PREPRINT UCRL- 81149

CONF-780801--1

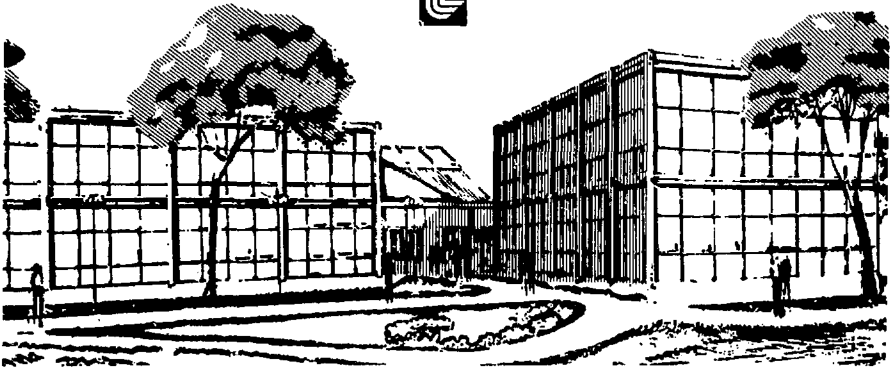
Lawrence Livermore Laboratory

MIRROR FUSION REACTORS

Gustav A. Carlson and Ralph W. Moir

19 May 1978

This paper was prepared for submission to
the Thirteenth Intersociety Energy Conversion Engineering
Conference, August 20 - 25, 1978 - San Diego, California



MASTER

MIRROR FUSION REACTORS

Gustav A. Carlson and Ralph W. Moir

Lawrence Livermore Laboratory
University of California
Livermore, California 94550

ABSTRACT

We have carried out conceptual design studies of fusion reactors based on the three current mirror confinement concepts: the standard mirror, the tandem mirror, and the field-reversed mirror. Recent studies of the standard mirror have emphasized its potential as a fusion-fission hybrid reactor, designed to produce fissile fuel for fission reactors. We have designed a large commercial hybrid based on standard mirror confinement, and also a small pilot plant hybrid. Tandem mirror designs include a commercial 1000 MWe fusion power plant and a nearer term tandem mirror hybrid. Field-reversed mirror designs include a multicell commercial reactor producing 75 MWe and a single cell pilot plant.

FIGURE 1 DEPICTS THE EVOLUTION of mirror fusion ideas as seen by researchers at Lawrence Livermore Laboratory. The early-conceived simple mirror proved to be an unstable plasma container and was replaced by the minimum $|B|$ mirror configuration. From the center of a minimum $|B|$ magnetic configuration, as produced by a pair of solenoids and Ioffe bars, a Baseball coil (shown in Figure 1), or a Yin-Yang coil, the magnetic field strength increases in all directions and ensures MHD stability for the plasma. We have come to call the minimum $|B|$ configuration a standard mirror. By standard mirror confinement we mean confinement of the fusion plasma in the minimum $|B|$ magnetic well of a single mirror cell. Until 1976, this mirror concept was essentially the only one under investigation at LLL. Baseball II (now decommissioned), 2XIIB (active), and MFTF (under construction, completion date 1981) are standard mirror experiments.

It is now clear that end losses from a standard mirror will severely limit the plasma Q (fusion power divided by trapped injected power) of such a device. The search for enhanced-Q mirror machines has led to work on two new concepts: the tandem mirror and the field-reversed mirror.

By tandem mirror confinement we mean three cells on a common axis wherein confinement in the central cell is enhanced by means of electrostatic stoppering provided by the plasma potential of the small end plug plasmas. The plug plasmas are confined in standard mirror cells; thus plug physics is an inherent part of the 2XIIB and MFTF experiments. TMX (under construction, completion date October 1978) is to provide a proof-of-principal demonstration of the tandem mirror concept.

By field-reversed mirror confinement we mean the confinement of plasma in a toroidal region of closed magnetic field lines generated by diamagnetic plasma currents in a nearly uniform background field. So far, efforts to produce field reversal in the 2XIIB facility by neutral beam injection have not succeeded, although they have come very close. Further experiments on this machine are planned. In addition, field reversal experiments will be conducted on TMX and MFTF.

The principles of a mirror fusion reactor are shown in Figure 2. (Figure 2 suggests a tandem mirror reactor, but the principles are the same for other mirror confinement concepts.) The deuterium and tritium fuel ions (D^+, T^+) are magnetically confined in the center of the reactor. (In the tandem reactor, axial confinement is enhanced by electrostatic stoppering.) Deuterium and tritium ions which fuse produce energetic neutrons and energetic alpha particles ($^4He^{++}$). The neutrons are unaffected by the magnetic field and enter the energy absorbing blanket. Neutron-lithium reactions in the blanket produce tritium makeup fuel for the reactor. The thermal energy deposited in the blanket is removed by the primary coolant (helium gas in Fig. 2). The coolant is passed through a steam generator, and the steam is used to produce electricity in turbine-generator units. Also shown in Fig. 2 is the end leakage of charged particles (unburned D^+ and T^+ as well as $^4He^{++}$) which occurs in all mirror reactors. The energy of this leakage can be recovered thermally or by direct energy converters which decelerate the particles in an electric field and collect their charge on collector electrodes.

We have carried out conceptual design studies of fusion reactors based on the three current mirror confinement concepts: the standard mirror, the tandem mirror, and the field-reversed mirror. Recent studies of the standard mirror have emphasized its potential as a fusion-fission hybrid reactor, designed to produce fissile fuel for fission reactors. We have designed a large commercial hybrid based on standard mirror confinement, and also a small pilot plant hybrid. Tandem mirror designs include a commercial 1000 MWe fusion power plant and a nearer term tandem mirror hybrid. Field-

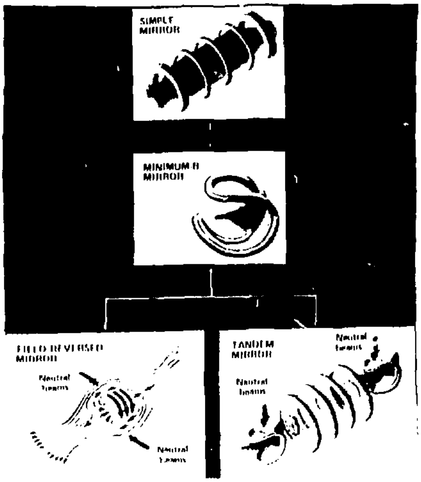


Fig. 1 - Evolution of mirror fusion ideas

reversed mirror designs include a multicell commercial reactor producing 75 MWe and a single cell pilot plant.

STATUS OF MIRROR CONFINEMENT EXPERIMENTS

2XIIB-The most important and successful mirror machine is the 2XIIB experiment which has gone through a number of evolutionary changes as the name implies. The device is shown in Figure 3. The density n, ion temperature T_i, and confinement time τ, are given in Table 1. The density is adequate for a reactor and the ion temperature for a reactor need only be increased by a factor of 10 which is possible by injection at higher energies. The confinement time must increase a thousand fold and is therefore the main issue. The lifetime of ions (confinement time) has been shown to scale as $T_i^{3/2}$ as can be seen in Figure 4. Simply raising T_i by a factor of 10 increases τ by 30. Raising the ratio of the mirror field to the central field, considering the favorable mass effects of tritium, the heating due to alphas, and less cooling due to cold plasma and cold electrons from the ends may result in another factor of 5 to 10. An additional factor of 3 to 6 in confinement time is needed for a fusion reactor. As will be seen later, possible candidates for this 3 to 6 enhancement factor are the tandem mirror reactor and the field reversed mirror reactor.

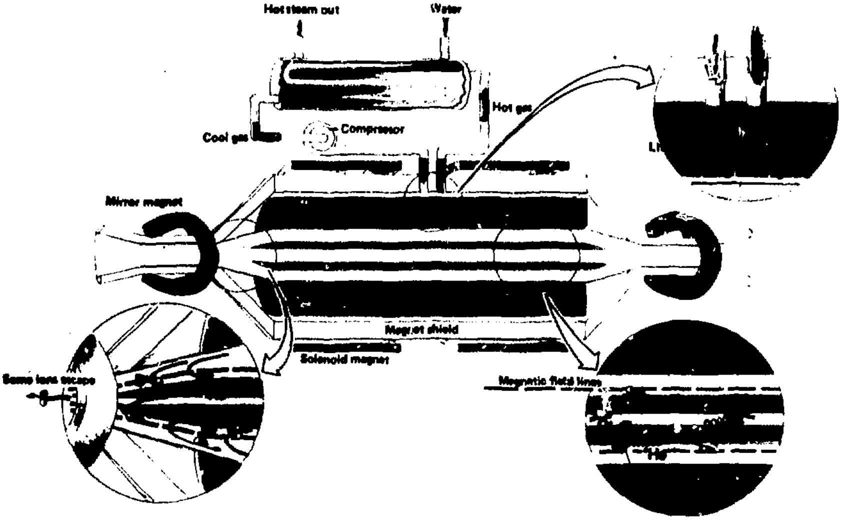


Fig. 2 - Principles of a mirror fusion reactor

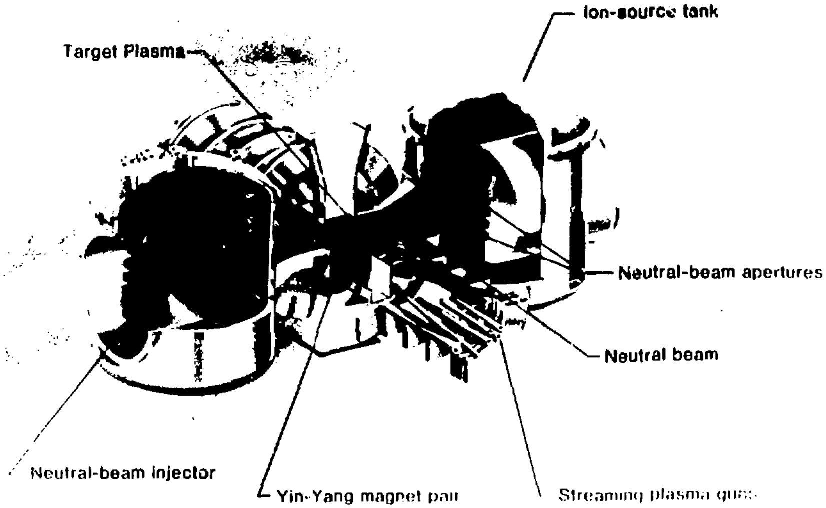


Fig. 3 - The 2XIIB mirror fusion experiment

Table 1 - Typical 2XIIB Parameters

Machine parameters	
Neutral beam	
Voltage (kV)	20
Current (A)	500
Duration (ms)	10
Magnetic field	
Field strength B_{VAC}(kG)	6.7
Mirror ratio	2:1
Length mirror-mirror L (cm)	150
Plasma parameters	
Density $\hat{n}$ (cm^{-3})	1.5×10^{14}
Ion energy W_i(keV)	13
Electron temperature (eV)	140
Beta $\hat{\beta} = 8\pi \hat{n} W_i / B^2_{VAC}$	1.7
Field reversal parameter $\Delta B/B$	0.7
$\hat{n}\tau_E$ (cm^{-3} s)	1×10^{11}
Plasma size	
Radius R_p (cm)	6
Length L_p (cm)	16
Volume (liters)	3.2
Vacuum gyro radius a_i (cm)	3.5
R_p/a_i	1.7
L/a_i	43

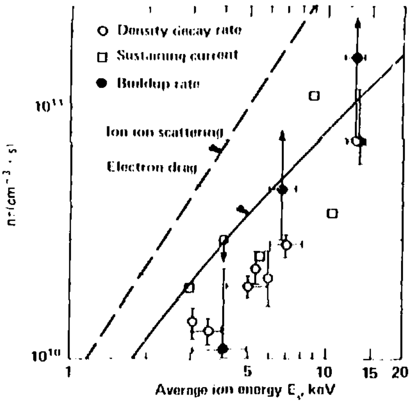


Fig. 4 - Particle lifetime $n\tau$ vs ion energy in 2XIIB

Many problems have been solved in 2XIIB and still many remain to be solved. Some will be discussed here. Gross motion of the plasma away from its equilibrium state is completely suppressed even at remarkably high plasma pressures where the plasma pressure averaged over the radial dimension is over 50% of the magnetic field pressure (i.e. $\beta = P_{\perp}/(B^2/2\mu_0) = nkT_{\perp}/(B^2\mu_0) \simeq 0.7$). Reactor designs are based on such values. The micro- turbulence due to the nonthermal ion energy distribution inherent to mirror confinement which have plagued mirror machines heretofore have been largely suppressed in 2XIIB by providing a relatively cold plasma which flows along the open field lines and occupies the space outside the mirror confinement region. The streaming plasma solved the microturbulence problem but created another problem. The cold plasma requires power to sustain itself, and the hot plasma is cooled by the cold plasma which is in contact with both the hot plasma and the end walls. This problem is called end wall or electron thermal heat conduction and is now the subject of considerable attention and concern.

Another solved problem is startup which has now been thoroughly demonstrated in 2XIIB. Impurities have been shown not to be a problem experimentally due to the strong positive plasma electric potential pushing outward any impurity ion which tries to enter. Also, the mirror plasma in 2XIIB is quite tolerant of a rather high gas pressure (10^{-5} torr) surrounding the hot plasma.

The 2XIIB or standard mirror cell is a building block for a new multicell machine idea called the tandem mirror.

TANDEM MIRROR-The electric potential which naturally occurs in a mirror plasma can be used to electrostatically confine plasma in a solenoidal magnetic field by locating a mirror cell at both ends. This concept looks so promising that a number of experiments are under construction to test out the idea. The largest device is under construction at LLL, called the Tandem Mirror Experiment (TMX), and is shown in Figure 5. Other tandem mirror experiments are under construction in Japan, USSR and at the University of Wisconsin. The important advance embodied in the tandem concept is the higher Q compared to the standard mirror. It appears that Q can be 5 to 10 whereas the standard mirror had a Q of 1 to 2. Besides the higher Q, there are a number of noteworthy features, e.g., the simple geometry that allows modularity.

The experiments will address a number of problems such as gross stability which is not guaranteed due to the connection of a slightly unstable solenoid to the stable end magnetic wells with a transition magnetic field that is unstable by itself. Another question is the verification of the theoretically predicted electrical potential profile. The impurity problem, which was no problem in a standard mirror, now becomes a worry and could lead to pulsed operation to purge impurities including the alpha particles resulting from DT fusion.

FIELD REVERSED MIRROR-The 2XIIB contains so much plasma pressure that its diamagnetism comes very close to reducing the 7 kG field to zero. With a factor of two more confinement, the field would be reversed which means the field lines would close on themselves. The lossy open lined standard mirror then can, in principle, become much less lossy; the loss being of a cross-field nature. Such field reversed states have routinely been attained with energetic electrons at Cornell University. A related field reversal generated by an electron beam has been obtained at NRL and UC Riverside. The theta pinch at LASL operated in the reversed field mode has achieved a field reversed state which is composed of warm (100 ev) ions and lasts for a long time (50 μsec) for such configurations. A

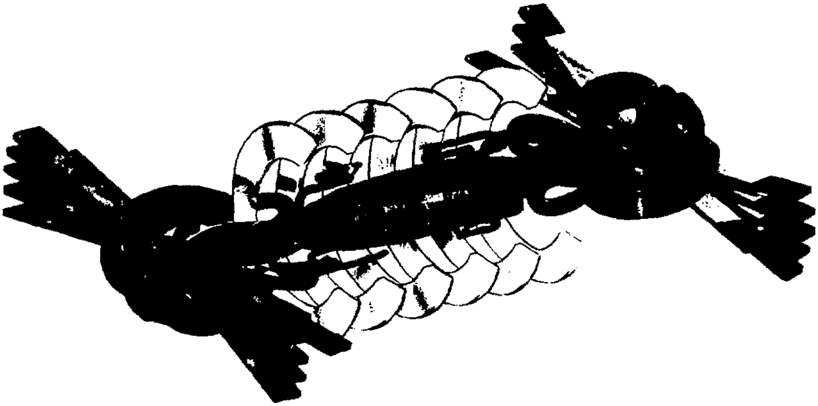


Fig. 5 - TMX magnet and neutral beam injection systems

similar result has been achieved in the USSR. The desired configuration is shown in Figure 1.

The field reversed mirror reactor concept is based on field reversal sustained in steady state by energetic neutral beam injection. The virtues of such a configuration are high Q (5) and small size. The problems are: how to create such a state and will it be stable and have a low enough loss rate.

MIRROR FUSION TEST FACILITY (MFTF)-The remarkable success of the 2XIIB experiment has led to a scaled up experiment called MFTF. It is about two times larger than 2X in linear dimensions and has three times higher field. It uses superconducting magnets. The injection energy is scaled up to 80 keV from 20 keV. The injection power will be raised from 12 MW to 40 MW and the beam time is 500 msec up from 10 msec. Besides scaling $n\tau$ with energy as shown in Figure 4, the radius of the plasma measured in ion gyroradii (as well as cm) will be scaled up to 10 from 2 (30 cm from 7 cm). The great importance of the radius scaling is the test of theoretical prediction that the important micro-instability called the drift-cyclotron-loss-cone-mode will become less vigorous as the radial density gradient is decreased. The MFTF is more thoroughly described in the companion paper by K. I. Thomassen.

STANDARD MIRROR REACTORS

Previous studies have shown that the standard mirror, as a fusion power reactor, would produce very expensive electricity. This is primarily because of the inherently low plasma Q of the optimized reactor design. (Q can be raised, for example, by depressing the central magnetic field strength and thus increasing the mirror ratio, but this decreases the fusion power density and shifts the design off-optimum, i.e., increases the cost of electricity still further.) Other studies have shown, however, that the standard mirror in large sizes would be a viable fusion-fission hybrid reactor. The purpose of the hybrid is to breed makeup fuel for fission reactors.

COMMERCIAL STANDARD MIRROR HYBRID-Figure 6 shows a standard mirror hybrid using a Yin-Yang coil set with a mirror-to-mirror length of 13 m and a maximum magnetic field strength of 8.5 T (permitting the use of niobium-titanium superconductors). This optimized commercial reactor has a Q of 0.64 and produces 600 MWe net electric power and 2000 kg/yr of plutonium, sufficient to provide make-up fuel for 6000 MWe of fission reactor (LWR) power. The estimated cost of electricity from this hybrid and its associated fission reactors is 30 mills/kWhr.

The injector design developed for the hybrid reactor is based on the positive ion LBL injector. The reactor requires deuterium injectors with acceleration to 125 keV and tritium to 187 keV. The total injected power is 625 MW.

The blanket of the hybrid reactor contains U_3Si, a fuel being developed in the Canadian nuclear power program for the CANDU reactor. Our reasons for this choice are (1) high uranium density (U_3Si is a metallic alloy), (2) ease of fabricability, and (3) a comparatively high burnup capability (for a metallic fuel), on the order of 2-3%. Economic optimization of the fuel cycle for this reactor dictates a total fuel exposure of about 5 MW-yr/m^2 of 14 MeV neutron energy through the first wall. In Table 2, the initial (beginning of life) and final (end of life) neutronic parameters of the U_3Si blanket are listed.

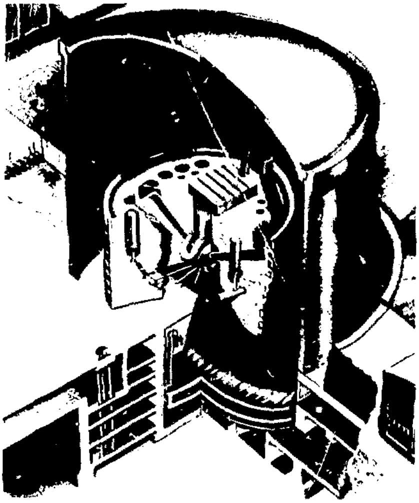


Fig. 6 - Standard mirror hybrid reactor

Table 2 - Time-Dependent U_3Si Blanket Neutronic Parameters

Exposure (MW-yr/m^2)	0	5
Blanket energy multiplication	8.8	18.4
Pu/n	1.85	1.75
% Pu	0	2.3
% Burnup	0	0.75
T/n	1.05	1.42

The mechanical design approach we have selected is to mount the magnet, blanket and primary heat transfer loop all within a prestressed concrete reactor vessel (PCRV), of the type developed for gas-cooled fission reactors. In the center of the PCRV are the magnet and blanket; the steam generators and He circulators are located around the periphery. The blanket is a spherical shell inside the magnet. In this way, the blanket and its cooling system are locked together so that no relative motion between them can occur, thus precluding the possibility of rupturing any of the coolant ducts. The PCRV also serves a second function, i.e., it provides the main restraining forces for the magnet.

The blanket design concept is one which avoids any major disassembly of the reactor during the blanket change operation but instead relies on remote operations to assemble and disassemble the blanket inside the PCRV. The blanket is made up of small cylindrical modules, approximately 50 cm in diameter, with the blanket structure being suspended directly from the inside wall of the PCRV as shown in Figure 7. Removal and replacement of blanket modules is accomplished with a refueling machine, which consists of a post which is inserted down through the center of the machine and has a pivoting arm to operate on the modules. The maintenance operation consists of a series of manipulations of each of the several hundred modules.

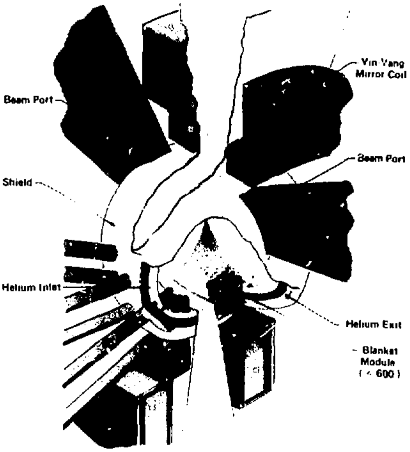


Fig. 7 - Blanket/shield for standard mirror hybrid

The local blanket multiplication and therefore local blanket power density increases by a factor two over the life of the fuel (see Table 2). By devising an appropriate fuel management scheme for the blanket, we are able to limit the peak-to-average variation in the total blanket thermal power to about 10% (3,600 MW average; 4,000 MW peak) and the primary heat transfer and power conversion loop capacity are designed to accommodate this power variation. The blanket modules are grouped into four quadrants and at time intervals of one quarter of the blanket life, the reactor is shut down and one quadrant of the blanket is refurbished with new fuel assemblies. In this way we are able to establish an equilibrium fuel cycle where the four quadrants are each at a different exposure.

STANDARD MIRROR HYBRID PILOT PLANT-Reducing the physical size of the standard mirror hybrid degrades its performance because of reduced Q and decreased blanket coverage. We have therefore designed a small standard mirror hybrid pilot plant as a net product producer (power generation by a fission reactor using the bred fissile fuel > electrical input into hybrid) rather than a net electric power producer. The minimum $|B|$ magnetic well is provided by the combination of a pair of solenoidal magnets and four Ioffe bars (see Figure 8). Because of reduced constriction at the mirror throat, we were able to design a smaller reactor with this magnet than with the spherical Yin-Yang magnet. The mirror-to-mirror length is 5 m, the inside radius of the solenoidal magnets is 1.4 m, and the radius to the outside of the Ioffe bars is 2.5 m. The central magnetic field strength is 2 T, the mirror field is 4 T, and the maximum field at the conductor is 8 T, thus allowing the use of niobium-titanium superconductor (as in MFTF and the commercial hybrid).

The neutral beam injection energies are 50 keV (D) and 75 keV (T). The predicted plasma parameters are a plasma radius of 34 cm, a Q of 0.18, and a fusion power of 3.7 MW. The peak first wall neutron loading is 0.24 MW/m^2.

The predicted performance of the standard mirror hybrid pilot plant with a U_3Si blanket is given in Table 3. Note that the reactor meets its net product criterion with no recovery of the plasma end leakage.

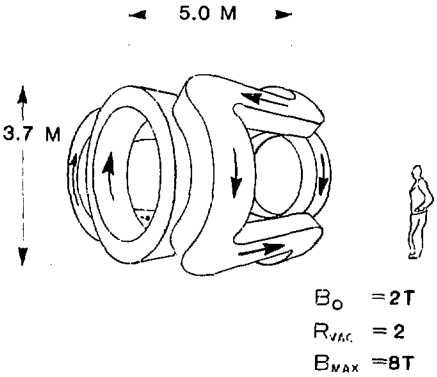


Fig. 8 - Magnet for small standard mirror hybrid

Table 3 - Power balance for the standard mirror hybrid pilot plant

Fusion power, MW_t	3.7
Injector input, MWe	34.7
Blanket power, MW_t	24.9
Hybrid Electric Power, MWe	8.72
Pu Production, kg/yr	18.0
Equivalent Electric, MWe	57.9
Gross Electric Power*, MWe	66.6
Net Electric Power*, MWe	31.9

*Hybrid and fission reactors

FIELD-REVERSED MIRROR REACTORS

We have developed a plasma model for the FRM based on very limited experimental and theoretical knowledge. Basic to our model is the assumption that a stable field-reversed plasma can be sustained by injection of a neutral beam current sufficient to balance the particle loss rate. We assume a long, fat toroidal plasma. Two additional assumptions are that the particle confinement time is proportional to the ion-ion scattering time and that the size of the field-reversed plasma, measured in terms of minor radius divided by ion gyroradius ($S \equiv a/\rho_i$) is limited by stability to about 5. A result of this latter assumption is that field-reversed plasma layers are predicted to be quite small, usually producing tens of MW of fusion power.

For a commercial FRM power reactor, we have proposed a multicell arrangement wherein a series of field-reversed plasma layers are arranged along the axis of a long superconducting solenoid which provides the background magnetic field. Using the plasma model coupled to an analytic model of a field-reversed mirror reactor cell (blanket, shield, and magnet coils), a power balance analysis, and a cost estimate we have optimized the parameters of a multicell FRM power reactor. This conceptual design study resulted in an 11 cell reactor producing 75 MWe net electric power. The reactor is shown in Figure 9 and a parameter list is given in Table 4.

One of the complications of a multicell FRM is that the attractive force between two adjacent plasma toroids (due to their field reversal currents) must be resisted by an axial magnetic well in each cell. We propose to produce these axial wells by placing a circular mirror coil between every two cells at the first wall radius (see Figure 10). The mirror coils are resistive coils made of copper.

It is anticipated that stability of the FRM plasma may require a radial magnetic well in each cell. We propose to produce these radial

Table 4 - Field Reversed Mirror Reactor Parameters

Performance	
Net Power	74 MWe
Fusion Power	220 MW
Plasma Q	5.5
Average neutron wall loading	1.7 MW m^{-2}
Recirculating power fraction	0.46
Plant efficiency	0.29
Physics parameters	
Injected current	18 A/cell @ 200 keV
β	1.5
Plasma minor radius	.07 m
Plasma major radius	.14 m
Plasma length	1.0 m
Peak plasma density	6.5×10^{14} cm^{-3}
Technology parameters	
B_0	4.1 T
Injection energy	200 keV
First wall radius	0.73 m
Cell length	2.0 m
Number of cells	11

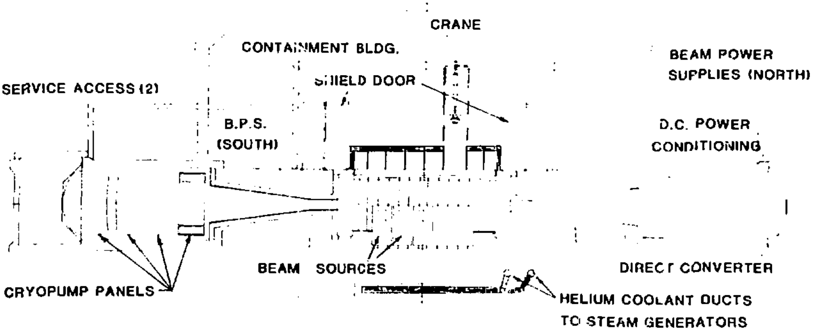


Fig. 9 - Multicell field-reversed mirror reactor

wells with a set of 4 Ioffe bars passing axially through the reactor (see Figure 10). These coils are also made of copper and placed at the first wall.

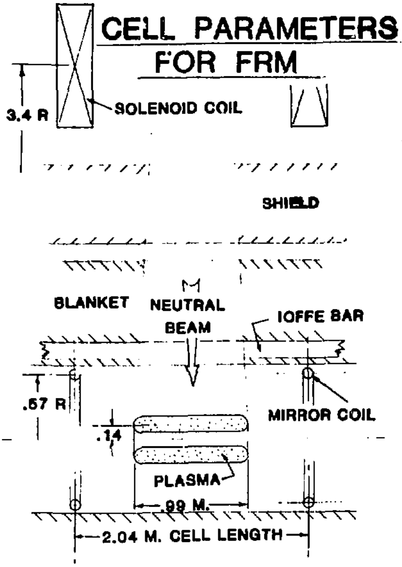


Fig. 10 - One cell of multicell FRM

We have designed a single cell version of the above reactor as a fusion pilot plant. For the single cell FRM the magnet design consists of a pair of large superconducting solenoids and a set of copper Ioffe bars placed at a radius of 60 cm (see Figure 11). The blanket and shield are between the Ioffe bars and the solenoids. The vacuum magnetic field strength at the center of the cell is 4.1 T. The maximum magnetic field strength at the conductor is 7.5 T, within the capability of niobium-titanium superconductor. The resistive loss in the Ioffe bars is 3.3 MW. In addition, neutron attenuation by the Ioffe bars causes an additional heat deposition in the copper equal to 1.9 MW.

The fusion power of the single cell FRM reactor is 20 MW. Taking the blanket energy multiplication to be 1.2 and the thermal conversion efficiency to be 0.35 and including the effect of neutron attenuation in the Ioffe bars, we calculate the gross electric power from the blanket to be 5.9 MW. Another 5.2 MW comes from the end leakage direct converters (including thermal conversion of their rejected heat). The neutral beam injectors (efficiency 0.7) require 5.3 MW input power, and the power requirement of the Ioffe bars is 3.3 MW. Thus the net electric power for this pilot plant is 2.5 MWe.

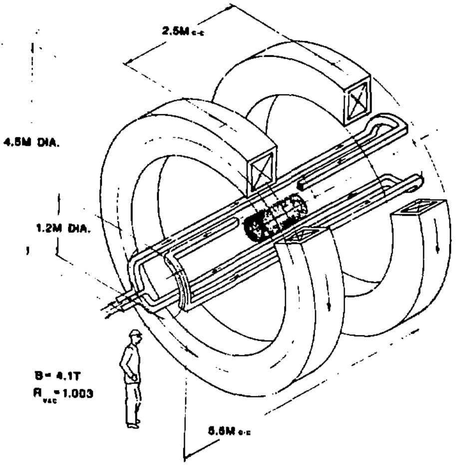


Fig. 11 - Magnet for single cell FRM

TANDEM MIRROR FUSION REACTORS

The TMR design is shown in Figure 12. Typical parameters for this design are given in Table 5. The reactor concept came out of an intensive search for a Q-enhanced mirror reactor and resulted in the best performing mirror reactor to date. The striking features are the high Q (≈ 5) and the simplicity of the basic cylindrical geometry. The simple geometry allows modular construction of the first-wall, blanket and magnet. The end plug plasmas are maintained by the continuous injection of 200 MW of 1.2 MeV D^0 into each plug. The superconducting magnet to hold the high density high energy plasma must produce a magnetic well having a central field strength of 17 T. The plasma which leaks out of both the plug and solenoidal regions is magnetically guided into the end expander tanks where direct conversion by a set of grids resembling a triode vacuum tube is accomplished. The problems which we have identified are: 1) the feasibility of an injector which will run continuously, and reliably and efficiently at 1.2 MeV; 2) means for keeping the steady state concentration of $^4He^{++}$ low. An improved magnet and shield for the end plugs is required. Means for getting higher Q's and for coping with recirculation power more efficiently and cheaply are needed.

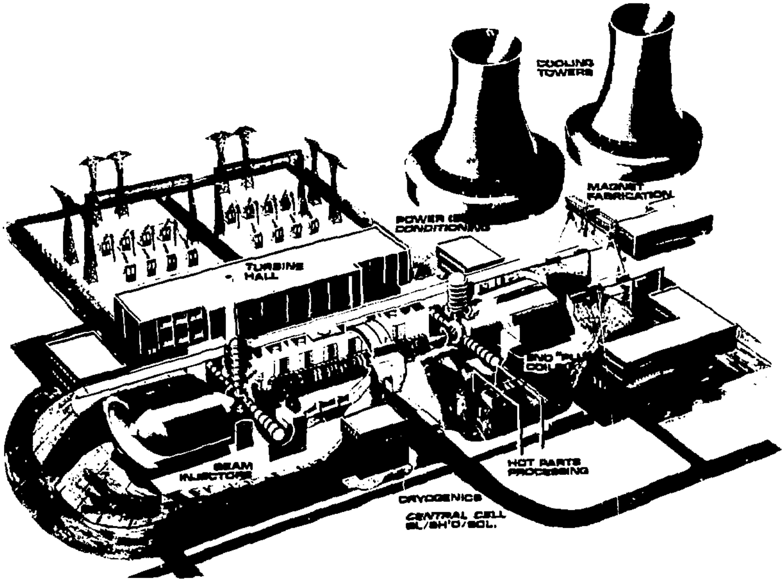


Fig. 12 - Tandem mirror reactor

Table 5 - Tandem Mirror Reactor Parameters

Performance	
Net power	1000 MWe
Fusion power	2500 MW
Plasma Q	4.8
Neutron wall loading	2 MW m^{-2}
Recirculating power fraction	0.43
Plant efficiency	0.34
Physics Parameters	
Trapped current into each plug	220 A @ 1.2 MeV
Plug β	1.0
Plug plasma radius	0.48 m
Plug particle $n\tau$	2.5×10^{14} s cm^{-3}
Central cell fueling current (cold)	1100 A
Central cell β	0.7
Central cell plasma radius	1.2 m
Central cell plasma density	8.6×10^{14} cm^{-3}
Central cell particle $n\tau$	7.7×10^{14}s cm^{-3}
Technology parameters	
Plug B_0	16.5 T
Plug B_{mirror}	17.6 T
Central cell B_0	2.4 T
Plug injection energy	1.2 MeV
First wall radius	1.6 m
Central cell length	100 m

Crucial information of a physics nature which may strongly affect the reactor design has to be obtained. The power required to maintain a stable plasma in the plug region is a critical factor. Estimates for this power range from negligible values to power levels comparable to the fusion power itself. Another crucial issue is the suppression of electron thermal heat conduction to the end walls. The grids of the direct energy converter are predicted to do this suppression. Gross stability of the solenoidal plasma by the plug plasmas must be verified.

TANDEM MIRROR HYBRID REACTOR (TMHR)

The use of the tandem mirror concept for the production of fissile material (^{233}U or ^{239}Pu), called the fusion-fission hybrid reactor or the fusion fuel factory, results in design parameters that are much less demanding. A preliminary drawing of the TMHR is shown in Figure 13. The two component operating mode is employed. Tritium at low energy is electrostatically confined in the solenoid and deuterium at 100-200 keV is injected into the tritium plasma. Some of the deuterium ions fuse during slowing down. Because the tritium is relatively cold, a greater leak rate than for the TMR occurs providing a greater streaming plasma in the end-plugs which will enhance

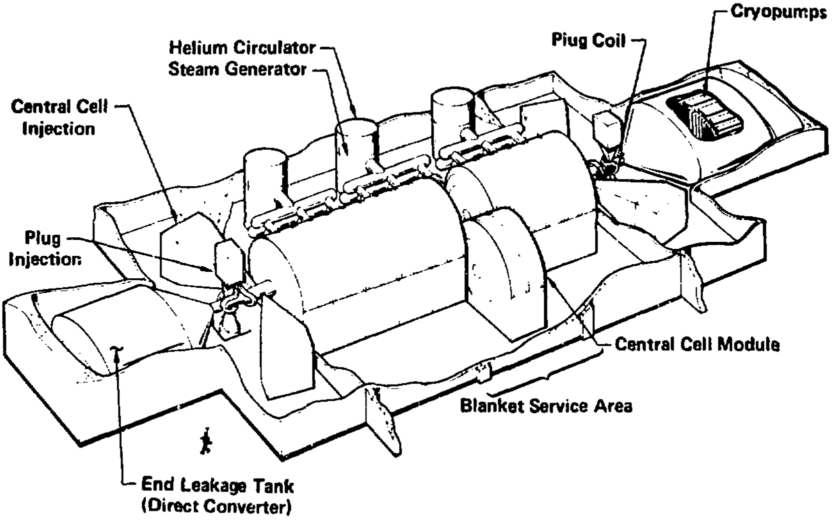


Fig. 13 - Tandem mirror hybrid reactor

stability. The lower electron temperatures results in lower potential plugging barriers which greatly alleviates the tendency of the end plugs to confine $^4He^{++}$ which can prevent a steady state burn as mentioned as a major worry above in the TMR discussion.

CONCLUSIONS AND FUTURE WORK

In order to be of practical use, fusion must pass beyond the present research phase to scientific feasibility, through engineering feasibility and on to economic feasibility. Future prediction is risky in fusion feasibility as in so many areas of human endeavor; to predict a date for success would be foolhardy. On the other hand, the virtues of fusion power potentially are great.

Low radioactivity and inexhaustible fuel supply are potential virtues of fusion. Fusion neutrons can be used to generate heat, and breed tritium and fissile fuel. This fissile fuel can be used to generate orders of magnitude more energy than from fusion alone by being burned in a fission reactor, and this application of fusion appears relatively near at hand.

The tandem mirror concept is apparently capable of values of 5 to 10 which is about 5 times higher than the standard mirror configuration and is in a class called Q enhanced mirrors. Another Q enhanced mirror concept is the field reversed mirror which has Q values of 5 or somewhat more depending on how optimistic one is about the particle loss rate. We find that the tandem and the field-reversed mirror hold the promise of making particularly simple reactors, and in the hybrid application these simplifications imply a much nearer term application.

The mirror fusion concepts described in this paper are evolving and need further inventions; perhaps the key new element will be supplied by the reader.

BIBLIOGRAPHY

1. "Standard Mirror Fusion Reactor Design Study," edited by R. W. Moir, Lawrence Livermore Laboratory report UCID-17644 (1978).
2. "Preliminary Design Study of the Tandem Mirror Reactor (TMR)," R. W. Moir, et al., Lawrence Livermore Laboratory report UCRL-52302 (1977).
3. "Conceptual Design of the Field-Reversed Mirror Reactor," G. A. Carlson, et al, Lawrence Livermore Laboratory report UCRL-52467 (1978).
4. "Small Mirror Fusion Reactors," G. A. Carlson, K. R. Schultz, A. C. Smith, Jr., Proceedings of the Third Topical Meeting on the Technology of Controlled Nuclear Fusion, Santa Fe, New Mexico (1978).
5. "Mirror Fusion Test Facility," K. I. Thomassen, these proceedings.

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48."