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TANDEM MIRROR REACTOR STUDIES AT
LAWRENCE LIVERMORE NATIONAL LABORATORY
FY 1980

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Abstract

The principles of tandem mirror operation with thermal barriers will be demonstrated in the upgrade of the Tandem Mirror Experiment (TMX-U) in 1981 and the tandem configuration of the Mirror Fusion Test Facility (MFTF-B) in 1984.¹ Continued analysis and conceptual design over this period will evolve the optimal configuration and parameters for a power-producing reactor. In this article we describe the progress we have made in this reactor design study effort during 1980.

In our concept of a tandem mirror fusion reactor, the fusion power will be produced in the straight, cylindrical central cell. The central-cell magnets are low-field solenoids. Because the central-cell plasma is near or at ignition, no plasma-heating hardware is required for the central cell. A basic design philosophy for the central cell is that of axial modularity, and a number of different module designs have been proposed which lend themselves to mass-production techniques.

Axial confinement of the central-cell fusion plasma is enhanced by the electrostatic potential of the end plug plasmas. The incorporation of thermal barriers (regions of depressed potential between the central-cell and plug plasmas) allows the confining potential to be created partly by an elevated plug electron temperature instead of solely by a higher plug density. The rapidly evolving knowledge concerning tandem mirrors with thermal barriers has

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resulted in a number of alternative end-plug configurations. Each of these configurations is different in its approach to obtaining magnetohydrodynamic (MHD) stability at high values of central-cell plasma pressure, which is essential for the achievement of economically high fusion power density. MHD stability in a tandem mirror requires a proper balance between good magnetic field line curvature (concave outward) and bad magnetic field line curvature (concave inward). The investigation and comparison of these different end plugs are the principal present efforts in our study of tandem mirror reactors.

End-plug technologies for tandem mirror reactors include high-field superconducting magnets, neutral-beam injectors, and gyrotrons for electron cyclotron resonant heating (ECRH). In addition to their normal use for sustenance of the end-plug plasmas, neutral-beam injectors are used for "dumping" trapped ions from the thermal barrier regions by charge exchange. An extra function of the axially directed pump beams is the removal of thermalized alpha particles from the reactor.

1. Introduction

The tandem mirror confinement concept, invented in 1976 by Logan and Fowler² and independently by Dimov³ in the USSR, is now the mainline effort of the mirror fusion program. The basic concept entails the improved axial confinement of a long, cylindrical, fusion plasma within a solenoid by means of strong electrostatic potentials at the ends, produced by mirror-confined, end-plug plasmas. Operation of the Tandem Mirror Experiment (TMX) at Lawrence Livermore National Laboratory has demonstrated the validity of the basic tandem mirror concept. The first conceptual fusion reactor design based on the concept was published in July 1977.⁴ Drawbacks of the first design included a somewhat modest plasma performance ($Q = \text{fusion power}/\text{total injected power trapped by the plasma} \approx 5$) and a requirement for high-technology components for the end plugs (17-T magnetic coils and 1.2-MeV neutral-beam injectors).

A major new invention for tandem mirrors--the thermal barrier concept--was reported in April 1979.⁵ This invention followed from the realization that the optimal use of electron heating in the tandem mirror involves the establishment of a hotter electron population in the plugs than in the central cell. However, in the normal tandem mirror, electron flow between the plugs and central cell is so high that only small temperature differences can be established, even with electron heating localized in the end plugs. The new concept introduces a barrier between the plug and central cell that effectively reduces the passing of central-cell electrons into the plug. The main function of the thermal barrier is to thermally insulate the electrons in the end plug from contact with those in the solenoid. The concept is sketched in Fig. 1,

which compares the plasma potential profiles in the neighborhood of an end plug for the basic tandem configuration and for the tandem mirror with thermal barriers. The new feature is a depression in the potential at the entrance to the end plug. This depression in the positive potential appears to the negatively charged electrons as a potential barrier and therefore serves as an electron "thermal barrier" between the end plugs and the central cell. If we now heat the electrons in the plug with electron cyclotron resonant heating (ECRH) or other auxiliary heating, the final potential peak needed to plug up ions leaking from the solenoid can be generated with a much lower plasma density in the end plug relative to the density in the central cell. It is this large reduction in plug density that is the advantage of thermal barriers.

The thermal barrier principle will first be tested in an upgrade of the MAX facility, scheduled for completion by November 1981. Plasma confinement in a large tandem mirror with thermal barriers will be explored in the tandem configuration of the Mirror Fusion Test Facility (MFTF-B), recently approved by DOE for construction at Lawrence Livermore National Laboratory (LLNL).¹ MFTF-B, which will incorporate the MFTF yin-yang mirror cell (already under construction) as one end plug, is scheduled for completion by October 1984, and is predicted to achieve a D-T-equivalent Q near unity (only deuterium will be used in the experiment).

A preliminary conceptual design of a power reactor based on the tandem mirror with thermal barriers was reported in September 1979.⁶ An overall view of the reactor is shown in Fig. 2. The D-T fusion plasma is contained in the 56-m-long central cell and produces 1770 MW of fusion

power. With $Q \approx 10$, the reactor will produce about 500 MW of net electricity. The power output of the reactor can be increased by increasing the central-cell length and retaining the same end-plug systems. The central cell consists of 28 2-m-long modules, each containing an annular blanket region, a magnet shield region, and two niobium-titanium solenoidal magnets. The end-plug magnets are housed in large cylindrical vacuum vessels at each end of the reactor. The plug plasmas are each sustained by a low-current, 400-keV neutral beam (shown only on the far end in Fig. 2). Also shown is the gyrotron tube system for microwave heating of the electrons on the plug side of the thermal barrier. The small neutral beams indicated on the end wall of the plug vacuum vessel are the barrier-region beams for charge-exchange pumping of the barrier and fueling of the central cell.

Unfortunately, in this preliminary design, our assumption concerning achievable central-cell plasma pressure proved to be inconsistent with subsequent MHD stability analysis. We assumed a central-cell β (ratio of plasma pressure to magnetic pressure) in excess of 50%, whereas MHD analysis for the magnet design predicted a β limit of only about 10%. This is the primary reason we began to investigate alternative end plug configurations for the tandem mirror reactor.

2. End Plug Configurations for Tandem Mirrors with Thermal Barriers

A number of thermal-barrier configurations are under consideration. One, called the inside barrier, has the thermal barrier and the final potential peak in separate mirror regions, with that for the barrier on the inside (toward the central cell). The originally proposed barrier

configuration⁵ was an inside barrier, as was the conceptual reactor design presented in Ref. 6. The magnet arrangement for the latter design is shown in Fig. 2. Beginning at the central cell end, we see the barrier coil (a solenoid), a transition coil to transform the magnetic flux bundle from circular to elliptical, the yin-yang plug coils, and a circularizing coil. The latter optional coil is used to recircularize the elliptical flux bundle emerging from the yin-yang pair and permits the use of a direct converter with a circular cross section. The barrier region (potential depression) exists between the barrier coil and the yin-yang pair. The potential peak exists in the mirror region created within the yin-yang. The yin-yang pair also serves the purpose of providing the primary region of good magnetic field line curvature (concave outward) essential for magnetohydrodynamic (MHD) stability. In this configuration, the magnetic field is unfavorably curved (concave inward) in the transition regions at the ends of the central cell, and therefore MHD stability places a limit on the plasma β in the central cell.

A second type of thermal-barrier configuration, called the A-cell barrier, is shown in Fig. 3. This configuration is the basis for the MFTF-B design¹ and also the preliminary conceptual design of the Tandem Mirror Next Step facility.⁷ The coil arrangement, looking outward from the central-cell solenoid, consists of a transition coil, a yin-yang pair, and a c-shaped coil with the same orientation as the outer coil of the yin-yang pair. Two mirror cells are created, one within the yin-yang pair, the other between the yin-yang and the c-coil. Both the thermal barrier and the final potential peak are created in the outer mirror

cell, called the A-cell, whereas mirror-confined ions injected into the yin-yang cell serve mainly to provide MHD stability. As with the inside-barrier configuration, bad magnetic field curvature at the ends of the central cell places a limit on the plasma β in the central cell. To create the A-cell potential profile, the ions are injected away from the bottom of the magnetic well. Consequently, the injected ions slosh back and forth, creating peaks in density at their turning points, and application of ECRH to the outer density peak produces the final potential peak.

A third thermal-barrier configuration, called the axisymmetric cusp,⁸ is shown in Fig. 4. This configuration uses all circular coils. The coil arrangement, looking outward from the central-cell solenoid, consists of axially spaced pairs of concentric coils. The smaller radius coil of each pair has current in the opposite sense from the central cell solenoid; the larger radius coil of each pair has current in the same sense. The resulting magnetic geometry has a point cusp on the machine axis encircled by a concentric ring cusp. Mirror regions--cylindrical on the axis with an encircling annular region--exist between the two primary pairs of concentric coils. (The middle pair of coils shown in Fig. 4 is for magnetic flux shaping.) The magnetic flux bundle threading the central cell maps through the annular mirror cell. A thermal barrier and a potential peak are created in each mirror region by an ECRH-heated, sloshing-ion distribution, just as in the A-cell of the previously discussed configuration. Unlike the inside and A-cell barrier configurations, this configuration has good magnetic field curvature in the central cell, and MHD stability places no limit on the

central cell β . The β is limited to some value less than unity, however, to ensure alpha-particle confinement.

A fourth proposed thermal-barrier configuration, called the axi-cell, uses only simple mirror cells, produced by circular coils. The coil arrangement is shown in Fig. 5. A thermal barrier and a potential peak are created in the axisymmetric mirror region by an ECRH-heated, sloshing ion distribution. MHD stability would be achieved by means of a hot electron ring in the mirror region, as is done in the Elmo Bumpy Torus (EBT). (A variant of the axi-cell configuration, should hot electron ring stabilization prove to be unfeasible, adds a yin-yang coil to each end of the machine for MHD stability. Although the configuration then becomes stabilized by means of a good magnetic curvature mirror cell, like the inside and A-cell barrier configurations, it is fundamentally different in that the fusion plasma confinement occurs in an axisymmetric geometry.)

3. MHD Stability and Magnetic Field Design

MHD stability is a crucial issue for all the end-plug configurations described above. Lacking experimental data for any of these configurations, we must at this point rely on theoretical models to predict stability limits and thus to guide our comparative studies. The development of theoretical models to assess MHD stability for tandem mirrors with thermal barriers is a quite recent and still continuing endeavor.

Two models have been developed to separately assess interchange and ballooning stability for straight-axis tandem configurations using good

curvature mirror cells.⁹ These models were derived using ideal MHD theory, and neglect effects due to the finite larmor radii (FLR) of the plasma particles. An interchange instability can be envisioned as a radial perturbation of an entire magnetic field line to a lower energy state. The interchange stability criterion is an integral requirement over the length of the tandem mirror machine, and regions of good magnetic field line curvature can compensate for regions of bad curvature. The interchange model has been found to establish necessary but not sufficient conditions for MHD stability. Because it is particularly simple and convenient to apply, it has proven to be a very useful tool for screening proposed coil designs.

Sufficient conditions for MHD stability are established by satisfying the more stringent requirements of ballooning. A ballooning instability can be envisioned as a radial perturbation of a magnetic field line localized in a region of bad curvature. Application of the model has shown that, for ballooning, regions of good curvature do not compensate for far-away regions of bad curvature to the same degree as they do in interchange.

The inside barrier tandem reactor design more than satisfied the conditions for interchange stability at the desired high value for the peak, on-axis central-cell $\beta(\beta_c \geq 0.5)$, but application of the ballooning analysis indicated a maximum β_c value of only about 0.1. Because of this result, our emphasis shifted to the A-cell barrier configuration, which we believed to have greater potential for ballooning stability at high β_c because the good curvature "anchor" is closer to the region of bad magnetic curvature.

A-cell barrier designs have yielded higher ballooning limits for β_c than the inside barrier design, but the determination of the maximum value achievable and an assessment of its adequacy for a power reactor are still incomplete. One significant result from the MHD stability analysis of the A-cell barrier configuration was the demonstration that lower central-cell magnetic field allows higher central-cell β . The stability limit was found to quite closely follow $\beta_c \beta_c^{1.6} = \text{constant}$.

A theoretical model for ballooning stability for the axisymmetric cusp configuration has also been developed. So far, results from this model are not exhaustive, but it is clear that the limit will be on plug β , not β_c . The best results achieved to date are plug $\beta = 0.25$ and $\beta_c = 0.8$. MHD stability considerations for the axi-cell configuration have just begun.

As stated above, these ideal MHD theory models neglect FLR effects. Recent theoretical work indicates that FLR effects may result in a significant increase in ballooning β limits, much closer to the β limits determined by the interchange criterion. Calculations are presently underway to evaluate ballooning β limits including FLR effects.

4. Plasma Modeling

Zero-dimensional and one-dimensional fluid codes have been developed to provide a macroscopic description of the plasma in tandem mirror fusion reactors with thermal barriers. Simply stated, the objective of our plasma model development is to provide a self-consistent set of equations, supported by physics theory and experiment, which can be used

to calculate all of the plasma dimensions, densities, energies, potentials, and confinement times in a tandem mirror reactor. The models we developed utilize results from other special purpose plasma codes in a number of ways: Fokker-Planck code results provide guidance for deriving various terms in particle balance equations, MHD codes provide guidance for stability limits on β values, etc. In order to be useful for parametric calculations, our plasma models are programmed for rapid solution by computer.

A series of plasma models has been developed at LLNL to predict the plasma performance for tandem mirrors with the A-cell barrier configuration. The second generation of this series, consisting of scaling laws for each input power requirement based on the MFTF-B design point, was used to calculate the results given here. A third-generation model, still under development, solves the detailed particle and energy balance equations as presented in Ref. 9. Reference 10 gives a progress report on the development of the third-generation model.

Example results for an A-cell barrier TMR are shown in Fig. 5. The figure shows calculated plasma Q as a function of assumed peak (on-axis) β_c for several different central-cell lengths. In all cases, the fusion power is 3500 MW, the yin-yang mirror and center fields are 9 and 6 T, the A-cell mirror field is 9 T, the barrier minimum field is 1.7 T, and the yin-yang and barrier β values are 0.7 and 0.5, respectively. The other constraint for the A-cell cases of Fig. 6 is that the radius of the plug plasma was held constant at about 1 m. This last constraint required that the central-cell field strength β_c be varied as a function of β_c . For the reference case labeled in Fig. 6, the value

for B_c is 3.4 T. The central cell plasma radius is 1.3 m and the first wall neutron loading is 1.9 MW/m^2 for the reference case.

It should be noted that the choice here of 9 T for the maximum on-axis magnetic field strength is motivated by the fact that for a yin-yang-shaped magnet, the maximum on-conductor magnetic field is typically $4/3$ times the maximum on-axis field. A high current capacity, 12 T conductor is the goal of the niobium-tin superconductor development program. All-circular coils such as those for the axi-cell configuration typically have lower ratios of on-conductor to on-axis fields, and thus for that configuration the same conductor can be used to generate higher magnetic field strengths in the plasma.

Coincidentally, the β_c , B_c relationship along the constant L_c curves of Fig. 6 (as forced by the constant plug radius) is very close to $\beta_c B_c^{1.6} = \text{constant}$, which was found in the MHD study to be a condition for constant stability. Thus, we would expect each constant L_c curve to be either stable or unstable in its entirety. For coil designs we have devised to date, the predictions of ideal MHD theory are that the A-cell configuration curves of Fig. 6 are unstable. For our best magnet design, we would have to reduce the central-cell field for the reference case from 3.4 T to about 1.3 T to satisfy the ideal MHD theory criterion for a stable β_c value of 0.5.

Reducing B_c as indicated above would result in an increase in the plasma radii if L_c and fusion power are held constant. The neutron wall loading would decrease, and the increase in plug plasma volume would result in a decrease in plasma Q . We predict that these lower values of fusion power density (as measured by first wall neutron loading) and

plasma C would result in an uneconomical reactor. Work is continuing in an attempt to raise the performance limits of the A-cell configuration. Most promising is the expectation that FLR effects will allow MHD stability at significantly higher values of B_c and B_z than allowed by ideal MHD theory.

Figure 6 also shows some preliminary results for TMR's with the axisymmetric-cusp end-plug configuration. (These results were calculated using a model similar in detail to the second-generation model for the A-cell configuration.) The axisymmetric-cusp cases have the same fusion power and plug mirror fields (9 T) as the A-cell cases. Higher Q's are expected with the axisymmetric cusp because of the near-unity peak beta achievable in the central cell. Note that the axisymmetric results are somewhat below the extrapolation of the A-cell curves; this is because of the additional plug plasma volume in the axisymmetric configuration (the on-axis plug volume which does not flux map to the central cell). Verification of these preliminary results for the axisymmetric-cusp configuration requires additional plasma performance calculations and MHD stability analysis.

5. Mechanical Design

The mechanical designs for the various end plug configurations are quite different from one another. Our final choice of an end plug configuration for the tandem mirror reactor will be guided partly by the relative complexity and cost of the several mechanical designs.

At the present stage of our study, we are unable to compare the mechanical designs on a consistent basis because of the incomplete

assessment of MHD stability and plasma performance for the various configurations. However, we have developed a design philosophy for the various configurations, and we are prepared to carry out specific designs for the purpose of comparison as soon as key parameters, such as radial size, are determined.

The mechanical design for an inside barrier configuration is described in Ref. 6. The mechanical design for the A-cell barrier Tandem Mirror Next Step is described in Ref. 7. We expect that an A-cell tandem mirror reactor would be very similar in design to the Next Step facility. The mechanical design for an axisymmetric cusp reactor is described in the Appendix of this report. The special design feature for this configuration is the cantilever structure used to support the inner coil of each concentric pair.

6. Barrier Pumping

For all thermal barrier configurations, it is necessary to pump away trapped ions accumulating in the barrier as a result of collisions among ions passing back and forth from the central cell. Such filling is unacceptable because it would negate the depression in plasma potential. It has been proposed (and will be tested experimentally on TMX-U and MFTF-B) that the pumping can be accomplished by having the trapped ions undergo charge-exchange interactions with neutral beams located at each end of the machine and aimed nearly along the axis. In a charge-exchange collision between a trapped ion and an axially aimed neutral, a trapped ion is exchanged for one that is not trapped. An advantage of this pumping method is that it is based upon well understood, classical

processes. Possible disadvantages are that access for axial injection may be difficult, and various inefficiencies may hurt the power balance. Other approaches to ion pumping in thermal barriers are also being explored.

Analysis of the charge-exchange pumping concept has shown that to minimize the power requirements for the pump beams a multistage pumping system is desirable. In this system, decreasing fractions of the total ion load are pumped by injectors of increasing energy level (a situation analogous to a multistage vacuum pumping system in which decreasing fractions of the total gas load are pumped at increasing vacuum levels). Charge exchange pumping systems have been designed for reactors with inside barriers, A-cell barriers, and axisymmetric cusp barriers.

An important extra function of the charge-exchange pumping system might be the removal of thermalized alpha particles from the reactor. Under certain conditions, the charge-exchange reaction $\text{He}^{++} + \text{D}^0 \rightarrow \text{He}^+ + \text{D}^+$ will lead to the loss of the He^+ ions over the potential peak. Preliminary estimates are that this ash-removal scheme can adequately restrict the accumulation of alpha particles, thereby making possible steady-state reactor operation.¹¹

Negative-ion-type neutral-beam injectors are preferred for charge-exchange pumping for two important reasons. First, for the high-energy pump beam, negative ions are desired for the usual reason of neutralization efficiency. The second reason is the normal presence of positive molecular ions in positive-ion-type sources, which produce atoms with 1/2 or 1/3 of the primary beam energy. The fractional energy components are undesirable in any neutral beam but are intolerable in a charge-exchange beam if they become trapped in the barrier potential well.

7. Plasma Heating

Tandem mirror plasmas are sustained in steady state by neutral-beam injection and microwave heating. Neutral-beam injectors are proposed for two different purposes in tandem mirror reactors with thermal barriers: sustenance of the end-plug plasma and charge-exchange pumping of the barrier regions, as discussed above. All of the neutral-beam injectors must operate continuously. Electron heating in the plug region is an important element of reactor design for TMR's with thermal barriers. We propose to accomplish the electron heating with microwave sources operating in the electron cyclotron resonant heating (ECRH) regime.

Although the introduction of direct electron heating and thermal barriers has reduced the necessary plug-plasma neutral-beam-injection energy from the 1.2 MeV specified in Ref. 4, the energy requirement is still in the 100's of keV. This is because the plug ions injected at the potential peak are in trapped velocity space only if

$$E_{inj} > \frac{\phi_c + \phi_e}{R - 1},$$

where $\phi_c + \phi_e$ is the height of the potential peak (see Fig. 2) and R is the ratio of the magnetic field strength at the mirror point to that at the injection point. As an example, the inside-barrier TMR design had $\phi_c + \phi_e = 265$ keV and $R = 1.9$; therefore the minimum plug injection energy was 295 keV. The design used 400-keV injection. The A-cell examples of Fig. 6 had $E_{inj} = 100$ keV in the yin-yang cell and 330 keV in the A-cell. We prefer the negative-ion type neutral-beam injector for the TMR plugs because its efficiency at the required energies is higher than that possible with positive-ion-type injectors.

The TMR neutral beam requirements point to the need for continued research and development of this technology, especially for negative-ion-type injectors. By comparison, MFTF-B will use 80 keV, positive-ion-type neutral beam injectors, with operating pulses of 30 s duration. Although not operated continuously, these MFTF-B injections will reach thermal equilibrium and are designed with active cooling, much as the reactor injectors will be.

In tandem mirror reactors with thermal barriers, ECRH heating of electrons is required in two regions of the plug: at the position of the final potential peak and at the potential minimum in the barrier. In ECRH, the resonant frequency is the fundamental or a harmonic of the electron cyclotron frequency; i.e.,

$$f = n f_{ce} = neB/2m_e = 2\pi Bn,$$

where n is the harmonic number, f is in GHz, and B is in teslas. Typical field strengths for a TMR are 2 T at the barrier minimum and 6 T at the final potential peak; thus, typical required ECRH frequencies are 56 and 168 GHz. Additional research and technology is also required for this technology. By comparison, the ECRH heating system for MFTF-B will operate at 28 and 60 GHz.

8. Conclusions

The successful operation of MFTF-B will demonstrate the scientific feasibility of tandem mirrors with thermal barriers. Beyond MFTF-B the next step in the mirror program is a continuously operating reactor, burning deuterium and tritium and producing substantial thermonuclear power. Extrapolation from this first power-producing tandem mirror will

lead to a prototype commercial power reactor. The goal of our reactor design study effort is to determine the optimal configuration and parameters for these power-producing reactors.

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Fig. 1. Plasma potential profile for the basic tandem mirror configuration and for the tandem mirror with thermal barriers.

Fig. 2. Preliminary design of a power reactor based on the tandem mirror with thermal barriers.

Fig. 3. Magnet arrangement for the A-cell barrier configuration.

Fig. 5. Magnet arrangement for the axi-cell barrier configuration.

Fig. 6. Plasma Q (fusion power divided by total injected power trapped by the plasma) as a function of assumed central cell beta for TMR's with A-cell barriers and axisymmetric cusp barriers.

Appendix

Axisymmetric Cusp End Plug Design

Introduction

The axisymmetric cusp end plug configuration employs concentric arrays of solenoids with the current flow of the smaller diameter coils opposite to that of the main solenoid. A cusp is created as shown in Fig. A-1. All flux lines from the central cell move radially outward around the cusp. Were it not for cross-field diffusion all escaping plasma ions would be in that outer annulus. Of course diffusion does occur, so some of those ions find their way onto the flux lines associated with the reversed current inner solenoid set. Energetic ion losses occur through both the outer annulus and the central "spindle". Plasma plugs are needed in both the annulus and the spindle to retard ion losses. Magnetic mirrors and energetic beam injection are required in both regions. The mirrors are provided by simple solenoid coils. They are precisely located to provide the field line contours for MHD stability. Additional coils in a conical array provide appropriate flair-out of field lines to an annular direct converter.

The simplicity of the coil shapes makes this magnet configuration very attractive. But the power of lost ions in the annulus is hundreds of megawatts. The annular beam of escaping ions would place an intolerable heating load on any structural supports placed in the annulus. The only permissible geometry is a long cantilever anchored to the building structure in the region of the direct converter.

This tapered cantilever supports all the solenoid coils whose current direction is opposite in sense to the central cell solenoid. In the particular case analyzed this is a mass of about 2500 tonnes extending more than 25 meters from the building structure. It has a nominal outside diameter of 8 meters and inside diameter of 2 meters. Nine solenoids--all superconducting--are supported, served with liquid helium, vented and powered. This cantilevered hollow cylinder has D-T plasma bombarding its free end with neutrons. It also is surrounded by D-D plasma, both outside and inside, associated with the plug plasma. The first-wall cooling requirements are formidable.

The structure's mass is largely controlled by the neutron shielding needed by the superconducting magnets. All cooling and magnet services must be supplied through the cantilever itself. And finally, the assembly must be easily broken down into crane-sized pieces for removal and replacement in the event of a coil or first-wall failure. The activation of structural members by neutron bombardment will require that all servicing be accomplished by remote manipulators.

Such a massive structure will have considerable static deflection, all gravity loads being perpendicular to its axis of symmetry. As will be shown, there are several inches of deflection at the free end when no magnets are electrically energized. When the magnets are conducting current a strong force acts on the cantilever tending to restore it to a concentric (undeflected) position.

The axial loads on the opposed-field coils act to repel them from the central cell. This strong compressive load on the cantilever will add to any existing deflection since the bending moments are of the same sense as those imposed by gravity.

Our method of analysis will be to assume several deflected conditions and calculate the magnetic loads using the EFFI computer code. Then we will apply those loads in addition to known gravity forces for a finite element analysis using the computer code SAP4. We will compare the deflection curve obtained from SAP4 with our assumptions and make adjustments so the magnetic forces can be recalculated. A few iterations between EFFI and SAP4 should produce the structural deflection curve of the active coil set. Once the magnet positions are known accurately we can evaluate the MHD stability of the true field line configuration. This latter step involves physics codes which predict plasma currents (hence self-fields) and evaluate the MHD quality of the resulting field line positions.

Structural Design of the Cantilever

Table A-1 contains weight estimates for the cantilever for its outermost 18.5 meters of length. Flairing of the field lines permits substantial strengthening of the cantilever beyond that station. Preliminary structural design and stress analysis by finite element techniques was limited to the region covered by Table A-1.

The static bending moment at this location (18.5 meters from the end of the cantilever) is about $2.14 (10)^9$ inch-pounds. From this we were able to estimate a structural design as a departure point for our stress analysis using the SAP4 code.

Table A-1 Cantilever weight estimates (see Fig. A-6 for magnet numbering scheme)

	<u>Mass</u>
Magnet #3	112 tonne
Case #3	137
Shield #3	511
Magnet #6	13
Case #6 }	230
Shield #6 }	
Spacer (#6 to #4,5)	151
Magnet #4	85
Case #4	210
Magnet #5	11
Case #5	57
Shield (#4,5)	180
Flair magnets	32
Flair Magnet cases and shield + structure	<u>598</u>
	2327 tonne
Add 10% for plumbing	<u>233</u>
	2560 tonne

The structural boundary conditions which had to be met were:

1. The magnetic flux surface defining the plasma boundaries must avoid the structure by a distance of three Larmor radii.
2. The shield thickness between plasma and superconductor must be at least 50 cm of steel.
3. Water cooling is permitted on all cantilever boundaries since no lithium is present (ie, no blanket in the end plugs).
4. No subassembly should weigh in excess of 500 tonnes. This was somewhat arbitrary but since it is comparable to a PWR vessel it will probably not require new handling technology.
5. Remote maintenance tools must be used for removal and re-installation of all subassemblies.

The coil geometry dictates a cylindrical structure for the cantilevered support. In the magnet locations there is no alternative. A cylindrical shell both inside and outside the coils is the only shape permitted by the plasma and structural constraints.

In the axial spaces between coils some choice exists. The concentric cylindrical shells from the coil regions can be continued.

Or, as shown in Fig. A-2, a system employing radial vanes with or without cylindrical covers could be employed. A structural cross-section with other than radial webs could also be employed, but this preliminary design evaluation does not warrant these more complex arrangements. Should it be necessary to alter the radial pattern of webs to meet space requirements for service lines the result of this comparison would be affected only slightly.

Any large structure, particularly if related to nuclear energy, will be exhaustively analyzed for its dynamic response to seismic activity. Dynamic analysis is beyond the present scope of this study. A structure was chosen which provides more strength in the vertical plane than the horizontal. We assumed here the possibility of seismic acceleration of one times gravity in any direction. Superimposed on earth's normal gravity this requires a structure capable of experiencing 2 g vertical acceleration and 1 g horizontal acceleration. We chose a structure employing thick radial vanes on the vertical and horizontal center line with thick plate bulkheads at both ends of each separable section. The moment of inertia of the web section (dubbed the "iron cross") was twice as large in the vertical direction compared to horizontal (see Fig. A-2).

Figure A-3 shows side and cross-section views of the alternative concentric cylinder structure. Compare them to Fig. A-2 showing the iron cross design. Note that differences occur primarily in the conical section nearest the built-in end of the cantilever. These two conceptual

designs are approximations of the actual structural members. The plate thicknesses are probably the most accurate part of the conceptual designs since beam deflection and nominal stress are strong functions of those thicknesses. Our chief concern was to judge whether a "reasonable" design could withstand the expected magnet weight combined with the weight of the cantilever structure. Our conclusion is that either design is plausible but we prefer the iron cross due to its maintainability. This will be discussed later.

In Fig. A-4 the deflection curves of the two designs are compared. Displacement of the iron cross design is about twice as large as the "concentric-cylinder" case. The iron cross design is slightly the heavier of the two. The moments of inertia of the two structures were nearly identical. However, the designs are more like short beams than we had realized, and shear deflections are very significant to the total effect. The shape of the iron cross placed higher shear loads on smaller shear area. The difference in deflection may not be important when magnetic centering forces are added to the analysis.

The highest plane stress levels are located in the vicinity of the 860 inch and 895 inch stations (horizontal distance from the free end). The values are about 104,000 psi (71.7 MPa). They were calculated from:

$$\sigma_{ii} = S_{ii} \pm \frac{6M_{ii}}{t^2}$$

where (+) is for the top of the element and (-) for the underside. Values of S_{ii} and M_{ii} were given in the SAP4 output. Shear stress is

about an order of magnitude less than the plane stress. This entire analysis is reported by Paul Silva in report ENC-80-9 (Engineering Note) at LLNL.

Cooling the Shield on the Cantilever Structure

This reactor's central cell was sized for a first wall neutron loading of 1.0 MW/m^2 . We assume the absorption of this power by the neutron shielding on the nose of the cantilever structure.

Superconducting magnets have liquid nitrogen temperature shields surrounding the 4.5 K superconductor jacket. The LN jacket at 80 K will receive thermal radiation from the structure containing the coil forces. It will help the thermal loading of the 80 K surface if the temperature of that structure is not over 150°C ($\pm 50^\circ\text{C}$). This implies a reversal of the usual practice of sending the coolest coolant to the first-wall. This design will send water coolant first to the region near the superconducting coils and then to the first-wall. It may be possible to have "fresh" coolant at both the first-wall and near the superconducting magnets, taking the warmer coolant out in the structural shield material between the two. But that could lead to even more complex coolant flow paths in an already complex system.

Heat transfer coefficients for pressurized water were obtained from the Heat Transfer and Fluid Flow Data Books of the General Electric Corporation. An average value of $3.6 \text{ W/cm}^2\text{-}^\circ\text{C}$ was used. If the heat transfer area is taken equal to the exposed surface area of the cantilever nose-section, then a film temperature drop of only 12°C is required. A temperature rise of 150°C was specified in the pressurized water cooling circuit. A 6.9 MPa (1000 psi) pump delivery pressure should assure that the pressure never falls below the saturation vapor pressure, 3.98 MPa (577 psia). We intend to avoid mixed phase water flow.

The temperature rise of the entire cantilever structure will average about 150°C. The total length of the cantilever is about 25 meters. For a 300 series stainless steel the thermal growth will be 6.5 cm. That much expansion will probably cause detrimental field effects. The design dimensions can be set so the coils are in their nominally correct positions after expansion occurs. It is possible that some auxiliary heating of the cooling circuit may be required. The cantilevered coils can thus be positioned correctly in advance of reactor start-up. Subsequent nuclear heating of the end-plug will allow the start-up heaters to be turned off.

Maintainability of the Cantilever Coil System

In the unlikely case of a magnet failure or a plumbing leak it may be necessary to remove part or all of the cantilever. Its position within the permanent building structure makes this removal and re-assembly problem a very challenging one. We have already mentioned that the cantilever should be assembled from crane-sized sub-assemblies weighing no more than 500 tonnes.

To eliminate the need to remotely cut or make major structural welds it was decided that the components should be bolted. The loads are comparable to those encountered in a Pressurized Water Reactor Vessel and the bolts will be up to seven or eight inches in diameter. There will be many of them on comparatively close centers. If external flanges were possible the methods employed could be borrowed from current PWR

practice. However, the magnetic flux surfaces carrying escaping ions pass quite closely to the external and internal structural cylinders, and external flanges would interfere with those ions. A nearly impossible cooling situation would develop. Also, those ions would be lost for use in a direct converter.

How about internal flanges--or bolting together the annular bulkheads which form the ends of each section? A large number of cryogenic lines (two to each coil), electrical busses, and water cooling lines will be present in this region. The remote operation of large wrenches in this maze of pipes inside an external structural cylinder is deemed impractical.

The iron cross has one apparent advantage: the outer structural cylinder is not present. A remote bolting tool and remote flange operators are accessible from the annular space surrounding the cantilever. The piping can be grouped in the quadrants formed by the "cross" to allow radial access to bolts. The bolt pattern would be one following the radial vane contours with a single bolt circle near the outer circumference of the bulkheads. Figure A-5 illustrates this approach but no specific bolt positions should be inferred. The complete arrangement of plumbing and electrical services for the cantilever must be designed in detail before the bolt pattern can be determined. This design has not progressed to that level of maturity.

In conclusion, the two-concentric-cylinder design looks impractical to service. It would even be difficult to build "hands-on" the first time when no radioactivity was present. The iron cross structural approach looks difficult but feasible. At least it offers direct access from outside the cantilever to all units requiring action during a component repair or replacement.

The Outer Mirror Coils

The outer mirror coils (designated 1 and 2 in Fig. A-6) are very large. A magnet 13 meters in diameter, employing 221 tonnes of superconductor, with a total mass of about 500 tonnes is required in two locations. The force in the axial direction which must be absorbed by the building structure is also very large. We propose that these two magnets be wound in place. That operation requires that spools of superconductor be moved about the cylindrical steel spool which forms the inner case of the coil. The two sides and inner case are attached to the reinforcing steel "skeleton" of the major building structure. After the superconductor is wound in place the outer coil case can be installed in sections and bolted or welded.

The space needed for a circular coil winding track is easily included in the building design. Nearby space is required for beam injectors so simple enlargement of that space serves the coils as well. Should a fault in coil 1 or 2 occur it will be possible to unwind the

conductor and make repairs. Such an operation would be expensive and require at least a year to accomplish but the likelihood of such trouble developing is small.

The Direct Converter

The outward-fanning annulus of escaping ions (see Fig. A-6) impinges on a direct converter. There the residual energy of the hot ions is converted directly to D.C. power. The ions collect electrons to form cold neutrals which are pumped by the vacuum system. The size of this direct converter is in part determined by the required size of the base of the cantilever structure. The width of the annulus must be such that the ion power density at the direct converter does not exceed 150 watts per cm^2 . That power density can be absorbed by forced convection cooling of the plasma electron collector grid.

The direct converter modules when assembled form a frustrum of a cone. Its outer diameter is about 30 meters and the width of the conical frustrum is about 5 meters. Several ideas for direct converter service are being evaluated now. A service car moving about the reactors centerline on a circular track could remove modules through vacuum doors situated behind each module. Once outside the vacuum this module could be transferred to a crane by moving the service cab. Modules situated below the cantilever structure could be moved on the circular track to the horizontal center (or above). There an overhead crane could take over to move them to a service area.

Fig. A-1 Magnet configuration for axisymmetric cusp tandem mirror.

0 5 10 M.
SCALE

Fig. A-2 Iron cross structure for axisymmetric tandem end plug.

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5.1 CM THICK

TYP. SECTION

BULKHEADS DENOTED BY
"K" ARE ALL 15.2 CM THICK

Fig. A-3 Concentric cylinder structure for axisymmetric tandem end plug.

Fig. A-4 Static deflection curves for two cantilever structures (gravity force only).

Fig. A-5 Typical bolt locations at structural separations - two cantilever structures.

Fig. A-6 End plug geometry for axisymmetric barrier tandem mirror reactor.