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MIRROR FUSION REACTOR DESIGN

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1. SUMMARY

The mirror fusion reactor is a steady state device, not pulsed like most toroidal machines. The magnetic field which confines plasma in a mirror fusion reactor differs greatly from the toroidal magnetic field of the Tokamak. Mirrors are not "closed" systems. The magnetic field lines leave the plasma region and penetrate the walls of the vacuum chamber in which the plasma has been created. Since charged particles move easily along field lines the plasma could quickly escape to the wall were not for special magnetic field geometry which reflects, i.e., "mirrors" ions and electrons back toward the hot plasma. The open field lines of mirrors have the distinct advantage of serving as an escape path for ash or impurity ions, leading them out of the plasma to the vacuum pumps.

Figure 1 depicts the evolution of mirror fusion concepts as seen by researchers at LLL. The early simple mirror proved to be an unstable plasma container and was replaced by the minimum- $|B|$ mirror. From the center of a minimum- $|B|$ magnetic configuration -- produced either by a pair of solenoids and Ioffe bars, by a "baseball" coil (shown in Fig. 1), or by a Yin-Yang coil -- the field strength increases in all directions and ensures gross (MHD) stability for the plasma. We call the minimum-$|B|$ configuration a standard mirror. Until 1976, this mirror concept was essentially the only one under study at LLL.

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

By tandem mirror confinement, we mean three mirror cells on a common axis: two standard mirror cells are placed at either end of a series of cylindrical coils that make up a solenoid (Fig. 1). Each end cell provides a minimum-$|B|$ magnetic field. Confinement in the solenoidal cell is enhanced by means of electrostatic stoppering provided by the plasma potential of the small end-plug plasmas.

2. MIRROR REACTOR DESIGNS

2.1 Standard Mirror

Previous studies[1] 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 optimized reactor designs. More recent studies[2] have show, however, that the standard mirror in large sizes could be a viable fusion-fission hybrid reactor, breeding makeup fuel for fission reactors.

The blanket of the standard mirror hybrid is helium-cooled and contains uranium silicide (U_3Si) for fissile fuel breeding and lithium deuteride (LiD) for tritium breeding. The blanket is highly modularized, consisting of about 600 cylindrical pressure vessels, approximately 50 cm in diameter, all mounted on a spherical surface surrounding the plasma.

The standard mirror hybrid uses a superconducting Yin-Yang magnet 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). The main restraining forces for this large magnet are provided by a prestressed concrete reactor vessel which completely encloses the magnet, blanket, and primary heat transfer loop.

Two neutral beam injectors provide the power required to sustain the plasma of the standard mirror hybrid. The injector design is based on the Lawrence Berkeley Laboratory's positive-ion injector. The reactor requires deuterium injectors with acceleration to 125 keV and tritium to 187 keV.

In this reactor, a 5% difference between the two mirror fields causes 90% of the plasma leakage to occur at the lower end of the reactor, where a large end tank contains a single stage electrostatic direct converter.

2.2 Tandem Mirror

Our first design for a tandem mirror fusion reactor has been reported in Reference 3 and is shown in Fig. 2. This reactor has a Q of 4.8 and produces 1000 MWe of net electric power. The fusion plasma is contained in the 100 m long central cell of the tandem mirror reactor, and the blanket is a cylindrical shell. The blanket contains canned liquid lithium for tritium breeding and is helium-cooled.

The central cell magnets are simple solenoidal coils of low magnetic field strength (2.4 T). The plug cell magnet must be minimum-$|B|$, and our design specified a Yin-Yang coil surrounded by a pair of niobium-tin superconducting solenoids. The Yin-Yang coil is a normal coil of high purity aluminum conductor. The maximum field strength at the superconducting solenoids is over 17 T.

Each plug cell of the tandem mirror reactor has two neutral beam injectors, each providing 120 A of 1.2 MeV deuterium atoms.

A different design for a tandem mirror fusion reactor was described by Logan in Reference 4. This reactor also produces 1000 MWe net power, but with a higher Q (10) and a lower fusion power density (the central cell length is 240m). To be cost-effective, such a design requires an inexpensive central cell design, and the proposed blanket consists of axially-oriented steel tubes supported by graphite. Lithium flowing through the tubes serves both as the tritium breeder and the primary coolant. The neutral beam requirements for this design are reduced to 75 A of 600 keV deuterium atoms for each plug cell.

2.3 Field Reversed Mirror

We have developed a plasma model for the field-reversed mirror based on 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. Our conceptual design considered field-reversed plasma layers with $Q = 5.5$ and 20 MW of fusion power.

For a commercial 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 that provides the background magnetic field. Our design is for an 11-cell reactor producing 75 MWe net power. Figure 3 shows one cell of such a plant. We have also considered a single version of this reactor as a fusion pilot plant.

The main magnets for the reactor are superconducting solenoids providing a uniform magnetic field of 4.1 T. In addition, the multicell reactor has normal mirror coils between cells and normal Ioffe bars, all located at the first wall. These coils provide shallow axial and radial magnetic wells to stably confine each plasma layer at the center of its cell. The single cell reactor has Ioffe bars, but the axial well is provided by the superconducting solenoids.

Each field-reversed plasma layer requires the injection of 18 A of 200 keV deuterium and tritium atoms. We propose to use neutral beam injectors of the negative ion type.

3. BLANKETS

3.1 Circulated Liquid Lithium

Liquid lithium can serve as both breeding agent and heat transfer agent. It is very corrosive to most common structural steels. Very pure iron or high-chromium, low nickel stainless steels show acceptable corrosion characteristics.

The chief obstacle to flowing lithium is the magnetohydrodynamic (MHD) pressure drop required to force the conducting fluid across magnetic field lines.

3.2 A Stagnant Breeder - Solid or Liquid - Gas Cooled

One approach to blankets employs a solid tritium breeding material such as lithium aluminate or lithium beryllate contained in an envelope of thin alloy, impervious to tritium. Coolant gas is circulated around the envelope structure containing the breeding material. Much of the coolant passes through tubes which penetrate the structure at appropriate intervals for good heat transfer.

Much of this reasoning was applied to our most recent ventures into thermal conversion blanket design. Two blanket designs have been evolved during the past two years in our program of reactor design studies. Both designs employ high pressure helium as the coolant.

4. MAGNETS

Nearly all design studies of fusion power production clearly demonstrate the necessity of using the technology of superconductivity at cryogenic temperature to generate the plasma-containing magnetic fields. The field strengths required to contain fusion plasma are so high and the system volumes are so great (so as to include the blanket and shield) that any attempt to design copper, aluminum, or even silver magnet coils will result in a design yielding little, if any, net power for sale.

4.1 Types of Magnets[5]

The simple mirror configuration, consisting of a long solenoid with increased field strength at the ends (magnetic mirrors), proved to be an unstable plasma container and was replaced by the minimum $|B|$ mirror configuration. The Yin-Yang minimum $|B|$ coil was chosen for the Mirror Fusion Test Facility (MFTF) experiment and recent conceptual designs of standard mirror reactors. For the multicell field-reversed mirror reactor concept we returned to the long solenoid configuration, augmented by normal copper mirror coils and Ioffe bars placed at the first wall radius to provide a shallow magnetic well for each field-reversed plasma layer. The central cell of the tandem mirror is also a long solenoid while the end plug cells require a minimum $|B|$ configuration.

In general, because of the high plasma energies involved, mirror reactors benefit from high magnetic field strengths. For example, a 17 T maximum field strength was chosen for the plugs of the tandem mirror fusion reactor, and 12 T is proposed for the nearer tern tandem mirror hybrid. We believe that mirror reactor magnets of these field strengths and even higher are possible.

4.2 Ioffe Bars

In The Field Reversed Mirror a special type of magnet coil is required which is uniquely difficult to design. In the FRM it is necessary to stably locate the field-reversed plasma layer which constitutes the fusion plasma. A small mirror ratio, both axial and radial, is essential and can be provided by small mirror coils near the plasma acting in conjunction with a set of quadrupole conductors (Ioffe bars) also close to the plasma. To achieve the desired results using small stabilizing currents one must abandon superconductors and resort to copper or aluminum coils and bars. These conductors will be subjected to the same neutron and gamma heating as the "first-wall" of the reactor and hence will probably have to be replaced at about the same frequency. Aluminum offers several advantages because of its lower neutron attenuation and lower activation, making it a much less severe disposal problem. Aluminum also tends to be self-healing with respect to neutron dislocation sites at the expected operating temperature of 150 to 200°C.

5. NEUTRAL BEAM INJECTORS

The various reactor concepts for magnetic mirrors all indicate the need for beam injectrion of deuterium and tritium ions with energy of at least 125 keV and in one case up to 1,200 keV. Charge exchange cross sections for positive ions become very small at energies over about 150 keV. To achieve reasonable efficiencies for the ion beam neutralization process, it seems necessary to develop negative ion beams. Means of accomplishing this are known and currently being applied to beam research activities at Berkeley.

Extraction grid cooling is a primary concern. All present sources are pulsed for no longer than .5 seconds. Fink has proposed a graphite grid structure, split at its center to allow thermal expansion, and cooled by conduction thru the graphite grid elements to a water cooled mount. Other beam line accelerating electrodes are surrounding the beam and have more modest cooling problems.

Potential radiation-induced problems associated with neutral beam lines are:

a) overheating of cryopanels and insulators

b) gamma flux-induced electrical conductivity increase of insulators

c) neutron and gamma fluence-induced damage to insulator materials.

6. DIRECT CONVERTERS

In a mirror fusion reactor, only a small fraction of the injected particles result in fusion before they escape out the mirrors. It is important to overall reactor efficiency to recover this "lost" particle energy. Similarly it is important to recover the unneutralized ion power in the neutral beam injectors. Several techniques are available.

The first ion beam direct converter concept involved magnetic deflection and then recovery in an immersed-grid direct converter. This converter type was tested steady state at 20 keV and 200 W/cm^2 in a series of experiments in 1970.

In 1974, an in-line, nonintercepting electrode converter was proposed. It can handle much higher power densities than the immersed-grid concept, but the product of beam thickness and current density is somewhat restricted.

Plasma direct converters can be divided into two general types according to whether the electrons are separated out magnetically or electrostatically.

In all cases the energetic ions are intercepted on electrodes whose voltage closely matches the ion total energy. Since this may require isolation at hundreds of kilovolts large insulators of the highest quality will be required. Because of thermonuclear neutron flux also coming through the plasma mirror regions, or, in the case of neutral injectors, streaming out the beam "window" toward the beam source, these insulators will be subjected to degradation.

One collector design employs graphite vanes, positioned by tungsten wires which are part of the vane and are maintained under constant tension. The vanes are cooled by radiation alone. The thermal expansion of the tungsten wires requires special tensioning mechanisms which also must be supported at high voltage since the tungsten and graphite cannot be separated by any known insulators at their operating temperature. Without the tensioning mechanisms, thermal expansion and column buckling would cause adjacent vanes to short electrically.

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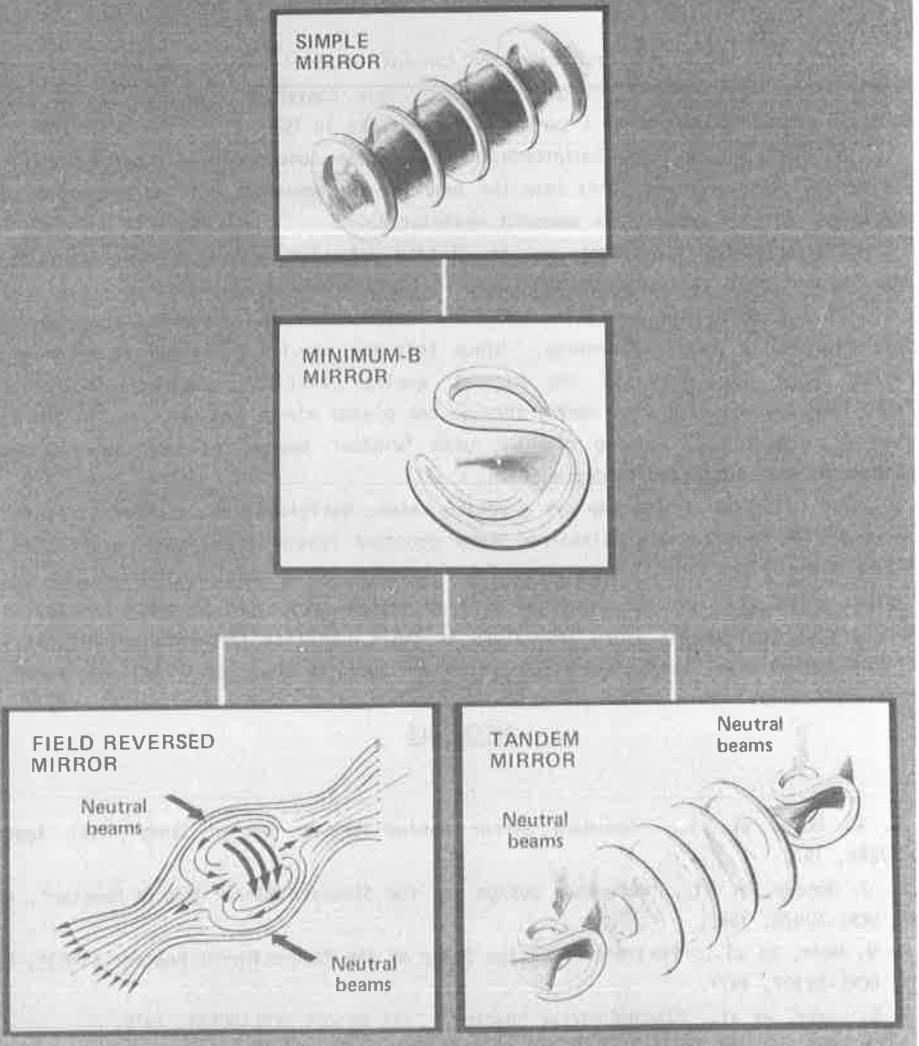
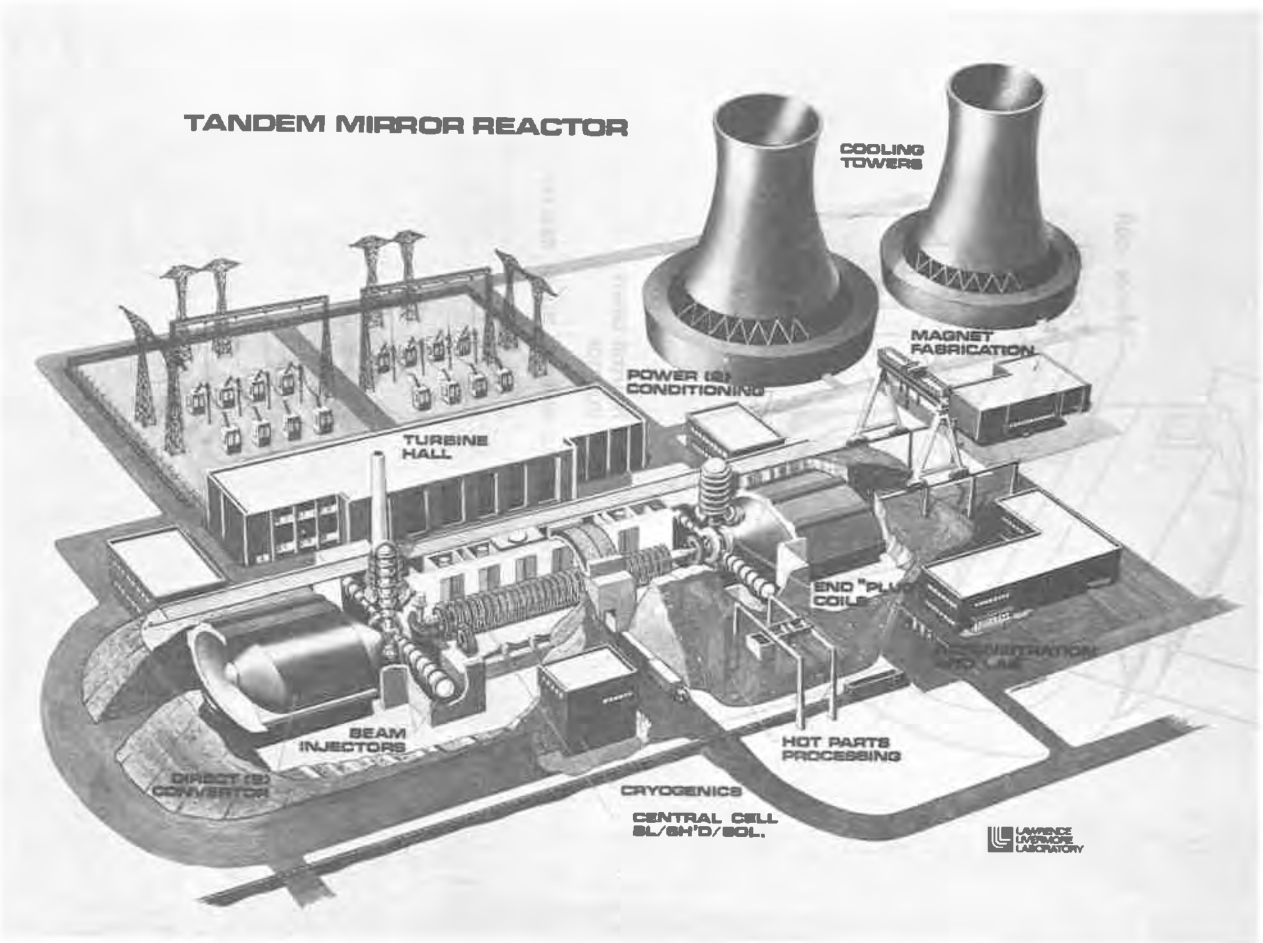
EVOLUTION OF MIRROR FUSION IDEAS





TANDEM MIRROR REACTOR

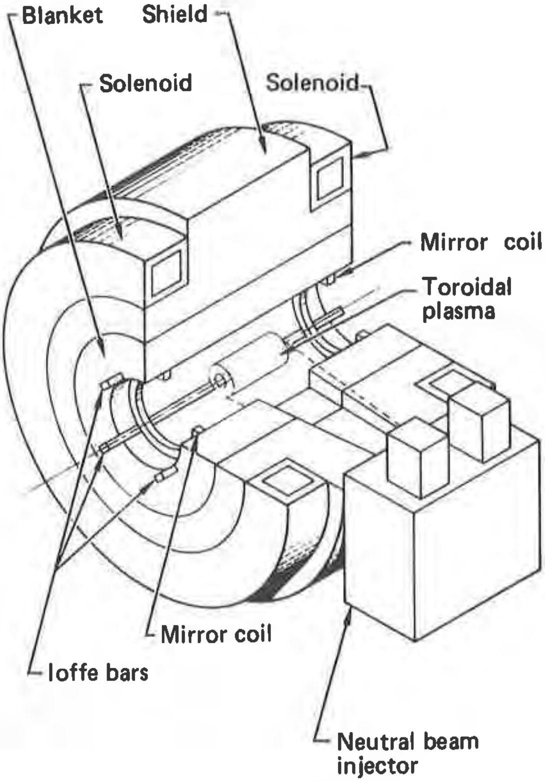


Figure 3 - One cell from a Field Reversed Mirror Reactor