

Lawrence Livermore Laboratory

Tandem Mirror Reactors

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TANDEM MIRROR REACTORS

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Abstract

Preliminary fusion reactor designs have been developed based on the tandem mirror confinement concept. These have included a 1000 MWe fusion power reactor and a nearer term fusion-fission hybrid reactor with reduced plasma confinement and technology requirements.

For the fusion power reactor we assume classically confined mirror plasmas in the plugs and use energetic neutral beam injection for the plug plasmas only. The injection energy is 1.2 MeV, the plug magnetic field strength is 17 T, and the central cell length is 100 m. The parameters of the reactor were optimized to obtain the minimum capital cost per unit of net electric power. The plasma Q for the optimized reactor was found to be near 5 and the direct capital cost was estimated to be \$1300/kWe. Auxiliary direct heating of electrons could lower the optimum neutral beam injection energy to about 500 keV. Two approaches which would yield both lower cost per unit power and higher optimum Q are to design for increased power output and to design a less expensive central cell.

For the tandem hybrid reactor we propose to use neutral beam-sustained, stream-stabilized plugs (as in 2XIIB) and also to inject energetic deuterium beams into a cold tritium target plasma confined electrostatically in the central cell (two component operation). With 200 keV injection and 12 T plug coils we predict a plasma Q near unity and a fusion power of 500 MW in a reactor with a 50 m central cell length. We believe that a tandem mirror with these parameters can be a commercially viable fissile-fuel producing hybrid.

The TMX experiment will operate in early 1979 as a proof-of-principle demonstration of the tandem mirror concept, and an upgraded MFTF experiment with a second standard mirror cell and a connecting solenoid is being considered as the next tandem experiment. A pilot plant version of the tandem hybrid reactor (somewhat smaller and lower technology than the commercial version) is one possible embodiment of the "mirror next step" presently being investigated at LLL and proposed for a beginning construction date of 1985.

Introduction

At Livermore we have developed preliminary fusion reactor designs

based on the tandem mirror confinement concept. These have included a 1000 MWe fusion power reactor and a nearer term fusion-fission hybrid reactor with reduced plasma confinement and technology requirements. In this paper I will discuss our analytic models for these reactors, the parametric studies which led to the reactor parameters, and some of the details of the reactor designs. The 1000 MWe tandem mirror power reactor is discussed in much more detail in Ref 1.

Tandem Mirror Fusion Reactor

Our analytic model for the tandem mirror fusion reactor (TMR) begins with a simple, self-consistent description of tandem mirror physics, as derived by Logan.^[1] The physics model relates the densities, energies, and containment times of the ions and electrons in the plugs and central cell. The plugs are assumed to be mirror machines having classical end losses and sustained by the injection of high-energy neutral beams of deuterium. The central cell is fueled by low-energy neutral beams of deuterium and tritium. Electrons heated by the energetic ions in the plugs in turn heat the cold ions in the central cell. The central cell ions are also heated by alpha particles. The ion densities in the plugs and central cell, n_p and n_c , are related to the vacuum magnetic fields, B_p and B_c , by pressure balance and the plasma betas β_p and β_c . The relative radii of the plug and central cell plasmas are determined by conservation of magnetic flux through the machine. The electron temperature and the density ratio between the plugs and central cell determine the amount by which the plug plasma potential exceeds the central cell potential:

$$\phi_c = T_e \ln(n_p/n_c)$$

Ion confinement in the potential well of the central cell is calculated using an analytic formula by Pastukov.^[2]

$$(n\tau)_c \propto T_i^{3/2} \frac{\phi_c}{T_i} \exp\left(\frac{\phi_c}{T_i}\right) = T_i^{3/2} \frac{T_e}{T_i} \left(\frac{n_p}{n_c}\right)^{T_e/T_i} \ln\left(\frac{n_p}{n_c}\right).$$

The equations of the physics model can be self-consistently solved in a number of ways. We find it most convenient to specify the plug injection energy, the plug mirror ratio, the mirror ratio between the plugs and the central cell, the plasma β in the plugs and in the central cell, and the temperature of the central-cell ions. The physics output then consists of the various energies, containment parameters ($n\tau$'s), density

ratios, the plasma volume ratio between the central cell and plugs, and Q (thermonuclear power divided by trapped injected power).

Next, we determine the particular reactor design. First, specification of a single magnetic field strength (usually the central field of the plug) 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 (of 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 dimensioning of the reactor. The plug magnets are designed to provide the specified magnetic field and to be large enough to contain the plug plasma. The design of the central cell begins at the cylindrical first wall (three alpha gyroradii away from the plasma) and proceeds outward through the blanket, shield, magnet, support structure, handling and maintenance equipment, and finally the reactor building. The plant design is completed by sizing the injectors, the direct converters, and the thermal conversion system.

Estimates of direct capital costs for all elements of the power plant permit an estimate of the cost of power. The cost of the central cell tends to be dominant and is therefore the most carefully evaluated. The other major systems of the power plant which are costed are the plugs and the thermal conversion, direct conversion, and injection systems. As an economic figure of merit, we add all of the 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.

We chose to specify a net electric power of 1000 MW(e) for the TMR point design. Other input parameters held constant in our search for an optimized point design were as listed in Table I.

The remaining input parameters that must be specified in order to calculate a TMR design are the injection energy, the temperature of the central-cell ions, and the vacuum mirror ratio between the center of the plug and the central cell. We varied these three parameters in our search for an optimized point design. The minimum cost of $\$1280/kW(e)$ occurs

for : Injection energy = 1.2 MeV
 Central-cell ion temperature = 30 keV
 Plug-to-central cell $R_{vac} = 7.0$

We chose this minimum cost design as the TMR point design. I will discuss some of the characteristics of this point design and return later to a discussion of the implications of the optimization for further improvements in the TMR.

The plasma characteristics of the optimized point design are given in Table II. Some physical characteristics of the reactor are given in Table III. The power-flow quantities are shown in Fig. 1.

Figure 2 shows an overall view of the TMR. The reactor is composed of a power-producing central cell, end-plug magnets, 1.2-MeV D^0 injectors to sustain the end-plug plasma, and direct converters at each end to recover the charged particles that leak out the ends. The power-producing section is a 100-m-long cylinder. The energy-recovery blanket is in the cylindrical section, and only shielding is provided in the plug region. The reactor is modular in construction, with sections of the solenoidal magnet, cylindrical blanket, and vacuum chamber all being of modest size. The blanket is helium cooled with a standard, high-temperature, gas-cooled, reactor power-conversion system. Waste heat is dumped into the atmosphere via wet cooling towers.

The central cell magnets are simple solenoids of low magnetic field strength (2.4 T). They are wound of niobium-titanium superconductor. The plug magnet shown in Fig. 3 is a hybrid superconducting and cryogenic magnet. The complex-shaped Yin-Yang magnet is about the size of the MFTF magnet. It is a normal coil wound of high purity aluminum conductor and cooled to cryogenic temperatures by gaseous helium. The Yin-Yang coil set carries about 12% of the total current in the plug coil system. The Yin-Yang coil incorporates an internal support structure that transmits the magnetic forces to an external structure (not shown). The internal structure is necessary to limit the compressive stress on the relatively weak aluminum conductors. Surrounding the Yin-Yang coil are a pair of niobium-tin superconducting solenoids which carry 88% of the total current in the plug coil system. The outside diameter of these coils is 11 m. The magnetic forces of the solenoids are restrained by periodic bands of stainless steel.

The plug magnet design requires additional work, and, in fact, we may finally decide against the hybrid superconducting and cryogenic design

described here. In future work we will consider an all-superconducting approach. Reasons for continued effort on the plug magnet design are:

- We found that thicker shielding will be required to limit the neutron-induced resistivity change in the aluminum conductor.
- The internal structural support for the aluminum Yin-Yang is a difficult problem.
- Our parametric analysis has shown that somewhat lower plug magnetic fields may be acceptable. For example, reducing the plug central field from 16.5 T to 15 T increases the plant unit cost by only 3 or 4%.

Figure 4 shows the conceptual design of a 120 A, 1.2 MeV D^0 injector for the TMR plug. Each plug of the TMR requires 2 of these injectors. The negative ions are produced from a 2 keV beam of positive ions by double charge-exchange in a cesium vapor cell. They are then accelerated to the final energy and neutralized in a cesium plasma stripping cell. The large injector assembly has walls which are covered with continuously regenerating cryopanel for gas pumping and a complex set of high-voltage electrostatic shields that inhibit voltage breakdown.

Now I will return to a discussion of our parametric study of the TMR. Parameter optimization for minimum cost involves tradeoffs between good power balance (as measured by high Q or, more directly, by a low recirculating power fraction) and high power density (as measured by neutron first wall loading or fusion power per unit of central cell length). The optimization of the plug to central cell mirror ratio, B_p/B_c , is illustrated in Fig. 5. The minimum cost occurs at $B_p/B_c = 7$, where Q is 4.8 and the fusion power per unit length is 25 MW/m. Similar optimizations were calculated for the plug mirror ratio, the central cell ion temperature, and the injection energy.

The optimum injection energy was found to be 1.2 MeV. The optimum is rather shallow for injection energies between 1.0 and 1.4 MeV, but the performance of the TMR degrades rapidly for lower energies. At 800 keV injection energy, Q has dropped to 2.9. At still lower injection energies, Q drops precipitously, primarily because the plugs can no longer support a large central-cell plasma at fusion temperatures. At 650 keV injection energy, Q is only 0.5 and the reactor can no longer produce net power.

One way to reduce the required neutral beam energy in the plugs is to somehow directly heat the electrons. In our investigation of the effect

of electron heating, we assumed that the electrical efficiency of such heating as well as its cost per unit power is the same as for the neutral-beam injectors. Figure 6 shows the optimum neutral-beam energy and the predicted cost of optimized 1000 MWe reactors as function of f_e , the fraction of the total heating that goes directly to the electrons. For our point 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 \$1160/kWe. The neutral-beam injection energy for this optimized reactor is 500 keV.

We have investigated the design of tandem mirror reactors with net power outputs greater than 1000 MWe. Figure 7 shows that the direct capital cost of optimized designs decreases with increasing power output, from \$1280/kWe at 1000 MWe to \$760/kWe at 5000 MWe. Note that the figures of merit for power balance and power density, Q and fusion power per unit length, both improve with power output. Q for the optimized 5000 MWe design is 6.4. This higher power reactor has a central cell length of 250 m.

Another way to achieve a less expensive TMR is to somehow design a less expensive central cell. We investigated the potential effect of this approach, but in the context of two other changes in our parametric model. The other changes were prompted by the conceptual design study of the 1.2 MeV injector which predicted an efficiency of 0.73 (instead of 0.8 as used in our previous calculations) and a cost about double the previously estimated value of \$200 per kW of injector input power. Figure 8 shows that with the lower injection efficiency and higher cost, the cost of power for an optimized design increases if the central cell cost remains the same. This optimized reactor has a higher Q but a lower fusion power per unit length than the original design. If the cost of the central cell per unit length is decreased, then the cost of power for optimized designs decreases. For these cases the optimum designs have higher Q and lower power density. If the central cell cost is halved, the original cost of power is reached again, and Q is 8.2. If the central cell cost is reduced to 1/3 the original cost, Q for the optimum design exceeds 10. Future work will investigate the possibilities for less expensive central cell design.

Tandem Mirror Hybrid Reactor

We have selected a two component mode of operation for a tandem mirror hybrid reactor to minimize plasma confinement and technology requirements.

For this mode of operation energetic deuterium is injected into the plugs and central cell; cold tritium is provided to the central cell. The deuterium is mirror confined in the central cell, and the tritium is electrostatically confined by the plug potentials. The reactor parameters are adjusted in such a way that the total end losses exactly match the streaming plasma requirement for suppression of the DCLC instability.

We have constructed a point model to calculate plasma properties for the two component tandem mirror (TCTM). For the central cell, standard rate equations have been used to calculate energy transfer between the hot deuterons, alphas, cold tritons, and electrons. The deuterons and alphas are assumed to be mirror confined for a cooling time on the tritons and electrons. The triton electrostatic lifetime is calculated using analytic formulas by Pastukhov with the central cell potential well depth given by $\phi_c = T_e \ln (n_p/n_c)$, where T_e is the electron temperature and n_p/n_c is the ion density ratio between the plug and central cell. The plug ions are assumed to have a mean energy E_p equal to their injection energy and a lifetime equal to the ion-electron drag time, as seen in the 2XIIB experiment in the presence of ion-cyclotron fluctuations. Coefficients in this simple point model have been adjusted to give agreement with Fokker-Planck calculations.

A crucial feature of the TCTM physics model is the constraint that the total end losses exactly match the streaming plasma requirement for suppression of the DCLC instability. Theory and recent 2XIIB experiments have led to the following formula for predicting the minimum required flux of ions streaming through the midplane of a mirror confined plasma:

$$J_{\min} = 1.24 \times 10^{-15} \left(\frac{5.5 T_e + \phi_c}{T_e} \right)^{3/2} \frac{n_p T_e^{3/2}}{\sqrt{A_i} (R_p - 1) E_p} C \left(\frac{3}{S} \right)^\gamma \text{ A/m}^2,$$

where A_i is the mass number of the streaming ions, R_p is the plug mirror ratio (as enhanced by the finite beta), and S is the ratio of plug plasma radius to ion gyro radius. We make the following estimates for C and γ :

for $S < 7$, $C = 1$ and $\gamma = 4/5$
 and
 for $S > 7$, $C = 1.76$ and $\gamma = 2$.

Thus, the streaming flux requirement decreases with increasing S , and decreases more rapidly for S greater than 7. The streaming flux consists of all the ions leaking through the plug, but the relatively poorly confined cold tritium in the central cell typically provides 80 to 90% of

the total. Thus, for a given reactor geometry, the streaming flux requirement is satisfied by a particular flux of tritium end loss, J_T , which in turn is determined by the tritium density and lifetime:

$$J_T = \frac{en_T^2 \pi r_c L_c}{(n\tau)_T \pi r_p^2} .$$

Additional discussion of the TCTM physics model can be found in References 3 and 4.

The analytic physics model for the TCTM has been used to investigate parameter space for hybrid reactors based on the concept. For a commercial TCTM hybrid our goal has been to obtain $Q > 1$ and a fusion power of 500 MW in a machine which is less than 100 m long. We believe that such a hybrid reactor can be economically viable. As a tentative point design case we have chosen a central cell length of 50 m, a maximum magnetic field strength of 12 T and a neutral beam injection energy of 200 keV. Other parameters for this case are given in Table IV. Q is predicted to be 1.1 and Q_{eff} , defined as Q times the neutral beam trapping fraction, is 1.0.

As indicated in Table IV, the central cell magnetic field strength, B_c , and the radius of the plug plasma (measured in ion gyroradii), S , have been optimized to maximize Q_{eff} . These optimizations were for each case shown in Fig. 9, which plots Q and Q_{eff} vs. L_c , E_{inj} , and $B_{o,p}$, with fusion power held constant at 500 MW. Choosing the best reactor design from Fig. 9 would involve a complete economic evaluation which we have not yet attempted for the TCTM hybrid. However, Fig. 9 gives several valuable insights:

- Reactors with central cell lengths shorter than 50 m suffer almost no penalty in Q_{eff} , but will have increased fusion power per unit length.
- Above 200 keV, increased neutral beam penetration prevents Q_{eff} from increasing.
- Plug central field strengths in excess of 7 T will increase Q_{eff} , and the optimum value must be found from detailed consideration of plug magnet design and cost.

We have not yet carried out any detailed component design work specific to the TCTM hybrid, but we have considered some of the general reactor design features. Figure 10 shows an overall view of a TCTM hybrid (with a 25 m central cell length instead of 50 m as discussed above). The general arrangement of components is much the same as for the 1000 MWe

tandem mirror fusion reactor. For the hybrid, concrete walls separate the highly radioactive central cell from the rest of the reactor. Entire central cell modules are moved on air-pads through a sliding shielding door into a blanket service area for recovery of the bred fissile fuel. A previously assembled and pressure tested module is similarly moved into the reactor room for replacement of the removed unit.

Conclusion

Although our conceptual designs are of a preliminary nature we believe that attractive fusion reactors can be based on tandem mirror confinement. The possibilities range from relatively near term fusion-fission hybrids producing fuel for fission reactors to central station fusion electric power plants.

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Table I
Parameters held constant in determining an optimized TMR
design, for net electric power of 1000 MWe.

Parameter	Value
Vacuum mirror ratio in plug	1.07
Beta of plug plasmas	1.0
Beta of central-cell plasma	0.7
Fraction of α -particles adiabatically confined	1.0
Vacuum central field of plug	16.5 T
Blanket energy multiplication	1.2
Thermal conversion efficiency	0.4
Direct conversion efficiency	0.6
Injection efficiency	0.8

Table II
Plasma parameters for the TMR point design

Parameter	Value
Injection energy	1.2 MeV
Average plug ion energy, E_p	878 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 $n\tau$	2.5×10^{14} s/cm ³
Central-cell particle $n\tau$	7.7×10^{14}
Central-cell to plugs plasma volume ratio	500
Plug-to-central cell ion density ratio	7.96
$\langle\sigma v\rangle_{DT}$	6.64×10^{-16} cm ³ /s
Plug ion density, n_p	8.57×10^{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	5.41 W/cm ³
First-wall neutron loading, Γ_n	2.06 MW/m ²
Q	4.81

Table III
Physical characteristics of the TMR point design.

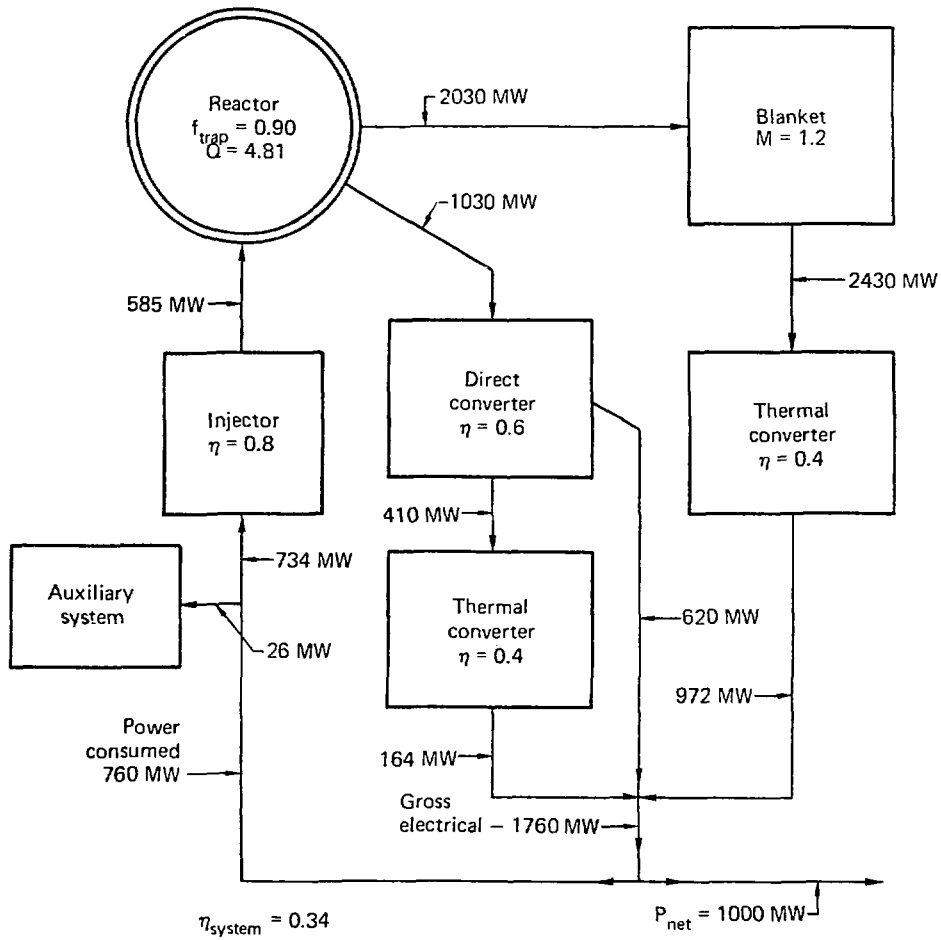
Item	Value
Plug vacuum mirror ratio, $R_{vac, plug}$	1.07
Plug vacuum central field, $B_{o, plug}$	16.5 T
Plug center-to-central cell mirror ratio	7.0
Central-cell vacuum field	2.4 T
Central-cell dimensions:	
Length, L_c	101 m
First-wall radius, r_{fw}	1.56 m
Outside radius	4.52 m

Table IV
Parameters for a two component tandem mirror hybrid

Plugs:	Stream stabilized
	$S = r_p/\rho_i = 16$ (optimized for maximum Q_{eff})
	$\beta_p = 0.7$
	$E_{inj} = 200$ keV
	$B_{max} = 12$ T ($B_{o,p} = 7$ T, $R_{vac} = 1.3$)
Central Cell:	
	$L_c = 50$ m
	$\beta_c = 0.8$
	$E_{inj} = 200$ keV (D)
	Cold-fueled T
	$B_c = 1.4$ T (optimized for maximum Q_{eff})
Performance:	
	$Q = 1.11$
	$Q_{eff} = 1.01$
	Fusion power = 500 MW = 10 MW/m
	First wall neutron loading = 2.2 MW/m ²

FIGURES FOR TANDEM MIRROR REACTORS

1. TMR power flow diagram
2. Tandem Mirror Reactor
3. Plug coil for TMR
4. 1.2 MeV injector for TMR
5. Optimization of plug to central cell mirror ratio
6. Optimum neutral-beam injection energy and predicted cost of optimized 1000-MW(e) TMR's as functions of f_e , the fraction of the total heating that goes to the electrons.
7. Optimum TMR designs for various power outputs
8. The effect of central cell cost on optimum TMR designs
9. Parameter variations for Tandem mirror hybrid reactors with 500 MW fusion power.
10. Tandem Mirror Hybrid Reactor



$$\text{Recirculating power fraction} = \frac{\text{power consumed}}{\text{gross electrical}} = 0.43$$

Figure 1
 TMR power flow diagram.

TANDEM MIRROR REACTOR

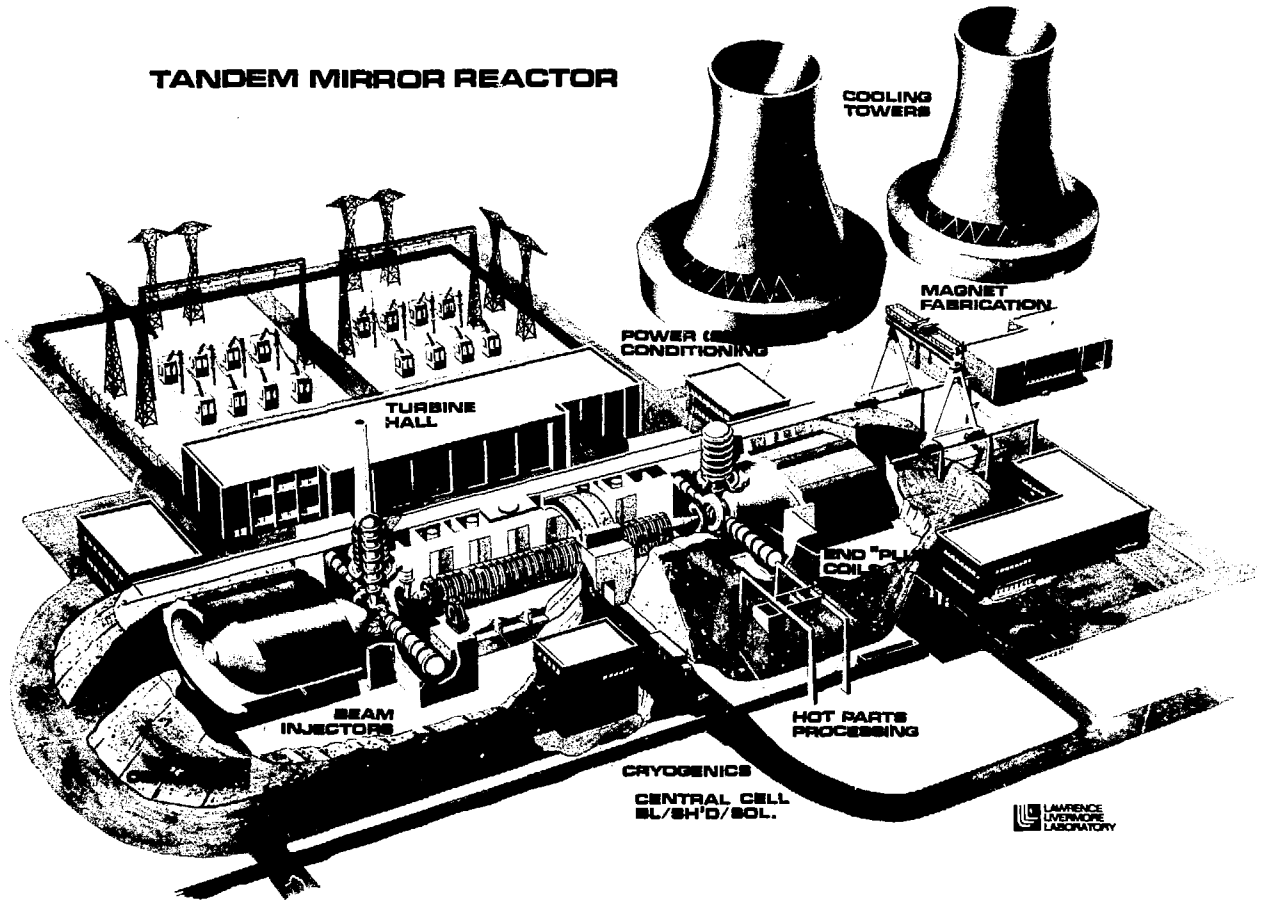
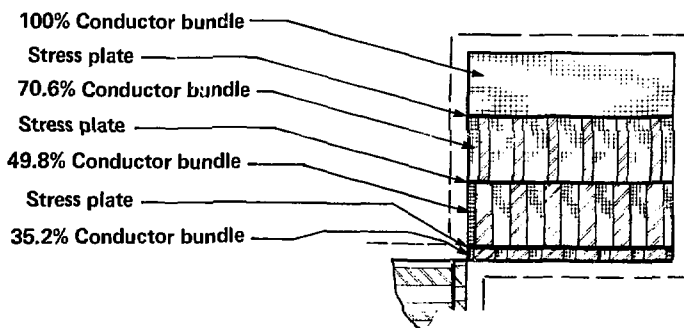
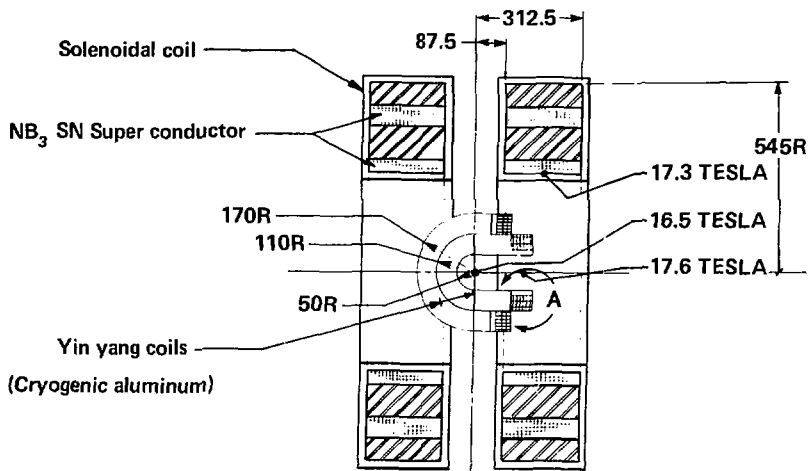


Figure 2

T-M-R PLUG COIL SET



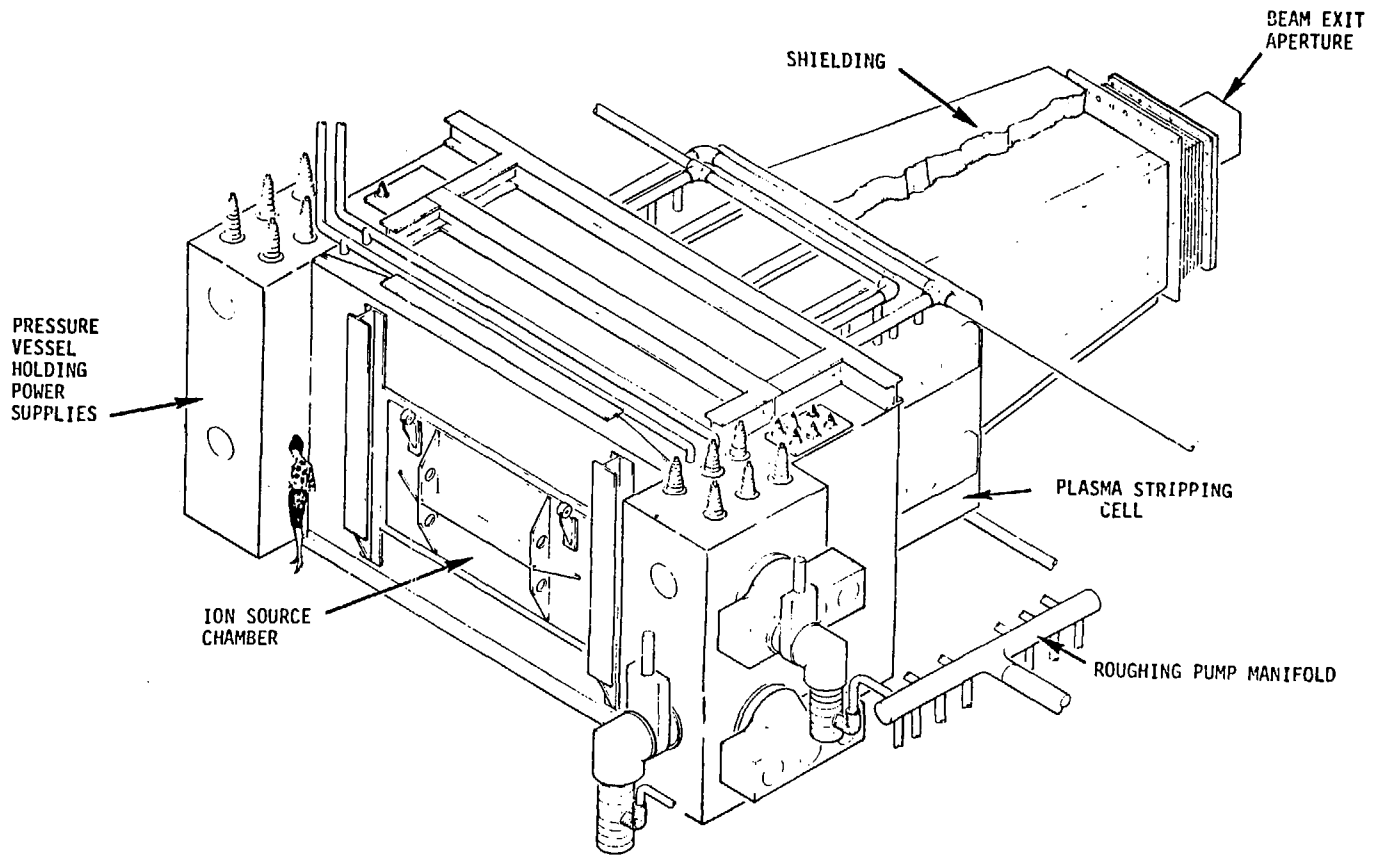
16.5 TESLA



Detail A

Figure 3

Figure 4
1.2 MeV Injector for TMR



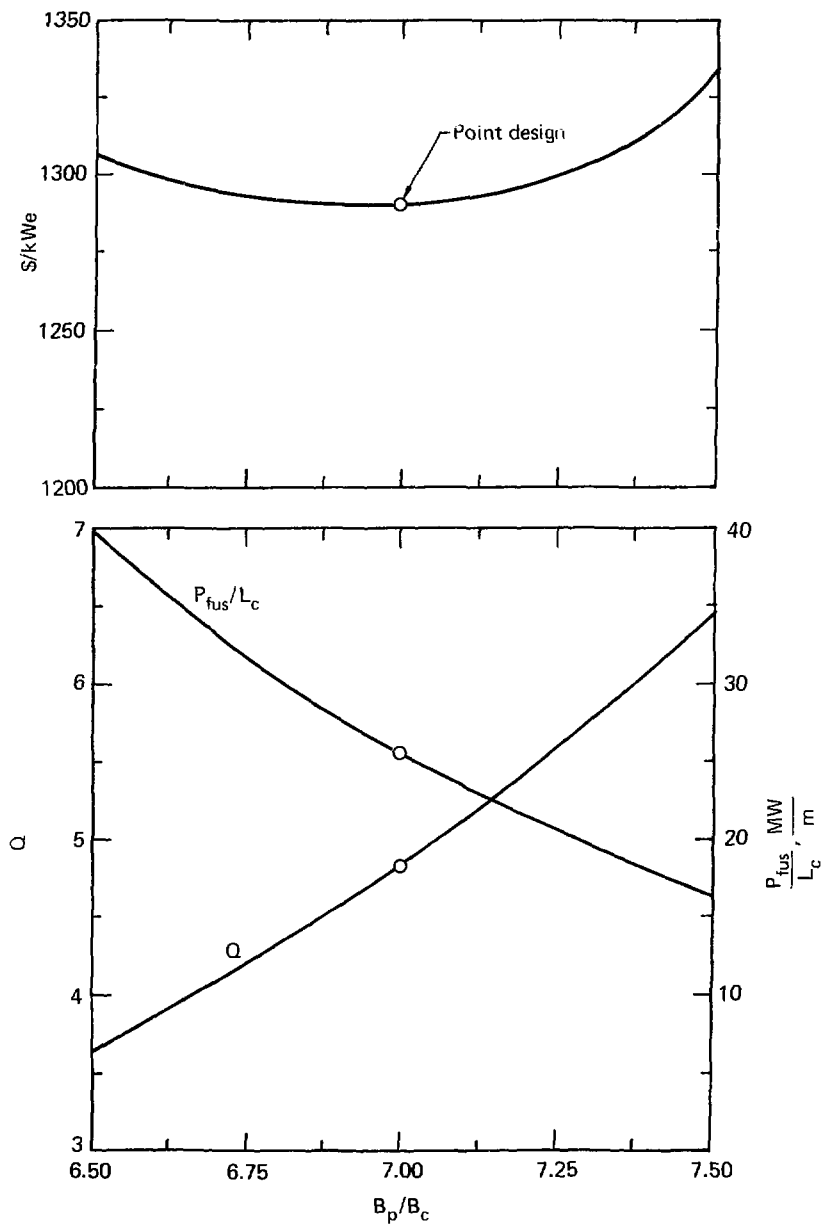


Figure 5
 Optimization of plug to central cell mirror ratio.

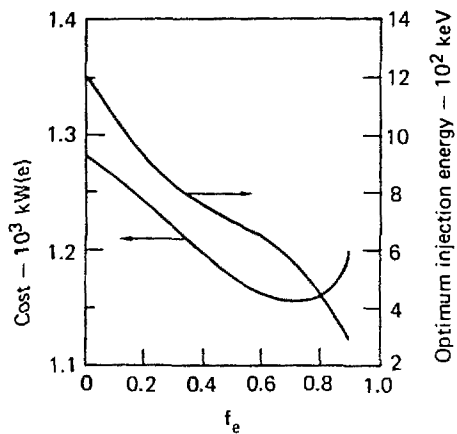


Figure 6. Optimum neutral-beam injection energy and predicted cost of optimized 1000-MW(e) IMR's as functions of f_e , the fraction of the total heating that goes to the electrons.

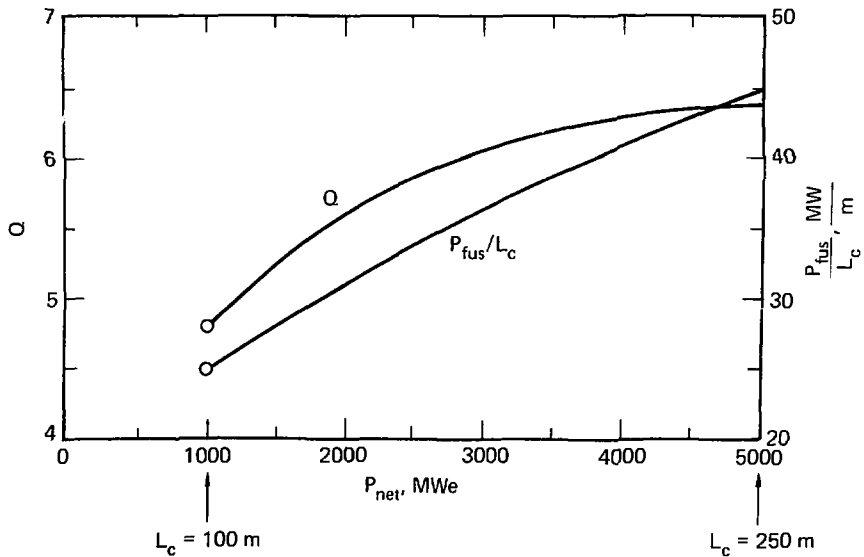
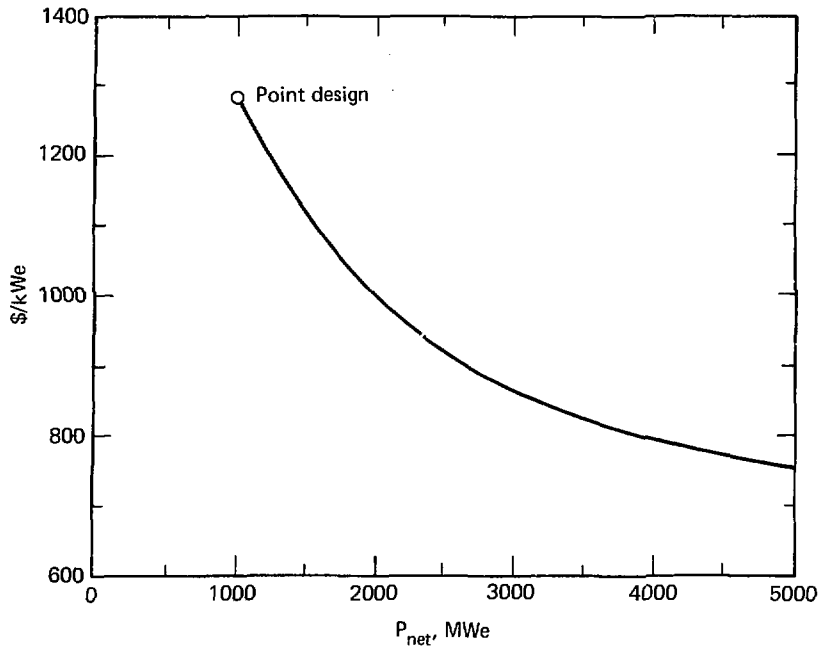


Figure 7
Optimum TMR designs for various power outputs.

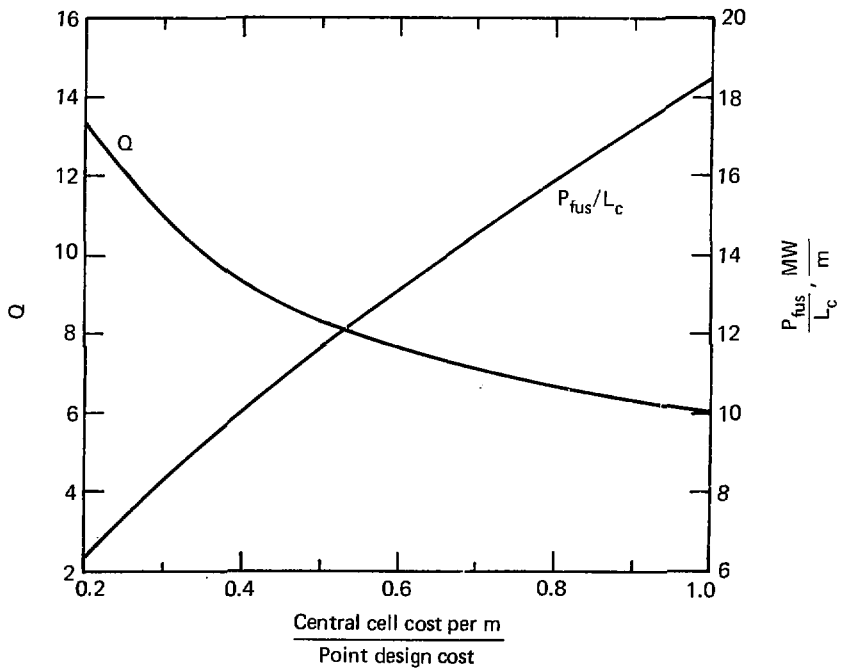
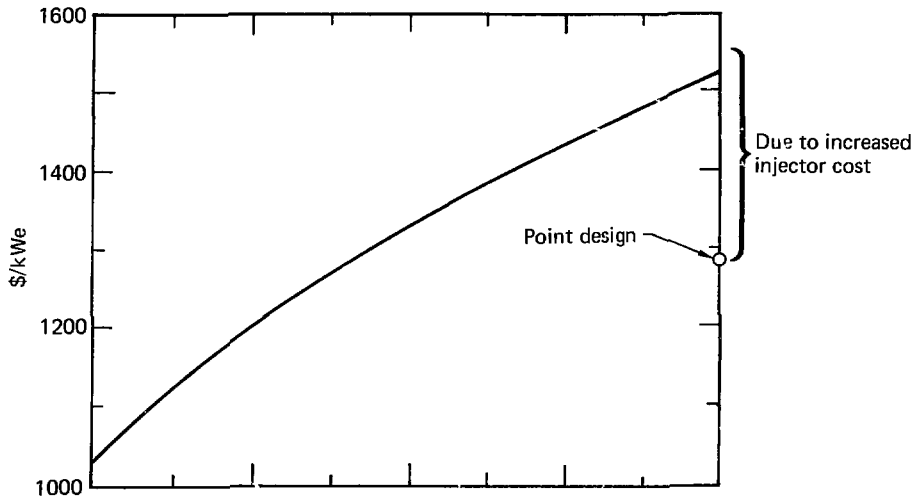
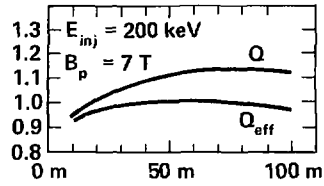
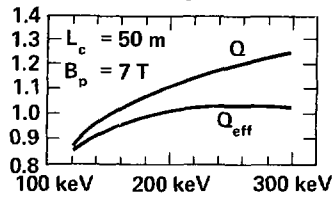


Figure 8

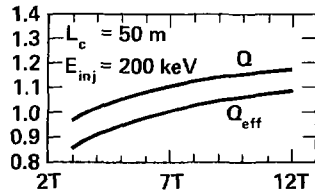
The effect of central cell cost on optimum TMR designs.



L_c



E_{inj}



B_p

Figure 9

Parameter variations for tandem mirror hybrid reactors with 500 MW fusion power.

TANDEM MIRROR HYBRID REACTOR

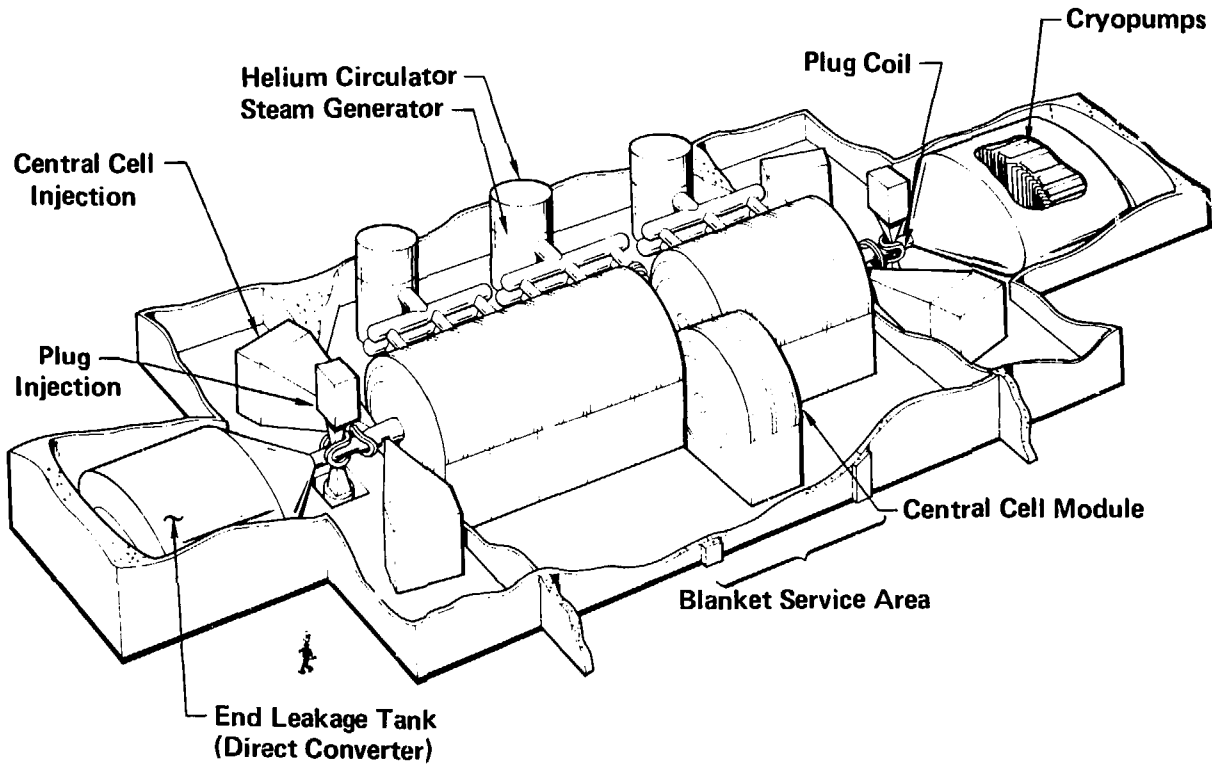


Figure 10