Lawrence Livermore Laboratory

MIRROR FUSION REACTOR DESIGN

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1. Introduction

Recent encouraging results in fusion physics experiments have again drawn attention to that most promising, but most elusive, means of nuclear power production. The toroidal devices called Tokamaks have received the largest share of research funding, and have reached some important milestones of density and temperature, while those fusion machines known as "mirrors" have also shown encouraging results. Both experiment and development of new theory have, in the past two years, brought "mirror" systems into a strong competitive position for consideration as future fusion power reactors.

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 it 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 field — produced either by a pair of solenoids and Ioffe bars, by a "baseball" coil (shown in Fig. 1), or by a Yin-Yang coil — 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. Baseball II (now decommissioned), 2XIIIB (active), and the Mirror Fusion Test Facility (MFTF, presently under construction) are standard mirror experiments.

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. Our tandem mirror experiment, or TMX, is to be a proof-of-principle 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 (Fig. 1). So far, efforts to produce field reversal in the 2XIIIB 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.

In this report we briefly describe our recent conceptual reactor designs based on mirror confinement and then discuss four components of mirror reactors for which materials considerations and structural mechanics analysis must play an important role in successful design. The reactor components are:

a) first-wall and thermal conversion blanket
b) superconducting magnets and their force restraining structure
c) neutral beam injectors
d) plasma direct energy converters.
Of these, only direct energy converters are unique to mirror systems. The other components are present in other fusion devices, but geometry differences are dramatic between closed toroidal systems and open-ended mirrors.

2. MIRROR REACTOR DESIGNS

2.1 Standard Mirror

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 optimized reactor designs. (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.) More recent studies have shown, however, that the standard mirror in large sizes could be a viable fusion-fission hybrid reactor, breeding makeup fuel for fission reactors. Figure 2 shows a standard mirror hybrid which, with a Q of 0.64, produces 600 MWe of net electric power and 2000 kg/yr of plutonium, enough to provide makeup fuel for light-water reactors producing 6000 MWe of power.

The blanket of the standard mirror hybrid is helium-cooled and contains uranium silicide (U$_3$Si) 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 (See Fig. 3).

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. The total injected power is 625 MW.

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. The input plasma power to this end tank is about 600 MW, 40% of which is converted directly to electricity.

2.2 Tandem Mirror

Our first design for a tandem mirror fusion reactor has been reported in Reference 3 and is shown in Fig. 4. 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. Axial modularization of the central cell allows access to the blanket, which is segmented azimuthally as well. 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. Negative ions are produced from a 2 keV beam of positive ions by double charge-exchange in a cesium vapor cell. They are then accelerated to the final energy and neutralized in a cesium plasma stripping cell.

The total power of the charged particle end leakage from the tandem mirror reactor is 1030 MW. Half of the particles exit at each end. The large plasma potential and the small central cell ion temperature result in good direct recovery efficiency (~60%) with only a single collector stage.
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 240 m). To be cost-effective, such a design requires an inexpensive central cell design, and the proposed blanket consists of axially-oriented steel tubes supported in 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. Part of this reduction is due to the higher Q; the remainder is due to the incorporation of direct electron heating approximately equal to the neutral beam power.

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. We have assumed that the size of the toroidally-shaped field-reversed plasma, measured in terms of minor radius divided by ion gyroradius, is limited by stability to about 5. As a result of this assumption, the field-reversed plasma layers are predicted to be quite small, usually producing tens of megawatts of fusion power. 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 multieell 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 5 shows one cell of such a plant. We have also considered a single-cell version of this reactor as a fusion pilot plant.

We have considered various helium-cooled blankets for the field-reversed mirror reactor, some using canned lithium and others using solid lithium compounds.
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.

Half of the charged particle end leakage occurs at each end of field-reversed mirror reactor. The total power of the end leakage is 84 MW for the 11-cell reactor. The direct recovery efficiency for a single stage direct converter is estimated to be 50%.

3. BLANKETS

There are many ways to build a fusion neutron energy conversion blanket. Two of the most obvious are described briefly here.

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. Every gram of lithium will have to flow twice across the magnetic field: into the blanket which lies within the confining magnets, and out from the blanket to the thermal conversion piping. The pressure loss can be as high as 300 psi in the lithium loop.
3.2 A stagnant Breeder - Solid or Liquid - Gas Cooled

J. D. Lee, et al. proposed an approach to blankets employing 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 Lee's 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. Helium has long been recognized as a strong candidate for this role. It is clean, non-reactive chemically, neutronically inert, nontoxic and, when pressurized, has good heat transfer properties. It is ideal from the aspect of reactor maintenance by remote handling technology. Its one drawback is the need to pressurize to about 50 atmospheres so the circulating power will not spoil the overall plant efficiency. We believe that on steady state machines pressure vessels can achieve adequate reliability since cyclic thermal stresses, which would induce fatigue, are absent during normal operation.

We collaborated with the General Atomic Company on a blanket for a fusion-fission hybrid "standard" mirror reactor. The blanket module is composed of two pieces, a fuel assembly and the Inconel 718 pressure shell (Fig. 6). It is in the shape of a cylinder capped with a hemisphere and has a first-wall thickness of only 2.4 mm. The fuel assembly threads into a socket in the permanent module support structure. The pressure shell is bolted to the support structure with six large bolts in a hexagonal flange at the base of the cylinder. The vacuum seal is a double mechanical Varian-type knife edge seal with secondary vacuum pumping between the two knife edges.

Helium is the blanket coolant, entering at $350^\circ C$ and exiting at $550^\circ C$ at a pressure of 50 atmospheres.
Inconel 718 was chosen as the shell material on the basis of its excellent yield stress at temperatures up to 650°C (137,000 psi or 630 MPa) which allows a thin pressure shell. Large temperature differentials across this 2.4 mm wall induce moderate thermal stress. The permeation rate of hydrogen through Inconel 718 is only slightly higher than through 316 stainless steel at 550°C. The question of possible hydrogen embrittlement is recognized but remains to be answered.

For the pure fusion Tandem Mirror Reactor a very different geometry was required. A totally new approach to serviceability was taken due to the simple cylindrical shape of the central cell. Our design is a gas-pressure vessel with a wedge cross-section. The amount of steel required for structural safety influenced the selection of breeding material.

An attempt to use pure lithium aluminate showed that sufficient breeding ratio could not be obtained. Even addition of a neutron multiplier such as lead did not make lithium aluminate acceptable. Lithium beryllate would make a good blanket but we did not want beryllium in the design at this time due to its cost. Lithium alone, encapsulated in stainless steel cans, will provide an adequate breeding ratio. When the neutronics of lithium aluminate was proven poor and pure lithium was selected, the blanket was, of course, no longer “solid.” However, the concept of a static blanket was retained with helium gas as the coolant. Figures 7 and 8 show the blanket module and the central cell module.

Inconel 718 would be an excellent alloy to use for blanket structure. We plan a vacuum cast structure with egg-crate cross section. To it would be welded a curved first-wall of .5 cm Inconel 718 sheet and a shield structure enclosing hastelloy-X plate and lead-cement. The whole assembly will be a pressure vessel for 50 atmosphere helium and, as such, would be exhaustively radiographed around all perimeter walls and welds. Each unit would be subjected to high-temperature pressurization tests at 150% design pressure before installation in a blanket module. The assembly of the segments to make a full circle does not imply that we would rely on side support from adjacent segments while pressurized.
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.

Some designs use combinations of superconducting solenoids surrounding "baseball" or Yin-Yang coils of copper or aluminum. Normal conductors tolerate the high magnetic fields, but at a high price. Power consumed by normal coils increases the recirculating power fraction of the power plant.

4.1 Types of Magnets

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.

The MFTF magnet is designed for a maximum magnetic field strength slightly under 8 T and is being constructed of niobium-titanium superconductor. The High Field Test Facility being built at Livermore will test 40 cm bore niobium-tin solenoids at 12 T. Also, a 12 T minimum $|B|$ -shaped demonstration coil has been proposed.
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 term tandem mirror hybrid. We believe that mirror reactor magnets of these field strengths and even higher are possible. The 12 T goal of the present niobium-tin program is not an upper limit. Niobium-tin conductor has a useful current density capability at considerably higher field strengths, and advanced superconductors such as niobium-aluminum-germanium may reach to the 20 T range. Heat transfer to ensure magnet stability and magnetic force restraint become increasingly difficult at higher fields, but within limits such problems are amenable to engineering design solutions.

4.2 Brittleness of Niobium-Tin

An early concern about niobium-tin superconductor was that the inherent brittleness of the material might limit its practical application. An encouraging development was the demonstration in 1977 that multifilamentary niobium-tin superconductor at 12 T can tolerate cyclic strain to 0.6% or higher without degradation of its current carrying capacity. This work was done at Lawrence Livermore Laboratory with a special tensile tester capable of applying simultaneously loads up to 50,000 pounds, currents to 12 kA, and magnetic field strengths to 12 T at 4 K. A summary of conductor performance with strain is shown in Fig. 9. As tension is applied to the conductor, its critical current increases, reaching a maximum at about 0.3% strain. The critical current then falls as the load is increased, reaching its initial value at about 0.6% strain. This behavior is believed to be due to pre-compression of the niobium-tin by differential contraction as the conductor is cooled from the reaction temperature of 700°C, at which the Nb₃Sn is formed, to the operating temperature of 4 K. Figure 9 shows recovery of one of the samples from a strain of 0.9%, but permanent damage for the other sample. No effect of cyclic strains, 0.6% in amplitude, could be detected up to 500 cycles. These results indicate that this conductor can be safely used in practical coils designs.
4.3 Magnet Forces

The unit loads to be constrained when dealing with magnetic fields in the 2 to 12 Tesla range are very large - up to $10^8 \frac{N}{m^2}$ (14,500 psi). One example is the Yin-Yang magnet for the most recent "standard" mirror fusion plant.\(^{11}\) The force on the main coil arc is $35(10)^9$ N (8 (10)$^9$ lbs)! That force must be transmitted from a superconductor bundle whose temperature is $4^\circ$K to a structure - preferably at room temperature - capable of reacting such loads. If the structure is at room temperature then the forces must pass through a good thermal insulator capable of withstanding 5000 psi compressive stress while not allowing excessive heat conduction. For every watt of load on a $4^\circ$K cryogenic system about 300 watts of refrigeration power must be supplied.

A thermal insulator suiting that description does not exist today. The closest material is the outer surface layer on the NASA Space Shuttle. That material is fabricated by Lockheed as LI-900. In its present form it has far from sufficient compressive strength but much lower than necessary thermal conductivity. Lockheed estimates that with 5 years development a material meeting our needs could be evolved from existing technology.

In dealing with the very large magnet loads, Bechtel Corporation\(^{11}\) and the General Atomic Corporation, have both recommended huge post-tensioned concrete restraining structures. Our recent "standard" mirror hybrid design includes such a structure, and it also supports the thermal power and fuel conversion blanket. Figure 2 shows the hybrid nuclear island. Note that the steam generators and helium coolant circulators are also supported by this circular concrete vessel. Penetrations for neutral beam access to the plasma chamber further complicate the internal geometry of the vessel. Very complex analytical techniques must be employed to calculate stress at various locations in the vessel. We also suggest experimental stress analysis on models of such a structure. Photo elastic analysis employing stress freezing techniques should prove useful in identifying areas requiring more detailed analytical treatment.
4.4 **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. The bars must, of course, be convectively cooled. Water coolant is under consideration as well as pressurized helium gas.

Substantial magnetic forces are exerted on these auxiliary coils because of the strong solenoidal field of 4 to 5 T. To support the Ioffe bars and mirror coils additional steel structure at or near the first wall is required. Since neutron heating is by far the biggest heat load near the first-wall, this support structure will itself have to be cooled and its bulk will determine the cooling power required. Much synthesis and analysis of this auxiliary coil structure remains to be done.

5. **NEUTRAL BEAM INJECTORS**

Presently operating neutral beam injectors are based on Lawrence Berkeley Laboratory positive-ion injector technology. The 2XIIB experiment and the TMX experiment, both at Livermore, employ such beam sources. Operating voltages are currently less than 40 kilovolts but tests have been successfully conducted at Berkeley up to 120 kilovolts.
The various reactor concepts for magnetic mirrors all indicate the need for beam injection 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\textsuperscript{12}. Means of accomplishing this are known and currently being applied to beam research activities at Berkeley.

All proposed injectors must function with great reliability for long service periods. Some service periods may be three months, some as long as one year. The redundancy of injectors economically tolerable is not likely to be more than 25% so an overall reliability factor exceeding 75% must be targeted.

Typical of the design requirements are the following:

- A hollow cathode ion source with tungsten impregnated emitters for long life.
- High-voltage insulators and power supplies, all of which are shielded from the neutron and gamma flux.
- A cesium vapor curtain to reduce the flow of gas along the beam line.
- Stationary cryopanels that are periodically outgassed.
- Injector system built of many ion sources to establish system reliability and redundancy.

As an example of the complexity of the beam injection problem consider the "standard" mirror hybrid design\textsuperscript{13}. Each injector array consists of 216 ion sources, arranged in 18 columns of 12 units, spread over an area of 6 x 9 m. To confine the injected beam within a maximum
half angle of $15^\circ$, the distance from the sources to the beam entrance aperture in the blanket is 17 m. Two such injector assemblies are required, each aimed at a different part of the plasma.

In a Tandem Mirror Reactor the plasma density of the "plugs" must be maintained by continuous injection of deuterium ions. The "plugs" are not a source of fusion power. Magnetic shielding requirements for the "plug" beam sources and magnets will be much less severe if only D-D reactions are occurring there; the D-T reaction producing useful thermonuclear power is confined primarily to the central cell. Early designs showed a required injection energy of 1.2 MeV. More recent efforts have shown a high Q (~10) reactor with plug injection energy at 600 keV. This is still beyond current practice but our designs appear practical considering the rate of progress in beam technology.

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.

A typical geometry for a beam line and its shielding is shown in Fig. 10. The heating rate in stainless steel produced by neutrons and gamma rays escaping through such an injection port is shown by Fig. 11. Heating on objects 10.5 meters from the plasma center is 15 watts per kilogram on the beam axis and only 0.5 watts per kilogram 60 centimeters off axis at the same radial distance.
Total heating must be limited to levels where the cost in both capital and energy needed for refrigeration is acceptable. There is an economic trade off between providing refrigeration and reducing heat loads by shielding or other means. To get an idea of whether the heat load indicated on figure 11 is acceptable, a typical beam line was evaluated using 0.5 watts per kilogram as the heating rate on the cryopanels. This total heat load was converted to refrigeration power and was then compared to the electrical power consumption of the neutral beam injector. The results showed that the neutron thermal load on the cryopanels was only 0.7% of the power required for beam injection. Any number less than 1% for cryopanel heating is considered acceptable to the power balance of the reactor.

The gamma ray exposure of electrical insulating materials may have important effects on performance and life. Reference 14 concludes that for a 1 MeV neutral beam line epoxy components receive up to 100 R s\(^{-1}\) of gamma radiation.

Direct effects of radiation on dielectric breakdown have not been studied adequately. The only data which we have found that is remotely relevant is shown in Fig. 12 for beryllium oxide exposed to 0.6 R s\(^{-1}\). In that range there appears to be no effect. To a first approximation, there is no particular reason to expect trouble at 100 R s\(^{-1}\). However, the combined effects of irradiation, reducing conditions (chamber vacuum and free atomic hydrogen isotopes), and conduction heating are an obvious invitation for growth of instabilities in material behavior, especially organic insulator materials. Growth of any conducting filaments (metal or carbon) would produce steep local fields and a cascading of breakdown processes.

The effects of radiation fluence are complex. Changes in thermal conductivity may alter the ability of an insulator to dissipate heat. Increased brittleness may make them more susceptible to thermal shock. Swelling may cause fractures or separation between different materials such as ceramic-metal joints. These may all be more important than any direct effect on electrical conductivity or dielectric breakdown strength.
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/cm² in a series of experiments in 1970. The problem with the concept was that the packing of a large array of beamlets for large beam currents would be difficult since the magnets are bulky.

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. Figure 13 shows that concept.

Plasma direct converters can be divided into two general types according to whether the electrons are separated out magnetically or electrostatically. For magnetic separation, the plasma is guided and expanded magnetically into a thin slab from which the magnetic field, and hence the electrons, can be abruptly diverted. The ions continue on with only a slight deflection if the expansion resulted in a sufficiently weak field. For electrostatic separation, the plasma stream is expanded in two dimensions to produce directed motion and to reduce the power flux to a level (~100 W/cm²) where immersed grids can be used to reflect the electrons. The fate of the electrons is different in the two types of separation. With magnetic separation, the electrons are removed from the beam and can be collected, while an immersed negative grid simply reflects the electrons without disposing of them. The sink for the electrons in this case is provided by a grounded grid which precedes the negative grid in the beam line and establishes ground potential (see Fig. 14).
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. The designer must be very ingenious in shielding the insulators from neutrons while at the same time holding the size of the direct converter within limits so cooling of the electrodes does not require very high convective coolant pressure drop.

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.

The direct converters for all mirror fusion reactors have neutron radiation-related design problems. The problems are similar to those encountered in the beam injector systems previously discussed, but there are two important differences that make the direct converter somewhat simpler to design. First, the distance from the reacting plasma is much greater, as much as five to ten times more distant than are beam source components. Second, not all of the direct converter "sees" the reacting plasma. The expanding magnetic field lines have pronounced curvature so the outermost extremities of grid vanes will not receive direct neutron and gamma flux.

However, the entire direct converter receives a large thermal load from ions escaping the fusion plasma region. This flux must be held to an average of 100 W-cm\(^{-2}\) with peak flux not exceeding 200 W-cm\(^{-2}\). Thermal loads in that range have been dealt with successfully in the laboratory in tests of direct converter designs by Moir and Barr.
The area of a direct converter is very large due to thermal loading considerations. Dimensions to be spanned by carbon vanes, tungsten wires, etc., are tens of meters. To combat distortion by thermal effects added to deflections due to gravity, the direction of the vanes should be vertical. Means of maintaining tension must be supplied and protected from overheating. It is much better to locate supports and electrical insulators around the periphery of the "flux-bundle" as it intercepts the plane of the direct converter. This eliminates direct neutron flux as a degradation agent or as a source of heat on both insulators and critically stressed tensioning mechanisms.

The length of the direct converter vanes also suggests that forced convection cooling will be very difficult if extreme pressures are to be avoided. This means radiation cooling must be investigated. If used, then a convectively cooled copper liner must receive that radiation - behind which will be the cryopumping panels which do all of the particle removal for the plasma region.
REFERENCES


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EVOLUTION OF MIRROR FUSION IDEAS

SIMPLE MIRROR

MINIMUM-B MIRROR

FIELD REVERSED MIRROR

TANDEM MIRROR

FIG. 1
FUSION-FISSION MIRROR
HYBRID REACTOR

FIG. 2
FUSION-FISSION MIRROR HYBRID REACTOR

- Removeable Radiation Shield
- Telescoping Mast
- Upper Guide for Mast
- Top of PCRV
- Module Change Arm Multiple Axis Motion
- Module Grapple with Assembly Tools
- Swing Out Guide for Mast Support
- Bottom of PCRV

FUEL MODULE CHANGE TOOL

FIG. 3
Flow Distribution Dome

MHR First Wall Module

0.002M

U₃Si Pins

Lithium Hydride Pins

Evacuated Double Varian Type Seal

Vacuum Sinus

Cool Helium

Plated Metal "O" Ring and Grafoil Slip Ring

Flow Control Orifice

Thermal Insulation

Hot Helium

Inner Assy Restraint Thread and Grapple

Diffuser

Neutron Shield Spike

Hex Flange

0.50M OD

1.17M

0.80M

FIG. 6
FIG. 7

TANDEM MIRROR REACTOR

BLANKET / SHIELD SEGMENT

MOUNTING RAIL

HELIUM COOLANT

OUT

IN

CRES CASE

HASTELLOY

CRES

BLANKET

CARBON LAYER

VACUUM LAYER

LITHIUM BLANKET PIN

SHIELD
BLANKET MODULE FOR TANDEM MIRROR REACTOR
Neutral Beam Line Geometry for Study of Neutron Flux Near Injector Axis
Fast neutron fluxes. Distributed source, neutrons/cm²-s.

Total heating rate in stainless steel. Point source, W/kg.

Dimensions in cm.

FIG. 11
FIG. 12. Electrical breakdown field strength as a function of temperature for BeO insulators with and without an impressed radiation field.
100 keV 10A NEUTRAL INJECTOR SYSTEM

120 keV ION SOURCE

DIRECT CONVERTER

D^+

D^0

LN COOLED NEUTRALIZER CELL

CRYO PANEL PUMP

FIG. 13
FIG. 14: Direct Converter Array showing typical grid and collector voltage