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FUSION TECHNOLOGY INSTITUTE

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A COMMERCIAL TANDEM MIRROR REACTOR DESIGN WITH THERMAL BARRIERS - WITAMIR-I

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Summary

A conceptual design of a near term commercial tandem mirror power reactor is presented. The basic configuration utilizes yin-yang minimum-B plugs with inboard thermal barriers. The maximum magnetic fields are 6.1 T, 8.1 T, and 15 T in the central cell, yin-yang, and thermal barrier magnets, respectively. The blanket utilizes $Pb_{83}Li_{17}$ as the coolant and HT-9 as the structural material. This yields a high energy multiplication (1.37), a sufficient tritium breeding ratio (1.07) and has a major advantage with respect to maintenance. The plasma Q is 28 at a fusion power level of 3000 MW_{th}; the net electrical output is 1530 MW_e and the overall efficiency is 39%. Cost estimates indicate that WITAMIR-I is competitive with recent tokamak power reactor designs.

Introduction

Since the early 1970's the conceptual fusion reactor design field has been dominated by the tokamak concept.[(1-9)] While there are several positive features of that concept, there are many undesirable aspects of the tokamak that have emerged. The major areas where improvement is desired are:

1.) The maintainability is inherently difficult because of the toroidal geometry and interlocking coil configurations. Potentially long repair times raise serious questions about reactor relevant availability times.

2.) The pulsed nature of the burn cycle induces severe fatigue problems in the first wall and magnet structures.

3.) It is necessary to keep the plasma 'clean' of impurities by the use of exotic divertor and/or limiter designs, most of which must operate under heat fluxes and erosion rates beyond the ability of known materials to last the lifetime of the reactor.

4.) The engineering power density is rather low (~ 1 MW_{th}/m^3) and this results in rather high capital costs.

Some of the above problems were addressed by two other major magnetic fusion reactor concepts in the 70's, the theta pinch[(10)] and the simple minimum B mirror[(11)], but both of these concepts introduced more problems than they solved. For example, the minimum-B mirror is a steady state device and does not require the plasma 'cleansing' configurations of the tokamak, but it has an uneconomically low Q (fusion power out divided by the input power) of only ~ 1.2.

In 1976 the tandem mirror concept was simultaneously suggested both in the U.S.[(12)] and in the USSR[(13)] and it had Q's of ~ 5-10. However, the TMR designs placed unreasonably large demands on fusion technologies such as magnets (17 T) and the neutral beams (1 MeV). Fortunately, in 1979 Baldwin and Logan[(14)] introduced the thermal barrier concept into the tandem mirror configuration which allowed much higher Q's (~ 10 to 20)

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to be considered while at the same time reducing the technology demands on the magnets and beams. The tandem mirror/thermal barrier concept appears to form the basis for an attractive commercial reactor design.

The objective of this paper is to summarize a conceptual commercial tandem mirror reactor design called WITAMIR-I. The details of the design can be found in a more detailed University of Wisconsin report[15] and only the major results will be reported here.

General Design Features

The basic configuration of WITAMIR-I is a long (165 m) solenoidal central cell terminated by an inboard thermal barrier and a yin-yang minimum-B plug. The mirror confined plasma in the plug provides the confining electrostatic potential and the good magnetic field curvature for MHD stability.

Perspective views of the WITAMIR-I reactor are shown in Figures 1 and 2 while Table 1 summarizes its major parameters. From the figures we can see that in contrast to the tokamak reactor, which is a large torus, WITAMIR-I is essentially linear in nature. While the geometries differ considerably, the total nuclear island volume of each device is comparable. For example a recent tokamak reactor, STARFIRE[9], which operates at roughly the same total power as WITAMIR-I, is ~ 34 meters in diameter and 25 meters high (~ 2.3×10^4 m^3) while WITAMIR-I is ~ 250 m long and an average of ~ 10 m in diameter (1.9×10^4 m^3).

With a plasma Q of 28, the DT power level of WITAMIR-I is 3000 MW_{th}. Due to an extremely good blanket multiplication of 1.37 and direct conversion of the charged particles leaking from the central cell along with those injected into the end plugs, the net plant output is 1530 MW_e. The recirculating fraction is only 18%, a relatively low value for mirror reactor concepts.

The magnetic fields in the central cell and yin yang coils are relatively modest with maximum fields of 6.1 T and 8.1 T, respectively. The most difficult problem is in the cylindrical barrier coil which has a maximum field of 15 T, but even that appears to be feasible with a hybrid superconductor design and superfluid helium coolant at 1.8 K.

The blanket is made up of only two materials, HT-9 structural and reflector material and a $Pb_{83}Li_{17}$ coolant. The latter gives a comfortable tritium breeding ratio of 1.07. Coupled with its high energy multiplication (1.37) and reasonably high neutron wall loading of 2.4 MW/m^2, the WITAMIR-I blanket design is one of the more attractive systems that has been designed to date.

Table 1

General Parameters of WITAMIR-I

Parameter	Value
Plasma Q	28
DT power	3000 MW_{th}
Net electrical output	1530 MW_e
Recirculating fraction	18%
Central cell length	165 m
Overall reactor length	250 m
Max. magnetic field - central cell	6.1 T
Max. magnetic field - barrier	15.0 T
Max. magnetic field - yin yang	8.1 T
Blanket material	HT-9
Neutron wall loading	2.4 MW/m^2
Blanket multiplication	1.37
Breeder material	$Pb_{83}Li_{17}$
Breeding ratio	1.07
Barrier pumping method (190 keV and 9.6 keV)	55.2 MW of NB
ECRH power - barrier	33.2 MW (40 GHz)
- plug	16.4 MW (112 GHz)
Plug neutral beam power (500 keV)	18.2 MW

The thermal barriers are maintained by neutral beam pumping. A total of 55.3 MW of 190 keV (42.5 MW) hydrogen particles and 9.6 keV (12.8 MW) hydrogen particles strategically placed keeps the ion density lower in the barrier region. The neutral beam power to the end plug is only 18.2 MW at 500 keV. Finally, the electrons are heated in the barrier region by 33 MW of ECRH power at 40 GHz while electrons in the plug region are heated with 16.4 MW of ECRH power at 112 GHz.

Plasma Considerations

WITAMIR-I is the first full scale reactor study to consider the consequences of the modified Boltzmann relationship between density, potential and electron temperature proposed by Cohen, et al.[16]:

$$e\Delta\phi = T_{ep} \ln \left[\frac{n_p}{n_b} \left(\frac{T_{ec}}{T_{ep}}\right)^{\nu_c}\right]$$

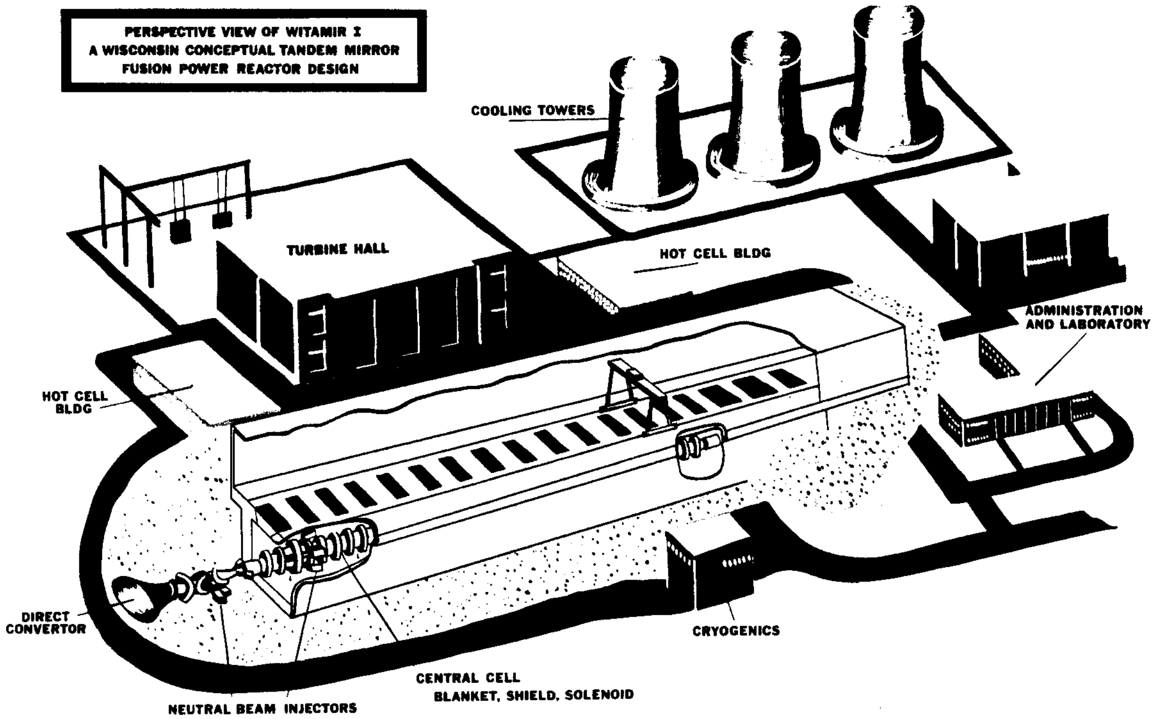


Figure 1.

PERSPECTIVE VIEW OF WITAMIR I
A WISCONSIN CONCEPTUAL TANDEM MIRROR
FUSION POWER REACTOR DESIGN

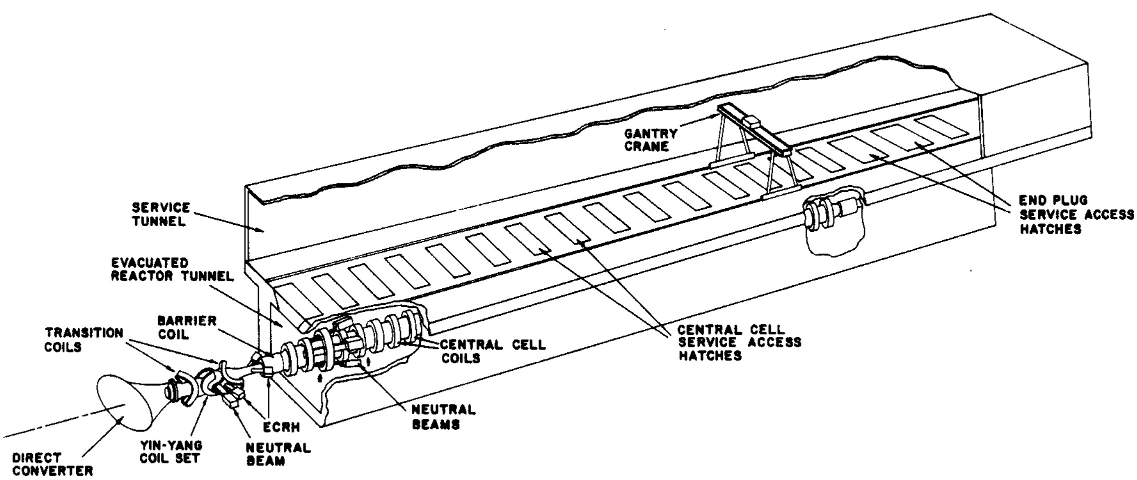


Figure 2.

where: $e\Delta\phi$ = plug potential
T_{ep}, T_{ec} = electron temperatures in the plug and central cell, respectively
n_p, n_b = ion densities in the plug and barrier regions, respectively
ν_c = parameter to account for non-Boltzmann distributions of ions.

The magnetic field, potential, and particle density profiles for one end of WITAMIR-I are shown in Figure 3 and the top/bottom cross sectional view of the end plug region is shown in Figure 4. The potential ϕ_b is created by the density drop from neutral beam charge exchange pumping and flux tube expansion as the magnetic field falls from 14 T to 1.4 T. The potential ϕ_c, which confines central cell ions, is created by RF heating of plug electrons and by neutral beam injection, and ϕ_e is the ambipolar potential occurring because electrons are more collisional than ions and scatter more quickly into the loss cone. The hot electron density, n_{eh}, is created by RF heating at the barrier center. More details on the plasma parameters are listed in Table 2. The pumping parameter, g_b, is the ratio of total barrier ions to passing ion density.

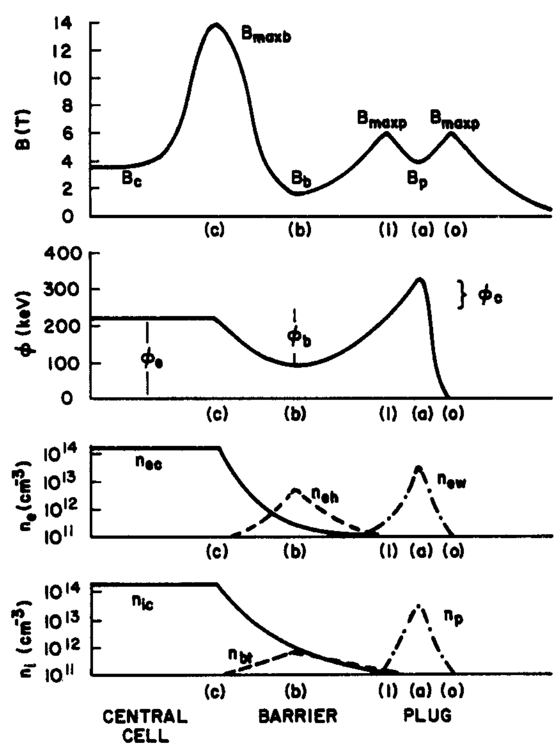


Figure 3. Summary of Selected End Plug Plasma Physics Parameters for WITAMIR-I.

Table 2

Plasma Conditions for WITAMIR-I

Parameter	Value
Central Cell	
Magnetic field on axis	3.6 T
Density	1.5×10^{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	
Magnetic field on axis	14.0 T
Average density	6.9×10^{12} cm^{-3}
Ion temperature	32.5 keV
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	
Maximum/minimum magnetic field on axis	6.0/4.0 T
Average density	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}

The detailed descriptions of the plasma physics model used to calculate the plasma parameters in Table 2 are contained in Reference 15 and much of the present work is based on the models proposed by Baldwin, et al.(14) The main terms in the power balance are heating by the

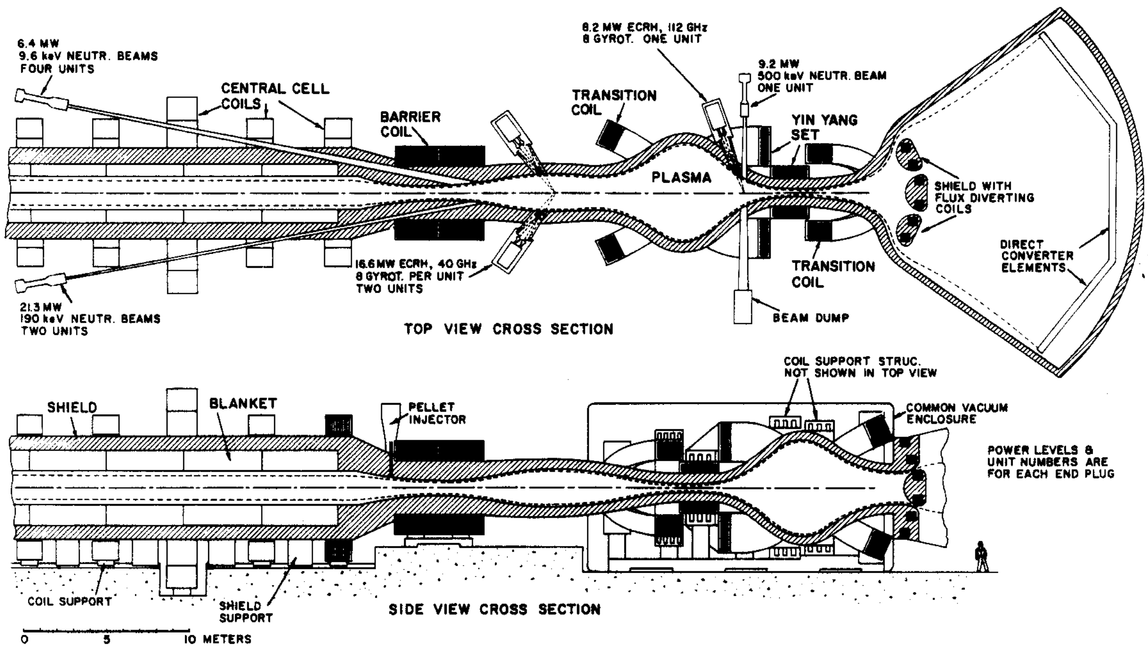


Figure 4.

alpha particles, neutral beams, and ECRF power balanced by end losses, radiative processes and energy carried out by charge exchange neutrals from the pumping process.

Whereas the central cell ions are deuterium and tritium, protons are used in the end plugs because of the desire to reduce neutron production and hence the amount of shielding required for the barrier coil and yin yang coils. Neutronics calculations show us that this approach was successful in reducing the radiation damage in the superconducting magnets to acceptable levels with only 10-20 cm of shielding. Better microstability is also expected with protons because they have smaller gyroradii than deuterium or tritium.

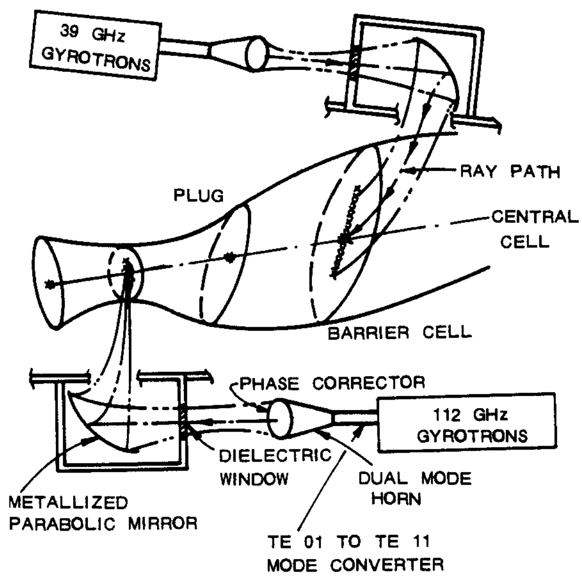
There are MHD stability questions with regard to the central cell beta. Theory now predicts values of roughly 25% although experiments have been consistently exceeding the theoretical limit. The value of 40% chosen here is lower than that used in past preliminary designs, but felt to be reasonable in light of probable future improvements in field design and the fact that MHD theory is somewhat tentative at this point.

The ions that are trapped in the barrier by collisional scattering must be 'pumped' out to maintain a density dip and therefore a potential ϕ_b. This is done in WITAMIR-I by charge exchange reactions with the neutral beams injected at approximately 10° to the axis, through the bore of an oversized central cell coil and a barrier coil (see Figures 4 & 6 for the WITAMIR-I reactor magnet configuration).

The electrons in the outside edge of the barrier coil will be heated by 33.2 MW of ECRH power at 40 GHz (see Figure 5) to maintain the appropriate potential profiles. The ECRH power is provided by gyrotrons and transported to the plasma using a beam waveguide system. While the use of ECRH lowers some technology requirements and allows somewhat higher Q's, a tandem mirror without barrier ECRH is viable but not quite as attractive with respect to Q.

The plug region is essentially a minimum-B mirror machine, for which a great deal of experimental and theoretical base currently exists. Perhaps the most serious technology challenge in the end plug is the requirement of 2.4 MW of steady state 500 keV negative ion beams absorbed in each end plug plasma zone. The plug plasma is also maintained by 8.2 MW of 112 GHz ECRH power at each end.

Finally, the direct convertor is designed to collect all of the ions which escape over ϕ_c. By maintaining ϕ_c slightly higher on one end of the machine, essentially all of the ions will escape out the other end, thus necessitating a direct convertor only on one end of the machine. Electrons are collected at the other end of the



ECRH TRANSPORT SYSTEM (Not to scale).

Figure 5.

WITAMIR-I MAGNET ARRANGEMENT

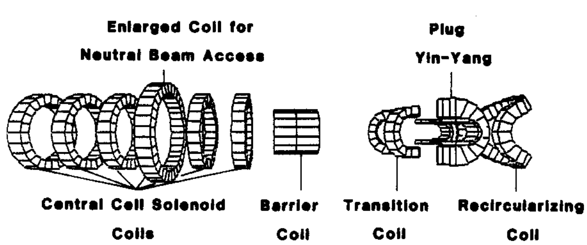


Figure 6.

machine. The direct convertor handling the ions converts 502 MW of power at an efficiency of 67%.

Summary of WITAMIR-I Magnet Designs

There are three major superconducting magnet systems in WITAMIR-I; the central cell solenoidal magnets, the barrier coils, and the plug coils consisting of transition/yin yang and recircularizing coils. A schematic of the coil configuration at one end is shown in Figures 4 and 6 while Table 3 lists the major characteristics.

There are 34 central cell coils, 2 barrier coils, 2 transition coils, 2 recircularizing coils and 2 yin yang coil sets. The two largest coils (11.4 m outside diameter) are those in the central cell which have to be expanded to accept the barrier pumping beams. The rest of the low field (6.1 T max.) central cell coils are only 8.6 meters in outside diameter and the high field (15 T max.) barrier coils are roughly 5 meters in diameter. The intermediate field (8.1 T max.) plug coils have outside dimensions of roughly 8 x 5 meters.

The construction of the central cell and plug coils should be straightforward with today's technology using NbTi superconductor and Cu or Al as the stabilizer. These coils will operate at 4.2 K and have modest average current densities of 800 to 1900 A/cm^2. On the other hand, the barrier coil is a hybrid design consisting of three zones. The high field region is Nb_3Sn, the intermediate zone is NbTiTa and the low field region is NbTi, all operating at 1.8 K. The average current densities are a maximum of 2000 A/cm^2 in the NbTi, and Cu is used as the stabilizing material for the entire barrier coil design.

Finally, the structural materials for the central cell coils are Al alloys while stainless steel is used for the yin yangs, the transition and recircularizing coils. In the barrier coils, CuNb is used for structure. The total weight of all the 44 magnets is 5762 tonnes.

Blanket and Shield Design

A schematic of the WITAMIR-I blanket and shield design is shown in Figure 7 and Table 4 lists the important operating characteristics. Figure 8 shows a cross sectional view and Figure 9 gives the blanket compositions.

The structural material was chosen to be a ferritic steel, HT-9, mainly on the basis of its resistance to fission neutron damage. The maximum operating temperature is 530°C and it is cooled by a $Pb_{83}Li_{17}$ eutectic alloy which ranges in temperature from 329 to 500°C. The inside diameter of the central cell is 1.94 meters and the blanket/reflector region is ~ 1 meter thick. A shield of 0.6 m thickness is placed around the blanket to reduce neutron damage in the S/C magnets to a level which could be safely accumulated over 30 years of operation at 70% plant factor (21 full power years, FPY's).

The neutron wall loading of 2.4 MW/m^2 is not considered to be excessive because the surface heat flux is so low (~ 2 W/cm^2). This allows the first wall to be cooled by the Pb-Li alloy rather than requiring high pressure water as in the case of most recent tokamak designs which may have heat loads at the 40 Watt/cm^2 level or higher.

Table 3

Major Superconducting Magnet Characteristics for WITAMIR-I

Parameter	Central Cell	Barrier Coil	Transition/ Recircularizing Coil	Yin Yang Coil
Number of magnets	32(+2)	2	2+2	2+2
Major radius - m	4.3(5.7)*	2.51	2.0	1.66
Wt. of coil - tonnes/coil	88.1(162.5)*	429	283	157
Overall current density-A/cm^2	950(800)*	1000/1500/2000	1480	1900
Op. temp. K	4.2	1.8	4.2	4.2
Max. field cond.-T	6.1	15	8.1	8.1
Max. field on axis-T	3.6	14	N/A	6
Superconductor	NbTi	Nb_3Sn/NbTiTa/NbTi	NbTi	NbTi
Stabilizer	Al	Cu	Cu	Cu
Structural material	Al	CuNb	SS	SS

* 2 oversize coils to permit neutral beam injection.

Table 4

Summary of WITAMIR-I Blanket/Shield Parameters

Parameter	Value
Structural material	HT-9
Breeder and coolant	$Pb_{83}Li_{17}$
Maximum structure temp. - °C	530
Inlet/outlet coolant temp. - °C	329/500
Inside diameter, central cell - m	1.94
Blanket/reflector/shield thickness - m	0.73/0.28/0.6
Neutron wall load - MW/m^2	2.4
Surface heat load - W/cm^2	2
Blanket multiplication	1.37
Tritium breeding ratio	1.07
Tritium inventory - kg	
Active	0.45
Storage (1 full power day)	2.14
Max. damage rate central cell magnets	
dpa/FPY - stabilizer (Al)	6.6×10^{-7}
rad/FPY - insulator	3.6×10^{6}
Afterheat at shutdown - MW	24
Radioactivity at shutdown - curies	3×10^{9}

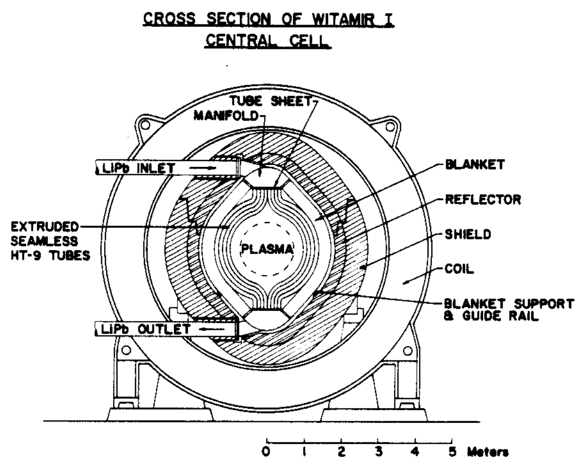


Figure 7.

The excellent neutronic properties of the Pb-Li alloy allow one of the highest blanket multiplication factors to be attained of any reactor that we have designed thus far. This fact can be verified by examining the energy multiplication values of our most recent tokamak designs listed below:

Reactor	Structure/ Breeder Combination	Blanket Energy Multiplication
UWMAK-I [1]	316SS/Li	1.17
UWMAK-II [2]	316SS/Be-$LiAlO_2$	1.28
UWMAK-III [3]	TZM/Li	1.29
NUWMAK [8]	Ti-6Al-4V/ Pb_{38}-Li_{62}	1.22
SOLASE [17]	C/LiO_2	1.09
WITAMIR-I	HT-9/$Pb_{83}Li_{17}$	1.37

The neutron multiplication of the Pb along with its low parasitic absorption cross section combines with the high gamma heating rate in the HT-9 to yield this very attractive blanket design. The lack of violent chemical reactions between $Pb_{83}Li_{17}$ and water, even at 500°C [18], will be a distinct safety advantage as well.

The tritium breeding ratio of 1.07 is considered adequate to account for inaccuracies in the T_2 breeding cross section, decay, and losses of tritium to waste streams. Because of the low tritium solubility in the Pb-Li alloy, the total 'active' inventory of T_2 in WITAMIR-I is a mere 0.45 kg. This extremely low value compared to past multi-kg inventories in Li coolants alone will be a distinct safety advantage. The storage of tritium for 1 full power day (2.14 kg) should not represent a significant hazard as it can be done away from the reactor in a solid form which is not prone to accidental release.

The totatl afterheat in the blanket and shield of 24 MW at shutdown is only 0.8% of the heat generated in the blanket during plasma operation. Such heat generation can be easily conducted away through the liquid metal coolant without significant temperature increases in the blanket material. The total radioactivity in the WITAMIR-I blanket and shield at shutdown is 3×10^9 curies. This level is comparable to previous reactor studies on a curie per watt basis, i.e., about 1 curie per watt.

The flow of reactor coolant and breeder material in WITAMIR-I is from the top to the bottom through seamless HT-9 tubes which are 9.75 cm in diameter. These large tube diameters allow rather low flow rates, 0.13 meters per second, which in turn should alleviate corrosion/erosion rates and pumping power losses. The removal of the welded zones to at least 1 meter behind the first wall should help to reduce failures because welded structures are notoriously susceptible to neutron damage.

The displacement damage to the HT-9 first wall material is 40.5 dpa per FPY and the helium production rate is 281 appm. While the helium production rates should not present a problem, we anticipate that we will have to replace the blanket modules after 3 full power years, or 3.8 years at 80% availability.

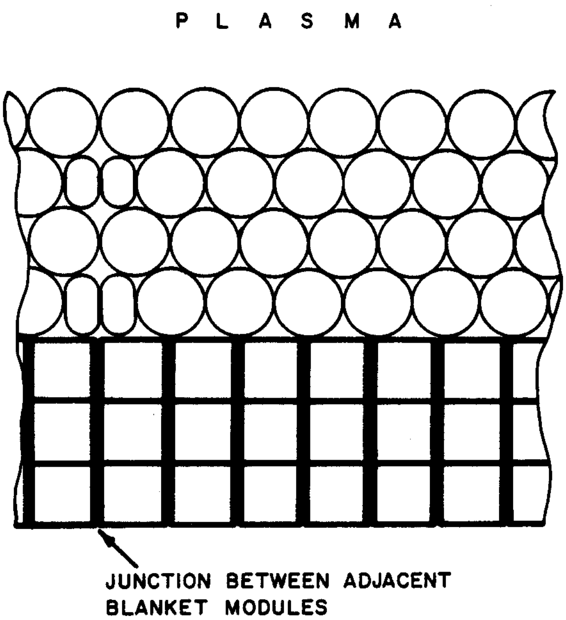


Figure 8. Cross section of the WITAMIR-I blanket showing a junction between adjacent blanket modules.

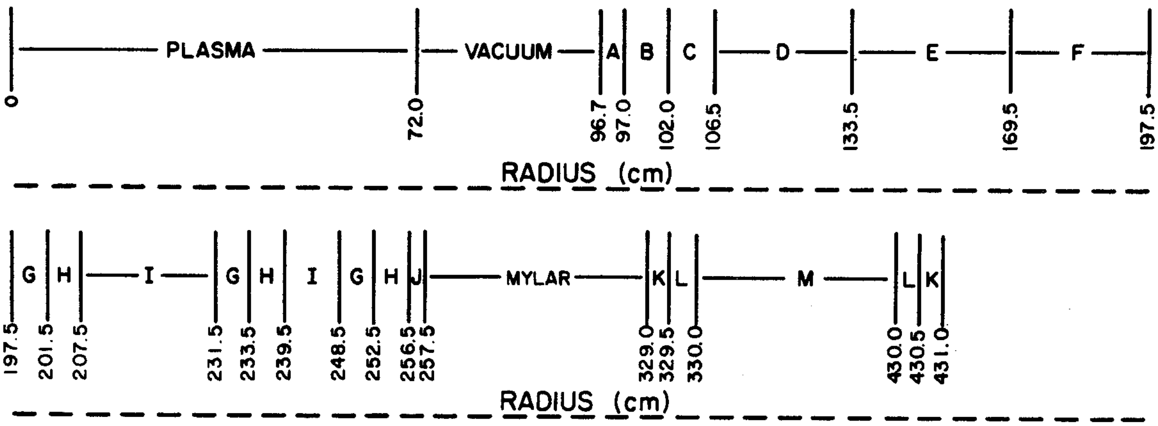
The procedure for replacing the blanket modules is shown in Figure 10. The central cell magnets on either side of the blanket module to be replaced are moved 0.75 m in each direction. The top shield is lifted off and the damaged module is removed through an access hatch in the evacuated reactor tunnel. Replacement of a new module follows the reverse procedure and the only connections that have to be made are the coolant headers. There are no welded joints to be broken because the blanket sections are not attached to adjacent modules. Vacuum tight seals are made at the back of the shield and the reactor tunnel is evacuated to 70 torr during operation.

Power Cycle Features

The production of useful electric power in WITAMIR-I has been given considerable attention. The thermal energy released from the DT reactor is converted to electrical energy by both a conventional steam cycle and by direct convertor. Table 5 and Figure 11 summarize the important parameters in this regard.

Starting from 3000 MW of DT power in the central cell we find 2400 MW of neutron power going to the blanket (plus 13 MW of neutron power

CROSS SECTION OF WITAMIR-I
USED IN RADIOACTIVITY CALCULATIONS



COMPOSITION TABLE

A - 100% FERRITIC STEEL (HT-9)

B - 79% $Li_{17}Pb_{83}$

C - 84% $Li_{17}Pb_{83}$, 7% FERRITIC STEEL (F.S.)

D - 81% $Li_{17}Pb_{83}$, 9% F.S.

E - 75% $Li_{17}Pb_{83}$, 25% F.S.

F - 5% $Li_{17}Pb_{83}$, 95% F.S.

G - 90% Pb, 5% H_2O, 5% F.S.

H - 87% B_4C

I - 95% F.S., 5% H_2O

J - 100% F.S.

K - 100% Al 2219

L - 100% He

M - 17.8% Al, 69% Al 2219, 4% He, 9.2% INSULATION

Figure 9.

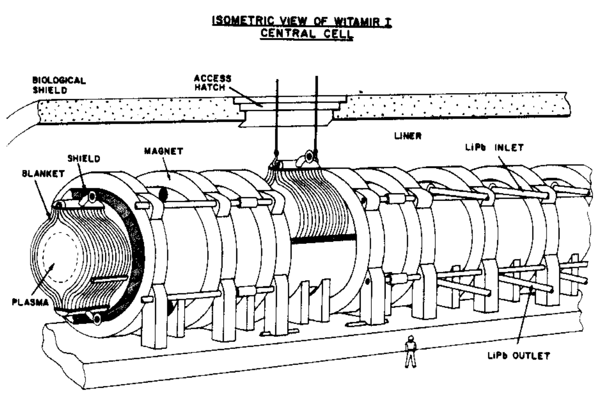


Figure 10.

from the kinetic energy of the reacting ions) and 600 MW in charged particle energy to the end plugs. With a blanket multiplication of 1.37 we find some 3306 MW of thermal power generated by the neutrons in the blanket, reflector and shield. The 2987 MW in the blanket is added to 30 MW from the barrier pump beams, 29 MW from surface heating of the central cell, 120 MW from the energy dump at the opposite end from the direct convertor, 59 MW from the barrier, 114 MW from the direct convertor plates and 310 MW from the reflector region to give 3649 MW to the primary heat exchanger. The gross efficiency of the steam cycle is 42% resulting in 1530 MW_e gross electrical output.

Because of the desire to keep the neutron shield cool, the difficulty in recovering the energy in the 500 keV beam that passes through the end plug plasma, and the difficulty in recovering energy from the director convertor grids, we make no attempt to recover the 9, 16 and 52 MW respectively associated with those regions. We also do not collect the 107 MW of beam power rejected from the formation of the neutral beams and ECRH system. Therefore, 2303 MW of thermal energy is dumped to the atmosphere.

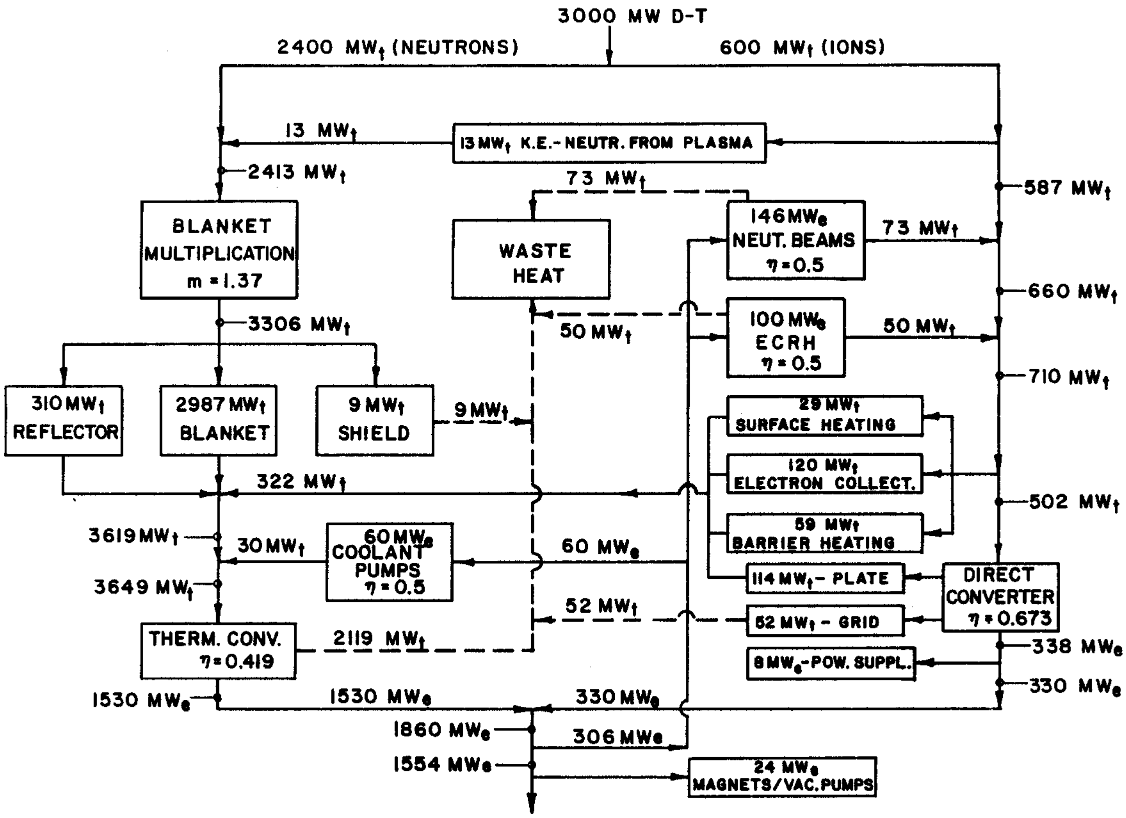


Figure 11. Power Flow Diagram for WITAMIR-I.

Out of the 600 MW in charged particles and electrons, the 73 MW of particles injected into the plug and the ECRH heat to the electrons in the barrier and plug (a total of 723 MW), only 502 MW is actually converted directly to electricity at a 67% efficiency. Of the 338 MW_e electrical output from the direct convertor, 8 MW is used for the power supplies and the resulting 330 MW_e is added to the electricity from the steam system (1530 MW) to give a gross plant output of 1860 MW.

The plant requirements for auxiliary electricity amount to 24 MW for cryogenics and vacuum systems and 306 MW for neutral beams plus ECRH heating systems. This power drain results in a recirculating fraction of 17.7%, a quite reasonable number compared to previous mirror reactor designs. The net output of the plant is 1530 MW and the overall net efficiency is 39.4%, again a very respectable value.

Economic Features of WITAMIR-I

The WITAMIR-I reactor was costed in accordance with the DOE guidelines on "Fusion Reactor Design Studies - Standard Accounts for Cost Estimates". A summary of the major reactor capital costs is given in Table 6 and the electricity costs in Table 7. Graphical representation of the reactor plant equipment cost components is given in Figure 12.

It can be seen from Table 6 that 76% of the direct costs of WITAMIR-I are related to the Reactor Plant Equipment (RPE) and it was found that ~ 25% of the RPE costs are for the magnet system (roughly half of the magnet costs are in the central cell).

The next largest cost is the primary heat transport system (23% of RPE) followed by supplemental heating costs (21% of RPE). This latter cost is much higher than in tokamaks where the heating is only needed for a few seconds for each burn cycle to heat to ignition. Including in the indirect costs of 722 million dollars, we find the total of direct and indirect costs is 2,785 million dollars. The total capital costs are calculated for both constant dollar (1980) and current dollar (1988) conditions assuming an 8 year construction time. These calculations reveal a constant dollar capital cost of 2130

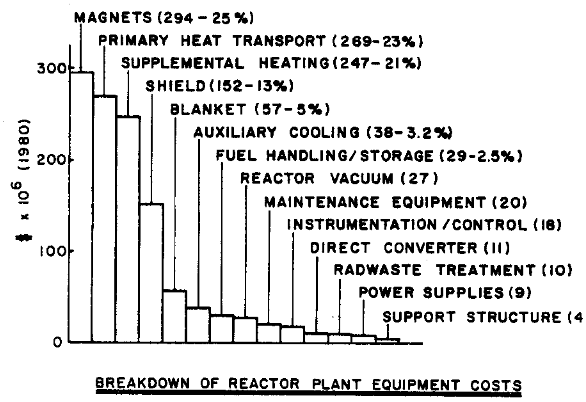


Figure 12.

Table 5

Summary of WITAMIR-I Power Parameters

DT power released in central cell - MW	3000
Neutron energy to blanket - MW	2400+13[a]
Blanket and shield multiplication	1.37
Total neutron power - blanket - MW	2987
Total neutron power shield - MW	310
Power to first wall - MW	29
Power from beams collected by steam cycle - MW	322
Total thermal power to steam cycle - MW	3649
Gross electric output steam cycle (η = 42%) - MW_e	1530
Total power to direct convertor - MW	502
Thermal power to plates - MW	114
Thermal power to grid - MW	52
Direct convertor efficiency - %	67
Net electrical power out - MW_e	330
Total gross electrical power reactor - MW_e	1860
Recirculating power - MW_e	330
Recirculating fraction - %	18
Net electrical output - MW_e	1530
Net efficiency - %	39.4

a) From kinetic energy of reacting ions

\$/kW_e (1980) and a current dollar cost of 3144 \$/kW_e (1988).

The cost of electricity from WITAMIR-I depends on capital, operation and maintenance (O&M), and fuel costs. Data from Table 7 show that the capital costs dominate the electricity costs (84-89% of the total) and they are followed by O&M costs (11-16%) and low fuel costs (< 1%). The electricity cost of 36.1 mills per kWh (based on an availability of 80%) is roughly half of the current dollar value (75.7 mills/kWh).

A comparison of capital and electricity costs of the tandem mirror reactor, WITAMIR-I, and the tokamak NUWMAK, is made in Table 8. Both reactors were costed on the same basis, by the same design group, and placed at the same dollar level. The main conclusion to be drawn from Table 8 is that, to the present level of understanding, both reactors cost the same and produce electricity at roughly the same value even though the reactor concepts are quite different. In some respects, NUWMAK represents a rather advanced design, invoking plasma physics and technologies that have yet to be proven in practice. However, NUWMAK is smaller (DT power 2100 vs. 3000 MW_{th}) and that may make it somewhat more expensive than WITAMIR-I on a per kW_e basis. Nevertheless, it is encouraging that the first full scale tandem mirror design has come so close to the economic assessment of the more advanced tokamak systems.

Conclusions

The WITAMIR-I reactor has several positive features that make it an attractive fusion power system compared to past tokamak designs.

Table 6

Summary of Estimated WITAMIR-I Costs

Account	Category	Constant Dollar x 10^6(1980)	Current Dollar x 10^6 (1988)
	Direct Costs		
20	Land and land rights	3	
21	Structure and site facilities	129	
22	Reactor plant equipment	1565	
23	Turbine plant equipment	200	
24	Electric plant equipment	145	
25	Miscellaneous plant equipment	18	
26	Special materials	3	
		2063	
	Indirect Costs		
91	Construction facilities	309	
92	Engineering and construction	309	
93	Owner's cost	103	
		722	
Total Direct and Indirect Costs		2785	2785
Time Related Costs		474	2024
Total Capital Costs		3259	4210
Capital Costs of WITAMIR-I (1530 MW_e) \$/kWe		2130	3144

Table 7

WITAMIR-I Cost of Electricity

mills/kWh

	Constant 1980 \$	Current Dollar 1988 \$
Capital	30.4	67.3
O & M	5.6	8.3
Fuel	0.1	0.1
	----	----
	36.1	75.7

Table 8

Comparison of Plant and Busbar Costs Between

WITAMIR-I and NUWMAK

	Constant Dollars (1980)	Current Dollars (1988)
Plant Costs		
WITAMIR-I	\$2130/kW_e	\$3144/kW_e
NUWMAK	\$2227/kW_e	\$3288/kW_e
Busbar Costs		
WITAMIR-I	36.1 mills/kWh	75.7 mills/kWh
NUWMAK	37.5 mills/kWh	79 mills/kWh

1.) Its steady-state power production eliminates the critical fatigue problems, both in the first wall and magnets, which have plagued the tokamak reactor designs for a decade.

2.) The linear geometry makes maintenance of the most highly damaged sections relatively easy.

3.) The lack of high first wall heat fluxes, plasma disruptions, or high magnetic fields in the neutron damage region makes blanket design relatively simple and allows more effective use of liquid metals.

4.) The use of a direct convertor allows a relatively high overall net electrical efficiency to be attained (~ e.g. 39% in WITAMIR-I).

5.) The decoupling of the highest technology components (i.e., end plug regions) from the intense neutron flux allows competitive capital and electricity costs to be attained. This is especially true relative to tokamak reactors which have had a longer history of study.

6.) Radiation streaming is much more manageable in WITAMIR-I than in tokamaks due to the absence of large penetrations to the reaction chamber. There is a small solid angle opening to the plugs which is also shielded and contains a blocking shield to line of sight, on axis streaming.

Other features of WITAMIR-I that need to be highlighted are:

1.) With a plasma Q of 28 the recirculating power is only 18%, much lower than past reactor designs.

2.) The use of the thermal barrier concept allows relatively high neutron wall loadings to be attained with modest extrapolations of current magnet and neutral beam technology. There are two exceptions to that statement, but neither is expected to present insurmountable problems:

A.) The design of the cylindrical superconducting barrier coil operating at a maximum field of 15T.

B.) The construction of ~ 40 MW of 500 keV, steady-state negative ion neutral beams to deliver 18 MW to the end plug plasmas.

3.) The damage induced by neutrons streaming into the end plug region does not appear to be a major problem. This is due to geometrical and R^{-2} effects.

4.) The physics basis for the thermal barrier concept needs to be verified experimentally (presumably in MFTF-B). Also, the stability limits to achieve reasonable central cell beta values of ~ 40% need to be verified.

5.) The cost of ECRH power needs to be carefully assessed. For example, if the ~ 100 MW of ECRH power in WITAMIR-I costs $1/Watt delivered, then this 100 million dollars represents a manageable amount of investment. However, should the cost of ECRH power rise to $5.00/Watt, then $500 million dollars would be needed for heating electrons, probably more than can be economically included in the capital costs.

Finally, it is our overall conclusion that tandem mirrors with thermal barriers represent a sufficiently attractive concept that further study is highly desirable. Such reactor concepts could make more attractive technology and materials test facilities than can be the case for tokamaks and future studies should explore these possibilities.

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References

1. B. Badger et al., "UWMAK-I, A Wisconsin Tokamak Reactor Design," University of Wisconsin Fusion Engineering Program Report UWFDM-68, Vols. I and II, 1974.

2. B. Badger et al., "UWMAK-II, A Conceptual Tokamak Power Reactor Design," University of Wisconsin Fusion Engineering Program Report UWFDM-112, 1975.

3. B. Badger et al., "UWMAK-III, A Noncircular Tokamak Power Reactor Design," University of Wisconsin Fusion Engineering Program Report UWFDM-150, 1976.

4. R. G. Mills et al., "A Fusion Power Plant," MATT-1050, Princeton Plasma Physics Laboratory, 1974.

5. A. P. Fraas, "Conceptual Design of the Blanket and Shield Region and Related Systems for a Full Scale Toroidal Fusion Reactor," ORNL-TM-3096, Oak Ridge National Laboratory, 1973.

6. R. Hancox, "Culham I Reactor Design," Int. School of Fusion Reactor Technology, Erice (1972) EUR-4999e, p. 135.

7. R. Hancox, MK-II Fusion Reactor Design, to be published.

8. B. Badger et al., "NUWMAK, A Tokamak Reactor Design Study," University of Wisconsin Fusion Engineering Program Report UWFDM-330, 1979.

9. C. C. Baker et al., "Starfire," to be published.

10. F. L. Ribe et al., "Engineering Design Study of a Reference Theta Pinch Reactor," in Fusion Reactor Design Problems, Nuclear Fusion Special Supplement, 1974, IAEA, Vienna, p. 99.

11. R. W. Werner et al., "Design Studies of Mirror Machines Reactors," p. 171, ibid.

12. T. K. Fowler and B. G. Logan, Plasma Physics 2, 167, 1977.

13. G. Dimov et al., Fiz. Pl. 2, 597, 1976.

14. D. E. Baldwin and B. G. Logan, Phys. Rev. Lett., 43, 1318, 1979.

15. B. Badger et al., "WITAMIR-I, A Tandem Mirror Reactor Study," University of Wisconsin Fusion Engineering Program Report UWFDM-400, Oct. 1980.

16. R. Cohen et al., Lawrence Livermore Laboratory Report UCRL-84147, 1980.

17. B. Badger et al., "SOLASE, A Laser Fusion Reactor," University of Wisconsin Fusion Engineering Program Report UWFDM-220, 1977.

18. P.A. Finn et al., "The Reaction of Li-Pb Alloys With Water," Trans. Am. Nucl. Soc. 34, 55, 1980.