CONF-820347--2
UCRL-87407
PREPRINT

UCRL--87407

DE82 015190

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This paper was prepared for submittal to
US-Japan Seminar/Workshop (A-19)
Open Systems Studies
Institute of Plasma Physics
Nagoya University, Nagoya, Japan
March 15-19, 1982

March 9, 1982

Lawrence Livermore Laboratory

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Abstract

We discuss the evolution of the tandem mirror reactor concept from the original conceptual reactor design (1977) through the first application of the thermal barrier concept to a reactor design (1979) to the beginning of the Mirror Advanced Reactor Study (1982).

* Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Original Tandem Mirror Concept

The tandem mirror confinement scheme was invented in 1976 by Fowler and Logan[1] at Livermore and independently in the USSR by Dimov.[2] A magnetic mirror cell, commonly called a plug, is located at each end of a cylindrical central cell which contains the fusion plasma. The fundamental concept is to use the positive potential of the mirror-confined plug plasmas to provide electrostatic axial confinement of plasma in the central cell. In the original concept, the confining potential was produced by plug plasmas of considerably higher density than the central cell plasma.

Three tandem mirror experimental facilities have successfully operated as proof-of-principle demonstrations of this concept. These are GAMMA-6 at the University of Tsukuba, TMX at Lawrence Livermore National Laboratory, and Phaedrus at the University of Washington. The TMX end plugs improved confinement of the central cell plasma by up to a factor of 9 over that which would have been attained if the end plug plasmas had not been present.[3] The experiments have also verified that overall MHD stability can be provided by minimum-B plugs.

Although straightforward, the extrapolation of the original tandem mirror concept to the reactor regime is technologically difficult because the high density plugs lead to high magnetic fields and high neutral beam injection energies. A preliminary tandem mirror reactor design, carried out at Livermore in 1977, required very high magnetic fields (> 17 T) in the large and complicated minimum-B plugs and very high energy neutral beams (1.2 MeV).[4] A short list of parameters for this design is given in the first column of Table 1. Even with the advanced technology plugs, the plasma Q (ratio of fusion power to trapped injected power) for this design was marginal ($\sim$ 5). However, the technological simplicity of the central cell of the tandem mirror reactor encouraged an intensive search for end plug improvements.

An improved design incorporating RF electron heating in the plugs and auxiliary mirror cells (A-cells) at each end of the machine was reported in 1979.[5] The purpose of the A-cell was to reduce the outward potential drop of the plug plasma and thus improve the plug confinement.

Parameters for this design are given in the second column of Table 1. The improvements allowed a reduction in neutral beam energy to 400 keV and

Table 1. Evolution of TMR parameters

	Original (1977)	Improved (1979)	WITAMIR-I (1980)	LLNL Axicell (1981)	MARS (1982, preliminary)
DT fusion power	2540	3000	3000	3500	3500
Wall loading, MW/m^2	2.0	1.3	2.4	2.3	4.8
Highest NBI energy, KeV	1200	400	500	250	300
Max on-axis magnetic field in minimum-B region, T	17	12.7	6	4	4.5
Highest on-axis B field in circular plug coils, T	--	--	14	20	28
Plasma Q value	5	10.5	28	22	24
Central cell length, m	100	320	165	150	150
RF electron heating	No	Yes	Yes	Yes	Yes
Thermal barrier	No	No	Yes	Yes	Yes

some reduction in plug magnetic field strength. Q increased to over 10, but the first wall neutron loading decreased to 1.3 MW/m^2, primarily because the central cell was designed to be long and thin. (This tandem mirror design strategy always increases Q at the expense of wall loading because it decreases the ratio of plug to central cell plasma volume.) A fundamentally limiting feature of the RF heating considered here was that the electron temperature rose everywhere, thus requiring a reduction in central cell ion density and fusion power for a given central cell magnetic field.

Thermal Barrier Concept

A solution to the above-mentioned limitation of RF heating is to heat the plug electrons to high temperature in order to obtain a large confining potential, but to avoid heating the central cell electrons. The thermal barrier, invented by Baldwin and Logan at Livermore in 1979, allows one to do this by insulating the plug electrons from those in the central cell.[6] The thermal barrier is a region of reduced magnetic field, plasma density, and plasma potential between the central cell and the plug. The potential depression reflects most central cell electrons, thus decoupling the central cell electron temperature from that in the plugs. A higher plug electron temperature is achieved by electron cyclotron resonant heating (ECRH). The reactor implications of the thermal barrier are striking: substantially higher Q (> 20) at reduced plug magnetic field strengths (8 to 12 T for minimum-B coils, higher for circular plug coils) and injection energies (200-500 keV).

Experimental verification of the thermal barrier concept must await the operation of several new experimental facilities. The first of these will be TMX-U at Livermore in 1982, followed by GAMMA-10 at Tsukuba in 1983. The large MFTF-B facility under construction at Livermore (scheduled for completion in 1985) also incorporates thermal barriers.

A number of end plug configurations have been considered for tandem mirrors with thermal barriers. A summary of most of the configurations is presented in Fig. 1. The various designs differ in the relative placement of the thermal barrier, the confining potential, and the MHD "anchor." Across the width of the figure there are two major types of design: one with

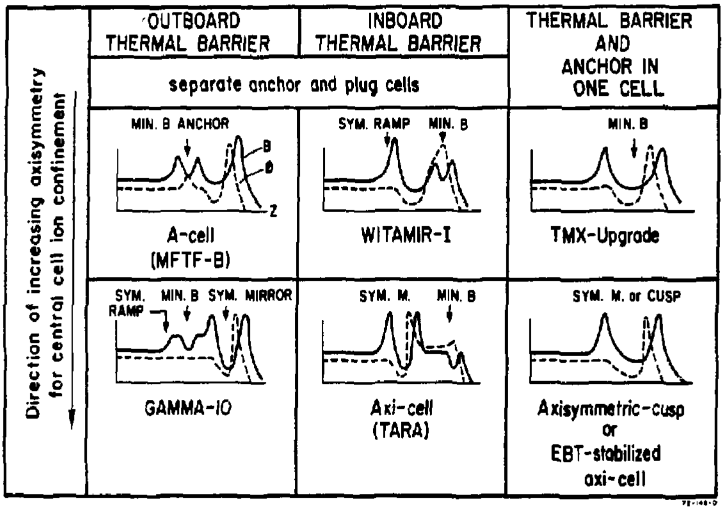

Fig. 1. Thermal barrier configurations

separate mirror cells for the anchor and thermal barrier and one with the anchor and thermal barrier combined in a single cell. Of the former type there are two subtypes: outboard barrier and inboard barrier. The figure shows two examples of the outboard barrier and two of the inboard. In three of these examples the potential peak is created in the same cell as the thermal barrier; in the fourth example (Witamir-I) the potential peak is created in the anchor. From the first row of the figure to the second there is an increase in the axisymmetry of the central cell ion confinement, that is, more of the central cell ions are reflected in a region of axisymmetry. This feature is expected to be advantageous in reducing radial transport, although quantitative estimates of such transport are still uncertain.

Several conceptual reactor designs have been completed for tandem mirrors with thermal barriers and are discussed in the following sections. The designs differ primarily in the magnetic configuration of the end plugs.

Inboard Barrier

The first configuration to be investigated, an inboard barrier, was used for reactor designs at both Livermore (1979)[7] and the University of Wisconsin (Witamir-I, 1980).[8] The end plug magnets consist of a high field circular coil followed by a transition coil and a yin-yang pair. The thermal barrier is created between the circular coil and the yin-yang pair; the potential peak is created inside the yin-yang, which also serves as the MHD anchor. An overview of the Livermore design is shown in Fig. 2. The final, outward-facing, C-shaped coil is an optional circularizing coil to permit the use of a circular cross-section direct converter. Parameters for the Witamir-I design are given in Tables 1 and 2. There is a significant increase in performance over previous tandem reactor designs. The neutron wall loading has increased to over 2 MW/m^2 and Q has increased to 28 while the plug technology requirements have eased considerably.

A possible problem with this inboard barrier configuration is that bad drifts in the barrier may prevent mirror confinement of hot electrons there (useful for enhancing the depression of the barrier potential). Microstability of the yin-yang plugs is also a concern for the designs developed so far, as yin-yang mirror ratios greater than the assumed 1.5 will probably be

Table 2. Tandem mirror power reactor designs

	WITAMIR-I (1980)	LLNL Axicell (1981)	MARS (1982, preliminary)
Power Parameters			
DT power, MW	3000	3500	3500
Plasma Q	28	22	24
Net electrical output, MW	1530	1065	1140
System efficiency	39%	26%	28%
Recirculating power fraction	18%	34%	31%
Neutron wall loading, MW/m^2	2.4	2.3	4.8
Magnetic Fields (on-axis), T			
Central cell	3.6	3	4.7
Circular plug coil	14	20	28
Min-B coil, mirror/midplane	6/2	4/2	4.5/1.5
Neutral Beam Requirements			
Anchor			
Energy, keV	500	150	150
Injected power, MW	18	15	28
Species	H^0	D^0	D^0
Barrier (including pump beams)			
Max energy, keV	190	250	300
Injected power, MW	55	167	161
Species	D^0	D^0	D^0
RF Requirements (ECRH)			
Frequency, GHz	40/122	64/128	100/150
Injected power, MW	33/17	43/9	31/14

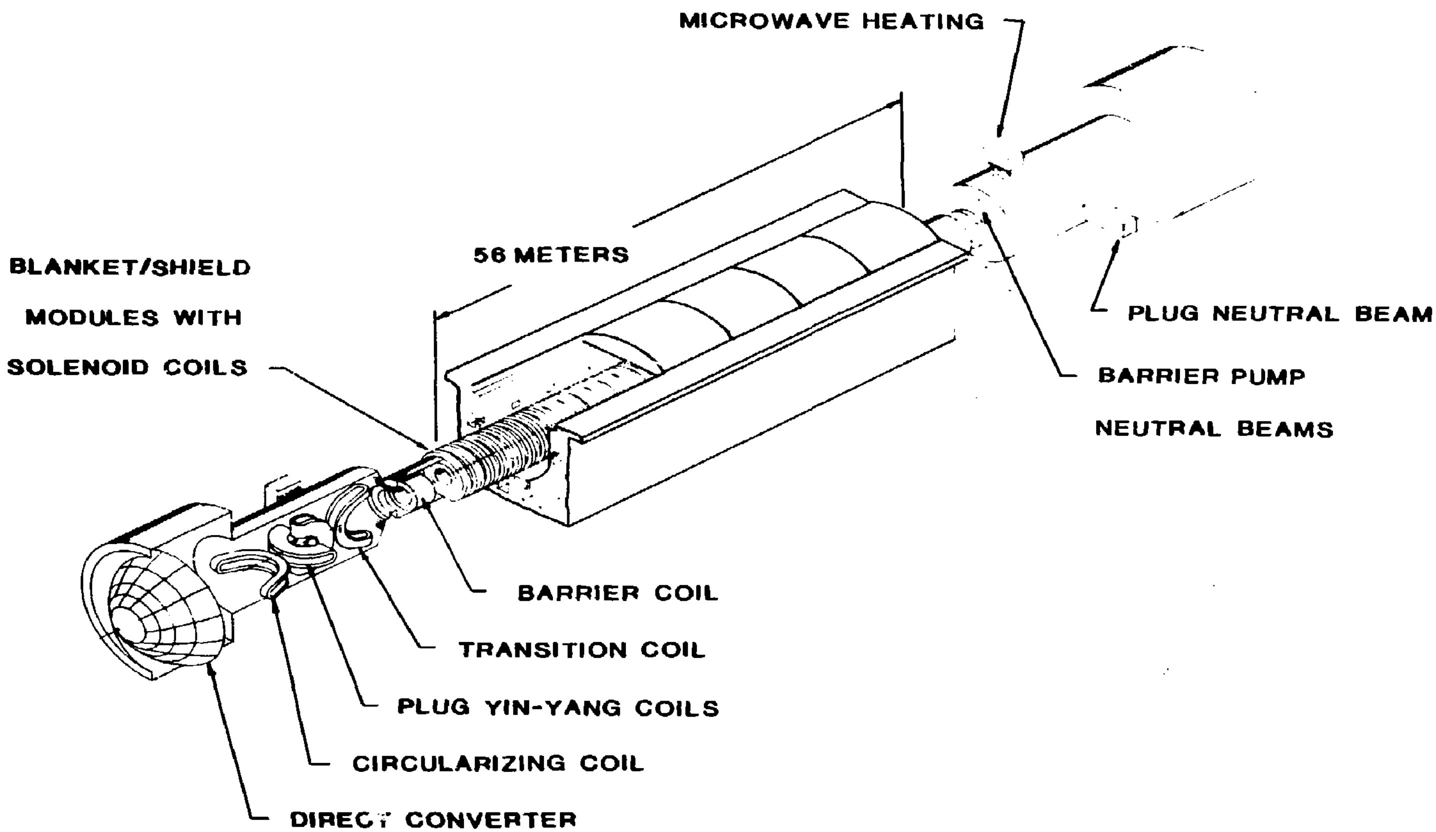

Fig. 2. 500 MWe tandem mirror reactor with inboard barrier

required to allow for sloshing ions.

A-Cell Barrier

The next end plug configuration to be investigated at Livermore was the A-cell configuration, consisting of a transition coil, a yin-yang pair, and a C-shaped coil oriented the same as the outer coil of the yin-yang pair.[9] Figure 3 shows the A-cell configuration. Both the thermal barrier and the potential peak are created in the auxiliary mirror cell (the A-cell) between the yin-yang and the C-coil, whereas mirror-confined ions in the yin-yang cell serve mainly to provide MHD stability. The large MFTF-B facility under construction at Livermore uses the A-cell configuration. The A-cell configuration alleviates some of the inside barrier concerns: mirror-trapped hot electrons can be used to enhance the barrier potential depression and microstability is provided by passing ions in the yin-yang and sloshing ions in the high mirror ratio A-cell. Unfortunately, A-cell reactors are predicted to be expensive because of the requirement for large, high field yin-yangs and A-cell coils to achieve acceptable performance.

For the A-cell reactor design the on-axis magnetic field strengths at the cardinal points were:

Central cell field, B_c = 3.4 T
Inner and outer yin-yang mirror fields, B_m = 9 T
Yin-yang midplane field, B_0 = 6 T
Minimum field in the A-cell, B_b = 2.3 T
A-cell mirror field, $B_{m,a}$ = 9 T

We discuss the comparison of the A-cell reactor with other designs in a later section.

Axisymmetric Cusp Barrier

Figure 4 shows the end plug magnets for the axisymmetric cusp configuration considered at Livermore.[9] (This present configuration is modified from the originally proposed cusp configuration,[10] which was found to be unacceptable due to poor alpha particle confinement.[11]) The plug coil arrangement consists of a high field solenoid followed by a concentric pair of solenoids. The current of the inner concentric coil opposes the current of

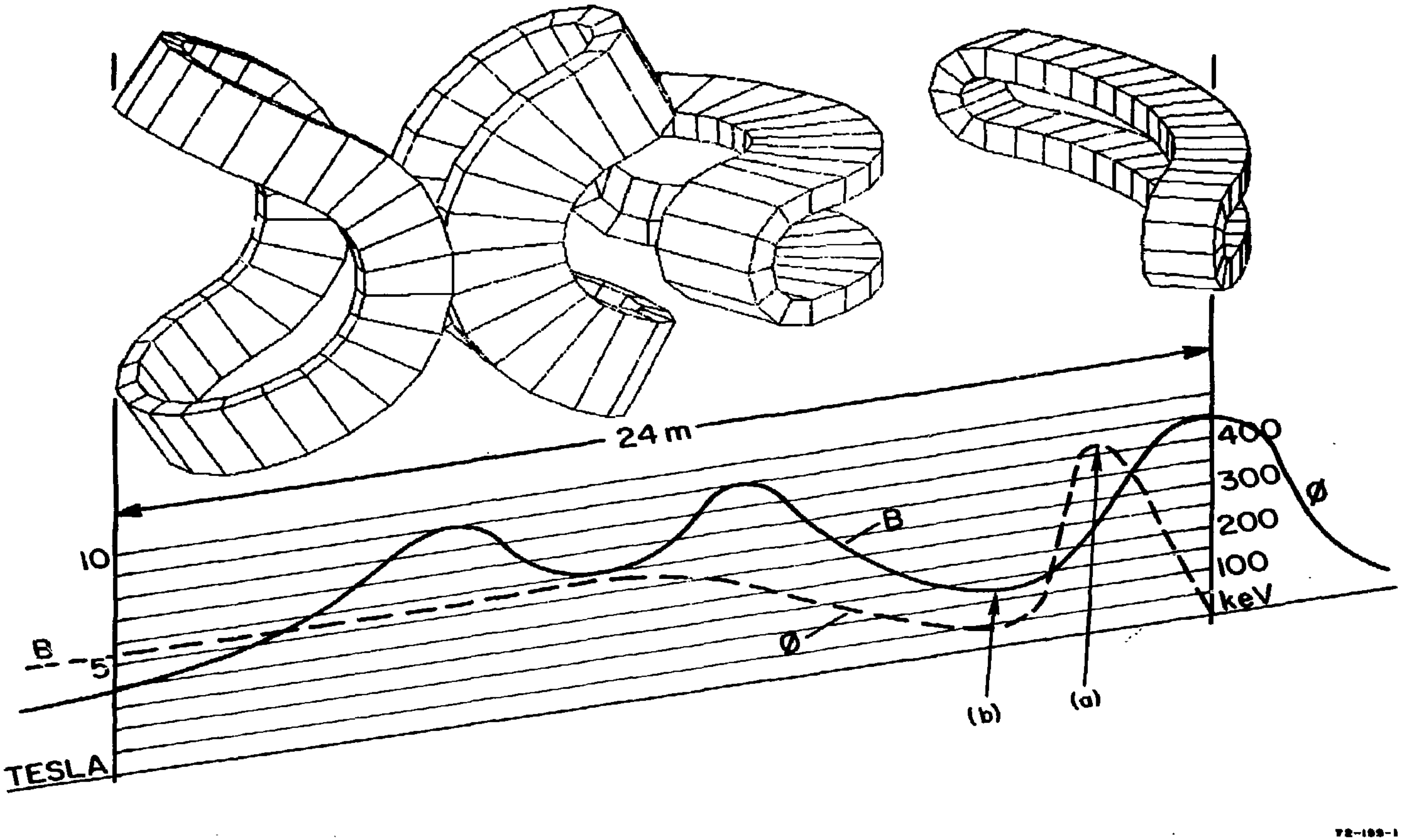

Fig. 3. End plug magnets for A-cell TMR

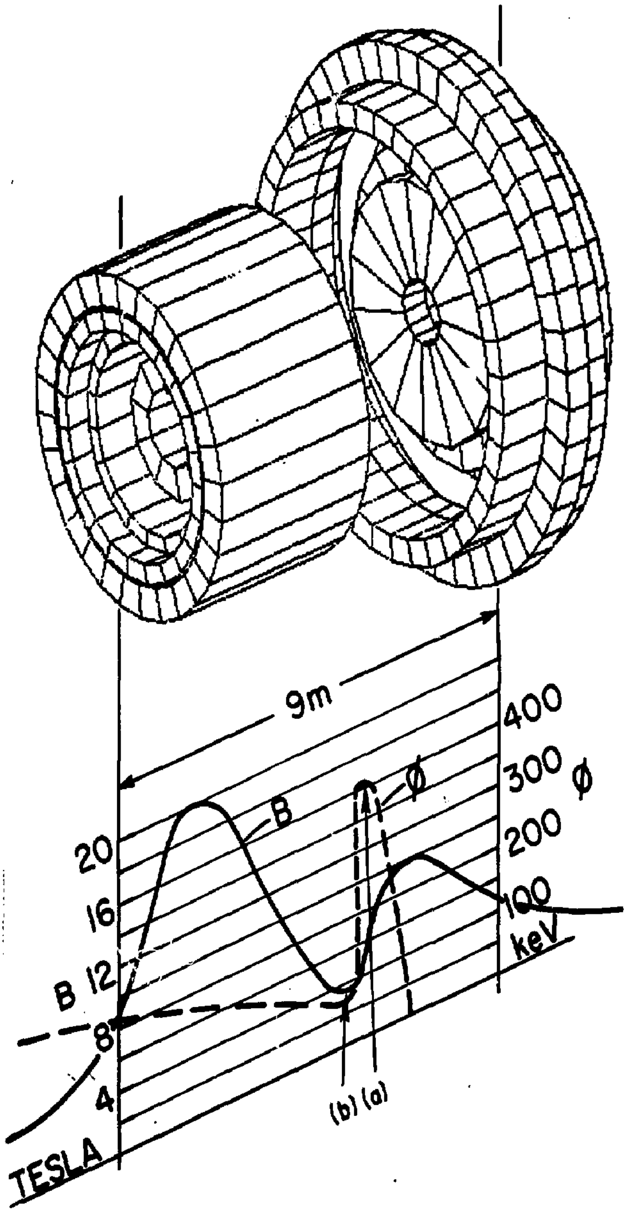

Fig. 4. End plug magnets for axisymmetric cusp TMR

all the other coils and produces a field null on the axis of the machine. A hollow plasma forms because of nonadiabatic losses near the axis. The magnetic flux bundle from the central cell passes as an annulus between the concentric solenoids. This configuration produces only one mirror cell, between the high field solenoid and the concentric pair of solenoids. Both the thermal barrier and the final potential peak are created in this mirror cell. MHD stability is obtained by a combination of favorable magnetic curvature and (for the inner radial region) hot electron stabilization or plasma rotation due to the radial electric field.

For the cusp reactor design the magnetic field strengths at the cardinal points were:

Central cell field, $B_c = 3.5$ T
Solenoid mirror field, $B_{m1} = 20$ T
Annulus minimum field, $B_b = 2.5$ T
Annulus mirror field, $B_{m2} = 9$ T

The 20 T inner mirror field is created by a compact, radially-zoned solenoidal coil composed of normal copper (inner zone) and superconducting Nb_3Sn and NbTi (outer zones). The maximum superconductor field strength is 14 T. We discuss the comparison of the cusp reactor with other designs in a later section.

Axicell Barrier

Figure 5 shows the end plug magnets for the axicell reactor design done at Livermore.[9] The plug coil arrangement consists of an axially spaced pair of solenoids (the first stronger than the second) followed by a transition coil and a yin-yang pair. (In the present design as shown in Fig. 5, we have included a third solenoid, midway between the main two, with its current opposite the other coils' currents. This bucking solenoid serves to shorten the axicell, which advantageously reduces the plasma volume there.) This configuration creates two mirror cells, one between the solenoids and one in the yin-yang. The thermal barrier and the final potential peak are created in the axisymmetric cell while the outboard yin-yang (the anchor) provides a region of favorable curvature for MHD stability. Microstability of the anchor is provided by sloshing ions.

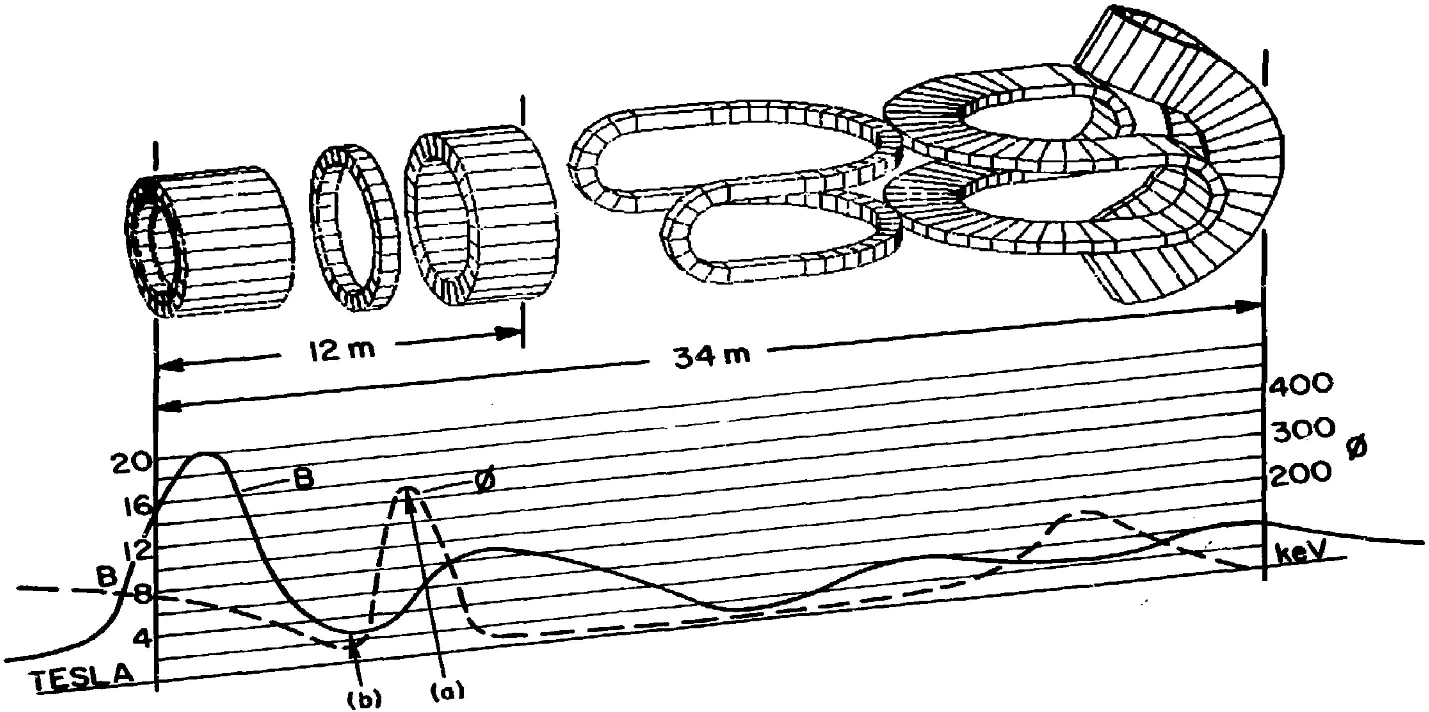

Fig. 5. End plug magnets for axicell TMR

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The on-axis magnetic field strengths at the cardinal points were:

Central cell field, B_c = 3 T

First axicell mirror field, B_{m1} = 20 T

Axicell *minimum* field, B_b = 2.3 T

Second axicell mirror field, B_{m2} = 9 T

Inner and outer yin-yang mirror fields, B_m = 5.0 and 4.4 T

Yin-yang midplane field, B_0 = 2 T

The first axicell mirror is provided by the same radially-zoned solenoid as used for the cusp reactor. Parameters for the axicell reactor are shown in Tables 1 and 2. In Table 2, the lower system efficiency and higher recirculating power fraction for the axicell reactor compared with Witamir-I is due partly to the lower Q and partly to the assumption of a lower energy multiplication in the blanket (1.2 instead of 1.37) and a lower thermal efficiency (35% instead of 42%). We discuss the comparison of the axicell reactor with other designs in the next section.

Comparative End Plug Study

In 1981, Livermore completed a comparative study of four thermal barrier configurations for a commercial tandem mirror reactor.[9] The first three configurations were the A-cell, the axisymmetric cusp, and the axicell discussed previously. The fourth case was a variant of the axicell which eliminated the transition coil and yin-yang pair and provided MHD stability by means of an EBT-type electron ring in the axicell.

To compare the various plug configurations on an equal basis, we coupled each end plug design with a 150-meter-long central cell producing 3500 MW of fusion power. Then we calculated the plasma performance, power balance, and capital cost for each reactor. Tables 3-6 present the results of the comparative study.

Table 3 shows the plasma parameters for the four cases. For the three cases with minimum-B stabilization, our MHD stability code predicts interchange stability and elimination of parallel current through the central cell at the β values listed in the table. All cases have the same neutron wall loading (due to the common central cell) but Q varies considerably. The cusp and the axicell have Q $\simeq$ 20 while the A-cell and axicell with EBT

Table 3. Plasma parameters from comparative end plug study

	A-Cell	Modified Cusp	Axicell	Axicell with EBT Stabilization
P_{FUSION}	3500 MW	3500	3500	3500
Q	10.3	19.7	22.3	12.2
Γ_{fw}	2.3 MW/m^2	2.3	2.3	2.2
Central Cell				
r_c	1.0 m	1.0	1.0	1.0
$r_{c,inner}$	--	0.5 m	--	--
r_{fw}	1.3 m	1.3	1.3	1.3
L_c	150 m	150	150	150
β_c	0.56	0.7	0.7	0.7
n_{ic}	$1.6 \times 10^{14} cm^{-3}$	2.2×10^{14}	1.6×10^{14}	1.6×10^{14}
T_{ic}	40 keV	40	40	40
T_{ec}	36 keV	33	32	33
ϕ_e	270 keV	260	240	240
Barrier/Plug				
L_B	8 m	7	8.6	8.6
β_B	0.63	0.61	0.71	0.36
n_{pass}	$5.0 \times 10^{12} cm^{-3}$	5.5×10^{12}	3.4×10^{12}	4.4×10^{12}
$E_{inj,B}$	350 keV	300	250	250
E_{eh}	520 keV	390	750	240
T_{ew}	93 keV	110	82	150
ϕ_B	230 keV	190	210	170
ϕ_c	150 keV	150	140	140
Anchor				
r_A	0.84 m		1.2	
β_A	0.7		0.3	
n_{iA}	$1.7 \times 10^{14} cm^{-3}$		1.5×10^{13}	
$E_{inj,A}$	200 keV		150	
E_{iA}	310 keV		150	
T_{eA}	--		32 keV	
ϕ_A	--		160 keV	
ϕ_{pc}	19 keV		--	

Table 4. Results of power balance analysis (all powers in MW)

	A-Cell	Modified-Cusp	Axicell	Axicell with EBT Stabilization
Trapped powers				
ECRH	97	60	47	154
Pump beams	148	98	93	97
Sloshing beams	66	20	12	35
Anchor beams	29	--	5	--
TOTAL	340	178	157	286
Injected powers				
ECRH	108	67	52	171
Pump beams	177	118	115	105
Sloshing beams	122	83	52	159
Anchor beams	30	--	15	--
TOTAL	437	268	234	435
Recirculated powers				
ECRH	216	134	104	342
Pump beams	354	236	230	210
Sloshing beams	244	166	104	318
Anchor beams	60	--	30	--
Copper coils	--	72	72	72
TOTAL	874	608	540	942
Thermal converter output	1176	1176	1176	1176
Direct converter output	520	439	429	493
TOTAL (Gross electrical)	1696	1615	1605	1669
$f_{REC} = \frac{\text{Recirculated power}}{\text{Gross electrical}}$	0.52	0.38	0.34	0.56
Net electrical power	822	1007	1065	727

Table 5. Costs in $M

	A-Cell	Modified Cusp	Axicell	Axicell with EBT Stabilization
Beams @$2/W injected	658	402	364	528
ECRH @$5/W injected	540	335	260	855
Plug magnets	628	251	302	175
Direct converter	158	83	152	127
Central cell	450	450	450	450
Reactor bldg.	165	154	162	149
BOP	470	470	470	470
TOTAL	3069	2145	2160	2754

Table 6. Costs in $/kWe

	A-Cell	Modified Cusp	Axicell	Axicell with EBT Stabilization
Beams @$2/W injected	800	399	342	639
ECRH @$5/W injected	657	333	244	1176
Plug magnets	764	249	284	212
Direct converter	192	82	143	152
Central cell	547	447	423	545
Reactor bldg.	201	153	152	180
BOP	572	467	441	569
TOTAL	3733	2130	2029	3473

stabilization have $Q \simeq 10$. The lower Q for the A-cell is due to the limiting mirror fields of the yin-yang and A-cell; the lower Q for the axicell with EBT stabilization is due to the lower barrier β consistent with present theory.

Table 4 shows the results of the power balance analysis for the four cases. The cusp and the axicell are superior (and nearly equal) in the production of net electrical power.

Table 5 shows the estimated direct capital cost for the four reactors. The cusp and the axicell are the least expensive, at 2.1 B$ and 2.2 B$, respectively. The A-cell is more expensive because of its requirement for more neutral beams and ECRH and its very expensive plug magnets. The axicell with EBT stabilization is more expensive because of its requirement for more neutral beams and ECRH, despite its less expensive plug magnets.

Finally, Table 6 shows the cost of power in units of $/kWe (direct capital cost divided by net electrical power). Again, the cusp and axicell are superior. Of these two configurations, we have chosen the axicell for further study because it retains the conservative yin-yang approach to MHD stability employed in many past and present mirror experiments.

MARS

To more fully characterize the tandem mirror reactor with axicell end plugs, Livermore has now begun a two-year Mirror Advanced Reactor Study (MARS) in collaboration with TRW and the University of Wisconsin. The end plug magnet configuration for MARS is the same as for the 1981 axicell design, but changes in magnetic field strengths are being investigated. The presently considered operating scenario is also the same as for the 1981 design, i.e., both the thermal barrier and the potential peak are created in the axisymmetric cell while the yin-yang serves only as an MHD anchor. An alternate scenario which might be considered would place the potential peak in the yin-yang.

A preliminary set of parameters for MARS are shown in Tables 1 and 2. Compared to the 1981 axicell design we have increased both the neutron wall loading and Q by increasing the first axicell mirror field (from 20 T to 28 T) and the central cell field (from 3 to 4.7 T). This improvement in performance was achieved despite the inclusion of a 10% density fraction of thermal alphas in the central cell plasma, a penalty which was ignored in the previous tandem mirror reactor designs.

An advantage of the higher central cell field in MARS is the reduced size of the magnetic flux bundle that must pass through the plug coils. Figure 6 compares the preliminary MARS magnet design with the 1981 axicell design. The outer diameter of the yin-yang anchor is reduced from 10.2 m to 6.2 m. (For comparison, the conductor bundle of the MFTF-B yin-yang is 5.8 m.)

We are now completing a parametric study which trades off the advantage of higher Q obtainable with high axicell mirror field with the disadvantage of increased cost and electrical input power for the hybrid normal/superconducting coils. Indications are that $B_{m1} \simeq 24$ T may be more optimal from the cost-of-power viewpoint than either 20 T or 28 T. Further parametric study and detailed component design and analysis will lead to a complete MARS conceptual reactor design by the end of 1983.

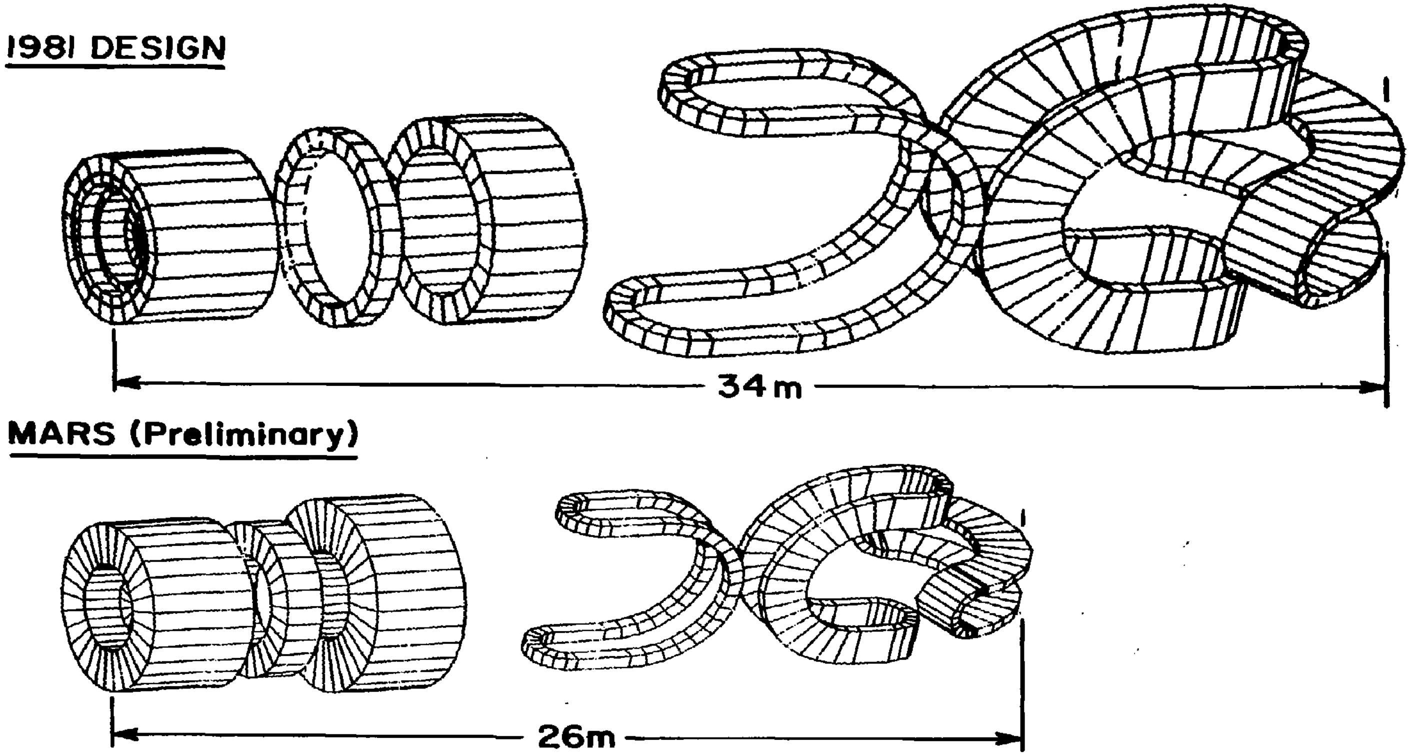

Fig. 6   Comparison of preliminary MARS end plug to 1981 axicell TMR

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