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AN MFTF-B UPGRADE FOR BLANKET-
TECHNOLOGY TESTING

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INTRODUCTION

Based on preliminary studies at Lawrence Livermore National Laboratory (LLNL), we believe the Mirror Fusion Test Facility (MFTF-B) could be upgraded for operation in a hot-ion "Kelley" mode in a portion of the central cell to provide fusion nuclear engineering data, particularly blanket technology information, by the end of the decade.* Cost of this mode of operation would be modest compared with that of the other fusion devices considered in the last few years for such purposes.

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*We wish to acknowledge the help of many people in carrying out this preliminary assessment: J. Osher and R. Campbell (operating scenarios); R. Bulmer and L. Pedrotti (magnet configurations); G. L. Kulcinski, J. Maniscalco, and J. Gordon (nuclear fusion testing); and S. Muelder (activation study).

With high density operation over a 5.6-m-long portion of the central cell, the MFTF-B Upgrade would yield 13 MW of fusion power in a 30-cm-diam plasma column. This would produce a steady 1.3 MW/m^2 of neutron flux on a 50-cm-bore surface of 7 m^2 for up to 10 hrs; one to two runs per month could be made without creating problems due to activation of the machine. With individual runs lasting 1 to 10 hrs, we could test both the thermal-hydraulic features of blankets and reach equilibrium concentrations of tritium in liquid-metal blankets. Tritium recovery from the blanket as well as from the unburned fuel could also be demonstrated in the facility.

The intense neutron source in the central cell is caused by the high density ($\sim 4 \times 10^{14} \text{ cm}^{-3}$) and high temperature ($\sim 49 \text{ keV}$) operation of MFTF-B Upgrade. To support this high density, we would increase the central-cell field to 4.5 T ($< 8 \text{ T}$ at the conductor) over the 5.6-m length by adding a pair of superconducting coils. The four axicell coils would be eliminated from the present MFTF-B axicell configuration. In addition, we would add two copper-alloy choke coils to produce 12-T mirror peaks at each end of the 5.6-m section. These coils will throttle plasma flow to the plugs, thus lowering the density to $\sim 10^{13} \text{ cm}^{-3}$ at each yin-yang anchor. The transition regions between the anchors and choke coils would have to be pumped to maintain the low density and potentials there.

Figure 1 shows the magnetic configuration and profiles of magnetic field (B), density (n), and potential (ϕ) of MFTF-B Upgrade. With the removal of the axicell coils, the solenoids would be moved towards the ends of the central cell to fill the old transition region and leave room for a central test section consisting of the two superconducting and two resistive coils. Table 1 lists the pertinent physics parameters for this upgrade, and Table 2 lists certain engineering parameters describing the facility.

Figure 2 depicts both the shielded center test section, the two beamlines needed to heat and fuel the central cell, and the 1-m-long removable test blanket section. Figure 3 illustrates the hot cells, which are provided where neutral-beam modules are to be removed for repair, the tritium processing area, and the general layout of the facility.

Contact maintenance will be possible at the vacuum vessel boundaries, according to preliminary calculations. Using a three-dimensional model of MFTF-B and the surrounding concrete vault, Muelder¹ has modified his Monte Carlo code for calculating neutron effects to include the shielding for the

Figure 1. Profiles of magnetic field strength (B), density (n), and potential (ϕ) in the proposed MFTF-B Upgrade facility for blanket technology testing.

Table 1. Physics parameters for the MFTF-B Upgrade facility for blanket technology testing.

Parameter	Value
<u>Central cell</u>	
Plasma length (m)	5.6
Plasma radius (m)	0.15
Solenoid field (T)	4.5
Peak beta	0.4
Electron temperature (keV)	6.2
Hot-ion average energy (keV)	49
Hot-ion lifetime (ms)	42
Hot-ion density (cm ⁻³)	3.8×10^{14}
Warm-ion temperature (keV)	9
Warm-ion density (cm ⁻³)	3.8×10^{13}
Beam voltage (kV)	80
Trapped beam power (MW)	16 (267 A/60 keV)
Fusion power (MW)	13
Neutron wall flux (MW/m ²) at R = 0.25 m	1.33
Potential, ϕ_e (kV)	37
<u>Choke/Transition region</u>	
Field at choke, $B_{\max}$ (T)	12
Plasma length (m)	14.6
Field at midplane (T)	1
Pumping beam current (each end)	50 A @ 50 kV
Injection angle, θ	$\sim 25^\circ$
Potential, ϕ_T (kV)	~ 27
<u>Anchors</u>	
Plasma length (m)	5.2
Plasma radius (m)	0.32
Plasma density (cm ⁻³)	$\sim 10^{13}$
Field at mirror (T)	3
Field at midplane (T)	1
Potential, ϕ_A (kV)	~ 18
Sloshing neutral beams (each end)	7 A @ 80 kV
Trapping fraction, F_T	0.34
ECRH ^a (each end)	~ 140 kW @ 35 GHz ~ 700 kW @ 28, 56 GHz
Hot electron energy (keV)	~ 285
Electron temperature (warm), T_e (keV)	22
Potential, ϕ_c (kV)	10.8
Pumping/beam current (each end)	5 A @ 60 kV

^aECRH = electron-cyclotron resonant heating.

Table 2. Parameters for MFTF-B Upgrade.

System	Value
<u>Overall</u>	
Type of operation	Continuous
Full-power-run length (hr)	10
Availability (% life average)	1
Year of operation	Late 1989
<u>Plasma</u>	
Length of central cell (m)	5.6
Radius of central cell (m)	0.15
Peak beta	0.4
<u>Test zone</u>	
First-wall radius (m)	0.25
Neutron wall load (MW/m ²)	1.33
Area available (m ²)	7
Heat load (W/cm ²)	10 to 50
Fusion power (MW)	13
<u>Tritium</u>	
Consumption rate (gm/hr)	0.07
Throughput (gm/hr)	35
Inventory (kg)	0.3
<u>Vacuum</u>	
Base pressure (Torr)	5×10^{-7}
Total pump speed (L/s)	1.2×10^8
<u>Magnets</u>	
<u>Superconducting</u>	
Material	NbTi
Peak conductor field (T)	<8
Peak center field (T)	4.5
<u>Resistive</u>	
Material	Cu alloy
Peak center field (T)	12
<u>Neutral beams</u>	
Mode	Continuous
Voltage (max) (kV)	80
<u>Power</u>	
Central cell (MW)	16
Pumping (MW)	5.4
Sloshing (MW)	0.9
<u>Wave Heating</u>	
Type	ECRH
Frequency (GHz)	35/60
Power (MW)	1.7

Figure 2. The MFTF-B Upgrade machine, showing the shielded central-cell test section, shielded beamlines, and vault.

Figure 3. Upgrade options for maintenance--neutral-beam hot cells, module service area--and the tritium processing area.

center section. He calculates that after a 10-hr run, the radiation levels will be only a few millirem/hr at strategic locations.

Ninety percent of the central-cell ions are magnetically confined between the 12-T mirror peaks, and this hot-ion component is responsible for the intense neutron production. The remaining 10% warm-ion background confined between the potential peaks in each anchor fills the loss cone of the mirror-confined hot ions and provides their microstability. Ion distributions in the anchors are microstable according to the calculations used in designing MFTF-B^{2,3}; therefore, stability by stream flow is not necessary. As a result, the central-cell electron temperature is relatively higher (6.2 keV), and the hot-ion lifetime is fairly long (42 ms). Thus, the hot-ion temperature is not substantially less than the mean energy of the central-cell beams. Because these beams provide all the particles for fueling the machine, half use deuterium and half use tritium. (There may be advantages to reducing the tritium fraction below this 50% mix.)

This hot-ion mode of operation is less demanding on physics than is the thermal mode used for reactors, yet we could achieve $Q \sim 0.50$. Only a 10-kV confining potential is needed to hold the 9-keV warm ions, and the total potential in the anchor is 48 kV, down from the 80-kV potential needed in MFTF-B for the reactor mode. Containment times are much shorter, and the plasma is much less sensitive to radial transport and rotation.

This upgrade of MFTF-B has many similarities to the Technology Demonstration Facility (TDF) proposed earlier.⁴ In fact, substantial design work on TDF during 1982 by a nationally constituted team has provided a good engineering basis for evaluating MFTF-B Upgrade as well as envisioning the required systems for steady-state heating, shielding, remote maintenance, and tritium handling and recovery. Descriptions of these required engineering systems are given later in this report.

In designing MFTF-B Upgrade for nuclear testing, we have been guided by the neutron flux and fluence necessary during a given run for performing the various generic nuclear fusion tests related to blanket technology: neutronics, thermal-hydraulics, tritium recovery, and lifetime (listed in increasing order of run time). The lifetime tests include both modest-life and long-life tests; the former includes corrosion life, sintering of solid breeder material, and damage to organic insulators, whereas the latter includes radiation damage to metals. Except for the neutronics tests, which

can be performed at relatively low flux, all other tests are best performed at 1 to 5 MW/m² of neutron flux to better simulate the reactor environment.

Figure 4 displays the test times and flux of neutrons required for each of these regimes. Note that neutronics tests require 1- to 10-s runs with low minimum flux levels. Other tests have a threshold of usefulness of about 0.5 to 1 MW/m². For thermal-hydraulics, runs last 0.1 to 1 hr; however, if the run is not at steady output, the tests might be compromised. For tritium recovery from liquid-metal systems 1- to 10-hr runs are required, whereas solid breeder blankets could necessitate between 30- to 300-hr runs for recovery demonstrations. Without further study, it is not known if the experimental run time of the proposed MFTF-B Upgrade could be extended to perform these solid breeder tests.

For comparison, Fig. 4 charts the capability of several proposed upgrades to the Tokamak Fusion Test Reactor (TFTR), including the Tokamak Fusion Engineering Test (TFET) I and II, the LITE ignition machine, TDF, and TASKA, plus the microstable-plasma (SP) version of TDF. At reduced volume, the Fusion Materials Irradiation Test (FMIT) facility can perform accelerated testing (>10 MW/m²) of small material samples.

Very early estimates show that the modification would cost \$200 to \$250 million in FY 82 dollars, excluding any research and development (R & D) activities necessary to ensure that the systems envisioned here can be built with acceptable technical risk. With a concerted design effort, these costs could be reduced. Assuming that MFTF-B is operational in January 1986 and operates through FY 88, the upgrade conversion could take place in FY 89 if modification and construction of most new systems parallels operations (to the extent that they are noninterfering). Operation of the MFTF-B Upgrade could then begin in October 1989.

Figure 4. Test capabilities of eight proposed machines, as displayed on a background of test regimes for neutronics, thermal-hydraulics, and tritium breeding and extraction (courtesy of J. Maniscalco and J. Gordon, TRW). The acronyms used refer to Fusion Materials Irradiation Test (FMIT), Technology Demonstration Facility (TDF), Tandem Spiegelmaschine Karlsruhe (TASKA), International Tokamak Reactor (INTOR), Mirror Fusion Test Facility (MFTF-B Upgrade), Fusion Engineering Device (FED), and Tokamak Fusion Engineering Test. The SP version of TDF is the microstable-plasma one.

OBJECTIVES

In MFTF-B Upgrade we would advance a number of mirror technologies, improve our physics experimental data base, and gain important nuclear engineering experience in the operation of the power and fuel cycles in fusion blankets. Through the construction and operation of this upgrade we would gain experience in the following:

- Steady-state physics performance, with significant alpha heating, including impurity control and operation in a vacuum equilibrium.
- Steady-state operation of plasma heating and particle control systems.
- Steady-state vacuum system operation.
- Integration of plasma production technologies and operation in a high level neutron environment.
- Tritium fuel-cycle operation, including blanket recovery and air/water cleanup systems.
- Equilibrium power-cycle operation with fusion blankets.
- Operation, maintenance, and safety requirements in an activated fusion device with a substantial tritium inventory.
- Verification of thermal-mechanical and tritium-breeding features in a variety of fusion blankets.

Of this list, the last item provides one of the most important reasons for upgrading the facility. Nonetheless, the remaining items on the list encompass a variety of activities that will significantly reduce the risks inherent in proceeding with construction of a full scale engineering test reactor.

FACILITY DESCRIPTION

MACHINE MODIFICATIONS

Operation in the hot-ion "Kelley" mode to achieve the physics parameters listed in Table 1 requires the changes in the magnet configuration shown in Fig. 1 as well as major changes in the neutral beams, and vacuum system for steady-state tritium operation. The beam system changes for MFTF-B Upgrade are fairly extensive, and include separate deuterium- and tritium-shielded beamlines in the central cell to provide up to 300 A (trapped), depending on the angle of injection. Ten sources--five deuterium at one end and five tritium at the other end of the center section--would be required. These would replace the 10 0.5-s sources now in the central cell of MFTF-B and would be upgraded for continuous operation. One sloshing and one high-energy pump beam in each anchor would be sufficient, so except for the modification for steady-state operation, this is unchanged from MFTF-B. Additional low-energy beam pumping (approximately 50 A of 50-kV beams at each transition) is required in the transition regions, which are longer in this configuration.

To maintain the vacuum environment in steady state, the cryopanel must be replaced with units that are cycled each hour, pumping 50 min and purging 10 min. An excess capacity of 20% is required to do this. This cycle rate avoids the holdup of a large inventory of tritium on the panel surfaces.

NEW SYSTEMS

As noted, the new central-cell magnet set consists of two superconducting and two resistive coils. In this magnet system, the superconducting coils provide the uniform 4.5-T magnetic field in the central cell and some of the field in the choke region. The resistive coils form a magnetic mirror with a peak field strength of 12 T. Their field profiles are shown in Fig. 1.

The resistive coils are a derated version of the internally cooled design developed for the TDF study by General Dynamics, whereas the superconducting coils are directly adopted from the TDF set. The superconducting coils are well within the state of the art; they are based on technology developed for MFTF-B and the Large Coil Project (LCP) at Oak Ridge National Laboratory and are situated in a region well shielded from

neutrons. The resistive coils are developmental. Although coils of higher field have been built and run, none have been required to operate for long periods of time or in a high radiation field.

In the beam system, two beamlines have been added to the central cell, each of these has five ion sources and provides a neutral particle current of 150 A. One of the beamlines operates on deuterium, the other on tritium. The voltage is the same as for MFTF-B (80 kV), but the pulse length is longer (10 hrs instead of 30 s); this will require some development work on the arc chamber whose running life is currently limited by filament burnout.

There are three major elements in the tritium system for MFTF-B Upgrade: fuel processing, atmospheric cleanup, and water decontamination. The first two elements are modeled after those incorporated in the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory. The water decontamination system will be based on previously developed systems such as those for the Canadian CANDU reactors.

The fuel processing system will purify, separate, store, and deliver fuels to the beam system. Input will consist of the entire output of the vacuum system as well as deuterium and tritium make-up from outside gas suppliers. The estimated tritium inventory of 300 g includes about 70 g resident on the primary cryopumps during operation. The throughput is 19 gram moles of gas/hr, with a species mix of 30% tritium (35 g/h) and 70% deuterium including a small amount of contaminants and helium. This compares with a TSTA throughput of 15 gram moles/hr of a 50/50 deuterium-tritium mix.

The atmospheric cleanup system will be capable of returning the vault to man-rated condition 24 hours after a maximum credible tritium spill. Increasing the volume of the vault for MFTF-B Upgrade to 31,000 m³--compared to the TSTA facility volume of 2800 m³--will be possible by incorporating larger components or using multiple systems.

The vast majority of the neutrons produced in the machine will be born in the central cell with a small but significant contribution from the end regions. ... The shielding system in the new central cell must be designed to ensure acceptable radiation levels for both the hardware and the vault as well as to minimize damage. The combination of uncollided neutrons streaming through the choke-coil bore and D-D neutrons produced in the

transition and anchor cells will produce some radioactive isotopes that will pose a potential radiation hazard. Preliminary dose-rate calculations (based on the MFTF-B neutronics model) for "maintenance" areas outside the vessel ends indicate that, subsequent to a few days cooldown following a 10-hr, full-power run, contact operations are feasible on a normal work schedule.

It may be necessary to shield the end of the vessel to prevent excessive activation of the end vault wall, and it will be necessary to add shielding in the bore of the existing solenoids to minimize streaming and the effects of scattered neutrons. Although activation will be a major design driver, it appears that the MFTF-B Upgrade system can be modified at reasonable cost to allow deuterium-tritium operation for a useful period of time.

Minor modifications to the facility include:

- Increase the steady-state rating of the 80-kV dc supply by adding cooling to the primary transformers.
- Seal the vault by epoxy coating the concrete, caulking the static joints, and adding seals to the access openings.
- Add a tritium processing room to the east end of the building in the area of the coil winder.
- Add hot cells in the area adjacent to the central cell of MFTF-B Upgrade.
- Add a service crane to the vault to allow maintenance of massive components without opening the vault to the atmosphere.
- Provide a secondary coolant loop in the vault to isolate the potentially contaminated coolant from the Low Conductivity Water (LCW) system.

BLANKET TECHNOLOGY TESTING

The primary mission of the facility is to demonstrate tritium breeding and power cycle operation in candidate blankets designed for eventual reactor use. To minimize facility costs yet perform meaningful tests we propose to run these tests many hours at a time and infrequently. To help determine the required time Sawan et al.⁵ have calculated the time to come to thermal equilibrium and reach equilibrium levels of tritium concentration in a blanket they have designed specifically for this facility. Shown in

Fig. 5, their blanket was zoned as either a pure lithium (Li) or lead-lithium ($\text{Pb}_{83}\text{Li}_{17}$) blanket, as illustrated in Fig. 6.

In 3 min at $\sim 1 \text{ MW/m}^2$, the $\text{Pb}_{83}\text{Li}_{17}$ blanket and cooling loop come into thermal equilibrium (blanket preheated to 330°C). The pure Li system reaches equilibrium in 5 min. However, with tritium extracted at $\sim 10^{-3}$ wppm in $\text{Pb}_{83}\text{Li}_{17}$ and 1 wppm in Li (because of the large difference in solubility), equilibrium concentrations are reached in 0.3 hrs in $\text{Pb}_{83}\text{Li}_{17}$ and 45 hrs in Li. Similar calculations would be interesting for solid breeder blankets, but our estimate of those corresponding times is given in Fig. 4.

Clearly one can verify the thermal-mechanical and thermal-hydraulic design features of both liquid and solid blankets during runs of about an hour, but tritium breeding in pure Li or in solid breeders would need 5 to 30 runs of 10 hrs each to reach equilibrium tritium recovery. Perhaps by careful design and preloading of the tritium into the blankets, a few runs would suffice. These studies, as well as a careful assessment of the maximum single-run time in the facility, need to be made to determine the ultimate capability for tritium breeding tests.

With an assumed availability of 1% (or one 10-hr run/month), the next level of questions on the blankets--those having to do with corrosion, sintering, mass transport, and other such issues that could lead to failure in a relatively short time (fluences of perhaps 0.1 to 1 MW-yr/m^2)--would remain unanswered. However, it is this expanded capability that requires facilities costing an order of magnitude more than this upgrade.

Figure 5. A horizontal cross section of the blanket planned for the MFTF-8 Upgrade test space, as designed by Sawan et al.⁵

a) $Pb_{83}Li_{17}$ BLANKET

b) Li BLANKET

Figure 6. Zones of materials for breeding, cooling, and shielding for the general blanket structure shown in Fig. 5. Note that S.S. refers to stainless steel and v/o indicates volume percent.

COST AND SCHEDULE

To develop an early and approximate cost for the upgrade, a work breakdown structure modeled on the MFTF-B structure has been developed. This structure is given in Table 3, along with our initial estimates of each element. Both the completeness of the elements and accuracy of each estimate must be noted with caution. Nonetheless, because both the MFTF-B and TDF design and construction experience were used to make these estimates, there is an early basis that might otherwise be lacking. Perhaps the greatest uncertainty is the overall cost of the tritium facility, maintenance facilities, and general modifications, each of which is a large fraction of the total cost.

Table 4 gives the schedule for building MFTF-B Upgrade. It was developed by working backwards from the target date of October 1989 for operations, since that would allow a year between MFTF-B end of operation and initial operation of the Upgrade.

This schedule assumes completion of MFTF-B by January 1986 and operation until October 1988, which allows nine months for debugging and initial plasma operations plus two years for a sequence of full performance operations. During FY 89 the machine will be out of operation for both installation of the upgraded hardware and complete system checkout.

The timing of this upgrade also permits an interim assessment of the tandem mirror program at the end of 1984, prior to any major expenditures. Project start is the beginning of FY 86, and first-year expenditures for final design and long-lead items would coincide with the first year of MFTF-B operation.

Table 3. Work breakdown structure and cost (in millions of dollars) for MFTF-B Upgrade.

Element	Cost
<u>Special facilities</u>	
Central-cell solenoids	20 to 25
Windings	
Power supply	
Choke coils	6 to 10
Windings	
Cooling	
Power supply	
Coil modifications	4 to 5
Axicell magnet removal	
5-m solenoid relocation	
Central-cell beam system	25 to 30
Beamlines	
Sources	
Power supplies	
Beam modifications	5 to 10
Sloshing beams	
Anchor pumping beams	
Transition pumping beams	
Shielding	4 to 5
Central cell	
Transition	
Miscellaneous	
Vacuum system modifications	15 to 20
Pumping panels	
Collector pumps	
Backing pumps	
Piping	
Tritium system	15 to 25
Fuel processing	
Atmospheric cleanup	
Water decontamination	
Maintenance facilities	20 to 35
General tooling	
Special purpose tooling	
General modifications	20 to 30
<u>Conventional facilities</u>	10 to 15
<u>Building 431</u>	
Vault seal	
Tritium process room	
Hot cells	
Primary power modifications	
General facility additions	

Table 3. (Continued)

Element	Cost
<u>Project management</u>	16 to 20
<u>Contingency</u> (at ~25%)	40 to 50
<u>Total</u>	200 to 250

Table 4. Construction schedule for MFTF-B Upgrade.

Fiscal year	Task
1983	Complete conceptual engineering design.
1984	Complete preliminary engineering design. Begin R & D on magnets, sources, and cryopumping.
1985	Complete preliminary engineering design. Complete R & D.
1986	Complete final engineering design. Complete procurement plan. Complete system requirements and engineering system specifications. Procure long-lead items.
1987/1988	Construct out-of-vault systems. Test subsystems.
1989	Install systems in vault. Build and install in-vault systems.
1990	Begin operations.

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