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A Review of Mirror Fusion Reactor Designs

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A Review of Mirror Fusion Reactor Designs*

D. J. Bender

At Lawrence Livermore Laboratory we are presently pursuing three magnetic confinement concepts, based on the mirror principle, which show promise for fusion reactor applications. These mirror concepts are summarized in Figure 1, and a brief description of the supporting experimental program is contained in Reference 1.

A. Fusion-Fission Hybrid Reactor

An appropriate starting point in a review of mirror reactors is the fusion-fission (hybrid) reactor, as it uses a classically-confined mirror plasma and many of the hybrid reactor components (injectors, direct converters, vacuum equipment) are also used in the tandem and field-reversed mirror reactors. Classical mirror confinement is illustrated schematically in Figure 2. Energetic atoms of deuterium and tritium, injected into a minimum B magnetic well, are trapped in the field when they experience ionizing collisions with the confined plasma. An ion remains in the confinement region, bouncing between mirror points, until ion-ion collisions scatter the ion velocity vector into the loss-cone, at which time the ion escapes from the well. Reference 2 contains a thorough discussion of classical mirror confinement.

The important characteristics of classical mirror confinement, from the standpoint of reactor design, are listed in Figure 3. The attainment of high β results in a comparitively high fusion power density, and steady-state operation simplifies reactor operation and blanket design. Unfortunately, this confinement method exhibits a maximum Q of only about 1; reactor studies have shown that this value of Q is too low for the plasma to be used as the energy source for an economically competitive

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*Work performed under the Auspices of the United States Energy Research & Development Administration Contract No. W-7405-Eng.-48 electric generating station. [3] However, because of the high fusion power density a classically-confined mirror plasma is an intense source of 14 MeV neutrons, and reactor studies have shown this plasma to be well-suited for the fusion-fission reactor concept. [4]

The fusion-fission (hybrid) reactor is distinguished by the incorporation of fertile heavy metals (^{232}Th or ^{238}U) into the blanket, resulting in the reactions shown in Figure 4. The blanket neutronics involve fast-fission of the heavy metal atoms by the 14 MeV fusion neutrons, and subsequent breeding of fissile isotopes (^{233}U and ^{239}Pu) and T_2 with the excess neutrons produced by fast-fission. These reactions produce two beneficial effects. First, the 200 MeV energy release from fission multiplies the energy per fusion neutron by a factor of about 10(allowing for the capture of some fusion neutrons in structural material) and secondly, the blanket produces 1 - 2 fissile atoms/fusion neutron that can be used to fuel fission reactors.

This type of reactor scheme is appropriate for the low Q classical mirror plasma since the additional fission energy release in the blanket compensates for the marginal power balance in the plasma, and the large neutron production rate of the plasma results in large fissile production rates in the blanket. The reactor is capable of net electrical power generation and can produce enough fissile fuel to operate 5 - 10 fission reactors (of thermal power comparable to that of the hybrid).

The coil design that has been developed to provide a stable magnetic well is shown in Figure 5 and is called a Yin Yang coil. Plasma is contained in the spherical region inside the coil set, and plasma leakage occurs through the slotted opening in each coil. In addition to the magnet, the main components of the "fusion island" portion of the reactor are the neutral beam injectors, the end-tanks to receive the plasma leakage, the vacuum system and the tritium handling equipment.

A conceptual design of a neutral beam injector module is shown in Figure 6. It consists of a diffuse plasma discharge from which ions are extracted and accelerated to the desired energy. Some of the ions are then neutralized by charge-exchange collisions with cold gas in the neutralizer cell; the remaining (un-neutralized) ions are electrostatically decelerated and their kinetic energy convertered back to electrical energy (a process called "direct conversion" [6]). The resulting neutral beam then proceeds down a duct into the plasma confinement region. Since a reactor-grade plasma typically requires several thousand amps of neutral current, the reactor injector system is constructed by using many of these individual modules in a single tank, as shown in Figure 7.

The functions performed by the plasma end tanks are listed in Figure 8. Essentially all of the atoms that are injected into the plasma escape into the end tanks ($Q \underset{\sim}{\sim} 1$ implies that less than 1% of the injected current experiences fusion reactions) and since in a mirror machine there is no diffusion of plasma energy to the walls of the confinement region, the ions escape into the end tanks with approximately the same energy at which they were injected. The plasma leakage is first expanded in the end tank to low density, then electrostatically decelerated, and collected on electrodes converting some of the plasma kinetic energy directly to electrical energy (direct conversion). This process is depicted in Figure 9. The remaining plasma kinetic energy is deposited as thermal energy in the electrode structure and is removed by active cooling. Upon intercepting the electrodes, the ions are neutralized and the resulting neutral gas load must be pumped away.

The primary sources of gas that make up the vacuum pumping load occur (1) in the injector tanks from gas that is introduced into the ion source but is not converted to energetic neutrals, and (2) in the end tanks from neutralized plasma leakage. This gas load is handled by cryocondensation vacuum pumping techniques [7], where the hydrogen isotopes are condensed on panels cooled to 4 °K by liquid He. A typical cryopanel is shown in Figure 10.

Proceeding now to the mechanical design of the reactor, the blanket configuration is shown in Figure 11. The blanket is a spherical shell that resides inside the Yin Yang magnet, and has appropriate openings for neutral beam injection and the plasma leakage fans. The entire magnet, blanket and primary heat transfer loop are contained in a concrete monolith, or Prestressed Concrete Reactor Vessel (PCRV), as shown in plan view in Figure 12. The concrete monolith serves to (1) restrain the main magnet forces, (2) support the blanket, and (3) support and restrain the primary heat transfer loop components. A cross-section through the reactor appears in Figure 13, showing the magnet, blanket, end tanks and vacuum shell in the PCRV; not shown in the drawing are the injector tanks and primary heat transfer loop components which are also located in the PCRV.

The blanket is cooled with helium, using components developed for gas-cooled fission reactors. The thermal energy is transferred from the He primary heat transfer loop into a steam thermal conversion loop. A cross section through the entire plant is shown in Figure 14.

B. Tandem Mirror Reactor

The tandem mirror reactor consists of three mirror cells on a common axis as shown in Figure 15. The end cells, or "plugs" establish minimum B magnetic wells and are connected by a large central cell which is a simple solenoid. The plasma envelope is shown below the coil in Figure 15. The physical principles governing plasma confinement in this configuration are described in Reference 8. Briefly, classical mirror confinement in the end cells is used to establish electrostatic potentials which provide end stoppering for the ions in the large central cell. The plugs are injected with a single species, D° or T°, and do not produce fusion power but rather serve just to electrostatically stopper the central cell. The central cell, where the fusion reaction is sustained, is fueled by low energy neutral beams of deuterium and tritium. Electrons heated by the energetic ions in the plugs in turn heat the ions in the central cell and help maintain the central cell reaction. The balance of the heating in the central cell is provided by the alpha particles created in the fusion process. The plasma Q increases with increasing central cell size; for a 1000 MWe unit, it appears possible to achieve $Q \geq 5$.

The major features of a tandem mirror reactor are listed in Figure 16. The difficult technological problems are concentrated in the small end plugs, which require high magnetic fields and high injection energy. In contrast, the large central cell has a simple cylindrical shape, low magnetic field and low injection energy.

The conceptual design of a 1000 MWe tandem mirror reactor is shown in Figure 17. The reactor is dominated by the ~ 100 m long central cell, with a neutral-beam-injected plug on each end. Outboard of each plug is an end tank with direct converters to collect the leakage from the plugs.

Central cell subdivision into 3 metre long modules is planned (Figure 18). Each, with 24 blanket/shield wedges, vacuum chamber, superconducting solenoid, coolant manifolds, and structured support, weighs 750 tonne. A tracked transporter allows the module to be displaced 10 metres from the central cell centerline. Servicing machines extract single blanket segments and move them to "hot parts" storage. One machine opens welded coolant pipes, the other removes and replaces module components. A special automatic welder cuts off and rewelds the vacuum joint at each end of a module.

The plug magnets represent a design problem due to the high magnetic field requirements. Field strengths in the 16 T to 20 T range at the conductor are necessary. As presently visualized the plug magnet system (Figure 19) uses a pair of superconducting solenoid coils set to create a minimum $|B|$ well of small mirror ratio (~ 1.10). Because of the high magnetic flux densities required and the low strength of the high purity aluminum conductor, the aluminum winding must have internal structure of relatively high strength alloy to transmit the magnetic forces to the external support structure. The refrigerator power required for the Yin Yang coil is kept to a reasonable level by its relatively small size and amperage.

Neutral beam injection of the plugs is nominally 1 MeV. Continuous beams of that energy have not been achieved, but lower energy pulsed beams of the same current density are now in use. A preliminary design (Figure 20) handles the high voltage in increments of 200 kV, using ±

600 kV from ground for a 1200 kV injector. It employs a cesium ionization cell, accelerator electrodes, and a photo-detachment neutralizer [9].

C. Field Reversed Mirror Reactor

The field-reversed-mirror confinement concept uses a neutral-beam injection pattern which establishes strong plasma currents which circle the axis of the applied mirror field as shown in Figure 21. These plasma currents are sufficiently strong to significantly alter the applied magnetic mirror field, converting the field configuration from open-field (typical of mirrors) to closed field lines. The significance of this field modification is that plasma containment is increased from $Q \sim 1$ in the open field (mirror) configuration to $Q \sim 5$ in the closed field (reversed-mirror) configuration. An additional benefit, from the engineering standpoint, is that much of the confining field is generated by the plasma itself rather than with expensive, complicated coil windings, thus simplifying the reactor mechanical design and reducing capital costs.

The plasma itself takes the shape of a "donut" (as shown in Figure 21), has very high fusion power density (~ 100 w/cc), and is comparatively small, producing tens of megawatts of fusion power. The field reversed mirror reactor takes advantage of this small power output per plasma donut by employing a modular concept for the reactor. For example, in Figure 22 four cells are shown linked together, the plasma in each cell being supported by a neutral injection system. The applied field is designed to hold each plasma cell in place and minimize interaction between the cells.

A preliminary conceptual design of an electric generating station based on a field-reversed-mirror fusion plasma has been completed [10]. A cross-section through the reactor is shown in Figure 23. Here, 12 cells are used to produce an electrical output of 120 MWe. The striking features of the reactor are its small size compared to fusion reactors based on other confinement concepts, and the simple cylindrical geometry. This later feature greatly simplifies mechanical design and ease of blanket maintenance operations. Examining Figure 23 in more detail, immediately outboard of the plasma is a set of copper (normal) coils used to establish a modest mirror field that localizes the individual plasmas. Then, proceeding radially outward, are the blanket and shielding, and finally a superconducting solenoid that provides the main applied field. The large structure outside the solenoid magnet houses the neutral beam systems that drive the plasmas. On both ends of the reactor, in the axial direction, end tanks with direct conversion are used to accomodate the plasma exhaust and recover much of the energy in this plasma flow.

A large central station power plant, of say 1000 MWe, would be constructed by using multiple units of the type shown in Figure 23. A top view of such a facility is shown in Figure 24, where several 100 MWe units share common facilities. The advantage of this configuration is that one or two units could be down for maintenance at any given time and the remaining units would provide continuous output to the power grid. Figure 25 is a cross section through the plant, showing location of the major components of the power station in relation to the fusion nuclear island.

References

(1) T. K. Fowler, "LLL Mirror Fusion Program: Summary", Lawrence Livermore Laboratory Report UCID-17387, 1977.

(2) D. E. Baldwin, "End-Loss Processes from Mirror Machines", submitted to Rev. Mod. Physics; also LLL Report UCRL-78406, 1976.

(3) G. A. Carlson and R. W. Moir, "Mirror Machine Reactors", Proc. of 2nd Topical Mtg. on Technology of Controlled Nuclear Fusion, CONF-760935-P2, p. 555, 1976: also, LLL Report UCRL-78148, 1976.

(4) Proc. US/USSR Symposium on Fusion-Fission Reactors, Livermore, California, 1976, CONF-760733, p. 13-54.

(5) J. W. Stearns, K. H. Berkner and R. V. Pyle, "Neutral-Beam Design Options", Proc. 2nd Topical Mtg. on Technology of Controlled Nuclear Fusion, 1976, CONF-760935-P4, p. 1221; also, LBL Report LBL-4492, 1976.

(6) W. L. Barr and R. W. Moir, "A Review of Direct Energy Conversion for Fusion Reactors", Proc. 2nd Topical Mtg. on Technology of Controlled Nuclear Fusion, 1976, CONF-760935-P4, p. 1181; also, LLL Report UCRL-78204, 1976.

(7) L. C. Pittenger, "Vacuum Engineering for Fusion Research and Fusion Engineering", Proc. Annual Symposium of Vacuum Soc. of Am., Chicago, 1976; also, LLL Report UCRL-78501, 1976.

(8) T. K. Fowler and B. G. Logan, "The Tandem Mirror Reactor", LLL Report UCRL-78740, 1976.

(9) Joel H. Fink, "Design Problems of a Continuous Injector of Many Amperes of MeV Deuterium Neutrals", Lawrence Livermore Laboratory Report UCID-17303, 1976.

(10) W. C. Condit, G. A. Carlson, R. S. Devoto, J. N. Doggett, W. S. Neef, and J. D. Hanson, "Preliminary Design Calculations for a Field-Reversed Mirror Reactor", LLL Report UCRL-52170, 1976.

MIRROR REACTOR DESIGNS

Fusion-Fission $Q \sim 0.7$ $W_{INJ} \sim 100$ keV	Classical Mirror Confinement	Low Physics Speculation	Low Technology
Tandem $Q \sim 5$ $W_{INJ} \sim 1.2$ MeV	Electrostatic Potential Confinement	Modest Physics Speculation	High Technology End Plugs Low Technology Reactor
Field Reversed $Q \sim 5$ $W_{INJ} \sim 200$ keV	Cross-Field Confinement	High Physics Speculation	Modest Technology

Figure 1

MIRROR MACHINE CONFINEMENT

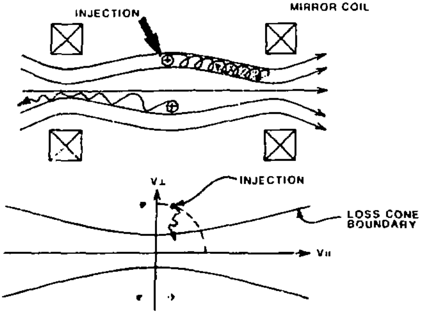


Figure 2

MIRROR CONFINEMENT

1. $N\tau \cdot (\bar{E}_p)^{3/2} m(R)$

2. High Beta

$$\beta = \frac{P}{(B^2/2\mu_0)} = 0.5 - 0.8 \qquad N_1 = \beta \frac{(B^2/2\mu_0)}{(RT)}$$

3. Steady State

4. Plasma Power Balance

$$Q = \frac{\text{Fusion Power}}{\text{Input Power}}$$

$$Q = \frac{N_D N_T \langle \sigma v \rangle E_f}{E_{inj} N_i / \tau} \qquad Q = (N\tau) \langle \sigma v \rangle \frac{E_f}{E_{inj}}$$

Figure 3

HYBRID BLANKET NEUTRONICS

1. Uranium

$$^{238}U + n(14\ \text{MeV}) \longrightarrow \text{F.P.} + 200\ \text{MeV} + 4n$$

$$^{238}U + n \longrightarrow {}^{239}U \xrightarrow{\beta} {}^{239}Np \xrightarrow{\beta} {}^{239}Pu$$

2. Thorium

$$^{232}Th + n(14\ \text{MeV}) \longrightarrow \text{F.P.} + 200\ \text{MeV} + 4n$$

$$^{232}Th + n \longrightarrow {}^{233}Th \xrightarrow{\beta} {}^{233}Pa \xrightarrow{\beta} {}^{233}U$$

Figure 4

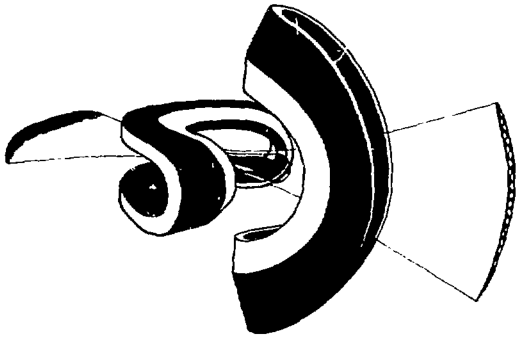


Figure 5

100 keV 10A NEUTRAL INJECTOR SYSTEM

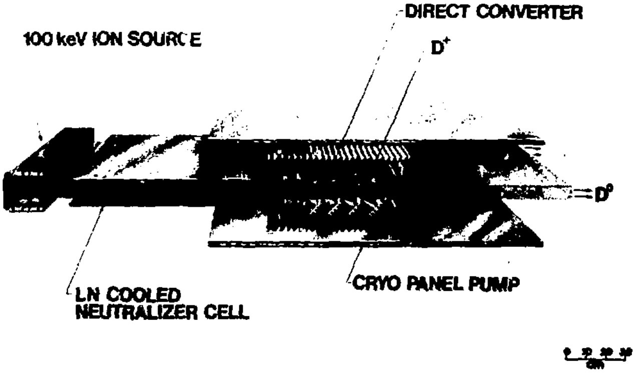


Figure 6

NEUTRAL BEAM INJECTOR ARRAY

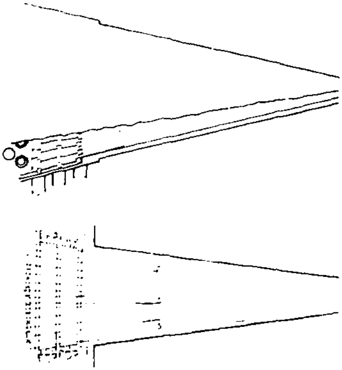


Figure 7

PLASMA LEAKAGE END TANKS

- Receives Plasma Leakage
- Electrostatic Deceleration of Ions (if Desired)
- Plasma Neutralization
- Thermal Energy Deposition & Removal
- Provides Vacuum Pumping Locations

Figure 8

Figure 9

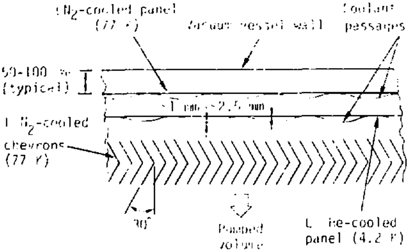
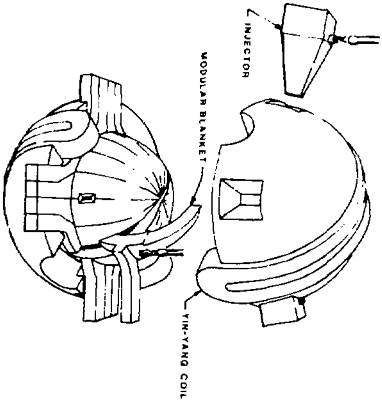


Figure 10



MIRROR REACTOR WITH SPHERICAL BLANKET

Figure 11

PRESTRESSED CONCRETE REACTOR VESSEL

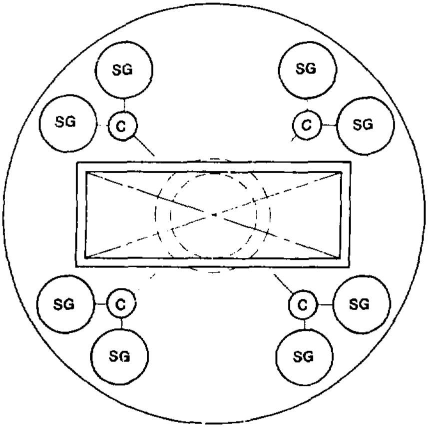


Figure 12

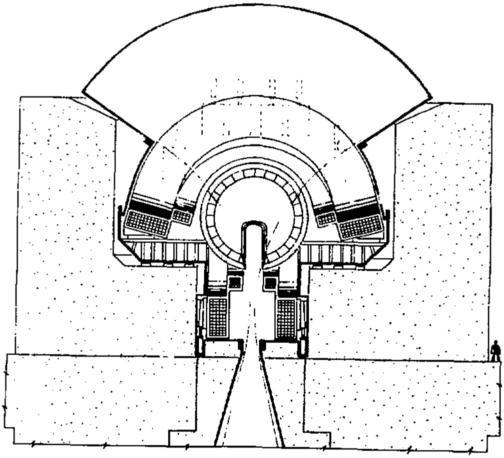


Figure 13

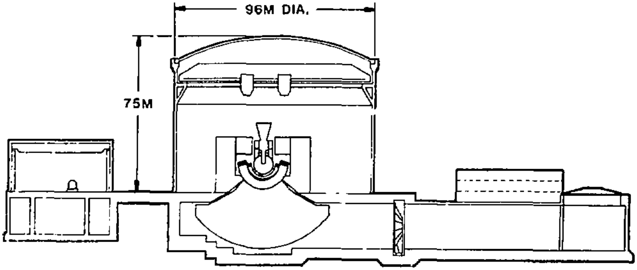


Figure 14

TANDEM MIRROR MACHINE

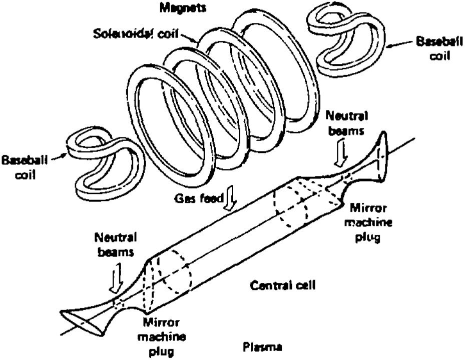


Figure 15

FEATURES OF TANDEM MIRROR REACTOR

- High Q
- Low central cell technology
  - Geometric simplicity
  - Modular construction
  - Magnetic field strength 2.5 T
- Power can be increased by adding central cell modules
- High plug technology
  - Magnetic field at conductor $\simeq$ 17 T
  - Injection energy $\simeq$ 1.2 MeV
- Periodic plasma flush required to remove accumulated ash ($^4He^{++}$ions)

Figure 16

TANDEM MIRROR REACTOR

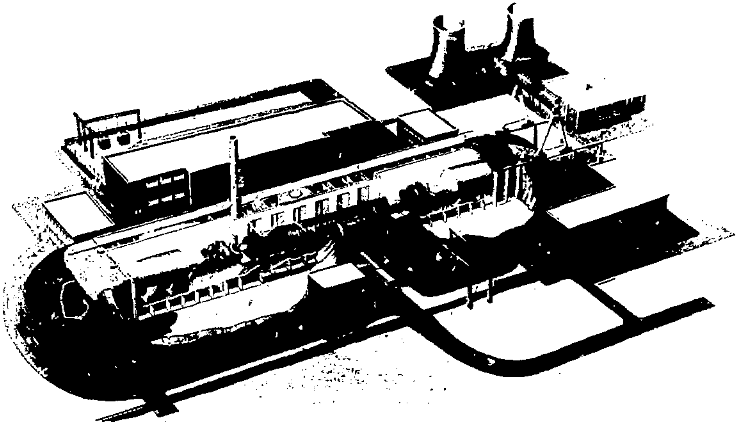


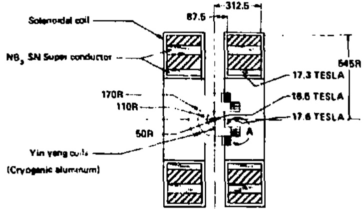
Figure 1

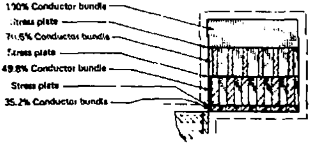
BLANKET MODULE FOR TANDEM MIRROR REACTOR

Figure 18

T-M-R PLUG COIL SET

18.5 TESLA

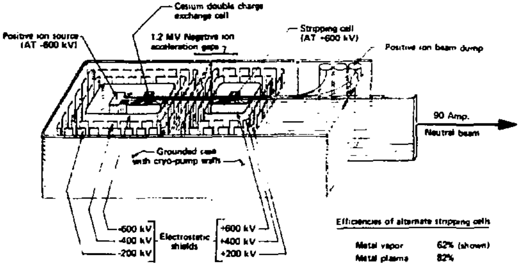




Detail A

Figure 19

1.2 MEV INJECTOR



Efficiencies of alternate stripping cells

Metal vapor	62% (shown)
Metal plasma	82%
Photo-detachment	95%

Figure 20

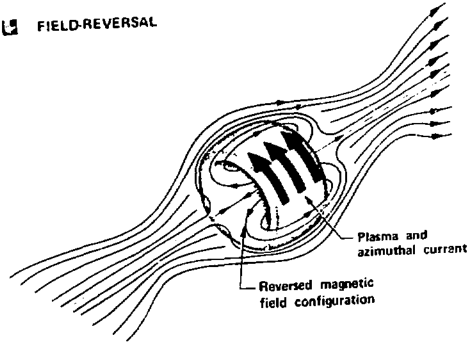


Figure 21

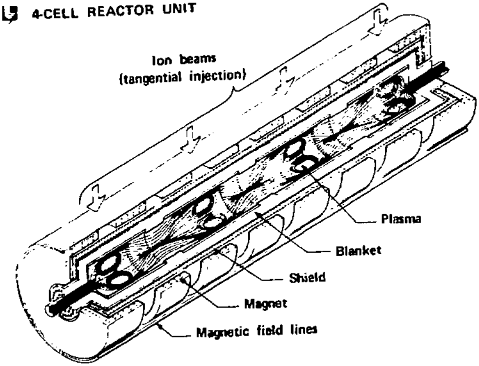


Figure 22

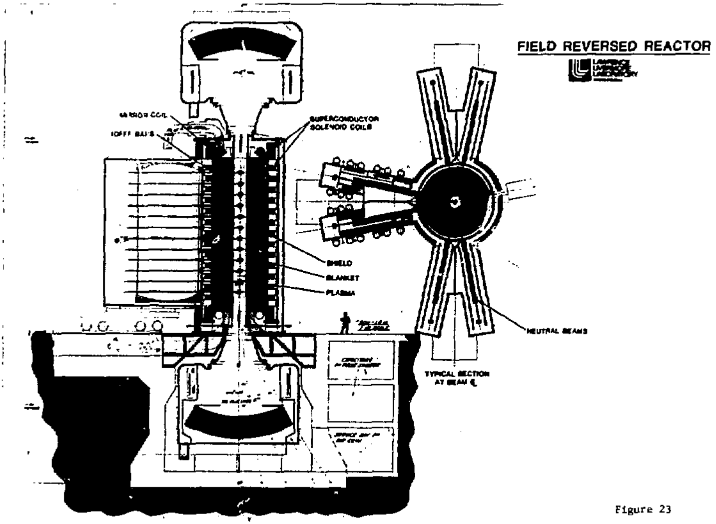


Figure 23

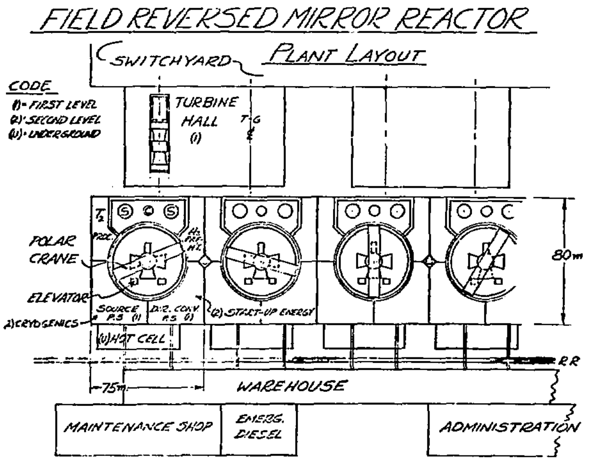


Figure 24

FIELD REVERSED MIRROR REACTOR

Section thru typical 120 MWe module

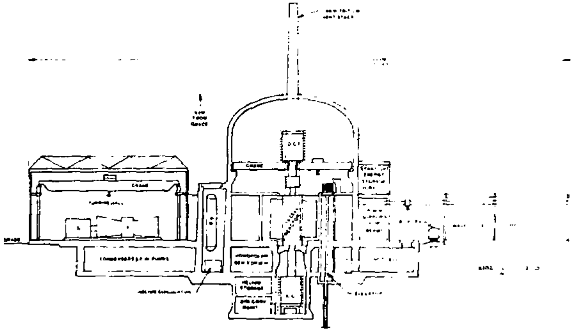


Figure 25