Evolution of the Tandem-Mirror Approach to Magnetic Fusion

Our understanding of the physics of magnetic-mirror fusion machines has progressed rapidly during the past decade. The next generation of tandem-mirror devices is designed to demonstrate plasma confinement under conditions approaching those of a commercial power reactor.

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For many years, the Laboratory's Magnetic Fusion Energy (MFE) Program has studied designs for a controlled-fusion reactor based on the magnetic-mirror approach to plasma confinement (see the box on p. 6). Years of research in both theory and experiment have brought us to today's design for a thermal-barrier tandem-mirror machine. The tandem-mirror design is a most promising candidate for a future commercial fusion reactor, but certain challenges remain. First, we must demonstrate adequate confinement of the plasma at near-reactor conditions. Facilities now existing or nearing completion were designed to pass this milestone by the end of the decade. Second, we must develop a reactor with a relatively small net output that is economically competitive with alternative energy sources. This goal also could be achieved by modifying today's demonstration facilities. In this article, we trace the evolution of the tandem-mirror design and describe some planned and proposed experiments.

The Magnetic Fusion Energy Program

The MFE Program reached a watershed in 1975, when a breakthrough in the physics of simple mirror devices opened the way for the tandem mirror. Experimenters working with LLNL's 2XIIB single-celled mirror machine finally controlled the rf fluctuations that are driven by the plasma's inherent anisotropic pressure and, if uncontrolled, hamper ion confinement. Thus, it became possible to heat the plasma by injecting ions in the form of energetic beams of neutral atoms; in the plasma, these neutral atoms ionize or undergo charge exchange with charged particles already in the plasma and, thereby, appear as new plasma ions. As a result, the energy density of the 2XIIB plasma rose to roughly that of the external magnetic field. Simultaneously with these experimental advances, our understanding of the causes of the rf fluctuations advanced to the point at which we could extrapolate the technique used in the 2XIIB experiment to other configurations.

These results were an exciting step forward in the physics of magnetic mirror fusion. Even with these improvements, however, reactor studies concluded that the simple mirror machine confined its fuel for too short a time to be an economically competitive reactor candidate. Mirror-fusion researchers, thus, were challenged to turn their recent physics successes into an economically attractive approach to fusion. Their response was the tandem-mirror concept, proposed at LLNL[1] and in the Soviet Union[2] in 1976.

From the outset, research into tandem-mirror designs has been double pronged, characterized by parallel efforts on the physics and on the technology of a reactor. The interplay between these efforts has produced several important design innovations that make the tandem mirror an attractive candidate for a reactor, provided our current theory is valid. Experiments with LLNL's Tandem Mirror Experiment (TMX) and the TMX-Upgrade (TMX-U), and with tandem-mirror machines at the Massachusetts Institute of Technology, at the University of Wisconsin, and in Japan, have borne out much of the theory. The Mirror Fusion Test Facility (MFTF-B), now completed at LLNL, was designed to test these principles at near-reactor conditions.

Simple Mirror Machines

The development of the tandem-mirror design from single-celled or simple, mirror machines is illustrated in Fig. 1. In this family of machines, the magnetic axis is linear and the magnetic lines leave the confinement volume; this is an "open" system and the relevant physics issues are quite distinct from those for a toroidal or "closed" system (typified by the tokamak design). Confinement in open systems relies on the mirror principle, whereby an axially increasing magnetic field reflects the rapidly gyrating charged particles back into the plasma, so long as their angle of motion with respect to the field lines is large enough. In other words, an axially increasing magnetic field can support a plasma pressure gradient, provided the pressure is sufficiently anisotropic.

The first mirror machines, constructed in the late 1950s, featured a linear set of simple solenoidal magnets whose field strength increased at each end (Fig. 1a). These early experiments underscored two universal features of open systems. First, simple mirrors are intrinsically lossy. Because collisions reorient the motions of the charged particles parallel to the magnetic field lines, particles can be magnetically confined only for their collision time (which scales as energy$^{3/2}$ × mass$^{1/2}$ × density^{-1}). Ions, the more slowly scattering charged particles, must be replaced on their collision time scale. The more rapidly scattering electrons, however, are electrostatically confined in the positive space-charge potential that preserves the net charge neutrality of the system.

The second feature of open systems is related to the magnetohydrodynamic (MHD) behavior found in all confinement systems. The plasma in axisymmetric machines (machines that are symmetric about their long axis) is subject to unstable motion, drifting

Principles of Mirror Fusion

Controlled fusion of the heavy isotopes of hydrogen (deuterium and tritium) would provide a virtually limitless supply of energy. The ultimate fuel for fusion—deuterium separated from the hydrogen in water—represents a fuel reserve that would last for billions of years. The near-term fuel—deuterium plus tritium derived from lithium—will provide a reserve for more than 2000 years while the problems of burning pure deuterium are being solved. The basic requirement for controlled fusion is to get the fuel mixture hot enough (10^8 degrees), at a high enough density, and for a long enough period of time to let a significant fraction of the fuel react (burn). To be practical, the process must release several times more fusion energy than is required to confine and heat the fuel.

At 10^8 degrees, the fuel gas is a fully ionized plasma, that is, a neutral assemblage of bare atomic nuclei (positive charges) and electrons (negative charges). To stay that hot, the plasma must be kept from touching the chamber walls. For an economical fusion reactor, this confinement must last long enough so that the confinement parameter $n\tau$, the product of density n (particles per cubic centimetre) and confinement time τ, exceeds about $10^{14}\ \mathrm{cm}^{-3}\cdot\mathrm{s}$.

Magnetic fields are one way to isolate the plasma (the other way being explored at LLNL is inertial confinement). Being electrically charged, plasma particles of both signs must spiral along magnetic field lines and cannot move readily across the field. In a region of increasing magnetic field strength, these spirals tighten up and reverse if the particle motion is not too nearly parallel to the field direction, reflecting the particle as from a magnetic mirror.

Between two such mirrors, particles can reflect back and forth many times until a succession of collisions with other particles lines them up with the field, placing them within the mirror loss cone. The higher the fuel temperature, the longer this scattering process takes and, hence, the better the confinement. The end loss of a mirror-confined plasma ultimately limits the confinement in a single mirror cell.

Since they are electrically charged, plasma particles are also susceptible to electrical forces. In a single-celled mirror system, the rapidly scattering electrons tend to escape quickly, leaving an excess of positively charged ions and generating a positive plasma-space potential. This potential builds until, by restraining the electrons and helping the ions escape, it reaches an equilibrium in which the loss rates of positive and negative particles are the same. The higher the electron temperature, the higher this potential will be and the more adversely it will affect the confinement of fuel particles within the vacuum chamber.

This positive plasma potential, detrimental to confinement in a single-mirror geometry, is converted to good use in tandem geometry. A tandem mirror consists of a large, sausage-shaped reacting region with a mirror cell of high positive potential at each end. Here, the combination of magnetic and electric forces confines the ions of deuterium and tritium fuel within the reacting region until, after perhaps hundreds of collisions, they gain enough energy to escape over the positive potential hill at either end. This makes the confinement time tens to hundreds of times longer, raising the possibility of tandem-mirror fusion reactors that are economically competitive with other sources of energy.

sideways in the direction of decreasing magnetic field strength (B). This motion is stabilized in machines with baseball-seam-shaped coils, such as the 2XIIB, in which the magnetic field lines everywhere have a convex curvature with respect to the plasma. (Magnetic field strength increases everywhere outward from the geometric center; hence such designs are known as "minimum-B" mirrors.) The high plasma pressure to which the 2XIIB plasma rose when its rf fluctuations were controlled showed that this MHD stability holds over wide ranges of pressure.

From 1965 to 1975, minimum-B configurations (Fig. 1b) provided much of the physics base for the tandem-mirror concept. By stabilizing MHD motion, the minimum-B magnet geometry permitted studies that led to control of rf fluctuations.

Conventional Tandem Mirrors

In a simple mirror device, the electrostatic potential of the plasma continually decreases from the center of the confinement vessel to the external ground potential. A positively charged ion trying to escape this repulsive potential field is reflected by the magnetic mirror if its velocity vector has a sufficient angle with respect to the magnetic field. Electrons trying to escape the plasma are constrained by the potential. In the tandem-mirror concept (Figs. 1c and d), the chief confinement volume is a large central cell similar to the original solenoid of Fig. 1a.

In contrast to the simple mirror, however, each end of the tandem mirror is fitted with a simple mirror cell. The end cells, or plugs, have both a higher electrostatic potential than the central cell and a minimum-B geometry. Thus, central-cell ions with energies less than the end-plug potential are both trapped by electrostatic fields and reflected by the magnetic mirrors. Because the end cells are so stable to MHD motion, they stabilize the whole system.

The central-cell ions have a distribution that is Maxwellian up to the energy of the confining potential. The plugs have anisotropic pressure distributions that require a continuous injection of power. If the central-cell plasma in a reactor can be confined sufficiently to ignite (that is, if the charged reaction by-products can heat cold fuel to fusion energy), it will be necessary to inject power into the end plugs only.

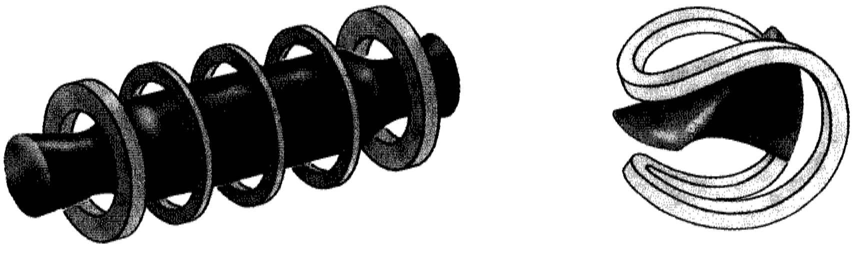
A useful measure of reactor performance, then, is the ratio of the fusion power produced in the central cell to the plug sustainment power, a quantity known as Q (which should be greater than about 15 for efficient operation). Because the same end plugs can be used to plug either long or short central cells, Q is higher in long reactors, which produce greater total power. However, such large sizes are not so attractive to utilities because of their reduced flexibility, the higher risks associated with a new technology, and other factors. To design a reactor with a high Q but with a relatively low total fusion power, the end plugs must require a relatively low sustainment power. Thus, there is clearly a premium on keeping the end-cell volume small.

The Tandem-Mirror Experiment

The design of our first tandem-mirror experiment, the TMX, was based on a theoretical picture of plasma confinement drawn from single-mirror cells. In this picture, energetic ions are injected into end plugs whose plasma density is higher than the density in the central cell. To equalize electron and ion losses and to satisfy local charge neutrality in the end-plug and central-cell plasmas (which are at different densities), there must be a net positive potential between them to balance the electron pressure in the two regions. This potential also confines the central-cell ions. Because the potential rises to satisfy conditions along each magnetic field line, its axial profile is determined on a line-by-line basis. Figure 2 shows the resulting profiles for the TMX in relation to its magnetic field strength, density, and plasma potential.

(a) Simple mirror

(b) Minimum-B mirror



(c) Tandem mirror

(d) TMX plasma

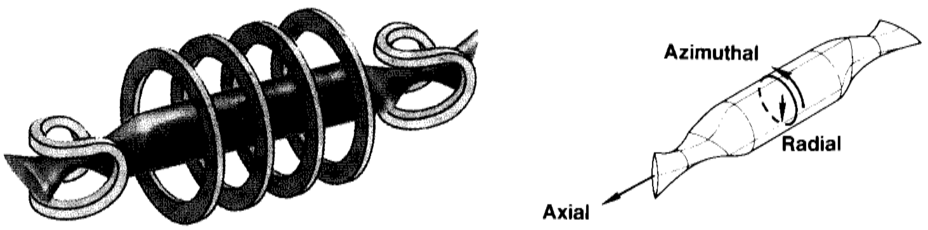


Fig. 1

Evolution of the tandem mirror. (a) The early axisymmetric simple mirror. (b) The minimum-B simple mirror. (c) The TMX tandem mirror (without the transition coil from the central cell to the end plug). (d) The TMX plasma; the magnetic field coils have been removed to show better the shape of the plasma cloud.

As the axial loss of ions is reduced, the radial (sideways) transport of particles and energy assumes greater importance. In the tandem mirror, the minimum-B end cells used for MHD stability, together with the long central cell, increase radial transport significantly beyond that expected for an equivalent axisymmetric system.[3] Ions passing into the end cells are radially displaced by the azimuthal components of the magnetic field. Such displacements can become additive when the axial bounce frequency of the ions in the central cell resonates with their azimuthal drift frequency. In contrast, the transport of electrons, which have bounce frequencies much higher than those of ions, is not similarly enhanced; instead, electrons are lost axially. Since this mechanism of radial transport affects only ions, it is termed "nonambipolar."

This picture of tandem-mirror confinement was tested in the TMX and in other first-generation devices between 1977 and 1980. To a considerable extent, these experiments performed as predicted. Their success reflected the emergence of a new plasma-confinement scheme designed *ab initio* and typified the rapid maturation of confinement physics over the preceding two decades.

The TMX experiments and theoretical studies identified three issues crucial to the design of a magnetic-fusion reactor: power-efficient axial confinement, radial confinement, and stability. Of these, the first is peculiar to open systems and was solved with the advent of the thermal barrier.

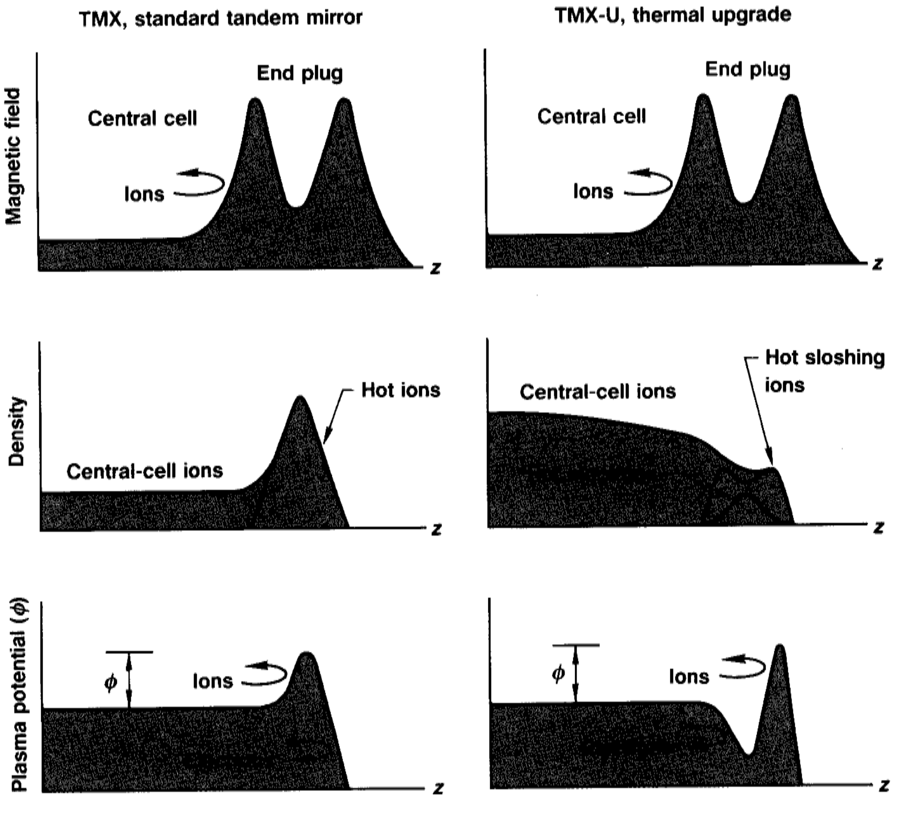


Fig. 2

Profiles of the end-plug magnetic field, density, and plasma potential in the conventional tandem mirror and the thermal-barrier tandem mirror. In all cases, the central cell is to the left. The axial loss rate of positively charged central-cell ions is reduced by magnetic fields and by electrostatic potentials in the end plugs. The thermal barrier, which solves the problem of axial losses in an open system with lower-density end plugs, consists of the dip in plasma potential between the central cell and the end plug. Preferential heating of the isolated end-plug electrons raises the local electrostatic potential peak above that in the central cell enough to stem axial losses.

The Thermal-Barrier Mirror Machine

The first version of the tandem mirror, with its high-density end plug, was a distinct improvement over the single-mirror concept, but studies indicated that it suffered some serious drawbacks as a candidate reactor. For instance, calculations showed that the end-plug potentials required for a reactor would entail a plug-to-central-cell density ratio of about ten. Such a ratio could be maintained only by supplying a large amount of power to the end-plug plasmas. Even then, central-cell ignition would be very difficult and would probably require auxiliary heating. Finally, the high end-plug pressures would have to be confined by extremely strong magnetic fields—prohibitively so if the end-plug coils were of the minimum-B type.

In response, we conceived the thermal-barrier end plug in 1979 (see Ref. 4). The objective with the thermal barrier is to create the high end-plug potential required for a reactor with plasma densities significantly lower than those of the earlier tandem mirror (now known as a "conventional" design). The trick is to heat electrons in the end plugs without heating those in the central cell. To do this, we must thermally insulate the electrons in the end plug from those in the central cell. The heating expedites the escape of electrons from the end-plug regions, raising the local plasma potential along with the local electron temperature.

The Thermal Barrier

The thermal barrier, which was first tested with the TMX-U, consists of a potential minimum between the central-cell and the peak plug potential (Fig. 2). When the magnitude of the barrier is several times the electron temperature, the central-cell and end-plug electrons are trapped in separate potential wells. Thermal contact between these two populations occurs by the trapping and detrapping of electrons passing between them. When the passing fraction is sufficiently small, the end-plug electrons can be preferentially heated.

Sloshing Ions

Theory indicates that a thermal barrier can be created by combining electron-cyclotron resonance heating (ECRH) with the injection of energetic ions in neutral beams. ECRH is first applied at the end-plug midplane to create a population of mirror-trapped hot electrons. Next, ions are injected at an angle to the midplane of the end plug's magnetic field. The injected ions oscillate in the field, behaving roughly as if they were balls released down the side of a bowl. The density peaks of the injected ions occur at their two turning points to produce a double-lobed or "sloshing-ion" distribution. The density difference between the sloshing ions and the hot electrons must be made up with cooler (thermal) electrons, and a potential profile springs up to ensure this.

Figure 2 shows that, as we move from the central cell into the end plug, the thermal-electron density (i.e., the difference in density between the ions and the hot electrons) first decreases to a minimum at the end-plug midplane, increases again at the outer lobe of the sloshing-ion distribution, and finally decreases beyond the turning point of the sloshing ions. If the electron temperature were constant along the magnetic field lines, the self-consistent potential would have qualitatively the same shape, varying as the logarithm of the density difference, with an outer maximum in potential equal to the inner maximum. However, if local electron heating is applied to the outer density lobe, only the local temperature increases. This raises the local potential peak above that in the central cell, thereby providing the potential plug.

Local heating is usually done with a second ECRH source, tuned to give bulk heating rather than to create a minority of energetic electrons. This process may be thought of as the boiling of electrons from the outer lobe of the sloshing ions. To maintain charge neutrality with this local heating, the local potential peak that is trapping the electrons increases in height, enhancing the plugging potential.

Removing Trapped Ions

The thermal-barrier dip in potential raises a new and important issue. Ions reflected by the potential after passing through the barrier will be trapped by collisions in the potential well and, unless removed, will destroy it. Thus, the removal of these trapped ions from the barrier, a process called pumping, is essential to its steady-state operation. In present experiments, ions are removed by charge exchange with neutral beams, both with the beams injecting sloshing ions and with special beams that are injected at too small an angle to the magnetic field to be trapped by the end-cell mirror. However, because the cross section for charge exchange declines rapidly as the ion energy increases, this technique is not applicable to commercial reactor systems, which will operate at higher temperatures. The currently favored alternative, to be tested in the TMX-U, uses externally applied low-frequency fields to selectively transport barrier-trapped ions to the plasma surface, where they are removed by axial flow.

Extension to Reactor Scale

The principles of the thermal barrier can usefully be viewed as extensions of those of the conventional tandem mirror. In each case, we use externally imposed magnetic fields to localize high-energy charged species in axial profiles that, by themselves, do not satisfy local charge neutrality, and we supply external power to sustain these density profiles. The plasma satisfies overall neutrality by establishing a potential profile and trapping thermal electrons in the end plugs. Energetic particles are relatively unaffected by the potential. By choosing appropriate energetic-particle density profiles therefore, we can create a potential profile that plugs the lower-energy central cell.

We have calculated that in a reactor with the thermal-barrier feature, the end-plug potentials required to axially confine the central-cell plasma can be generated with an end-plug plasma density that is less than that in the central cell. This represents an order-of-magnitude improvement over the conventional tandem-mirror plug. The thermal-barrier end plug requires both energetic ions and electrons that are provided, respectively, by neutral beams and ECRH. This thermal-barrier technique is more complex than a conventional plug, where only neutral beams are used. However, the lower density of the thermal-barrier end plug results in a sharp gain in consumed power. Consequently, the calculated Q values for a thermal-barrier reactor increase by a factor of five to ten.

Thermal-Barrier Experiments

In 1982, we upgraded the TMX to demonstrate operation of the thermal barrier. To date, these experiments have been successful at low to moderate densities. As we have increased power to the machine and improved the vacuum, the central-cell density has also increased. Because, at each stage, the thermal barrier forms in competition with ion-collision processes, density increases must be accompanied by ion heating.

The thermal-barrier end plug is a technique for limiting end losses from the tandem-mirror configuration within acceptable power requirements. Thus, pending the results of the TMX-U tests, it appears that the open-system problem of axial loss has been solved. There remain, however, the issues of MHD stability and radial transport. These issues are coupled in the sense that radial transport is induced by the same departures from axisymmetry that cure MHD instability. This twin problem is being addressed by several approaches, ranging from those that reduce transport in minimum-*B*-stabilized geometries to those that use alternatives to achieve MHD stability in nearly or completely axisymmetric geometries. The outcome of these studies will strongly determine the suitability of the tandem-mirror approach to a commercial fusion reactor.

Impact of Transport and Stability

Minimum-*B* end cells were well suited to ensure MHD stability in early tandem-mirror experiments where it was important to focus on the physics of end plugging. However, they make it difficult to design tandem-mirror configurations able to control radial transport on the one-second scale of a reactor. We are investigating two methods in particular of coping with transport in these thermal-barrier tandem-mirror systems.

Calculational analyses indicate that by placing a circular, high-field throttle coil between the central cell and each nonsymmetric end cell, we can reduce the fraction of central-cell ions undergoing transport in the end cells. Reactor performance is calculated to improve as the throttle-coil field is increased. Current ideas for high fields, feasible because of the simple shape of the magnet, envision hybrid combinations of superconducting and resistive conductors. The MFTF-B magnet set, shown in Fig. 3, includes such throttle coils. Its end cells have been designed with compensating drifts that greatly reduce the size of the transport step at the expense of making the end-cell region much longer, including the volume that must be pumped.

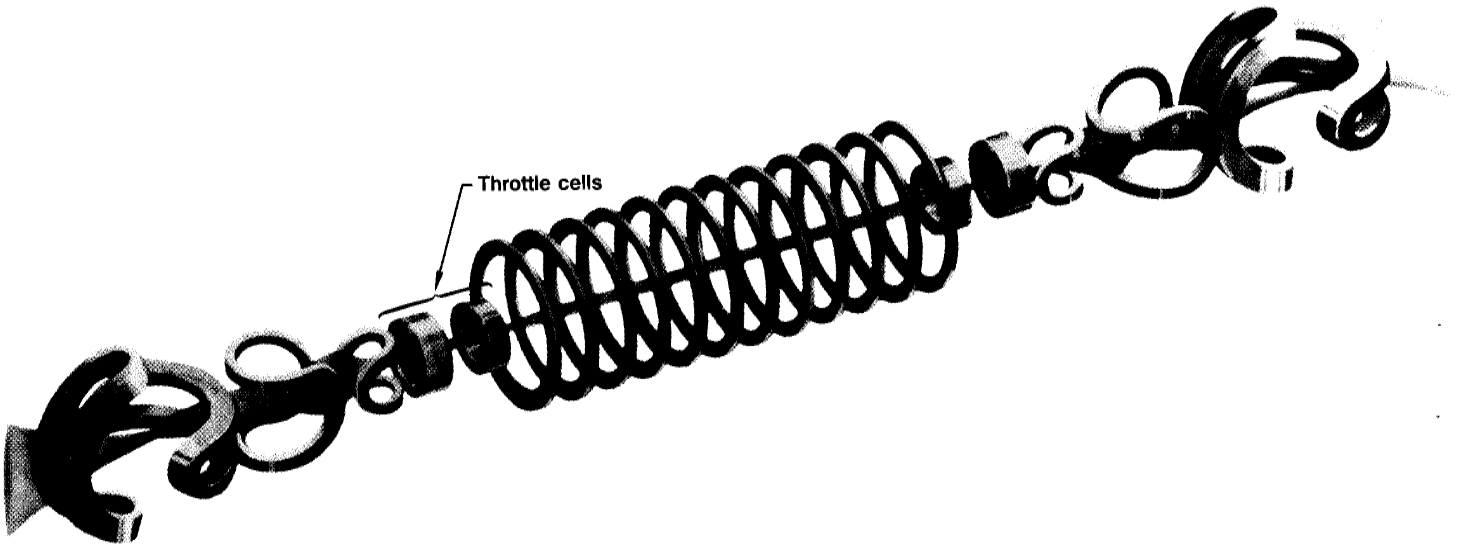
In addition, we have begun experiments with the TMX-U to control the radial potential profile in the central cell with biased rings mounted on the end wall. In theory, we can reduce transport by altering the radial electric field, eliminating the resonance between the ion azimuthal drift frequency (due to the radial field) and the axial bounce frequency. Experiments, so far, have shown that transport is markedly reduced when the rings are floated to negative potential, corresponding to a reduced radial field in the central cell.

MARS and Beyond

These ideas were included in the Mirror Advanced Reactor Study (MARS),[5] which quantified the characteristics of a reactor based on the MFTF-B design

Fig. 3

Computer-generated rendering of the MFTF-B thermal-barrier tandem mirror; the apparent distortion is caused by the computer-generated isometric perspective. High-field throttle coils confine a large fraction of central-cell ions and reduce their radial loss rate.



(Fig. 4). Although the resulting conceptual design shares many performance parameters with tokamak designs for fusion reactors (including wall loading, power density, net power, and cost of generated electricity), it has proved disappointing insofar as it does not fully exploit the potential of the long, straight central cell. The difficulty with the MARS design is in its end cells, which are of the longer, transport-reducing variety. A smaller, more efficient reactor would require smaller end cells.

The key to reducing end-cell size is a cell that is more nearly axisymmetric and yet still preserves MHD stability. The payoff is illustrated in Fig. 5, which compares the end-cell magnet set for the MARS design with its axisymmetric equivalent. The resulting reduction in magnet mass is a measure of the saving in capital cost. The reduction in end-cell volume is a measure of the reduction in injected plasma power required to sustain the end plugs. As Fig. 5 suggests, the smaller end cells would make it feasible to design a reactor producing less net power.

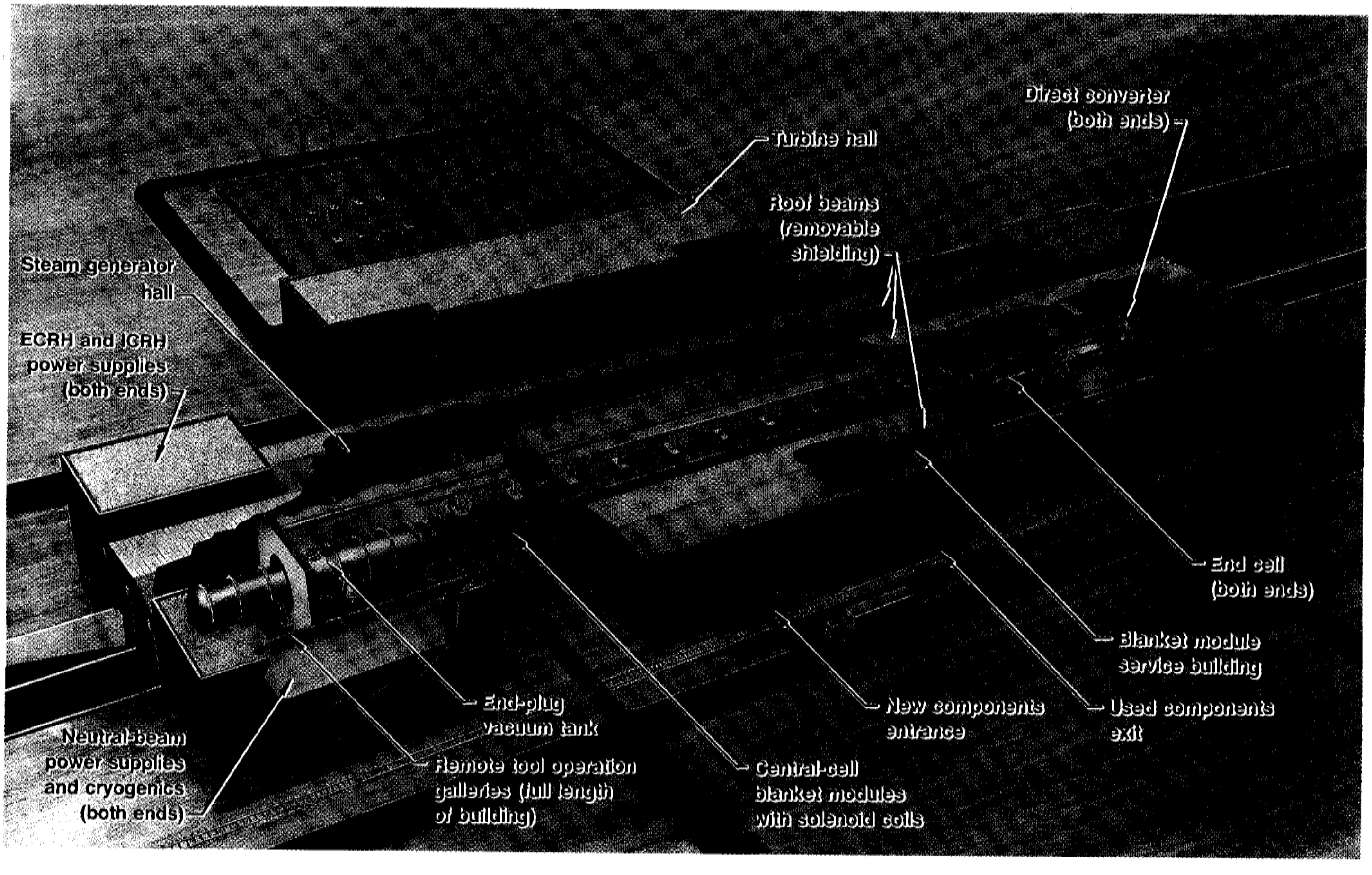
Within the broader mirror program, several approaches to axisymmetry are being pursued, and, over the next few years, these will be tested and compared. When a clear leader emerges, we will modify the MFTF-B by installing relatively inexpensive axisymmetric end cells, permitting experiments under conditions of long confinement time. The various approaches to axisymmetry (Fig. 6) are characterized most notably by their end-cell magnet sets.

Octopole End Cells

An octopole end cell (Fig. 6a) is being considered for our TMX-U. Although this configuration is not strictly axisymmetric, its nonsymmetric region is restricted to the surface, and the central-cell flux maps only to the relatively symmetric end-cell core.

Fig. 4

Artist's conception of the Mirror Advanced Reactor Study (MARS) thermal-barrier tandem-mirror reactor. This design is based on the magnet set to be installed in the MFTF-B.



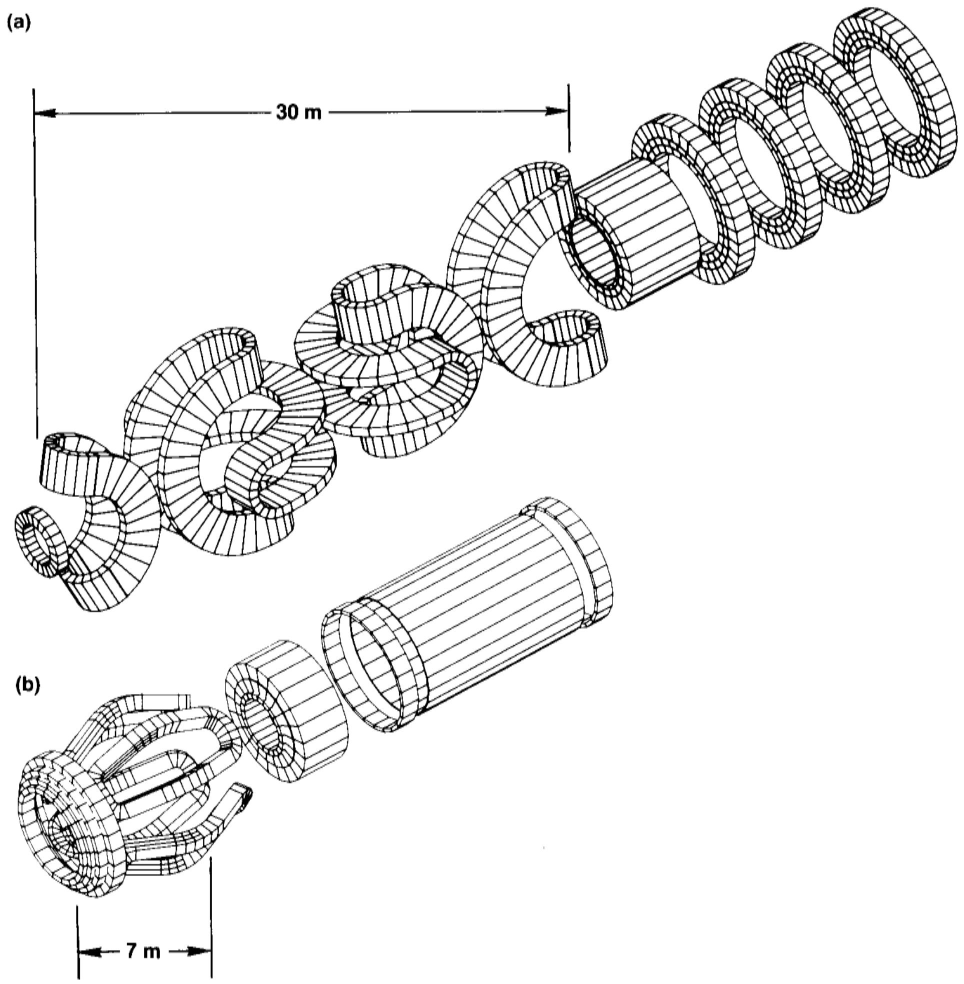


Fig. 5

Design of the end-cell magnet configuration for (a) the MARS conceptual reactor, which has a magnet mass of 16 000 tonnes and (b) a tandem-mirror reactor with its nonsymmetric fields localized to the surface, with a magnet mass of 3000 tonnes. Because its end plugs are shorter, the axisymmetric design would permit an economic reduction of net power from the MARS value of 1200 MW$_e$ to about 500 MW$_e$.

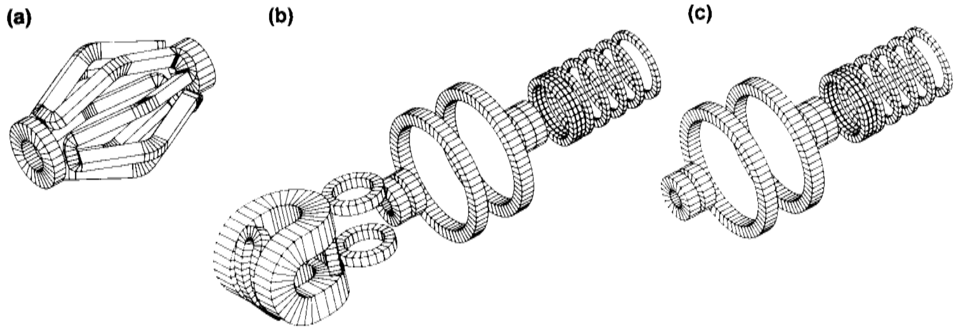


Fig. 6

End-cell magnet sets for various approaches to stabilizing an axisymmetric end cell in a tandem-mirror machine. (a) The octopole design (LLNL) places good line curvature at the plasma surface. (b) The TARA design (Massachusetts Institute of Technology) features a minimum-*B* anchor outside the end plug. (c) The design proposed both by the University of Wisconsin and by UCLA/TRW seeks to stabilize a completely axisymmetric configuration.

Much of the pressure in the octopole anchor would result from hot electrons. Thus, an important issue is whether the required density and pressure profiles can be generated efficiently.

The TARA Machine

In the TARA machine (Fig. 6b), located at the Massachusetts Institute of Technology, the plugging potential is formed in a strictly axisymmetric cell. Outside the plug is a minimum-*B* anchor cell that is electrically connected with the plug only through electron conductivity. The central-cell ions, kept out of the anchor by the plugging potential, are maintained in an axisymmetric geometry and, therefore, do not suffer enhanced transport. Because its anchoring magnetic field can be relatively weak, such a geometry would make an attractive reactor candidate. The important physics question that must be answered is the nature and degree of electrical contact with the central cell required for the anchor to be effective.

Recently, the TARA central cell has been fitted with a modified coil geometry that theoretically will be stable even in pure axisymmetry. Success in experiments with this geometry would strongly influence our thinking about tandem-mirror designs and would make the ideal of an axisymmetric configuration a practical reality.

The PHAEDRUS Machine

The PHAEDRUS machine, at the University of Wisconsin, is being used to investigate the use of ion-cyclotron resonance heating (ICRH) to develop a ponderomotive potential with a positive radial gradient. The effect of this potential on particle stability is similar to that of the convex curvature of magnetic field lines. Such a technique would permit a completely axisymmetric machine (Fig. 6c). Early experiments have been very encouraging, but many questions must be answered before the viability of the technique on a reactor scale can be determined. Such questions include whether the plasma is stable at high pressures, how much power the plasma absorbs from the rf field, and what the secondary effects are of the rf field on the plasma.

Summary and Conclusions

The past decade of research in the mirror-fusion program has emphasized practical methods for reducing end loss along the open magnetic field lines. The result is the tandem-mirror design with the thermal-barrier end plug. The calculated reactor Q values have increased from near unity for the simple mirror to 25 or more for the thermal-barrier tandem mirror, depending on net power. Early tests of the thermal barrier have been encouraging, but much more stringent studies at higher density and longer confinement times are needed.

With the end-loss problem conceptually solved and awaiting detailed experimental verification, emphasis in the MFE Program has shifted to optimizing magnet geometry to reduce the net power and capital costs of an operational reactor. The key, here, appears to be axisymmetric end cells. Several competing techniques to stabilize tandem mirrors without the use of minimum-B cells are being assessed. These approaches will be studied over the next few years to identify the most promising for inclusion in MFTF-B, should restart of this facility become possible.

The evolution of the mirror machine clearly demonstrates one of its most distinguishing characteristics: flexibility. The open magnetic geometry, although raising special problems, also has proved a strength by enabling control of the radial electric field. As fusion power moves toward commercialization, attention will focus on reducing the minimum size of an economical power station and on reducing the cost of generated electricity. The goal is a power station as small as today's moderately sized fossil-fuel plants, producing electricity at a competitive cost. In meeting this challenge, the flexibility inherent in the open magnetic-mirror system may prove our greatest asset. ■

Key Words: confinement time; electron-cyclotron resonance heating (ECRH); magnetic fusion energy (MFE); magnetic mirror—simple, tandem; magnetohydrodynamics; Mirror Advanced Reactor Study (MARS); MFTF-B; minimum-B geometry; neutral beam; octopole; PHAEDRUS; sloshing ion; TARA; thermal barrier; throttle coil; TMX; TMX-U; 2XIIB.

Notes and References

1. T. K. Fowler and B. G. Logan, *Comments on Plasma Phys. and Controlled Fusion* **2**, 167 (1977).
2. G. I. Dimov, V. V. Zakaidakov, and M. E. Kishinevsky, *Fizika Plazmy* **2**, 597 (1976); *Sov. J. Plasma Phys.* **2**, 3261 (1976).
3. D. D. Ryutov and G. V. Stupakov, *Fizika Plasmy* **4**, 501 (1978); *Sov. J. Plasma Phys.* **4**, 278 (1978).
4. D. E. Baldwin and B. G. Logan, *Phys. Rev. Lett.* **43**, 1318 (1979).
5. *MARS (Mirror Advanced Reactor Study) Report*, B. G. Logan, Ed., Lawrence Livermore National Laboratory, Rept. UCRL-53480 (1984); see also the summary in the November 1984 *Energy and Technology Review* (UCRL-52000-84-11), p. 1.

MFTF-B: The Mirror Fusion Test Facility

The plant and capital equipment tests recently conducted on the MFTF-B mark the completion of LLNL's largest construction project, a unique national facility for research on mirror-fusion energy.

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In the decade since the idea of confining fusion plasma with tandem mirrors was conceived concurrently by researchers at LLNL and in the Soviet Union, the Laboratory has built the Mirror Fusion Test Facility (MFTF-B), the largest superconducting-magnet fusion facility in the world. Housed in a 58-m-long stainless-steel vacuum vessel and weighing over 1250 tonnes, the 26 major magnets in MFTF-B store more energy (1200 MJ) than any other superconducting magnet system. Now MFTF-B, the flagship of the national program to develop mirror-fusion energy, has successfully passed a series of stringent engineering tests of its many subsystems.

MFTF-B is the Laboratory's largest and most expensive construction project. Building it cost $242 million, and an additional $110 million in operating, research, and development funds was provided during construction. MFTF-B construction began in 1977 and was finished in February 1986 with the successful conclusion of the plant and capital equipment (PACE) tests, which verified that all major subfacilities operated as designed. The completion of the MFTF-B project makes available to the fusion community one of the largest test facilities in the world for continuing studies on plasma physics and furthering the engineering technology necessary for future fusion experiments. This engineering overview of MFTF-B is followed by articles on results of the PACE tests.

The MFTF-B Mission and History

Building a machine that can confine plasma at temperatures close to that required for nuclear fusion, an important step on the way to fusion power plants, has been the mission of the MFTF-B project since its origin. The first version of the machine, started in 1974, was a simple, single-celled mirror machine designed to explore physics scaling laws and to advance the technology of mirror-fusion devices. This machine, the Mirror Fusion Test Facility (MFTF), had a 1600-m^3 vacuum vessel in which were suspended a pair of superconducting C-shaped magnets, called the yin-yang pair. This vessel also supported an internal cryopumping system, an external vacuum-pumping system, neutral-beam injectors, and a diagnostic system.

While MFTF was being designed and constructed, researchers at LLNL and in the Soviet Union conceived the idea of increasing productivity in fusion machines by confining the plasma between two magnetic mirrors.

Taking this new approach, we built and operated our first tandem-mirror machine, the Tandem Mirror Experiment (TMX), in 1979. TMX was expected to confine the plasma better than a single-mirror machine could do. As a result of our significant achievements with TMX, we received the approval of the Department of Energy (DOE), in 1980, to convert the single-celled MFTF to a tandem-mirror machine. This revision in the MFTF project was called MFTF-B.

A concept called the thermal barrier, which had been first tested on the TMX, was also incorporated into the MFTF-B. The thermal barrier was designed to diminish a fundamental physics problem in mirror machines: the leakage of plasma from the ends of the central cell. The thermal barrier is a region of hotter electrons between the central cell and end cell. Heating the electrons in this barrier region higher than those in the central cell creates an electrostatic confining potential without requiring a higher plasma density in the ends. Consequently, there is a lower power density in the end regions (called end plugs) that deters plasma from escaping out the ends of the machine. In engineering terms, the thermal barrier permits the neutral-beam voltage and magnetic-field strength to be lower than in a conventional tandem mirror.

To achieve a tandem design for MFTF-B, we duplicated the original vacuum vessel and its yin-yang magnets; we inserted a third, central vessel with 14 solenoid and two transition magnets between the two end vacuum vessels. In addition, an auxiliary, C-shaped magnet, called an A-cell, was placed outboard of each of the two yin-yang magnet pairs.

The detailed design work on MFTF-B began as our engineering staff and their subcontractors were finishing the assembly of the original MFTF. During the first half of fiscal year 1982, we conducted a very successful series of engineering tests (the technology demonstration), on the original MFTF vacuum vessel, yin-yang magnets, and other systems to verify their design parameters. Immediately after making the tests, we disassembled MFTF and reconfigured it as part of the tandem MFTF-B. The new machine used essentially all the MFTF hardware.

In 1982, with the continuing objective of improving plasma confinement and simplifying the magnet design, we made one other major change to the machine. The modification resulted from physics studies and was undertaken to complement the main-line mirror approach to fusion reactors fostered by the National Magnetic Fusion Program. This third version of MFTF was then called the MFTF-B axicell design, although we now refer to it simply as MFTF-B. The axicell configuration increased the number of major magnets from 22 to 26 and eventually added 16 smaller magnets called trim coils. In addition, every magnet had to be relocated, which caused changes to the vacuum vessel and other systems. Figure 1 shows the

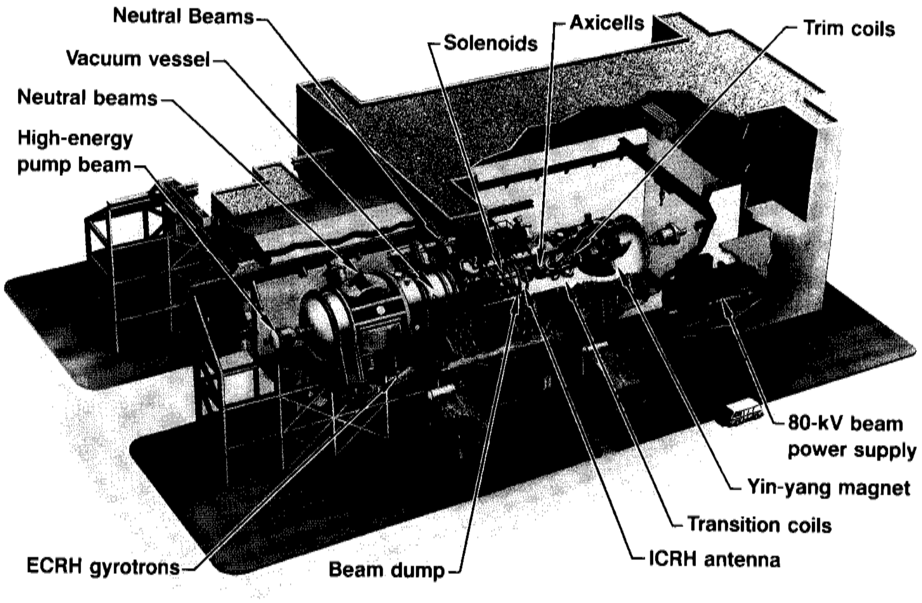

Fig. 1

Artist's rendering of final MFTF-B configuration. The vacuum vessel inside the shielding concrete building is cut away to reveal one half of the magnet assembly. It took eight years to construct the machine as it now stands. The plant and capital equipment tests that ended in February 1986 confirmed that the machine met the specified engineering requirements.

configuration of the final version of MFTF-B and its major systems.

The detailed design, fabrication, and field erection of both MFTF and MFTF-B were awarded to subcontractors through competitive bidding processes. The CVI Corporation of Columbus, Ohio, won the MFTF mechanical systems contract, which included the vacuum vessel, the cryogenic systems, and the internal, external, and rough vacuum-pumping systems. Later, the CVI Corporation subcontracted the initial vacuum vessel to Pittsburgh-Des Moines Corporation (PDM) of Pittsburgh, Pennsylvania. The magnets were built by LLNL, General Dynamics of San Diego, California, and Chicago Bridge and Iron of San Francisco, California. The major electrical work was done by Brown, Boveri et Cie (BBC) of Baden, Switzerland, and New Brunswick, New Jersey; Dynapower, Farmington, Michigan; Hewlett Packard, San Ramon, California; Perkin-Elmer Data System Group, Santa Clara, California; RCA, Lancaster, Pennsylvania; Universal Voltronics Corporation, Mt. Kisco, New York; and Varian, Palo Alto, California.

Table 1 Machine parameters for MFTF-B.

Parameter	Value[a]
Magnets	
End-plug midplane field	1.0 T
Plug-mirror ratio	3:1
Plug length	5.0 m
Transition length	7.7 m
Central-cell field strength	1.6 T
Central-cell mirror ratio	7.5:1
Central-cell length	20.0 m
Neutral beams	
Injection voltage	80 (80) kV
Plug-injection current, each plug	100 (20) A
Central-cell injection current	100 (20) A
Pulse duration	0.5 (30) s
Electron-cyclotron resonance heating	
Number of 200-kW gyrotrons	8 (10)
Frequency	28, 35, 56 GHz
Duration	30 s
Ion-cyclotron resonance heating	
Power	1.0 MW
Frequency	6–20 MHz
Duration	30 s
Vacuum system	
Volume	4300 m
Machine length	58 m

[a] Values in parentheses are for the second phase of MFTF-B operation, after 30-s, low-impurity neutral beams are added.

Technology Objectives

According to the 1982 *National Mirror Fusion Program Plan,*[1] the MFTF-B technology objectives were to:

- Gain experience in constructing and operating a large superconducting magnet system.
- Learn how to construct and operate reliable, long-pulse, high-current, high-voltage neutral-beam sources, as well as equipment for electron-cyclotron resonance heating.
- Maintain high vacuum in the vessel even as its walls interact with the plasma.
- Handle intense particle and plasma-energy deposition on surfaces in the vacuum vessel (without deleterious effects to the plasma or vessel).
- Operate a large fusion facility by means of a remote computer system.

At the time the A-cell design was approved by the DOE, both the Mirror Senior Review Panel and the Fusion Review Panel of the Energy Research Advisory Board recommended that we continue to work toward a more nearly axisymmetric design for a tandem-mirror reactor that would build on thermal-barrier physics. In addition, the design should reduce radial transport of the plasma, increase the power gain factor Q, and reduce magnet complexity in the ends of the machine so as to decrease capital costs. The exact design parameters of MFTF-B are listed in Table 1.

The feasibility of the MFTF technology was successfully demonstrated as of February 1982; by that time, we had operated the original MFTF yin-yang magnet and evacuated the vacuum chamber to 13.3 μPa. In addition, we had tested the magnet at the full design current of 5775 A at a temperature of 4.5 K. The engineering requirements of the MFTF-B were confirmed in the five-month-long PACE tests that ended in February 1986.

The MFTF-B Project

Preliminary design studies for fusion reactors have identified major mirror-fusion technologies worthy of long-range research and development. These include high-field superconducting magnets, steady-state neutral beams, radio-frequency power including both electron-cyclotron resonance heating (ECRH) and ion-cyclotron resonance heating (ICRH), and large vacuum and cryogenic systems for steady-state operations. Each of these technologies has been employed in MFTF-B running on a 10% duty cycle (i.e., sustaining a 30-s pulse each five minutes). The magnets use niobium titanium conductors and operate at steady state.

MFTF-B Operation

The primary physics objective of MFTF-B is to achieve long plasma-confinement times by using thermal barriers to establish good confining potentials. To meet this objective, we have set certain requirements for densities, temperatures, and potentials. To reach these conditions, we inject neutral beams of 80-kV deuterium into the central cell and yin-yang cells. Separate sources of ECRH create the confining potentials at each end of the machine and help establish the thermal barriers.

Neutral beams at each end will excite (pump) to a higher energy level the ions that become trapped in the potential well at the thermal barrier. We expect that MFTF-B ultimately can be operated with a central-cell particle density of approximately 3×10^{13} cm^{-3} and with ion energies of 10 to 15 keV. To meet these operating parameters, we need a confining potential of 20 to 30 kV. This confining potential results from heating those electrons at each end of the machine that are thermally isolated from the central-cell electrons by the thermal barrier.

The MFTF-B Systems

The MFTF-B project required the combined resources of the Laboratory and private industry; about 80% of the funds were spent in the private sector. Where possible, we wrote performance contracts that allowed industry to do the engineering design, fabrication, installation, and acceptance testing of a given component or system. More than three dozen industrial firms participated in the construction of MFTF-B.

The major systems of MFTF-B—the magnets, the vacuum vessel (including internal and external vacuum), the cryogenics system, the neutral-beam power sources, the radio-frequency heating systems (both ECRH and ICRH), and the computer control and diagnostics system—are briefly described here. The physical location of these systems in relation to each other is shown in Fig. 2.

Magnet System

The superconducting-magnet system in MFTF-B provides an environment for investigating the physics of tandem-mirror-confined plasmas. A magnet becomes a superconductor, and consequently uses far less energy than an ordinary magnet, when it is cooled to an extremely low temperature. For MFTF-B, this temperature is 4.5 K above absolute zero. The magnets are maintained at this temperature by a large cryogenic system outside the vacuum vessel which circulates liquid helium through the magnet coils and liquid nitrogen through the thermal shields that surround the magnets.

To create the confining magnetic field for MFTF-B, there are 24 superconducting, niobium-titanium coils consisting of 12 central-cell solenoids, four axicell solenoids, four transition coils, and four yin-yang coils (see Fig. 3). To produce the high field, there are two superconducting, niobium-tin insert coils, and to aid in