WITAMIR-I: A TANDEM MIRROR POWER REACTOR

G.A. EMMERT*, G.L. KULCINSKI*, J.B. BEYER*,
W. MAURER**, C.W. MAYNARD*, J. SANTARIUS*,
J.E. SCHARER*, D. SCHLUDERBERG***,
I. SVIATOSLAVSKY*, D.K. SZE*, W.F. VOGELSANG*

* Nuclear Engineering Department,
University of Wisconsin,
Madison, Wisconsin,
United States of America

** Kernforschungszentrum Karlsruhe GmbH,
Karlsruhe,
Federal Republic of Germany

*** Babcock and Wilcox,
Lynchburg, Virginia,
United States of America

Abstract

A conceptual design of a near term commercial tandem mirror power reactor will be presented. The basic configuration utilizes Yin-yang minimum B end plugs with inboard thermal barriers, which are pumped by neutral beam injection. 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 breeder, and HT-9 as the structural material. This configuration yields a high energy multiplication (1.37), a sufficient tritium breeding ratio (1.07) and has a major advantage with respect to maintenance. A single stage direct convertor is used at one end and an electron thermal dump at the other end. The plasma Q is 28 at a fusion power level of 3000 MW_{th}; the net electrical output is 1530 MWe and the overall efficiency is 39%. Cost estimates indicate that WITAMIR-I is competitive with recent tokamak power reactor designs.

1. 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

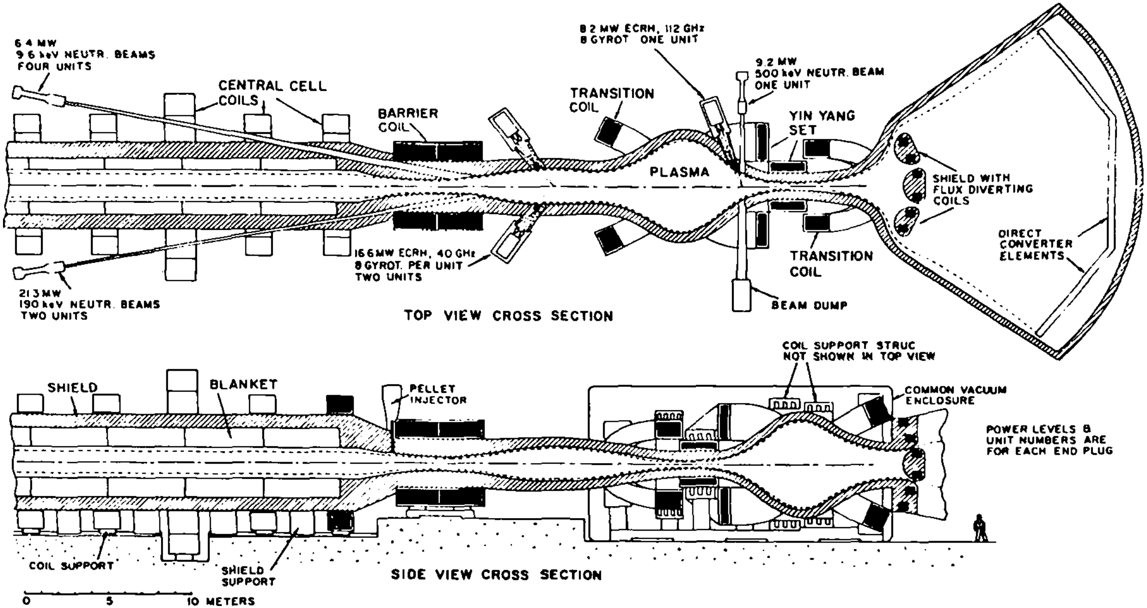

FIG. 1. Cross sectional view of WITAMIR-I, a Wisconsin conceptual tandem mirror fusion power reactor design.

emerged. The major areas where improvement is desired are: (1) maintainability, which is made difficult by the toroidal geometry and interlocking coil configurations; (2) the pulsed nature of the burn cycle which induces fatigue problems; (3) the need for exotic divertor or limiter designs for impurity control; (4) the low engineering power density (~ 1 MW_{th}/m^3), which results in rather high capital costs.

In 1976 the tandem mirror concept was simultaneously suggested both in the U.S. [10] and in the USSR [11] and it had Q's (fusion power/input power) 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 [12] introduced the thermal barrier concept into the tandem mirror configuration which allowed much higher Q's (~ 10 to 20) 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 [13] and only the major results will be reported here.

2. General Design Features

The basic configuration of WITAMIR-I is a long (165 m) solenoidal central cell terminated by inboard thermal barrier and a yin-yang minimum-B plugs. A cross sectional view of the WITAMIR-I reactor is shown in FIG. 1 while Table I summarizes its major parameters. 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.

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 particle end loss from the plasma, the net plant output is 1530 MW_e. The recirculating power fraction is only 18%, a relatively low value for mirror reactor concepts.

Table I. 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 magnetic fields in the central cell and yin yang coils are relatively modest with maximum fields at the conductors of 6.1 T and 8.1 T, respectively. The most difficult problem is 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 utilizes HT-9 as the structural and reflector material and $Pb_{83}Li_{17}$ as the 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 have been designed to date.

3. Plasma Considerations

The on-axis magnetic field, potential, and particle density profiles for one end of WITAMIR-I are shown in FIG. 2. The potential ϕ_b is created by the density drop from neutral beam

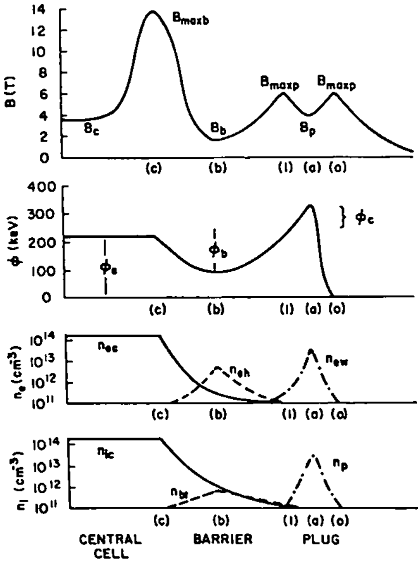

FIG. 2. Axial profiles of magnetic field, potential, and density in WITAMIR-I.

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 into the plug, and ϕ_e is the potential of the central cell relative to the end wall. The hot electron density, n_{eh}, is created by RF heating at the barrier center. The pumping parameter, g_b, is the ratio of total barrier ions to passing ion density. Table II summarizes the major plasma parameters in the plug, central cell, and barrier regions.

A detailed description of the plasma physics model used to calculate the plasma parameters in Table II is contained in Ref. 13 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 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.

Table II. 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	
Mean hot electron energy, E_{eh}	270. keV
Pumping parameter, g_b	2.0
Potential, ϕ_b	141. keV
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
Beta, β_p	0.64
Plasma radius	0.77 m
$(n\tau)_{ip}$	9.8×10^{13} sec cm^{-3}

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. Because of the large plug radius coupled with the low density and high beta, the plug plasma is expected to be stable against the drift-cyclotron-loss-cone mode. A sloshing ion distribution in the plug with trapping of warm plasma could be used to improve stability against other possible microinstabilities as well.

Trapped ions are removed from the thermal barriers by selective ion charge exchange using neutral beam injection at

10° to the magnetic field. This requires 42.5 MW of 190 keV and 12.8 MW of 9.6 keV D^0 beams. Refuelling of the central cell is accomplished by ionization of the barrier pump beams and by pellet injection. The electrostatic potential in the barrier is further depressed by the creation of a hot, magnetically trapped species of electrons in the barrier. This requires 33.2 MW of ECRH power which is provided by gyrotrons and transported to the plasma using a beam waveguide system. While the use of ECRH in the barrier lowers some technology requirements and allows a somewhat higher Q, a tandem mirror without barrier ECRH is still viable.

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 machine.

4. 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. 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 have a maximum of 2000 A/cm^2 which is in the NbTi, and Cu is used as the stabilizing material for the entire barrier coil design. The total weight of all the 44 magnets is 5762 tonnes.

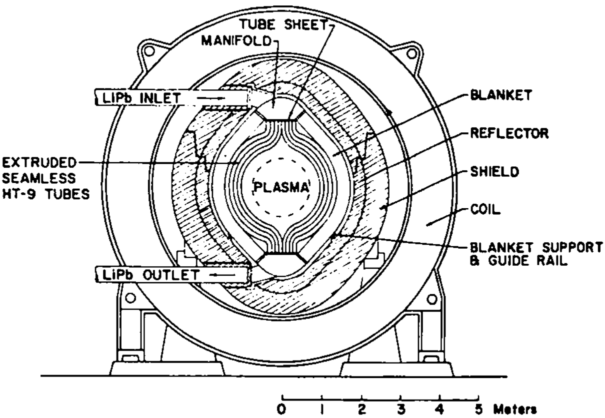

FIG. 3. Cross section of WITAMIR-I central cell.

5. Blanket and Shield Design

A schematic of the WITAMIR-I blanket and shield design is shown in FIG. 3 and Table III lists the important operating characteristics. 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 III. 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}

The excellent neutronic properties of the Pb-Li alloy allow one of the highest blanket multiplication factors (1.37) to be attained of any reactor that we have designed thus far. 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 [15], 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 total afterheat in the blanket and shield of 24 MW at shutdown is only 0.8% of the heat generated in the blanket

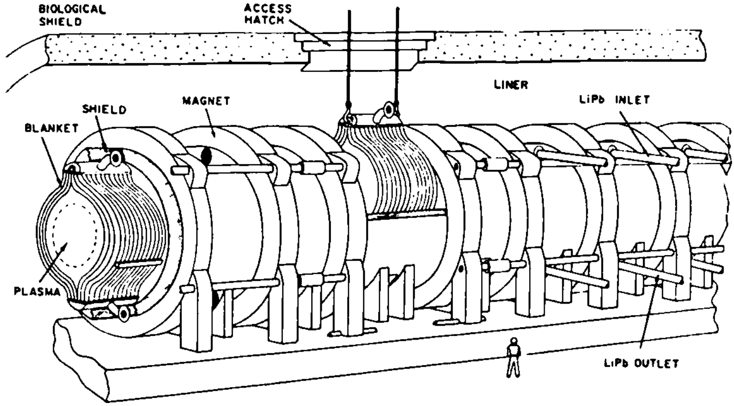

FIG. 4. Isometric view of WITAMIR-I central cell showing blanket replacement procedure.

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 x 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.

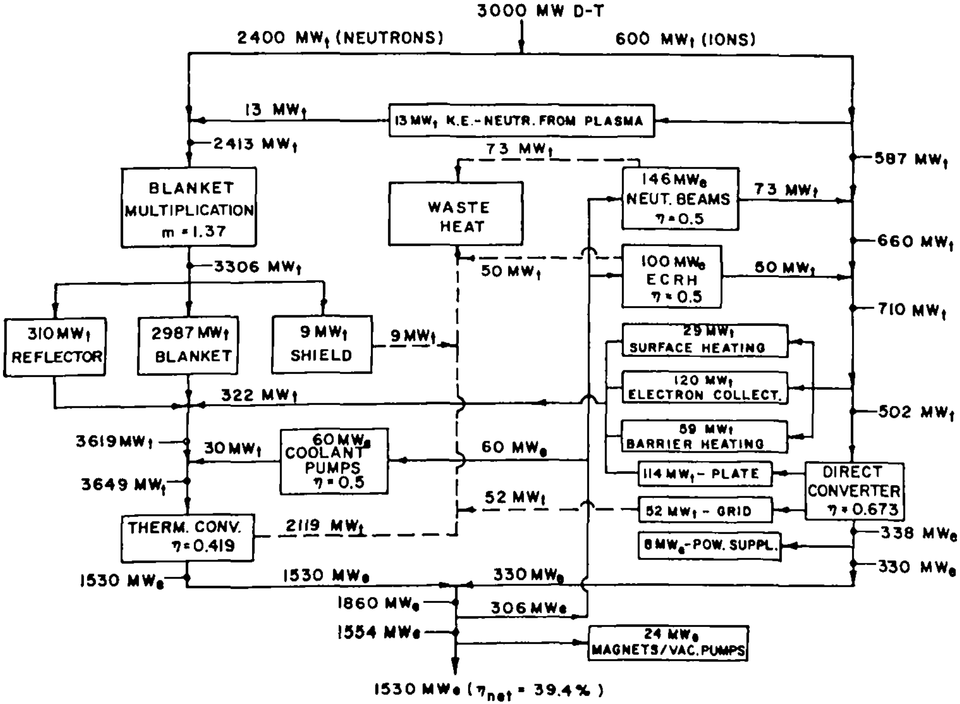

FIG. 5. Power flow diagram for WITAMIR-I.

The procedure for replacing the blanket modules is shown in FIG. 4. The central cell magnets on either side of the blanket module to be replaced are moved axially 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.

6. 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 a direct convertor. FIG. 5 summarizes the important parameters in this regard. The DT fusion power is 3000 MW. With a blanket energy multiplication of 1.37 and recovery of the heat removal from the direct convertor and surface heating in the barrier and central cell, the thermal power to the primary heat exchanges is 3649 MW. The gross efficiency of the steam cycle is 42%.

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.

7. 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". Graphical representation of the reactor plant equipment cost components is given in FIG. 6.

It is found that 76% of the direct costs of WITAMIR-I are related to the Reactor Plant Equipment (RPE) and ~ 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

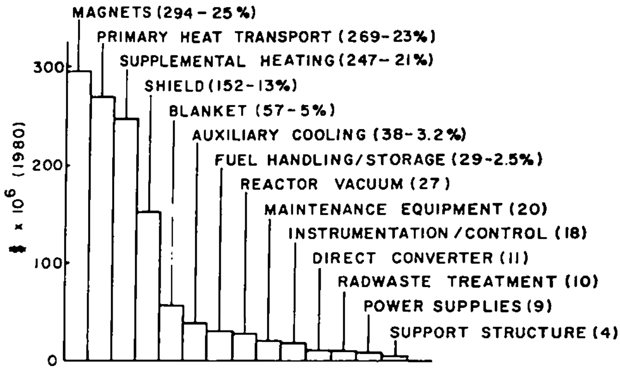

FIG. 6. Breakdown of reactor plant equipment costs.

Table IV. 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

few seconds for each burn cycle to heat to ignition. Adding 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 \$/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. 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 constant dollar 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 IV. 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 IV 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.

8. Conclusions

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

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. This results in a high energy multiplication ratio in the blanket.

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 TMX-Upgrade). 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.

Acknowledgment

The authors of this report would like to acknowledge the partial support of this study from the Department of Energy - Office of Magnetic Fusion, and the Wisconsin Electric Utilities Research Foundation. We are grateful to the Karlsruhe Nuclear Laboratory in the Federal Republic of Germany and to the People's Republic of China for participation of their scientists in this program. We also wish to thank Mr. Dennis Bruggink, Ms. Linda Kraft, Ms. Beth Brown, and Ms. Gail Herrington for their assistance in this project.

References

[1] BADGER, B., et al., UWMAK-I, A Wisconsin Tokamak Reactor Design, University of Wisconsin Fusion Engineering Program Report UWFDM-68 Vols. I and II (1974).
[2] BADGER, B., et al., UWMAK-II, A Conceptual Tokamak Power Reactor Design, University of Wisconsin Fusion Engineering Program Report UWFDM-112 (1975).
[3] BADGER, B., et al., UWMAK-III, A Noncircular Tokamak Power Reactor Design, University of Wisconsin Fusion Engineering Program Report UWFDM-150 (1976).
[4] MILLS, R.G., et al., A Fusion Power Plant, Princeton Plasma Physics Laboratory MATT-1050 (1974).
[5] FRAAS, A.P., Conceptual Design of the Blanket and Shield Region and Related Systems for a Full Scale Toroidal Fusion Reactor, Oak Ridge National Laboratory ORNL-TM-3096 (1973).
[6] HANCOX, R., "Culham I Reactor Design," Int. School of Fusion Reactor Technology, Erice, EUR-4999e (1972) 135.
[7] HANCOX, R., MK-II Fusion Reactor Design, to be published.
[8] BADGER, B., et al., NUWMAK, A Tokamak Reactor Design Study, University of Wisconsin Fusion Engineering Program Report UWFDM-330 (1979).
[9] BAKER, C.C., et al., Starfire - A Commerical Tokamak Fusion Power Plant Study, Argonne National Laboratory Report ANL/FPP-80-1 (1980).
[10] FOWLER, T.K., LOGAN, B.G., Plasma Physics 2 (1977) 167.

[11] DIMOV, G., et al., Fiz. Pl. 2 (1976) 597
[12] BALDWIN, D.E., LOGAN, B.G., Phys. Rev. Lett. 43, (1979) 1318
[13] BADGER, B., et al., WITAMIR-I, A Tandem Mirror Reactor Study, University of Wisconsin Fusion Engineering Program Report UWFDM-400 (Oct. 1980).
[14] Physics Basis for MFTF-B, (BALDWIN, D.E., LOGAN, B.G., SIMONEN, T.C., Eds.) Lawrence Livermore National Laboratory Report, UCID-18496 (1980).
[15] FINN, P.A., et al., The Reaction of Li-Pb Alloys With Water, Trans. Am. Nucl. Soc. 34 (1980) 55.