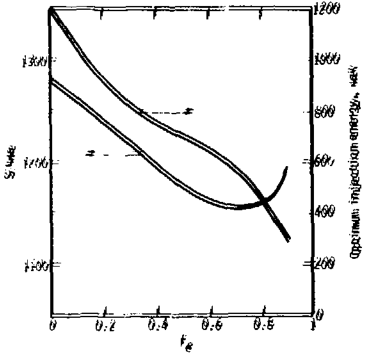

Figure 9

TMR Cost vs Fraction of Heating Direct to Electrons