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An Assessment of the U.S. Mirror Fusion Program

*Report of the 1980
Mirror Senior Review Panel*

February 1980

Published April 1980

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U.S. Department of Energy
Office of Energy Research
Office of Fusion Energy
Division of Mirror Confinement Systems

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**Prepared by
The 1980 Mirror Senior Review Panel,
William R. Ellis, Chairman**

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Office of Energy Research
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Washington, D.C. 20585**

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 Microfiche: \$ 3.00

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I. INTRODUCTION

Schemes for the magnetic confinement of high temperature plasmas for the release of fusion energy fall into two general categories: open systems and closed systems. The tokamak is the major example of a closed, or toroidal, system. The magnetic mirror is the primary example of an open, or linear, system.

Progress in magnetic mirrors, as in other systems, is measured mainly by the degree of success achieved in reducing plasma losses, i.e., increasing the plasma confinement time. For magnetic mirrors, the primary loss channel has been the loss of plasma out the ends of the container along the direction of the magnetic field lines.

As the end loss is reduced in a magnetic mirror, the amount of energy released, or Q-value (Q is defined as the fusion power output divided by the power input required to sustain the plasma) projected for a mirror reactor increases. Fusion reactor designs based on single cell, minimum-B magnetic mirrors typically have Q-values of about unity, barely releasing as much fusion energy as they consume.

At the time of the last mirror Senior Review Panel, in early 1976, the single cell mirror reactor was judged to be unacceptable as the basis of a pure fusion reactor. However, there was a strong belief that methods could be found to "enhance the Q". As the present review shows, this belief was amply justified.

There have been two major conceptual advances since the 1976 review. The first advance was the discovery, independently at LLL and in the USSR, of the tandem mirror principle. This concept consists of using two single-cell mirrors to confine plasma electrostatically in a long solenoidal central cell. Q values in reactors of 2-5, and possibly as high as 10-12, were projected. The higher Q-values were very demanding of the reactor technology. These projections surpassed the minimum value of $Q = 2-3$ which the 1976 Panel stated was the "threshold for reactor interest". The Tandem Mirror Experiment (TMX) was built specifically to test the new tandem ideas. Experiments in TMX during the past year have given strong evidence in support of the tandem concept.

The second major advance in the mirror program has been the development at LLL during the past year of the thermal barrier concept, as an additive feature to the tandem mirror. Although not yet confirmed by experiment, nor completely explored theoretically, the basic concept appears well founded.

The consequences of the concept are to reduce significantly the technology requirements for achieving a given Q , or alternatively, for a given technology, to permit a higher Q than in the tandem alone. For the first time, mirror reactor designs are being considered which permit ignition in the central part of the machine. LLL has proposed to upgrade TMX to test the thermal barrier concept and to modify the MFTF device, at a construction cost of \$111 M, into a major tandem mirror facility with thermal barriers, called MFTF-B.

In addition to the above facilities, the mirror program also includes other areas of research. At the University of Wisconsin, the Phaedrus tandem mirror is used to investigate rf heating and fueling problems. The STM (Symmetric Tandem Mirror) facility at TRW is used to study axisymmetric tandem configurations stabilized by relativistic electron plasmas, based on techniques developed for the ELMO and EBT experiments. Research into basic mirror physics problems, both theoretical and experimental, is conducted at several university and industrial laboratories. As a backup to the tandem approach, the mirror program supports research in the area of field reversal, whereby field reversed plasma configurations are created in (or injected into) mirror traps. This work is pursued in the Beta II facility (reconfigured from 2XIIB) at LLL, and in FRX-A and B at LASL.

The LLL proposal for MFTF-B was independently reviewed from a project point of view by the DOE/SAN, MFTF Project Office (SPO) who issued a report ("Independent DOE Review of MFTF-B Engineering, Cost, and Schedule Baselines", January 1980). With this report information, the 1980 Mirror Senior Review Panel and its technical advisors and consultants met for five days, January 28 - February 1, 1980, at LLL to address the following program questions:

Charge to the Panel

1. Has the mirror program responded to the charge to develop credible technical concepts which have the potential of leading to attractive high- Q fusion reactors? Is the tandem mirror such an approach?
2. Does the tandem mirror concept appear to be confirmed by the experimental data from TMX? Is it timely to initiate a larger tandem mirror experiment now?

3. How close to equivalent DT breakeven is MFTF-B? What will be the impact on the fusion program if MFTF-B performs as proposed?
4. Is MFTF-B an appropriate sized step between TMX or TMX-Upgrade and a DT-burning tandem mirror test facility?
5. Does the Panel wish to comment on the engineering, cost, schedule, etc. presented for MFTF-B?
6. Is MFTF-B as proposed consistent with the conceptual evolution of tandem mirror ideas? Are the risks and benefits of proceeding with MFTF-B as proposed properly balanced?
7. What is the optimum phasing of MFTF-B with the existing MFTF project?
8. Does the Panel recommend proceeding with MFTF-B? If so, with what stipulations and conditions, if any?
9. What recommendations does the Panel wish to make in other areas of the mirror program? Do specific theoretical, experimental, or technology development areas need to be re-directed or strengthened as a result of the Panel's recommendation on MFTF-B?

The Panel's report follows.

II. PANEL FINDINGS

- The mirror program, under the leadership of LLL, has successfully responded to the challenge of finding and developing Q-enhancement ideas which potentially lead to high-Q reactors.
- The Panel commends the LLL team for rapidly achieving successful operation of TMX, attaining the expected physics results, and developing the thermal barrier concept.
- The Panel notes with satisfaction that progress and performance on the existing MFTF project has been excellent, and commends the LLL project team for its performance.
- TMX experimental results, in substantial agreement with expected performance, provide strong evidence for electrostatic reduction of end losses from a tandem mirror configuration without thermal barriers.
- Thermal barriers, when added to the basic tandem configuration, are expected to further reduce the energy losses by a significant amount. The Panel believes the thermal barrier tandem mirror (TBTM) concept represents a major improvement in performance potential beyond the basic tandem mirror.
- Based on LLL calculations, the proposed MFTF-B configuration (with outside thermal barrier A-cells) offers the exciting prospect of suppression of loss cone modes to innocuous levels and, for the first time, the promise of classical electrostatic and magnetic confinement in an open-ended system.
- The performance parameters projected by LLL for MFTF-B are truly impressive. The goals include central cell $n\tau$ values of $5 \times 10^{13} \text{ cm}^{-3} \text{ sec}$, ion temperatures of 15 keV, equivalent D-T Q values of order unity, and 30-second pulse lengths. The Panel believes that the achievement of more modest parameters (e.g. $n\tau \sim 10^{13} \text{ cm}^{-3} \text{ sec}$, $T_{ic} \sim 5 \text{ keV}$) would still be a significant advance, and would justify the Panel's recommendations on MFTF-B.

FINDINGS

- The Panel has considered other options for the mirror program than proceeding directly with MFTF-B, including the completion and operation of MFTF-A and intermediate sized steps between TMX-Upgrade (TMX-U) and MFTF-B. The Panel finds proceeding at this time with MFTF-B to be the best option.
- The testing of thermal barrier physics in an integrated tandem mirror system (TMX-U) is a key experiment for verifying the total TBTM concept.
- Additional diagnostic capabilities are needed for the TMX and TMX-U experiments, and MFTF-B. In particular, the level of diagnostics required for the barrier regions will be similar to that for the plugs. Data acquisition and analysis capabilities may require strengthening.
- The 80 kV, 30-second neutral beam source development program for MFTF-B is highly success oriented and does not allow for major design iterations. It also assumes that the required test facilities, not presently available, will be provided.
- The presently existing 60 GHz, 30-second gyrotron development program is able to develop the needed gyrotrons on the most aggressive MFTF-B schedule. However the production and qualification testing of the required 8 tubes may not be compatible with this schedule.
- A reactor based on the TBTM concept has the potential to achieve high Q, high β , steady state operation at reasonable levels of magnet and heating technology. A further attraction of the TBTM reactor is its possibility for evolving to D-D operation and axisymmetric plugs. The Panel notes, however, that a self-consistent TBTM reactor design is not yet available for review.
- The existing mirror support programs, especially in systems studies and technology development, are not commensurate with the strong technical promise of the TBTM program.

III. PANEL RECOMMENDATIONS

- The Panel recommends that the tandem mirror approach utilizing thermal barriers (TBTM) continue to be the principal focus of the mirror program.
- The Panel recommends that the MFTF-B proposal for rescoping MFTF into a thermal barrier tandem mirror facility in an expeditious fashion be approved, and that DOE seek the required funding and project authorization.
- The Panel generally agrees with the cost and schedule estimates for MFTF-B as proposed by LLL and reviewed in more detail by the DOE/MFTF Project Office (SPO).
- The reversed-field mirror concept combines technological advantages of axisymmetric mirrors with physics advantages from closed-line systems. The Panel recommends continued strong support for this important back-up approach.
- The TMX-Upgrade experiment should be given a very high priority within the fusion program so that experimental verification of thermal barrier performance can be obtained at an early date.
- Additional diagnostic capabilities are recommended for TMX and TMX-U. Beyond techniques now in use on TMX, these capabilities should include time, space and ionization-state resolved spectroscopy, radiometry and x-ray diagnostics for determining the hot-electron distribution, microwave scattering $S(\underline{k}, \omega)$ measurements, and surface-physics measurements for TMX. The inclusion of thermal barriers in TMX-U will increase the diagnostic requirements. Recognizing the urgency to establish a definitive thermal-barrier tandem-mirror experimental data base, the Panel urges that the funding for TMX-U be adequate to (1) enlarge the experimental staff, (2) increase the number of stations for present diagnostics and to introduce new diagnostic techniques, and (3) provide data acquisition and analysis capability commensurate with the increased complexity and sophistication of the required measurements.

RECOMMENDATIONS

- The Panel, recognizing strong benefits to be derived both for near-term TMX and TMX-U operations and for the longer-term MFTF-B applications, recommends that LLL evaluate the immediate integration of MFTF data-acquisition capability with the TMX diagnostic effort.
- The Panel recommends a significant strengthening of technological and scientific support efforts to address needs in key mirror program areas, commensurate with the strong technical promise of this program to produce an attractive fusion reactor.
- Theoretical thermal barrier studies should be extended to include: 1) the three-dimensional nature of the barrier structures and their effects on neoclassical transport, 2) more detailed models for the production and maintenance of the electrostatic confining potential, and 3) start-up scenarios, and be utilized to confirm MFTF-B barrier pumping and ECRH system specifications.
- A significant pre-conceptual design effort on a tandem mirror next step (TMNS) should be initiated as soon as possible.
- The Tandem Mirror Next Step (TMNS) and subsequent mirror reactors will probably require direct energy conversion and negative-ion beams. Methods of electron heating other than ECRH may also be useful. Programs directed to develop these technologies should be put in place or strengthened as required.
- The Panel recommends that, as proposed by LLL, key systems of the existing MFTF project, such as the superconducting Yin-Yang magnet, and selected beams and power supplies, should be completed and tested on the current project schedule to demonstrate these advanced technologies at an early date.
- The Panel recommends not freezing the detailed MFTF-B design, particularly the thermal barrier cell, prematurely, in order to take maximum advantage of theoretical refinements, testing of MFTF components and systems, and preparations for TMX-U experiments.

RECOMMENDATIONS

- Steps should be taken to provide MFTF-B with the required 30-second neutral beam test capability. The Panel suggests that DOE consider the advantages of an arrangement whereby the MFTF-B project management assumes responsibility for the HVTS (High Voltage Test Stand).
- Theoretical and advanced systems studies of the TBTM concept should be increased to support the recommended larger role of mirrors in the fusion program. Particular emphasis should be placed on 1) maximizing beta, 2) improving axisymmetry, 3) developing additional heating and barrier schemes, and 4) considering possible reactor applications of advanced fuels (e.g., D-D).
- Strong support should be continued for axisymmetric TBTM development. This approach is consistent with the existing program approach of minimum-B end plugs and thermal barriers, and offers a potentially important avenue of improvement.

IV. DISCUSSION AND PERSPECTIVE

A. Mirror Experiments

The Tandem Mirror Concept

Loss from a "classical" magnetic mirror plasma-confinement device occurs by collisional drag or by pitch-angle scattering into the loss cone. Electrons scatter much more rapidly than ions into the loss cone, modifying this process. The initial fast loss of electrons sets up an electric potential (the so-called "ambipolar potential"), producing an electric field which reduces electron losses and, simultaneously, increases ion losses, to the point that these two loss rates are equal to each other. This results, for the confined ions, in an enlarged "hole" in velocity-space beyond the pure magnetically-determined loss-cone, and it is this large hole that drives the so called loss-cone microinstabilities which, for years, have afflicted magnetic-mirror confinement experiments.

The principle of the tandem mirror is to partially fill this velocity-space hole for the bulk of the mirror-confined ions. High-density plasmas, mirror-confined at the two ends of the central chamber, create an electric potential which is positive with respect to the central-chamber plasma potential. This potential distribution may be considered the simple consequence of the generalized Ohm's Law for a plasma, taken parallel to $\bar{B}$,

$$E_{\parallel} + (1/n_e e) \nabla_{\parallel} p_e = 0.$$

which, with $\bar{E} = -\nabla\phi$ and $p_e = n_e kT_e$, leads to the familiar Gibbs distribution for an isothermal electron population,

$$n_e = n_0 \exp (e\phi/kT_e).$$

The spatial variation of ϕ in the basic tandem mirror is such as to confine all low-energy ions in the central chamber, eliminating the instability-driving source of free energy formerly represented by the large velocity-space hole. Some of the particles in the high-energy tail will escape over the barriers; however, the central-cell plasma is expected to be essentially stable to loss-cone modes. The price paid for this improvement is, however, difficult magnetic technology and a large beam power required

to maintain the high-density, high-temperature end-plug plasmas.

The TBTM Concept

The "thermal-barrier" development addresses the above problems. The first step of the thermal-barrier solution is to raise the electron temperature in the end plugs, increasing the potential there approximately in accordance with the isothermal Gibbs distribution law. The second step is to reduce electron communication between the end plugs and the central chamber, in order to inhibit rapid thermalization of the two electron populations, now at different temperatures. Again, electrostatic potentials are invoked -- this time by creating a low-density region either between the plug and the central chamber, or beyond the plugs. Referring once more to the behavior indicated by the isothermal Gibbs distribution law, this low density region causes a relative depression in the electric potential, which serves as the desired "thermal barrier".

In bringing about a quantitative test of the thermal-barrier tandem-mirror (TBTM) concept, it is the job of the experimental physicist to first create the desired spatial distributions of electron temperature and ion density. The major tools at his disposal are ultra-high frequency microwave power, for raising the electron temperature, and energetic neutral beams, for controlling the ion density. Injected obliquely to the field lines, the beams can populate a "sloshing-ion" distribution in the barrier regions, and injected nearly along the field lines, they remove trapped ions by charge exchange, thereby acting as "pumps" to decrease the ion density in the barrier region.

The experimentalist's second job is to measure and confirm the results of his efforts. To compare anticipated and actual performance, the experimentalist is called upon to report on measurements of the electron and ion distribution functions, $f_e(\bar{r}, \bar{v}, t)$ and $f_i(\bar{r}, \bar{v}, t)$, and the potential $(\bar{r}, t)$, and also on the plasma parameters, fluctuation frequencies and wavelengths, and radial and axial loss rates for both particles and energy. The complexity of these measurements should not be underestimated. A satisfactory diagnosis of a TBTM experiment will require not only increased data-taking capability using existing techniques, but the introduction of new diagnostics to record, for example, the subtle characteristics of the sloshing-ion distribution, the radial and axial potential profiles, and local values of the electron temperature.

TMX

The present experimental data base for tandem mirror configurations derives largely from the Tandem Mirror Experiment (TMX) at the Lawrence Livermore Laboratory. The Gamma VI experiment is also operating in Japan. The TMX experiment has produced a quasi-steady-state plasma in a tandem mirror configuration. Neutral beams fuel the end plugs and heat the plasma in both the plug and center-cell regions. The following plasma parameters have been achieved under these quasi-steady state conditions:

Table I - TMX Parameters

<u>Parameter</u>	<u>Center Cell</u>	<u>End Plug</u>
$n \text{ (cm}^{-3}\text{)}$	$1 - 3 \times 10^{13}$	$2 - 4 \times 10^{13}$
$T_e \text{ (eV)}$	$140 - 260^*$	$140 - 260$
$T_i \text{ eV}$	$50 - 250$	-
$W_i \text{ (keV)}$	-	$10 - 20$
β	$10 - 20\%$	10%
$n\tau \text{ (cm}^{-3}\text{sec)}$	$3 - 7 \times 10^{10}$	$\geq 2 \times 10^{10}$
$\phi \text{ (V)}$	$200 - 400$	$300 - 700$
$\Delta\phi (= \phi_p - \phi_c) \text{ (V)}$	$100 - 300$	-

* Not yet measured directly.

Here, W_i is the mean plasma ion energy, ϕ is the plasma potential (with respect to ground), $\Delta\phi$ is the potential which confines central cell ions, and the other symbols have their usual meanings.

The TMX data provides quantitative evidence for the tandem mirror concept and strong qualitative support for electrostatic confinement. Four independent observations indicate electrostatic confinement in TMX:

(1) the measurement of $n\tau_c/n\tau_F = 3-9$ during steady-state TMX operation ($n\tau_F$ is the calculated confinement-time parameter for free-flow throttled by the mirror-throat constriction, i.e., the collisional free-flow loss time from a magnetic-mirror bottle; $n\tau_c$ is the measured center cell $n\tau$).

(2) the increase in the escaping axial flow observed at one end following the sudden switch-off of neutral beams into that end cell, thereby dropping the density and eliminating the electrostatic plugging of that end cell,

(3) the change in the energy spectrum of the escaping ions under conditions of (2), indicating the sudden disappearance of the repulsive electrostatic end-sheath, and

(4) the direct potential measurements obtained with the thallium-ion beam probe.

In addition, the improved electron confinement over that in single-cell mirrors has resulted in significantly higher electron temperatures (100 - 260 eV in TMX versus 50-140 eV in 2XIIB).

Comparison of the TMX results summarized here with the performance criteria set forth in the document DOE/ET-0115/1 shows that TMX operation has equalled or exceeded each of the four listed expectations: (1) overall configurational MHD stability, (2) conventional (2XIIB-like) end cell performance, (3) enhanced electron temperatures, and (4) enhanced nT 's (by a factor up to ten) due to the potential barriers.

As in all mirror experiments to date, the existence of a loss cone in the TMX end plugs leads to rf fluctuations, presumably arising from ion cyclotron instability modes, and these fluctuations, in turn, have been observed to heat the central-cell ions in TMX, enhancing their escape over the potential barrier and degrading plasma confinement somewhat. TMX-Upgrade is predicted to operate without such microinstabilities, which is the most direct way of overcoming the problem.

TMX-Upgrade

The incorporation of thermal barriers with the tandem mirror concept is proposed to be first tested in the TMX-Upgrade (TMX-U) facility and will represent a significant advance in the performance potential of mirror systems. Modification of TMX into TMX-U will include:

- a. Addition of A-cells, involving three or four new magnet coils, together with the physical extension of the vacuum chamber on each end by approximately three meters.
- b. ECRH power for electron heating at the barriers: 800 kW @ 28 GHz and 100 kW @ 14 GHz.
- c. ICRH power for central-cell heating: 0.5 - 1 MW at about 1 MHz.
- d. Rearrangement of the existing neutral beams (16 sources @ 20 kV, 8 sources @ 40 kV).
- e. Added diagnostics.

Goals of the TMX-U experiment include: setting up the thermal barriers using ion pumping and ECRH; investigating the microstability of the plug and

outer A-cell; studying the MHD stability of the barrier-tandem configuration; investigating electron heating of the outer A-cell; investigating the establishment of an electron temperature difference across the thermal barrier region; and investigating the establishment of sloshing trapped ions in the barrier region. The minimization of magnetic field errors in TMX-U may require careful alignment of the various magnets. TMX-U will incorporate new concepts (thermal barriers, ECRH, sloshing-ion populations, and barrier pumping) which will require both the extension of present techniques and the addition of new diagnostics to determine the physics of the TBTM configuration. The question of beta limits in a tandem mirror is an important issue, in view of the relatively low (20%) beta values which TMX has thus far achieved. An early test of β limits should be an explicit part of the TMX-U experimental plan. The timely implementation of the TMX-U experiment will provide important confirmation of the barrier-tandem concept and should impact the operation of the MFTF-B device. The Panel recommends that a very high fusion program priority be given to this important experiment.

The TMX-U proposal is still in preparation, and the performance parameters are still somewhat tentative. At the time of the review, the plasma parameters projected by LLL for TMX-U were as follows:

Table II - TMX-U Tentative Parameters

<u>Parameter</u>	<u>Center Cell</u>	<u>End Plug</u>	<u>A-Cell</u>
$n \text{ (cm}^{-3}\text{)}$	4×10^{13}	1.5×10^{13}	1×10^{13}
$T_e \text{ (keV)}$	1.0	-	-
$T_i \text{ (keV)}$	1.0	-	-
$W_i \text{ (keV)}$	-	20	30
$n\tau \text{ (cm}^{-3}\text{sec)}$	$2 \times 10^{11} - 10^{12*}$	$\leq 1.8 \times 10^{12}$	2×10^{12}
β	0.36	0.7	0.1
$\phi \text{ (kV)}$	4	4	6
$\Delta\phi (= \phi_A - \phi_C) \text{ (kV)}$	2	-	-
$r_{\text{plasma}} \text{ (m)}$	0.15	-	-
$L \text{ (m)}$	5.5	-	-

*(Footnote to Table II: The "end-loss" $n\tau$ will be increased to $\sim 10^{12}$ cm^{-3} sec in TMX-U. Radial losses, which aren't well calculated, could degrade $n\tau$. TMX-U magnet modifications to reduce radial loss effects are under consideration.)

The question of radial losses is a critical one for tandem mirrors, and should be tested as soon as possible. TMX-U is not ideally suited for such measurements because of its small size and short pulse lengths. TMX-U (and TMX) can achieve somewhat longer pulse lengths by serially turning on the 25-msec beams. The limit, determined by vacuum pumping requirements, is ~ 100 msec.

Most of the TMX-U plasma parameters will be increased significantly in the follow-on MFTF-B device, in which plasma in the long central chamber will be in the collisionless reactor regime. MFTF-B is much better suited to radial loss studies than in TMX-U, particularly in view of its longer (multisecond) pulse lengths. The central plasma ion temperature and n , and the barrier potentials will be increased in MFTF-B by more than an order of magnitude.

MFTF-B

The achievement of the expected performance in TMX, and the development of the TBTM concept has resulted in the proposed conversion of the single-cell MFTF device into a thermal-barrier tandem mirror facility, MFTF-B. Utilizing the equipment and materials now under construction for MFTF, the MFTF-B facility could be completed in 1983-1984. The Yin-Yang magnet and vacuum vessel for MFTF will provide one end plug; a duplicate end plug will be constructed for the other end of MFTF-B. A new 30-m length solenoid will form the center cell in MFTF-B. Anticipating the possible conversion of MFTF into a tandem mirror, LLL, in concert with DOE, has already made modifications to MFTF which allow for an orderly transition. Conversion at this time permits effective scheduling and integration of the tandem features into the facility at minimum cost.

Thermal barriers, which should significantly reduce both the end-plug technology requirements and the power input needed to maintain the "potential well" for ion confinement in the solenoid, are an essential feature of the MFTF-B design. MFTF-B will use 30-sec 80-kV neutral beams in the end plugs and A cells: one in each plug, one in each A cell, two as "pump" beams, and one in the center cell. Other 80-kV beams with 0.5-sec duration will be utilized to establish and heat the plasma during startup.

In addition to the long-pulse beams, thermal-barrier operation will also require ECRH (~ 0.8 MW per plug) to heat the end plug and barrier electrons.

The parameters projected by LLL for MFTF-B are given in Table III.

Table III. MFTF-B Parameters

<u>Parameter</u>	<u>Plasma Parameters</u>		
	<u>Center Cell</u>	<u>End Plugs</u>	<u>A-Cell</u>
n (cm^{-3})	2.1×10^{13}	5.5×10^{13}	7.0×10^{12}
T_e (keV)	9	-	-
T_i (keV)	15	-	-
W_i (keV)	-	84	80
β	0.2	0.4	0.3
$n\tau$ (cm^{-3}sec)	5.2×10^{13}	1.2×10^{13}	1.0×10^{13}
ϕ (kV)	50	59	78
$\Delta\phi (= \phi_A - \phi_C)$ (kV)	28	-	-
r_{plasma} (m)	0.56	0.40	-
L (m)	~ 34	-	-

Magnet Parameters

A-cell C-coils:

Field at the coil = 8 T

Mirror ratio = 6.5:1

Barrier well field = 1.0 T

Yin-Yang plugs:

Midplane field = 2 T

Mirror ratio = 2

Mirror field = 4T

Max field at winding = 7.7T

$L_{\text{mirror to mirror}} = 3.6$ m

Transitions:

Field at the winding = 3.5 T

Center cell:

Field = 1 T

Length = 30 m

Overall machine length between plug midplanes = 40 m

Other Experimental Considerations

A-Cells

The A-cell thermal barrier design offers a possible solution to the mirror physics problem of microstability in the end plugs. Achievement of microstability with the thermal barrier would allow the central cell and end plugs to operate with virtually no loss cone, and should allow the attainment of axial loss $\sim 10^{12} \text{ cm}^{-3}\text{s}$ at 1 keV in TMX-U upgrade, and breakeven conditions in MFTF-B. The A-cell itself is effectively stabilized by the existence of the sloshing-ion population and residual streaming losses. With improved neutral beams based on negative ions and possibly augmented by ICRH, MFTF-B has the potential capability of achieving Q-values greater than unity. In preparation for steps beyond MFTF-B, ideas and developments to improve the historical baseball and Yin-Yang end-plug designs should be pursued, including axisymmetric designs that promise simpler construction, reduced radial transport, and higher center-cell beta values.

Auxiliary Heating

Efforts have begun in the Mirror Program in the area of auxiliary heating, at LLL, the University of Wisconsin, TRW, SAI, and Yale University. These efforts include experiments on ECRH at LLL and TRW, and ICRH at Wisconsin. The Panel recommends that LLL expand its own efforts in this area. It would be desirable to increase LLL and other laboratory experimental and theoretical staff in the RF heating area in order to investigate the application of RF to TMX-U and MFTF-B in more detail. RF heating methods beyond the currently proposed techniques of ICRH and ECRH (e.g. lower hybrid) should be rapidly explored.

Diagnostics

The present TMX experiment has a fairly complete set of diagnostics which has been capable of establishing the macroscopic parameters and RF fluctuation levels. This diagnostic set has established a credible data base for the tandem mirror concept. However, the Panel feels that significant further development in the diagnostic and data acquisition area is fundamental to the establishment of a definitive data base for tandem mirrors with thermal barriers. TMX-U will require a near doubling of the number of diagnostics if the barrier is to be characterized in fine detail. Such an increased number of diagnostics will add significant new demands on the

diagnostic computers. It is essential that funding be provided to meet these needs. Areas where the Panel feels new diagnostic capabilities should be added are outlined below.

1. Spectroscopy - significantly increased capability is required.

These diagnostics should be capable of measuring time, space and ionization-state resolved impurity concentrations and impurity confinement times, ExB rotational doppler shifts and radial electron temperature profiles. X-ray spectroscopy capable of analyzing hot electron populations will be fundamental to TMX-U and MFTF-B.

2. Potential Measurements - Although a heavy ion beam and light ion beam were designed for TMX, only minimal data has been provided by these diagnostics due to technical difficulties. High priority should be placed on these diagnostics to guarantee their availability for TMX-U and their continued improvement for MFTF-B.

3. Scattering Measurements - Livermore has used microwave scattering for ion cyclotron fluctuation measurements. However, significant further work is required in this area. In the end plugs the spectral density $S(\underline{k}, \omega)$ should be measured over all relevant values of $\underline{k}, \omega$ to give detailed comparison between theory and experiment. Ion cyclotron fluctuations are not eliminated in TMX but rather a marginal stability is achieved in which velocity space diffusion is reduced to tolerable levels. A detailed understanding of the marginal stability level would be most helpful, even if future mirror machines are microstable. It is also desirable to extend scattering measurements up in frequency to the electron plasma frequency. The need to carry out scattering in the barrier region will add to the demand for these measurements. Collaboration with the Bell Laboratory group for such measurements is strongly recommended.

4. Plasma-Surface Interactions - In view of the fundamental role of plasma-surface interactions in fusion experiments, the Panel recommends that LLL establish a surface physics group, as has been done in the major tokamak laboratories.

5. Radiometry - A radiometer is under construction for T_e measurements in TMX. This measurement will be increasingly important when barriers are installed in the TMX-U. Stability of the barrier electron velocity distribution will set limits on the maximum attainable potential confinement. Radiometry is well suited for analysis of both stable and unstable electron populations.

6. Impurity Injection - Injection of impurities is now an established diagnostic method for tokamaks. Such diagnostics can shed light on electrostatic confinement of impurities (and alpha particles in D-T plasmas).

7. Magnetic Field Measurements - Accurate magnetic field alignment techniques need to be developed for TMX-U. This work needs to be factored into the MFTF-B design at the earliest possible time.

Only limited information on MFTF-B diagnostics was presented as a part of the MFTF-B proposal. Additional diagnostics will presumably be funded from the operating budget. In order to assure that a full data base on MFTF-B will be generated as early as possible, it is desirable to integrate the diagnostic development between TMX-U and MFTF-B. The possibility of using MFTF-B computers for TMX data acquisition and analysis should be pursued, as it could assist both programs. It may also be desirable to integrate the TMX-U and MFTF-B diagnostic teams.

B. Mirror Theory

The new physics features incorporated in the MFTF-B design with thermal barriers are intended to decrease substantially the plasma end losses and thereby increase Q to reactor-relevant values. The proposed device also has the potential to minimize or eliminate loss-cone instabilities and the associated detrimental influence on confinement properties. Implementation of the thermal barrier concept will make use of several interrelated classical processes occurring simultaneously: barrier pumping with neutral beams, potential well and hill formation by ECRH and oblique neutral beam injection, and a high degree of thermal isolation of various classes of particles distributed nonuniformly along the magnetic field. Although extensive preliminary theoretical investigations have been made, only a limited experimental data base exists which establishes the nature of the individual basic effects, and semi-quantitatively verifies the magnitude of the effects in the parameter range of interest to MFTF-B. In addition, the various processes (which are required to be mutually supportive), are highly coupled in the MFTF-B scenarios. Nevertheless the Panel believes that the implications of full microstability in the tandem mirror configuration are so profound for mirror fusion systems that a commitment to MFTF-B should be made now to explore the thermal barrier concept at reactor-grade plasma conditions. In this regard, particular emphasis should be placed on the following physics items:

- Further theoretical analysis, together with experimental verification of the mostly classical processes underlying the thermal barrier concept, including detailed quantitative measurements and scaling experiments which can be used to verify the theory.
- Continued investigation of loss-cone and pressure gradient-driven microinstabilities (drift-cone, drift-cyclotron, Alfvén ion cyclotron, axial loss cone, etc.), including means of suppression or at least reduction to a negligible scaled level.
- Optimization of the overall magnetic configuration to determine the maximum plasma beta stable against MHD instabilities, e.g. those of the ballooning type.

In addition, in order to continue optimization of the TBMT concept, the Panel recommends that continued emphasis be placed on the following critical theoretical research problems:

1. The physics of thermal barriers should be developed in greater detail. The analysis needs to be fully three dimensional, but is presently only one dimensional, namely, with variations along the magnetic field lines. Consideration should be given to the radial and azimuthal variation of the ambipolar potential, and the attendant effects on radial transport and the axial thermal isolation feature of the barrier. The azimuthal variation could lead to radial mixing caused by the greater lack of omnigeneity in some of the cells and thus limit the magnitude of the ambipolar potential "hill" in the thermal barrier by radial "short-circuiting" of the barrier to some degree. Also, collisional (and perhaps collective-instability-induced) relaxation of the anisotropic electron and ion distribution functions needs to be investigated in greater detail to determine accurately the minimum power requirements for maintenance of the thermal barrier.
2. The electron cyclotron resonance heating (ECRH) processes utilized to form and maintain an anisotropic electron distribution function, self consistent with the electron axial thermal isolation, should be explored in greater detail. The Panel has some concern over the radial power deposition and ultimate power required to maintain the thermal isolation characteristics of the thermal barrier, particularly in the transient startup phase and in the face of diffusive relaxation of the anisotropic electron and ion distribution functions and possible nonideal effects. Alternatives to ECRH in forming the thermal barrier should continue to be investigated.
3. High Q and microstability are the anticipated main advantages of the present MFTF-B design. It is important that microstability studies continue, including investigations of possible new instabilities due to the mixed populations in various regions. Consideration should also be given to studies of the sensitivity of the interrelated plasma components to low level RF excitations.
4. Alternative barrier pump schemes should be carefully considered. Clearly it would be desirable to avoid the inefficiency of the neutral beam pumping method and minimize the associated vacuum technology needs.
5. Low-frequency stability studies for optimizing the central cell beta, the magnetic configuration, and subcell ordering along the tandem axis should continue. Included in the ongoing research should be appropriate consideration of the influence of the parallel electric

field, trapped particles, ion bounce resonance in the thermal barriers, and finite Larmor radius effects for both high azimuthal mode numbers (eikonal approximation) and the 2-D consideration more appropriate to lower azimuthal wave numbers.

6. Consistent with the low frequency stability results, the (neo)classical transport studies should include finite-beta effects and possible azimuthal and radial variations of the ambipolar potential and Yushmanov (combination magnetic and electrostatic) trapped particles. Considerations should include the effects of non-omnigenous radial mixing effects on end losses.

7. Extensive modeling studies of the combined stability and transport elements in the various cells with the appropriate heat and particle sources should be carried out to define the expected Q more accurately and to optimize the operating scenario.

8. Impurity control, while seemingly only of limited concern to MFTF-B but of greater concern with regard to helium ash removal in a reactor, should be self consistently considered along with the radial and end loss models. Impurity accumulation resulting from high injected beam power, startup effects including initial plasma trapping, and the existence of electrostatic potential wells, should be studied with the best power and particle flow models available.

C. Technology and Reactor Aspects

It has long been recognized that single cell mirror systems with Q values in the range 1-2 lead to generally unattractive fusion reactor designs. The development of the basic tandem mirror concept provides a more promising reactor, but requires advanced technologies: magnetic fields of 15-17T, and hundreds of megawatts of 350-1200 keV neutral beam heating power.

The introduction of thermal barriers into a tandem system has lowered substantially the technological requirements and at the same time offered the possibility of a microstable mirror system and even the possibility of ignition in the central cell. This evolution in reactor studies, illustrated in Table IV below, is still continuing:

TABLE IV. Improvements in Tandem Mirror Reactor Designs

	A. First TM Design (1976)	B. Improved TM Design with direct elec- tron heating	C. Thermal Barrier Design with A-cells
Q (plasma)	4.8	10	18
Neutral beam energy, keV	1200	350	150
Max. magnetic field, T	17	15 to 17	14 to 16
Central cell length, m	100	320	125
Neutral beam power, MW	530	42	107
Direct electron heating, MW	0	250	92
Central cell beta	0.7	0.7	0.5
Fusion power, MW	2500	3000	3500
First wall loading, MW/m ²	2.0	1.3	2.6

The Panel notes that, although the thermal barrier reactor design in column C above assumes a beta value of 50%, present MHD theory for that specific magnetic field design indicates a central cell beta limit perhaps as low as 20%. A beta limit higher than 20% will be required for the

realization of an attractive TBTM mirror reactor. Such an improvement may come about through other magnetic field designs or changes in theoretical understanding of the present designs.

As shown in Table IV the overall neutral beam requirements have been substantially reduced but the power levels are such that high efficiency systems are still necessary. This need and the desirability of monoenergetic high energy beams strongly suggests the use of negative-ion systems. Negative ions are projected for use in the mirror program, and might first be used in an eventual upgrade of MFTF-B. The development of practical direct conversion techniques will probably be required for TMNS and subsequent machines. A significant experiment ($\geq 1 \text{ MW}_e$) on direct conversion should be considered for MFTF-B. The Panel, therefore, recommends that development programs for direct convertor and negative-ion beam technology be supported at a reasonable level.

There are several potential improvements to the present TBTM reactor embodiment which appear meritorious for investigation in future reactor studies. The LLL reactor designs do not seem to capitalize on the basic simplicity of the tandem configuration, especially with regard to their complex blanket design choices. Axisymmetric end plugs, which are stabilized by hot-electron plasmas, higher betas, or other techniques, may lead to reduced radial transport losses, and higher Q, and allow circular, lower-field magnets. Axisymmetric TBTM concepts are compatible with the existing program approach of using minimum-B end cells, and should continue to be pursued. The TBTM conceptual approach also incorporates some basic features which appear well suited to eventual D-D operation: possibility of direct conversion of charged reaction products, high ion temperatures, lower electron temperatures, and high beta in the reacting volume.

The Panel notes in passing that the evolution of mirror confinement concepts has been driven in large part by the recognized need for a more attractive reactor design. The present level of support for mirror systems studies and technology development does not seem commensurate with the strong technical promise of the TBTM program.

Support Technology

The Panel does not find any serious technological impediments to the ongoing TMX or upcoming TMX-U experiments.

Much of the technology required for MFTF-B is already in hand due to the advanced state of the existing MFTF project. It appears that only two critical technological developments remain, i.e., 30-second neutral beam sources and 30-second, 60 GHz gyrotrons. The Panel strongly recommends, however, that LLL's proposal to test the superconducting Yin-Yang magnet, selected neutral beam sources and power supplies, and other technologies developed for MFTF, be followed, and that information from these tests be factored into MFTF-B project planning.

The multisecond 80-kV beams proposed for MFTF-B will require actively cooled grids in the source and actively cooled dumps on both the beam lines and the main device. Test facilities for developing these beams must be provided. Beyond the near term need for developing the 30-second beams, there may be a further need in the longer term for a committed test facility for servicing and conditioning the nearly 50 neutral beams which MFTF-B will incorporate. The cost of adding the required beam dump to HVTS appears relatively small, and the Panel suggests this facility be considered if stray magnetic fields (e.g., from MFTF-B) are acceptable.

The 60 GHz gyrotron development program, with the EBT program needs providing a strong driver, appears at this time to be on its way toward a completion date generally consistent with the MFTF-B schedule. However, the Panel is concerned that the demands on gyrotron tube production in the 1984 time frame from EBT, tokamaks, and other mirror programs will not be satisfied unless plans are made and steps initiated in 1982-1983 to ensure that adequate production and qualification testing capability is available to meet the needs of the entire fusion program.

Steady state vacuum pumping for the 30-second MFTF-B pulses represents a technology requirement not encountered before in fusion experiments, but extrapolation of the cryopanel design used in MFTF indicates the pumping speed will be maintained for that period of time or longer. However, the higher gas loads will result in more frequent regeneration conditioning, perhaps as often as every few days, assuming a 30-second run every five minutes, two shifts per day, each day.

D. PROGRAMMATIC CONSIDERATIONS

The Panel examined several options for the mirror program other than the recommended one of converting MFTF to MFTF-B at this time. Less expensive and less aggressive options were examined to see if these might be in the best interest of the mirror program, or fusion generally, but the Panel did not find this to be the case.

The Panel discussed options which were alternatives to the TBTM strategy, such as field reversal, axisymmetric configurations, waiting for new inventions, etc. Based on the significant technical lead and promise that the TBTM strategy offers over the others, it quickly emerged as the most rational approach.

With respect to the time relationship between MFTF-B results and Tandem Mirror Next Step (TMNS), the Panel concluded that because the potential impact of thermal barriers upon mirror reactor designs is so significant, the mirror program should take steps to develop a sustained momentum through and beyond MFTF-B in order to realize the full reactor potential of mirrors. While no direct competition with tokamaks is intended, it will be necessary to instill a sense of urgency in the mirror technology support efforts as well as the construction project, in order to keep the mirror program strongly focused on achieving its reactor potential.

Six programmatic options considered by the Panel were:

1. Complete MFTF and TMX-U, then go directly to a DT experiment (TMNS).
2. Design and build a new, optimized TBTM experiment which would be smaller than the proposed MFTF-B. MFTF could be completed and operated separately, or the vessel and magnet set could be scrapped, perhaps salvaging the NbTi superconductor.
3. Complete MFTF-B as a simple tandem mirror without thermal barriers.
4. Complete MFTF and TMX-U. Then proceed with MFTF-B if results are positive. (TMX-U will operate in early 1982).
5. Proceed with MFTF-B, but delay any decisions on the barrier design until TMX-U results are available.
6. Proceed with MFTF-B, testing MFTF technology and maximizing the inputs from TMX-U experimental preparations and theory, but do not delay critical design decisions.

The first option was discarded because the parameters achievable in MFTF and TMX-U were judged by the Panel as not sufficient to commit to a D-T reactor step that could cost well in excess of \$500 M. Also, the MFTF

physics objectives of testing various means of stabilizing microinstabilities in a large mirror cell are not as relevant for a TBTM, especially one with a nearly filled loss cone, as would be similar experiments in a more reactor-like geometry. Because of its relatively small size, TMX-U cannot explore adequately the scaling laws for microstability in the end regions, or radial transport in the solenoid. As a single cell, MFTF could address some aspects of the microstability problem, but not radial transport, which requires a tandem geometry.

The second option was examined in detail by LLL prior to selecting their proposed MFTF-B approach. Cost estimates were completed on a system with end plug magnets approximately one half the size of those in MFTF-B with a solenoid length of approximately 25 meters. It was assumed that MFTF power supplies, controls and other support equipment could be utilized. The cost of the new machine turned out to be within 10% of the cost of MFTF-B and the physics performance was significantly lower. The Panel concurs with LLL that this is not a cost effective option.

Option three was judged not to be attractive because the total cost would still be substantial (~\$80M PACE) and the performance would not be greater than that of TMX-U with thermal barriers. The Panel concluded that such modest performance was not worth the large cost, and the results would in some ways be redundant to those from TMX-U.

The fourth option would be the lowest overall risk, but would be very costly in both funding and lost schedule time. As noted above, the evolution of the TBIM system makes physics operation of the single cell MFTF less critical than when it was originally proposed. MFTF operation, therefore, represents an expenditure of time and resources that could be better utilized otherwise, except that MFTF technologies would be demonstrated. If a decision to proceed with MFTF-B were delayed until MFTF and TMX-U provided definitive results (mid FY82 or later for TMX-U, mid FY83 or later for MFTF), MFTF-B operation would be delayed by three years or longer, and the total program cost would be much higher. Added escalation costs alone would amount to \$25-35 M, and the lost momentum would be severely damaging to the mirror program.

Option five is similar to, but slightly less severe than, option four. Certain MFTF-B modifications would proceed, but major portions of the design would be placed "on hold" until definitive TMX-U results were available, delaying barrier coil design work by 15-21 months. As the barrier coil

system is the critical path item with little or no schedule margin, the MFTF-B completion date would slip by a similar amount. Escalation costs would add \$15-20 M and the less optimized manpower loading for the slowed project would add additional costs. The Panel concludes that this approach is not desirable for the above reasons, and because in any case the magnet design of MFTF-B will probably not be affected by TMX-U results.

Adjustments in ECRH and beam power might, however, be indicated by TMX-U, and could be accommodated by the MFTF-B design approach.

The sixth option offers the lowest cost approach for obtaining reactor-level plasma performance in a TBTM system. Since many of the classical processes required for successful plasma operation have already been demonstrated in some degree, the technical risks associated with proceeding with MFTF-B are judged acceptable. Depending on the detailed schedule, there is up to one year to "factor in" new experimental and theoretical results before the magnet design for MFTF-B is frozen, and the details of the ECRH and neutral beam power locations can be finalized even later. The technologies which are considered highest risk on MFTF (namely the superconducting magnet and the neutral beam system) can and should be tested on essentially the original MFTF schedule, to confirm the technical approach on these systems before major MFTF-B costs are incurred.

The Panel members and the technical advisors were of the unanimous opinion that LLL's proposal to convert now to MFTF-B offered an acceptable level of technical risk, the most rapid path to obtaining reactor-level plasma data upon which a D-T TMNS step can be based, and the lowest overall program cost, and is therefore the correct option for the program.

Development Needs

Turning to project-related development issues, the Panel notes that the excellent success of MFTF in staying within cost and schedule is largely due to the strong project discipline and leadership of the MFTF project managers. To ensure continued success as MFTF evolves into MFTF-B, it is highly desirable to give the project management a large measure of control over sub-system developmental programs and their associated test facilities. The key technology issues related to MFTF-B are the 80 kV, 30-second neutral beams and 60 GHz, 30-second gyrotrons. Each of these is addressed below.

1. Neutral Beams

Development work sponsored by D&T is now underway at LBL on water-cooled ion sources which are required for 30-second operation. This is a

significant development task, and almost all experience to date is on short pulse sources. Also, full development of water-cooled sources requires a test stand capability which does not now exist. As part of any commitment to proceed with MFTF-B, a commitment to provide such a stand must be made. The schedule for completing all the required development, including testing, possible prototype fabrication by industry, and production of final sources is judged to be very tight on LLL's proposed end-of-FY 1983 MFTF-B completion date. For later completion dates, the beam work can be accomplished more easily. Another development task is that associated with beam dumps for 30-second operation, but this is judged less difficult than the water-cooled sources.

Once MFTF-B comes into operation, a test facility may be needed for repair, maintenance, upgrading, and conditioning the numerous neutral beam sources in use. With nearly 50 beams involved, if each source fails on the average only once per year, one beam per week will need to be repaired and reconditioned.

In the Panel's opinion, the neutral beam development conditioning issue is a key one for the Project, and responsibility for its resolution should rest with the MFTF-B project management. The Panel suggests that LLL and DOE evaluate this matter, and consider the possible advantages of designating HVTs as a committed facility for MFTF-B.

2. Gyrotrons

A D&T sponsored program is now underway to develop the required 60 GHz tubes. The successful development of these tubes will require added test stand capability. Although the development of the required tubes may be compatible with the most rapid schedule proposed by LLL, it is not clear to the Panel that the production and subsequent qualification testing of the required eight tubes for MFTF-B can be accomplished without additional test stand facilities and more time for tests.

The Panel also suggests that, due to the present unreliable nature of developmental gyrotrons, a dedicated gyrotron test stand be made available somewhere to meet the needs of the fusion program in training staff, developing and testing wave guide components, and maintaining and repairing the tubes.

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APPENDIXPosition Statement of the FPCC on the
EBT-P and MFTF-B Projects

The FPCC has considered the issue of starting two new major facilities for the fusion program: the proof-of-principle facility EBT-P, and the thermal barrier tandem mirror facility MFTF-B. The total line item construction costs estimated for these facilities are \$85M for EBT-P and \$111M for MFTF-B. These costs and the associated R&D activities are to be spread over several fiscal years. Funding to initiate both projects exists in present budgets and the base planning projections of DOE; owing to overall budget constraints, however, there may be shortfalls in 1981 and 1982 compared to optimum project funding profiles.

The FPCC notes that both the EBT P and MFTF-B project proposals have undergone intensive peer reviews and have received strong technical endorsements. Both projects represent timely, logical extensions of carefully formulated program plans in their respective areas. Both projects are supported by aggressive experimental and theoretical activities which are funded in the present program. Furthermore, considerable momentum has been established for both projects. Both can, in a sense, be considered as continuations of on-going efforts: EBT-P is a congressionally authorized and funded project in FY 1980 and FY 1981, and MFTF-B represents an upgrade and rescoping of the MFTF project also funded in FY 1980 and FY 1981.

In view of the above, we, the FPCC, consider the performance goals of these two projects to be impressive and supportive of the Department of Energy's policy for the development of an optimum fusion system. We conclude that continuation of both these efforts is in the best interest of the national fusion energy program.

The FPCC endorses both projects and recommends that the required additional funding be sought to keep these projects as near to the proposed optimum schedules as possible.

February 13, 1980

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Wednesday, February 13, 1980

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