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FUSION BLANKET TESTING IN MFTF-a + T

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FUSION BLANKET TESTING IN MFTF- α +T

ABSTRACT

The Mirror Fusion Test Facility- α +T (MFTF- α +T) is an upgraded version of the current MFTF-B test facility at Lawrence Livermore National Laboratory, and is designed for near-term fusion-technology-integrated tests at a neutron flux of 2 MW/m^2 . Currently, the fusion community is screening blanket and related issues to determine which ones can be addressed using MFTF- α +T. In this work, the minimum testing needs to address these issues are identified for the liquid-metal-cooled blanket and the solid-breeder blanket. Based on the testing needs and on the MFTF- α +T capability, a test plan is proposed for three options; each option covers a six to seven year testing phase. The options reflect the unresolved question of whether to place the research and development (R&D) emphasis on liquid-metal or solid-breeder blankets. In each case, most of the issues discussed can be addressed to a reasonable extent in MFTF- α +T.

1. INTRODUCTION AND EXECUTIVE SUMMARY

1.1. INTRODUCTION

The MFTF- α +T facility is an upgraded version of the current MFTF-B test facility. The upgraded version is designed for the near-term fusion-technology-integrated tests that will follow the successful operation and demonstration of the scientific feasibility of fusion in MFTF-B. In addition to its major physics role in the mirror fusion program, the MFTF- α +T version would enable, for the first time, engineering tests of major components; e.g., blanket modules, plasma interactive components, heating systems, shielding, high field magnets, and on-line tritium-recovery processes in a steady-state deuterium-tritium (DT) fusion environment with appreciable flux and fluence goals.

General ideas concerning an experimental program in MFTF- α +T are discussed in Refs. 1, 2, 3, and 4, where Ref. 1 emphasizes the physics issues to be addressed and Ref. 4 outlines the integrated engineering testing issues.

A more comprehensive assessment of the issues and testing needs of a fusion demonstration reactor are addressed in the recent FINESSE study.⁵ Reference 6 shows qualitatively that the great majority of critical and high concern nuclear issues can be addressed in MFTF- α T and complimentary facilities.

The aim of this report is to quantify the potential of MFTF- α T as a test bed for integrated-nuclear-blanket tests and to propose a reasonable test plan within the scope of MFTF- α T. Currently, a 10-year overall test program is being considered³ consisting of the following:

- One year of preparation and on-line tests of individual systems.
- Two years of operation for device performance tests.
- Six to seven years of operation to perform integrated blanket tests.

This report focuses on the latter seven-year blanket test period.

1.2. EXECUTIVE SUMMARY

1.2.1. Overview

The MFTF- α T device could, besides its major physics role in the mirror program, enable for the first time in the mid-1990s integrated engineering tests of fusion-reactor components in a DT fusion environment. The major part of the device mission (about six to seven years) would be dedicated to testing candidate blanket concepts within a broad R&D program. The goal of these tests would be to develop a viable blanket option for a demonstration reactor.

The testing constraints, set by the MFTF- α T configuration, are in the achievable neutron flux (2 MW/m^2 max) and fluence ($0.2 \text{ MW}\cdot\text{yr/m}^2$), which limit the tests to early-in-life conditions. Also the test module envelop dimensions of 1.3-m diameter by 1-m length do not allow full-size testing of tokamak blankets. However, many issues can be adequately addressed in MFTF- α T. The goal of this work is to check the capability of the device relative to the blanket issues seen today and to outline a reasonable test

plan for a six-to-seven-year in-pile test program in MFTF- α +T. The procedure adopted to meet these goals is as follows:

- All of the blanket and related issues collected in the FINESSE study⁵ are screened to determine which ones can be addressed in MFTF- α +T (Sec. 2).
- The minimum testing needs to address the issues in MFTF- α +T are identified for the two blanket groups currently under discussion: the liquid-metal-cooled blanket and the solid-breeder blanket (Sec. 3).
- Based on the testing needs and on the MFTF- α +T capability, a test plan is proposed (Sec. 4) and pertinent test-module schemes are presented (Sec. 5).

1.2.2. Issues Review

The issues in fusion nuclear technology that need to be resolved with respect to the design of a demonstration reactor are comprehensively addressed in FINESSE.⁵ In the FINESSE study, a total of 118 issues are identified and characterized by the following criteria:

- Overall priority
- Neutron-environment testing requirements
- Major test parameters other than a neutron environment
- Suitability for being tested in fusion or nonfusion test facilities.

The majority of the FINESSE issues (82 out of 118) is devoted to the blanket/first wall and related areas (e.g., tritium handling, shield, and instrumentation and control). These 82 blanket related issues have been condensed and regrouped into a total of 21 key issues (Table 1-1); each issue comprises several of the original FINESSE issues. A more complete listing of the issues, which are traced throughout this report, is given in Sec. 2, Table 2-1. The issues are also briefly described in Sec. 2.2, which includes a statement concerning the probable value of MFTF- α +T testing in resolving the issues. The unique value of MFTF- α +T is that it provides a DT fusion environment for integrated tests.

Table 1-1. Key blanket issues to be addressed in MFTF- α T.

1. Structure-mechanics issues
 - 1.1 Heat flux, cycling, transients
 - 1.2 Corrosion effects degrading the structure
 - 1.3 Irradiation effects
 - 1.4 Plasma interactive effects at the first wall
2. Breeder-multiplier structure interaction^a
 - 2.1 Breeder-structure interaction
 - 2.2 Breeder-structure heat transfer
 - 2.3 Neutron-multiplier mechanical interaction
3. Thermal-hydraulic issues
 - 3.1 Response to transients
 - 3.2 Flow and temperature distribution
 - 3.3 Magnetohydrodynamic pressure drop^b
 - 3.4 Corrosion and mass transport
4. Tritium-related issues
 - 4.1 Tritium processing
 - 4.2 Tritium permeation
 - 4.3 Tritium-breeding uncertainty
 - 4.4 Tritium-extraction efficiency^b
 - 4.5 Tritium-recovery and inventory
5. Nuclear issues
 - 5.1 Shield optimization
 - 5.2 Nuclear-heating rate prediction
 - 5.3 Prediction and control of normal effluents
 - 5.4 Structural-activation product inventory
6. Instrumentation and control

^aSolid-breeder blanket only.

^bLiquid-metal blanket only.

1.2.3. MFTF- α +T Testing Requirements Needed to Address the FINESSE Issues

The nature of MFTF- α +T makes this device suitable for integrated tests, i.e., to study synergistic effects in a nearly prototypical nuclear environment. Such synergisms of particular interest in blanket testing include the following: the stress state and neutron damage in structure mechanics; the neutron-induced material restructuring and heat/tritium transport in solid breeders; the magnetic field and volumetric heating in liquid-metal thermal hydraulics; the tritium production and transport in the breeder, coolant, and structure; the neutron flux and material spatial distribution in the nuclear assessment; and the magnetic field, electrical field, and neutron fluence in instrumentation and control (I&C) (the preceding list consists of one example for each of the six issues groups in Table 1-1). These synergisms require that the test objects be representative with respect to geometry, which leads to sizable and complicated test modules. For each issue identified in Sec. 2, a judgement is made about the minimum testing requirements to address that particular issue using MFTF- α +T. The requirements are established with respect to the test volume, the test time, and the operational mode of the test device. Also the test variables of primary interest and the required extra (auxiliary) test equipment are briefly discussed in Sec. 3. The results of the testing needs are listed in Sec. 3, Table 3-1 for a typical liquid-metal-cooled blanket module, and in Sec. 3, Table 3-2 for a typical solid-breeder blanket module; these results can be summarized as follows:

More than 50% of the issues require a full test module, which includes a maximum test module size in MFTF- α +T of 1.3-m o.d., 0.5-m i.d., and 1-m length (referred to as one full module). For the remaining issues, approximately one-quarter or one-half of a full test module would be sufficient. In some cases a thimble-like test space rather than a fraction of the test module would be more appropriate. With respect to testing time, more than half of the issues require at least 1000-hours operation time, which is equivalent to approximately one calendar year (assuming a device availability of 10%). For the remaining issues, the testing time can be significantly shorter. Finally, most of the issues require steady-state operation of the device at rated power, only a few require cycling operation (as typical in tokamaks), or special transients.

Given the above spectrum and a total testing phase limited to six or seven years, clearly, the test program must be tailored for the most appropriate tests and with the goal of performing several compatible tests simultaneously, as discussed next.

1.2.4. Outline of Blanket Tests in MFTF- α +T

Based on the issues and testing needs, and on the test objectives attainable in MFTF- α +T (Sec. 4.1), a test plan is proposed here. For this step assumptions must be made to determine the blanket group to be tested. Three options are developed:

- Option A: Assuming that the test program will pursue both liquid-metal blankets and solid-breeder blankets.
- Option B: Assuming that the test program will focus on the liquid-metal blanket.
- Option C: Assuming that the test program will focus on the solid-breeder blanket.

To be more specific, generic blanket groups and blanket concepts had to be chosen for each option to outline a test plan (Sec. 4.2). For the liquid-metal blanket, the self-cooled lithium blanket with a vanadium alloy structure (Li/Li/V) is chosen as an example. The blanket concepts selected for these test plans should not be regarded as a prejudice in the blanket comparison and selection process. They merely reflect the high ranking of these concepts in the blanket comparison and selection study (BCSS) study^{7,8} and show the capability of MFTF- α +T to address practically all the generic issues to a reasonable extent for a given blanket concept. Any modification, as for instance a LiPb/LiPb/FS blanket instead of a Li/Li/V blanket or a molten-salt-cooled blanket instead of a helium-cooled solid breeder blanket, would have been treated in a similar way.

The test plans for the three Options A, B, and C are shown in Sec. 4, Figs. 4-1 through 4-3; each plan covers a total test period of six calendar years. The device operating time is assumed to be 10% on the average with operating intervals of about 100 hours. This is roughly a 100-hour test period per month. The remaining time is used for maintenance and repair (a very important by-product in the whole mission) and for test preparations.

For each test sequence, the parameter setting, the mode of operation, and the duration is dictated by a leading test. The leading tests are considered the most appropriate tests and are expected to yield quantitative results. Among these results are the effects of heat flux, cycling and transients, breeder-structure interaction, response to transients, flow and temperature distribution, MHD pressure drop, tritium processing, and tritium recovery and inventory. Simultaneously with the leading tests, a number of accompanying tests can be conducted, but some test conditions may have to be compromised. A third group of tests, the passive tests, which merely benefit from the accumulation of time and fluence, require special attention only in the pre- and post-test phase. An extra test port (see Secs. 1.2.5 and 5.1) provides the opportunity for additional ad hoc small-scale tests.

By staggering the tests, practically all of the issues covered can be addressed in MFTF- α +T to a reasonable extent, where the term reasonable refers to the test objectives stated in Sec. 4, Table 4-1. This objective implies though, that the in-pile test program is supported by a broad out-of-pile test program and by a respective analytical effort.

1.2.5. Design Considerations

The test module is located in the center of the DT axicell and provides vertical access for module replacement. The module has envelop dimensions of 1.3-m outer diameter, 0.5-m inner diameter, and 1-m length, excluding reflector and shielding sections (Sec. 5, Fig. 5-1).

A trade study of the DT axicell magnetic configuration in Ref. 4 led to the proposal to include a background-field copper coil surrounding the test module. This coil would penalize the blanket module design and maintenance and should be eliminated. An additional test port with a cross section of $0.2 \times 0.5 \text{ m}^2$ has been proposed. This port is located adjacent to the test module and penetrates the axial shield section vertically down to the plasma. Through this port, a test thimble, for miscellaneous and as yet unspecified tests, could be inserted independent of the main test module.

According to the three test plan options proposed, three test module scope designs are outlined (Sec. 5, Figs. 5-2 to 5-4), featuring a liquid-metal-cooled tandem-mirror-reactor blanket, a liquid-metal-cooled tokamak-type (poloidal/toroidal) blanket, and a helium-cooled solid-breeder blanket. For the latter type, the test module thickness of 40 cm should be enlarged to the expense of the radial reflector/shield section.

2. ISSUES APPROPRIATE FOR MFTF- α +T TESTING

2.1. SCREENING THE FINESSE ISSUES

The issues in fusion nuclear technology that need to be resolved with respect to the design of a demonstration reactor are comprehensively addressed in FINESSE.⁵ A total of 118 issues are identified and characterized by the following criteria: overall priority, neutron environment testing requirements, major test parameters other than a neutron environment, and suitability for being tested in fusion or nonfusion test facilities. The majority of the FINESSE issues (82 out of 118) is devoted to the blanket/first wall and related areas (e.g., tritium handling, shield, and instrumentation and control). The remaining issues refer to plasma interactive components and to magnets. For ease of overview and discussion in this context, the 82 blanket-related issues have been condensed and regrouped into a total of 21 issues; each one of these "super" issues comprises several of the original FINESSE issues. Only a few of the FINESSE issues have been neglected because they are considered unsuitable for being addressed in MFTF- α +T. Six groups have been established, reflecting the major engineering disciplines in preparing the tests. These issue groups are as follows:

1. Structure mechanics
2. Breeder-multiplier structure interaction
3. Thermal hydraulics
4. Tritium
5. Nuclear
6. Instrumentation and control.

Table 2-1 lists the 21 issues and pertaining subissues. A brief description of the issues is given in Sec. 2.2 along with a qualitative statement about the possible test value of MFTF- α +T testing to resolve the issue.

Table 2-1. Issues appropriate to MFTF- α T testing.

-
1. Structure-mechanics issues
 - 1.1 Effects of heat flux, cycling, and transients
 - a. Creep rupture and yielding
 - b. Flaw growth leading to coolant leakage
 - c. Stress concentration at hot spots
 - d. Failure at welds and discontinuities
 - e. Fatigue, shakedown, and ratcheting
 - f. Structural response to transients
 - 1.2 Corrosion effects degrading the structure
 - a. Wall thinning and potential failure
 - b. Liquid-metal embrittlement
 - c. Clad corrosion from breeder burnup products^a
 - d. Stress corrosion cracking
 - e. Self welding
 - 1.3 Irradiation effects
 - a. Embrittlement (DBTT^b of ferritic steel)
 - b. Swelling and creep on operating stress
 - c. Swelling and creep on stress during transients
 - d. Swelling and creep on stress after shutdown
 - 1.4 Plasma interactive effects at the first wall
 - a. Erosion by sputtering, arcing, and chemical effects
 - b. Plasma disruptions
 2. Breeder-multiplier structure interaction^a
 - 2.1 Breeder-structure interaction
 - a. Choice of operating temperature
 - b. Strain accommodation by creep and plastic flow
 - c. Thermal expansion and cyclic effects
 - d. Breeder swelling
 - 2.2 Breeder-structure heat transfer
 - a. Thermal conductivity changes
 - b. Gap conductance
 - 2.3 Neutron-multiplier mechanical interaction
 - a. Swelling in beryllium
 - b. Strain accommodation by creep in beryllium
 - c. Integrity of unclad beryllium
 3. Thermal-hydraulic issues
 - 3.1 Response to transients
 - a. Operating transients
 - b. Fault condition transients

Table 2-1. (Continued.)

-
- 3.2 Flow and temperature distribution
 - a. Geometric nonuniformities^a
 - b. Magnetohydrodynamic (MHD) effects^c
 - c. Eddy currents in manifolds
 - d. Helium bubble formation
 - e. Hot spots and hot channel factors
 - f. Flow induced vibration
 - 3.3 MHD pressure drop^c
 - a. Excessive stresses
 - b. Geometric complexity
 - c. Temperature dependent effects
 - d. Corrosion and irradiation effects
 - 3.4 Corrosion and mass transport
 - a. Deposition of activated material
 - b. Deposition of corrosion products
 - c. Effectiveness of corrosion inhibitors (coatings)
 - d. Temperature sensitivity
 - e. LiOT mass transfer^a
 - 4. Tritium-related issues
 - 4.1 Tritium processing
 - a. Impurity removal in the fuel cleanup process
 - b. Tritium extraction from water coolant
 - c. Tritium monitoring
 - d. Breeder tritium-extraction stream characteristics
 - e. Tritium-processing system integration
 - f. Atmospheric cleanup process
 - 4.2 Tritium permeation
 - a. From primary to secondary coolant
 - b. Permeation at low pressure
 - c. Effect of radiation
 - d. Effectiveness of permeation barriers
 - e. Stability/kinetics of tritium^a
 - 4.3 Tritium-breeding uncertainties
 - a. Breeding models and nuclear database
 - b. Tritium inventory and losses
 - c. Lithium burnout effects^a
 - d. Uncertainties associated with system definition
 - 4.4 Tritium extraction efficiency^c
 - a. Uncertainty in diffusivity
 - b. Impurity composition and transport
 - c. Extraction process effects

Table 2-1. (Continued.)

-
- 4.5 Tritium recovery and inventory^a
 - a. Equilibrium concentration
 - b. Purge-stream chemistry effects
 - c. Radiation effects
 - d. Diffusivity
 - e. Surface migration and desorption
 - f. Purge-stream transport phenomena
 - 5. Nuclear Issues
 - 5.1 Shield optimization
 - a. Effectiveness of shield configuration
 - b. Neutron streaming through ports
 - c. Local shielding of highly sensitive components
 - d. Biological doses during operation and maintenance
 - e. Assembly/disassembly procedures
 - f. Analytical techniques and database
 - 5.2 Nuclear-heating rate prediction
 - 5.3 Prediction and control of normal effluents
 - 5.4 Structural activation-product inventory
 - a. Long-lived isotopes
 - b. Contribution of material impurities
 - 6. Instrumentation and control
 - 6.1 Transducer lifetimes
 - 6.2 Breakdown of insulation resistance
 - 6.3 Decalibration
 - 6.4 Ceramic insulator/substrate seal integrity
 - 6.5 Optical window, lens, and prism darkening
 - 6.6 Shielding of instrument penetrations
 - 6.7 Cable noise from rf, magnetic field, and charged particles
 - 6.8 Adequacy of I&C for safe plant operation
-

^aSolid-breeder blanket only.

^bDuctile-brittle transition temperature.

^cLiquid-metal blanket only.

2.2. ISSUES DESCRIPTION AND SUITABILITY FOR MFTF- α +T TESTING

2.2.1. Structure-Mechanics Issues

2.2.1.1. Effects of Heat Flux, Cycling, and Transients. The blanket structure and first wall are subjected to high temperature, large thermal gradients, coolant pressure, magnetic forces, and severe radiation. They will encounter cyclic stress conditions that will cause cumulative damage resulting in fatigue, ratcheting, creep, and crack growth. In addition, hot spots can be generated by inadequate local cooling (e.g., stagnation points, stratification, and MHD effects) or by excessive surface heat flux caused by the plasma (i.e., charge exchange, ripple, and misadjustment). These effects can fluctuate and thereby impose another cyclic stress state. Stress analysis is further aggravated by the complex geometry and imponderable material behavior, even without radiation damage. The issue is extremely design, material, temperature, and stress-history dependent, which can hardly be simulated.

Tests using MFTF- α +T allow researchers to discover design or fabrication deficiencies or other unexpected early failures in a variety of cycling and transient operating modes. It is assumed that the device can be operated in a cycling mode with controlled power ramps or in small steps. On the order of 10^3 to 10^4 cycles (instead of typically 10^5 to 10^6 cycles) can probably be achieved. Unless separate heating is provided, the device will fall short in surface heat flux (0.05 instead of 1 MW/m²).

2.2.1.2. Corrosion Effects Degrading the Structure. In a liquid-metal-cooled blanket, the potential corrosion effects on the structural integrity are wall thinning, embrittlement, and self-welding. Wall thinning is not likely to be important for section thicknesses >3 mm. Instead, the limiting factor for candidate material combinations seems to be mass transfer (Sec. 2.2.3.4). However corrosion is very sensitive to temperature and the actual chemical environment and needs interactive effects tests. Liquid-metal embrittlement can lead to fractures along grain boundaries far below normal yield strengths. Embrittlement might be induced in local chemistry variations, such as exist in heat-to-heat variations, and in welds or in combination with neutron irradiation damage. Finally, self-welding of similar

or dissimilar materials has been observed in reduced atmospheres at moderate contact pressures and is sometimes regarded as a potential maintenance concern at high swelling rates.

In solid-breeder blankets, a major concern is clad corrosion resulting from breeder burnup products. In Li_2O , highly corrosive LiOT may be formed. In ternary ceramics, such as LiAlO_2 and Li_8ZrO_6 , nonstoichiometry will change the chemical environment. In addition to the wall thinning, stress corrosion cracking is a potential failure mode.

The MFTF- α +T device can be used to confirm performance goals developed from nonfusion corrosion tests at early-life conditions. Liquid-metal embrittlement tends to show up early in life, if the system is susceptible. Self-welding effects need exposure times in the range of only 100 to 1000 hours. However the conditions in MFTF- α +T are not suitable for self-welding tests.

2.2.1.3. Irradiation Effects. Neutrons produce displacements of lattice atoms, nuclear transmutations, and He and H atoms. The mechanical property changes (such as tensile strength, ductility, fracture toughness, creep, crack initiation and growth) and the density changes (swelling) depend on, for instance, temperature, grain size, composition, neutron fluence, and spectrum. Because of swelling and creep, the stress state will be altered according to local or global constraints. Significant swelling is expected to occur above 30 to 100 displacement per atom (dpa) depending on temperature and material. Irradiation creep can relieve stresses at steady-state operation. However at shutdown, these relaxations will create reverse stresses and can cause cracking. In ferritic steel, the ductile-brittle transition temperature (DBTT) can be shifted into temperature regimes above 100°C at relatively low fluences (~ 10 dpa).

Tests in MFTF- α +T cannot reach the fluence goals necessary to verify swelling effects or mechanical property changes in candidate materials. However, integrated effects such as welded regions, hot spots, temperature gradients, coolant environment, fusion spectrum, and plasma interaction can lead to unknown early failure or deficiencies that could be experienced in MFTF- α +T for the first time. Fluence levels in MFTF- α +T seem to be high enough to obtain embrittlement in ferritic steels.

2.2.1.4. Plasma Interactive Effects at the First Wall. Major concerns in fusion technology are wall erosion resulting from particle bombardment and vaporization and melting by plasma disruptions. The first-wall surface is subjected to damage from charged particles, neutrons, neutral atoms, and electromagnetic radiation; these cause sputtering of atoms from the free surface, blistering by implantation, and transmutation. For tokamaks, heat and particle fluxes at the first wall in the range of 0.5 to 1 MW/m^2 and 10^{20} to $5 \times 10^{20} \text{ m}^{-2}\text{s}^{-1}$, respectively, are predicted, leading to estimated wall erosion rates of $1 \text{ mm/full power year (FPY)}$. Plasma disruption can also cause life limiting erosion damage. In tandem mirror reactors, the wall loading is much lower and plasma disruptions are a minor concern.

In MFTF- α +T, typical tokamak first-wall particle fluxes cannot be simulated, except possibly in areas near the neutral beam injection. Also the plasma disruption conditions that are expected in tokamaks probably cannot be obtained. Therefore, MFTF- α +T is not an adequate test device to address this issue. However, MFTF- α +T confirmation that plasma/first-wall interactive effects are not a major structure-mechanics problem in tandem mirror reactors would be very valuable.

2.2.2. Breeder-Multiplier Structure Interaction Issues (Solid Breeder only)

2.2.2.1. Breeder-Structure Interaction. The operating temperature range of a solid breeder is a viable design parameter, influencing tritium production and recovery, heat removal, LiOT transport, and mechanical interaction. A critical mechanical-interaction subissue is the strain accommodation in the cladding, which in steady-state operation is influenced by plastic flow in the solid breeder, initial density and gaps, clad deformation capability, and stress concentration at discontinuities. Furthermore, cycling may cause cracking, ratcheting, and particle relocation that make the mechanical interaction behavior unpredictable. Swelling in Li_2O is possibly a life limiting factor; in ternary compounds, swelling seems to be of low concern.

The MFTF- α +T device can be used to investigate the mechanical interaction effects for a variety of materials, unit cell designs, and operating conditions, including cycling. Post-test examination should reveal

valuable information on appropriate temperature windows and early-life performance in a fusion neutron environment. More basic nonfusion experiments would supplement these tests, including radiation effects.

2.2.2.2. Breeder-Structure Heat Transfer. The subissues in breeder-structure heat transfer are thermal conductivity changes in the breeder material itself and the breeder-structure interface heat transfer. Both qualities are long term effects and are very closely related to the structural behavior discussed in Sec. 2.2.2.1. Again the proper operating temperature window is the major design and performance concern for solid breeders. Changes in thermal conductivity are expected to begin at low fluence levels ($>1 \text{ MW}\cdot\text{yr}/\text{m}^2$). Changes in gap conductance are likely to appear early in life because of cycling effects and may then gradually change with increasing fluence level and with breeder/clad contact conditions.

Tests in MFTF- α +T can confirm performance goals developed from nonfusion testing at early-life conditions. The tests would be essentially the same as for the breeder-structure interaction with emphasis on temperature measurements within the solid breeder. Typical maximum-power densities in the breeder (e.g., $40 \text{ MW}/\text{m}^3$ in Li_2O) probably cannot be obtained in MFTF- α +T. However, most portions of a blanket are operating at 0.1 to $10 \text{ MW}/\text{m}^3$, which can be reached.

2.2.2.3. Neutron-Multiplier Mechanical Interaction. Helium production in beryllium is expected to cause a $>10\%$ swelling in the bulk material at high temperature and moderate fluences ($5 \text{ MW}\cdot\text{yr}/\text{m}^2$). This causes mechanical interaction problems in the cladding that might be alleviated by radiation creep. In case of unclad beryllium, the integrity is questionable because of embrittlement leading to redistribution, particle transport, or changes in cooling characteristics.

The fluence in MFTF- α +T is too low to obtain significant swelling and consecutive structural changes. However in combination with other test objectives, as for instance the nuclear issues, testing of beryllium inserts could explore early failure modes or unexpected effects. The temperature range of interest is 400 to 600°C .

2.2.3. Thermal-Hydraulic Issues

2.2.3.1. Response to Transients. System transients include normal operating transients during startup and shutdown, and fault-condition transients (e.g., loss of primary coolant flow, loss of heat sink, and loss of fusion power). All of these transients might be accompanied by magnetic field changes. The blanket/first wall has to be designed to survive such transients for specified times. Hence, the ability to predict system response is needed. Major concerns for fusion technology are adequate startup and shutdown control of the heat removal system, liquid-metal and molten-salt coolant transients in steady-state or changing magnetic fields, structural damage minimized by inherent features or by counteracting control actions, and instrumentation and control.

The MFTF- α +T device can simulate major features of the environment at a sufficient scale to show unexpected phenomena, to verify or improve transient modeling, to develop control mechanisms including the necessary instrumentation, and to verify the safeguard effectiveness. Limitations are seen in the geometry in the test article when compared with a full scale tokamak blanket.

2.2.3.2. Flow and Temperature Distribution. All blanket designs have multiple-parallel coolant paths, sometimes with branches and subbranches. Solid-breeder blankets typically employ small parallel channels, subject to relatively large changes in passage dimensions. In liquid-metal-cooled blankets, magnetic field effects and global eddy currents tend to dominate the flow distribution; but also nonuniform heat loads, gravitational forces, channel length, manufacturing tolerances, trapped-helium bubbles and partial-power operation can cause deviations from the rated-flow distribution. In the blanket design, these uncertainties are accounted for in hot-channel and hot-spot factors that for plant performance reasons and for blanket lifetime assessment should be kept at a minimum. Flow-induced vibration has to be considered in high velocity flows.

The MFTF- α +T device cannot fully simulate the geometry and magnetic field typical for a tokamak blanket, which are viable parameters for the liquid-metal breeder blanket. However, most of the other effects including

volumetric heating as well as channel entrance/exit points and bends in a fairly high magnetic field can be investigated in MFTF- α +T. Thus, performance goals for a complex test module developed from nonfusion testing can be confirmed in integrated tests at beginning-of-life conditions. At end of life, dimensional changes from corrosion and swelling (especially in solid-breeder blankets) have to be taken into account, which can, as a first approach, be simulated by built-in channel-width variations.

2.2.3.3. Magnetohydrodynamic (MHD) Pressure Drop (Liquid-Metal Breeder only). The MHD pressure drop in a self-cooled liquid-metal blanket can be a significant factor in stress analysis and, thus, is tied to both thermal hydraulic and structural behavior. Major uncertainties come from geometric and flow distribution effects, but temperature dependent properties and changes in electrical properties (also at the fluid-structure interface) may be important too. Typical volumetric heating rates ($\sim 5 \text{ W/cm}^3$) (see Ref. 10) and surface heat loads ($\sim 1 \text{ MW/m}^2$) are highly desirable in testing MHD behavior.

Primarily, a better understanding of MHD pressure drop must be developed in nonfusion test stands. Thermal-hydraulic tests in MFTF- α +T would be an intermediate step (with respect to size and degree of integrity) between those fundamental tests and full-scale performance tests. The magnetic field in MFTF- α +T would be close to that in the outboard region of a tokamak blanket. Extra effort to address this issue would be only necessary in excessive instrumentation.

2.2.3.4. Corrosion and Mass Transport. The implications of corrosion on structural mechanics is discussed in Sec. 2.2.1.2. With respect to the thermal-hydraulic design (e.g., operating temperature range), the deposition of corrosion products and activated material seems to be the limiting factor. For example, in a mirror advanced reactor study (MARS) type design, corrosion/redeposition rates of 1 to 100 $\mu\text{m/yr}$ and contact dose rates in a primary pipe of 10^{-1} to 10 rem/hour (see Ref. 7) are expected. Release of activated wall material into the coolant flow is enhanced by neutron recoil sputtering (typically $< 0.1 \mu\text{m/yr}$). Corrosion processes are very temperature sensitive and design specific.

The MFTF- α +T tests can confirm performance goals for a specific test-module/coolant-loop configuration developed from nonfusion testing.

Particularly, the transient behavior of contact dose rates over days or months at various loop sections and components can reveal valuable information for maintenance schemes.

2.2.4. Tritium-Related Issues

2.2.4.1. Tritium Processing. The tritium-processing subissues to be addressed are the following:

1. Impurity removal in the fuel cleanup process (flow rates, impurities, T_2/T_2O ratios, and operating temperature);
2. Tritium extraction from water coolant;
3. Tritium monitoring (on-line monitoring and dynamic modeling);
4. Breeder tritium-extraction stream characteristics (T_2/T_2O ratio, isotopic abundances, impurity concentrations and type, and tritium phase and chemical compound flow rate);
5. Tritium-processing system integration;
6. Atmospheric cleanup process (cleanup capacities and times, and methods).

Although many of the subissues will be addressed in Tritium Systems Test Assembly (TSTA), MFTF- α +T would offer a unique test device to exercise the tritium-processing system integration with different breeding-blanket concepts on a technical scale (~ 1 kg/d). Facilities related to the subissues (1), (2), and (6) above will be provided independent of the blanket test program as part of the plant design. The experience gained in conjunction with nonfusion test programs should enable extrapolation to full scale conditions.

2.2.4.2. Tritium Permeation. Permeation from the liquid-metal breeder into the secondary coolant path is a major concern for LiPb because the low solubility of tritium creates a high tritiated-vapor pressure. In Li, permeation is less important. Also at low tritium pressures, as occur in secondary coolant systems, the tritium permeation has to be assessed for environmental reasons. Important parameters are the structure temperature (~ 300 to 600°C), tritium pressure (1 to 200 Pa), and the whole chemistry.

Neutron damage may affect the permeation, especially if tritium barriers are used. In blanket systems using He as purge gas or coolant or in draw salt, the stability of tritium as tritiated water vs the elemental form will affect tritium permeation and must be known.

Permeation must be investigated on a broad basis in nonfusion experiments. The MFTF- α +T tests can confirm performance goals developed from those experiments under reactor-typical operating conditions in a technically achievable chemical environment. Radiation damage goals (~ 100 to 200 dpa) cannot be met in the MFTF- α +T.

2.2.4.3. Tritium-Breeding Uncertainties. Prediction of the tritium-breeding performance includes three categories of uncertainties:

1. Those associated with calculation models (geometric modeling, nuclear data, and methods);
2. Those associated with the tritium inventory (in blanket, fueling, storage, etc. including decay between production and use);
3. Those associated with system definition (first wall/blanket design details, choice of limiter vs divertor, heating systems, shield, penetrations, etc.).

The overall uncertainty in the prediction of the tritium-breeding ratio for a projected reactor system is expected to be between 20 and 30% and must be improved.

Benchmark experiments, addressing especially the category 1 uncertainties above, are useful with point neutron sources. Category 2 requires performance tests in integrated systems. The MFTF- α +T tests can verify both category 1 and 2 prediction models without the need for tritium self-sufficiency. Category 3, which is tied to the tokamak, cannot be addressed sufficiently in a mirror device.

2.2.4.4. Tritium Extraction Efficiency (Liquid Breeder only). Tritium bred in the liquid metal must be recovered under steady-state conditions at acceptable levels of tritium concentration (< 1 wppm). This has to be demonstrated on an engineering scale, particularly for LiPb. The

uncertainties in this area involve the tritium diffusivity in liquid metals; impurity composition, transport, and deposition in the extractor; and effects of the extraction process on the liquid-breeder loop (extractor compounds, corrosion, thermal effects, and required throughputs).

The MFTF- α +T tests can confirm performance goals of a candidate extraction process developed primarily from nonfusion loop tests. Interactive neutron-related effects influencing the impurity generation can be demonstrated along with the entire tritium-reprocessing system. Typical times to reach equilibrium tritium concentration of, for instance, 1 wppm are 30 hours (Ref. 10) at MFTF- α +T conditions.

2.2.4.5. Tritium Recovery and Inventory (Solid Breeder only). The tritium release from the solid breeder depends on many interconnected mechanisms that are not sufficiently understood. Tritium is partially dissolved, chemically bound, and physically trapped in the solid, and there is substantial uncertainty in the thermochemistry of these systems, especially for ternary compounds. Purge-stream chemistry (H_2 or O_2 content) and radiation (Li transmutation, bubble formation, and dislocations) complicate the picture. The effects of temperature, grain size, and radiation on the tritium diffusivity are uncertain as well. After diffusing to the grain surface, migration along the grain boundaries and desorption govern the entrance to the purge stream. Finally, the purge stream transport is influenced by the temperature, temperature gradients, and grain structure, which in itself is time and fluence dependent. The tritium release during transients is important in the safety assessment.

The key engineering question is, what is the equilibrium or quasi-equilibrium tritium inventory in the breeder during steady-state or pulsed operation, respectively? Predictions so far⁵ indicate that equilibrium times are on the order of several FPY and cannot be approached in MFTF- α +T experiments. However, early-in-life tritium-release rates can be measured, over several 100 hour cycles and during transients and can be compared with modeled and extrapolated design goals. Additional unit cell tests in nonfusion devices would be required to distinguish between mechanisms needed for extrapolation.

2.2.5. Nuclear Issues

2.2.5.1. Shield Optimization in Complex Geometries. Many shielding issues evolve from the complex tokamak geometry, particularly at the inboard and at limiter/divertor openings. Concerns common to tokamaks and mirror devices include the following: the effectiveness of shield configurations, neutron streaming through ports and gaps, local shielding of highly sensitive components, biological dose during operation and maintenance, assembly/disassembly procedures, and improvements in the analytical techniques and database.

The MFTF- α +T tests can confirm performance goals developed mainly from nonfusion testing for particular configurations that match the test objectives of other blanket module tests. The extent to which special subissues can be quantitatively evaluated depends on the achievable measurement accuracy. The MFTF- α +T facility offers flexibility to simulate idealized local effects; e.g., penetrations, gaps, and local shields.

2.2.5.2. Nuclear Heating Rate Predictions. The uncertainty associated with local or global heat generation in a blanket is attributed to geometrical definition, modeling, calculational methods, and nuclear data. A target accuracy of $\sim 15\%$ in the spatial distribution and of $\sim 10\%$ in the global value seems appropriate. For afterheat predictions, more basic data related to the decay processes are needed.

MFTF- α +T provides the necessary neutron and gamma ray environment to confirm performance goals and predictions for early-life conditions. The tests could be combined with other blanket module tests and would essentially require only additional post-test measurements and evaluation. This issue is closely related to the thermal-hydraulic and tritium issues.

2.2.5.3. Predictions and Control of Effluents Associated with Fluid Radioactivity. Several fluids will be activated (i.e., the breeder, the blanket coolant, shield coolant, and high-heat-flux-component coolants) through activation of the fluid itself or impurities and through sputter and corrosion products from the walls. Because many potential paths exist for radioactivity to reach the environment, standards have to be established and respective safeguards have to be provided.

The MFTF- α T tests would provide valuable experience in actual leak rates, amount of activation, types of activation products, purification procedures, cleaning methods, and maintenance steps for various types of coolants.

2.2.5.4. Structural Activation Product Inventory. The concerns about structural activation are in the areas of maintenance exposure, release in corrosion and sputtering, potential release during accidents, and waste disposal. The key uncertainties are in determining the product cross sections of some very long-lived isotopes, the actual impurity levels, and corresponding activation in engineered materials.

Basic tests to measure cross sections have to be performed with point neutron sources. Tests in MFTF- α T could confirm predictions for fusion neutron spectrum in several engineered blanket modules at early-life conditions. Material qualification and post-test examination would be additional testing efforts when combined with other tests.

2.2.6. Instrumentation and Control Issues

Instrumentation at or near the first wall will experience radiation levels on the order of 10^{22} to 10^{23} n/cm² for which there is very little information. Potential failures produced by radiation damage and transmutations involve, for example, breakdown of insulation resistance, decalibration of sensors, failure of ceramic insulator/substrate seal integrity, darkening of optical windows, lenses, and prisms. Other failures may arise from cable noise and inadequate shielding of instrumentation penetrations. The adequacy of I&C for safe plant operation has to be proven.

The development of I&C requires neutron testing, preferably in a fusion spectrum. Point neutron sources are appropriate tools for extensive probe tests. The value of using MFTF- α T for these tests lies in the integrated nature of MFTF- α T, where neutron and magnetic field, rf effects, vacuum, and design related requirements (e.g., space limitations, penetration shielding, fabrication, etc.) are combined. Also the adequacy and reliability of signal generation for plant control and protection can be developed with MFTF- α T. The neutron fluence in MFTF- α T will fall short at least an order of magnitude compared with the ultimate goal.

3. REQUIRED MFTF- α +T TESTING CAPABILITIES

3.1. INTRODUCTION

Each issue identified in Sec. 2 requires extensive testing. In many cases a differentiated test program, consisting of several steps, is needed; e.g., single effects experiments with small probes, multi-effects tests using characteristic unit cells or elements, integrated tests with candidate blanket modules (not necessarily to full scale and not necessarily including all key environmental conditions), and up to full scale and full environmental component tests with a reference blanket. The MFTF- α +T device with its relatively large test volume and its integrated environmental features is suitable for integrated subscale module testing.

The testing needs described here are not intended to characterize all test steps necessary to resolve the issues because these steps are surveyed in the FINESSE report.⁵ This testing-needs characterization outlines the amount of MFTF- α +T capacity needed to address the individual issues. Thus, the requirements are discussed in device specific terms in Sec. 3.2. The rationale for the entries in Tables 3-1 and 3-2 are given in Sec. 3.3. From these compiled testing needs, a testing scheme is derived in Sec. 4 for a given mission time of MFTF- α +T.

3.2. TESTING-NEEDS SUMMARY TABLES

Table 3-1 summarizes the testing needs required to address the individual issues using MFTF- α +T for testing a liquid-metal-cooled blanket design. Table 3-2 does the same for a solid-breeder blanket design. Table 3-3 lists the footnotes for Tables 3-1 and 3-2. The entries in Tables 3-1 and 3-2 are given in device specific terms as explained below.

Test Volume. The test article has to be tailored to a device-compatible test module that is capable of being easily replaced. The maximum test module size in MFTF- α +T is assumed to be a hollow cylinder of 1-m length, 1.3-m o.d. and 0.5-m i.d. This is considered as a full MFTF- α +T test module and does not include axial and radial shielding for which extra space will be allotted in the device. For some test purposes the module might be divided into axial sections or radial segments, using only a fraction of the complete module.

Table 3-1. Testing needs for a typical liquid-metal-cooled blanket module.

Issues	Test volume (1 = full MFTF- α +T test module)	Test time (No. of 100-hr periods)	Mode of operation ^a	Major test variables ^b controlled/ uncontrolled	Remarks ^c
<u>1. Structure-mechanics issues</u>					
1.1 Heat flux, cycling, transients	1	9	C,T	- σ ,T,D	HC,EH
1.2 Corrosion effects	$\geq 1/2$	10 to 30	S	-/T,C	
1.3 Irradiation effects	$\geq 1/4$	35 to 105	S	-/T,F,M	
1.4 Plasma interactive effects	1	>10	S	-/φ	
<u>3. Thermal-hydraulic issues</u>					
3.1 Response to transients	1	6	T	-/T,v,B	Simultaneous tests
3.2 Flow and temperature distribution	2 x 1/2	2	S	A,D,Q/T,v,B	
3.3 MHD pressure drop	2 x 1/2	2	S	D/T,v,B	
3.4 Corrosion and mass transport	1	>10	S	-/T,v,C	
<u>4. Tritium-related issues</u>					
4.1 Tritium processing	1	~10	S	-/T,C	Simultaneous tests
4.2 Tritium permeation	1	~10	S,C	-/T,C,PH	
4.3 Tritium-breeding uncertainty	1	<10	S	-/T,C,PH	
4.4 Tritium-extraction efficiency	1	10 to 30	S	-/T,C,I	
<u>5. Nuclear issues</u>					
5.1 Shield optimization	Any	Negligible	Pulse	D/φ	
5.2 Nuclear-heating-rate prediction	Any	Negligible	S, Pulse	-/φ	
5.3 Prediction and control of normal effluents		Footnote d			
5.4 Structural-activation product inventory	$\geq 1/4$	~1	S	M/F	
<u>6. Instrumentation and control</u>	Thimble	Footnote d			

^aSee (1) on Table 3-3.^cSee (3) on Table 3-3.^bSee (2) on Table 3-3.^dSee (4) on Table 3-3.

Table 3-2. Testing needs for a typical solid-breeder blanket module.

Issues	Test volume (1 = full MFTF- α +T test module)	Test time (No. of 100-hr periods)	Mode of operation ^a	Major test variables ^b controlled/ uncontrolled	Remarks ^c	
<u>1. Structure-mechanics issues</u>						
1.1 Heat flux, cycling, and transients	1	9	C,T	-/g,T,D	HC,EH	
1.2 Corrosion effects	$\geq 1/2$	10 to 30	S	-/T,C		
1.3 Irradiation effects	$\geq 1/4$	35 to 105	S	-/T,F,M		
1.4 Plasma interactive effects	1	>10	S	-/φ		
<u>2. Breeder-multiplier structure interaction</u>						
2.1 Breeder-structure interaction	4 x 1/4	>10	S,C	M,D/T,Q,%,	HC HC HC	Simultaneous tests
2.2 Breeder-structure heat transfer	4 x 1/4	>10	S,C	M,D/T,Q,P,N		
2.3 Neutron-multiplier mechanical interaction	2 x 1/4	>10	S,C	M,D/T,Q,N		
<u>3. Thermal-hydraulic issues</u>						
3.1 Response to transients	1	6	T	-/T,v,P	A,D,Q/T,v,P -/T,v,C	
3.2 Flow and temperature distribution	2 x 1/2	2	S			
3.4 Corrosion and mass transport	1	>10	S			
<u>4. Tritium-related issues</u>						
4.1 Tritium processing	1	~10	S	-/T,C	Simultaneous tests	
4.2 Tritium permeation	1	~10	S,C	-/T,C,P _H		
4.3 Tritium-breeding uncertainty	1	<10	S	-/T,C,P _H		
4.5 Tritium recovery and inventory	1/4	3 to 5;100	S	T,C/D		
<u>5. Nuclear issues</u>						
5.1 Shield optimization	Any	Negligible	Pulse	0/φ		
5.2 Nuclear-heating-rate prediction	Any	Negligible	S, Pulse	-/φ		
5.3 Prediction and control of effluents		Footnote d				
5.4 Structural-activation product inventory	$\geq 1/4$	~1	S	M/F		
<u>6. Instrumentation and control</u>						
	Thimble	Footnote d				

^aSee (1) on Table 3-3.^cSee (3) on Table 3-3.^bSee (2) on Table 3-3.^dSee (4) on Table 3-3.

Table 3-3. Footnotes for Tables 3-1 and 3-2.

(1) Mode of operation

C = cycling, S = steady state, T = transient

(2) Major test variables

A = dimensions (area)	P_H = tritium pressure
B = magnetic field	Q = power density
C = chemical environment	v = velocity
D = design details	ϕ = flux
F = fluence	σ = stress state
I = impurities	
M = material parameters	

(3) Remarks

HC = hot cell

EH = extra heater

(4) Subordinate to other tests.

Test Time. It is anticipated that MFTF- α +T can be operated without interruption for a period of about 100 hours before it has to be shutdown and reconditioned. The required test times in Tables 3-1 and 3-2 are given in multiples of average 100-hour running periods to indicate that there will be an anticipated number of shutdowns (including transients and down times) during the course of longer tests. Keep in mind that at a projected availability of 10%, nine such 100-hr test periods are equivalent to approximately one calendar year.

Mode of Operation. Most of the issues will require steady-state operation (S) at rated power. If cycling effects are involved, a cycling mode of operation (C) has to be provided according to an as yet undefined scheme. This can be achieved by either power cycling of the device or temperature cycling by the test module coolant system, if appropriate. Transient tests will require controlled system transients (T), again by either power control or temperature control. It is assumed that MFTF- α +T will be capable of both the C and the T mode.

Major Test Variables. Variables, which are intentionally varied throughout the test and thus require different test runs or test articles, are considered as controlled test variables. Typical examples are the power, a characteristic temperature, the design modifications, and the material specification. In contrast, uncontrolled variables are not intentionally altered, but are the result of the entirety of the test conditions. They must be recorded extensively for test evaluation. Typical examples are the temperature distribution, stress state, fluence, material properties, chemical environment, velocity distribution, etc.

Extra Test Equipment. Each test module requires a number of auxiliary supply and makeup systems, some of which may be part of the MFTF- α +T plant itself (e.g., vacuum system, tritium extraction system, shield cooling, maintenance equipment, and biological shielding); others may be specific to the type of blanket under investigation (liquid-metal breeder circuit, helium-purge circuit, heat-removal circuit, tritium-recovery system, etc.); and a third group of equipment may be necessary for a particular issue under investigation. Only the last group is considered

here to indicate major cost contributors for specific issues. Examples are extra heating systems, extensive post-test examination in hot cells, undeveloped measurement equipment, additional safety measures, etc.

3.3. RATIONALE FOR TESTING NEEDS

The following is a brief description of the entries in Tables 3-1 and 3-2. The arguments are applicable to both the testing needs for a typical liquid-metal-cooled blanket module (Table 3-1) and those for a typical solid-breeder blanket module (Table 3-2), unless otherwise stated.

3.3.1. Testing Needs for Structure-Mechanics Issues

3.3.1.1. Effects of Heat Flux, Cycling, and Transients. The test for heat flux, cycling, and transients should comprise one full test module in order to have a representative number of manifolds, joints, welds, and discontinuities, which are the critical parts with respect to structure mechanics, fabrication, and quality assurance. The behavior during typical operational cycling and off-normal transients is the primary goal. Assuming a pulsed mode of 200-s burn time and 100-s dwell time that would allow for 1200 cycles per 100-hr period, a minimum of 10^4 cycles should be achieved resulting in about eight 100-hr periods. An additional period is needed for transients. Extensive post-test examination in hot cells is essential. An extra heating device to improve the surface heat flux is desirable, but would have to be developed.

3.3.1.2. Corrosion Effects. One-half module would be sufficient for corrosion-effects tests because the test focuses on local effects (e.g., hot-spot conditions or high-velocity or turbulent regions) rather than loop wide effects (like transport and deposition). To discover unexpected phenomena or to qualitatively confirm corrosion models in early life, a test time of at least 1,000 to 3,000 hours (10 to 30 periods) seems to be necessary. After this amount of time, effects like liquid-metal embrittlement and stress-corrosion cracking should appear if the system is susceptible to these effects. Quantitative corrosion tests require at least 5,000 to 10,000 hours of testing. The operation mode should be steady state at rated conditions. The temperature and chemical environment are the most important parameters.

3.3.1.3. Irradiation Effects. One-quarter of a full test module would be sufficient to demonstrate irradiation effects in an integrated performance test. Typical minimum damage rates that would show significant effects would be 50 to 100 displacement per atom (dpa) for swelling and 10 to 30 dpa for other mechanical material property changes. The amount of 10 to 30 dpa translates to about 0.4 to 1.2 FPY in MFTF- α +T, equivalent to 35 to 105 100-hour periods. This is considered as an absolute minimum test time to address irradiation effects in structure mechanics. The mode of operation should be steady state to ease interpretation. Temperature, fluence, and material parameters are also important.

3.3.1.4. Plasma Interactive Effects. The plasma interactive effects issue is not test driving because tokamak conditions cannot be simulated. To confirm tandem-mirror performance in the vicinity of neutral beam injection, a full module is desirable with test times of at least ten 100-hour periods. The spatial distribution of the charge-exchange flux is of interest.

3.3.2. Testing Needs for Breeder-Multiplier Structure Interaction Issues

3.3.2.1. Breeder-Structure Interaction. The breeder-structure test should comprise at least one-quarter of a full test module for one set of parameters in order to have a representative number of unit cells and to simulate the complex cooling conditions. Four sets of test parameters seem to be adequate in a first step, where the material and details of the unit cell design are potential test variables. According to FINESSE⁵ a fluence goal of 3 to 5 MW $\cdot$ yr/m² is needed to reduce the prediction uncertainties. However, much smaller fluences can be helpful to discover unknown effects early in the life. For this purpose at least ten 100-hour periods (~ 0.2 MW $\cdot$ yr/m²) should be accumulated. Steady-state operation and, after intermediate inspection, cycling are of interest. Temperature and power density are major test parameters that automatically vary in the radial direction. Extensive post-test examination in hot cells is necessary.

3.3.2.2. Breeder-Structure Heat Transfer. The breeder-structure heat transfer issue would be addressed simultaneously with the issue in Sec. 2.2.2.1 (breeder-structure interaction). The same testing needs apply. In addition, the gas pressure is an important parameter. Extensive

instrumentation for temperature measurements in selected breeder elements is essential.

3.3.2.3. Neutron-Multiplier Mechanical Interaction. Basic neutron-multiplier mechanical interaction tests must be performed in nonfusion facilities before fusion testing. Early-life performance can then be investigated in MFTF- α +T in connection with other mechanical interaction experiments pertaining to the issues in Secs. 2.2.2.1 and 2.2.2.2. An additional test volume of one-half module seems adequate if the multiplier is not yet included in the designs covered in Secs. 3.3.2.1 and 3.3.2.2. The other testing needs are the same as described in Sec. 3.3.2.1.

3.3.3. Testing Needs for Thermal-Hydraulic Issues

3.3.3.1. Response to Transients. Thermal-hydraulic transients should be conducted with a full module to trace 3-D temperature distributions. It is assumed that within one 100-hour period 4 to 10 transients can be conducted and that a total of six 100-hour periods will be needed (i.e., one period for normal operating transients, two periods for fault condition transients, one period to test control mechanisms, and two periods to repeat selected runs after a certain burnup). Important test parameters as a function of time are the coolant and structure temperature, flow velocities or flow rates, and magnetic field in the case of a liquid-metal blanket, or gas pressure in the case of a gas-cooled/purged solid-breeder blanket.

3.3.3.2. Flow and Temperature Distribution. The flow and temperature distribution module may be designed in two halves simulating, for instance, beginning-of-life and end-of-life channel widths and/or other design details. One 100-hour test run should be performed at beginning-of-life and a second should be performed at the end of this module's test mission after it has accumulated some burnup. Steady-state operation at rated power and at partial power is the main testing mode. A few transients can be conducted as described in Sec. 3.3.3.1. Instrumentation and test parameters are also essentially the same as for the transient tests.

3.3.3.3. MHD Pressure Drop. The MHD pressure drop issue would be tested simultaneously with the issue flow and temperature distribution, and it needs the same test provisions. Different designs in critical MHD areas, such as bends and insulation between parallel channels, can be accommodated in portions of the two test module halves. Extensive temperature measurements seem to be the only means for test evaluation besides several pressure readings.

3.3.3.4. Corrosion and Mass Transport. Activation measurements must be taken at the external coolant loop components. To obtain representative results, a full module should be tested, preferably of a uniform design. It must be determined whether two module halves of different designs as proposed in Sec. 3.3.3.2 are also appropriate. At least 1000 hours of accumulated test time at rated power seem to be necessary to override initial impurity effects and to obtain stable conditions. Interruptions may be acceptable, as long as the chemistry in the loops being investigated can be maintained. Besides the chemistry, temperature, and velocity given by the design are the most important test parameters. The mean temperature would be an interesting test variable, but this would require additional testing time.

3.3.4. Testing Needs for Tritium-Related Issues

3.3.4.1. Tritium Processing. To demonstrate tritium processing in a technical scale, a full test module seems appropriate. The main processes involved (like tritium extraction, impurity removal in the fuel cleanup process, tritium system integration, and atmospheric cleanup) require a quasi-steady-state operation with respect to process streams and composition. This can be achieved after a few days of operation. The whole demonstration of tritium processing may require ten 100-hour test periods, where the backfitting procedures in the hardware determine the actual time needed. The process-stream chemistry and temperature are key test parameters although they do not drive blanket design.

3.3.4.2. Tritium Permeation. Measurements of tritium permeation will be used to demonstrate that permeation rates are within design limits. Representative test volumes of about one full module and the pertaining coolant loops should

be used. Test times depend on the blanket design and the tritium-processing system, which determine the quasi-equilibrium tritium pressure in the different subsystems. These measurements should be conducted simultaneously with the tritium-processing demonstration described in Sec. 3.3.4.1. In addition to temperature and chemistry, the tritium pressure is a key parameter. The durability of tritium barriers can only be proven early in the life and after a number of thermal cycles (about 10^3 cycles).

3.3.4.3. Tritium-Breeding Uncertainty. Overall breeding uncertainties probably cannot be narrowed in integrated tests. However, measurements should be taken where possible to check system and process related tritium losses. These measurements can be made simultaneously with the tritium processing and permeation experiments described in Secs. 3.3.4.1 and 3.3.4.2, respectively, and do not need additional test volume and time. On the other hand, assessment of the tritium production rate in solid breeders requires long term operation (see Sec. 3.3.4.5).

3.3.4.4. Tritium-Extraction Efficiency. The tritium-extraction efficiency issue is part of the tritium processing described in Sec. 3.3.4.1 with emphasis on the extraction process from liquid metal. A special feature here is the long term behavior with respect to impurity deposition in the extractor. This requires longer test times of at least 10 to 30 100-hour periods. The impurities generated by neutron irradiation need special attention.

3.3.4.5. Recovery and Inventory (Solid Breeder). A test volume of one-quarter test module is ample to analyze tritium production and transport to the coolant/purge stream in a multicell blanket unit. Tritium release measurements require several hours of steady-state operation for one set of test parameters. Measurements can be taken at different average breeder temperatures and purge stream conditions for a given design. Three to five 100-hour testing periods should be sufficient to demonstrate recovery goals at the early-in-life condition. Tritium inventory measurements require test times of at least one FPY because of the long equilibrium times predicted.⁵

3.3.5. Testing Needs for Nuclear Issues

3.3.5.1. Shield Optimization. For a first confirmation of performance goals and verification of analytical methods, measurements should be taken with various blanket/shield configurations designed for other test purposes and constituting different degrees of geometrical complexity. Required test times are only a few seconds, so that these tests can be performed with the other test programs. The degree to which special features can be addressed by use of special shielding inserts depends on the attainable measuring and modeling accuracies. This will not significantly drive the test plan. Substantial neutron and gamma monitoring is needed.

3.3.5.2. Nuclear Heating Rate Prediction. Global performance tests can be conducted simultaneously with the thermal-hydraulic tests, where calorimetric measurements are taken in steady-state operation. However, these tests will probably not resolve the spatial distribution with sufficient accuracy because of flow velocity uncertainties in the subchannels. Another method is to measure the temperature at many points in the blanket with stagnant coolant in response to a short power pulse. There are other methods that involve specially designed inserts, but they disturb the flux distribution in the test object. It is proposed that in a first step more experience be gained by applying one or both of the first two methods with a minimum of extra effort. Neutron and gamma flux are key parameters.

3.3.5.3. Prediction and Control of Effluents Associated with Fluid Radioactivity. The objective is to obtain experience in actual effluents from integrated systems. Any of the tests described in Sec. 3 can contribute valuable information without additional testing effort, except for some extra analysis. No special testing needs are foreseen.

3.3.5.4. Structural-Activation Product Inventory. The structural-activation product-inventory test can be performed in connection with any of the tests described in this study that are conducted at steady-state conditions and sufficiently long [>10 hours (see Ref. 10)]. Measurements include the dose rate at various locations inside and outside the shield as a function of time after shutdown, and post-test activation measurements at various locations and

parts of the blanket structure. Otherwise no extra test provisions are needed unless special blanket designs made from low activation materials are investigated. Material composition and fluence are important parameters.

3.3.6. Testing Needs for Instrumentation and Control.

To provide adequate instrumentation in the test modules described in this section requires further development and nonfusion testing. It is assumed that fundamental measuring techniques for beginning-of-life conditions in MFTF- α +T will be available. Their application in different tests are considered as performance tests for early-life conditions. These techniques include temperature measurements with thermocouples in structure, fluid, and breeder; static pressure measurements in selected subchannels; strain measurements at the first wall; fluence and spectrum measurements at various locations within the test module with miniature activation foils. The sensors will be part of the respective test modules and do not require extra test volume nor time (except for initial calibration).

More sophisticated instrumentation (e.g., in-situ pressure transducers, optical methods for strain measurements, calorimeters, bolometers, self-powered neutron detectors, and on-line monitoring for tritium production rates) need a special test volume, preferably at the axial edge of the test module in the form of a thimble for easy access. Parallel tests can then be performed throughout the whole test program without influencing the schedule.

4. OUTLINE OF BLANKET TESTS IN MFTF- α T

4.1. TEST OBJECTIVES AND LIMITATIONS

As discussed in Secs. 2 and 3, virtually all of the issues covered here can be addressed in MFTF- α T to a reasonable extent. The available test volume is adequate and the minimum required test time is, for most of the issues, about 1,000 operating hours or less (see Tables 3-1 and 3-2), which is approximately one calendar year or less at a projected device availability of 0.1.

However, serious device related restrictions do exist, that limit the test value in several respects. The most important limitation with regard to structure mechanics is the relatively-low attainable neutron fluence, on the order of a few dpa, allowing only beginning-of-life conditions in the material properties. For solid breeders, the long term breeder and multiplier structure interaction caused by swelling, creep, restructuring, and embrittlement, which is in some respects comparable or even worse than the situation in fission reactor fuel rods at very high burnups, cannot adequately be simulated in MFTF- α T. In the thermal-hydraulics field the most critical issue for liquid-metal cooled tokamak blankets (the MHD effects and related coolability) cannot be solved sufficiently because of size and magnetic-field inadequacy. Also the tritium issues, though effectively addressable in MFTF- α T, should not be expected to be ultimately solvable here because measurement uncertainties, configurational imponderabilities, and uncertainties in losses and basic data will remain. (Note that even the breeding ratio of a fast-breeder fission-reactor system including the fuel cycle still cannot be predicted within an uncertainty of $\pm 10\%$.) The other nuclear issues (shielding, heating rates, effluents, and activation products) depend very strongly on the system integration, i.e., the actual design, the nuclear environment, the materials involved, impurities, leakages, maintenance procedures, etc. Again these conditions cannot be duplicated for a prototype reactor in MFTF- α T. On the other hand, these issues are not considered as critical with respect to feasibility. Finally the development of adequate I&C should be considered as a long term innovative process that is particularly demanding during the R&D phase, when detailed measurement is necessary.

The examples given above are admittedly strong restrictions in an MFTF- α +T test program. Where are the benefits? The objectives of the proposed seven-year blanket testing phase can be generally stated as follows:

For the first time perform nuclear integrated tests with candidate blanket concepts in a DT fusion environment and in a technical scale, and demonstrate the thermomechanical operability and the tritium controllability under early-life conditions.

More specifically, an MFTF- α +T blanket test program should pursue the following goals with respect to the six groups of issues traced through this report:

- Discover mechanical design or fabrication deficiencies and confirm the expectation that first-wall erosion resulting from plasma material interaction is not critical in tandem mirror reactors.
- Discover unknown solid-breeder and multiplier-structure interactive effects and/or confirm early-life performance goals.
- Verify thermal-hydraulics predictability and hot spot temperature controllability.
- Exercise tritium-processing integration in a technical scale and confirm performance goals with respect to tritium production, recovery, and losses.
- Gain field experience in maintenance procedures and in the amount of activation and type of shielding required to establish safety criteria.
- Demonstrate the adequacy of selected sensors and signal transmission lines in a fusion device and develop signal generation techniques for plant protection.

A one-line test objective for each issue is summarized in Table 4-1. More detailed objectives can be formulated as the test module design work progresses, but this will depend heavily on the actual breeder concept selected and the design details (e.g., wall thicknesses, materials, joints, and welds to name but a few). Note that, in the course of more detailed

Table 4-1. Issues and test objectives.

Issue	MFTF- α +T test objective
<u>1. Structure-mechanics issues</u>	
1.1 Effects of heat flux, cycling, and transients	Discover design or fabrication deficiencies
1.2 Corrosion effects	Confirm performance goals early in life
1.3 Irradiation effects	Provide integrated effects early in life
1.4 Plasma interactive effects at first wall	Confirm plasma material interaction as noncritical in tandem mirror reactors
<u>2. Breeder-multiplier structure interaction</u>	
2.1 Breeder-structure interaction	Discover unknown effects early in life
2.2 Breeder-structure heat transfer	Confirm performance goals early in life
2.3 Neutron-multiplier mechanical interaction	Multiplier integrity and structural changes
<u>3. Thermal-hydraulic issues</u>	
3.1 Response to transients	Verify predictions, confirm controllability
3.2 Flow and temperature distribution	Confirm short-term performance goals with volumetric heating
3.3 MHD pressure drop	Intermediate step between nonfusion
3.4 Corrosion and mass transport	testing and full-scale testing Confirm activation dose rates in components, gain handling experience
<u>4. Tritium-related issues</u>	
4.1 Tritium processing	Exercise tritium-processing integration in technical scale
4.2 Tritium permeation	Confirm design limits in fusion environment
4.3 Tritium-breeding uncertainties	Verify prediction in early-life conditions
4.4 Tritium-extraction efficiency	Confirm performance goals in neutron environment
4.5 Tritium recovery and inventory	Confirm release rate predictions, verify fission reactor tests
<u>5. Nuclear Issues</u>	
5.1 Shield optimization	Confirm performance goals in neutron environment
5.2 Nuclear-heating-rate prediction	Confirm performance goals and predictions
5.3 Prediction and control of normal effluents	Gain field experience in amount and type of activation and cleanup
5.4 Structural activation product inventory	Confirm predictions early in life
<u>6. Instrumentation and control</u>	
	Demonstrate suitability in integrated tests, develop signal generation techniques for plant protection

analysis and design and also during testing, new and presently unknown issues can become apparent and may stimulate accompanying test activities. This innovation is an essential part in the blanket R&D process.

4.2. PROPOSAL FOR BLANKET CONCEPTS TO BE TESTED

In the discussion of the issues (Sec. 2) as well as in the assessment of the testing needs (Sec. 3), the issues are treated as equally important, rather than applying a ranking scheme. The reason for this treatment is that any ranking scheme must consider the blanket concept to be pursued, and this concept is not yet identified. For example, the MHD effects pose a feasibility question for self-cooled liquid-metal tokamak blankets, whereas they are of less concern in tandem mirror reactor blankets, and MHD concerns do not exist in nonliquid metal blankets. In contrast, the tritium issues are generally more relaxed in liquid-metal blankets as compared with solid-breeder blankets; also, the structure-mechanics issues are extremely design specific. Therefore, to outline a blanket test program for MFTF- α +T, a target blanket or several options must be assumed.

The primary objective of the BCSS study^{7,8} is to define a limited number of blanket concepts that should provide the focus of the blanket R&D program. This BCSS study is nearly complete. The study found 10 out of 30 concepts potentially attractive for a detailed comparative evaluation. These ten concepts are listed in the left column of Table 4-2 and include the following:

- Four self-cooled liquid-metal blankets,
- Four He-cooled blankets with solid and liquid breeder,
- One water-cooled solid-breeder concept,
- One nitrate-salt (NS) cooled solid-breeder concept.

Table 4-2 also contains the key issues pertaining to each blanket concept and shows that most of the key issues are generic to a group of blankets or to a specific material involved. Therefore, the number of alternatives can be further reduced for this first testing outline.

Table 4-2. Key issues for the blanket concepts.

Blanket concept	Structure mechanics	Breeder-multiplier structure interaction	Thermal hydraulics	Tritium	Nuclear and safety	I&C
(1) Li/Li/V (Tok) ^a	Difficult manufacture, compatibility with non-vanadium BOPC	--	MHD, corrosion	Extraction, permeation	Coolant radiation inventory, water components	Pressure distribution
(2) Li/Li/V (TMR) ^b	Difficult manufacture, non-vanadium BOP	--	MHD, corrosion	Extraction, permeation	Coolant radiation inventory, water components	
(3) Li/Li/FS (TMR)	Limited HTS, ^d heat treatment	--	MHD, corrosion	Extraction	Coolant radiation inventory, water components	
(4) LiPb/LiPb/V (TMR)	Difficult manufacture, corrosion, non-vanadium BOP	--	MHD, corrosion	Tritium control permeation	Coolant radiation inventory, spill cleanup, water components	
(5) Li ₂ O/He/FS (Tok & TMR)	Limited HTS, heat treatment, DBTTE	Temperature window, swelling, thermal expansion, brittleness	Transients, flow in parallel channels, LiOH mass transfer	Tritium control and recovery, breeding, permeation		Temperature measurement

Table 4-2. (Continued.)

Blanket concept	Structure mechanics	Breeder-multiplier structure interaction	Thermal hydraulics	Tritium	Nuclear and safety	I&C
(6) TC/He/Be/FS (Tok & TMR)	Limited HTS, heat treatment, DBTT	Multiplier- structure interaction	Response to transients, flow in paral- lel channels	Inventory, permeation, temperature window, recovery, release from Be		Temperature measurement
(7) L1/He/FS (Tok & TMR)	Limited HTS, heat treatment, DBTT	--	Transients, flow in paral- lel channels, corrosion	Extraction	Water com- ponents	Temperature measurement
(8) FLIBE/He/Be/FS (Tok & TMR)	Limited HTS, heat treatment, DBTT	Multiplier- structure interaction	Poor coolant, response to transients	Tritium control, inventory, recovery, release from Be	Cleanup after spill	Temperature measurement
(9) TC/H ₂ O/Be/FS (Tok & TMR)	Limited HTS, heat treatment, DBTT	Multiplier- structure interaction		Inventory, temperature window, recovery, permeation		
(10) TC/NS ^f /Be/FS (Tok & TMR)	Heat treatment, DBTT, corrosion		Temperature window	Tritium control	Salt stability, activation product control, compatibility	

^aTokamak.^bTandem mirror reactor.^cBOP = balance of plant.^dHTS = high temperature strength.^eDBTT = ductile brittle transition temperature.^fNS = nitrate salt.

Three blanket concepts have been selected for this MFTF- α +T test proposal, representing the most promising variants according to the BCSS Study⁸:

1. The Li/Li/V blanket in the tokamak version,
2. The Li/Li/V blanket in the tandem mirror reactor version,
3. The Li₂O/He/FS (FS = ferritic steel, HT-9 type) blanket, for which the module design may be similar for tokamaks and tandem mirror reactors.

The variants 1 and 3 also have been used as the leading candidates in the FINESSE Study,⁵ and variant 2 is very similar to the MARS design.⁹ By the time MFTF- α +T evolves, a better judgement will be possible as to which blanket concept should be the focus of the test program. For the time being three options are pursued as summarized in Table 4-3:

1. Option A: Splitting the test activities between the Li/Li/V (mirror) and the Li₂O/He/FS variant;
2. Option B: Splitting between the Li/Li/V mirror and tokamak variant;
3. Option C: Testing the solid-breeder variant, Li₂O/He/FS, only.

4.3. TEST PLAN OPTIONS

As described in Sec.4.2, the target blanket and even the type of the DEMO reactor (i.e., tokamak vs tandem mirror reactor) are not yet defined. To demonstrate the capability of MFTF- α +T for accommodating a flexible six to seven year blanket test program, three options have been outlined, as summarized in Table 4-3. These options are based on the minimum testing needs discussed in Sec. 3. The three options are as follows:

1. Option A: Three years of tests with a tandem mirror reactor self-cooled liquid-metal Li/Li/V blanket module followed by three years of tests with a helium-cooled solid-breeder blanket module (Li₂O/He/FS).
2. Option B: A six year liquid-metal-breeder test program; i.e., three years with a tandem mirror reactor type Li/Li/V blanket module, followed by three years of tests with a curtailed and in some respects act-alike tokamak Li/Li/V module.

Table 4-3. Proposed blanket concepts for tests in MFTF- α +T.

Blanket concept Breeder/coolant/structure	Test duration for test plan options (calendar yr)			Remarks
	A	B	C	
Li/Li/V (Tok) ^a		3		Highest ranking in BCSS ^c , FINESSE reference design ^d
Li/Li/V (TMR) ^b	3	3		Highest ranking in BCSS, for tandem mirror reactors; geometry like MARS reference design ^e
Li ₂ O/He/FS (Tok and TMR)	3		6	BCSS ranking is 2/3 for tokamak/tandem mirror reactor, respectively, FINESSE design option

^aTOK = tokamak.

^bTMR = tandem mirror reactor.

^cSee Ref. 7.

^dUsed in FINESSE (Ref. 5) as reference design for a self-cooled liquid-metal breeder blanket.

^eThe MARS design (Ref. 9) uses LiPb/LiPb/FS.

3. Option C: A six year solid-breeder test program applicable to tokamak and tandem mirror reactor blankets with a $\text{Li}_2\text{O}/\text{He}/\text{FS}$ module.

These options should be regarded as typical and, from the present point of view, the most likely testing scenarios. As the tests proceed, there will be enough demands for either stretching the tests or adding new ones for a seven-year program or beyond, if appropriate. Note that each of these in-pile testing scenarios requires intense pretesting as well as analytical effort, particularly in the structure-mechanics area and in thermal hydraulics.

Figures 4-1 through 4-3 outline the proposed test sequences. These figures cover the issues and testing needs defined earlier to the maximum extent possible. The testing requirements can be achieved by conducting several tests in parallel. Because, however, different tests in many cases require different conditions and parameters, only compatible tests can be grouped together for simultaneous runs.

According to a qualitative judgement on the importance of the different tests and their adequacy in MFTF- α +T, three types of tests are distinguished below:

- Leading tests: They dictate the test parameter setting, the mode of operation, and the duration. They are considered as the main *focusing points and are expected to yield quantitative results.*
- Accompanying tests: They are subordinate to the leading tests, therefore, some test conditions may be compromised; quantitative test evaluation should be possible from these tests.
- Passive tests: They basically require attention in the pre- and post-test phase and focus on time and fluence dependent effects. The results are expected to show trends rather than quantities.

The rationale for the three test plan options is described in Secs. 4.3.1 through 4.3.3.

4.3.1. Test Plan Option A (Figure 4-1)

The MFTF- α +T tests will most likely provide the basis for a choice between a liquid-metal blanket and a solid-breeder blanket for further

Fig. 4-1. Test plan Option A: liquid-metal and solid-breeder blanket test program.

Type of test	Time (calendar years)						
	0	1	2	3	4	5	6
	Liquid-metal-blanket			Solid-breeder-blanket			
<u>1. Structure-mechanics tests</u>							
1.1 Effects of heat flux, cycling, transients			CCCCCCCCCCT			CCCCCCCCCCT	
1.2 Corrosion effects degrading the structure	.....	.....	.....	.....	.....	.....	.....
1.3 Irradiation effects	.....	.....	.....	.....	.....	.....	.....
1.4 Plasma interactive effects	.....	.....	.....	.....	.....	.....	.....
<u>2. Breeder-multiplier structure interactions</u>							
2.1 Breeder-structure interaction				SSSSSSSSSS	-----	-----	-----
2.2 Breeder-structure heat transfer				-----	-----	-----	-----
2.3 Neutron-multiplier mechanics interaction							
<u>3. Thermal-hydraulic tests</u>							
3.1 Response to transients			TTTTTTT		TTTTTTT		
3.2 Flow and temperature distribution	SSS	---		SSS	-----		---
3.3 MHD pressure drop	SSS	---					
3.4 Corrosion and mass transport	.....	.....		.....	.....		
<u>4. Tritium-related tests</u>							
4.1 Tritium processing	SSSSSSSSSS				-----		
4.2 Tritium permeation			---	---	-----		---
4.3 Tritium-breeding uncertainties	---	---	---	---	-----		---
4.4 Tritium-extraction efficiency	-----	-----	-----	-----	-----		-----
4.5 Tritium recovery and inventory					-----		
<u>5. Nuclear tests</u>							
5.1 Shield optimization	--		--	--			
5.2 Nuclear-heating-rate prediction	--		--		--		
5.3 Prediction and control of normal effluent	-----	-----	-----	-----	-----		-----
5.4 Structural-activation product inventory	.....	.....	.....	.....	.....		.....
<u>6. Instrumentation and control tests</u>	-----	-----	-----	-----	-----		-----

SSSSSSS Steady state

TTTTTTT Transient

CCCCCCC Cycling

Leading tests

---- Accompanying tests

..... Passive tests

Fig. 4-2. Test plan Option B: liquid-metal-cooled blanket test program.

Fig. 4-3. Test plan Option C: solid-breeder blanket test program.

development; therefore, both types are given the same attention. For the liquid-metal blanket (Sec. 4.3.1.1), the Li/Li/V tandem mirror reactor version was chosen because of its structural simplicity compared with other designs and is placed in the first half of the six year test plan. Section 4.3.1.2 discusses the probably more complicated helium-cooled solid-breeder blanket ($\text{Li}_2\text{O}/\text{He}/\text{FS}$). A multiple switch from one coolant type to the other has been avoided to minimize preparations connected with the heat removal system.

4.3.1.1. Liquid-Metal-Blanket Test Plan. The proposed test sequence for the Li/Li/V blanket is discussed in the following material.

Three Months of Thermal-Hydraulic Tests. Intense flow, temperature, and pressure measurements in steady-state operation at partial and rated power are included in the thermal-hydraulic tests. Several operational transients can be added. The emphasis is on bulk flow and temperature distribution among parallel channels resulting from volumetric heating, geometric, and magnetic effects. Probably, local effects (eddy currents, stratification, and mixing) can only be traced as far as they manifest themselves in hot spots within the structure, which is the main concern. These tests are placed at the beginning of life of the test module, when the instrumentation failure rate should be the lowest.

Twelve Months of Tritium-Related Tests. The tritium-processing issues (Secs. 2.2.4.1 and 3.3.4.1) will determine the actual test sequence in the tritium-related tests. Most of the test runs are expected to be steady state at rated power and should accumulate as much operation time as possible during the one year period (presumably ~10%). The anticipated 90% downtime of the device is supposed to be used for tritium-processing backfitting measures. Accompanying tests are measurements in connection with tritium permeation, breeding, and extraction from Li. Also measurements concerning shielding efficiency of actual configurations and nuclear heating rates at various locations can be performed early in this test sequence. At the end of the sequence selected thermal-hydraulic tests should be repeated for verification. Attention can also be given to possible corrosion product deposition in external loop components after the approximately 0.1 FPY of operation.

Eight Months of Transient Tests. Normal operating and fault condition transients to verify the dynamic behavior of the blanket and heat removal system are included in the transient tests (Secs. 2.2.3.1 and 3.3.3.1). Most of the operating time will be needed to condition the device, reach thermal equilibrium in the test object, and calibrate the instruments. Parameters will be set according to the predicted behavior, so that design limits are approached but not exceeded. At the end of the sequence, tritium permeation measurements can be repeated, if appropriate. If the module can be designed accordingly without penalizing other issues, it is also advisable at this point to replace one module half by a new one before the following cycling tests.

Twelve Months of Structure-Mechanics Cycling Tests. Demonstrating the mechanical integrity at anticipated temperature and stress cycles is the purpose of the structure-mechanics cycling tests. Critical areas are in plastic regimes, at discontinuities, in welds, and at hot spots. Cycling parameters will be set according to predicted and allowable stress histories. Several variants of design details with respect to stress concentration can be built into the test module. If one module half is replaced at the onset of this sequence, then at the end of this sequence three module halves can be compared in the post-test examination with respect to their vulnerability to stress cycles: one of the halves will have experienced the steady-state operation plus transient sequences, one of the halves will have experienced the cycling mode, and the one of the halves will have experienced all of the above. During this sequence, there should be the opportunity to repeat some of the nuclear measurements.

During the entire three-year test phase with the liquid-metal blanket, the effluents control (Secs. 2.2.5.3 and 3.3.5.3) and the I&C (Secs. 2.2.6 and 3.3.6) will require sporadic attention. Also qualitative information will be obtained on time dependent effects like corrosion, irradiation damage, plasma-material interaction, and activation.

4.3.1.2. Solid-Breeder-Blanket Test Plan. The three year test phase for the $\text{Li}_2\text{O}/\text{He}/\text{Fs}$ blanket is proposed in a way similar to the liquid-metal blanket test phase, but emphasizes the solid-breeder-specific issues. The test sequences are discussed in the following material.

Three Months of Thermal-Hydraulic Tests. Intense flow and temperature measurements in steady-state operation at various power levels, flow rates, and gas pressures are included in the thermal-hydraulic tests. Several operational transients can be added. The emphasis is on bulk flow and temperature distribution in narrow gas channels and, hopefully, within the solid breeder material. Local effects like channel dimension variations and stagnation regions are of interest with regard to hot-spot formation. Predicted channel dimensions for beginning-of-life and end-of-life situations can be built into the tests for comparison. The test module can contain regions with design modifications. This sequence is placed at the beginning, when the instrumentation failure rates should be the lowest.

Twelve Months of Breeder-Structure Interaction Tests. The breeder-structure interaction tests will be made at basically steady-state operation, where early burnup effects (like breeder restructuring, embrittlement, clad distortions, heat transfer changes, LiOT transport in the purge stream) may become visible. For post-test evaluation, the test conditions should stay as constant within the design window as possible throughout this sequence. Accompanying tests will focus on mass transfer phenomena in the coolant and purge gas loops, and on the tritium-related issues as indicated in Fig. 4-1 and described in Secs. 2.2.4 and 3.3.4. Also, measurements concerning shielding efficiency of actual configurations shall be performed in this sequence. At the end of the sequence, selected thermal-hydraulic tests should be repeated for verification. After finishing this sequence, one-half of the test module should be replaced by a new one to allow post-test examination.

Eight Months of Transient Tests. Normal operating and fault condition transients to verify the dynamic behavior of the blanket and heat removal system (Secs. 2.2.3.1 and 3.3.3.1) and after-heat removal situations are included in the transient tests. Parameters will be set according to the predicted behavior, so that design limits are approached but not exceeded. Measurements of the nuclear heating rate can accompany the transient test start-up phase.

Twelve Months of Structure-Mechanics Cycling Tests. Demonstrating the mechanical integrity of the submodule's pressure boundary at anticipated

temperature and stress cycles is the purpose of the structure-mechanics cycling tests. Critical areas are in plastic regimes (if existing), at discontinuities, in welds, and at hot spots. Other major concerns are the breeder-structure interaction during cycling and the geometric stability of the breeder elements, i.e., breeder/clad deformation, clad cracks, welds and discontinuities, creep, breeder restructuring, and embrittlement. Several variants of design details can be built into the test module. Cycling parameters will be set according to predicted and allowable stress histories. At the end of the sequence, thermal-hydraulic and tritium permeation measurements shall be repeated and compared with the beginning-of-life behavior.

During the entire three year test phase of the solid-breeder blanket and, in particular, during the twelve-months of steady-state and cycling test sequences, tritium recovery and inventory measurements are important to support predictions. Also the effluents control (Secs. 2.2.5.3 and 3.3.5.3) and the I&C (Secs. 2.2.6 and 3.3.6) will require sporadic attention. In a manner similar to the liquid-metal blanket tests, however with different materials, information will be accumulated about corrosion, irradiation damage, plasma-material interaction, and activation.

4.3.2. Test Plan Option B (Figure 4-2)

Option B concentrates on the liquid-metal blanket concept and proposes a three-year test program with a Li/Li/V tandem mirror reactor blanket module followed by a three-year test program with a curtailed Li/Li/V tokamak blanket module.

4.3.2.1. First Half of Option B. The first three-year test plan for the tandem-mirror-reactor-type blanket is identical to the test plan Option A (Sec. 4.3.1.1) and consists of the following sequence of leading tests:

- Three months of thermal-hydraulic tests
- Twelve months of tritium-related tests
- Eight months of transient tests
- Twelve months of structure-mechanics cycling tests.

4.3.2.2. Second Half of Option B. The second half of the test plan is devoted to the so called poloidal/toroidal blanket concept, which is considered the most viable design option for a self-cooled liquid-metal tokamak blanket.^{5,8} The special features to be investigated are the mechanical design and the thermal hydraulics in the transition region from the poloidal to the toroidal coolant flow channels, and the structure mechanics of the first wall aimed at act-alike conditions. An act-alike stress state can only be approached if a typical surface heat flux of 0.5 to 1 MW/m² can be simulated in the test by using additional heating that has not been developed yet. The test sequences can then be similar to the test sequence for the tandem mirror reactor blanket, described in Sec. 4.3.1.1, with some modifications. Like Option A, there are a number of accompanying tests distributed over the three-year test period as shown in Fig. 4-2, but the main test sequences for this option are as follows:

Six Months of Thermal-Hydraulic Tests. The complexity of the design may require variable orifices for flow adjustment; therefore, this sequence has been extended.

Six Months of Transient Tests. The transient test will repeat the transients performed with the tandem mirror reactor blanket with an entirely different design and additional surface heating.

Twelve Months of Structure-Mechanics Steady-State Tests. The structure-mechanics steady-state tests are intended to accumulate material damage to the maximum extent possible (2.5 dpa at a load factor of 0.1, which can probably be increased at this advanced testing stage of MFTF- α +T).

Ten Months of Structure-Mechanics Cycling Tests. The structure-mechanics cycling tests are similar to Option A.

Two Months of Thermal-Hydraulic Tests. The thermal-hydraulic tests are to verify measurements taken at beginning of life.

4.3.3. Test Plan Option C (Figure 4-3)

In Option C, the entire six-to-seven-year blanket test program is dedicated to the solid-breeder blanket. The lobed $\text{Li}_2\text{O}/\text{He}/\text{FS}$ helium-cooled concept is chosen as a reference design, as in Option A (Sec. 4.3.1.2). The test program is essentially the same as described in the respective phase in Option A, but the benefits of the expanded schedule allow emphasis on time consuming issues like tritium recovery (test 4.5 in Fig. 4-3) and structure-mechanical issues (tests 1.3 and 2.1).

4.3.3.1. Test Sequence Rational

Six Months of Thermal-Hydraulic Tests. The thermal-hydraulic tests provide tests up to design limits as described in the respective three months test sequence in Option A (Sec. 4.3.1.2).

Six Months of Extended Thermal-Hydraulic Tests. A specifically instrumented submodule [for instance, the size of one lobe, (see Sec. 5.2)] that can be separately controlled with respect to temperature and tritium recovery will be used for the extended thermal-hydraulic tests. The intention is to go beyond normal operating limits up to safety limits. Tritium recovery is an important accompanying test during this sequence to investigate the temperature dependence of the tritium-release mechanisms. This test can be extended into and combined with the next sequence.

Twelve Months of Tritium Recovery and Inventory Tests. The tritium recovery and inventory tests will be conducted at various breeder temperatures and purge flow and chemistry conditions. Test runs are expected to be mainly steady state at rated power in order to approach equilibrium tritium concentrations. Tritium permeation from the purge gas into the main coolant and the entire tritium processing are accompanying tests.

Eighteen Months of Breeder-Structure Interaction Tests The breeder-structure interaction tests will be performed at basically steady-state operation, where early burnup effects may become visible, like breeder

restructuring, brittleness, clad distortions, heat transfer, LiOT transport in the purge stream. For post-test evaluation throughout this sequence, the test conditions should stay as constant as possible within the design window, where a burnup of approximately $0.3 \text{ MW}\cdot\text{yr}/\text{m}^2$ will be reached. Accompanying tests will focus on mass transfer phenomena in the coolant and purge gas loops and on the tritium-related issues as indicated in Fig. 4-3 and described in Secs. 2.2.4 and 3.3.4. Also measurements concerning shielding efficiency of actual configurations will be performed early in this sequence. If the reference design calls for a neutron multiplier, this sequence is appropriate for testing multiplier-structure mechanical interaction.

Two Months of Thermal-Hydraulic Tests. Thermal-hydraulic tests will be used to verify the measurements at beginning-of-life or to detect burnup related changes. After this test sequence, one-half of the test module should be replaced by a new one for post-test examination and to upgrade the instrumentation for the next sequence.

Eight Months of Transient Tests. For normal operating and fault condition transients, the transient tests will be used to verify the dynamic behavior of the blanket and heat-removal system (Secs. 2.2.3.1 and 3.3.3.1) and after-heat removal situations. Parameters will be set according to the predicted behavior, so that design limits are approached but not exceeded.

Twelve Months of Structure-Mechanics Cycling Tests. The structure-mechanics cycling tests for Option C will be the same as in Option A, Sec. 4.3.1.2.

Eight or More Months of Irradiation Tests. A submodule that experiences all the previous runs accumulates a fluence of about $0.8 \text{ MW}\cdot\text{yr}/\text{m}^2$ ($\sim 10 \text{ dpa}$). This is at the lower fluence edge, where material property changes can be expected (Sec. 3.3.1.3). It is also below the fluence goal (3 to 5 $\text{MW}\cdot\text{yr}/\text{m}^2$), where breeder-structure interaction effects may become significant. However, according to present knowledge, the 1 to 5 $\text{MW}\cdot\text{yr}/\text{m}^2$ fluence regime is likely to provide relatively more information concerning interactive effects. If the availability of MFTF- α T could be raised to more than about 20% at this stage, then additional test sequences with the

purpose of accumulating as much fluence and lifetime as possible are very attractive. Not only the structure-mechanics issues, but also the tritium recovery issue, the corrosion and mass transfer issue, and other issues would benefit from these extended tests.

During the entire six-year test phase, experience would be gathered in the control of effluents (Sec. 2.2.5.3) and in the area of instrumentation and control (Sec. 2.2.6).

5. DESIGN CONSIDERATIONS

5.1. DEUTERIUM-TRITIUM AXICELL DESIGN

The MFTF- α +T device is made up of various systems and components integrated into a configuration that meets the machine requirements while making maximum use of the existing MFTF-B experimental facility.¹ The MFTF- α +T device configuration can be divided into three main areas: the DT axicell, the central cell, and the end cells; only the DT axicell will be briefly described here.

The DT axicell portion of the fusion chamber is shown in Fig. 5-1. The test module is located in the center of the DT axicell providing vertical access for module replacement by removing the whole test hatch insert. The coolant supply lines and an instrumentation nozzle are integrated parts of the insert. The different axial and radial shield sections as well as the two small choke coils can also be replaced by lateral and vertical motion after removal of the test module insert as described in Ref. 4. Also shown in Fig. 5-1 are the nearly horizontal ducts for two beam lines that penetrate the DT axicell near the test module.

This DT axicell design is essentially the same as described in Refs. 1 through 4; however, two modifications should be pointed out: the elimination of the background-field magnet and the inclusion of a vertical test thimble adjacent to the test module.

A trade study of the DT axicell magnetic configuration⁴ led to the proposal to include a background-field copper coil surrounding the test module as indicated in the Fig. 5-1 insert. This would allow a reduction in the size and cost of the two large superconducting central-cell coils. The additional coil would, however, seriously aggravate the performance of the blanket tests for several reasons:

1. The test module design, particularly the supply lines and the instrumentation access, would be much more stringent.
2. The radial reflector design would have to emphasize coil protection rather than breeding and test considerations.
3. The water-cooled copper coil surrounding a liquid-metal-cooled test module would raise safety concerns.
4. Remote maintenance would be complicated.

Figure 5-1. Deuterium-tritium axicell design of MFTF- α +T (modified) showing the test module, test thimble, and shielding.

Because of the above concerns, it is important that these consequences be considered in any new trade-off.

To include an additional test port, the second modification constitutes an enlargement of the test-module hatch insert in an axial direction. This port of $0.2 \times 0.5 \text{ m}^2$ cross section penetrates the axial shield section radially and would allow the insertion of a test thimble for miscellaneous tests. The insertion of the test thimble would be independent of the insertion of the test module proper. Candidate tests are in the area of instrumentation (as pointed out in Tables 3-1 and 3-2), shielding effectiveness, and other small-scale multiple-effect tests that, necessarily, must not be part of the main-line test program.

5.2. TEST MODULE DESIGN

According to the three test-plan options described in Secs. 4.2 and 4.3, three different test-module scope designs are outlined below:

- A liquid-metal-cooled blanket module representing a tandem mirror reactor blanket,
- A liquid-metal-cooled blanket module representing key features of a tokamak blanket,
- A helium-cooled solid-breeder blanket module comprising a number of breeder elements that are frequently envisaged for both a tokamak and a mirror reactor.

All designs are tailored to the test module envelop dimensions of 1.3-m o.d., 0.5-m i.d., and 1-m length. No analysis has been done so far.

The tandem mirror reactor version of the liquid-metal-cooled blanket module is shown in Fig. 5-2. It is essentially the scaled down MARS⁹ design, consisting of an inner tubular zone and an outer beam zone. The coolant ducts are welded to the manifolds at the bottom and top. The upper manifold is divided into two chambers, i.e. the upper and the lower chamber. The coolant enters the upper chamber, is axially distributed, and flows downward through the rectangular ducts in the beam zone. The flow is reversed in the lower manifold and directed upward through the tubular zone into the lower chamber of the upper manifold, from where it

Figure 5-2. Liquid-metal-cooled blanket module for tests in MFTF- α +T showing the modified MARS design tailored to the MFTF- α +T test cell dimensions with coolant supply lines coming from the top.

exits the module. This scheme is different from the MARS⁹ design, which has an inlet at the top and an outlet at the bottom, providing parallel downward flow in all coolant channels. The thermomechanical implications have to be analyzed. It is believed, though, that equivalent stress conditions can be maintained.

The tokamak liquid-metal blanket can only be partially simulated in the MFTF- α T test module because of space limitations and differences in the magnetic field. The schematic diagram for a test module in Fig. 5-3 is an attempt at simulating the flow pattern relative to the magnetic field as present in the poloidal/toroidal blanket, which is the reference design in the BCSS study.⁷ The test module has an inner zone, resembling the toroidal channels of the first wall structure of the tokamak blanket, and an outer zone. The outer zone in turn is divided into two end chambers and the middle section. The coolant enters into one end chamber, is circumferentially distributed to the axial channels of the inner and outer zone, and is recollected in the opposite end chamber. Flow calibration to the different axial channels is provided by orifices in the baffle, separating the inlet end chamber and the middle section. This design features the flow redirection from circumferential to axial flow, equivalent to the poloidal/toroidal flow pattern in the tokamak blanket. The design is very simple and has several advantages over the tubular design in Fig. 5-2: it contains more breeder, has a smooth surface facing the plasma, and has only a few high quality welds. For test purposes the orifices in the baffle plate can easily be made adjustable by a second rotatable plate that may partially mask the orifices.

Figure 5-4 shows the schematic arrangement of eight solid-breeder units forming a test module. Assuming a 10-cm allowance at the outer edge for a constraint and header structure and considering the lobed contour at the plasma side, the usable breeder zone can be approximately 16-cm wide. This is only about one third of a typical breeder thickness in a tokamak and seems to be an inherent shortcoming of the limited module thickness (40 cm) for gas cooled designs that require much space for manifolding. An enlargement of the test module by about 20 cm in radius to the expense of the radial reflector/shield section should be considered. This enlargement would double the breeder-zone thickness; ample radial space exists if the background-field magnet could be eliminated.

Figure 5-3. Liquid-metal-blanket test module simulating the poloidal/toroidal flow pattern in a tokamak blanket (dimensions in cm).

Figure 5-4. Schematic of a solid-breeder test module showing the arrangement of the lobular breeder units.

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