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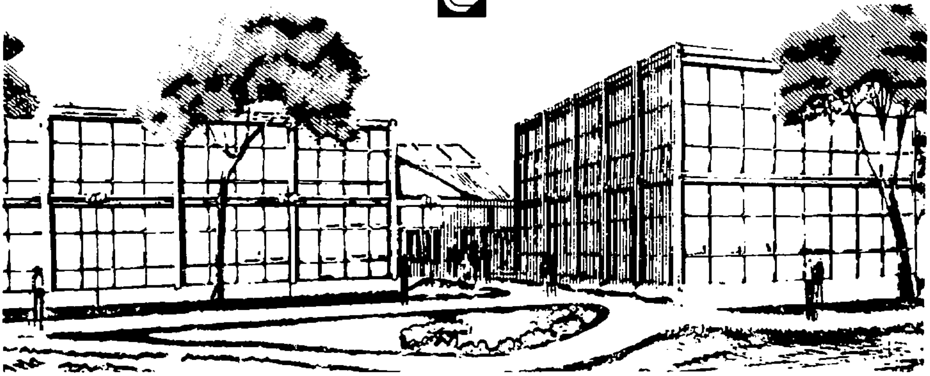

SMALL MIRROR FUSION REACTORS

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We have investigated the design of small pilot plant fusion reactors based on mirror confinement concepts. Basic requirements for the pilot plants are that they produce a net product and that they have a potential for commercial upgrade. We have investigated a small standard mirror fusion-fission hybrid, a two-component tandem mirror hybrid, and two versions of a field-reversed mirror fusion reactor -- one a steady state, single cell reactor with a neutral beam-sustained plasma, the other a moving ring field-reversed mirror where the plasma passes through a reaction chamber with no energy addition.

INTRODUCTION

The participation by an electric utility in the construction and operation of a small pilot fusion reactor would be a significant step in the commercialization of fusion. Such a pilot plant should be small and fairly inexpensive in terms of total capital cost, but perform in such a way as to gain public recognition and to provide significant operating experience to the electric utility. Sponsored by the Electric Power Research Institute (EPRI), we are attempting to determine what this pilot plant might be.

Specifically, the objective of our project is to evaluate various mirror fusion reactor concepts which might result in small systems for the effective production of electrical power or stored energy (e.g., nuclear and chemical fuels). The basic two-year program goal is to select a particular concept and develop the conceptual design of a pilot plant which could provide a useful output from fusion and be built and operated in the late 1980's. The project team consists of a unique combination of personnel from a national laboratory (Lawrence Livermore Laboratory), the nuclear energy industry (General Atomic Company), and an electric utility (Pacific Gas and Electric Co.). This team was chosen to encourage the development of working relationships among the kinds of participants necessary for the effective utilization of fusion power. In order for fusion power to become a reality, a

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*The authors wish to gratefully acknowledge the contribution of the project teams at LLL, GA, and PG&E.

common ground must be found which combines what is possible in plasma physics and fusion technology, what is practical in the nuclear industry, and what is attractive to the electric utilities.

We are nearing the end of the first year of the project. During the first year a scoping study was initiated consisting of parametric analyses and preliminary conceptual designs of a number of reactor options. In the second year we will select one of the preliminary designs for a more detailed conceptual design study.

In this paper we will discuss the present status of the project.

Project Guidelines

One of the project accomplishments has been the development by the project team of a set of general guidelines for the project. These guidelines are shown in abbreviated form in Table 1.

- PHYSICALLY SMALL AND LOW TOTAL COST
- NET PRODUCT PRODUCTION
- COMMERCIAL UPGRADE POTENTIAL
- NEED NOT DEMONSTRATE ALL ASPECTS OF COMMERCIAL PLANT
- PLASMA PHYSICS EXTRAPOLATION PERMITTED
- MID 1980's TECHNOLOGY IF POSSIBLE
- ENVIRONMENTALLY AND SOCIALLY ACCEPTABLE

TABLE 1. Project Guidelines for Pilot Plant

We agreed that "small" means physically small and low cost, and that the pilot plant to be designed should be as small as possible consistent with a requirement for net product production and commercial upgrade potential. By "net product production" we mean that the plant produce net electricity if electrical power is its intended product, or, if fuel is its intended product, that the fuel's electrical value (if burned) is greater than the input power to the pilot plant. By "commercial upgrade potential" we mean that a scenario must be identified whereby the pilot plant can be shown to lead to an economically attractive commercial reactor.

There is no requirement that the pilot plant produce an economical product; the low cost specification refers to total capital cost and is intended as an encouragement for the commitment to building such a pilot plant. Of course, the ultimate commercial plant must be economical on a cost-per-unit-product basis. Recognizing the potential advantages of a small commercial electric power plant (ease of siting and financing, and decreased dominance of the electric power grid), we agreed that, in decreasing order of desirability, commercial upgrade of electrical power producers should be via replication of small units, addition of modular elements, possible near-term advances in technology, or (as a last resort) scale-up beyond 100-200 MWe. Small size for a commercial fuel producer is less of a potential advantage since such a plant could be remotely sited and need not be on the electric power grid.

Although the pilot plant must have most of the systems of the commercial plant in order to provide significant operating experience to the electric utility, it need not demonstrate all aspects of the commercial plant. For example, the pilot plant need not breed all of its required tritium fuel (although it may be desirable from the experience viewpoint to breed some). Mirror concepts with varying physics risk may be considered and no concept is to be excluded on the basis of inadequate physics data base alone. However, the study should indicate what additional physics R&D is required. It would be highly desirable if the technologies to be incorporated into the design could be limited to those which can be expected to be available by the mid 1980's based on presently committed R&D programs. If this is not possible, the study should indicate what additional technological R&D is required. Finally, we recognized that environmental and social concerns will play an important role in the evaluation of the desirability of the pilot plant design.

Mirror Confinement Concepts

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.

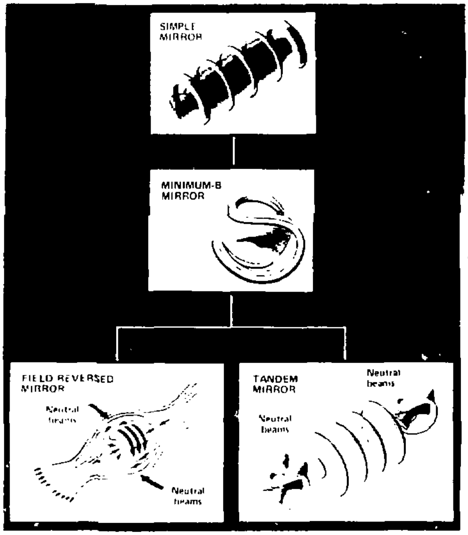

FIGURE 1. Evolution of mirror fusion ideas

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 back-ground field. So far, efforts to produce field reversal in the 2XIIB facility by neutral beam injection have not succeeded, but further experiments on this machine are planned. In addition, field reversal experiments will be conducted on TMX and MFTF.

We have carried out scoping studies of small pilot fusion reactors based on the three current mirror confinement concepts: the standard mirror, the tandem mirror, and the field-reversed mirror.

Blanket Options and Power Conversion Options

A number of blanket and power conversion options were proposed for use with the small mirror reactors. Based on preliminary technical evaluations, three blanket concepts were chosen for more detailed consideration. In this section we briefly describe all of the blanket options we have considered. The three options chosen for more detailed work are discussed further in the sections on the specific reactors.

The fast spectrum hybrid blanket is a high performance blanket with a large energy multiplication, good neutronic performance, and prolific fissile fuel production. It is particularly suited to a low Q device because the large fuel production can allow a pilot plant to produce a net product even though the reactor itself may not produce net electrical power. The thermal spectrum hybrid blanket is based on graphite fuel HTGR technology. This option is attractive because of the inherent safety and high temperature capabilities of the graphite based fuels. This option was dropped because of its modest energy multiplication and fuel production performance. Incorporation of chemical production in a blanket (e.g., radiolysis of water to produce hydrogen) was considered as a means of increasing the overall performance of a reactor. This option was dropped because of the primitive state of the art for chemical production blankets, and our failure to identify a chemical reaction of high efficiency that could be straightforwardly incorporated into a blanket design. The lithium alloy blanket appears to . the most straightforward approach to a power-producing blanket. Use of lithium alloys or lithium ceramics in helium-cooled metal structure allows both efficient power conversion and adequate tritium production. The circulating ball blanket is an innovative concept wherein solid composite spheres of Li_2O and graphite are circulated through circular passages in a blanket made of graphite blocks. The spheres are heated by internal neutron attenuation and by radiation heat transfer from the otherwise uncooled blocks. Although the concept has a number of potential advantages, it was dropped from our study because of insufficient resources to develop such a new idea. The low residual activation blanket is an attempt to maximize the environmental and maintenance advantages of a small fusion reactor. The blanket considered is based on aluminum structure, helium cooling, and ceramic blanket materials. The three blanket concepts chosen for more detailed work are the fast spectrum hybrid blanket, the lithium alloy blanket, and the low residual activation blanket.

In the area of power conversion options we have chosen the conventional steam cycle for all three blankets. In addition, we are considering the direct cycle gas turbine power conversion system for application with the low residual activation blanket.

Standard Mirror

For the standard mirror we have used a two zone model for plasma confinement. For the inner radial zone (plasma core) we assume classical mirror confinement. For the outer radial zone (boundary layer), taken to be 3 ion gyro-radii in thickness, we assume that auxiliary streaming plasma must be supplied to suppress the DCLC (drift cyclotron loss cone) instability. The addition of streaming plasma depresses the electron temperature in the boundary layer, and degrades the confinement (as compared to the core). Thus, this model predicts that Q for the standard mirror improves with plasma size and approaches the value for classical mirror confinement. Since the 2XIIB plasma is essentially all boundary layer, verification of this model must await the operation of MFTF.

Previous studies conducted for the Department of Energy (DOE) have shown that the standard mirror, as a fusion power reactor, would produce very expensive electricity.(1) 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 DOE-funded studies have shown, however, that the standard mirror in large sizes would be a viable fusion-fission hybrid reactor. Reference 2 describes 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 (MFTF has a mirror-to-mirror length of 3.4 m and a maximum field strength of 7 T). 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.

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 2). 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).

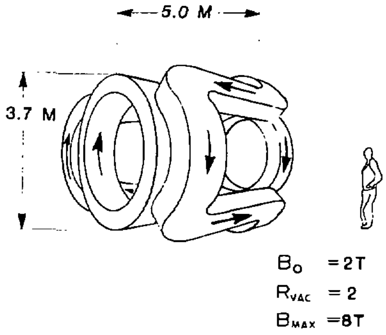

FIGURE 2. Coils for the small standard mirror

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 coil design for the hybrid pilot plant results in a reactor with cylindrical geometry and good axial access for blanket change operations. We have chosen a reactor configuration based on a prestressed concrete reactor vessel (PCRV) as shown in Figure 3. The PCRV accomplishes 5 functions:

1. Magnet force restraint
2. Blanket and shield support
3. Coolant pressure containment
4. Primary coolant loop component support
5. Biological shielding

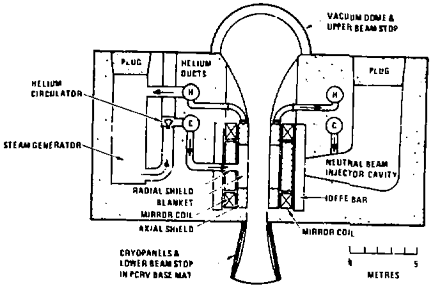

FIGURE 3. Small standard mirror hybrid

We have selected a fast spectrum metallic fueled blanket with a helium-cooled fuel rod configuration to maximize performance and the application of fission reactor fuel technology. We have considered fissile fuel breeding zones containing natural uranium (in the form of U_3Si) to breed plutonium or thorium to breed ^{233}U, or combinations of the two breeding materials. Table 2 gives the estimated blanket performance for the three options along with the performance of burner reactors utilizing the bred fissile fuel. The neutronic performance of the uranium-fueled blanket is superior to that of the thorium-fueled blanket, but because of the higher efficiency and conversion ratio of the ^{233}U-burning HTGR, the thorium-fueled blanket produces a more valuable fuel.

HYBRID OPTIONS	U$_3$Si	Th	U$_3$Si/Th
Blanket			
Multiplication, M	8.42	2.67	5.6
Breeding performance			
T/n	1.0	1.0	1.0
Pu/n	1.56	-	0.59
^{233}U/n	-	0.63	0.62

BURNER OPTIONS	Pu(LWR)	^{233}U(HTGR)
Conversion ratio	0.6	0.85
Thermal Efficiency	33%	39%
Make-Up Fuel Requirement (Kg/MWe-Yr)	0.31*	0.162

*Pu requirement assuming natural uranium fertile feed. Total fissile including ^{235}U is 0.46.

TABLE 2 Fuel Options for the Pilot Hybrid Reactor

Table 3 demonstrates that all three of the fuel options for the pilot hybrid reactor will satisfy the net product guideline. For these power balance calculations the thermal conversion efficiency was taken to be 35%, the efficiency of the neutral beam injectors was taken to be 60%, and there was no conversion to electricity of the 25 MW of charged particle power leaking from the ends of the reactor. Note that direct conversion of this power at 50% efficiency plus a thermal bottoming cycle at 35% efficiency would yield 17 MWe, still not enough for the hybrid itself to break even electrically.

The blanket shape for the standard mirror hybrid is a cylindrical shell. An axial fuel rod orientation was chosen as shown in Figure 4. This orientation was found to be better than a radial orientation for a number of reasons: less rods, simplified coolant flow ducting, and better thermal-hydraulic performance.

Blanket Options	U$_3$Si	Th	U$_3$Si/Th
Fusion power, MW$_t$	3.7	3.7	3.7
Injector input, MWe	34.7	34.7	34.7
Blanket power, MW$_t$	24.9	7.9	16.6
Hybrid Electric Power, MWe	8.72	2.77	5.80
Pu Production, kg/yr	18.0	-	6.78
Equivalent Electric, MWe	57.9	-	21.8
^{233}U Production, kg/yr	-	7.03	6.92
Equivalent Electric, MWe	-	43.3	42.9
Gross Electric Power*, MWe	66.6	46.1	70.5
Net Electric Power*, MWe	31.9	11.4	35.8

*Hybrid and fission reactors

TABLE 3 Power balances for the standard mirror hybrid pilot plant.

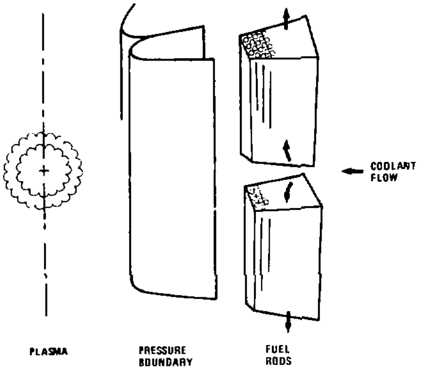

FIGURE 4. Blanket for the small standard mirror

To assess how well the standard mirror hybrid pilot plant meets the project guidelines, we make the following observations: It is physically quite small, the mirror-to-mirror distance being only 50% greater than for MFTF. It produces net product but not net electrical power. There is a commercial upgrade potential for this machine, but it involves a considerable scale-up in size. The hybrid pilot plant could demonstrate all aspects of the commercial plant (except net electrical power production), but some systems could be deleted in favor of simplicity. For example, it was shown that the reactor meets its net product requirement without direct conversion of the plasma end leakage. The plasma parameters and fusion technologies for this reactor are quite conservative and require a minimum of extrapolation beyond MFTF. Finally, the political and social acceptability of the standard mirror hybrid pilot plant depends on the outcome of the present debate on hybrid reactors in general. It is our position that the hybrid can offer a nuclear fuel cycle flexibility that permits resolution of nuclear proliferation issues.

Field-Reversed Mirror

We have considered two variants of the field reversed mirror, a steady state, neutral beam-sustained field-reversed mirror (FRM), and a moving ring field-reversed mirror (MRFRM) in which a succession of field-reversed plasma layers would be compressed and launched through a reactor chamber with no additional energy input. In this section we will discuss the FRM; in the next section we will discuss the MRFRM.

We have developed a plasma model for the FRM based on very limited experimental and theoretical knowledge. We assume a long, fat toroidal plasma (see Fig. 5). 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 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, funded by DOE, resulted in an 11 cell reactor producing 75 MWe net electric power.[3] For the EPRI study we have designed a single cell version of this machine.

The FRM plasma has a minor radius of 7 cm, a major radius of 14 cm, and an overall length of 1 m. It requires a nearly uniform background magnetic field of 4.1 T. The neutral beam injection energy is 200 keV and the injected power is 3.7 MW. The plasma Q is 5.4 and the fusion power is 20 MW.

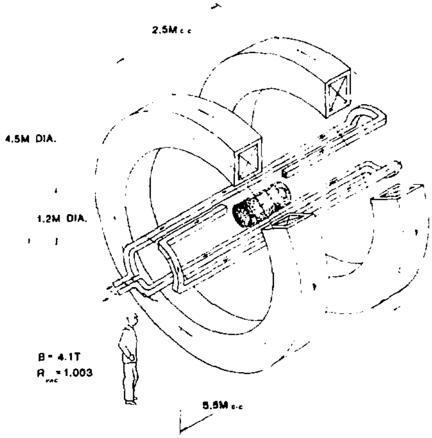

FIGURE 5. Coils for the single cell FRM

In order to stably maintain a field-reversed plasma layer at the center of its cell it is necessary to provide shallow axial and radial magnetic wells in the vacuum background field. 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 Fig. 5). The blanket and shield are between the Ioffe bars and the solenoids. The solenoid cross sections are 65 x 65 cm and the bulk current density is 2500 A/cm^2. 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 copper Ioffe bars each have a cross section 15 x 15 cm and the bulk current density is 1500 A/cm^2. The resistive loss in the Ioffe bars (80% copper at a resistivity of 2×10^{-8} m) 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 axial and radial vacuum magnetic mirror ratios (measured from the location of the plasma surface to the center of the cell) produced by this coil set are 1.003 and 1.0002.

The predicted performance of the single cell FRM reactor is shown in Table 4. 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 injections (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.

FUSION POWER	20 MW
GROSS ELECTRIC POWER	
FROM BLANKET (M = 1.2, $\eta_T = 0.35$)	5.9 MW
FROM END LEAKAGE ($\eta_{DC} = 0.5$, $\eta_T = 0.35$)	5.2 MW
TOTAL	11.1 MW
RECIRCULATED POWER	
INJECTOR INPUT POWER ($\eta_I = 0.7$)	5.3 MW
COPPER COIL POWER	3.3 MW
TOTAL	8.6 MW
NET ELECTRIC POWER	2.5 MW

TABLE 4 Performance of the single cell FRM

The peak first wall neutron loading (just outside the Ioffe bars) is 3.4 MW/m^2. A blanket for the field-reversed mirror was designed with Li_7Pb_2 as the tritium breeding material. Neutronic and thermal-hydraulic calculations were done to develop a design with a tritium breeding ratio 1.1 and to ensure acceptable hot spot fuel and cladding temperatures.

The chosen blanket configuration is cylindrical in geometry, with a one piece, replaceable first wall and removable breeding compound modules as shown on Fig. 6. The modules are packed with vented plate-type containers, made of .25 mm thick Inconel 718. The gap between the plates is .5 mm for the passage of the helium coolant. The plate-type containers are filled with Li_7Pb_2 granules at 80% packing fraction. The containers are vented for pressure equalization and to help allow the bred tritium to reach the helium coolant, but the vent holes are small enough to ensure that the vaporization of lithium from the Li_7Pb_2 during the life-time of the reactor is less than one percent. There are 16 modules in the reactor and each module has 18 plates.

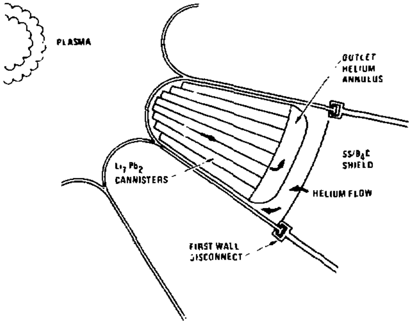

FIGURE 6. Blanket for the single cell FRM

A one dimensional, cylindrical geometry P_3S_6 ANISN neutronics model was used to calculate the tritium breeding ratio, the heat deposition rate and the neutron flux distribution in different regions of the blanket. The blanket thickness was restricted to a maximum of 40 cm. Using only a single blanket zone of naturally enriched Li_7Pb_2, the blanket tritium breeding ratio was below one. With two breeding zones, one containing 25 cm of naturally enriched Li_7Pb_2 and the other containing 15 cm of Li_7Pb_2 enriched to 90% ^{6}Li, a breeding ratio of 1.07 was obtained. In this calculation, the effects of Ioffe bars and neutral beam ports were included.

A two-dimensional heat transfer model was used. The temperature distributions in the helium coolant, the Inconel 718 cladding and the Li_7Pb_2 breeding material from edge to center line were determined along the length of the plate. With the input variables of the coolant gap size and the number of plates in each module, the geometry of the breeder plate was determined by requiring that the center line temperature including hot spot factor not exceed the melting point of Li_7Pb_2. Because of the exothermic ^{6}Li(n,)t reaction in the 90% enriched second blanket zone, the maximum temperature of the center line of the breeder plate occurs at a location just beyond the beginning of the second blanket zone. The pressure drop of helium through the narrow gap between the plates is estimated to be equal to 4.2 kPa which is quite acceptable. The relatively low melting point of Li_7Pb_2 (726°C) restricts the thickness of the breeder plates to about 2 cm.

Figure 7 shows a sectional view of the single cell FRM reactor. A neutral beam port is shown, but the source and beam line components are not included in the picture. The top "dome" of this machine supports the Ioffe bar assembly. After moving aside the direct converter this dome can be lifted straight up, then translated to a hot-shop for Ioffe bar replacement. The upper blanket (II) can then be lifted out with its associated helium manifolds. The lower direct converter must be disconnected and moved aside to permit replacement of the lower blanket/manifold. A hydraulic elevator can then lower the blanket to a service passageway beneath the reactor where a rail car carries it to another hot-shop. Four large coolant ducts must be opened and closed remotely to allow this maintenance scenario.

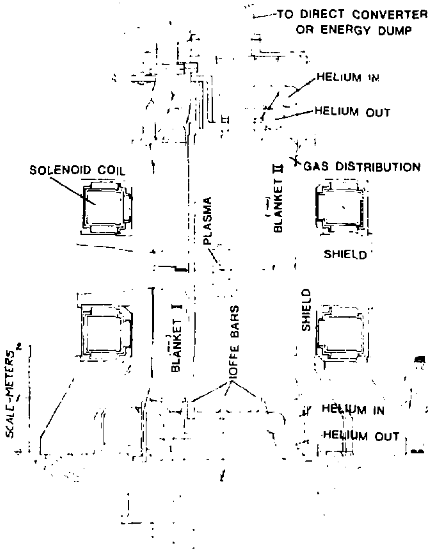

FIGURE 7. Single cell FRM reactor

The solenoidal magnets and shielding form a permanent assembly with no scheduled replacement or service during the plant life. However, should coil replacement be required, their accessible location permits accomplishment in about one month if a spare coil is available.

The single cell FRM pilot plant is small and *produces net electric power. It is upgradeable* to a commercial reactor via the multicell concept. The single cell FRM can demonstrate most of the characteristics of the commercial reactor except the interactions between cells. Magnet technology is modest, but the injection energy required (200 keV) does necessitate the development of negative ion neutral beam systems (in order to achieve the high injection efficiency required for net power production by the FRM). Direct conversion of the end leakage is also necessary for net power production. However, the biggest uncertainty for the FRM is that the physics model assumed is highly speculative and requires experimental verification before the final design of such a pilot plant could proceed.

<u>Moving Ring Field-Reversed Mirror</u>

Like the FRM Reactor scheme, the Moving-Ring FRM Reactor Concept envisions production of power by burning magnetically field-reversed rings of fusion fuel trapped in the trough of a magnetic mirror well. A sketch of the Moving-Ring FRM appears in Figure 8. This device would use a pulsed start-up mechanism (such as intense ion beam sources, plasma guns, or relativistic electron beams) to generate an initial, field-reversed "Minimum-B" magnetic confinement geometry filled with fuel plasma in a relatively low background magnetic field ("Ring Former" section in the sketch). A local "moving mirror" (provided by sequentially energizing sets of "push coils" located in the wallof the reactor) would then drive the plasma ring into the high magnetic field of the burner solenoid section, thereby compressing the ring and heating it to the initial burn temperature. Experimental and theoretical understanding of the precise heating to be expected is somewhat uncertain, but if C is the compression ratio of a characteristic linear dimension of the ring, then the plasma temperature after compression should scale from the initial temperature roughly as $T_f/T_i \sim C^n$, where $1 < n < 2$.

The description of the Moving-Ring FRM given so far could equally serve as a possible start-up mechanism for the steady-state FRM. The distinction between the two concepts is in what follows compression in the Moving-Ring FRM: whereas the steady-state FRM would procede to locate the confined plasma ring in a fixed magnetic well and inject it with high-energy neutral beams for refueling and sustenance of the diamagnetic cur-

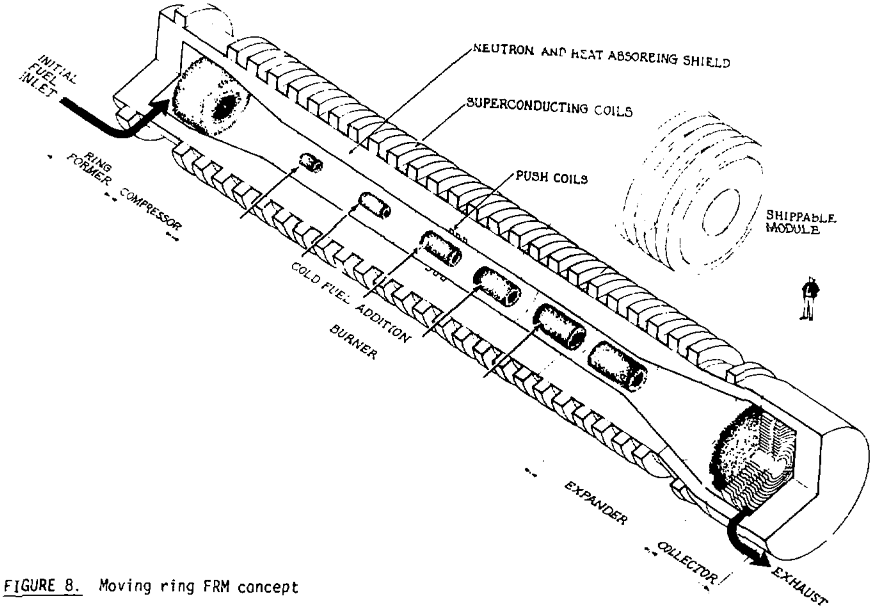

FIGURE 8. Moving ring FRM concept

rents, the Moving-Ring FRM concept seeks to invest little additional energy in the plasma but, instead, transports the burning the plasma ring (using "push coils") down the solenoidal "burner section" of the reactor. During its transit of the burner section, the ring could be re-fueled with cold plasma (either as pellets or via low-energy plasma guns); moreover moving the ring down the axis of the reactor would clear the way for the next ring in the procession to enter the throat of the burner. Cold-ion refueling al[illegible] s the power produced by the plasma ring to be held constant--or varied, as the case may be--by controlling the ion temperatures and densities. Without energetic beam refueling, the field-reversed confinement--in the absence of anomalous effects--will be sustained by the ring's self-inductance. For fusion rings of interest, this time can easily be at least of the order of tens of seconds. Therefore, diffusive particle losses will probably determine the overall ring lifetime. The moving rings might be radially centered in the burner by either wall eddy currents or by a quadrupole field.

Depending on the fuel composition and purpose of the reactor, heat could be extracted in the conventional manner from the blanket. When the plasma burn is nearly quenched (due to the cold-ion refueling), the plasma rings may be exhausted out the "expander" end of the device into a direct converter.

To date, most of the work on the Moving Ring FRM has centered on studying the characteristics of pulsed burns of DT fuel plasmas. Our goal has been to see whether adequate plasma energy gains and sustained power levels might be possible during the pulsed burn of these fuels. To this end, we have modified a non-thermal Fokker-Planck Code to study the plasma burn. The plasma is assumed to be isotropic and contined by pressure balance by an external magnetic field. The basic model for plasma particle confinement has been that of the Field Reversed Mirror (confinement proportional to ion-ion scattering time) and, for stability reasons, the plasma rings are assumed to be limited in size to a minor radius of five ion Larmor radii.

The Fokker-Planck Code is still under development, but some preliminary results will indicate what we might expect from the pulsed burn of a field-reversed plasma ring of 100 keV, 50/50 DT fuel, in a uniform magnetic field of about 8T, assuming beta = 1.5. For the sake of illustration, assume that the particle confinement time is proportional to the ion-ion scattering time but about 8 times better than that assumed for the FRM.

Specifically, consider two different plasma burn conditions: (A) the case where a fuel plasma is formed, magnetically compressed to the initial burn conditions and then allowed to burn with no external fuel addition to influence the burn characteristics ("no cold fuel addition"), and (B) the case with identical initial fuel plasma conditions, but where we now add cold fuel ions at a rate which is set by the constraint that the total ring radiated power (neutrons + X-rays) is held constant ("cold fuel addition").

A comparison of the time histories of the total ring neutron power for the two cases is shown in Figure 9. Without adding cold fuel to the plasma, the ring power starts at about 11.5 MW, but quickly drops to about 1 MW after 2.6 seconds. The cold fuel addition case, however, shows a sustained ring power level of 11.5 MW until it drops rapidly to zero 1.9 seconds into the burn.

The reasons for this behavior for the two different burn situations may be summarized as follows: After about two seconds into the burns, adding cold fuel has increased the total number of deuterons in the DT plasma by about a factor of 2 over the case where cold fuel ions have not been added. Without adding cold fuel ions, the temperature of the fuel ions remaining in the burning plasma (those not lost by diffusion) rises from an initial value of 100 keV to over 170 keV after two seconds. Adding cold fuel ions

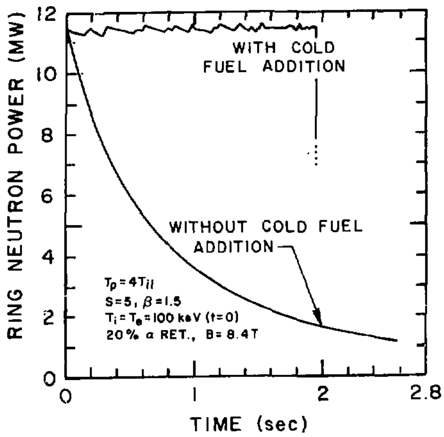

FIGURE 9. MRFRM neutron power

to the plasma permits some heating (and burning) of the added fuel while, at the same time, dramatically cooling the rest of the plasma. Moreover, the plasma density when cold fuel is added *is considerably greater than the density without* cold fuel addition. That is, the ion density has been increased in a way which holds the overall power production rate at a constant--even though both the total number of particles and the reactivity of the fusion reactions are decreasing (because of the decreasing ion temperatures). These combined effects significantly influence the plasma Q values for these two cases, as shown in Figure 10: after 1.9 seconds, the total fusion plasma Q without adding cold fuel is about 6.7, while adding cold fuel during the plasma burn raises the Q to over 15, an increase by nearly a factor of 2.

It is emphasized that these computations are *preliminary* and that further calculations are being done to check these results.. Also, this example depended on what may turn out to be an optimistic assumption about the particle confinement times: a factor of 5 shorter confinement time would drop the plasma Q values to about 2.5. However, these numbers illustrate the qualitative effects of tailoring the pulsed plasma fuel burn to meet reactor engineering design criteria. Although the Moving-Ring FRM plasma burns would indeed be transient events, the device could be designed to permit a fairly uniform wall heat load--as though the plasma energy source were stationary and the burn steady-state--by utilizing a succession of burning rings.

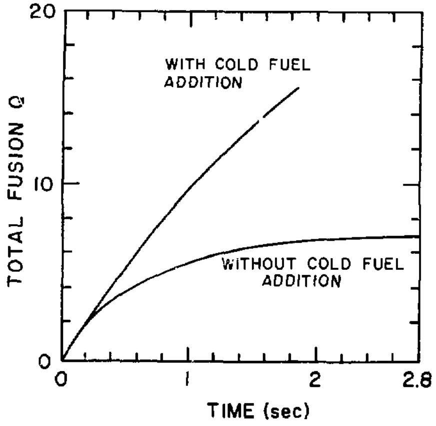

FIGURE 10. Plasma Q for MRFRM

The same blanket as proposed for the FRM could be used on the MRFRM. An alternate blanket design based on the low activation concept and a direct cycle gas turbine power conversion system is also being investigated.

The MRFRM pilot plant could be made as small as about 20 MW fusion power. It could be upgraded to commercial size by increasing the burner region length and the production rate and speed of the plasma rings. The fusion technology requirements are modest although direct conversion of the plasma exhaust may be necessary for net power production in the pilot plant. The physics of the MRFRM is highly speculative and requires further theoretical work as well as experimental verification.

Tandem Mirror

Three different modes of operation have been investigated for the tandem mirror. The first assumes energetic neutral beam injection of the end plugs only; the central cell ions are heated by the electrons which in turn are heated by the end plug ions. The analytic model describing this mode of operation was used in the DOE-funded conceptual design study of a 1000 MWe tandem mirror reactor.[4] This reactor had a Q of 5, a central cell length of 100 m, and used advanced end plug technology (1.2 MeV beams and 17 T coils). Relaxing the plug technology, especially the injection energy, quickly degrades the performance because it becomes increasingly more difficult to maintain the central cell ions at a thermonuclear temperature. This led us to consider energetic injection of the central cell as well as the end plugs. This second mode of operation is a viable confinement concept with modest plug technology, but the attainable Q is not as high as for the first mode of operation.

Neither of these two modes of operation provide enough streaming plasma (i.e. end leakage) to fully stabilize a small plug based on experimental results from 2XIIB. If we have large plugs (plasma radius >> ion gyro-radius) and use the two zone model for plasma confinement (as we did for the standard mirror) then we predict stable plugs with good confinement. But since large radius plug plasmas mean an even larger radius central cell plasma, these modes of operation are not viable for small tandem mirror reactors.

A third mode of operation has been proposed which permits small radius plugs and at the same time requires less extrapolation of physics than the other two tandem concepts or even the small standard mirror. (Recall that the two zone plasma model requires MFTF operation for verification). The proposal is to operate a tandem mirror in a two component mode-energetic deuterium would be injected into the plugs and central cell; cold tritium would be provided to the central cell. The deuterium would be mirror confined in the central cell, and the tritium would be electrostatically confined by the plug potentials. The reactor parameters would be adjusted in such a way that the total end losses would exactly match the streaming plasma requirement for suppression of the DCLC instability. We have constructed an analytic physics model for such a two component tandem wherein we have estimated the streaming plasma requirement from 2XIIB results, taking no credit for improved stability that may result from plasmas larger than 2XIIB, i.e., we provide for streaming plasma over the entire plasma cross section, not just a boundary layer. Unlike the two zone model, this model for plug confinement follows directly from 2XIIB and does not require the demonstration of a classical plasma core in MFTF.

Preliminary calculations using the analytic model of the two component tandem mirror indicate that its Q is probably limited to between 1 and 2. This is too low for a fusion reactor, but quite acceptable for a hybrid. (Recall that the commercial standard mirror hybrid had a Q of only 0.64.) The simple geometry and central cell modularity of the tandem concept combined with the physics conservatism of the two component model have encouraged us to investigate the two component tandem mirror hybrid. Figure 11 shows a commercial version of the tandem mirror hybrid with a 25 m long central cell.

We have used the analytic model of the two component tandem mirror to calculate the performance of a small tandem pilot reactor with much the same technology as the standard mirror hybrid pilot plant. The parameters of the two pilot reactors are given in Table 5.

The tandem pilot reactor has a central cell length of 10 m, uses 100 keV injection of deuterium, and has a maximum magnetic field strength of 8 T. Its performance in terms of Q and first wall neutron loaking is very similar to that of the standard mirror pilot reactor, and its fusion power is 70% higher. Therefore, the tandem mirror pilot reactor, fitted with a uranium or thorium blanket, will produce a net product in the same way as the standard mirror pilot reactor. The parameters and performance of the commercial upgrade of the two component tandem mirror hybrid are somewhat uncertain because of the preliminary nature of the analysis, but present indications are that the tandem hybrid will be more attractive than the large standard mirror hybrid.

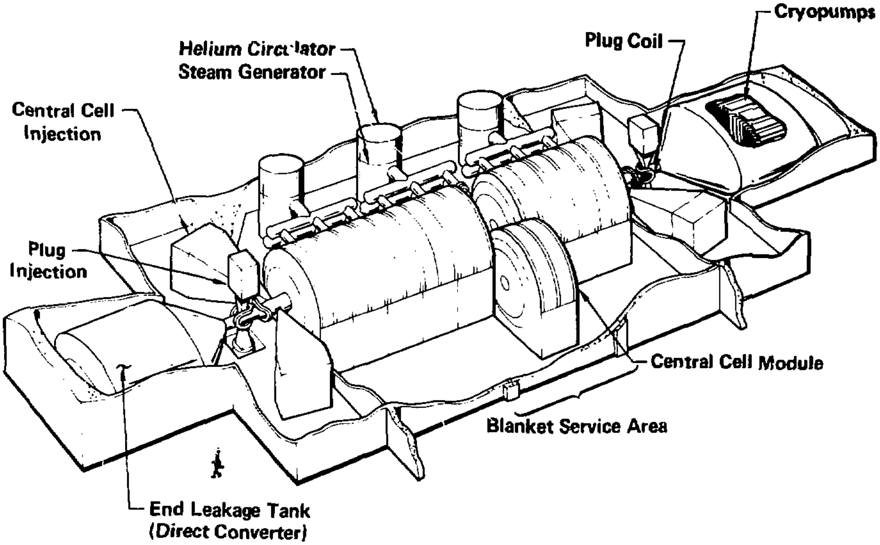

FIGURE 11. Tandem mirror hybrid reactor

	STANDARD MIRROR	2-COMPONENT TANDEM (TYPICAL)
MAXIMUM B FIELD	8 T	8 T
INJECTION ENERGY	50 KEV (D), 75 KEV (T)	100 KEV (D)
PLASMA BETA	0.7	0.7 (PLUG), 0.8 (CENTRAL CELL)
TRAPPED INJECTION POWER	21 MW	31 MW
Q	0.18	0.22
FUSION POWER	3.7 MW	6.8 MW
PLASMA LENGTH	5 M	10 M (CENTRAL CELL)
PLASMA RADIUS	0.34 M	0.19 M (PLUG) 0.38 M (CENTRAL CELL)
PEAK NEUTRON WALL LOADING	0.24 MW/M^2	0.23 MW/M^2 (UNIFORM)

TABLE 5 Plasma Parameters for Hybrid Pilot Plants

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4. R. W. Moir, editor, *Preliminary Design Study of the Tandem Mirror Reactor*, UCRL-52302, May, 1978.

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