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A DT-BURNING UPGRADE TO MFTF-B

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1. Introduction

Long-range planning for future uses of the Mirror Fusion Test Facility (MFTF-B) at Lawrence Livermore National Laboratory (LLNL) has begun, and several options to upgrade the device have been studied [1]. These options all burn deuterium-tritium (DT) fuel and anticipate better performance than in MFTF-B. Specifically, in the MFTF-B tandem mirror, which will operate in 1986, we expect to demonstrate good confinement of reactor-grade plasmas (ion temperature ≈ 10 keV). The axicell design of MFTF-B [2] is advanced in its concept compared with existing experiments, incorporating features such as the double-fan transition [3] to improve radial transport, trim coils [4] to adjust for magnet misalignments, and high-field choke coils to enhance end plug performance.

The axicell concept has been improved further in the Mirror Advanced Reactor Study (MARS) design developed at LLNL [5], notably by the addition of an anchor cell in the transition region, optimization of the end plug magnet set (the MFTF-B end plug designs were constrained to use the original MFTF yin-yang coils), and the introduction of end region pumping [6] in conjunction with a halo scraper. This pumping scheme is vital to operating tandem mirrors in steady state because it avoids the very large cryopanels characteristic of both MFTF-B (which has a 1500-m^2

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liquid-helium-cooled surface) and earlier reactor concepts. In principle, pumping can be done at high pressure (typically, about 10^{-3} Torr) in plenum chambers associated with the end region pumping system.

Finally, in all DT-burning tandems the alpha particles must be removed radially in the end region by radio frequency (rf) drift pumping. Thus, unlike present experimental devices, the axial confinement time must be about 10 times longer, by design, than the radial confinement time. In turn, for DT-burning devices, whether they be subignited or ignited devices (in the central cell), one must have $n\tau_{radial} \approx 10^{14}$ if the alpha particles are to remain in the device long enough to be a significant central cell power source, and yet have sufficient loss rates, once thermalized, to prevent large alpha-ash fractions in steady state.

Upgrades to MFTF-B will play at least two major roles in the mirror program. They will test the new configuration concepts, and they will give us experience with steady-state DT-burning systems. Lately, a third role has also been envisioned--namely to gain operating experience with fusion reactor blankets to confirm their thermal/hydraulic and tritium breeding/recovery features. This we can do by adding a short, high-field, axisymmetric mirror cell to the central cell of the upgrade. This cell becomes a test region for blanket modules. Beam-driven to high density, the hot ions in this region produce fusion reactions at a high rate. Power densities of about 50 W/cm^3 (total fusion power of about 11 MW) and a wall loading of about 2 MW/m^2 at a 25-cm-radius wall are possible with about 200 A of 80-kV DT beams. When operated in this mode (high-Γ), the confining potential at each end is reduced to allow the greater particle throughput.

Of the options studied, one is currently favored for its ability to address all three roles mentioned above. This report describes that option, termed MFTF α+T or MFTF Upgrade. (The α refers to α-particle production and the T stands for for technology. More precisely, the technology is that associated with blanket testing in the central cell insert.) In this upgrade, performance is improved by a factor of 3 to 5 over MFTF-B.

2. Description of the upgrade

To improve MFTF-B, one must raise the ion energy and the electrostatic confining potential. This requires higher beam energy (200 keV in this case) and, to preserve end-plug adiabaticity and hold higher plasma density in the central cell, 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^{o}, 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

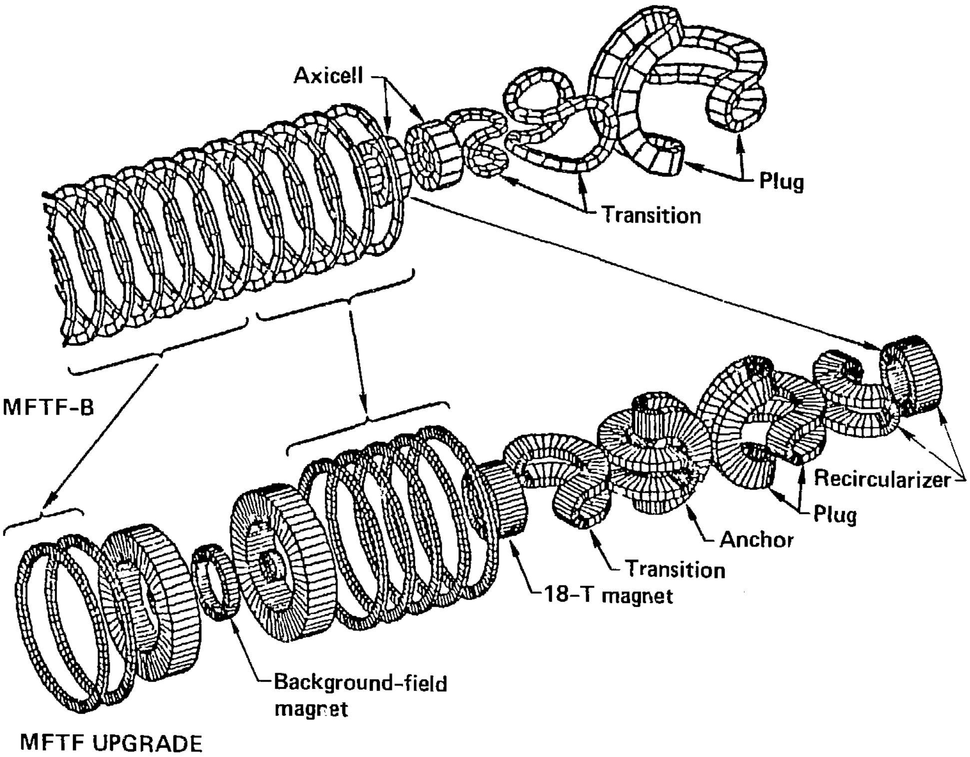

Fig. 1. Comparison of the magnet set for MFTF-B with that for the DT-burning upgrade, called MFTF α+T or the MFTF Upgrade.

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 β 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.

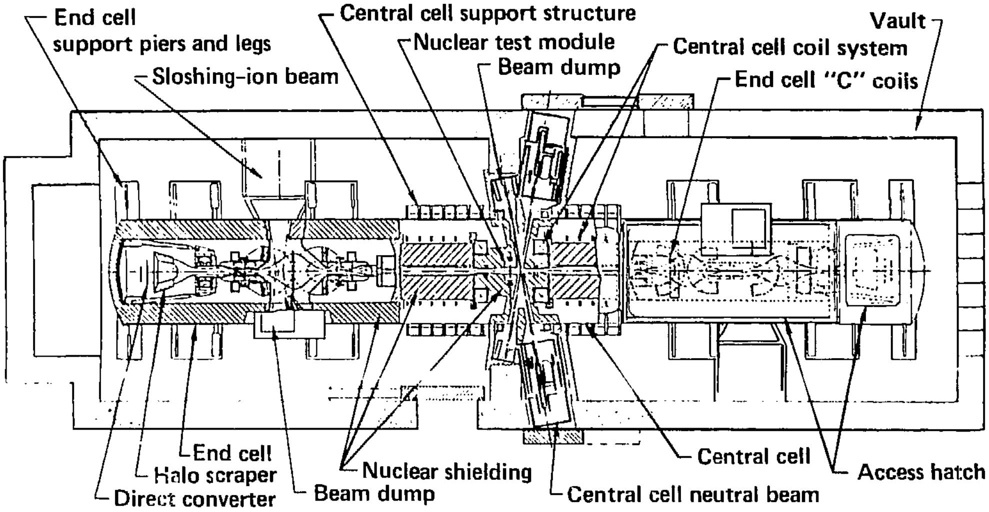

Fig. 2. Cross section of the MFTF Upgrade in the existing MFTF-B vault.

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_o = 70 to 80 kHz, Δf_o = $\pm$16 kHz, N = 12 discrete oscillators) and in the plug (f_o = 600 kHz, Δf_o = $\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 ($\overline{E}_b$ = 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 Γ_n = 2 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

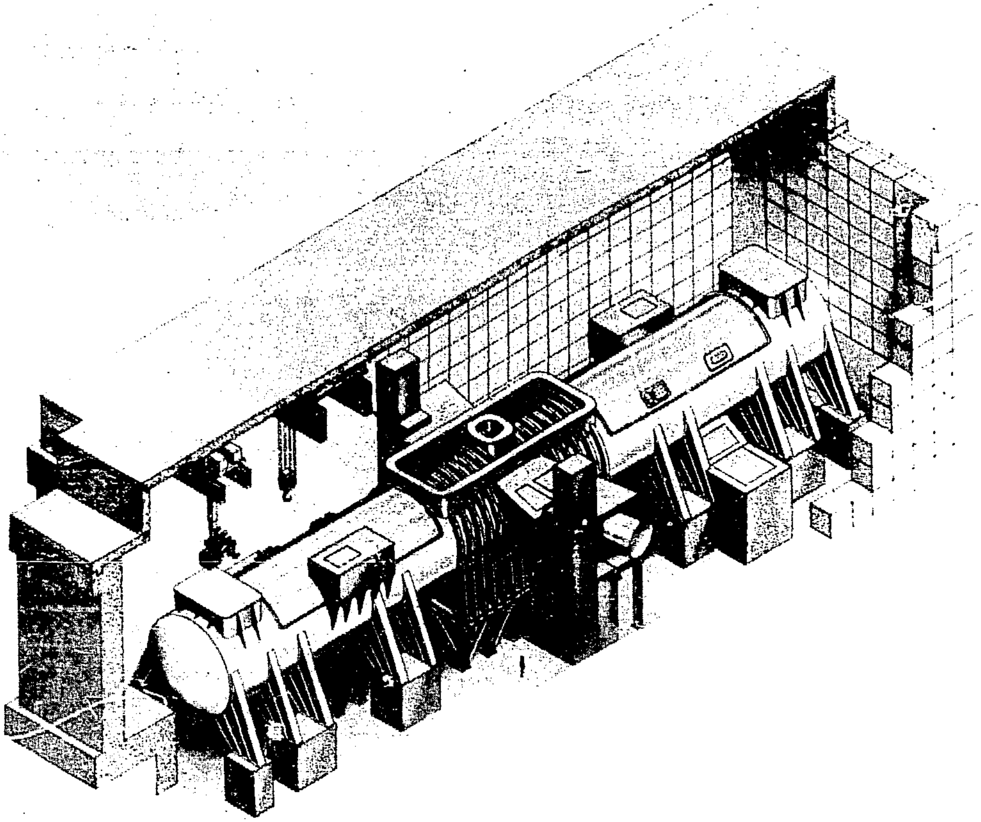

Fig. 3. A three-dimensional external view of the Upgrade.

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 x 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

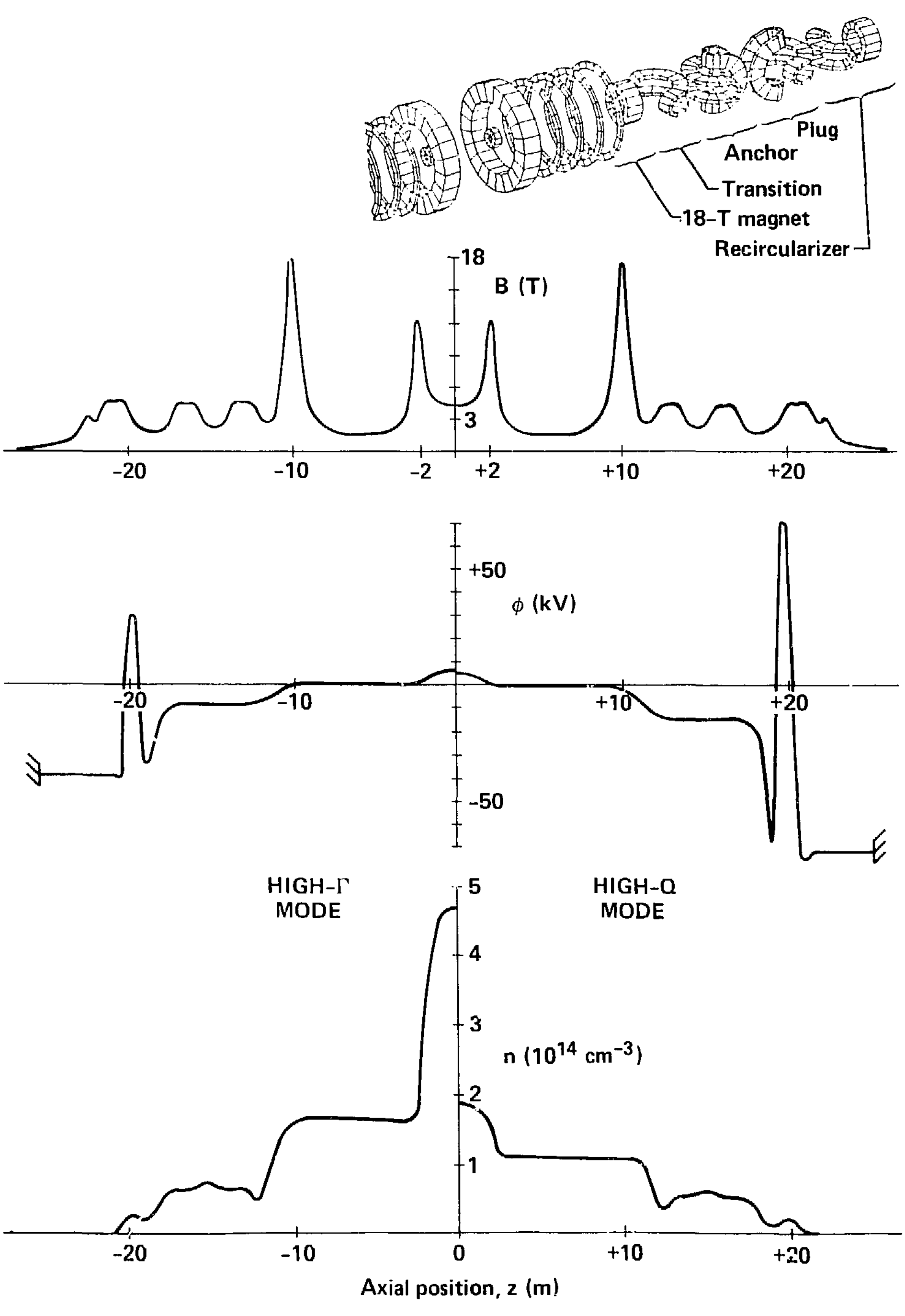

Fig. 4. Profiles of the magnetic field (B), density (n), and potential (ϕ) for the two different operating modes in the Upgrade: high-Γ and high-Q.

that the E x 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.

Table 1
Characteristic times for four types of fusion blankets

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

4. Engineering for the 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 [7,8], the high-field unshielded copper coils, and the drift pumping system. However, 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 brief description of each of the major systems in the Upgrade is given below; a more detailed discussion is found in Ref. 9.

Table 2
New engineering features of the MFTF Upgrade

Component/system	Design status
Negative-ion beams (200 kV) Hybrid copper superconducting coils (18 T)	Included in the Fusion Technology Development Plan
Rf drift pumping Direct converter with potential control End region pumping with halo scraper	Develop at existing facilities
Full shielding for contact maintenance Remote maintenance for internal components Tritium processing systems Safety and monitoring systems for DT operation	Nuclear technology based on existing designs or facilities

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 axicell, 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.

4.3 Heating, Fueling, and Drift Pumping

On the MFTF Upgrade, rf power is used for almost all heating and particle pumping functions. Neutral beam injection is employed in the central cell to fuel the plasma and in the end cells to maintain a high-energy sloshing-ion population (fig. 5).

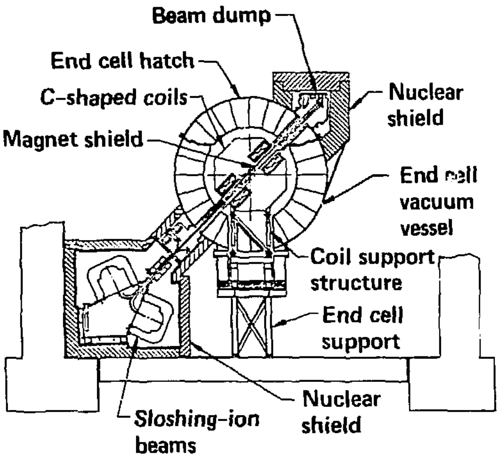

Fig. 5. Sloshing-ion beamline for MFTF Upgrade with negative-ion sources, gas neutralizers, and beam dumps.

Electron-cyclotron resonant heating (ECRH) is used to provide thermal and potential barriers in the end cells. Ion-cyclotron resonant heating (ICRH) is needed in the anchor cells to increase beta. Specifically, the MFTF-B central cell equipment is to be converted to 25 MHz; two additional systems with frequencies of 25 and 50 MHz are required. Both ECRH and ICRH are based on MFTF-B technology and hardware.

For rf drift pumping, very-low-frequency high-current signals are used to excite coils placed in the anchor and end cells (fig. 6). The flux created by these coils perturbs the end cell magnetic fields, which increases the ion radial transport. Virtually all of the ions are lost radially and collected on the halo scraper. The direct converter plates collect the electrons, thereby simplifying the direct conversion of energy carried out by particle flow to electric power [10].

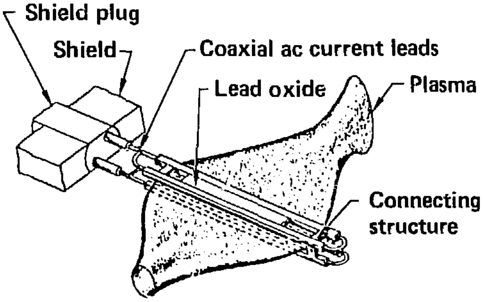

Fig. 6. Antenna arrangement for the rf drift pumping.

4.4 Halo Scraper, Direct Converter, and Vacuum Pumping

This device, MFTF Upgrade, will be the first to feature a halo scraper for impurity removal. The materials and the location of the scraper, selected through trade studies, are expected to allow this component to last for the lifetime of the device. A gridless direct converter (see above) to control the plasma potential and to extract heat and electrical energy from the plasma is included in the Upgrade design. (To keep capital costs low, no provision for processing this energy is included.) Vacuum pumping during the plasma burn can be performed at much higher pressure than would be possible without the halo scraper, which allows the use of turbomolecular pumps rather than cryopumps. This, in turn, reduces the tritium inventory. The halo scraper and direct converter are shown in fig. 7.

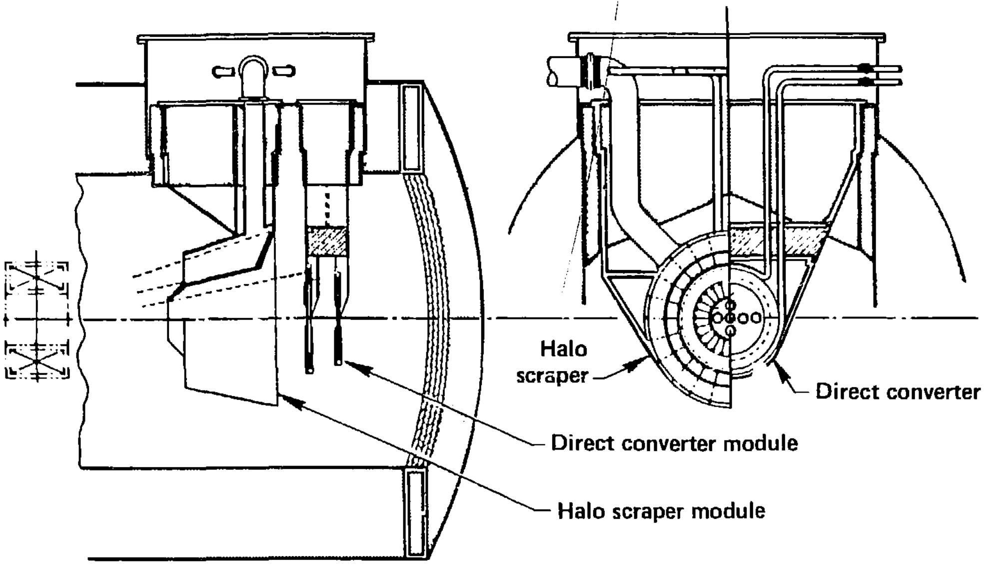

Fig. 7. Halo scraper and direct converter.

4.5 Tritium Systems

The fueling requirements of MFTF Upgrade, which will produce 17 MW of fusion power with a burn fraction of 0.02 plus pulses lasting over 100 hours, 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 System Test Assembly (TSTA) presently underway at the Los Alamos National Laboratory.

4.6 Vacuum Vessel, Support Structure, and Shielding

Cost, ease of maintenance, and machine availability were important factors in the selection of concepts for the MFTF Upgrade vacuum vessel and support structure. For example, the central cell and the end cells have the same diameter (which lowers tooling and fabrication costs), the existing end cell support piers are incorporated, and the integrated vacuum vessel/shield design of the end cells efficiently uses the structurally required material. An indication of this approach is depicted in fig. 8.

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 mrem/hr[1] (after the machine has been shut down for 24 hours).

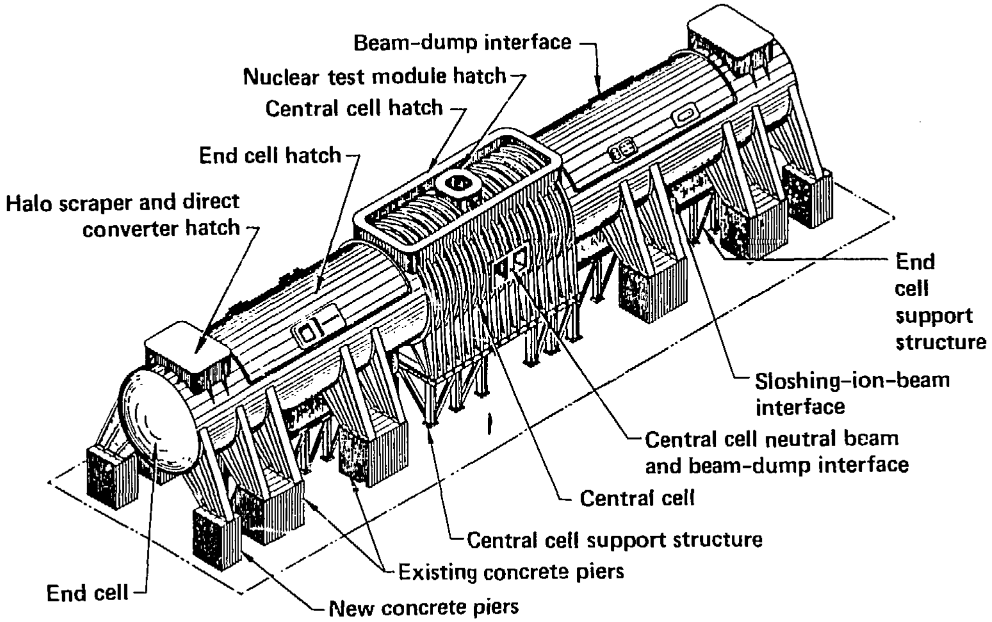

Fig. 8. External view of the vacuum vessel and support structure.

4.7 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.

4.8 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 (fig. 9).

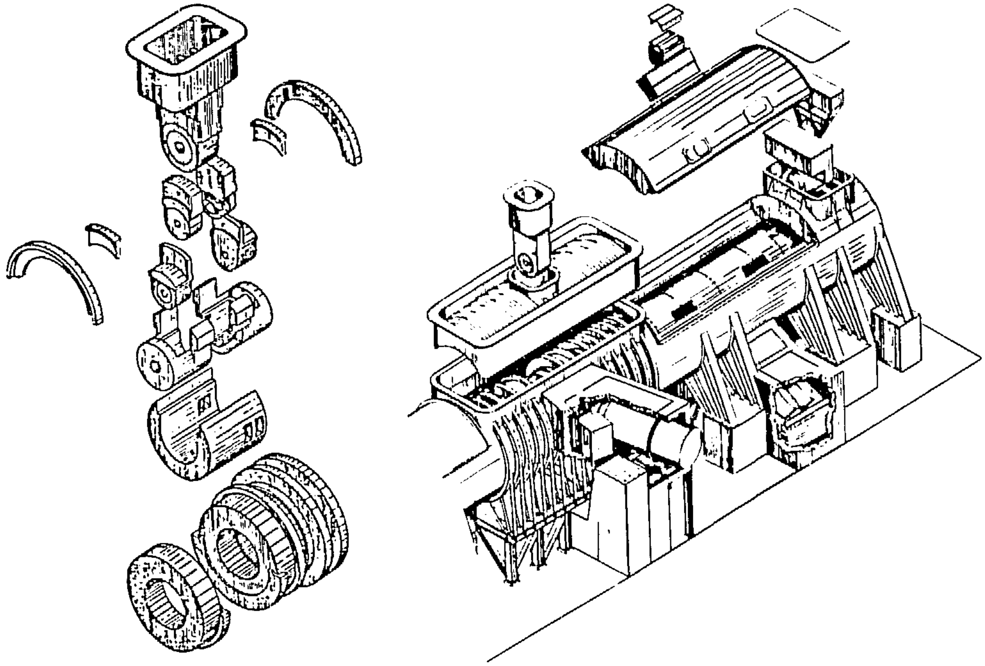

Fig. 9. Test station assembly and access points for the major components.

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. 10). 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

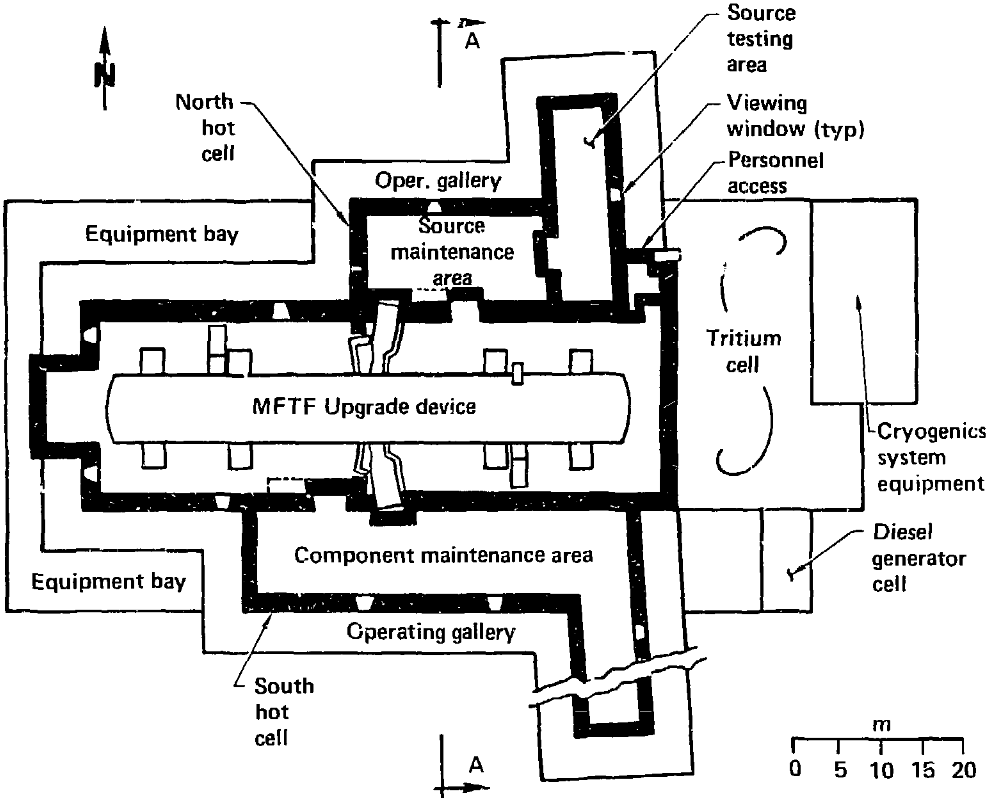

Fig. 10. Use of space for the MFTF Upgrade within the existing MFTF-B facility.

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.

4.9 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.

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-Γ 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-Γ 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.

Acknowledgments

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