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FUSION TECHNOLOGY INSTITUTE

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I. Introduction

The recently completed tandem mirror reactor study, WITAMIR-I, contains a detailed cost analysis at a reference point.(1) Motivated by the existence of that analysis we have developed a model to obtain the dependence of cost on the most important variables. Reactor parameters are varied using POWBAL, an equilibrium power balance code based on physics described in ref. 1. Then, POWBAL output plus cost parameters are fed into the subroutine COST. We limit the analysis to configurations similar to WITAMIR-I, expanding costs about the reference point. This is a simplified model that allows for parametric studies without necessitating the detailed evaluation done for the reference design. It is useful in setting design parameters that minimize the cost of electricity as well as in analyzing the relative importance of the different parts of the plant.

II. Cost Analysis

1. Reference Design

WITAMIR-I is an inside barrier tandem mirror reactor, described in detail in ref. 1. One boundary of the barrier region is formed by a large solenoidal magnet placed between the central cell and yin-yang plug. This differs from an A-cell barrier tandem mirror where no large solenoid appears and an extra C coil is placed outside of the yin-yang. The WITAMIR-I magnet configuration is shown in Fig. 1. Axial magnetic field, potential, and density profiles are shown in Fig. 2.

Electron cyclotron range of frequencies (ECRF) heating is used in the plug to heat electrons, and is used in the barrier to create a hot, magnetically trapped electron population. Neutral beam injection in the plug maintains plug density, and is used at two energies in the barrier to charge-exchange pump undesired trapped ions.

Figure 1

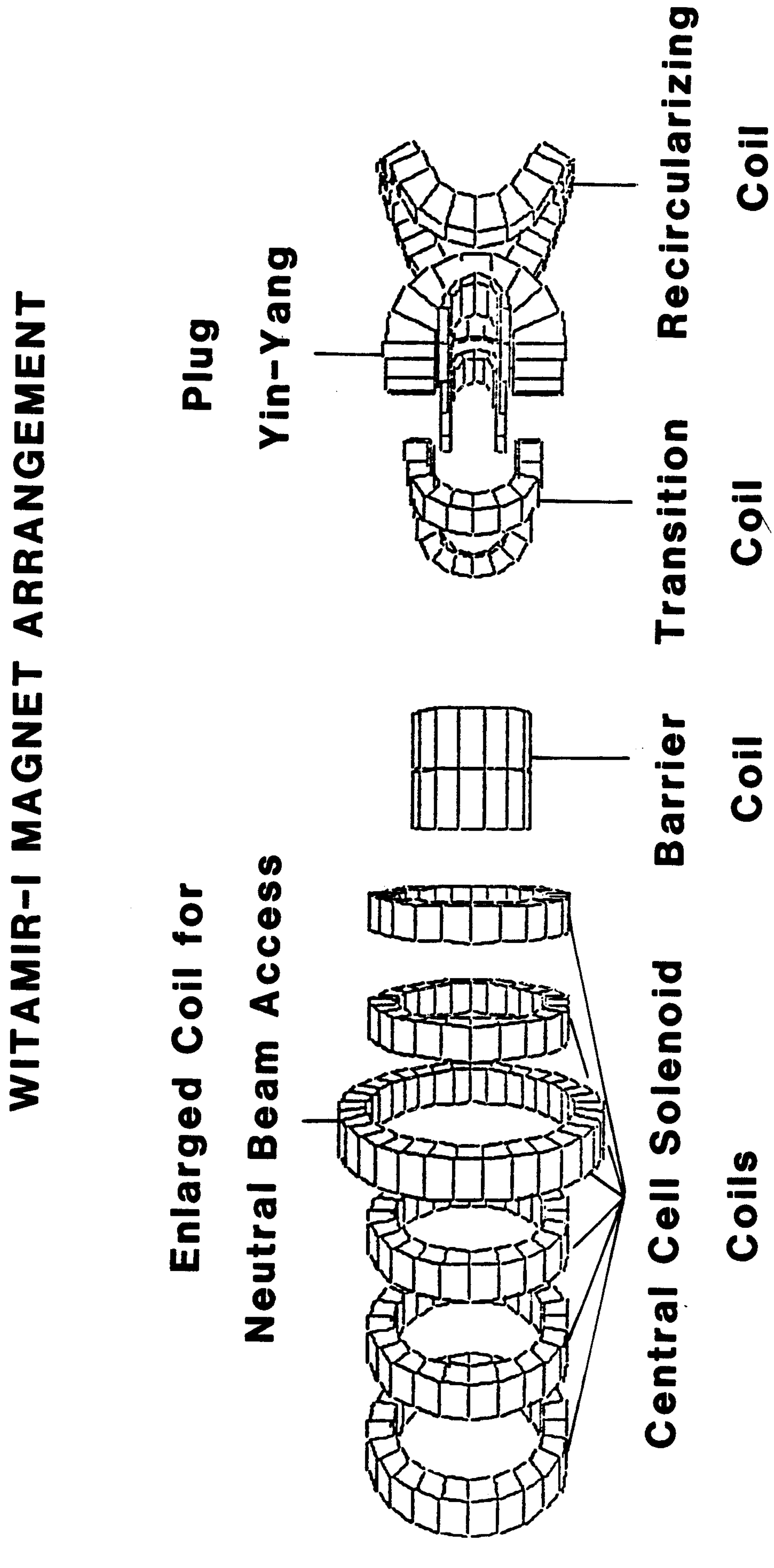
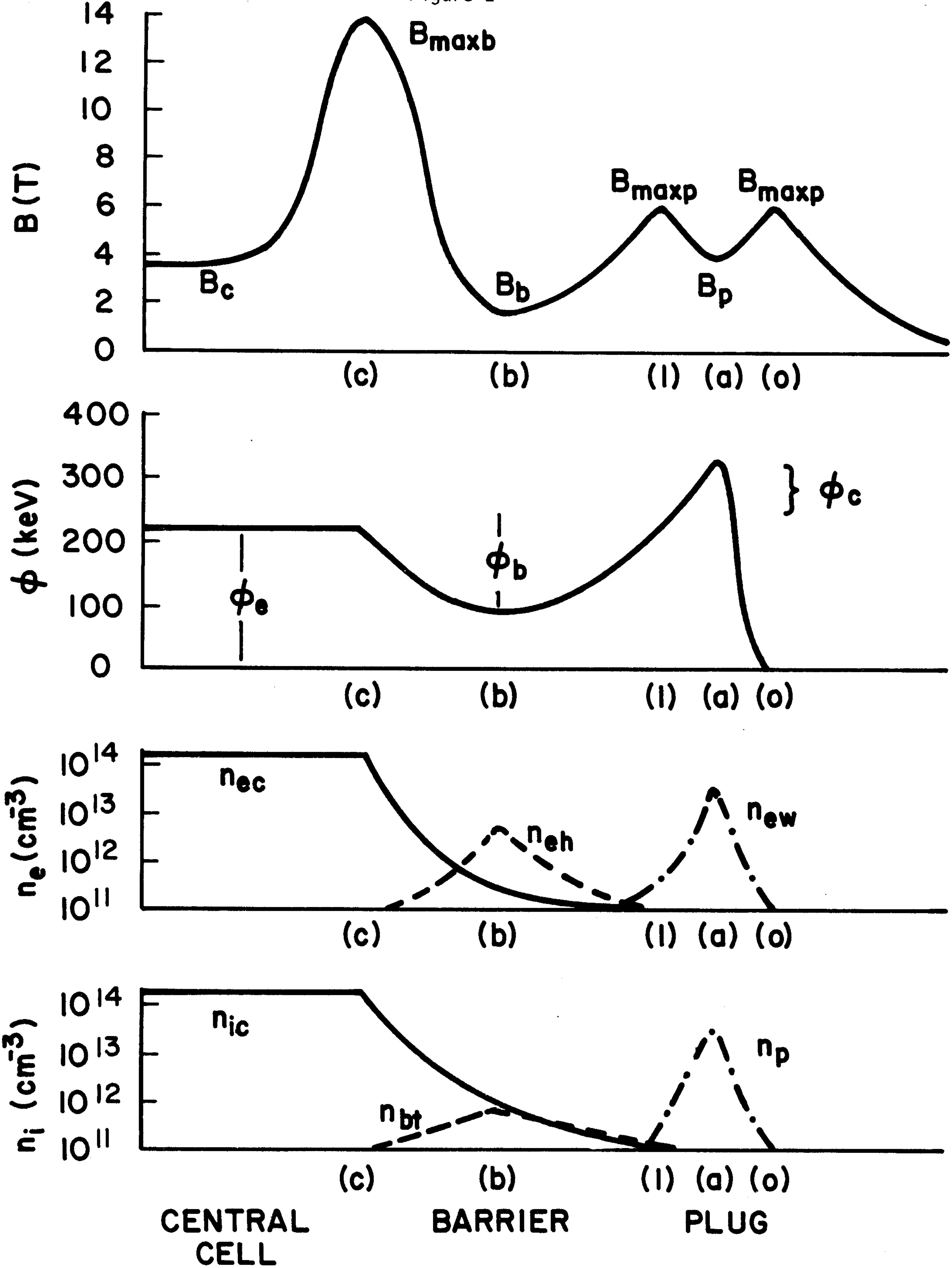

WITAMIR-I MAGNET ARRANGEMENT
Enlarged Coil for
Neutral Beam Access
Plug
Yin-Yang
Recircularizing
Coil
Transition
Coil
Barrier
Coil
Central Cell Solenoid
Coils

Figure 2


B(T)
Bmaxb
Bmaxp
Bmaxp
Bc
Bb
Bp
(c)
(b)
(l)
(a)
(o)
φ (keV)
φc
φb
φe
ne (cm-3)
nec
neh
new
ni (cm-3)
nic
nbt
np
CENTRAL CELL
BARRIER
PLUG

The underlying physics is described in ref. 1 and will not be reproduced here. Machine, power, and plasma parameters for the WITAMIR-I reference design are given in Tables I and II.

2. Model

We evaluate the cost of central cell, barrier and plug magnets, power systems and reactor building. The cost of other parts of the plant has been scaled from the estimate done for the reference design using the net electric power of the new design. The general outline of this analysis is similar to that of ref. 2. The methodology for the reference design cost estimate follows the guidelines proposed by the DOE.[3] The unit costs used in this study are the same as the ones used in WITAMIR-I. The basis for the unit costs comes from ref. 4 and from best educated guesses for price reductions on extrapolated technologies within a fully developed fusion economy operating in the year 2020.

In the central cell we analyze the blanket, shield, reflector, vacuum chamber and magnets. Materials, volumetric fractions, densities and unit prices of the reference design are kept constant, as are the thicknesses of the blanket, shielding, reflector and vacuum chamber. Variables are the first wall radius, length and thickness of coils and coil structure. The simplified model for the central cell of the reference design is given in Table III.

To obtain the thickness of the coil and coil structure a simplified model of the central cell solenoid is used. It keeps constant the basic coil structure and density of each material. The thickness of each layer is then scaled by:

Inner and Outer Structure:

$$t_{cs} = t_{cs}^{r} \times \left(\frac{B_c}{B_c^r}\right)^2 \times \left(\frac{r_{cs}}{r_{cs}^r}\right)^3$$

Table I

Model Reactor Power and Machine Parameters

Powers Are Given As Absorbed Plasma Power Without Efficiencies Folded In

Parameter	Value
Q	28.0
Fusion power	3000 MW
Neutron wall loading	2.4 MW/m^2
Central cell power density	11.3 MW/m^3
Plug ECRF power	16.5 MW
Plug neutral beam power at 500 keV injection	2.4 MW
Plug trapping fraction	0.13
Barrier ECRF power	33.3 MW
Barrier neutral beam power at 9.6 keV injection	12.7 MW
Barrier neutral beam power at 190 keV injection	42.5 MW
Central cell surface heat load	2.75 W/cm^2
Plug surface heat load	3.43 W/cm^2
Barrier surface heat load	50.0 W/cm^2
Central cell wall radius	0.97 m
Central cell length	165 m
Barrier length	10. m
Plug length	5.5 m
Central cell magnetic field	3.6 T
Barrier maximum field	14. T
Barrier minimum field	1.4 T
Plug maximum field	6.0 T
Plug minimum field	4.0 T

Table II

Model Reactor Plasma Parameters

Central Cell	
Density	1.51×10^{14} cm^{-3}
Ion temperature	32.5 keV
Electron temperature	32.8 keV
Potential, ϕ_c	102. keV
Beta, β_c	0.40
Plasma radius	0.72 m
$(n\tau)_{ic}$	7.8×10^{14} sec cm^{-3}
Barrier	
Density average	6.9×10^{12} cm^{-3}
Mean hot electron energy, E_{eH}	270. keV
Passing electron fraction, F_{ec}	0.27
Pumping parameter, g_b	2.0
Pumping fraction at low energy	0.95
Pumping fraction at high energy	0.05
Potential, ϕ_b	141. keV
Beta, β_b	0.235
Plasma radius average	0.59 m
Plug	
Density average	2.7×10^{13} cm^{-3}
Mean ion energy	905. keV
Electron temperature	123. keV
Potential, $\phi_c + \phi_e$	326. keV
Cohen parameter, ν_c	0.5
Beta, β_p	0.64
Plasma radius	0.77 m
$(n\tau)_{ip}$	9.8×10^{13} sec cm^{-3}

Table III

Simplified Model of Central-Cell (WITAMIR-I)

Plasma Radius = 0.71 m

First Wall Radius = 0.93 m

		Thickness	
Blanket	1st zone	0.098	81.3% Li_{17}-Pb_{83}
			3.4% HT-9
			15.3% void
	2nd zone	0.270	81 % Li_{17}-Pb_{83}
			9% HT-9
			10% void
	3rd zone	0.355	75% Li_{17}-Pb_{83}
			25% HT-9
Reflector		0.285	95% HT-9
			5% H_2O
Shielding		0.600	60% HT-9
			15% Pb
			15% B_4C
			5% H_2O
Vacuum		0.764	
Magnets	Inner structure	0.385	100% high strength Al
	Coil	0.230	3% Nb-Ti
			97% high purity Al
	Outer structure	0.385	100% high strength Al

Coil:

$$t_c = t_c^r \times \left(\frac{B_c}{B_c^r}\right)^2 \times \left(\frac{r_c}{r_c^r}\right)$$

where r_{cs}, r_c, t_{cs} and t_c are the radius and thickness of the coil structure and coil, respectively, B_c is the magnetic field at the axis, and the superscript r denotes the reference design value. The current density and stress of structural material are considered constant.

For each layer of the central cell we model the cost by

$$C_j \text{ (\$1 M)} = \pi \, (r_{j+1}^2 - r_j^2) \sum_m \rho_m \, v_m \, c_m$$

where

j = layer, m = material

ρ, v, c = density, volumetric fraction and unitary cost in \$/kg

r_j = radius of the jth layer.

The total central cell cost will be

$$C_{cc} \text{ (\$)} = \sum_j C_j \, L_c$$

where L_c is the central cell length.

For the cost of the barrier solenoid, recircularizer coils (two) and yin-yang magnets at each end of the central cell, we use the following scaling laws:

$$C_{barrier} = C^r_{barrier} \left(2.4 \frac{B_{maxb}}{B^r_{maxb}} - 1.4\right)$$

$$C_{recir.} = C^r_{recir.} \left(\frac{B_{minb}}{B^r_{minb}}\right)$$

$$C_{plug} = C^r_{plug} \left(1.6 \frac{B_{maxp}}{B^r_{maxp}} - 0.6\right)$$

where $B_{max,b}$ and $B_{min,b}$ are the maximum and minimum fields in the barrier; $B_{max,p}$ is the maximum field in the plug and the C^r's are the reference cost of each magnet (see Table IV).

The cost of the reactor building is obtained according to

$$C(\$) = 1{,}600 \times [L_c\ d_c^2 + 2(L_b\ d_b^2 + L_p\ d_p^2)]$$

where L_c, L_b, L_p are the lengths of central cell, barrier and plug and d_c, d_b, d_p are their diameters.

To obtain the cost of the power systems we consider the power flow diagram as sketched in Fig. 3, where:

f_t = trapped fraction of injected power

f_n = fraction of fusion energy carried by neutrons

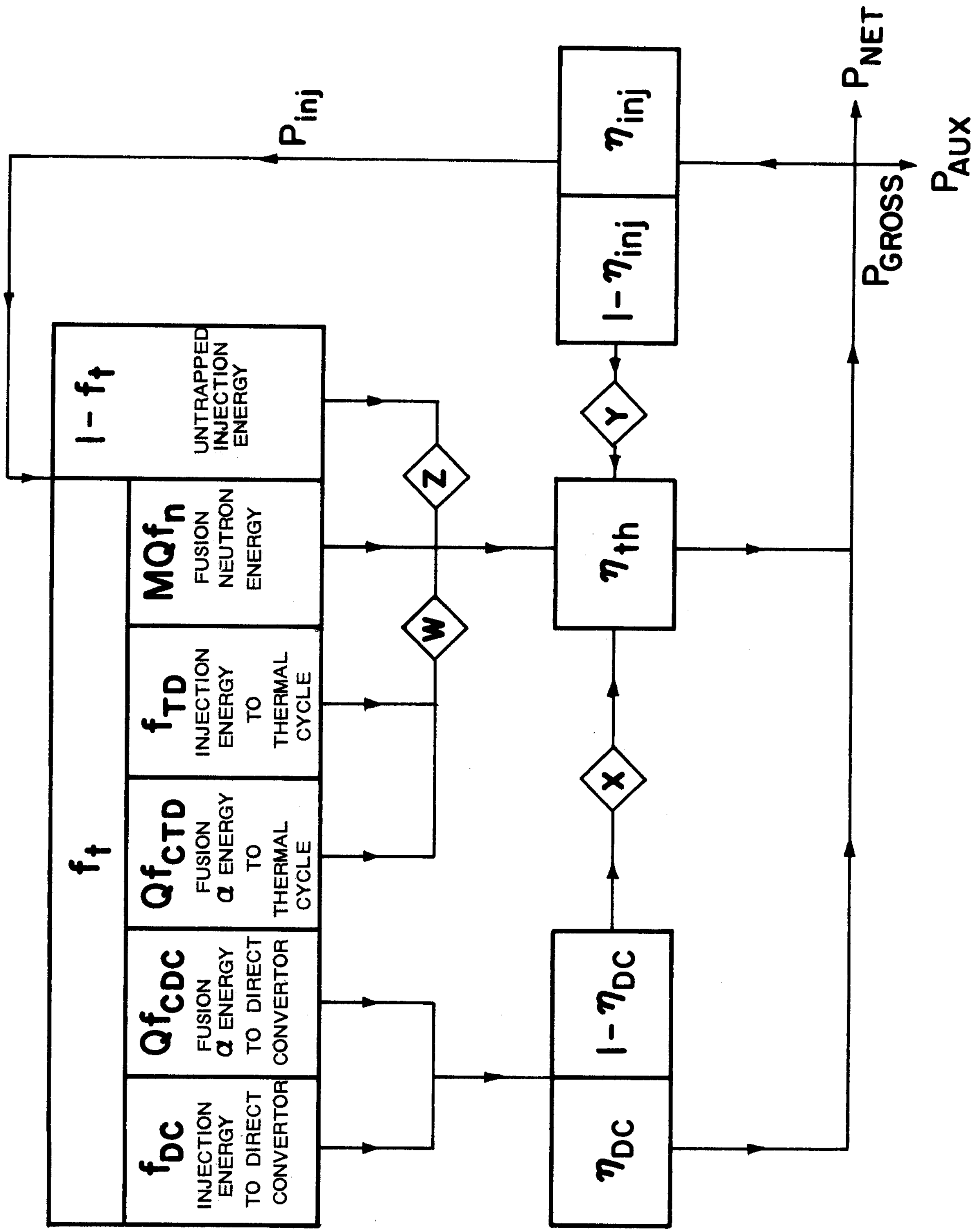
f_{CDC}, f_{CTD} = fraction of fusion energy carried by charged particles that goes to direct converter or thermal dump

f_{DC}, f_{TD} = fraction of trapped injection energy that goes to direct converter or thermal cycle

$\eta_{DC}^{\alpha,i}$, η_{th}, η_{inj} = efficiencies of direct conversion (α,i), thermal cycle and injection

W ≡ switch for recovery of charged particle power into thermal dump

Figure 3



Power Flow

Table IV

Reference Design Cost Analysis Parameters

$$M = 1.37$$

$$\eta_{th} = 0.42$$

$$\eta_{DC} = 0.75$$

$$\eta_{RF} = 0.6$$

$$\eta_{NB} = 0.5$$

$$x = 1,\ y = 0,\ z = 0,\ w = 1$$

$$f_n = 0.8,\ f_{CTC} = 0.13,\ f_{CTD} = 0.07,\ f_{DC} = 0.8$$

$$f_{TD} = 0.2,\ f_{tRF} = 1.0,\ f_{tNB} = 0.13$$

$$P^r_{aux} = 100 \text{ MW}$$

$$P^r_{th} = 4114. \text{ MW}$$

$$P^r_{net} = 1517. \text{ MW}$$

Unitary cost of power systems ($/kW handled)	
Thermal converter	150.
Direct converter	25.
Neutral beam	2,000.
RF system	2,000.

Cost of barrier solenoid = 32 x 10^6 each

Cost of recircularizers = $14 x 10^6 each

Cost of yin-yang = $22 x 10^6 each

X ≡ switch for recovery of direct converter thermal energy

Y ≡ switch for recovery of injector waste heat

Z ≡ switch for recovery of untrapped injector power

M = blanket multiplication factor

Q ≡ fusion power/input power

P_{th} = thermal power

P_{Ge} = gross electric power

P_{net} = net electric power

P_{aux} = auxiliary power

$P_{inj} = P_{RF} + P_{NB}$, total injected power (RF and neutral beams)

and

$$\eta_{inj} = \frac{P_{inj}}{\frac{P_{RF}}{\eta_{RF}} + \frac{P_{NB}}{\eta_{NB}}} .$$

η_{RF}, η_{NB} are the efficiencies of RF heating systems and neutral beam injectors,

$$f_t = \frac{P_{RF}\, f_{tRF} + P_{NB}\, f_{tNB}}{P_{inj}} ,$$

f_{tRF}, f_{tNB} are the trapped fractions of injected RF and neutral beam power.

By specifying the efficiencies and M (Table IV), while taking Q, f_t, and the power distribution fractions from the physics results of POWBAL, we can obtain the powers in and out of every system in the plant. Then taking the real injected power (RF + NB) that is also calculated by the physics code we can calculate the power handled by each system as well as the net electric power, plant efficiency and recirculating power fraction. There are several branches (W,X,Y,Z) in the diagram that can take values between zero and one depending on the percentage of heat that is going to be recovered through each of them.

The powers handled by the direct converter, thermal cycle and injectors are:

$$P_{DC} = f_t \, [f_{DC} + Q \, f_{CDC}] \cdot P_{inj}$$

$$P_{thC} = P_{th} + f_t \, [f_{DC} \, ((1 - \eta^{i}_{DC}) \cdot X - 1) + Q \cdot f_{CDC} \, ((1 - \eta^{\alpha}_{DC}) \cdot X - 1)] \cdot P_{inj}$$

$$P_{injectors} = \frac{P_{inj}}{\eta_{inj}} \, .$$

The auxiliary power is modelled by

$$P_{aux} = \frac{P^r_{aux}}{P^r_{th}} P_{th}$$

where P^r_{aux}, P^r_{th} are the reference values. Also,

$$\eta_G = \frac{P_{Ge}}{P_{th}} = \text{gross plant efficiency}$$

$$F_R = \frac{P_{Ge} - P_{net}}{P_{Ge}} = \text{recirculating power fraction}$$

$$\eta_n = \frac{P_{net}}{P_{th}} = \text{net plant efficiency.}$$

Then, from Fig. 3

$$P_{th} = (A + BQ) \cdot P_{inj}$$

$$P_{Ge} = (C + DQ) \cdot P_{inj}$$

$$P_{net} = (E + DQ) \cdot P_{inj} - P_{aux}$$

where:

$$A = f_t \ (f_{DC} + W \ f_{TD}) + z \ (1 - f_t) + \frac{1-\eta_{inj}}{\eta_{inj}}$$

$$B = f_t \ (f_{CDC} + W \ f_{CTD} + M \ f_n)$$

$$C = f_t \ f_{DC} \ (\eta^i_{DC} + (1 - \eta^i_{DC}) \cdot x \cdot \eta_{th}) + \eta_{th} \ (f_t \cdot W \cdot f_{TD} + Z \ (1 - f_t) + Y \ (\frac{1}{\eta_{inj}} - 1))$$

$$D = f_t \ (f_{DCD} \ (\eta^\alpha_{DC} + (1 - \eta^\alpha_{DC}) \cdot x \cdot \eta_{th}) + (W \ f_{CTD} + M \ f_n) \ \eta_{th})$$

$$E = C - \frac{1}{\eta_{inj}} .$$

In order to get the cost of the power conversion and supply systems the power handled is multiplied by the unit cost ($/kW), obtained for the reference design (Table IV). The unit cost for the thermal conversion system includes electric plant, turbine plant, and main heat transfer systems. The direct converter cost includes all the equipment except the vacuum tank.

So far we have taken into account the main systems in the plant but, in order to consider all contributing factors,[3] we also need to estimate the cost of other items such as: other buildings besides the reactor building, reactor support structure, vacuum system, power supplies, tritium extraction, auxiliary cooling systems, radwaste treatment and disposal, fuel handling, remote maintenance equipment, handling equipment, special materials, instrumentation and control, land and land rights and structure and site facilities.

The detailed estimate of these costs for the reference design is $\$3.5 \times 10^8$.(1) We have considered the following scaling laws for different net electric powers:

$$C_{others} = \frac{C^r_{other}}{2} \times \left(1 + \frac{P_{net}}{P^r_{net}}\right) .$$

The total direct cost (TDC) is obtained by adding all of the preceding costs. From it we also obtain the cost in \$/kWe. Indirect and time related costs are evaluated by using standard factors in the current dollar mode, assuming eight years for the construction of the plant. These include the costs of construction facilities, equipment and services, engineering and construction management services, owner's costs, and interest and escalation during construction. The total indirect cost factor turns out to be 2.33.

The busbar cost (mills/kWh) is also calculated using the current dollar mode. We evaluate the duty factor, δ, of the plant as

$$\delta = \frac{\phi_N/\Gamma_n}{\frac{\phi_N}{\Gamma_n}\left[1 + \frac{t_o}{52}\right] + \frac{t_D}{52}}$$

where

ϕ_N = allowable first wall loading ($MW \cdot yr/m^2$)

Γ_N = neutron wall loading (MW/m^2)

t_D = downtime for total blanket replacement (weeks)

t_O = other downtimes (weeks/year)

then,

plant capacity factor $C_f = \delta \times P_{net} \times 8760$

and,

busbar cost $(\frac{mills}{kWh}) = 0.15 \times C_{cap} + (O + M + B_{\ell k}) \times (1.05)^8$

where

$$C_{cap} = \frac{TDC \times 2.33}{C_f}$$

(O+M) = cost of operation and maintenance (mills/kWh)

$B_{\ell k} = \frac{\text{Cost of Blanket}}{\phi_N/\Gamma_n \times P_{net} \times 8760}$, is the cost of the blanket replacement.

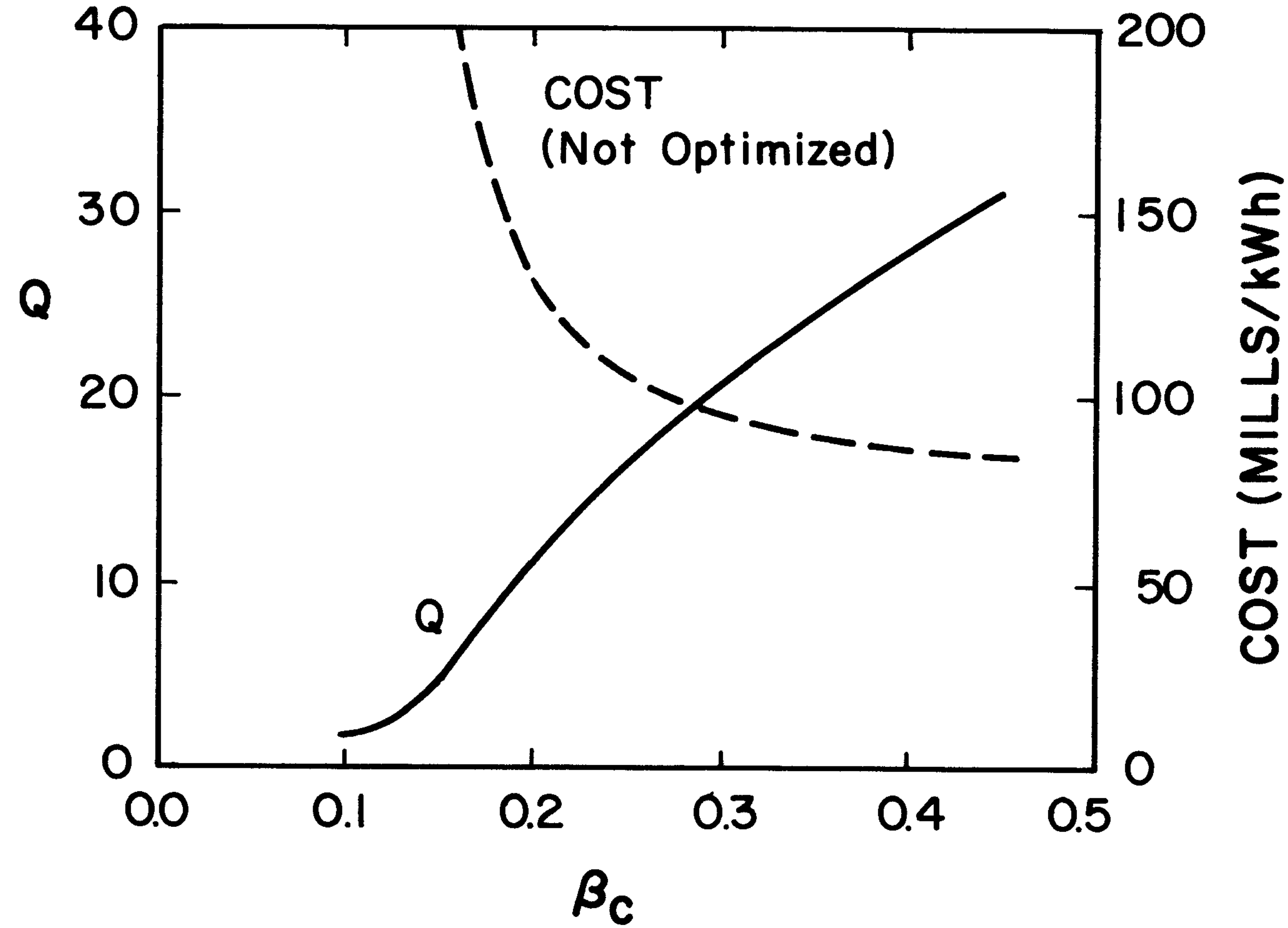
III. Results

This model has been programmed as COST, a subroutine of POWBAL, the Barrier Tandem Mirror Physics Code. Although it was developed to do parametric cost analysis of barrier TMR's of design similar to WITAMIR-I, minor modifications allow evaluation of other designs with similar physics.

The results can generally be explained by taking into account the effect on the cost of the variation of each physical parameter. The change in dimensions affects the total mass of materials. Different magnetic field strengths act on the size and cost of the magnet system. The duty factor of the plant depends on the neutron wall loading. Q and the trapped energy fraction are directly related to the coefficients of the power flow diagram, and with different injected powers we get a variation of every power handled in the system.

One of the most important parameters is central cell beta, β_c, the ratio of plasma pressure to magnetic field pressure. Fig. 4 shows the variation of

Figure 4



Effect of Central Cell Beta on Q and Cost

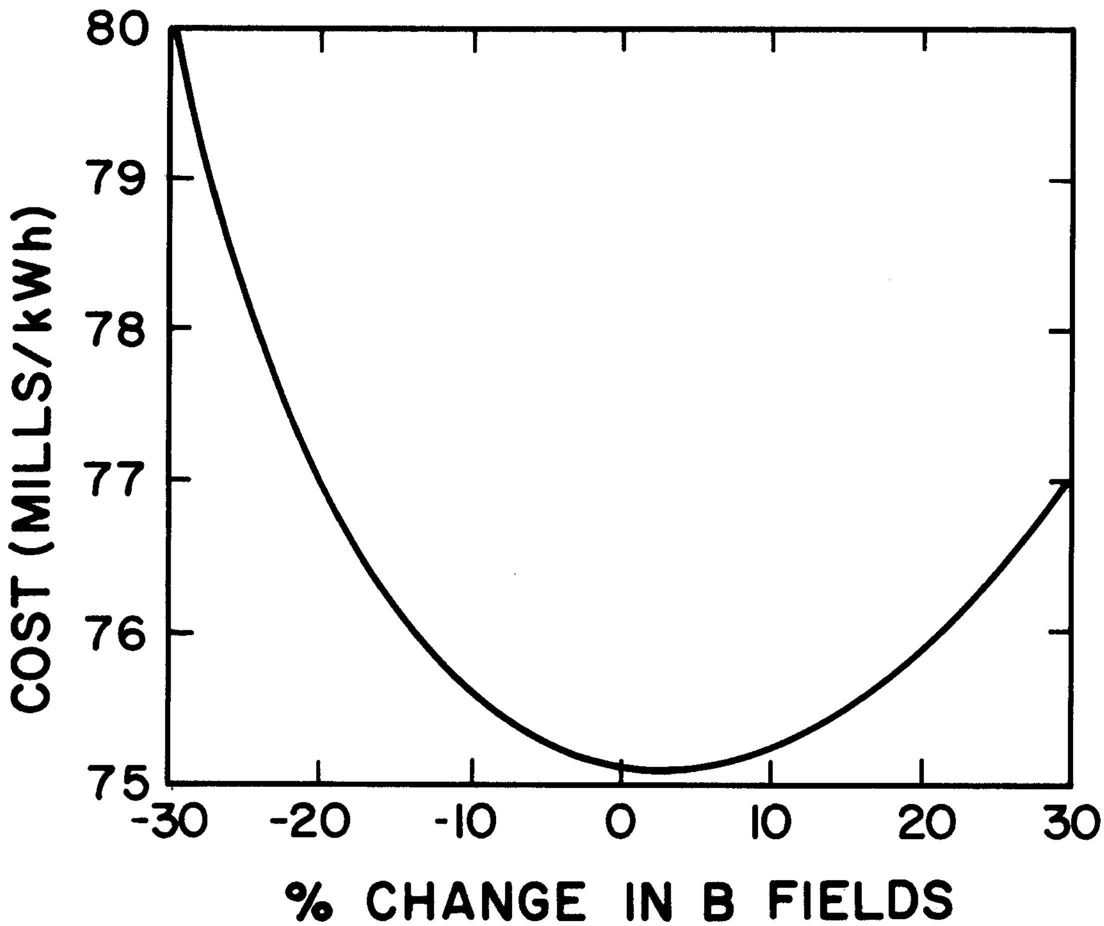
Q and cost as β_c is varied. It is interesting to note that $\beta_c \approx 0.25$ gives only a slight rise in cost as compared to $\beta_c = 0.4$. WITAMIR-I used $\beta_c = 0.4$, but some controversy existed over whether this was too high; present theory indicates that β_c may, in fact, be conservative. Fig. 4 does not, however, have the plug radius folded into the costs, and low β_c costs are probably somewhat underestimated.

When all of the magnetic fields are uniformly varied, the results are shown in Fig. 5. Since the WITAMIR-I reference case was set some time before the COST subroutine was operational, the seeming optimization with respect to B field magnitudes is more fortuitous than designed. It may be, however, indicative of a general trend, possibly relating to trade-offs between densities and radii.

The results of varying the barrier mirror ratio, R_b, are shown in Fig. 6. For these cases, the maximum barrier field was held constant at 14 T, and the minimum field was changed to achieve the desired R_b. Raising R_b requires either increasing barrier length, and therefore power, or using a coil with reversed current to "buck" the field; the result will be a slight lowering of the given Q values. As R_b rises, the allowable n_c also rises, giving a large improvement in Q by increasing B_c which is tied to n_c by the beta limit. However, there are theoretical questions surrounding the relationship between B_c and β_c, and increasing B_c has not been pursued here.

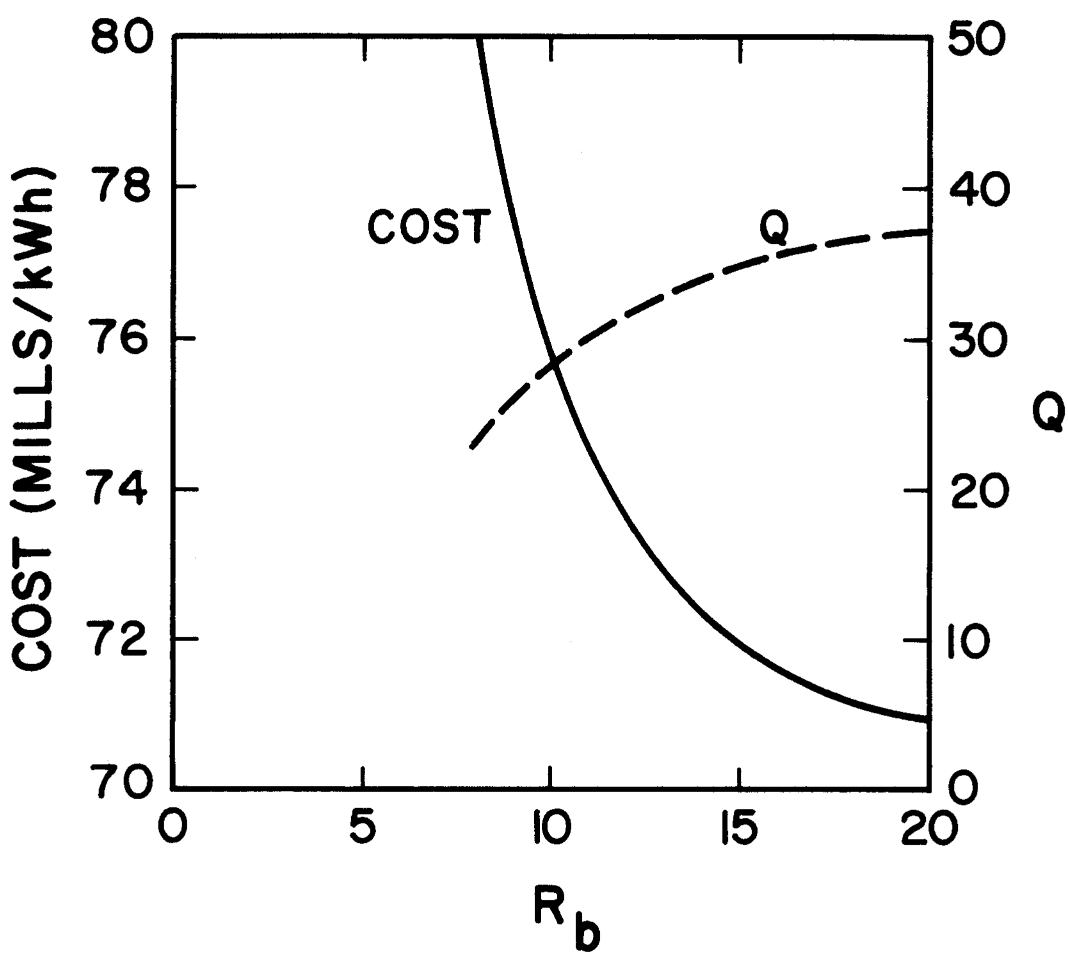
When the total fusion power is varied, keeping central cell length constant but allowing radii and wall loading to vary, the cost varies as shown in Fig. 7. Because magnet and building costs remain constant, drastic cost increases do not occur until P_{fus} drops below about 1500 MW. This indicates that a plant with net electric power of perhaps 750 MWe would not be prohibitively expensive.

Figure 5



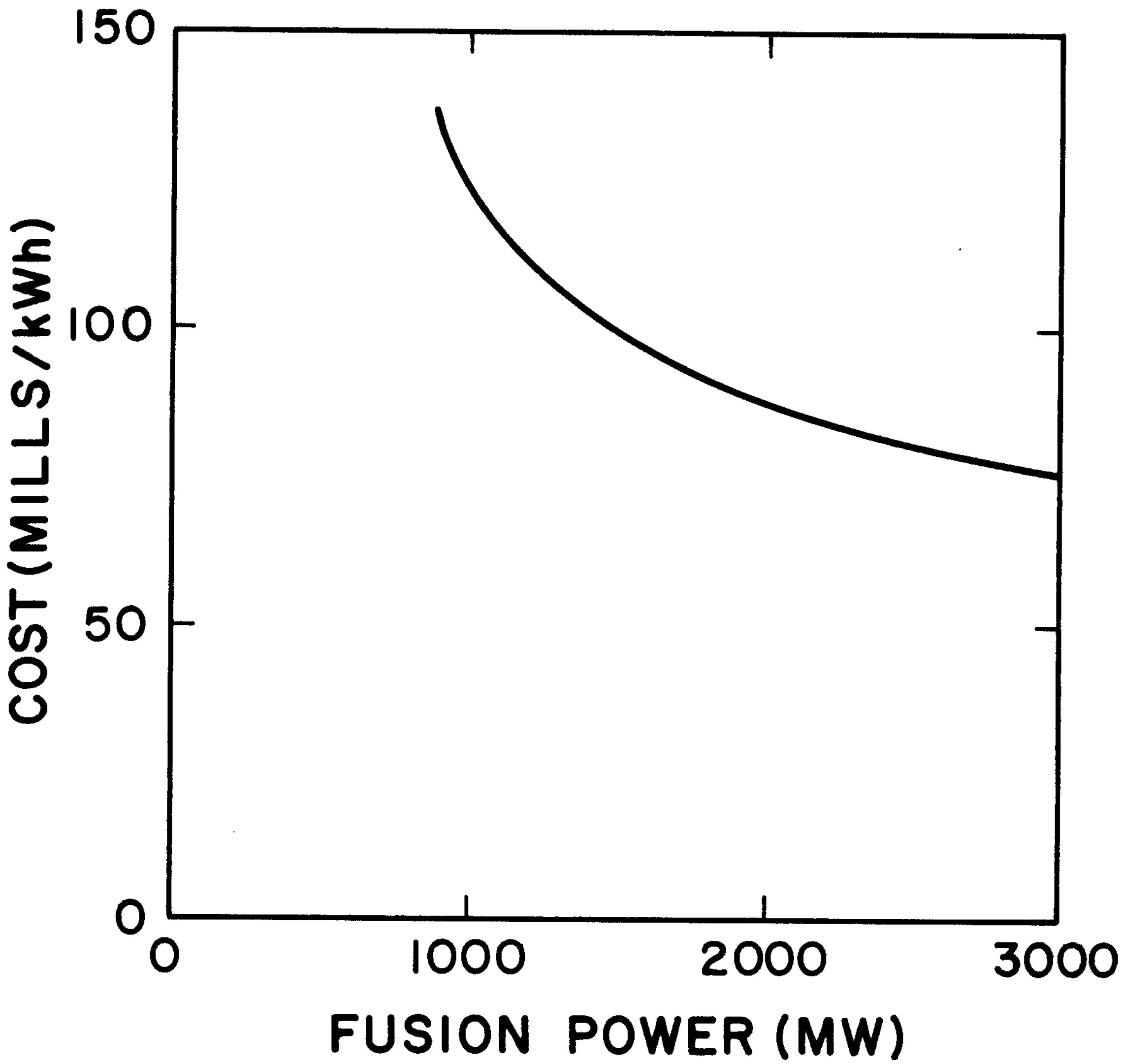
Variation of Cost With Magnetic Field Magnitudes

Figure 6



Dependence of Cost on Barrier Mirror Ratio

Figure 7



Dependence of Cost on Fusion Power

When the central cell length is varied, keeping fusion power constant, the cost varies as in Fig. 8. The shorter central cell will give a larger radius throughout the machine, therefore increasing plug and barrier volumes and powers.

When efficiencies of injection and of the direct converter and thermal cycle are varied, the cost varies as shown in Fig. 9. Obviously, the most important efficiency is η_{th}, since the thermal cycle handles the largest fraction of output power. The importance of the thermal cycle is of particular note for a tandem mirror reactor since the ease of central cell access makes it particularly amenable to a wide range of possible blanket schemes. Injection power efficiency is, of course, also important, but direct converter efficiency has surprisingly small effect.

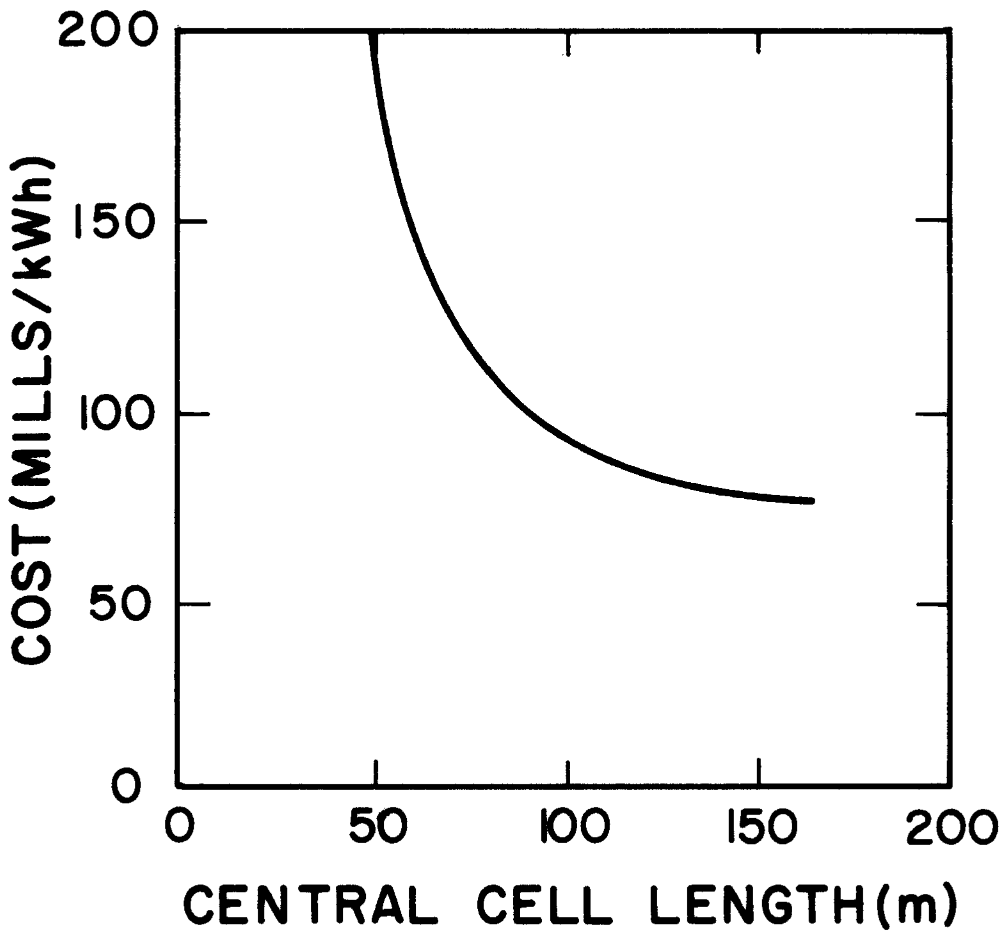
When the fraction of power recovered in various cycles is varied, the results are shown in Fig. 10. A significant effect is obtained if the energy lost in the direct converter and injector, as well as the energy of charged particles which do not end up into the direct converter, is recovered. In the case of total energy recovery in the thermal cycle the cost of electricity is reduced by 10%.

There is no large effect of plug injection energy on cost until E_{inj} drops to a value near the effective potential trying to thrust ions from the plug;[(1)] cost then rises dramatically. This energy is lower for lower central cell ion energy since potentials are somewhat tied to temperatures.

IV. Conclusions

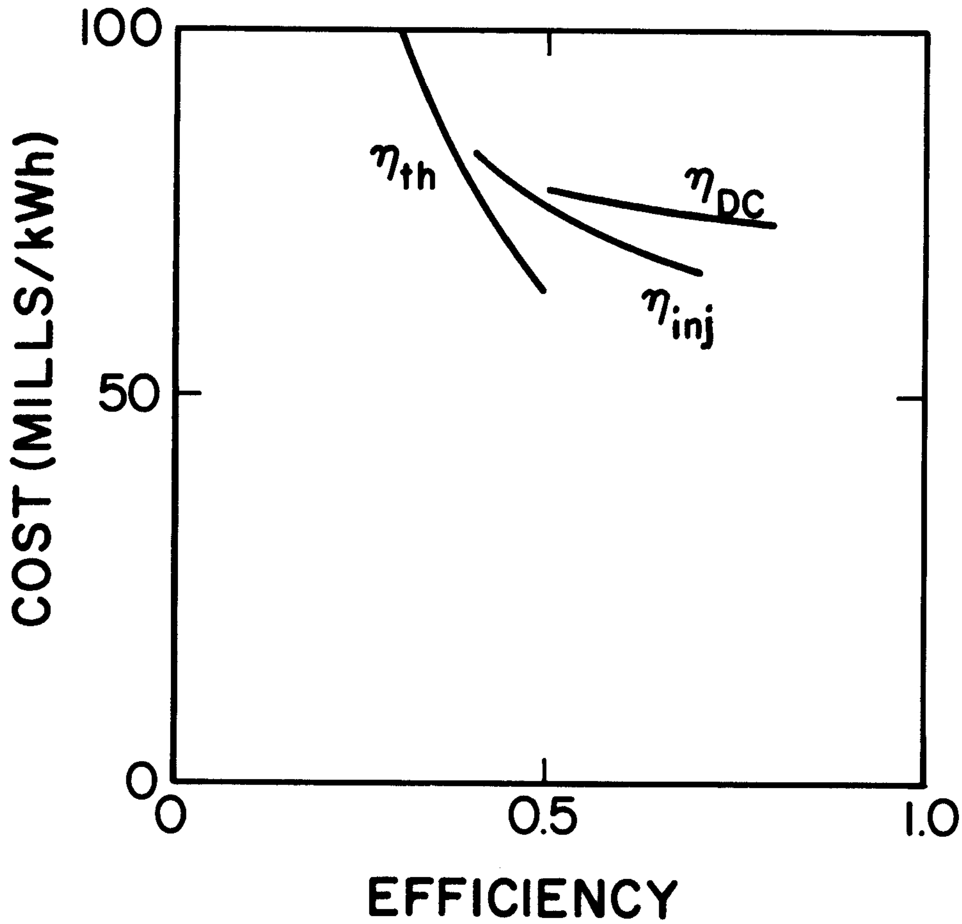
Perhaps the most important conclusion, shown in Fig. 7, is that a smaller machine, on the order of 1000 MWe or less, would not be prohibitively more expensive than the WITAMIR-I design of 1500 MWe.

Figure 8



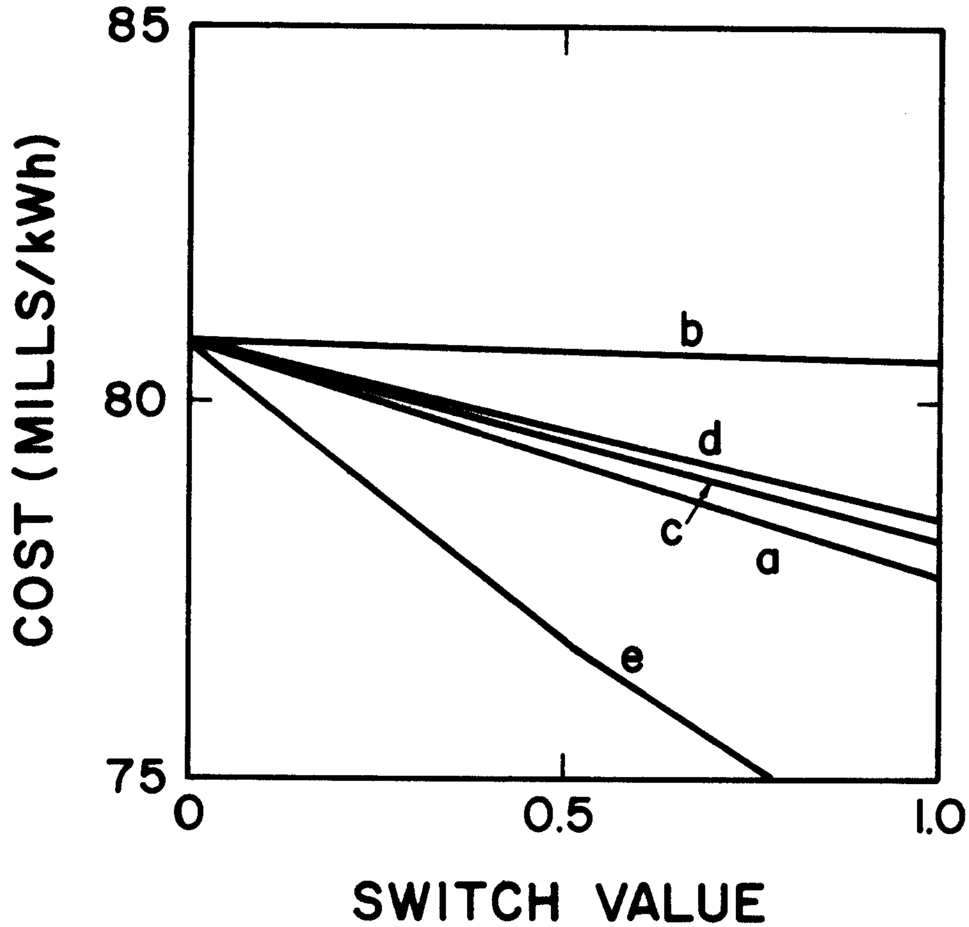
Dependence of Cost on Central Cell Length

Figure 9



Variation of Cost With Thermal Cycle, Direct Converter, and Injection Efficiencies

Figure 10



Variation of Cost With Switch Variables
(a) $W \neq 0$, Recovery of Charged Particle Power by Thermal Dump;
(b) $Z \neq 0$, Recovery of Untrapped Injector Power;
(c) $Y \neq 0$, Recovery of Injector Waste Heat;
(d) $X \neq 0$, Recovery of Direct Converter Thermal Energy;
(e) Recovery of All Branches

Some improvement over WITAMIR-I appears possible by raising R_b, although detailed study is necessary.

Fig. 9 shows that great benefit derives from increasing the thermal cycle efficiency, but direct converter efficiency has little effect. This situation would reverse if most of the fusion energy appears as charged particles, as in an advanced fuel system.

Acknowledgement

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