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AN UPGRADE OF MFTF-B FOR FUSION TECHNOLOGY

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1. INTRODUCTION

Plans to build an Engineering Test Reactor (ETR) in the 1990s have been discussed at various forums debating the future of the fusion program. However, yet to be considered during these discussions are the required development steps that would make acceptable the risks in this venture. These risks depend on our expectations of the ETR performance as well as the role we perceive for that program step. A generally accepted view of the ETR mission is that it is primarily an engineering one, and the device should demonstrate fuel and power cycle operations in fusion blankets. A low plant availability is unacceptable because we would fail to gather sufficient engineering data to establish confidence in building a fusion demonstration power plant.

A question that must be addressed is whether or not our first integrated test experience with fusion blankets will be in the ETR or in some other fusion device. If it is the former, there is a risk that this expensive facility (ETR), with attendant high operating costs, will have a significant "downtime" for blanket operations because of initially high failure rates. To cut this failure rate (by gaining our initial operating experience on blankets

with a much lower cost facility) would be very cost advantageous to the program and hasten the engineering data-gathering for which the ETR is intended.

One of the few low cost options for early blanket testing in fusion devices--perhaps the only one--is the deuterium-tritium or DT-burning tandem mirror with a short, dedicated test space in the central cell. That test space can be the entire central cell if it is not long (8 m or less), or it can be a reactor-like insert in a longer central cell. We describe this latter device, the Mirror Fusion Test Facility Upgrade (MFTF Upgrade) at Lawrence Livermore National Laboratory (LLNL) in this paper. (The present machine, MFTF-B, will begin operations in 1986.)

We take as a constraint that the device must have an uninterrupted running time at least equal to the longest of several relevant blanket time constants. These include neutron dosimetry time (a few seconds), thermal time constants, and tritium equilibration times. Because thermal time constants are generally much less than the time needed to reach an equilibrium concentration of tritium with an operating recovery system, the latter dictates the running time. For ceramic breeding materials this time is on the order of 100 hours. Test runs of this length should confirm the thermal/hydraulic performance of blankets, verify their ability to breed and recover tritium, and uncover unanticipated problems.

Various tandem mirror designs of dedicated nuclear technology test devices have been proposed, [Badger et al., 1983; Doggett et al., 1984] but their high cost and their lack of "physics relevance" have discouraged their incorporation into fusion program plans. In response to this criticism, we have considered ways to use MFTF upgrades for nuclear technology testing, in

addition to their intended programmatic roles of advancing mirror physics. These programmatic roles are threefold: to test new concepts, like those introduced by the Mirror Advanced Reactor Study (MARS) [Henning et al., in press], to operate tandem mirrors steady state with DT fuel, and to produce significant fusion power to address alpha-particle physics issues.

From our study of various upgrade options [Thomassen and Doggett, 1983], we decided to add an axisymmetric mirror cell to the center of the machine for a second mode of operation. This insert will be driven with neutral deuterium and tritium beams to produce a high density/temperature plasma. In this mode a high fusion power density ($\sim 50 \text{ W/cm}^3$) and high wall loading ($\sim 2 \text{ MW/cm}^2$) are achieved in this short section, yet the fusion power is modest ($\sim 11 \text{ MW}$). Without this section, the machine is the same as we would design for the programmatic roles listed above, but it would be operated in a different mode to optimize confinement. So, the cost effectiveness of this approach to integrated testing lies in the relatively low cost of adding the insert and designing for approximately 100 hour runs (compared with, say, 100 to 300 second runs). To be more concrete, our initial cost estimate for the entire upgrade described here is approximately \$400,000,000 (FY 1983 dollars). About a third of this cost is associated with the added nuclear technology role.

2. DESCRIPTION OF THE UPGRADE

To improve on the performance of MFTF-B, one must raise the ion energy and the electrostatic confining potential. This requires higher beam energy (200 keV in this case) and a higher level of magnetic field. In the MFTF Upgrade we also want to incorporate the new end plug configuration first

invented for the MARS reactor. This new magnet design is compared in Fig. 1 with the present MFTF-B magnet set. The differences include the addition of a pair of recircularizing coils on the ends to be used in conjunction with the end region pumping and direct converter schemes, the use of a yin-yang pair rather than a baseball-type coil in the transition, and the elimination of the axicell in favor of the simple choke coil. Also, as noted earlier, an axisymmetric mirror cell is imbedded in the central cell.

In MFTF-B, the baseball coil in the transition region serves to twist the fan-shaped plasma flux surface through 90° , thereby producing a geodesic field curvature whose integral through the transition region vanishes. By so doing, the radial transport is made small and there is no generation of parallel currents into the central cell. This coil also produces a region of "good" normal curvature, but its axial extent is limited and, therefore, not exploited. In the Upgrade, however, by introducing a yin-yang pair to serve in this role, the axial extent of the region is greater and a pocket of rf-heated ions is held there. Pressure in this good curvature region contributes to the pressure-weighted stability integral, augmenting the interchange stability provided by hot electrons in the plug (the other major contribution). Furthermore, the location of this anchor in the transition region reduces the connection length to the end of the central cell and improves the stability to ballooning modes. As a result, average beta values of 40% are achieved in the central cell.

A layout of the upgraded machine in the present MFTF-B vault is shown in Fig. 2. The device has a short central cell--20 m between the 18-T coils--limiting the Q (fusion power/power absorbed by the plasma) to the values of the order of unity. Overall length between the final recirculating coils is 50 m; the vessel itself is 65 m long.

In each plug, a negative-ion beam at 200 kV provides the sloshing-ion population used to help build the thermal barrier. Electron heating with 35- and 56-GHz gyrotrons forms the barriers and electrostatic plugs. Ion heating with 25- and 50-MHz rf at the fundamental and second harmonic in each anchor cell provides the plasma pressure needed for magnetohydrodynamic (MHD) stability. Drift pumping in the anchor ($f_0 = 70$ to 80 kHz; $\Delta f_0 = \pm 16$ kHz; $N = 12$ discrete oscillators) and in the plug ($f_0 = 600$ kHz; $\Delta f_0 = \pm 42$ kHz; $N = 12$ discrete oscillators) maintains these low potential regions against collisional filling. It also removes alpha particles from the DT reactions.

In the high power density insert, 80-kV beams ($\bar{E}_b = 60$ keV) that are injected at 75° maintain the plasma density in this cell. For high-Q operation, only two sources (45 A incident) are needed, but in the high fusion power mode, when $\Gamma_n = 2 \text{ MW/m}^2$, six sources are required. Each of the two beamlines houses four sources, so in the high power mode there is a spare source in each of them. One beamline has deuterium sources and the other has tritium sources.

Extensive internal shielding is required to allow contact maintenance at the surface of the vessel. This shielding also allows access to the vault 24 hours after shutdown. Access to components inside the vessel is through the six hatches on top of the vessel. These are seen in the conceptual drawing in Fig. 3--an external view of the upgraded vessel inside the 2-m-thick shielded vault that now houses MFTF-B.

3. OPERATING SCENARIOS

There are two modes of operation for this upgrade, distinguished by their different density and potential profiles: high-Q and high- Γ . Shown in Fig. 4, the high-Q mode has a 70-kV confining potential and minimal particle feed into the central cell. In this high-Q mode, 31 A are trapped of the 45 A incident on the plasma; the wall loading is only 0.33 MW/m^2 from a fusion power of 2.25 MW.

In the high- Γ mode (Γ = wall loading), the incident current is increased to 240 A, with 190 A trapped. The wall loading increases to 2 MW/m^2 and the fusion power is 11 MW. An additional 5.9 MW is produced in the rest of the central cell (at a wall loading of 0.14 MW/m^2). As seen in Fig. 4, the confining potential is reduced to 22 kV to allow the high particle flow through the machine (relative to the flow in the high-Q mode).

Control of the plasma potential in the central cell is essential to reducing radial transport to acceptable levels. By negatively biasing the plasma at the end wall with potential control plates, the radial electric field is forced to vanish in the central cell. Plasma $E \times B$ rotation is then eliminated, and there are no resonant particles (those that are 90° displaced azimuthally in one transit of the central cell). With this bias, the radial electric field is turned inward in the transition regions so that the $E \times B$ drifts present are opposite to the field gradient drifts. This is important in controlling radial step sizes for particles that pass through the double-fan transition regions, thereby reducing transport by this (random-walk) mechanism.

To heat the electrons in the high-Q mode at the thermal barrier requires 320 kW trapped at a frequency of 35 GHz and 300 kW at 56 GHz. In the high- Γ

mode these become 500 kW and 400 kW, respectively, for each plug. Power at 56 GHz is also needed to produce the confining potential peak. The machine requires 60 kW and 100 kW, respectively, trapped in each plug for the high-Q and high- Γ modes.

Sloshing-beam currents are 4.2 A and 2.2 A incident for the high-Q and high- Γ modes, respectively. Drift pumping requirements also differ in these modes. In the anchor, the MFTF Upgrade requires 3 MW of reactive power for the high- Γ mode and 0.66 MW for high-Q. In the plugs, 200 kW is required for either mode. Finally, the ion heating in the anchor also differs. For the high-Q mode, the Upgrade needs 350 kW absorbed at 25 MHz and 67 kW at 50 MHz. For the high- Γ mode, these become 400 kW and 170 kW, respectively.

For high-Q physics operation we would operate the machine in stages, probably beginning with short-pulse deuterium-deuterium (DD) operation. Early DT operation would also use short pulses (perhaps tens of seconds), but we would eventually run at sufficient pulse lengths to demonstrate all steady-state physics issues for DT-burning tandem mirrors (perhaps some fraction of an hour). In the high- Γ mode, the machine is designed for 100-hr runs at an availability of 10%.

The time needed to reach an equilibrium concentration of tritium in a solid breeder blanket, when a recovery system is operating, is roughly 100 hours. As indicated in Table 1, thermal time constants are generally much shorter, as are tritium recovery times for liquid-metal blankets. Thus, our 100-hr run time should be sufficient for design confirmation of the power and fuel cycle issues of fusion blankets.

4. ENGINEERING FEATURES OF MFTF UPGRADE

The MFTF Upgrade design (Fig. 3) incorporates existing hardware and modifies existing components wherever possible to maximize the contribution of MFTF-B. The Upgrade also features some totally new systems (Table 2). The most technologically innovative are the continuous 80- and 200-keV neutral beams [Cooper and Pyle, 1983; Fink, 1983], the high-field unshielded copper coils, and the drift pumping system. Aggressive development programs will be needed to make these items available in time. The new features that will have the greatest impact on operations are the introduction of tritium fuel and the maintenance of an activated machine. A description of each of the major systems in the Upgrade is given below.

4.1 Configuration

As shown in Fig. 3, the external configuration of MFTF Upgrade is basically a cylinder--8.3 m in diameter and 65 m in length. (By comparison, MFTF-B has an end cell diameter of 11.6 m and is 58 m in length.) The major systems and components are shown in Fig. 2. In this cutaway, the components have been rotated onto a plane for the sake of clarity. All of the end cell components (and the halo plasma outline) are actually oriented at 45° to the plane of the drawing.

For engineering purposes, the device can be divided into three areas: the 4-m-long DT axicell for blanket testing, the central cell, and the end cells. The DT axicell consists of a new structure that accommodates one central background-field copper coil, two 12-T copper mirror coils, two

positive-ion-based neutral beam injectors, and a nuclear test module. The test module is located at the midpoint of the machine between the 12-T coils, and its background field is provided by the large superconducting coils and the central copper coil. The central cell extends for 8 m on either side of the DT axis, ending at the 18-T coils. Each half of the central cell contains five solenoid coils recycled from MFTF-B. The end cells contain all of the systems required for plasma plugging and stabilization, vacuum pumping, impurity removal, and potential control.

4.2 Magnet System

The magnet system differs significantly from that of MFTF-B. Major additions are the MARS-like end cells and the nuclear test module in the central cell. However, the superconducting magnet technology is extrapolated from MFTF-B, and 12 of the 24 superconducting coils in the Upgrade will be taken from MFTF-B, as shown in Fig. 1.

The entire magnet set (24 niobium-titanium superconducting coils and 5 normal copper coils) will be shielded from the DT neutron environment. In addition, all of the superconducting coils are removable, and the normal coils are accessible for repair or replacement.

Of the five normal coils, four are inserts to superconducting coils. These coils, which will produce on-axis fields of 12 and 18 T, represent significant extensions of the state-of-the-art. Although small in size, these insert coils are subject to very large, magnetically induced stresses and heat

loads. The conductors are of high-strength copper alloy (Amzirc), which is able to withstand the magnetic stresses but does increase the power requirements above what would be required for pure copper. The fifth normal coil is located in the DT axicell region where its use lowers the cost of the background superconducting magnets.

There are two designs for the superconducting insert coils used in the 18-T "choke" coil. Both are being studied at LLNL, and one will be chosen for development for the high-field magnet program. Specifically, each 18-T coil uses an 8-T NbTi background coil, but incorporates a different Nb₃Sn insert. Both of these 60-cm-bore inserts raise the on-axis field to 15.4 T; with the final 25-cm-bore copper-coil insert, the field is raised to 18 T. One Nb₃Sn design uses He-I coolant at 1.8 K, whereas the other uses forced-flow He-II at 4.2 K. A high-field superconducting 18-T insert--to replace the copper insert--is being designed by the magnet group at KfK Karlsruhe, West Germany. The German researchers plan to develop the conductor and wind a small test magnet.

4.3 Heating, Fueling, and Drift Pumping

Although many of the rf and neutral beam components or systems of MFTF-B are used in the Upgrade, they must be modified for steady-state operation. The new design also calls for increases in electron-cyclotron resonant heating (ECRH) and ion-cyclotron resonant heating (ICRH) power, the addition of rf drift pumping in each anchor and plug, and a 200-kV sloshing-beam system. These requirements are summarized in Table 3.

Three options for the 200-kV beam system were considered by Fink [1983]. The first--a positive-ion beam with a magnetic separator to remove molecular ions--has a 3.5-m-long neutralizer and is only 13% efficient.

However, it requires no cryopumps and is 40% gas efficient, introducing 5.7 Torr ℓ /s of gas into the beamline. Very little development is needed for such a system.

The second option has 200-kV negative-ion sources and a 2.25-m-long gas neutralizer. It uses three ribbon beams--3 cm x 52 cm--from three sources to produce 9.4 A of which 4.2 A is incident on the plasma. It is 12% gas efficient and introduces 6.9 Torr ℓ /s of gas into the beamline. Like the first option, it requires no cryopanel in the beamline.

The third option (Fig. 5) adds a transverse field focusing (TFF) section (Fig. 6) to the components of the second system, taking the source and accelerator out of the streaming neutron path. However, to reduce the beam loss by charge exchange near the TFF electrodes, the pressure must be kept low. Consequently, the neutralizer can no longer be fed from the source, and gas must be introduced at the middle of the neutralizer. Cryopanel are required in the source region to lower the pressure in the TFF section against the gas flows from both the sources and neutralizer. This system is 41% efficient.

For redundancy, a spare source and transport system will be provided in the sloshing-ion system. The aiming of the four sloshing-ion sources is shown in Fig. 7, which also depicts the ECRH and drift pump antennas in the plug region.

In Fig. 2 the two central cell beamlines are shown: one uses deuterium gas and the other uses tritium. Each houses four sources--three active and one spare--and each source delivers 40 A at an average energy of 60 keV (an 80:15:5 species mix for each 80-kV source). Anticipating a regular schedule for component changeout, either the source or the entire beamline (cryopanel

and ion dumps as well as sources) can be removed to a transfer cell from the back end (Fig. 8). Although these 80-kV beams are quite similar in their electrical and thermal behavior to those now in MFTF-B, the introduction of neutrons complicates the design significantly. Radiation damage and high heat loads from neutrons must be accommodated.

Electron heating in the barrier and plug can be accomplished with 200-kW steady-state gyrotrons. At each barrier, six gyrotron tubes are needed--three at 35 GHz and three at 56 GHz. The plugging potential will be created with one tube at 56 GHz. Thus, the Upgrade uses 14 tubes, whereas MFTF-B uses only 8. We must expand the system and convert from 30-s pulses (10% duty cycle) to steady state.

In MFTF-B, a 400-kW (absorbed) ICRH system at 6 to 20 MHz heats ions in the central cell. In the Upgrade, this system would be converted to 25 MHz and used in one anchor; an additional 400 kW would be needed for the other anchor. Also, to maintain the proper ion velocity distribution, the Upgrade would require 170 kW at the second harmonic (50 MHz) in each anchor. Placement of these heating systems in their anchor and plug locations is shown in Fig. 9.

Figure 9 also depicts the drift pump coil at the plasma fan between the anchor and choke coil. Drift pumping will be accomplished by applying an rf magnetic field at the trapped-ion bounce frequencies. (There are a range of frequencies corresponding to the range of energies of the trapped particles). This field will be applied perpendicular to the broad plasma fan for the region in question. A schematic of the technique is given in Fig. 10. There, the return flux also penetrates the fan, a situation to be avoided because it weakens the integrated field (flux) through the fan. A different antenna

arrangement is required in practice to efficiently supply the specified net flux across the fan.

Trapped particles will be pumped radially in steps, the step size determined by the geodesic curvature introduced by the rf field perturbation. As these particles move outward, they will fall out of resonance unless the pump frequency changes because their energy and bounce frequency vary with radius. The required frequency spread is not large because the ions are accelerated into the transition region (see Fig. 4 for the axial potential profile) to energies several times their thermal energy. In the anchor the spread is $\pm 20\%$ of 70 to 80 kHz, whereas in the barrier (plug region pump) it is $\pm 7\%$ of 600 kHz. In this design the spread is covered by 12 discrete frequencies in the band.

Recent work suggests that fewer frequencies (perhaps only a few) may be sufficient. Also, current thinking is that the pumping should occur at the ion drift frequency and not at the bounce frequency. There is a fundamental difference between these two approaches, namely that the second adiabatic invariant is broken in the latter case and not in the former. In consequence, bounce-frequency pumping may trap more ions than are pumped—thus, the change to a drift-frequency-based system.

Circuit designs for drift pumping are in a very evolutionary state, and an optimum approach has not been found. Approaches under consideration include individual oscillators to cover the frequency range as well as frequency modulation schemes, including sinusoidal and square-wave modulation of the basic frequency. High-Q circuits will be required if the driving power is to be manageable. For the design here the anchor-driving antenna has a Q of 70 (4- μ h inductance and 25-m Ω resistance), but the overall system Q will degrade as the required spectrum is filled in.

4.4 Halo Scraper, Direct Converter, and Vacuum Pumping

Halo pumping [Fink, 1983] and direct conversion [Barr and Logan, 1984] schemes have had a major impact on the end region design of tandem mirrors, simplifying them enormously. These systems are a natural outgrowth of the radial separation of the ions from the plasma in the transition region, a separation that directs the ions to the halo scraper and the electrons to the direct converter. The direct converter then becomes a simple collecting plate instead of the gridded structure that would be needed if the ions were decelerated. Also, the relatively simple halo-scraper plates, pumping duct, and plenum chamber will replace the large-surface-area cryopanel's resembling those used in MFTF-B. As a direct result, the end vessel can be reduced substantially in size.

The halo-scraper and direct-converter plates are shown in Fig. 11. The outer plate and duct leading to a pumping plenum have been designed to act as a pumped limiter in a tokamak. There must be sufficient energy fed to the halo--and it must be sufficiently dense--to prevent backstreaming of the neutrals formed at the outer plate when the halo impinges on it. In this equilibrium the particle pressure, starting from the low energy halo plasma and continuing through the plate region to the duct and plenum, will be constant. In a properly designed pumping system, the duct design will allow enough gas recycling at the outer plate to produce the high density halo. Energy for the halo can be supplied by those alpha particles in the central cell with orbits that pass through the halo.

Whereas both the inner and outer plates are grounded to the vessel walls, the potential upstream of these two plates can be quite different.

With the high recycling at the outer plate and resultant low electron temperatures in the halo, the upstream potential is also at ground everywhere. Because the inner plate is axially removed (upstream) from the outer plate and collects a small current, there is no large source of recycled gas, and the upstream temperatures and potentials can rise above ground. This is important for grading the potential radially between the high potential plasma core and the grounded halo. To effect this radial separation of the core from the halo, the inner plate must collect ions over a radial width corresponding to at least a Larmor radius of the drift-pumped ions.

Particle energies and heat loads are higher on the inner plate even though the flux to the outer plate (10^{23} particles/cm²) is 200 times higher than that to the inner plate. Peak heat loads to the inner plate are about 300 w/cm², whereas those to the outer plate are an order of magnitude lower. A more complete view of the proposed halo pumping system and direct converter is shown in Fig. 12.

4.5 Tritium Systems

The MFTF Upgrade will produce 17 MW of fusion power in pulses lasting over 100 hours with a burn fraction of 0.02. These fueling requirements make it imperative to include a continuous tritium processing system. Without reprocessing, a tritium supply of 2 to 3 kG would be needed for each 100-hr-run; with the complete fuel cycle designed for the Upgrade, less than 450 g will be required. Furthermore, the cost of tritium over the device lifetime is reduced by a factor of 10 or more--even when the capital cost of the reprocessing system is taken into account. The lower inventory is also a

safety factor. The system includes components for processing and storage, secondary containment, atmospheric tritium recovery, waste processing, accountability analysis, and safety. This tritium processing and cleanup system is based on the developments of the Tritium Systems Test Assembly (TSTA) presently underway at the Los Alamos National Laboratory.

4.6 Vacuum Vessel and Support Structure

Cost, ease of maintenance, and machine availability were important factors in the selection of concepts for the vacuum vessel and support structure in the Upgrade. For example, the central cell and the end cells will have the same diameter (which lowers tooling and fabrication costs), the existing end cell support piers will be incorporated, and the integrated vacuum vessel/shield design of the end cells will efficiently use the structurally required material.

The MFTF Upgrade vacuum vessel is a double-walled structure designed to hold the annular water shield described below. The ribbing between the two walls stiffens the vessel, giving an economical design that meets both the maintenance and shielding requirements. The assembly/disassembly scheme utilizes vertical movement of all major components. Access to the internal components is through large removable hatches in the vacuum vessel. These hatches are vacuum-sealed with elastomer gaskets that are located outside the shielding. This location will guarantee good access for both leak detection and necessary gasket replacement in the contact maintenance mode.

The different vessel sections are self-supporting, open-sided structures (Fig. 13) that are 8.3 m in outside diameter. (With the large area hatches,

each vessel section structurally resembles a bathtub rather than a closed cylinder.) The continuous water shield fills the space between the double walls of the vessel sections. The shield walls and their internal stiffeners will be used to generate a structure capable of supporting all vacuum, seismic, and dead loads independent of the structural contribution of the hatches.

The hatches will also serve as independent structures carrying all operating loads, including the support of the major internal components. In maintenance operations that require hatch removal, the shielding water will be drained to storage tanks to lessen the crane load.

4.7 Shielding

To support the philosophy of hands-on maintenance of components outside the vacuum vessel by 24 hours after shutdown, the bulk shielding is located inside the vacuum vessel. Low-cost shielding materials (water and concrete) will be used wherever possible. This shielding is sufficient to allow 10% availability and to keep radiation at the end of the machine lifetime to $<0.5 \text{ mrem/hr}^1$ (after the machine has been shut down for 24 hours).

Shielding for the Upgrade differs in the various regions of the machine. Starting from the insert (where the radiation is most intense), a 60-cm-thick blanket of $\text{Li}_{17}\text{Pb}_{83}$ will make up the test module. This will be backed by 25 cm of water (90% H_2O , 10% steel), 10 cm of B_4C (80% B_4C , 10% H_2O , 10% steel) to absorb thermal neutrons, 10 cm of lead (to absorb the hard gamma rays from steel), 90 cm concrete (which sees $\sim 1 \text{ MW/cm}^3$ and therefore does not hydrate because of the B_4C and lead), followed by 5 cm of

B_4C (same composition as above), and 5 cm of lead. The concrete will thermalize the intermediate energy neutrons, which are absorbed in the B_4C , and the last lead shield will stop the hard gamma rays generated in the outer steel vessel and concrete reinforcing rebar.

In the axicell test region (where there is no test blanket), the shield will be composed of 60 cm of 60% steel balls/40% water, 25 cm of 90% H_2O /10% steel, 10 cm of B_4C (composite), and 10 cm of lead. This will be followed by the same concentrations of concrete, B_4C composite, and lead as noted previously. Finally, the central cell will be shielded with 30 cm of 60% steel balls/40% H_2O , 85 cm of 90% H_2O /10% steel, 5 cm of B_4C composite, and 5 cm of lead.

Inside the yin-yang coil slots there will be 15 cm of 90% steel/10% water, whereas outside there will be a 130-cm-thick water region, followed by B_4C and lead. All the water regions will be emptied to reduce the mass of the lifted loads, thereby simplifying maintenance operations.

4.8 Electrical Systems

The MFTF Upgrade electrical systems include the ac power system, the power conversion system, the instrumentation and control (I&C) system, and the data acquisition and processing system.

Two ac power substations are to be upgraded, and four diesel generators will be added to provide backup power for the tritium and safety systems. Power for the magnets is provided by 17 MFTF-B magnet supplies plus 7 new power supplies (needed to meet the higher current requirements of the copper choke coils and the center background-field coils).

The MFTF-B neutral beam power supplies are to be modified to provide dc power to the neutral beam injectors and rf systems. The cooling system will also be changed to allow continuous operation of these supplies at reduced current. The primary controls will use reliable process measurements that are compatible with the I&C on MFTF-B, although considerably more I&C will be required for the rf power systems on MFTF Upgrade.

Much of the equipment used for diagnostic signal conditioning and data acquisition on MFTF-B external to the vacuum vessel can be re-used for MFTF Upgrade. Specifically, the diagnostics for MFTF Upgrade are designed to provide information about the problems of operation in a highly radioactive environment, about the DT axicell plasma despite limited access, and about real-time feedback control.

4.9 Maintenance

Our maintenance philosophy for MFTF Upgrade is a four-fold approach based on providing operational flexibility for this near-term device and accomplishing numerous maintenance tasks between operating runs. The design meets the following maintenance requirements:

- Contact operations at the shield boundary are permitted 24 hours after device shutdown.
- Major maintenance and disassembly operations can be accomplished remotely under both normal and emergency conditions.
- Modularized component installations are arranged for independent disassembly procedures.
- Proven remote-equipment technology is used.

The design of the vacuum vessel and support structure takes into account these needs for maintenance and high availability. Hatches and access ports are provided to allow direct removal of major components where possible. Figures 14 and 15 show these access ports and the removal of end region components.

The equipment needed to maintain this system is generally available or under development in other programs. A necessary constituent is a mockup facility, which will be used over the lifetime of the device to improve and verify equipment use, assess component design, and train operators.

The Upgrade makes maximum use of the MFTF-B facility itself at LLNL. Building 431 and the reactor vault are used in their entirety, as are the existing buildings for MFTF source testing and the space formerly used to house an experimental test accelerator (Fig. 16). However, modifications of the reactor vault are needed to make it meet the more stringent seismic requirements of a tritium-burning device and to provide remote maintenance facilities. A hot-cell facility and a tritium-processing plant are to be added, and some modifications to the power supply and cooling systems are required.

4.10 Safety and Siting

One objective of MFTF Upgrade is to demonstrate safe operation of a DT-burning fusion facility with minimum environmental impact. A preliminary assessment of the effects of normal operation, component failure, and failure induced by natural phenomena indicates that a major release of tritium (the primary source of environmental and safety concern) is highly improbable

(<10⁻⁶ per year), given the multiple levels of confinement barriers to all major sources of tritium.

Major considerations include the seismicity of the LLNL site, the location of the site boundary, and the proximity of population zones outside the site boundary. All safety-related structures are to be designed to accommodate maximum credible seismic forces. The site boundary is located 0.5 km from the facility. Preliminary estimates indicate that, for normal operation or for conditions following an accident, an individual at the site boundary or a member of the general public residing in the nearest population zone would receive a radiation dose far lower (by several orders of magnitude) than the limits allowed by the U.S. Department of Energy (DOE).

5. OPERATION AND TEST PROGRAM

The 10-year test program currently proposed for the MFTF Upgrade is divided as follows:

- One year of preparation and on-line checkouts of individual systems;
- Two years of operation in the high-Q mode for device performance tests;
- Seven years of operation in the high-I mode to collect engineering reliability data and to test blanket designs for engineering test reactors (ETRs).

The ability to perform long-pulse high-flux neutron irradiation testing as well as physics experiments is a unique capability of the MFTF Upgrade. In particular, the MFTF Upgrade facilities will allow testing of nuclear components under conditions near those of a fusion power reactor. The

first-wall uncollided neutron flux of 2.0 MW/m^2 is adequate for demonstrating the operation of blanket models for both energy recovery and tritium breeding. With the 10% duty cycle specified for the Upgrade and the high-I operating lifetime of seven years, the total first-wall neutron fluence will be 1.4 MW yr/m^2 . While this is not sufficient for testing structural materials to their lifetime limits in neutron irradiation, it is adequate for uncovering unexpected early failures and improving system reliability.

The physics testing program will focus on two areas: nuclear system demonstration and low fluence testing of sensitive materials and assemblies. Neutronics testing to verify shielding parameters only requires operating times of minutes and very low fluence. These tests will occur early in the test cycle and be repeated for new configurations as new or modified components are added. Blanket module tests will vary in length, depending on the breeding material chosen and the heat and tritium removal systems employed. All blanket systems come to thermal equilibrium very quickly, but the time to get to tritium-breeding equilibrium may vary from a few minutes for liquid-metal breeders to more than 100 hours for solid breeders. The MFTF Upgrade testing cell is capable of this full range of tests.

Materials tests will consist of deliberate irradiation of bulk specimens in test thimbles and the normal exposure of subassemblies to the plasma. The bulk samples will help correlate the results of testing in other devices, such as fission reactors, the Rotating-Target Neutron Source (RTNS-II), and the Fusion Materials Irradiation Test facility. Based on past experience with fission systems, it is very likely that unanticipated damage will occur in such areas as weldments and brazements and where different materials are

brought in close contact (i.e., metallic vacuum seals). MFTF Upgrade, because of its many exposed subsystems, will be a powerful tool for observing this kind of effect.

From the engineering standpoint, one of the most useful testing programs on the Upgrade will be the process of building, running, and maintaining a device that must operate in this very hostile environment. The design for maintenance--one of the most challenging parts of the engineering--will provide information that can be applied directly to the next generation of machines.

All of the testing will be integrated with the overall experimental program. In the early stages of the physics program, the shielding neutronics tests will be completed. Also, during this stage, early mode failures will be identified and corrected. This process will proceed as the device moves through DD and into DT operation. When the Upgrade is turned over to full testing operation, the exposure rate will increase with the higher duty cycle available in the engineering testing phase.

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Table 1. Characteristic times for four types of fusion blankets.

Symbol	Time (hr)	Blanket type
τ_N	1/1000	--
τ_{TH}	1/10 1/2	Liquid metal Ceramic breeder
τ_{TR}	1/10 10 100	Lithium-lead Pure lithium Ceramic breeder

τ_N = Characteristic time for neutronics measurements (a few seconds).

τ_{TH} = Thermal time constant. For thermal/hydraulics the test time should be several times τ_{TH} .

τ_{TR} = Tritium production and recovery are in equilibrium when the tritium inventory reaches a steady state. Characteristic buildup time is τ_{TR} .

Table 2. New engineering features of the MFTF Upgrade.

Component/system	Development plan/Data base
Negative-ion beams (200 kV)	Included in the DOE Fusion Technology Development Plan
Hybrid copper superconducting coils (18 T)	
Rf drift pumping	Develop in existing tandem mirror facilities
Direct converter with potential control	
End region pumping with halo scraper	
Full shielding for contact maintenance	Nuclear technology based on design studies and on TSTA ^a (for tritium)
Remote maintenance for internal components	
Tritium processing systems	
Safety and monitoring systems for DT operation	

^aTSTA = Tritium Systems Test Assembly (at Los Alamos).

Table 3. Requirements for neutral beam and rf systems in MFTF Upgrade.

Parameter	High-Q mode	High-T mode
<u>Central cell</u>		
80-kV incident/trapped current (A)	45/31	240/190
<u>End plug^a</u>		
200-kV incident current (A)	4.2	2.2
ECRH: barrier (kW)	320 (at 35 GHz)	500 (at 35 GHz)
	300 (at 56 GHz)	400 (at 56 GHz)
ECRH: plug (kW at 56 GHz)	60	100
ICRH: anchor (kW)	350 (at 25 MHz)	400 (at 25 MHz)
	67 (at 50 MHz)	170 (at 50 MHz)
Drift pumping: anchor		
Frequency f_0 (kHz)	80	70
Band Δf_0 (kHz)	16	14
Drift pumping: plug		
Frequency f_0 (kHz)	600	600
Band Δf_0 (kHz)	42	42

^aValues are for each plug. Absorbed power values are listed.

FIGURE CAPTIONS

- Fig. 1. Comparison of the magnet set for MFTF-B with that for the DT-burning upgrade, called the MFTF Upgrade.
- Fig. 2. Cross section of the MFTF Upgrade in the existing MFTF-B vault.
- Fig. 3. A three-dimensional external view of the Upgrade.
- Fig. 4. Profiles of the magnetic field (B), density (n), and potential (ϕ) for the two different operating modes in the Upgrade: high- I and high- Q .
- Fig. 5. Slashing-ion beamline for MFTF Upgrade with negative-ion sources, gas neutralizers, and beam dumps.
- Fig. 6. A schematic drawing of the TFF accelerator concept. Beams can be transported with or without acceleration.
- Fig. 7. Parts of the negative-ion beamline to produce slashing ions. Shown are the injection paths for the four sources, the beam dump, and the cryopumping in the dump tank to minimize gas recycling (Section A-A: rotated).

Fig. 8. Arrangement for neutral beam maintenance. This job is performed by removing sources or the entire beamline through shielded access doors to the transfer cell.

Fig. 9. Heating and pumping systems in the anchor and plug regions. Not shown is the sloshing-beam path through the end plug (Fig. 7).

Fig. 10. Drift pump antenna arrangement, illustrating how rf magnetic fields perpendicular to the plasma fan might be generated.

Fig. 11. Schematic of halo scraper and direct converter plates.

Fig. 12. Detailed view of halo scraper and direct converter systems.

Fig. 13. External view of the vacuum vessel and support structure.

Fig. 14. Test station assembly and access ports for the major components.

Fig. 15. Modular halo scraper maintenance.

Fig. 16. Use of space for the MFTF Upgrade within the existing MFTF-B facility.

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