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ETF Mission Statement Document

ETF Design Center Team

Engineering Test Facility
Design Center

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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ETF MISSION STATEMENT DOCUMENT

ETF Design Center Team

Date Published: April 1980

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ABSTRACT

The Mission Statement Document describes the results, activities, and processes used in preparing the Mission Statement, facility characteristics, and operating goals for the Engineering Test Facility (ETF). Approximately 100 engineers and scientists from throughout the U.S. fusion program spent three days at the Knoxville Mission Workshop defining the requirements that should be met by the ETF during its operating life. Seven groups were selected to consider one major category each of design and operation concerns. Each group prepared the findings of the assigned area as described in the major sections of this document. The results of the operations discussed must provide the data, knowledge, experience, and confidence to continue to the next steps beyond the ETF in making fusion power a viable energy option. The results from the ETF mission (operations are assumed to start early in the 1990's) are to bridge the gap between the base of magnetic fusion knowledge at the start of operations and that required to design the EPR/DEMO devices.

1. INTRODUCTION

In September 1978 John Deutch, Director of Energy Research for the U.S. Department of Energy (DOE), articulated the DOE policy for fusion energy.[1] This policy statement, which covered both the magnetic confinement and inertial confinement approaches, outlined a three-phase strategy to develop fusion energy as an economically attractive and environmentally acceptable energy option. These three phases focus on scientific feasibility, engineering testing, and reactor demonstration.

It is anticipated that the scientific feasibility of both the magnetic confinement and inertial confinement approaches will be achieved during the 1980's. Following the achievement of scientific feasibility, each of the two approaches will move from applied research into an engineering testing phase. The vehicle by which the fusion program will move into this phase of development is designated the Engineering Test Facility (ETF). The ETF will provide a fusion environment test-bed for the reactor components. These components will be the essential building blocks of the facilities to be constructed and operated during the reactor demonstration phase: the Engineering Prototype Reactor (EPR) and the Commercial Demonstration Reactor (DEMO).

In order to initiate preliminary planning for the ETF decision in the magnetic confinement approach, the Office of Fusion Energy (OFE) established the ETF Design Center activity at Oak Ridge National Laboratory (ORNL) to prepare the design of a tokamak ETF. At the same time, a mirror ETF design task was established at Lawrence Livermore Laboratory (LLL). ETF design tasks will be considered for other confinement concepts as their physics performance is brought up to the level achieved by the tokamak and mirror experiments. Currently the tokamak ETF effort at the ETF Design Center is receiving the highest level of support because tokamaks have achieved the highest level of plasma performance. In any case, many of the key technological and engineering problems of magnetic confinement fusion concepts are generic in character; thus, the emphasized effort directed to the tokamak will be of general value to the magnetic fusion program. Such generic issues are highlighted by the needs in materials, magnets, plasma heating by beams and by radio frequency (rf) energy, impurity control and ash removal, tritium handling, remote maintenance, and availability/reliability.

As a point of departure for the ETF activities, it was deemed essential to establish a well-defined statement on the mission of the ETF in the overall fusion program strategy. In the FY 1978 The Next Step (TNS) activities, the various design teams addressed the issue of the mission for the TNS. The Office of Fusion Energy used the mission statement results of last year's TNS activities to develop a preliminary mission statement for the ETF. In order to develop a more detailed and complete mission statement for the ETF, the ETF Design Center organized and conducted an ETF Mission Workshop, held in Knoxville, Tennessee, February 13-15, 1979. The Workshop focused on a tokamak-based ETF; however, the engineering and technology requirements of alternate concepts represented an essential element of the Workshop deliberations. The Mission Workshop brought together a broad range of expertise from within the fusion community and involved representatives from both the fusion research centers and industry. Approximately 100 representatives of 25 organizations participated in the Workshop.

In preparing for the Workshop, six elements were emphasized as being critical to its success:

(1) a well-defined reference case,
(2) a comprehensive set of topics,
(3) the selection of chairmen and participants expert in these topics,
(4) a broad fusion community representation and participation,
(5) detailed guidelines for conducting the Workshop, and
(6) preliminary discussions and interactions with the chairmen.

The reference case for the Workshop consisted of three elements: (1) the TNS design parameters (see Appendix A.8), which provide a reference set of characteristics for the ETF; (2) current EPR/DEMO parameters (see Appendix A.8), which provide a reference set of component requirements for the ETF achievements and milestones; and (3) the Preliminary Mission Statement drafted by DOE, which lists reference objectives and a test plan for the ETF (see Appendix A.8). It is interesting to note that the major differences in plasma characteristics among the TNS, EPR, and DEMO designs are in the areas of burn time and power density while the major differences in component requirements among these designs are in the areas of availability and efficiency. The ETF objectives proposed in the Preliminary Mission Statement were cast in the context of seven workshop subgroups, as indicated in Table 1.1. Subgroup chairmen and participants were chosen to represent a high level of technical expertise in each subgroup area. The subgroup chairmen and their respective institutions are also indicated in Table 1.1.

Table 1.1. ETF Mission Workshop subgroups and chairmen

Subgroup area	Chairman
Alternate concepts	R. Aronstein, Bechtel Corporation
Blanket/first wall/shield technology testing	C. A. Flanagan, Westinghouse Electric Corporation
Heating/fueling technology testing	L. D. Stewart, PPPL/Exxon Nuclear Company
Materials testing	E. E. Bloom, ORNL
Plasma operations testing	J. M. Rawls, GA
Remote maintenance and engineering operations testing	D. L. Kummer, McDonnell-Douglas Astronautics Company
Tritium/particle collection technology testing	V. A. Maroni, ANL

The ETF Mission Workshop was highly successful because of the efforts of the chairmen and participants and the planning done before the Workshop began, particularly the discussions and meetings held with the subgroup chairmen. The contributions of the chairmen and the participants were essential to the success of the Mission Workshop. The Workshop output was very valuable and has contributed significantly to the preparation of the ETF Mission Statement.[2]

The output of the Mission Workshop subgroup deliberations consisted of charts that listed the following items for each subgroup area:

(1) the key issues, (2) the assumed status of the data base in 1990, (3) the necessary milestones and achievements that would have to be demonstrated by the ETF, (4) the requirements for the ETF in terms of its overall design and facility capabilities in order to achieve the milestones, (5) the requirements in terms of testing time in order to achieve the milestones, and (6) the major impacts relative to the reference case in terms of design, facility, and testing requirements.

The ETF Design Center Team took the output of the subgroup areas and developed it into a consistent format. At this time some thought was given to setting priorities in each subgroup area. The results were circulated back to the subgroup chairmen and subgroup participants for their comments. Presented in Appendixes A.1-A.7 are the results of these activities. The subgroup input was then integrated into an overall operating schedule, and issues of overall priorities and impacts on the ETF were evaluated and assessed. A discussion of the Mission Statement is included in Sect. 2 of this report. Appendix A.8 contains relevant background information and a list of the Workshop participants.

The Mission Statement[2] represents a point of departure; it will be updated and reviewed as the ETF Design Center activities proceed. With the Mission Statement as a guide, the ETF Design Center will engage in systems analysis and design specifications aimed at developing the most cost-effective facility for achieving the goals and objectives set forth in the Mission Statement. The design specifications will then be used to lay out an engineering design for the ETF. During this time a comprehensive R&D needs assessment will also be taking place. The R&D needs assessment is being carried out as a fusion community activity and will serve the requirements of both the ETF Design Center and the International Tokamak Reactor (INTOR) activity being conducted under the auspices of the International Atomic Energy Agency (IAEA). The output of the R&D needs assessment will be integrated and evaluated by the ETF Design Center relative to the specific requirements of the ETF. The results of this evaluation and integration, together with the detailed design work, will be used to make recommendations to OFE relative to the ETF program, cost, and schedule. At this point the mission of the ETF will also be reevaluated.

The ETF Design Center will then focus on the detailed conceptual design of the ETF, with a continuing updating of the R&D needs assessment and refining of the ETF Mission Statement. The ultimate objectives of these activities are to prepare the ETF design and to perform the associated project engineering and planning functions in sufficient detail to support a decision point for the ETF at the earliest possible date.

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2. ETF MISSION STATEMENT

2.1 INTRODUCTION

The ETF Mission Statement[2] was prepared by the ETF Design Center based on available information, notably the suggestions and recommendations of the ETF Mission Workshop. The ETF Advisory Committee reviewed the document and provided significant guidance, which was integrated into the Statement. The ETF Mission Statement was also reviewed and approved by the Department of Energy's Office of Fusion Energy. This document represents a point of departure and will be revised as necessary at least once a year. A continuing effort will be maintained to obtain and incorporate all pertinent suggestions from throughout the fusion community.

2.1.1 Definition of the Mission Statement

The Mission Statement defines the ETF activity during its operating life. The results of those operations must provide the data, knowledge, experience, and confidence to continue to the next steps beyond the ETF in making fusion power a viable energy option. The results from the ETF mission (operations are assumed to start early in the 1990's) are to bridge the gap between the base of magnetic fusion knowledge at the start of operations and that required to design the EPR/DEMO devices.

The ETF mission must represent the most expeditious way of proceeding to these demonstration activities, even though the magnetic fusion concept to be used is not yet confirmed. The facility is to address the engineering and technology issues of the march toward the fusion energy option. The understanding that most of these issues are generic to any magnetic fusion concept loosens the bounds that might otherwise restrict or delay the choice of concepts and directs the attention to the earliest fusion core that can provide the reactor environment for resolutions that will benefit almost equally the contending fusion approaches. These generic issues include materials, superconducting magnets, neutral beams, rf energy injection, fueling, impurity control and helium ash removal, tritium handling, maintenance, plasma disruptions, and availability/reliability/operations/cost. The emphasis on the tokamak as the first fusion core for the ETF is based on its unique advanced stage of scientific feasibility demonstration. The ETF mission will also include planned operations in support of the test and study of nongeneric or alternate-concept-specific engineering and technology issues necessary to achieve the best design foundation for proceeding with any of the probable approaches. The cost-effectiveness of these design flexibilities will be carefully considered before inclusion in the ETF design.

2.1.2 Purpose of the Mission Statement

The definition of the ETF mission is a major step in the iterative process of defining and planning the ETF project. The Mission Statement characterizes the demands to be placed on the ETF operations and hence the design requirements necessary for the facility to meet those demands. The iterative process includes the following major items:

(1) DOE policy,
(2) fusion power strategy,
(3) ETF role in the strategy,
(4) ETF mission,
(5) ETF design requirements, and
(6) ETF costs, schedule, and R&D needs.

Feedback loops abound and permit the broad iteration needed. The DOE policy has been published.[1] The fusion power strategy includes the key milestones of (1) scientific feasibility, (2) the ETF, (3) EPR/DEMO, and (4) finally a commercial power reactor (CPR). The role of the ETF in the strategy is to bridge the gap between scientific feasibility knowledge and the knowledge required for the EPR/DEMO projects.

The determination of the ETF mission, operations, and tests that will bridge the gap requires two sets of data: (1) the data, knowledge, and confidence needed for an EPR/DEMO project and (2) the data, knowledge, and confidence that will exist in 1990 at the beginning of ETF operations. Then the role of the ETF can be defined and the designs can proceed.

The ETF Mission Statement uses the past studies on EPR/DEMO projects (see Appendix 8) to provide guidance as to what should be accomplished before such a project is undertaken. Next, the 1990 data base assumptions were made, largely with the input from the ETF Mission Workshop, with the guidelines that (1) only those major projects now planned or under way, plus modest upgrades, will be available to add to the data base and (2) the effective level of effort in applied plasma physics, confinement physics, and development and technology will stay the same as in FY 1979.

The time-phased data requirements that must be met to support the ETF design process are being identified and will in turn provide a basis for assessing the adequacy of the presently planned R&D programs to meet these needs. Iterations of the plans for these areas will be needed to meet the project needs. Variations in the planned R&D will, of course, alter the 1990 assumptions and thereby modify the ETF mission; revisions of the Mission Statement will reflect these changes.

The steps followed in preparing the ETF mission were to define, in order, these areas: (1) the 1990 data base assumptions, (2) the achievements/milestones required from ETF operation for the EPR/DEMO projects, (3) the necessary device/facility characteristics, and (4) the testing schedules required for the achievements/milestones.

2.2 ASSUMPTIONS OF THE 1990 DATA BASE

The start of the ETF facility operations is assumed to be in the early 1990's. In order to define the required ETF testing program or mission that will provide the achievements needed for EPR/DEMO, the data base of physics, technology, and engineering that is expected to be available prior to ETF operation must be assumed. Additionally, the data base required to move to EPR/DEMO must be identified. The difference between the assumed 1990 knowledge base and that necessary for the EPR/DEMO designs is to be supplied by the ETF operations/mission. The assumptions are based on the guidelines that only those machines now planned (plus modest upgrades) are to be considered in estimating the data base.

The ETF is expected to be the major magnetic fusion facility in the 1990's, and although its primary role will not be for plasma physics experimentation, the requirements for operation in new plasma parameter regimes dictate an exploratory phase to define the physics relevant to the subsequent engineering/technology testing phases. Safe, reliable, and repeatable plasma operations are needed for the engineering test phase.

The ETF device must generate a data base adequate to proceed with EPR/DEMO designs. The designs used in the follow-on reactors must be confirmed by appropriate testing of the ETF systems. Ignition is the goal for the machine, and it is to be designed to produce a deuterium-tritium (D-T) burning plasma to provide the environment for technology qualification. The burn times will be targeted for hundreds of seconds, limited by the volt-second capability. Necessary divertor action to avoid limitations on burn time caused by impurities and helium buildup will be a key part of the design.

The development of the testing needs described in the ETF Mission Statement assumed an adequate machine availability and a design approach that would provide the flexibility needed to address some alternate-concept-specific key issues in addition to defining the device sensitivity to various operating parameter variations.

Some key assumptions made in preparing the ETF Mission Statement may have considerably more impact on the ETF design than others. In many cases these crucial assumptions were also the most difficult to substantiate. Such assumptions include methods of impurity control; types and combinations of plasma heating systems; the dynamics of complete plasma scenarios, including disruptions; maintenance philosophy; test-proven bases for remote maintenance systems design; tritium processing and control; security classification problems of tritium extraction; and desired test conditions (wall loading in megawatt-years per square meter, etc.) for materials and blanket modules. There are two important categories of assumptions: those that affect the basic machine design and those that help define the testing program. The former must consider that the basic design is to be frozen shortly after the projected start of Title I. The latter can be incorporated into the device if sufficient flexibility is retained during design and construction.

The more important assumptions of the data base available in 1990 are noted below.

2.2.1 Plasma Operations

- Impurity control

  (1) Understanding of divertor physics and long pulse impurity control feasibility under high power load; demonstrations limited to short pulse experiments with modest particle and heat fluxes.

  (2) Exploration of divertorless operation on a variety of devices.

- Dynamic scenarios data base

  (1) Startup — quantifiable information on all aspects.

  (2) Heating — demonstration of density buildup, overdense injection heating, and rf heating feasibility.

  (3) Stability — determination of plasma beta and its control.

  (4) Burn — information on high Q ($Q > 1$) operation from core of Tokamak Fusion Test Reactor (TFTR) or Joint European Torus (JET) by 1990.

  (5) Shutdown — understanding of fusion quench and current rampdown and abort scenarios.

2.2.2 Heating/Fueling Technology

- Neutral beams

  (1) Positive ion systems — 150-keV, 5- to 6-s-pulse, 50-MW systems, operating at 40% efficiency with direct recovery and producing 2 kW/cm^2 of D^0.

  (2) Negative ion systems — beam development tests at $\sim$250 keV.

- RF heating
    1. (1) Electron cyclotron radiofrequency (ECRF) — significant testing accomplished on T-10, the Impurity Study Experiment (ISX), and the ELMO Bumpy Torus (EBT-II).
    2. (2) Ion cyclotron radiofrequency (ICRF) — significant testing accomplished on the Princeton Large Torus (PLT), the Poloidal Divertor Experiment (PDX), TFTR, and Doublet III.
    3. (3) Lower hybrid heating (LHH) — megawatt-range testing on Doublet IIA, Alcator C, and PLT.

Test results will have determined the efficacy of rf preheating and the relative capabilities of the different methods for bulk plasma heating.

- Pellet injection
    1. (1) Demonstration of system that can provide 20-100 pellets, 1-3 mm in diameter, per second at speeds of 1000-3000 m/s.

2.2.3 Tritium/Particle Collection Technology

- Technology for between-pulse pumpdown in hand.
- Resolution of divertor question and demonstration of particle collection method.
- Demonstration in the Tritium Systems Test Assembly (TSTA) of a workable system for fuel processing.
- Verification of tritium supply, control, and accounting methods.
- Resolution of security classification issues.

2.2.4 Blanket/First Wall/Shield Technology

- Substantial data from many machines and facilities, although with modest particle and heat fluxes.
- Broad technology advancements, limited by lack of adequate nuclear test facilities.
- Complete control and/or avoidance of plasma disruptions not established; essentially disruption-free operations obtained.

2.2.5 Remote Maintenance and Engineering Operations

- Test-proven techniques for designing remote maintenance systems.
- Confirmation of the need and value of extensive mockups and models through use in ETF design and assembly.

2.2.6 Materials

- Adequate confidence to build the ETF, provided by testing of materials in various facilities including the Oak Ridge Research Reactor (ORR) and the Fusion Materials Irradiation Test (FMIT) facility.
- Adequate nonirradiated materials properties proven by test prior to ETF operation.

2.2.7 Alternate Concepts

- Status of alternate-concept-specific data in the research or development testing phase.

2.3 ACHIEVEMENTS/MILESTONES

The ETF Design Center has considered the achievements that must be realized and the milestones that must be met to add to the assumed 1990 base of knowledge so that the level of understanding and confidence at the end of the ETF will be sufficient to confirm the design bases for the EPR/DEMO programs. The considerations for each major area are described in some detail in Appendixes A.1-A.7. The highlights of the recommended achievements/milestones are listed below.

2.3.1 Plasma Operations

- Impurity and particle control

  (1) Achieve reactor-prototypical impurity control: low Z_{eff} with low Z impurities for long (hundreds of seconds) pulses.

  (2) Demonstrate successful fueling and helium removal.

- Dynamic scenarios
  1. Optimize startup.
  2. Achieve reactor-level beta over long pulse (∼100 s).
  3. Demonstrate stably controlled burn.
  4. Optimize the termination of high energy density plasma discharges.

2.3.2 Heating/Fueling Technology

- Beams — obtain high availability (∼90%) of 50 MW.
- RF — achieve high availability (∼90%) of selected system at power levels of 10-50 MW.
- Pellets
  1. Achieve 98% availability in sustained fueling mode.
  2. Optimize pellet size, penetration, and feed rate.

2.3.3 Tritium/Particle Collection Technology

- Demonstrate successful particle collection and recycling for long (∼100 s) pulse D-T burns.
- Demonstrate the tritium-handling and control capabilities necessary for EPR/DEMO designs.

2.3.4 Blanket/First Wall/Shield Technology

- Determine the adequacy of first wall designs for EPR/DEMO applications, withstanding physical and chemical sputtering, load cycling, neutron damage, and plasma disruptions and permitting ready replacement.
- Determine the adequacy of tritium-breeding blanket designs for EPR/DEMO applications with respect to breeding ratio, cyclic thermal hydraulic conditions, neutron damage, and replacement.

- Determine the adequacy of EPR/DEMO shield design concepts, including penetration shields, with regard to shielding effectiveness, activation, shield cooling, repair, and replacement.

2.3.5 Remote Maintenance and Engineering Operations

- Demonstrate maintainability of device components.
- Obtain experience from ETF operation for maintainability and design of EPR/DEMO.

2.3.6 Materials

- Determine the performance of critical EPR/DEMO materials in the fusion environment (requires at least 6 MWyr/m^2).

2.3.7 Alternate Concepts

- Determine specific problems that can be addressed with no major ETF design impact, incorporate necessary flexibility, and accomplish tests.

2.4 TESTING SCHEDULE REQUIREMENTS

The necessary ETF achievements/milestones fall into three categories: (1) machine dedicated — other test activities are largely interfered with, (2) noninterference — other concurrent significant test activity can continue, and (3) continuous — activities that are conducted as a part of the normal operation. Obviously the largest schedule impact results from the machine-dedicated tests that prevent the performance of other tests.

The purposes of the tests are two-fold: (1) to provide the necessary confidence level to design EPR/DEMO and (2) to aid in the best concept selection from competing possibilities. The latter area would encompass such concerns as bulk plasma heating by neutral beams and by radiofrequency, impurity control concepts, and plasma dynamics control approaches.

There is a recognized need for a hydrogen test period, a shakedown period during which the integrated operation of the ETF is checked out in an essentially hands-on mode. In this period an ambitious test schedule for plasma operations is required, and some of the remote maintenance techniques must be proved. The highlights of the testing needs in the hydrogen test phase are shown in Table 2.1. Some of the tests within a subgroup area may be done in parallel, so the individual test times do not add up to the total time required as shown for the area. The highlights of the D-T test phase are shown in Table 2.2, which indicates a rather extensive set of needs.

2.5 INTEGRATION AND PRIORITIES

As planned, the ETF Mission Workshop concluded with the presentation of the findings of the various subgroups. These results have been integrated with other findings, and relative priorities have been established by the ETF Design Center. Reviews and periodic updates of these considerations are planned.

The integration and priorities deliberations are concerned with the apparent problem that the total needs suggested by various considerations do not easily mesh into the reference case designs and mission. The ETF Mission Workshop subgroups addressed their assigned areas only, and the results of their work had to be integrated with other considerations to reflect the relative importance of the suggested approaches. The priorities determination used consists of three parts: (1) first priority is given to work on those elements that are expected to be a basic part of the EPR/DEMO, (2) second priority is given to activities that pertain to determining whether a competing approach is preferred for EPR/DEMO, and (3) last priority is given to the remaining more generic recommendations that add to the general data base.

The first priority tests aim at the establishment of confidence in the reliability and availability of systems that are expected to form the foundation for the EPR/DEMO designs. Second priority tests would include the testing of rf plasma heating to determine if it is a better approach than neutral beams or if a combination would be preferred.

Table 2.1. Hydrogen phase test needs (∿1 year)

Subgroup	Test area	Test time[a]
Plasma (assuming 25% machine availability)		Dedicated time $\leqslant$ 1 year
	Achieve adequate cleanliness in hydrogen	3 months
	Optimize I_p initiation and rampup	2 months
	Achieve $n\tau > 10^{14}$ cm^{-3} s	7 months
	Achieve adequate heating scenario (physics)	4 months
	Produce and control modest beta plasmas	
	Optimize shutdown for high energy density hydrogen plasmas	
Heating/fueling technology		Noninterference time $\leqslant$ 1 year
	Achieve necessary beam heating and pellet injection test experience and confidence to enter D-T phase	
Particle collection technology		Noninterference time $\leqslant$ 1 year
	Demonstrate divertor to the extent hydrogen operation will permit	
Maintenance/engineering operations		Noninterference time $\leqslant$ 1 year
	Test maintenance techniques and procedures that cannot be done on major mockups and during machine assembly	

[a] Tests within a subgroup may be in parallel so that the total subgroup time will not equal the sum of the specific test times.

Table 2.2. D-T phase test needs (>15 years)

Subgroup	Test area	Test time
Plasma (assuming 25% machine availability)		Dedicated time ∼ 1 year
	Achieve $Q > 5$	6 months
	Demonstrate thermal control	
	Quantify alpha particle heating and transport	
	Produce and control high beta, ignited, D-T plasma for long times	6 months
	Demonstrate reactor-prototypical impurity control	
	Demonstrate fuel depletion and ash accumulation control	
	Establish reliable fusion core operation for engineering testing	
	Validate scaling laws in reactor-relevant regime	Continuous
	Optimize fusion plasma performance	
Heating/fueling technology		Noninterference time ∼ 7 years
	Demonstrate efficiency and reliability for EPR/DEMO	
Tritium/particle collection technology		Noninterference time ∼ 10 years
	Divertor collector tests for EPR/DEMO	∼5 years
	Performance and reliability necessary for EPR/DEMO	∼2 years
	Demonstrate fuel processing and tritium inventory control for EPR/DEMO	∼8 years
Blanket/first wall technology		∼14 years
	Test and qualify first wall design for EPR/DEMO	∼5 years
	Electricity production demonstrated	∼5 years
	Tritium-breeding blanket design tested and qualified (two tested) for EPR/DEMO	∼7 years
	Shield concepts tested and qualified for EPR/DEMO	∼10 years
	Synfuel blanket candidates tested and qualified	∼4 years

Table 2.2 (continued)

Subgroup	Test area	Test time
Maintenance and engineering operations		Continuous
(Maintenance/repair/replacement as needed)		
Materials	Noninterference time 1 year + 9 years ∿ 10 years	continuous
Correlation with other test data	∿1 year	
Test candidate materials ($\geqslant$6 MWyr/m^2)	∿9 years	
Alternate concepts technology		Continuous
Alternate concepts technology needs also met by ETF tests include		
First walls		
Blanket and shield		
Fueling		
Vacuum systems		
Blanket processing (tritium and synfuel)		
Power conversion		
Materials		
Tritium handling		
Reliability/availability		
Alternate concepts technology needs largely met by ETF tests include		
Superconducting magnets		
Neutral beam systems		
RF systems		
Power supplies		
Impurity control and ash removal		
Cryogenic systems		
Heat transport systems		
Remote maintenance		
Alternate concepts technology needs requiring separate tests include		
Instrumentation and control		
Direct power conversion		
Poloidal field energy recovery		

Last priority tests would include the evaluation of a synthetic fuel (synfuel) blanket that provides data valuable for all reactor design considerations but not necessarily essential to the EPR/DEMO success.

The results of the integration and time phasing of test priorities provide the basis for a general description of a facility with the following characteristics, which are designated the ETF preliminary design requirements.

(1) The first fusion core, a tokamak, is to be an ignited, long pulse, D-T burning machine.

(2) The initial conceptual design effort should include a divertor system, and it is expected that a divertor system will be included throughout the conceptual design phase. Continuing parallel studies will provide guidance in comparing a bundle divertor (in the present baseline design) with a poloidal divertor and divertors with divertorless operation. Although it is doubtful that experiments would support the selection of a divertorless ETF design before 1984, the appropriate design modifications to reflect this choice could be made even into the Title I design phase.

(3) The device design should include neutral beams as the prime plasma heating approach but provide the flexibility for rf heating at equivalent power levels. Narrowing the rf candidate frequencies to one is desired. The capability for combined rf and neutral beam heating should be planned.

(4) The device availability (defined as the percentage of calendar time when the machine is operational for testing) shall be targeted for 25% during hydrogen operation and the first two years of D-T operation. The target availability thereafter is 50%. All systems shall be designed to their necessary reliability goals to achieve this availability.

(5) Fueling will be provided by pellet injection and gas puffing.

(6) The device design will have a secondary vacuum enclosure.

(7) The ETF maintenance concept shall be reactor relevant. Design envelopes shall be established for areas in which remote, semiremote, and hands-on maintenance will be applied. Specific means

for repair or replacement of all components within the remote and semiremote envelopes that are subject to failure during the expected lifetime of the facility must be developed and demonstrated prior to ETF initial operation. Emphasis is to be placed on minimizing the size of the envelopes within which remote and semiremote maintenance will be required, consistent with the need to achieve the lowest mission cost. An ETF design goal shall be to allow hands-on maintenance external to the toroidal field (TF) coil shield.

(8) The means for testing different blanket, first wall, and shield modules will be incorporated. Ease of changeout of test items will be a design requirement. Reactor-relevant electricity and synfuel production modules and tritium-breeding blanket modules will be tested.

(9) Material test stations will be provided in the design. Their number and size will be assessed in the conceptual design phase.

(10) The device is to provide a time-integrated wall load of $\geqslant 6$ MWyr/m^2 during its mission.

(11) Systems shakedown and check-out will be completed during assembly and prior to the beginning of scheduled operations.

(12) The feasibility and impact of providing for the testing of fusion-fission hybrid blanket modules will be assessed, and recommendations to OFE on their inclusion in the facility will be made in the conceptual design phase.

(13) A decommissioning and post-mortem period will be incorporated to permit remote maintenance and disassembly and materials investigation.

(14) Testing and qualification of reactor-relevant diagnostics will be included.

The test schedule that has evolved from these considerations is shown schematically in Fig. 2.1.

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1. John M. Deutch, *The Department of Energy Policy for Fusion Energy*, DOE/ER-0018, Directorate of Energy Research, Department of Energy, Washington, D.C. (1978).
2. ETF Design Center Team, *Mission Statement for the Engineering Test Facility*, ORNL/TM-6732, Oak Ridge, Tennessee (1979).

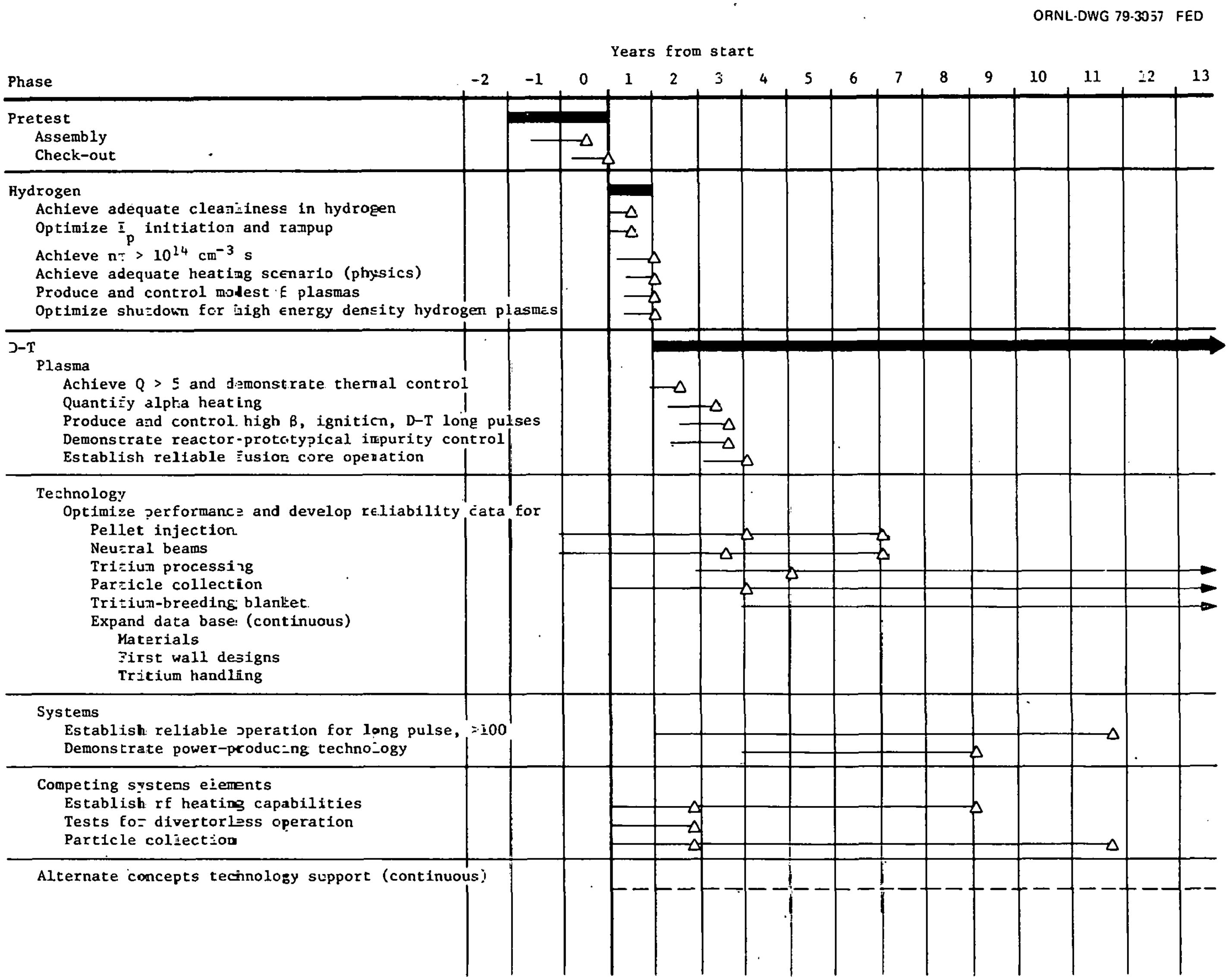

Fig. 2.1. Operations schedule for the Engineering Test Facility.

APPENDIXES

A.1. PLASMA OPERATIONS TESTING
A.2. HEATING/FUELING TECHNOLOGY TESTING
A.3. TRITIUM/PARTICLE COLLECTION TECHNOLOGY TESTING
A.4. BLANKET/FIRST WALL/SHIELD TECHNOLOGY TESTING
A.5. REMOTE MAINTENANCE AND ENGINEERING OPERATIONS TESTING
A.6. MATERIALS TESTING
A.7. ALTERNATE CONCEPTS
A.8. ETF MISSION WORKSHOP

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APPENDIX A.1

PLASMA OPERATIONS TESTING

A.1.1 INTRODUCTION

Plasma operations testing was considered at the ETF Mission Workshop by a subgroup including the participants listed in Table A.1.1. This appendix summarizes the discussions of this subgroup.

The ETF will be the prime magnetic fusion facility in the 1990's, and although it will not be a plasma physics experimental device, a period of physics investigations will be necessary. Because the device must operate in wholly new parameter regimes, a lengthy exploratory phase is essential to define the parameter space relevant to the subsequent engineering/technology testing phases. In addition, a thorough plasma operations testing phase will help to ensure the safety, reliability, and repeatability needed for subsequent phases.

The design philosophy is that the device must generate a data base adequate to proceed with power reactor design and establish a long pulse fusion core adequate for engineering testing. Ignition is a goal, but even if the plasma does not ignite, in principle one can still generate the requisite data base for component qualification with $Q > 5$. However, in that case there would be gaps in the physics data base for EPR/DEMO.

Under this philosophy several key issues in the physics operation testing of the ETF have been identified: transport, heating, impurity control, plasma stability control, and dynamic scenarios. The issues, the assumptions supporting them, the milestones to be achieved, and the device requirements are listed in Table A.1.2. The testing schedule is shown in Fig. A.1.1.

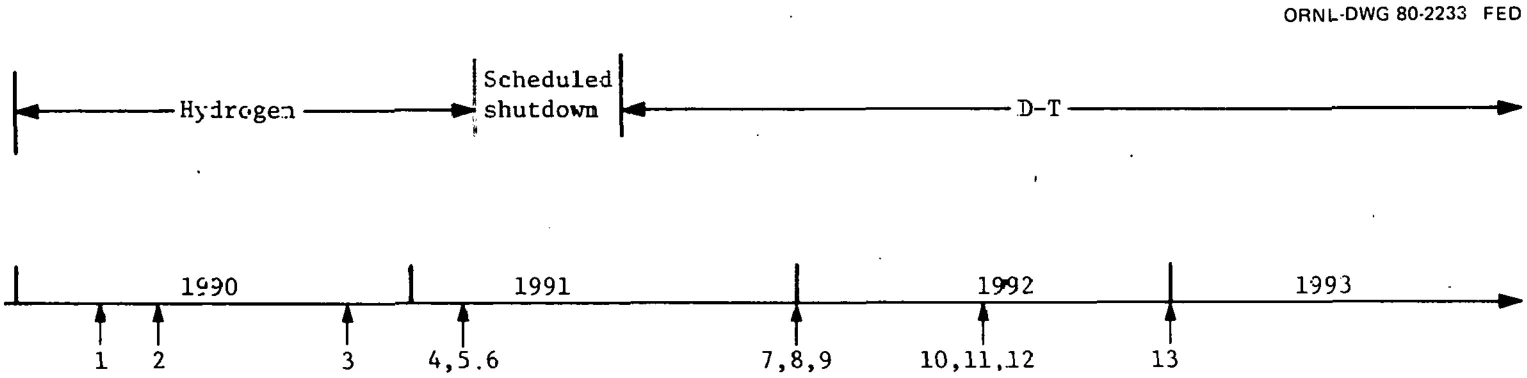
In evaluating these key issues, it has been assumed that the machine design will be frozen in 1984 and that information acquired after that date will be too late to have a significant impact on major design principles. Design flexibility is desirable, but only to the extent that initial capital costs are not appreciably affected. It has further been assumed that the machine is adequate from a technology standpoint to produce a long pulse, D-T burning plasma.

Table A.1.1. Participants in plasma operations testing subgroup

J. M. Rawls, Chairman	GA
J. D. Callen	ORNL
J. F. Clarke	OFE
D. Cohn	MIT
R. W. Conn	University of Wisconsin
G. A. Emmert	University of Wisconsin
G. E. Guest	GA
R. L. Miller	GA
Y-K. M. Peng	ORNL
J. A. Schmidt	PPPL
J. H. Schultz	MIT/Westinghouse Electric Corporation
S. Yoshikawa	PPPL

Table A.1.2. Key issues for plasma operations testing
(assuming design in 1984 and operation in 1990)

Key issues	Assumptions	Milestones	Device requirements
Transport	Current transport results extrapolatable to reactor regime Thermal alpha and fast alpha understood sufficiently not to undermine the above	Confirm bulk transport predictions	Achieve $n\tau > n\tau$ min
Heating	Positive ions — thoroughly tested RF — results of high power experiments using ICRF, LHH, and ECRH Negative ions — results extrapolatable from positive ion results Compression — negligible data by 1984	Achieve $Q > 5$ via complementary auxiliary and alpha heating Demonstrate acceptable coupling efficiency and profile effects	50-70 MW of auxiliary power that penetrates and is absorbed by the plasma
Impurity control	Improved understanding of surface and boundary physics Wall conditioning optimized Data base from JET and JT-60 before 1990	Achieve reactor-prototypical operation Assess fuel depletion and ash accumulation situation	$Z_{eff} < 1.5$, low Z only Reduction of heat loads to manageable levels Possible poloidal or bundle divertor
Stability control	Demonstration and control of $\beta > 5\%$, short pulse hydrogen plasma Demonstration of improved disruption control techniques Understanding of disruption mechanisms and time scales in hydrogen plasmas	Produce and control high beta, D-T burning plasma for long time Establish disruption-free operating regime	Adequate PF coil design and PF power supplies for I&C First wall capable of surviving minimum number of disruptions
Dynamic scenarios	Quantifiable information on all aspects of startup Information on finite Q operation from core of TFTR and JET by 1990 Understanding of current rampdown and abort scenarios	Optimize startup Operate with $Q > 5$ for a long time Optimize termination of high energy density plasma discharges	Adequate power supplies, preionization techniques, and volt-seconds Adequate PF coil time response and first wall



14,15 (noninterfering, carried out through machine life)

1. Achieve adequate cleanliness in hydrogen.
2. Optimize current initiation and rampup in hydrogen.
3. Produce plasmas with $n\tau > 10^{14}$ cm^{-3} s.
4. Perform adequate heating and scenario simulation in hydrogen or deuterium.
5. Produce and control modest beta plasmas in hydrogen or deuterium.
6. Optimize shutdown procedure for high energy density hydrogen plasmas.
7. Achieve Q > 5 (ignition if possible) via complementary auxiliary and alpha heating.
8. Demonstrate thermal control.
9. Quantify alpha particle heating and transport.
10. Produce and control high beta, high Q, D-T plasma for long time.
11. Demonstrate reactor-prototypical impurity control.
12. Assess fuel depletion and ash accumulation situation.
13. Establish disruption-free, reliable operating regime with fusion core adequate for engineering testing.
14. Validate scaling laws in reactor-relevant regime.
15. Optimize fusion plasma performance.

Fig. A.1.1. Plasma operations testing timetable and milestones.

A.1.2 TRANSPORT

A.1.2.1 Assumptions

There already exists a voluminous body of information for bulk transport; by 1984 additional transport information should be available on high temperature plasmas and alpha particles. Gaps will exist in the data base for thermal alpha and fast alpha transport at reactor-relevant n_α/n_e. However, for the most part bulk transport predictions for the ETF will involve only modest extrapolation.

A.1.2.2 Achievements/Milestones

The uncertainty in the bulk transport is such that while high Q operation is a virtual certainty, ignition cannot be guaranteed in a device of INTOR parameter size and heating power.

A.1.2.3 Device/Facility Requirements

Achieving high Q operation will require that $n\tau > n\tau$ min and only a small fraction of the central power may be lost through radiation.

A.1.2.4 Testing Schedule Requirements

Testing of plasma transport should be carried out during the entire plasma operations testing phase of the device, which, it is estimated, will take three years of machine time. Maintenance of and further improvements in plasma operations should be carried out through the machine life on a noninterfering basis (see Fig. A.1.1).

A.1.3 HEATING

Many of the aspects of heating are discussed under the general subgroup of heating and fueling. Here an assessment is made with regard to plasma operations.

A.1.3.1 Assumptions

Auxiliary heating options considered are discussed below.

150-keV positive ions

By 1984 positive ion source neutral beams will have a thorough testing in a variety of devices, and it is possible that relevant startup scenarios will then be tested in TFTR. Ripple injection will be tested in ISX.

Negative ions

The data base for negative ions in 1984 will be scant, but results may be inferred from the extrapolation of positive ion data. Negative ion source neutral beams present an uncertain but potentially significant heating mechanism.

RF heating

Results of high power experiments using ICRF, LHH, and ECRH will be available in 1984. ICRF and LHH are technologically attractive and potentially cost-effective whereas ECRH is technologically difficult for high field, high beta applications. However, the extrapolation of ICRF and LHH results to an ETF plasma is not understood. ECRH is potentially attractive as a profile control mechanism.

Compression

Neutral beam heating boosted by compression provides a high probability for success, although the impact upon the design of the poloidal field (PF) coils, first wall, etc., may make this scheme unattractive. TFTR may provide some relevant information by 1984 and more by 1990. A compression-boosted ITR may generate directly applicable data.

Alpha heating

Alpha heating is an essential component in achieving high Q operation or ignition. Although there will be negligible data by 1984, by 1990 the TFTR Improvement Project (TIP), JET, and possibly ITR will provide plasmas with core energies significantly affected by alpha particles.

A.1.3.2 Achievements/Milestones

The primary milestone for heating is to achieve high Q or ignition with a combination of auxiliary and alpha heating. In addition, any of the auxiliary heating mechanisms must demonstrate (in the ETF) acceptable coupling efficiency and acceptable profile effects for reactor-grade plasmas.

A.1.3.3 Device/Facility Requirements

Achieving high Q or ignition will require 50-70 MW of auxiliary power that penetrates and is absorbed by the plasma.

A.1.3.4 Testing Schedule Requirements

During the hydrogen phase, heating tests and scenarios will be conducted to achieve $n\tau > 10^{14}$ cm^{-3} s and modest beta values. In the D-T testing phase, auxiliary heating should produce high Q or ignition (see Fig. A.1.1).

A.1.4 IMPURITY CONTROL

Impurity control may be the least understood of the key plasma issues. Furthermore, the data base available in 1984 will not be as relevant as necessary because present and planned devices include pulses that are too short, heat and particle fluxes that are too small, and problems of ash accumulation that are not being confronted.

A.1.4.1 Assumptions

It is assumed that the data base available in 1984 will provide improved understanding of surface and boundary physics and that wall-conditioning techniques will have been optimized. By 1990 JET and JT-60 will provide more reactor-relevant results because of their longer pulses and increased heat loads.

The impurity control technique that would have the largest overall impact upon the ETF design is the divertor. However, the 1984 data base for divertor operation will be of limited use because of the short pulses and modest particle and heat fluxes.

A.1.4.2 Achievements/Milestones

The primary milestone with regard to impurity control will be the achievement of reactor-prototypical operation. Once this is done, it will be important to assess the problems of fuel depletion and ash accumulation.

A.1.4.3 Device/Facility Requirements

Requirements for the ETF device are $Z_{eff} < 1.5$, only low Z impurities, and heat loads reduced to manageable levels. Satisfying these requirements should allow the ETF to achieve reactor-prototypical operation and should also allow an assessment of fuel depletion and ash accumulation. Use of a divertor will complicate the field coil design, require a divertor collector, and modify the fueling systems. On the other hand, divertorless operation may limit burn time to tens of seconds or less because of helium ash buildup.

A.1.4.4 Testing Schedule Requirements

It will be necessary to test impurity control techniques during the entire plasma operations testing phase. The major requirement is to control impurities for long pulses with high power loads (see Fig. A.1.1).

A.1.5 STABILITY CONTROL

Control of plasma stability is necessary to achieve high beta operation and to avoid major plasma disruptions.

A.1.5.1 Assumptions

The assumed data base for this key issue is an encouraging one. By 1984 theory and experiment will have merged on the issue of beta limits, demonstration and control of $\beta \gtrsim 5\%$ in short pulse hydrogen plasmas will have been acquired, and improved disruption control techniques will have been demonstrated experimentally.

By 1990 there should be increased confidence in shaping and control techniques, and some long pulse data will be available from JT-60 and JET. There will also be information on spatial and temporal behavior and the deposition of high Q, D-T disruptions.

A.1.5.2 Achievements/Milestones

Milestones for ETF operation in this area are to produce and control high beta, D-T burning (or high Q) plasmas for long times and to establish an essentially disruption-free operating regime for future engineering testing.

A.1.5.3 Device/Facility Requirements

Control will require an adequate PF coil design and PF power supplies sufficient for instrumentation and control. The possibility of disruptions will also affect requirements for the first wall.

A.1.5.4 Testing Schedule Requirements

Primary testing of stability control will occur during high beta, low Q operation of the D-T plasma operations phase (see Table A.1.2 and Fig. A.1.1).

A.1.6 DYNAMIC SCENARIOS

The final key issue in the area of plasma operation testing, dynamic scenarios, has been divided into three phases: startup, burn, and shutdown.

A.1.6.1 Assumptions

Of the three phases, startup should be the best understood by 1984, when quantifiable information will be available on all aspects of startup. Although skin currents could present a problem in a device the size of the ETF, this issue may also be understood by 1984.

On the other hand, there will be no data base in 1984 that will directly address the burn scenarios. Information on high Q operation from the core of TFTR and JET will be available before 1990. An ITR would be required to provide the relevant data base for an ignited plasma.

It is assumed that there will be a better understanding of current rampdown and abort scenarios by 1984 and particularly by 1990. This should provide input for the required PF coil time response and first wall design on the ETF.

A.1.6.2 Achievements/Milestones

The milestones for this issue are straightforward: optimization of startup, achievement and control of burn, and optimization of the termination of high energy density plasma discharges.

A.1.6.3 Device/Facility Requirements

Device requirements for optimized startup scenarios include adequate power supplies and volt-seconds, which will depend upon the type of preionization selected.

The device requirements to ensure adequate burn will depend upon the burn control mechanism (compression, ripple, fueling, etc.).

Specific current rampdown and abort scenarios will impose requirements on the PF coil time response and first wall design.

A.1.6.4 Testing Schedule Requirements

Startup and shutdown scenarios must be tested throughout the hydrogen and D-T plasma operations testing phases. The burn phase must be tested during the entire D-T phase.

A.1.7 TEST REQUIREMENTS AND DATA BASE

The proposed schedule for plasma operations testing has been determined assuming that assembly and shakedown will proceed to the point that the device becomes available for meaningful experimental tests in 1990. The plasma operations testing milestones and timetable appear in Fig. A.1.1, where it can be seen that the assumed total period required from initial hydrogen discharges to the establishment of a disruption-free, long pulse, high Q, D-T operating regime is three years. To meet this ambitious milestone schedule in three years will require device operation with no significant unscheduled downtime and with all systems available when needed. This is expected to result in stringent requirements on component reliability.

The proper evaluation of the key physics issues and their impact on the ETF design hinges on the anticipated 1984 design base. It has been assumed that in most physics areas, information acquired after that date will be too late to have an impact on the ETF design if the device is to be completed by 1990. An evaluation of the 1984 data base is presented in Table A.1.3. Each of the key issues is rated on a scale from A (excellent) to C (acceptable) in three areas: (1) the diversity of the data base, (2) the promise the data base holds for a beneficial impact on the ETF design, and (3) the relevance of the data base to the ETF design. This table is meant to serve as a rough guide to interpreting the anticipated status of each of the key issues. It can be seen that the success of impurity control and dynamic scenarios will be the most difficult control to ensure, based on the assumed status of the data base. On the other hand, the areas of transport, heating, and stability control should be much better understood and should provide reasonable confidence for extrapolating to ETF regimes.

Table A.1.3. Evaluation of the 1984 data base for plasma operations testing

Issue	Diversity	Promise	Relevance
Transport	A	A	B
Heating	A	A	B
Impurity control	B	C	[a]
Stability control	B	B	C
Dynamic scenarios	C	B	C

[a] Theoretical work will be available. Experimental evidence available by 1984 may not be relevant.

APPENDIX A.2

HEATING/FUELING TECHNOLOGY TESTING

A.2.1 INTRODUCTION

The heating/fueling technology testing subgroup divided its deliberations into two separate items, fueling and heating. Participants in this subgroup are listed in Table A.2.1.

A.2.2 KEY ISSUES

The key issues in fueling are determining the need to inject the fuel to the center of the plasma vs to the rim or edge and then successfully developing a device to handle the required pellet size, velocity, and repetition rate. The discussions indicated that there is an advantage to fueling off-center and that the present injector development at ORNL can lead to a satisfactory application for the ETF.

The key issues with regard to heating are the need for neutral beam injection higher than 150 keV, which would favor the development of negative ion techniques, and the need for or desirability of rf heating. Assuming that rf heating is desirable or required, the next issue is to determine the best type of rf heating. There was a clear indication that positive ion neutral beam injection is the present leader, but no agreement was reached on the need for higher energy injection or the possibility that rf heating might be more advantageous.

A.2.3 ASSUMPTIONS

A.2.3.1 Fueling

It was assumed that fueling will be accomplished by a combination of gas puffing and pellet injection. For pellet injection it was assumed that a pellet accelerator with an integrated pellet injection line will be available. The accelerator will be based on either a presently operating accelerator concept (mechanical centrifugal accelerator,

Table A.2.1. Participants in heating/fueling technology testing subgroup

L. D. Stewart, Chairman	PPPL/Exxon Nuclear Company
R. Botwin	Grumman Aerospace Corporation
R. L. Freeman	GA
H. H. Haselton	ORNL
J. C. Hosea	PPPL
R. A. Langley	ORNL
T. S. Latham	United Technologies Research Center
W. Marton	OFE
J. G. Murray	PPPL
P. Parks	GA
R. V. Pyle	LBL
J. Scharer	University of Wisconsin
T. J. M. Sluyters	BNL
J. R. Treglio	General Dynamics, Convair Division
S. S. Waddle	DOE/Oak Ridge Operations
D. M. Weldon	LASL
P. A. Willis	GE
K. E. Wright	PPPL

pneumatic accelerator, or liquid droplet injector) or a technique still in the conceptual stage (laser acceleration, liquid jet, or magnetic accelerator).

A.2.3.2 Heating

Positive-ion-based neutral beams

It was assumed that the ETF will require a 150-keV beam energy, a 5- to 6-s pulse, and 50 MW and that this technology will be available along with direct recovery to allow a 40% efficient system.

Negative-ion-based neutral beams

It was assumed that the substantial R&D required to prepare negative ion systems for the ETF will be undertaken and will be successful. The considerations, requirements, and impacts for a 150-keV negative-ion-based system will be the same as for a positive-ion-based system, except that a 50% efficient system is assumed.

Ripple injection

Ripple injection, it was assumed, will be effective and highly efficient (∿50-70%).

Electron cyclotron heating

It was assumed that electron cyclotron heating (ECH) will be effective and that successful development of 150-GHz, ∿1-MW long pulse units with ⩾30% source efficiency (ηH) and low-loss coupling units will be accomplished.

Ion cyclotron heating

It was assumed that ion cyclotron heating (ICH) will be proven effective and that a concerted R&D effort will result in the development of long pulse, 10-MW modules with suitable coupling structures.

Lower hybrid heating

It was assumed that lower hybrid heating (LHH) will be proven effective in the megawatt range and that optimized coupling systems will be developed.

Low frequency heating

For low frequency heating (LFH) it was assumed that a larger physics base will be developed, including large-scale heating experiments, 30% heating efficiencies, and the design of coupling systems.

Compression

It was assumed that the usefulness of compression will be demonstrated on TFTR.

A.2.4 ACHIEVEMENTS/MILESTONES

A.2.4.1 Fueling

The recommended ETF missions are to demonstrate the reliability and availability of sustained fueling operation and to optimize pellet penetration, size, and feed rate. The demonstration of reliability is necessary for ETF operation and therefore must be obtained primarily off-site prior to ETF operation.

Parameter optimization requires extended operation integrated into normal plasma maintenance and control operations. Each injector requires a significant throughput of tritium ($\sim$0.3 g/s) to maintain plasma burn and particle losses.

A.2.4.2 Heating

For positive ion neutral beam systems, the recommended ETF mission is to attain 90% availability of the 50-MW system while increasing the system efficiency to 50%. The 90% availability is particularly important if beams are to be the primary heating system.

The milestones for the other heating systems on the ETF are also to obtain availability data and to increase efficiency. ECH may be effective in providing profile control and startup and in complementing other heating systems. ICH would demonstrate a 5-keV preheat, discharge duration heating to high Q, ignition with shorter pulse duration, and minimization of neutron escape by coupler design optimization. Compression would be used on the ETF to optimize the ignition scenario as a complement to another heating technique.

A.2.5 DEVICE/FACILITY REQUIREMENTS

A.2.5.1 Fueling

Because gas puffing was not treated explicitly in some of the reference designs, only a potential reference design impact is noted. The tritium-handling and divertor design must anticipate the high particle recycling rates.

A.2.5.2 Heating

It was suggested that the torus heating segments be designed with ports and access compatible with either positive or negative ion neutral beams or with any of the rf techniques. It is recommended that, if a primary heating method is selected to ensure the achievement of other ETF goals, an additional port or ports be made available for the testing of alternative heating techniques.

For positive ion beams it was estimated that five beam lines will be required to provide 50 MW and that one additional beam line will be necessary to provide 90% availability through redundancy. This means that more space, power supplies, and facilities will be required than estimated in the reference design, which assumed four beam lines.

It is noted that a positive-ion-based neutral beam system designed for 50 MW of D^0 will provide only about 25 MW of H^0. If a higher beam energy is required and/or obtainable with negative ion beams, fewer beam lines may be required. This would result in less of an impact on the reference design, and higher energy would be available during H^0 operation than with the positive ion system.

For ripple injection vertical beam lines will be required in place of horizontal lines. The application of beam lines above or below the torus would require a significant change in the reference magnetics design.

Two impacts on the reference design were noted for ECH: (1) the launching structure and torus design may have to be integrated and (2) relatively small access is required.

For ICH the mission requires six sector coupling systems, including one backup system to ensure 90% availability and one system devoted to coupler optimization. Impacts on the neutral-beam-based reference design heating system are (1) the possible need for integrated wall and coupling structure designs, (2) designed access through the blanket, and (3) space outside the machine cell area for rf sources and supplies.

For LHH the ETF will need access for 50 MW at 2 kW/cm^2. The impacts on the reference design are more space for the remote siting of power systems and the lack of a direct line-of-sight requirement, easing neutron-streaming problems.

It is possible that LFH might require a difficult integration of the coil and torus design.

With compression the reference design will require a redesigning of the torus, magnetic systems, and electrical systems.

A.2.6 TESTING SCHEDULE REQUIREMENTS

A.2.6.1 Fueling

The injection line and injector would have to be developed in a tritium-handling area; thus, a major time period to place it in operation on the ETF would not be required. To obtain the optimization of pellet size, penetration, and feed rate, two years would be required, with about one year of this time under D-T operation.

A.2.6.2 Heating

Two to three years of ETF operation are required for all the heating systems to complete the mission goals of improving efficiency and optimizing components. Their operation for longer periods would provide additional data on efficiency, reliability, and availability.

For remote handling of neutral beams, an important ETF mission would be the remote replacement of both a major subsystem, such as a magnet or cryopump, and a complete beam line. For rf systems the remote replacement of an entire system would be sufficient. Six months of machine downtime during the hydrogen phase was an estimated requirement.

A.2.7 CONCLUSIONS

The conclusions of the heating/fueling technology testing subgroup are summarized in Tables A.2.2 and A.2.3.

Table A.2.2. Fueling technology

Key technical components	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Pellets	Accelerator type: mechanical centrifuge, pneumatic gun, or liquid jet Pellet radius: 1-3 mm Velocity: 1000-3000 m/s Frequency: 20-100/s	Information obtained on sustained fueling mode and on optimization of pellet penetration, pellet size, and feed rate	A back-up and a spare injection line should be considered	Short shakedown period followed by extended operation integrated into normal machine schedule	Minimal impact on tritium-handling system and divertor design
Gas puffing	None	Contributions to control of machine parameters determined	Small port and space required	Short shakedown period followed by operation integrated into normal machine schedule	Tritium-handling and divertor systems must be designed for higher particle recycling

Table A.2.3. Heating technology

Key technical components	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Positive ions	150 keV, 5 to 6 s, 50 MW, 2 kW/cm^2 D^0, 40% efficiency with direct recovery	Obtain availability information; achieve 50% efficiency	Extra beam lines for required availability and maintenance should be considered	2 years of machine operation after hydrogen phase	Space, power supplies, and facilities required for extra beam lines
Negative ions	150 keV, 2 kW/cm^2 D^0, 50% efficiency without direct recovery	Obtain availability information; achieve 70% efficiency (implement direct recovery)	Back-up and spare beam lines should be considered	2 years of machine operation after hydrogen phase	Space, power supplies, and facilities required for extra beam lines
Negative ions	250 keV, 4 kW/cm^2 D^0, 50% efficiency without direct recovery	Obtain availability information; achieve 70% efficiency (implement direct recovery)	Extra beam lines for required availability and maintenance should be considered	2 years of machine operation after hydrogen phase	None (alleviates previous space problems)
Ripple injection	90 keV, 3-4 kW/cm^2 D^0, 50% efficiency without direct recovery	Obtain availability information; achieve 70% efficiency (implement direct recovery)	Extra beam lines for required availability and maintenance should be considered	2 years of machine operation after hydrogen phase	Ports and space allocation required for vertical injection, magnetics system design; no horizontal space requirements
ECRF heating	Positive results on T-10, ISX, EBT-II (ηH = 30% on electrons); R&D effort to obtain 150 GHz; megawatt systems with low-loss coupling system, $\eta H > 30\%$, and long pulses	ηH = 30% on electrons for profile control 10-MW system operation; profile control startup; complement other heating scenarios	No special requirements	2 years of machine operation	Small access region required; possible inside/outside launching
ICRF heating	Efficient heating (ηH = 50%) capability demonstrated on large tokamaks (PLT, PDX, TFTR, Doublet II, etc.); impurity influx controlled; deposition profile controlled; long pulse, 10-MW modules available; R&D of suitable coupling structure	Obtain availability information; $\eta H > 50\%$ (overall); 5-keV preheat and long pulse (~6 s for ignition or discharge duration for driven high Q operation); minimize neutron escape	Sector coupling systems (~2 kW/cm^2) with consideration for availability and spares; 1 sector devoted to coupler optimization (modular design preferred)	2 years of hydrogen and 3 years of D-T machine operation; downtime for coupler changer	Designed access through blanket; coupling structure design may be integrated with wall design; rf sources and supplies require space outside machine cell area
Lower hybrid heating	Megawatt range heating experience available from Doublet IIA, Alcator C, PLT, and other large devices (Doublet III, PDX, TFTR) or a dedicated rf device; optimized coupling systems; physics understanding of coupling, wave propagation, and heating efficiencies	Obtain availability information; demonstrate reliable operation with overall heating efficiency $\geq$50% for 50-MW power levels	Port access for 50 MW (~kW/cm^2) with consideration for availability and spares	Check-out during hydrogen phase; 3 years of operation during ignition phase for reliability and optimization studies	Remote siting of power systems waveguide coupling avoids internal structures; direct line-of-sight not required
Low frequency heating	Coupling system design; large-scale heating experiments required; more physics base; ηH = 30%	Obtain availability information; $\eta H > 50\%$ (overall)	Possible integration of coil "in machine design"	2 years of machine operation after hydrogen phase	If large coils are required, must be integrated with machine design
Compression	Demonstrated as useful on TFTR	Optimize ignition scenario	Determination of advantages of compression for future applications	2 years of machine operation after hydrogen phase	Torus and magnetic system must be designed for compression

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APPENDIX A.3

TRITIUM/PARTICLE COLLECTION TECHNOLOGY TESTING

A.3.1 INTRODUCTION

The key issues in the area of tritium/particle collection technology testing were selected by teams within the subgroup and considered in simultaneous detailed deliberations. The team results were then reviewed by all the subgroup participants, and final comments and recommendations were made. Participants in the subgroup are listed in Table A.3.1. The findings of the subgroup are summarized in Table A.3.2 and in Fig. A.3.1.

A.3.2 KEY ISSUES

The six key issues selected are as follows:

(1) Toroidal vacuum, particle collection, and first wall/plasma interface. Detailed areas of concern are between-pulse pumpdown, means of particle collection (i.e., bundle or poloidal divertor or passive recycling), and interface of first wall with fuel cycle, heat load, and particle flux.

(2) Effects of tritium and particle streaming on heating and fueling devices, specifically neutral beam, pellet injection, and gas puffing systems.

(3) Fuel processing. Areas of concern are chemical purification, enrichment, circulation pumping, storage, materials compatibility, and maintenance.

(4) Tritium containment, cleanup, and waste control. Specific areas of concern are primary containment (including evaluation of heat exchangers, breeders, and nonbreeding applications), secondary containment, and the containment building (i.e., vacuum or ambient; if ambient, air or inert atmosphere); atmospheric and secondary cleanup systems; waste treatment and waste disposal, including means of storage and transportation; and materials compatibility, maintenance, and safety and environmental aspects.

Table A.3.1. Participants in tritium/particle collection technology testing subgroup

V. A. Maroni, Chairman	ANL
J. L. Anderson	LASL
T. H. Batzer	LLL
W. R. Bauer	Sandia Laboratories
M. H. Dandridge	Grumman Aerospace Corporation
N. J. Hoffman	Energy Technology Engineering Center
J. S. Watson	ORNL
W. M. Wells	ORNL
W. R. Wilkes	Monsanto Research Corporation
T. F. Yang	Westinghouse Electric Corporation

Table A.3.2. Tritium/particle collection technology

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Toroidal vacuum, particle collection, first wall/ plasma interface	Technology for between-pulse pumpdown in hand; divertor question resolved; particle collection method demonstrated	Sufficient demonstration to provide adequate confidence for progression to EPR/DEMO	Interface with fuel cycle, heat load, and particle flux must be tolerated by first wall and/or divertor	Many aspects critical to initial operation; extended testing in D-T phase	Particle collection method for divertor; passive recycle must work if no divertor is used; gas load affects size and cost of fuel-handling equipment and inventory
Fueling/heating devices	Vacuum and delivery hardware tested for ETF; all tritium/ fueling/heating interfaces for ETF resolved	Reliability of devices during startup and burn phase demonstrated for EPR/DEMO; high repetition rate achieved	Remote maintenance equipment and special hot cells provided in ETF; requirements for electrical power met	First few weeks critical; many continuing tests	Critical components must work for ETF to be successful
Fuel processing	TSTA will have demonstrated a workable system by 1990	Upgrade performance and demonstrate system reliability for EPR/DEMO	Remote-handling facilities	Tests carried out mostly in conjunction with ETF operation	Cost reductions and decreased tritium inventory through optimization essential
Blanket processing for modular tests	Tritium recovery, impurity control, and compatibility demonstrated on a reasonable scale by 1990	EPR/DEMO performance and reliability verified	Initial ETF facility design must accommodate modular inserts	1-2 years per modular test	Modular experiments could extend design phase; downtime required for changeout
Tritium containment, cleanup, waste control, vacuum building	Technology developed, integrated, and tested by 1990	EPR/DEMO performance level demonstrated	Comparmentalized facilities and emergency power maintenance plan complete	Continuing through life of facility to permit upgrading; some hydrogen phase testing desirable	Successful demonstration crucial to ETF
Tritium inventory control[a]	Site security plan approved by 1984; supply/control/ inventory methods verified by 1990; classification issues resolved	Demonstrate supply/conrol/ accountability for EPR/DEMO	Site security plan essential	Continuous testing and verification	Early clarification necessary to ensure orderly phase

[a] Without a divertor, tritium inventory will be ~10 kg; with a divertor, >>10 kg.

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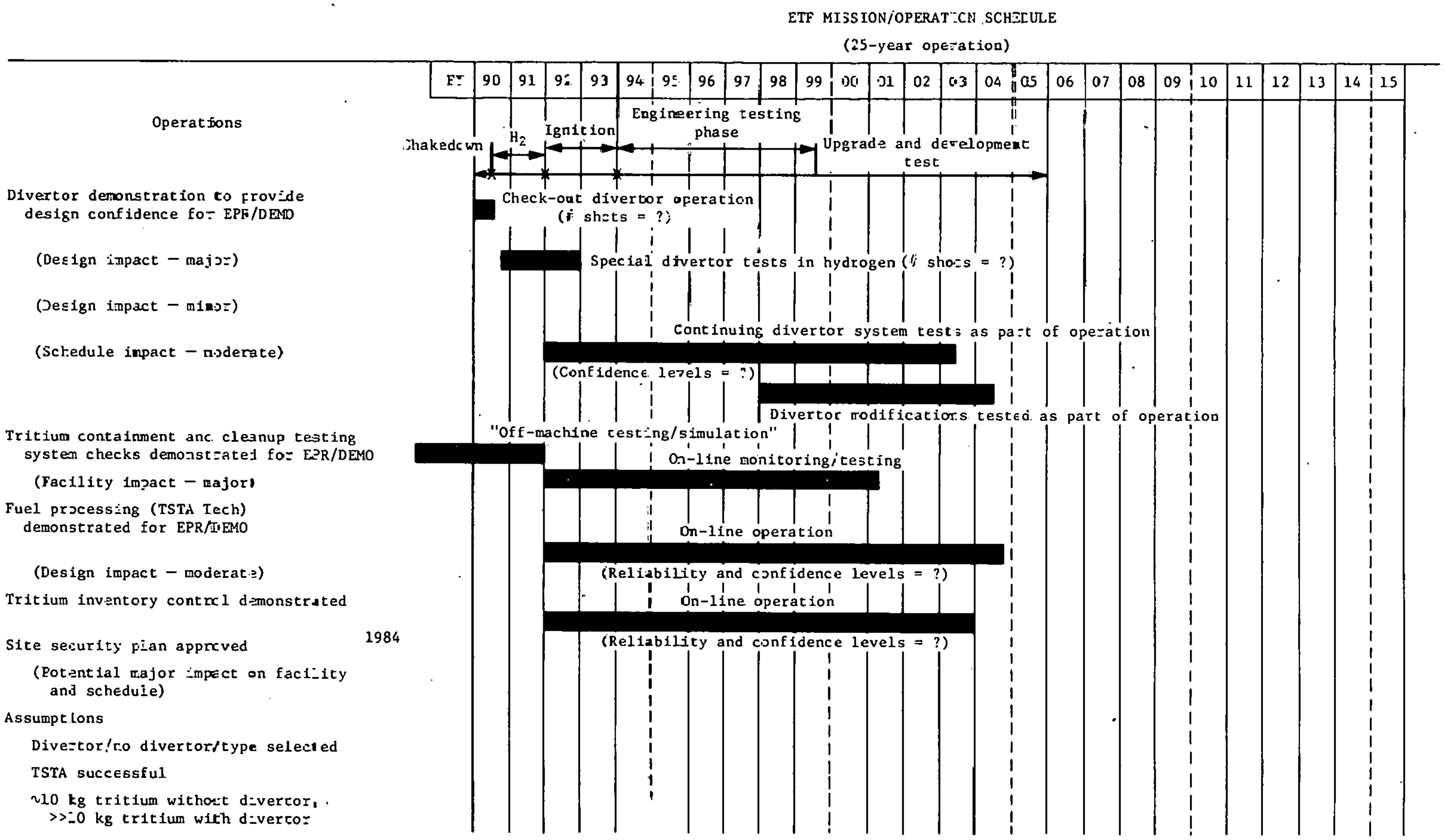

Fig. A.3.1. Schedule of tritium and particle streaming.

(5) Blanket processing for modular tests. Areas of concern are tritium recovery and impurity control, including evaluation of liquid lithium, liquid or solid lithium alloys, and ceramics (e.g., Li_2O); and materials compatibility, maintenance, and safety and environmental aspects.

(6) Tritium control, including necessary inventory, accountability requirements, classification issues, and site control.

The worksheets used by participants at the ETF Mission Workshop to address these key issues are included as Tables A.3.3-A.3.8.

Perhaps the most significant areas of concern are the divertor question and the areas dealing with tritium handling and control (including the potential security classification problem). The impacts of the key issues on the ETF facility, testing schedule, and design are evaluated below.

A.3.3 DEVICE/FACILITY REQUIREMENTS

Among the key issues the requirements imposed by tritium processing, handling, cleanup, and inventory will have the most impact on the ETF facility. Building characteristics must be chosen with these needs in mind. Modifications that may facilitate tritium handling, such as the use of compartmentalized buildings, are encouraged.

A.3.4 TESTING SCHEDULE REQUIREMENTS

The issues having the greatest impact on the ETF testing schedule are divertor check-out, performance mapping, and qualification for EPR/DEMO needs. Because the need for a divertor appears likely, the testing schedule should include divertor testing.

A.3.5 IMPACTS ON ETF DESIGN

The choice of divertors (bundle or poloidal) or passive recycling may have a major impact on the ETF design. Intensive consideration of this choice is needed so that the ETF design can proceed with the best guidance available. Until better data are available, it may be necessary

Table A.3.3. Toroidal vacuum, particle control, and first wall/plasma interface

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
General needs	Technology for between-pulse pumpdown in hand; divertor question resolved and particle collection method demonstrated	Must provide adequate confidence for progression to EPR/DEMO	Interface with fuel cycle; heat load and particle flux must be tolerated by first wall and/or divertor	Many aspects critical to initial operation; extended testing in D-T phase	Develop particle collection method for divertor or passive recycling techniques if no divertor is used; gas load affects size and cost of fuel-handling equipment and tritium inventory
Toroidal vacuum pumping system	Suitable pumps for hydrogen, deuterium, tritium, and helium developed on TSTA	System verified in operating tokamak (helium load and impurities in addition to hydrogen isotopes)	Pumpdown time must meet duty cycle requirements	Required for initial operation	None (basic design requirement)
Particle collection	Choice made between divertor and passive recycling; method developed and tested	Must demonstrate long pulse operation with D-T and helium	Interface with fuel recycling/processing system	Required for initial operation	Heat load and particle collection are critical R&D items; extensive study needed; mechanical limiters may be required
Bundle divertor	Fully developed (existing data base, from ISX-B and DITE, adequate only for small machines)	Must demonstrate long pulse operation and high duty cycle	Handle heat and particle (D-T and helium) loads at >100 MW of power	Because of limited experiments on existing and planned machines, will require extended testing in hydrogen phase	Heat loads on collector surfaces exceed capabilities of conventional heat transfer systems; liquid metal collectors (which would need processing equipment) or specially designed solid targets may meet requirements
Poloidal divertor	Physics feasibility demonstrated on existing experiments (PDX, JT-60, ASDEX)	Must demonstrate long pulse operation and high duty cycle	Handle higher heat and particle loads than present and planned experiments; handle substantial amounts of helium	Several months (less time for bundle divertor than for other options because of broad data base)	Develop advanced solid collector systems to meet heat and particle loads
Passive recycling (e.g., cold gas blanket)	Successful recycling with hydrogen demonstrated on short pulse (<1 s) machines (longer pulse tests may be done on TFTR); confidence in reasonable burn time	Must demonstrate long pulse operation with D-T and helium	First wall must take full heat loads; helium and impurities must be removed	Extended period; helium removal must be available for D-T operation	Successful passive recycling a desirable design alternative
First wall/plasma interface	Limited data on recycling with hydrogen available from short pulse (<1 s) machines (e.g., TFTR, JET, PLT, PDX)	Must demonstrate long pulse operation with D-T and helium; impurity control strategies must be thoroughly studied and the results well understood	First wall must take full heat and particle loads with acceptable impurity generation; helium must be removed	Required for initial operation; may need extensive testing before D-T operation	Will need extensive study; may require mechanical limiters

Table A.3.4. Fueling/heating devices

Key technical issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
General needs	Vacuum and delivery hardware developed and tested for ETF; all tritium/fueling/heating interfaces for ETF resolved	Reliability of devices during startup and burn phases demonstrated for EPR/DEMO; high repetition rate achieved	Remote maintenance equipment and special hot cells provided in ETF; requirements for electrical power met	First few weeks of operation critical; many continuing tests	Critical components must work for ETF to be successful
Neutral beams	150-keV beams available; ultrahigh vacuum valves and fast shutter valves available; some remote maintenance/repair demonstrated on TFTR and JET	Long pulse, high availability operations with/without disruptions; safe shutdown, regeneration, and restart after disruption	Beam modules and vacuum system must be fully compatible with tritium	Short period (~weeks)	Impact due to tritium small provided beams are designed to be maintained remotely due to neutron activation; may have some tritium in injector coolant circuits
Pellets	Delivery of frozen hydrogen pellets demonstrated on ISX-B; high repetition (10-20 s) demonstrated	Demonstrate sustained high repetition rates for long pulse operation under reactor conditions (i.e., with heat loading)	System must produce frozen pellets from a small total inventory; pellets must survive self-heating and reactor heat loads	May be necessary for initial operation	Needed for divertor operations and long pulse, D-T operations
Gas puffing	Demonstrated on TFTR and JET (a start has been made with PLT and Alcator)	Demonstrate sustained gas fueling for long pulse operation under reactor conditions	Gas delivery system must be fully compatible with tritium	May be necessary for initial operation	Needed for long pulse, D-T operations

Table A.3.5. Fuel processing

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Fuel processing	TSTA will have demonstrated a workable system	Upgrade performance, demonstrate system reliability required for EPR/DEMO	Remote-handling facilities	Mostly in conjunction with ETF operation	Cost reductions and decreased tritium inventory through optimization essential
Chemical purification	Particulate removal: ETF mission (guided by TFTR) will have defined nature of problem, TSTA will have performed "cold" tests to verify removal methods; helium removal: will have been demonstrated; other impurity removal: alternate concepts will be tested	Demonstrate radioactive particulate removal that extrapolates to EPR/DEMO; demonstrate optimized system for EPR/DEMO impurity control	Remote maintenance equipment and hot cells	Partial testing during hydrogen phase; critical testing throughout D-T phase; performance verification based on several years of successful operation during D-T phase	May complicate rough pumping operations; essential to fuel recycle; essential to device
Enrichment	TSTA will have demonstrated isotopic separation and enrichment on ETF scale; divertor use will result in need for increase in separation capacity	Demonstrate system reliability needed for EPR/DEMO; demonstrate increase in separation capacity	Requires cryogenics; depends on divertor scenario	Several years during D-T operation (tested as part of divertor shakedown)	Cost and inventory impacts enrichment equipment; increases size, cost, and tritium inventory of fuel cycle
Circulation pumping	Adequate circulation pumps will be available	Demonstrate continual pumping improvements	Flexibility of pumping apparatus for component changeout	Several years during D-T operation	None
Storage	Technology already on hand				
Materials compatibility	TSTA and OFE/M&RE will have workable materials, but new materials will be available for testing	Proof test in reactor environment; evaluate and qualify new materials as they are developed	Interchangeable test modules for blankets, heat exchangers, first wall materials	Months to years (depending on nature of test)	Improvements in performance and cost reductions
Maintenance	For tritium contamination only, technology is largely in hand, technology for combined tritium plus neutron-activated handling will be available from TFTR and from nuclear fuel reprocessing (alpha, beta, gamma wastes)	Demonstrate safe maintenance of contaminated equipment	Hot cells designed for tritium containment	Part of routine maintenance; integral part of remote maintenance scenario	Cost, space, and time for maintenance

Table A.3.6. Tritium containment

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
General needs	Technology developed, integrated, and tested	Demonstrate EPR/DEMO performance level	Compartmentalized facilities; emergency power; complete maintenance plan	Continuing through life of facility to permit upgrading; some hydrogen phase testing desirable using tritium-spiking methods	Successful demonstration crucial to ETF
Containment building	Decision made on use of vacuum building (vacuum buildings now exist but may not have been demonstrated for fusion reactor containment)				Building approach must be decided early in design phase because of overall impact on many components
Vacuum building	Vacuum building will be used on EPR/DEMO	Demonstrate tritium containment with vacuum building [note: tritium will absorb on exposed surfaces within vacuum structure (particularly true of cryogenic surfaces)]	Tritium cleanup for vacuum system exhaust; equipment compatibility with tritium environment; possible inert gas flushing	Continuing through life of facility	Cryogenic systems within vacuum building still require dedicated vacuum enclosures
Ambient building (air or inert atmosphere)	Vacuum building will not be used on EPR/DEMO	Demonstrate tritium containment with standard containment structures and cleanup systems	Atmospheric and secondary cleanup systems of very large scale; compartmentalized reactor hall	Continuing through life of facility	Potential conflict between accessibility requirements and remote maintenance
Secondary containment	Techniques well established for nonbreeding systems; criteria for determining appropriate degree of containment established; for breeding and/or thermal extraction, containment may not be well established without test facilities in 1980's	Demonstrate secondary containment on full-scale reactor system; test, evaluate, and demonstrate secondary containment for thermal extraction and breeding modules	Secondary containment support and cleanup systems	Continuing through life of facility; for thermal extraction and breeding modules, 1-5 years	Potential conflict between secondary containment and system versatility/access
Primary containment (routine applications, breeders, and heat exchangers)	For moderate temperatures and pressures, criteria and techniques will be established; for breeding and heat exchanger applications, materials will be developed but not thoroughly tested	Test, evaluate, and demonstrate primary containment materials in breeder and heat exchanger systems	Test modules	1-5 years for testing materials	
Waste treatment	Adequate methods now exist; new approaches will need evaluation	Test and evaluate new methods as required		Continuing	
Waste disposal (including storage and transportation)	Adequate disposal site available; storage and transportation technology well established	Develop improved waste treatment techniques to reduce volume of tritium waste		Continuing	
Cleanup systems (atmospheric and secondary)	Medium-scale atmospheric systems demonstrated on TSTA; secondary systems technology well established	Achieve scaleup to full reactor-hall volume	Electrical power; emergency power; large cleanup systems	Must be available throughout D-T operation	Atmospheric cleanup systems high-cost items
Materials compatibility	Workable materials available; improved materials should become available for testing	Test and evaluate new materials as they are developed; proof test high temperature and/or high stress materials in reactor environment; evaluate and qualify low temperature, low stress materials as required			
Maintenance	Technology well in hand				
Safety and environmental aspects	Adequate tritium containment demonstrated on TSTA; firm basis established for ETF design	Demonstrate continued adequate containment on reactor		Continuing through life of facility	Essential to meeting site safety and environmental criteria; successful demonstration crucial to ETF

Table 4.3.7. Blanket processing

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
General needs	Tritium recovery, impurity control, and compatibility demonstrated on a reasonable scale	Verify performance and reliability for EPR/DEMO	Facility design must accommodate modular inserts	1-2 years per modular test	Modular experiments could extend design/development phase; downtime required for changeout
Tritium recovery/ impurity control	Thermal hydraulics and mechanics demonstrated	Demonstrate performance adequate for scaleup to EPR/DEMO			A major demonstration for ETF
Liquid lithium, liquid lithium alloys	Tritium recovery method demonstrated for stagnant and/or breeder/coolant concepts			Preliminary testing during hydrogen phase would be of value	High duty cycle necessary for meaningful modular test program
Solid lithium alloys, ceramics (e.g., Li_2O)	Tritium recovery method demonstrated for in situ and/or flowing solid concepts		Space required for peripheral processing/heat exchanger components; fire protection scenario for blanket/ coolant or blanket/ atmosphere reaction may be factor		May need auxiliary modular heating during hydrogen phase and low duty cycle testing
Materials compatibility	Confidence in materials for all testable concepts verified	Demonstrate compatibility consistent with EPR/DEMO requirements and/or reasonable changeout schedule		1-2 years per test	May have impact on schedule for EPR/DEMO materials selection
Maintenance	Tested concept available	Demonstrate limited aspects of maintainability required for EPR/DEMO	Special remote maintenance equipment and hot cells required	Dependent on design; maintenance plan can be tested in hydrogen phase in conjunction with other remote maintenance equipment	Proof testing may extend hydrogen phase test period
Environmental	Confidence in tritium containment established for modules and associated equipment	Verify tritium containment in blanket/ coolant/heat exchanger modular tests sufficient for EPR/DEMO; characterize tritium migration patterns in heat exchanger, piping, etc.; determine release rates via steam generator and ventilation (or building vacuum) system	Tritium-monitoring equipment, cleanup systems, interface with fuel-processing equipment	Can be done in conjunction with other tests; may be possible to conduct some tests during hydrogen phase using tritium spiking	Meeting ICRP guidelines on tritium release could have impact on construction and operating costs

Table A.3.8. Inventory control

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
General needs	Supply, accounting, and control methods verified; classification issues resolved	Demonstrate supply, control, and accountability	Site security plan essential	Continuous testing and verification	Early clarification necessary to ensure orderly design phase
Tritium inventory		Demonstrate inventory supply and control for EPR/DEMO	Facilities for receiving and initial storage of fuel	Continuous cross-checking to verify performance of containment and accountability systems	Will require careful early planning to provide initial inventory; significant problems anticipated in obtaining replacement fuel
Without divertor	Inventory should be ≤10 kg				
With divertor	Inventory should be ≥10 kg		Requires many shipments to deliver initial inventory (present standards require 12 g per container, with a total package volume of ∿50 gal)		Major problems anticipated in obtaining startup inventory of >>10 kg; major policy decision may be required to ensure adequate supply of replacement fuel
Accountability	Addressed on TFTR and TSTA; further advances may be required	Demonstrate accountability ∿10-kg inventories with large throughput and high burnup rates for EPR/DEMO	Large quantity of special equipment required		May have major impacts on cost and availability
Classification	Major issues resolved; tritium extraction from blanket addressed in 1980's				
Site control	Plan developed and approved				Site control will be required and will have impact on cost

to include divertors (bundle or poloidal) as part of a conservative conceptual design to ensure that cost and schedule envelopes for the line-item project adequately cover all systems likely to be selected. In addition, the heat load and particle collection requirements of the divertor systems may have a significant impact on the designs because the power densities at collection areas will tax the capabilities of known concepts.

APPENDIX A.4

BLANKET/FIRST WALL/SHIELD TECHNOLOGY TESTING

A.4.1 INTRODUCTION

The blanket/first wall/shield subgroup deliberations are summarized in this appendix. Participants in this subgroup are listed in Table A.4.1 (part-time observers are not identified).

The blanket/first wall/shield subgroup adopted the viewpoint that an ETF will be designed, built, and ready for initial operation in 1990. The subgroup then addressed the general question of what achievements can and should be accomplished on the ETF in the blanket/first wall/shield areas in order to advance to EPR and DEMO. It was recognized that in the process of designing and building the ETF, it will be necessary to use fully the information derived from the balance of the fusion program. In addition, it was recognized that substantial R&D will most likely be required, specifically to support the design and construction of the ETF, and it is assumed that this will be done.

A number of physics and technical assumptions were made concerning the data base that will be available in 1990. It was recognized that by this date, substantial advancements will have been made through the fusion devices and facilities now operating or planned in this country and abroad. Table A.4.2 identifies some of these devices and facilities.

In addition to the variety of information that will be provided by these devices and facilities, numerous advances in technology will be derived based on the experimental information obtained from these fusion devices and from as yet unidentified experiments. Particular assumptions made in this regard include the following.

(1) Neutronics data for the 0- to 14-MeV energy range will become available from planned experiments. Mockup shield experiments will also be completed.

(2) Special thermal hydraulic testing will be completed for systems using water or helium as coolants.

(3) Tritium behavior (permeation, solubility, etc.) will be determined in materials of interest.

Table A.4.1. Participants in blanket/first wall/shield technology testing subgroup

C. A. Flanagan, Chairman	Westinghouse Electric Corporation
D. A. Dingee, Recording Secretary	Battelle-Pacific Northwest Laboratories
M. A. Abdou	Georgia Institute of Technology
R. J. Beeley	Energy Technology Engineering Center
E. S. Bettis	Science Applications, Inc.
D. W. Graumann	GA
T. J. Huxford	ORNL
D. J. McFarlin	United Technologies Research Center
P. H. Sager, Jr.	GA
R. T. Santoro	ORNL
M. C. Stauber	Grumman Aerospace Corporation
I. Sviatoslavsky	University of Wisconsin
F. H. Tenney	PPPL
C. A. Trachsel	McDonnell-Douglas Astronautics Company
F. G. Welfare	Babcock and Wilcox

Table A.4.2. Fusion devices and facilities contributing to data base by 1990

- Alcator C
- Doublet III
- EBT
- FMIT
- ISX-B
- JET
- JT-60
- Mirror Fusion Test Facility (MFTF)
- PDX
- PLT
- Rotating Target Neutron Source II (RTNS-II)
- TFTR
- Tandem Mirror Experiment (TMX)
- Tritium Systems Test Assembly
- T-10M

(4) Minimal leak detection capability will be available.

(5) Austenitic stainless steel/nickel-based alloys will be tested to prototypical helium generation and dpa levels, but no other structural materials will be qualified by 1990.

(6) Limiters will be available for short burn (several seconds) fusion devices.

(7) All nonnuclear qualification of engineering issues will be completed to the level required. The exact requirements are not obvious at this time. However, all testing of blanket/first wall/shield issues that can be performed in a nonnuclear environment will be planned and completed to the extent possible before testing begins in the nuclear environment of the ETF. This includes, but is not limited to, the testing of coolant thermal hydraulic system designs (with simulated heating), magnetic effects, remote maintenance, etc.

(8) The necessary instrumentation will be qualified for use in the ETF environment.

(9) Adequate remote maintenance techniques and equipment will be available for use with ETF experiments.

(10) Complete control or avoidance of plasma disruptions will not have been established. This item is of major concern. The deliberations of the group led to the conclusion that it cannot be assumed that plasma disruptions will not occur on the ETF; therefore, the ETF and all blanket/first wall/shield tests involving direct interactions with the plasma must be designed to accommodate plasma disruptions.

With these physics and technology assumptions, a mission analysis was conducted for the key blanket/first wall/shield issues.

A.4.2 KEY ISSUES

The key issues considered by the subgroup are listed in Table A.4.3. Basically the areas investigated include those issues or components associated with the first interface with the plasma, the blanket issues, and the shield issues. Specifically excluded from the deliberations were issues associated with divertors, buffered energy storage, and power conversion.

Table A.4.3. Key issues for blanket/first wall/shield

First wall/first wall modifiers
Tritium-breeding blanket
Shielding
Neutron source distribution
Activation
Synfuel production blanket
Fusion-fission hybrid systems
Electric power capability demonstration

A subjective assessment of priorities for the key issues is indicated by the order of the listing in Table A.4.3. Qualification of the first wall, tritium-breeding blanket, and shielding designs for EPR is assigned first priority. Experimental data on neutron source distribution and materials activation are also considered important. Qualification of designs for synfuel production blanket systems and fusion-fission hybrid systems will become important if the development of either of these systems is pursued. The demonstration of electric power generation capability is considered less important from a technical standpoint because such demonstration is straightforward and can be accomplished on EPR. A tentative schedule for the key issues is shown in Fig. A.4.1.

A.4.3 FIRST WALL AND FIRST WALL MODIFIERS

A.4.3.1 Assumptions

It was assumed that the requirements of impurity concentration limits will be well enough understood that ignition conditions will have been established and that low Z coating candidates will have been selected and tested under short pulse conditions.

A.4.3.2 Achievements/Milestones

(1) Test candidate armor compositions and designs for protection of the plasma chamber from typical plasma disruption energy distribution and neutral beam impingements. Qualify armor designs for EPR and DEMO.

(2) Test coating concepts, including in situ coating techniques with the ability to coat penetration surfaces. Qualify coating systems for EPR and DEMO.

(3) Test first wall designs, including armor and coatings. Demonstrate the ability of the first wall to survive cyclic thermal and mechanical loading under bombardment from charged particle and neutron flux irradiation. Qualify first wall designs for EPR and DEMO.

(4) Test limiters for locating the plasma edge during long plasma burns (e.g., with actively cooled, low Z surfaces). Qualify limiter designs for EPR and DEMO.

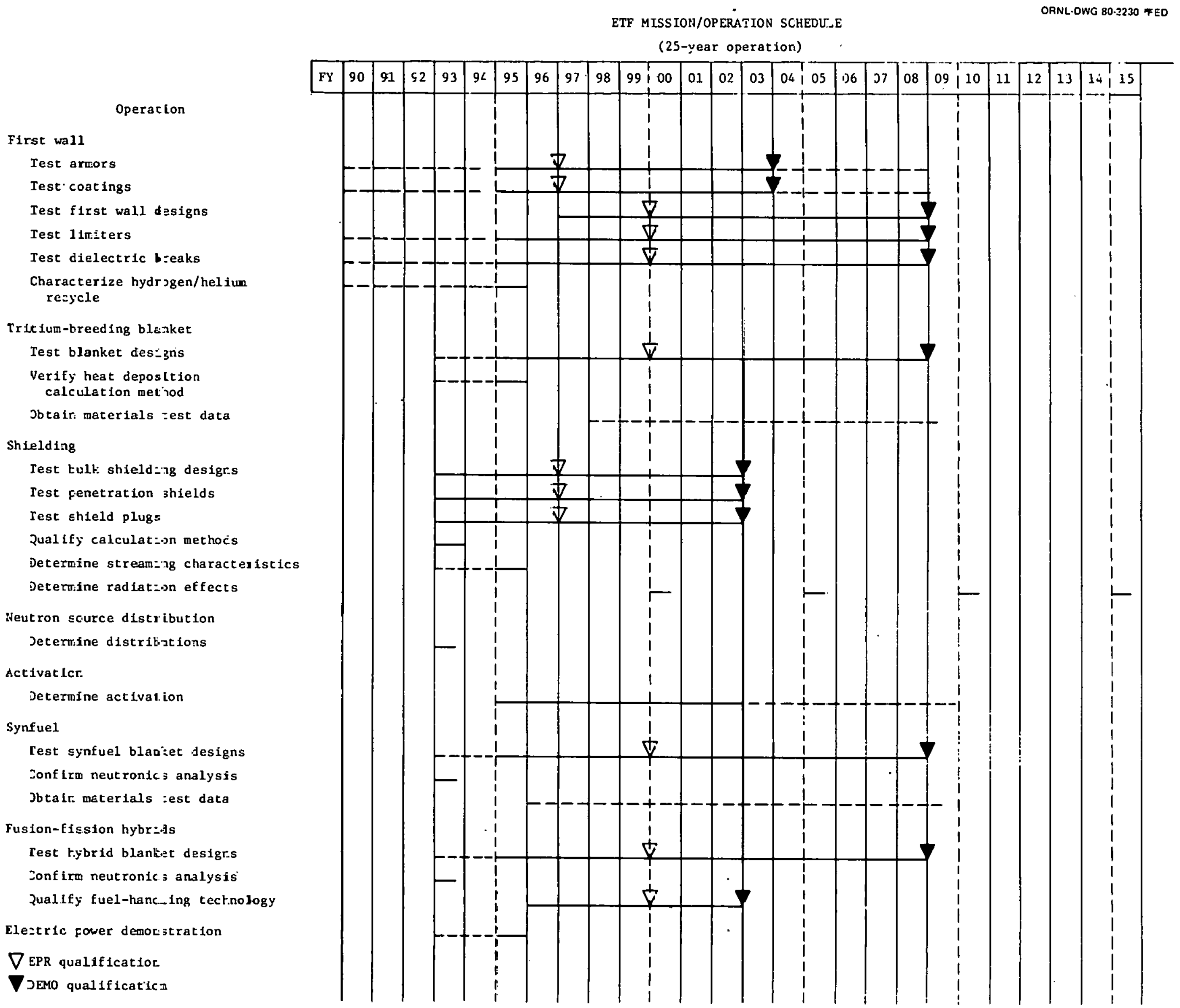

Fig. A.4.1. Key issues in blanket/first wall/shield technology testing.

(5) Test dielectric breaks for first wall and module insulation. Qualify dielectric breaks for EPR and DEMO, including all environmental considerations and potential failure modes.

(6) Determine hydrogen and helium recycle characteristics of candidate first wall designs including candidate liners, coatings, armor, etc.

A.4.3.3 Device/Facility Requirements

In general, the milestones require that all candidate designs be tested while exposed to the plasma. Thus, the ETF should be designed to provide test stations that allow test modules or samples to have direct access to the plasma (i.e., there must be no intermediate material interface). Appropriate hot cell areas and techniques for removing and testing candidate modules and samples are required, as are in situ diagnostics to monitor hydrogen and impurity fluxes, temperatures, and stress levels at the first wall.

The testing requirements also point to the need for the very high reliability of candidate designs; otherwise, frequent failures will result in considerable device downtime.

To achieve the milestones, a neutron wall loading of $\geqslant 1$ MW/m^2, a burn time of $\geqslant 30$ s, and a total of $\geqslant 5 \times 10^5$ burn cycles are required. Although displacement damage levels of $\geqslant 30$ dpa are desirable, it may not be possible to achieve this goal with the ETF, considering the current EPR and DEMO schedules.

A.4.3.4 Testing Schedule Requirements

The time required for completing the first five milestones will be several years. The sixth milestone will take several months.

A.4.4 TRITIUM-BREEDING BLANKET

A.4.4.1 Assumptions

It was assumed that currently planned integral experiments in this area will be completed.

A.4.4.2 Achievements/Milestones

(1) Test the performance of candidate tritium-breeding blanket design systems, including variation in candidate designs such as compositions and configurations. Qualify tritium-breeding blanket designs for EPR and DEMO.

(2) Verify calculation methods for predicting the spatial variations in heat deposition in the various components of typical blanket designs.

(3) Contribute to the materials data base by evaluating materials effects during simultaneous application of temperature, cyclic stress, radiation, and chemical environment.

A.4.4.3 Device/Facility Requirements

Achievement of the milestones will require the following:

(1) a reactor-grade plasma with representative heat deposition rates and burn times,

(2) appropriate diagnostic equipment and normal protection instrumentation,

(3) appropriate coolant loop(s) with tritium extraction capability,

(4) space for testing a number of candidate designs simultaneously (perhaps up to six module test stations),

(5) capability for remotely maneuvering modules and test equipment, and

(6) appropriate hot cell areas and techniques for assembling, disassembling, inspecting, and evaluating the modules.

A.4.4.4 Testing Schedule Requirements

The time required for completing the first milestone will be several years; for the second milestone, it will be several months. The third milestone will be accomplished over the lifetime of the plant.

A.4.5 SHIELDING

A.4.5.1 Assumptions

It was assumed that key integral and mockup shielding experiments that are part of the present fusion program will have been completed and that evaluated nuclear data and appropriate calculational methods will be available.

A.4.5.2 Achievements/Milestones

(1) Test candidate bulk shield concepts. Qualify bulk shield designs for EPR and DEMO.

(2) Test the effectiveness of key materials and geometric configurations for penetration shields. Qualify penetration shield designs for EPR and DEMO.

(3) Test movable shield plugs designed for use in vacuum and beam injection ports. Qualify shield plug designs for EPR and DEMO.

(4) Obtain data to qualify the associated calculational methods.

(5) Determine radiation-streaming characteristics and the effects of varying the size, shape, and configuration of the penetration.

(6) Determine the effect on performance characteristics of key components exposed to radiation. Key components include cryogenic pumping panels for auxiliary heating systems (rf and neutral beam), superconducting magnets, diagnostic instrumentation, etc.

A.4.5.3 Device/Facility Requirements

Achievement of the milestones will require the following:

(1) a neutron wall loading of $\geqslant 1$ MW/m^2, with a total of >5 MWyr/m^2 for the requirements of milestone (6),

(2) availability of in situ diagnostics, and

(3) appropriate hot cell areas and remote maintenance techniques to remove and test candidate designs and samples.

A.4.5.4 Testing Schedule Requirements

Several years will be required to complete milestones (1), (2), and (3). Completion of milestones (4) and (5) will require about a year. Milestone (6) will be accomplished over the lifetime of the plant.

A.4.6 NEUTRON SOURCE DISTRIBUTION

A.4.6.1 Assumptions

It was assumed that evaluated nuclear data and appropriate calculational methods will be available, as will appropriate neutron diagnostics.

A.4.6.2 Achievements/Milestones

(1) Determine experimentally the poloidal and toroidal distribution of nuclear parameters as a function of neutron source distribution. It is imperative that the spatial variation in neutron wall loading as a function of the spatial variation in the neutron source distribution be known and predictable in order to develop efficient blanket/shield designs for EPR/DEMO.

A.4.6.3 Device/Facility Requirements

It is highly desirable to be able to vary the plasma profile by MHD shift control in order to deliberately change the spatial neutron source distribution over some range. Collimators, detectors, and data acquisition capability will be required for a minimum of three poloidal and two toroidal locations.

A.4.6.4 Testing Schedule Requirements

At least 200 pulses will be required to complete the tests needed for the milestone.

A.4.7 ACTIVATION

A.4.7.1 Assumptions

It was assumed that evaluated nuclear data and appropriate calculational methods will be available, as will appropriate neutron diagnostics.

A.4.7.2 Achievements/Milestones

(1) Obtain information to extend and verify available knowledge of the buildup of radioactivity in candidate materials for fusion reactor components (e.g., superconductors, stabilizers, insulators, etc.). It is imperative that criteria be established on the effects of radioactivity on critical components so that design criteria can be established for the shielding attenuation levels that must be provided.

A.4.7.3 Device/Facility Requirements

Achievement of the milestones will require the following:

(1) a quick insertion/withdrawal system with the ability to handle a large number of small samples and

(2) appropriate laboratory facilities for performing activation evaluations subsequent to irradiation.

A.4.7.4 Testing Schedule Requirements

The time required to achieve the milestone is variable, depending on the samples tested.

A.4.8 SYNFUEL PRODUCTION BLANKET

A.4.8.1 Assumptions

It was assumed that candidate processes will be limited to those for which proof of principle has been demonstrated.

A.4.8.2 Achievements/Milestones

(1) Test candidate blanket designs to achieve the design temperatures required by candidate synfuel processes and tritium-breeding capability, consistent with synfuel production reactor requirements. Qualify blanket designs for synfuel production in EPR and DEMO.

(2) Obtain experimental information to confirm neutronics analysis.

(3) Obtain materials test data from synfuel production blanket modules exposed to the simultaneous application of temperature, cyclic stress, radiation, and chemical environment.

A.4.8.3 Device/Facility Requirements

Achievement of the milestones will require the following:

(1) a neutron wall loading of ≥ 1 MW/m^2,

(2) a total of $\geq 5 \times 10^5$ 30-s burn cycles,

(3) space for testing promising candidate designs,

(4) appropriate internal diagnostics (thermocouples, etc.) in the modules, and

(5) appropriate heat dumps.

A.4.8.4 Testing Schedule Requirements

Completion of milestone (1) will require about a year; completion of milestone (2) will take several months. Milestone (3) will be accomplished over the lifetime of the synfuel production blanket test program.

A.4.9 FUSION-FISSION HYBRID SYSTEMS

A.4.9.1 Assumptions

It was assumed that evaluated nuclear data and appropriate calculational methods will be available and that all predemonstration analyses and nonnuclear engineering tests will have been performed for candidate designs.

A.4.9.2 Achievements/Milestones

(1) Test candidate hybrid designs to obtain technical data on thermohydraulic performance, tritium breeding, fissile breeding, fuel burnup, radiation damage, and mechanical integrity. Qualify hybrid blanket designs for EPR and DEMO.

(2) Obtain experimental information to confirm neutronics analysis.

(3) Qualify fuel-handling technology requirements needed for EPR/DEMO.

A.4.9.3 Device/Facility Requirements

Achievement of the milestones will require the following:

(1) a neutron wall loading of $\geqslant 1$ MW/m^2,

(2) a total of $\geqslant 5 \times 10^5$ 30-s burn cycles,

(3) space for testing promising candidate designs,

(4) appropriate internal diagnostics (foils, detectors, thermocouples, strain gages, etc.) in the modules,

(5) appropriate shutdown techniques and emergency coolant for each module,

(6) capability for quick and routine access to the modules,

(7) appropriate heat dumps, and

(8) appropriate hot cell areas, transfer casks, and heat removal and maintenace techniques.

Fission reactor safety criteria should be employed in all aspects of module design and testing.

A.4.9.4 Testing Schedule Requirements

Completion of milestones (1) and (3) will require several years; completion of milestone (2) will take several months.

A.4.10 ELECTRICAL POWER CAPABILITY DEMONSTRATION

A.4.10.1 Assumptions

No assumptions were made in this area.

A.4.10.2 Achievements/Milestones

(1) Demonstrate the capability of a candidate blanket and shield design to generate, in a representative fusion environment for a sufficient period of time, the design temperature conditions needed for electrical power generation.

A.4.10.3 Device/Facility Requirements

Achievement of the milestone will require the following:

(1) appropriate diagnostics and
(2) space for testing one or more candidate designs simultaneously.

A.4.10.4 Testing Schedule Requirements

Completion of the milestone will require 6-12 months.

APPENDIX A.5

REMOTE MAINTENANCE AND ENGINEERING OPERATIONS TESTING

A.5.1 INTRODUCTION

The ETF must offer the operational experience necessary for the tokamak fusion program to proceed with assurance to the EPR and DEMO stages. In particular, the maintainability of a radioactive machine must be examined and the reliability of the machine's components correlated with operating conditions and design principles. Also, an overriding requirement of a power reactor will be availability. This will depend, among other things, on the time required for changeout and maintenance operations. The feasibility of and time required for these operations must therefore be assessed in the ETF.

Because the ETF will be a long pulse tokamak with a superconducting TF system, significant statistical information about failures and their causes may be obtained from it. Therefore, data gathering will be an important mission. Information on faults, their causes, and their frequency of occurrence must be adequately recorded and interpreted.

Remote maintenance and engineering operations testing are missions that largely relate to the period after construction of the ETF. However, information will also be acquired during the design and construction of the machine. Accordingly, one objective of the ETF mission is the design of the machine for maintainability. Participants in the remote maintenance and engineering operations testing subgroup are listed in Table A.5.1.

A.5.2 KEY ISSUES

Three key issues have been identified:

(1) demonstration of the maintainability of ETF components,

(2) acquisition of data from ETF operation for the improved maintainability of future reactors, and

(3) acquisition of data on the problem of designing for maintainability.

Table A.5.1. Participants in remote maintenance and engineering operations testing subgroup

D. L. Kummer, Chairman	McDonnell-Douglas Astronautics Company
J. E. Baublitz	OFE
R. F. Beuligmann	General Dynamics, Convair Division
J. G. Crocker	EG&G Idaho
D. Field	GA
J. W. French	EBASCO Services
G. Fuller	McDonnell-Douglas Astronautics Company
E. P. Gagnon	United Technologies Research Center
P. N. Haubenreich	ORNL
J. B. Joyce	PPPL
F. A. Puhn	GA
W. Marton	OFE
L. Masson	EG&G Idaho
D. J. McFarlin	United Technologies Research Center
R. E. Mullen	Aerojet Manufacturing Company
V. S. O'Block	Westinghouse Electric Corporation
M. Sniderman	Westinghouse Electric Corporation
P. T. Spampinato	Grumman Aerospace Corporation
I. N. Sviatoslavsky	University of Wisconsin
S. S. Waddle	DOE/Oak Ridge Operations
K. E. Wakefield	PPPL
J. E. C. Williams	MIT
N. E. Young	EBASCO Services

The first and second issues can, to some extent, be interrelated. Table A.5.2 shows the data and maintenance experience to be obtained for each of the ETF components. The letters suggest the relative importance of the mission functions. In particular, the chart identifies those components that may require maintenance evaluation in mockup form prior to startup in 1990. The three key issues are described in the following sections.

A.5.3 DEMONSTRATION OF COMPONENT MAINTAINABILITY

The objectives of the demonstration are (1) to obtain information about the effect on maintainability of the design of components, (2) to obtain information about maintenance operations, and (3) to establish confidence that maintenance times will ultimately allow necessary plant availability for cost-competitive fusion power.

The key ETF components to be considered for the demonstration of maintainability are as follows:

(1) first wall, with particular attention to modular changeout and in situ repair (holes, leaks, lines, low Z coatings),

(2) blanket,

(3) shield,

(4) limiter,

(5) vacuum pumps (particularly cryosorption),

(6) fueling equipment,

(7) neutral beam lines and ion sources,

(8) divertor,

(9) TF coils,

(10) PF coils,

(11) OH coil and central core, and

(12) maintenance equipment.

This list of components is representative of a reactor.

Components 1-8 are likely to require replacement or repair during the lifetime of the ETF as a result of normal operation. Therefore, they will be designed for maintainability, and a maintainability demonstration will be part of the expected normal operations.

Table A.5.2. Remote maintenance and engineering operations testing matrix (A indicates top priority; B, second priority; 0, probably not applicable; M, a mockup experiment will be done before 1990)

Mission function	ETF subsystem											
	First wall and vacuum vessel	Blanket	Shield	Limiter test bays (ports)	Pumps	Fueling systems	Neutral beams and sources	TF coils	EF coils	OH coils	Divertor	Remote maintenance equipment
Statistics on failures and causes	A	A	A	A	A	A	A	A	A	A	A	A
Environment radiation survey	0	0	0	0	A	A	A	A	A	A	A/B	B
Fault location efficacy	A	A	A	A	A/B	A	A	A	A	A	A	B
Data for preventive maintenance	A/M	A/M	A/M	A/M	A	A	A	A/M	A/M	A/M	A/M	B/M
Fluid line seal performance	A	A	A	A	B	A	A	B	B	B	A	0
Assessment of contact maintenance	A	A	A	A	B	A	B	B	B	B	A	A
Effect of radiation environment on maintenance	A	A	A	A	A	A	A	A	A	A	A	A
Maintenance with magnets cold	A/M	A/M	A/M	A/M	0	0	0	A/M	A/M	A/M	A/M	0
Vacuum seal evaluation	A	0	0	0	A	A	A	A	A	A	A	0
Maintenance procedure evaluation	A/M	A/M	A/M	A/M	A	A	A/M	A/M	A/M	A/M	A/M	A/M
Areas of great difficulty in maintenance	A	A	A	A	B	A	A	A	A	A	A	B

Components 9-11 may have a very long lifetime, and maintenance may not be required during the operating life of the ETF. Relatively long maintenance times may be allowed for the repair of these systems. Consequently, the requirement for a demonstration and the approach for accomplishing the demonstration must be examined carefully.

A.5.3.1 Assumptions

Only limited remote maintenance of some components will have been demonstrated on TFTR. Even where data are available, the design of the TFTR components will be substantially different and generally simpler. Also, the time permitted for TFTR maintenance operations will be longer than for the ETF and subsequent reactors. Data are currently available from fission reactor refueling, breeder reactor development, and remote operations at facilities such as the N Reactor and the Purex Facility at Richland, Washington. Future information from these fission facilities probably will not be significantly different from that currently available.

A.5.3.2 Achievements/Milestones

Advancements are required in (1) the time to replace components; (2) the in situ repair of selected components and types of failures; (3) the effectiveness of inspection procedures for preventive maintenance and acceptance of a repaired or replaced component; (4) the design of simple, modular components, especially if frequent replacement is anticipated; and (5) the development of rapid and reliable fluid and electrical disconnects. These and other milestones are described in Tables A.5.3-A.5.8.

Modular components and experiment packages of significant size and complexity will have to be replaced by remote techniques. The replacement times permissible will probably vary from a few days for small components with an expected short life to months for large components with a long life that are inherently difficult to replace.

Table A.5.3. Remote maintenance — nuclear island

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
General needs			Removal and requalification procedures; establishment of maintenance time line; operational proving of equipment design (may be accomplished in mockup); qualification of personnel (may be accomplished in mockup)	Operational procedures and equipment design verified in mockup	Requires early availability and qualified equipment reflecting current hardware design (may include upgrading the equipment as the design is evolved)
First wall	Removal and replacement experience on TFTR; materials data in hand	Develop methods of replacing first wall sections and requalification after replacement		First changeout of activated first wall segment within 3 years following D-T operation; replacing first wall of 1 sector should take about 2 months	
Blanket	Materials data only	Develop replaceable module, including provisions for handling, attachment, and coolant joints		Replacing blanket module of 1 sector should take about 2 months (normally done at same time as first wall sector replacement)	
Shielding	Limited data on handling of shielding blocks	Develop shielding module, including provisions for remote handling, support, restraint, and coolant joints		Access to blanket and first wall provided by removing external shielding only; internal shielding to be removed with a complete module segment	
In situ maintenance of first wall	Experience in remote maintenance of limiters, armor plate, and in situ diagnostics on TFTR	Develop nondestructive in-vessel inspection techniques, fault isolation devices, and special equipment to perform maintenance functions; provide suitable interface for mounting and supporting in-vessel equipment and allowing for ingress/egress; develop methods for applying protective coatings to first wall		Minor in situ maintenance should take about 2 weeks (if fault has been isolated)	Requires incorporation of access ports and provision of in-vessel support and interface for in situ equipment
Replacement of limiter blades	Experience on TFTR	Improve limiter blade design to facilitate remote replacement; provide for disconnecting cooling lines (if required); develop specialized equipment to remove and replace blades		Changeout should take about 3 weeks	Requires incorporation of access ports and provision of in-vessel support and interface for in situ equipment

Table A.5.4. Remote maintenance — magnet system

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Coil removal and replacement			Demonstrate the feasibility of removing and replacing a coil (could be accomplished during initial assembly)[a]		
TF coils	Experience on TFTR, LCP, T-15, and Doublet III[b]	Develop remote disconnect for electrical busbars, remote cryogenic couplings, and specialized handling equipment		Activity of major magnitude; unscheduled maintenance will require >1 year. If coils are designed for rapid replacement, time could be reduced to <6 months[c]	TF coil size dictates the need for a coil-winding facility that could be used to repair failed units
Inner PF coils	Experience on ASDEX, PDX, and Alcator C	Develop remote disconnect for electrical busbars, mechanical joint for segmenting coils, remote connections for coolant lines, remote handling fixtures, and remote viewing systems		Replacement of 1 coil should take about 3 months	Design must facilitate visibility and access to allow remote maintenance
Outer PF coils	Experience on TFTR, PDX, and Alcator C	Develop remote disconnect for electrical busbars, remote cryogenic couplings, mechanical joint for segmenting coils or winding coils in place		Replacement of 1 upper coil should take about 2 months; of 1 lower coil, about 6 months	Requires a circular maintenance well to allow disassembly/reassembly of lower PF coils and storage area within reactor building for upper PF coil support structure
Divertor maintenance	Experience with (1) external-type divertor on Model C Stellarator, (2) poloidal divertor on PDX, ASDEX, and JT-60, (3) bundle divertor on DITE and possibly ISX-B; data on maintenance on bundle divertors from Culham Laboratory; experience with liquid metals on LMFBR-related programs	Develop handling equipment		Replacement of a bundle divertor should take about 1 month	Requires ability to maneuver component to repair area
Central core OH coil replacement	Experience on TFTR, PLT, PDX, DITE, ASDEX, JET, and Alcator C	Develop specialized maintenance equipment for handling and viewing		Unscheduled maintenance activity may take more than 1 year	Requires vertical clearance to remove center column

[a] It is assumed that coils will be designed for maximum reliability; their removal and replacement are not expected to be necessary during the design life of the ETF.

[b] TFTR's TF coils are copper and approximately one-half the size of ETF's; LCP's TF coils are superconducting and approximately one-half the size of ETF's.

[c] A design that permits easy removal of the TF coils may have an impact on the remote maintenance of other components.

Table A.5.5. Remote maintenance — equipment

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Recovery from maintenance equipment malfunction	Composite experience from remote nuclear technology	Develop mobile viewing and manipulator system to appraise failure mode	Establish failure mode analysis and determine specialized systems and back-up systems		Requires provision of viewing interior of reactor building
Component replacement, including vacuum pumps (cryosorption), fueling equipment, neutral beams, neutral beam ion sources, rf ionization equipment, and rf heating equipment	Experience on TFTR, PLT, MFTF, EBT, and Alcator C with vacuum pumps, neutral beams, and fueling, rf ionization, and rf heating equipment[a]	Improve design for remote maintenance and handling; design for more severe environment; consider tritium contamination for reactor building and balance of plant; develop specialized equipment for transport of large and/or heavy components with close-tolerance positioning capabilities	Establish failure mode analysis and determine specialized systems and back-up systems	Vacuum pump: 2 weeks to remove and replace; fueling equipment: 2 weeks to replace; neutral beam: 1 week to replace; ion source: 2 days to replace; rf ionization equipment: 2 days for maintenance; rf heating equipment: 2 days for maintenance	Requires adequate access to maneuver components to repair area; floor loading/surface condition adequate for transport of heavy components; hot cell facilities close to reactor building for component maintenance

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[a] Much of this equipment is designed for hands-on maintenance.

Table A.5.6. Engineering operations — maintenance statistics

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Subsystem failure rates and causes	Experience on JT-60, T-15, JET, TFTR; data from TSTA, LCP, FMIT, and MFTF; history of reliability of neutral beams, rf sources, and operating fusion devices	Operate machine for significant number of shots at high output; obtain failure data on items such as superconducting coils, fueling devices; publish report	Adequate data collection and analysis	Throughout operation of machine	Failure detection equipment required
Vacuum seal adequacy and seal maintenance (mechanical seals or welds)	Performance data available on TFTR, JET, Doublet III, etc., in smaller sizes	Operate vacuum system at design pressure and temperature; obtain data on failure rates, causes, time to repair, integrity after repair, etc.; publish report	Installation of adequate instrumentation and leak detection equipment; maximum number of operating cycles at maximum burn time	Collect data on successive remotely removed flanges, seals, etc., after use; analyze failed seals to determine cause; inspect condition of seals during routine maintenance operations and record history	Design adequate instrumentation, leak detection, and easy inspection capability
Adequacy of maintenance procedures and equipment	Experience on TFTR and other devices with remote maintenance	Write maintenance procedures; test maintenance procedures off-site, on mockup, and on ETF using actual equipment; document record of evaluation of maintenance procedures and equipment capability		Time for demonstration of maintenance operations, including simulation of abnormal situations	Mockups and other special facilities required to test maintenance procedures and equipment
Items/areas of extremely difficult maintenance		Complete operation of device; define and describe difficult maintenance tasks as they are identified during design, on mockup, during assembly, during operation, and during postoperation maintenance demonstrations; provide timely input to designers of EPR		Recovery from schedule slippage due to lengthy maintenance tasks that impact machine availability	Possible redesign of areas identified as difficult to maintain

Table A.5.7. Engineering operations — maintenance experience

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Effectiveness of locating and detecting failures and minimizing damage	Failure detection history from TFTR, LCP, TSTA, etc.	Demonstrate techniques for positive early detection of vacuum leaks, superconducting coil malfunctions, tritium system leaks, etc., during shakedown; publish report	Adequate data collection and analysis, including time to detect failure, take corrective action, and identify cause and location	Thorough check-out during installation and shakedown; analysis time required after a failure; inspection of related components and instrumentation required after a failure, including review of procedures	Failure detection equipment and special controls or other devices required to minimize damage; develop design and operative philosophy relating to failures being designed for
Techniques for monitoring device operation to obtain data for use in anticipating need for maintenance	Limited performance data available from operational devices	Operate machine; develop instrumentation plan; publish report	Installation and operation of adequate instrumentation for measuring strain, temperature, crack propagation, flow rates, radiation, pressure, time, deflections, currents, voltage, fields, etc.	Check-out and calibration of instrumentation during assembly; data monitored and analyzed during machine operation	Requires adequate instrumentation that does not compromise machine reliability
Fluid line joint and seal performance, leak detection, and repair	Operating data from previous devices on fluid line joint performance for moderate line sizes; nuclear power plant data will exist for water lines; TFTR data available for tritium and gas lines; liquid helium data available from TFTR, other neutral beam applications, LCP	Operate fluid systems; obtain data during machine operation, record data on performance, and analyze failures (type and frequency); publish report	Installation of adequate instrumentation, failure detection equipment, and test loops for seals and joints to be used in future devices	Data monitored and analyzed during machine operation; time required during operation for removal and replacement of experiments	Provide for special test loops; adequate instrumentation required; design adequate failure analysis equipment
Determine potential for contact and semiremote maintenance	Experience with maintenance on TFTR	Consistent with reactor-room radiation, determine applicable tasks for contact maintenance, demonstrate feasibility prior to D-T operation, and implement into maintenance plan those tasks shown to be beneficial; publish report		Time to perform contact or semiremote maintenance tasks as appropriate (demonstrate personnel protection devices in radiation environment prior to use in ETF)	Special tools/shielding may be required for specific tasks
Feasibility of maintenance with magnets cold	Data from maintenance operations on LCP, MFTF, T-15, MHD, PMS, etc.	Identify tasks that can be performed with magnets cold		Time to perform maintenance tasks as appropriate with magnets cold	Design device to minimize number of tasks requiring warm-up of superconducting coils; mockup may be required to evaluate maintenance operation

Table A.5.8. Engineering operations — radiation effects

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Reactor-room and component radiation environment	Limited data from TFTR, JET, TSTA, etc.	Obtain radiation data for all components and reactor room over a range of operative parameters and history; publish report	Adequate data collection and analysis	Throughout D-T operations	Means of monitoring required
Effect on maintenance of radiation environment, temperatures, vacuum, or corrosion	Limited radiation damage data available from TFTR, FMIT, laser fusion; fission reactor data available; operation data (temperature, vacuum, corrosion, sputtering, etc.) available from other operating fusion devices	Analyze failures and degradation of characteristics as components are available for inspection; publish report	Maximum operating time at critical parameters	Time required to remove and analyze components and to analyze effect of operating environment on their functions	Capability for materials test experiments must be provided

The design of ETF components to satisfy maintenance time and confidence goals will have an impact on the design effort and impose design constraints. Maintenance features will have to be known early in the design and will be one more requirement influencing the final design. In close coordination with the component design, maintenance equipment and procedures must be established.

Functional mockups will be needed to support the development of maintainable designs, maintenance equipment, maintenance procedures, and personnel training techniques. Maintenance equipment will include some specialized equipment. Equipment to recover from the malfunction of the normal maintenance equipment will be required. For certain components, such as ion sources, hot cells will be needed to recondition the components after they are removed from the reactor room.

A.5.3.3 Device/Facility Requirements

Specific functional and performance requirements for the ETF components, equipment, and facilities involved in remote maintenance must be established in concert with design and overall device specifications. General requirements include (1) establishment of detailed component removal, repair, and requalification procedures; (2) establishment of accurate maintenance operation time lines; (3) proving of equipment design and procedures by preoperational check-out; and (4) qualification of personnel.

A.5.3.4 Testing Schedule Requirements

Most maintenance operations must be performed with the device shut down. This means that those operations that cannot be or are not carried out on mockups during design and/or assembly will have a significant effect on the machine's operational availability. Because the ETF components to be maintained and the maintenance equipment and procedures to be used are yet to be designed, goals for the maintenance times should be established. These goals should be selected considering (1) the expected maintenance frequency, (2) the time during the program when the maintenance takes place, (3) the ETF availability requirement, and (4) the maintenance time/availability requirement for EPR and DEMO.

Maintenance demonstration may be performed (1) during device assembly, (2) prior to D-T operation, (3) after D-T operation, and (4) during decommissioning. Lengthy and risky demonstrations such as TF coil replacement might best be accomplished during assembly, during design or mockup, or during decommissioning.

A.5.4 ACQUISITION OF DATA FOR IMPROVED MAINTAINABILITY OF FUTURE REACTORS

The objective of this issue is the recording, analyzing, and dissemination of information for reactor maintenance. This information will be applied to the design and operation of future fusion reactors to improve their maintainability and overall performance. Key items of data and information desired are

(1) subsystem failure rates and causes,
(2) reactor room and component radiation environment,
(3) effectiveness in detecting and locating failures and minimizing damage,
(4) techniques for monitoring device operation to obtain data for preventive maintenance,
(5) fluid line joint and seal performance, leak detection, and repair,
(6) determination of potential for contact and semiremote maintenance,
(7) effects of radiation environment, temperatures, vacuum, or corrosion on component removal, replacement part fit, and mechanical joining,
(8) feasibility of maintenance with magnets cold,
(9) evaluation of vacuum seal adequacy and seal maintenance (mechanical seals or welds),
(10) evaluation of adequacy of maintenance procedures and equipment, and
(11) identification of items/areas of particular difficulty.

A.5.4.1 Assumptions

Some data will be available from fusion devices, including TFTR, JT-60, T-15, Doublet III, JET, and MFTF. Other experimental devices such as Alcator C, PLT, and PDX can also provide some information. However, not all of these machines maintain complete failure logs. The testing of subsystems to support the development of fusion devices will also provide data. (Included in this category are LCP, TSTA, and FMIT.) Fission power plants, breeder development reactors, and special nuclear facilities will be additional sources of data and information. However, none of these provides a combination of environment, size, and design that closely resembles the fusion reactor. The ETF provides a unique test-bed in this regard.

A.5.4.2 Achievements/Milestones

Accomplishment of the data acquisition mission does not in itself require advancements. It will be achieved primarily by instrumentation and planned experiments that are compatible with the ETF. The reactor-like features of the ETF, its long cumulative operating time, and the design of many components for maintainability will provide the conditions that make the ETF an excellent facility for this mission. Only a small impact on the device characteristics, facilities, or schedule is anticipated.

A.5.4.3 Device/Facility Requirements

The instrumentation and special experiments required should impose a minimum need for new functional and performance requirements for the ETF device and facility. Plans for the required instrumentation and the special experiments necessary to acquire the desired data must be defined early in the ETF program. Also, to ensure completeness the data recording and dissemination required should be established early. Some of the data needs will require special experiments. One example might be determining the effects of radiation environment, high temperatures, vacuum, or corrosion on the binding up of parts that must move for maintenance and the fitting of the replacement part. Swelling, creep, corrosion products, or vacuum deposition might cause distortion or binding. A special experiment to evaluate a range of parameters influencing such distortion or binding may be the best way to obtain the needed data. Another example is determining the potential for contact and semiremote maintenance. In this case, different sectors of the torus might use different degrees of shielding and/or penetrations to evaluate alternatives. Furthermore, protective mobile shields might be instrumented and placed in the reactor room at appropriate locations to confirm shield effectiveness.

A.5.4.4 Testing Schedule Requirements

This mission can probably be accomplished within the operating times and downtimes established by other missions. Although the added instrumentation appears simple, its presence and maintenance may add to the total maintenance time requirements. The special experiments are considered to be relatively straightforward and can be designed so that their failure would not cause the device to be shut down.

A.5.5 ACQUISITION OF DATA ON DESIGNING ETF FOR MAINTAINABILITY

The ETF will be a system of high visibility, and its availability as perceived by the utilities will be particularly noted. Notwithstanding its precursor function, its availability will be interpreted as indicative of future systems. For a base load electrical generating plant, the target for the gross annual availability is ⩾85% and for shorter periods it is >95%. Therefore, during the entire ETF project from design to decommissioning, great care must be taken to provide adequate facilities for service, maintenance, and repair in order to achieve a final target of (for instance) 50% availability. Furthermore, during the engineering stages of the ETF, the influence of the demands of maintainability on the design will be noted and evaluated. The following guidelines to be used during the design of the ETF are offered:

(1) modularization of components,
(2) tradeoff on vacuum (primary and secondary) boundary location and shielding,
(3) identification and assessment of critical path maintenance actions (including high frequency activities),
(4) tradeoff of number and size of TF coils vs performance, cost, and access (including consideration of trimming coils),
(5) minimization of number and size of trapped PF coils,
(6) design for inspection,
(7) provision of back-up and redundant operation in design,
(8) appropriate use of mockups,
(9) maximum use of off-the-shelf maintenance equipment,
(10) evaluation of the ability to perform contact maintenance consistent with environment in reactor room,
(11) povision of clear access to elements requiring maintenance,
(12) choice of fluid/electrical joints based on tradeoff between replacement time, frequency, and reliability,
(13) provision for recovery from maintenance equipment failure,
(14) adoption of parts standards when remote handling is involved,
(15) development of maintenance procedures during component design and check-out with mockup and during assembly, and
(16) assistance and support from the newest hazardous environment operations technologies (e.g., space, undersea, fission, chemical plant, and machine actuation, production, and control systems) that may be of use in a fusion reactor environment.

This list of guidelines must be reevaluated and expanded. For maximum effectiveness, the design guidelines for maintainability must be established at the beginning of the program and their application enforced throughout the design period.

A.5.6 MILESTONE CHART AND MISSION ANALYSIS TABLES

Figure A.5.1 indicates probable dates for the completion or occurrence of the deliberate maintenance events described in Tables A.5.3-A.5.8 and for the review of cumulative operational data.

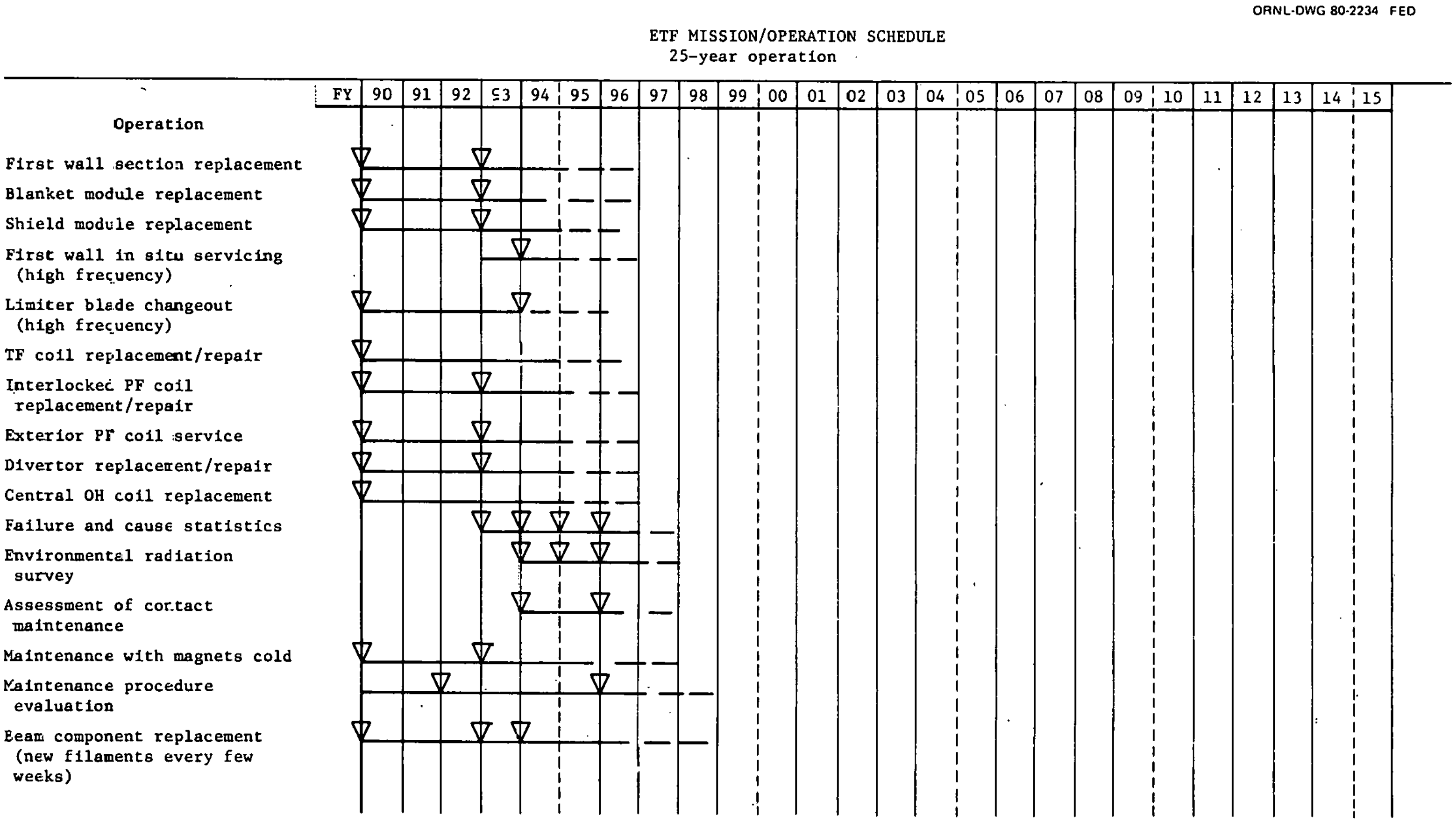

Fig. A.5.1. Maintenance schedule.

As indicated in the text and in Table A.5.2, many mockup and assembly trials of maintenance procedures are scheduled to take place before hydrogen startup in 1990. Before D-T operation (assumed to start in 1993), data on failures will be reviewed and maintenance operations reviewed and tested.

Immediately after the start of D-T operations, radiation surveys will be made and the areas of possible contact or shadow-shielded maintenance determined. Thereafter, statistical information will be obtained largely at random. However, accumulating information will be reviewed at least annually.

The ETF mission is summarized in Tables A.5.3-A.5.8, which show the relationship of the maintenance and operational functions to the ETF program.

APPENDIX A.6

MATERIALS TESTING

A.6.1 INTRODUCTION

Materials testing has been identified as one of the principal ETF missions for providing the data base for an EPR. In the materials testing subgroup the approach taken was to address materials testing from a functional viewpoint. Five materials categories were identified, and a separate category for plasma/wall interactions was established. Participants in the subgroup are listed in Table A.6.1. Key findings are summarized in Tables A.6.2–A.6.7.

Testing for fusion-produced radiation effects was the only consideration proposed for the ETF materials testing mission. It is assumed that testing of material properties (e.g., corrosion of breeding and cooling fluids) will be provided at other test facilities.

The use of the ETF as a materials test facility was found to have a significant impact on its operating and lifetime requirements. In addition, the timing between the ETF and EPR will probably not permit the long-term testing required to develop a design data base. An alternate proposal may be required in which the ETF provides correlations between the radiation effects produced in a reactor environment and the data base that will be available from fission test reactors.

A.6.2 KEY ISSUES

As a basis for the materials mission analysis, testing requirements were considered for six functional materials areas.

A.6.2.1 First Wall and Blanket Structural Materials

The first wall and blanket structural materials category includes all metallic materials to be used as structural elements within the radiation-affected zone of the blanket and shield.

Table A.6.1. Participants in materials testing subgroup

E. E. Bloom, Chairman	ORNL
R. E. Clausing	ORNL
J. W. Davis	McDonnell-Douglas Astronautics Company
M. J. Davis	Sandia Laboratories
J. H. DeVan	ORNL
R. E. Gold	Westinghouse Electric Corporation
N. J. Hoffman	Energy Technology Engineering Center
R. G. Micich	Grumman Aerospace Corporation
S. N. Rosenwasser	GA
D. L. Smith	ANL
J. L. Straalsund	Hanford Engineering Development Laboratory
F. W. Wiffen	ORNL

Table A.6.2. Materials testing — structural materials

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Engineering data base, basis for design methods	Data available from ORR, FMIT, EBR-II, HFIR, and FFTF for 70-300 dpa on paths A, B, C, and D[a] and ferrous alloys and for end of life (EOL) in helium for paths A and B alloys	Examine candidate materials for EPR/DEMO in fusion environment; correlate with fission data base; conduct tests lasting at least one-half the design lifetime of candidate alloys at 6 MWyr/m^2; develop capability to test at up to $\sim$20 MWyr/m^2 for EPR/DEMO qualification	125-liter test volume; neutron wall loadings of $>$2 MW/m^2; fully instrumented and controlled test stations with independent cooling; rapid (1-3 days) access to test stations; full hot cell and handling facilities	Examination of candidate materials, $\sim$1 year after full power D-T operations; testing to one-half of design lifetime, $\sim$6 years; testing to $\sim$20 MWyr/m^2, $>$10 years	Longer operation schedule for ETF; increase in product of duty factor and wall load to $>$2 MW/m^2; possible effect on compatibility with vacuum building; need for separate controlled systems for loading, cooling, etc.
Eliminations and judgments based on Alloy Development for Irradiation Performance (ADIP) program	Correlation on selected alloys from FMIT; extensive data base on unirradiated material properties; better definition of limiting properties of various materials	Post-mortem on ETF components at end of mission		Will take place at end of facility life	
Surface/bulk synergisms	No data available	Verify predictive capability for bulk properties in presence of plasma	Fully instrumented and controlled test stations with exposure to plasma	3 years	Requires $\sim$5 test stations, with and without exposure to plasma, fully instrumented, and $\sim$50 cm square by 10 cm deep

[a] Four paths of approach are being pursued in the ADIP program: A, austenitic stainless steels; B, higher strength iron-nickel-chromium alloys; C, refractory and reactive metals; D, innovative concepts.

Table A.6.3. Materials testing — nonmetallic materials

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Current break, insulators in high flux coils, waveguides, and neutral beam lines	Unirradiated properties data base available; irradiation effects data based on fission reactor irradiations available; no in situ information available	Test swelling, mechanical properties, and electrical properties to at least one-half the design lifetime of materials at 6 MWyr/m^2	Nothing beyond requirements for structural materials (see Table A.6.2)	Testing of materials to one-half design lifetime, 6 years; in situ testing for correlation, 3 years	Nothing beyond requirements for structural materials (see Table A.6.2)

Table A.6.4. Materials testing — heat sink materials

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Beam dumps, limiters, armor, divertor/collector, liners	Data available on beam dumps, limiters, and armor from TFTR; preliminary divertor/collector data from PDX; data available from neutral beam test stands; good thermal design background; very limited data on irradiation effects	Evaluate performance in actual fusion reactor environment; examine performance of near-full-scale divertor/collector materials if divertor is used on ETF	Capability for visual inspection of beam dumps and limiters during routine shutdowns and for removal or replacement of portions of components for inspection	Continuing over life of machine	Capability for inspection and replacement of beam dump and limiter materials; dedicated limiter for candidate materials with ready access, on-line surface temperature measurements

Table A.6.5. Materials testing — tritium-breeding materials[a]

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Chemical and physical properties of liquid lithium, liquid lithium alloys (e.g., Pb-Li), solid lithium compounds, molten salts	Adequate data base available except for the fusion spectrum	Confirm expected behavior through examination of blanket modules	Blanket modules for solid and liquid breeder materials that can be retrieved for examination; on-line recovery instrumentation	Continuing over life of machine	Requires separate cooling loops, retrievable blanket modules, on-line recovery instrumentation

[a] Joint effort with blanket/first wall/shield technology testing. See Appendix A.4.

Table A.6.6. Materials testing — magnet materials[a]

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Swelling, mechanical properties, electrical properties	Unirradiated properties established; some data on irradiated properties but at wrong spectrum	Test materials to at least one-half of design lifetime at 6 MWyr/m^2	Nothing beyond requirements for structural materials	~6 years	Nothing beyond requirements for structural materials

[a] The ETF will be used to test nonsuperconducting magnet materials under high fluence conditions. It is assumed that superconducting materials will be tested elsewhere.

Table A.6.7. Materials testing — plasma/wall interactions[a]

Key technical components/issues	Assumptions	Milestones	Device/facility requirements	Testing time	Reference design impacts
Effects of gas retention and recycle (of fuel and helium) on plasma and materials; effects of wall erosion (including sputtering, arcing, blistering, chemical attack, metallic snow, etc.); effects of impurity recycle (helium and wall associated)	Individual phenomena measured in laboratories and short pulse devices; collective phenomena and synergistic effects unknown, especially in long pulse, high neutron flux, tritium environments	Verify predictions based on models (i.e., test modules) and scaling effects; provide data for EPR/DEMO	Surface stations for analysis and testing similar to those on ISX-B and PLT (on-line, real-time); time-resolved diagnostics for plasma edge conditions; incident fluxes of particles and radiation, and emission fluxes from surfaces	Gas retention and recycle: 4 years of hydrogen operation and 2 years of D-T operation; wall erosion and impurity recycle: 4 years of hydrogen operation and 3 years of D-T operation	Surface stations will require $500\ \text{cm}^2$ per station at plasma position and transfer tubes through all machine peripherals and radiation shields; evaluation of wall erosion and impurity recycle requires a hot surface analysis laboratory on-site
Testing and verification of materials and processes for bare or coated components (in particular, for in situ coatings) for first wall, divertor plate (if used), limiters, beam dumps, insulators, and rf windows	Individual properties (i.e., thermal shock resistance, hydrogen recycling, arcing resistance, etc.) measured in laboratories; some experience and testing on ISX-B, TFTR, Doublet III, and Alcator C; no data on long burns in D-T plus neutron environments	Test coating adhesion and durability in reactor plasma and evaluate effects of failure; select coatings and/or materials for EPR/DEMO; quality coatings, materials, and processes for EPR/DEMO	Component-testing facility with full instrumentation, removable components, separate cooling, and electrically insulated wall section, divertor section, limiter section, etc.	Continuous over life of machine; also, destructive end of life tests	Dedicated test sections to represent each critical component; component sections must be fully instrumented and visually observable during operation and preferably removable or at least retractable without machine downtime; removable independent limiters and divertor plate; hot surface analysis laboratory on-site

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[a] If a divertor is used, separate sets of diagnostics will be required. Conditions in the divertor will be significantly different and in some cases much more demanding.

A.6.2.2 Nonmetallic Materials

The nonmetallic materials were included primarily to cover nonmetallic thermal and electrical insulators that may be used within the area of neutron radiation.

A.6.2.3 Heat Sink Materials

Heat sink materials include the nonstructural metallic materials such as liners, limiters, neutron shielding, and particle/beam dumps to be used for protective armor, shielding, or heat absorption.

A.6.2.4 Breeder Materials

Breeding materials were included for testing of chemical and physical properties. This testing should be carried out as a joint effort with the blanket/first wall/shield subgroup testing of breeding materials for neutronic performance.

A.6.2.5 Magnet Materials

Magnet materials were identified as a testing category to include the nonstructural elements of magnets that may be used inside the TF coils and exposed to the high energy neutron radiation. Knowledge of the radiation effects on electrical and mechanical properties is required. No testing of superconducting coil materials has been proposed. It was assumed that acceptable neutron fluences and heat loadings can be established with presently available facilities.

A.6.2.6 Plasma/Wall Interactions

Plasma/wall interactions were included as a special materials category to establish the effects of plasma/particle interactions with first wall surfaces. Gas retention, erosion, sputtering, and coating properties should be evaluated.

A.6.3 ASSUMPTIONS

A major function of the ETF is to provide a test-bed for the development and qualification of materials, design methods, and components for EPR and DEMO. For materials outside the radiation-affected zone, it was assumed that a sufficient data base will be available (or provided as required) from other sources. Therefore, the ETF will be required to test only those materials that are close enough to the fusion reaction to require evaluation of the effects of the high energy neutron spectrum on material properties.

A significant materials data base will be available from the ongoing fusion materials program, primarily from fission reactor testing with some correlations between the fission reactor data; a high energy neutron spectrum will be available from the Fusion Materials Irradiation Test (FMIT) facility. It was assumed that funding for these programs will be sufficient to support the design needs for the evolving DOE strategy and schedule for the construction of EPR.

A.6.3.1 Fission Reactor Simulations

A significant materials data base will be established for a wide range of helium and atom displacement levels. Primary sources of information will be the Oak Ridge Research Reactor (ORR), the High Flux Isotope Reactor (HFIR), the Experimental Breeder Reactor (EBR-II), and the Fast Flux Test Facility (FFTF). An adequate data base for design of EPR could be established from tests using these reactors provided that a correlation can be established in the ETF between the actual fusion spectrum and the fission simulations.

A.6.3.2 Beam Fusion Testing

The FMIT facility will provide some early indications of the correlations between helium production and atom displacement in fusion- and fission-produced neutrons. The correlations will help to bracket the problem, but the added restrictions of the small sample-testing capability and the beam-produced neutrons with energies greater than 14 MeV will prevent achieving the level of confidence on which to proceed with an EPR.

A.6.3.3 Tokamak Experimental Programs

TFTR will provide some information on unirradiated heat sink materials used as beam dumps, limiters, etc. Also, PDX and ISX-B will provide basic materials design data on divertor collectors. Additional plasma/wall interaction data will be available from these and other hydrogen test devices.

A.6.3.4 Shortfalls and Priorities

No data will be available prior to ETF operation on the surface/bulk synergistic effects. The combined influence of these effects can be determined only in reactor-like D-T devices that operate with plasmas. Although a large irradiated materials data base is assumed, the ETF will provide the all-important correlation for actual fusion reactor conditions, with the added advantage of a large test volume. Therefore, first priority should be given to obtaining correlations with the fission-produced data base for the major materials categories. Although a data base provided by the ETF is a good long-range goal, it may not be practical because of the long-term operations required.

A.6.4 ACHIEVEMENTS/MILESTONES

The primary materials testing achievements identified for the ETF mission are described under the following three milestones, listed in the order in which they would occur in the materials testing schedule.

A.6.4.1 Correlations

The first and most important milestone is to provide correlations between testing in a simulated fusion environment and the actual D-T plasma. Typical correlations are

1. (1) fission materials data with fusion plasma,
2. (2) FMIT data with fusion plasma,
3. (3) plasma/wall interaction hydrogen experiments with fusion plasma,
4. (4) in situ testing with postirradiation testing, and
5. (5) synergisms between surface and bulk.

A.6.4.2 Data Base Provided by ETF

To obtain the necessary materials data base for EPR, a minimum test time of one-half the design lifetime of candidate materials must be provided at full power D-T operating conditions in the ETF. The design lifetime goals of EPR/DEMO and commercial power reactors will therefore have a strong impact on the operating lifetime of the ETF if it is to be a materials test reactor for establishing the primary data base for future reactors.

A.6.4.3 Post-Mortem Testing

Possibly the most significant materials design information can be obtained by testing and inspection of the ETF components at the end of the mission. Complex design features that are difficult to simulate in test samples (such as mechanical joints and welds, multidimensional stress fields, and environmental effects) can be evaluated using the actual hardware.

A.6.5 DEVICE/FACILITY REQUIREMENTS

Requirements on the ETF device and facility were found to be rather modest, considering the importance of the materials testing mission. The principal requirements are summarized below.

A.6.5.1 Test Modules

A volume of ~125 liters is required with a minimum of five test locations, 50 × 50 × 10 cm, at the first wall. Some test samples will require direct exposure to the plasma. Independent cooling will be required for each location and possibly for submodules at a single location. Fully instrumented and automatically controlled sample test fixtures will be required within each location.

A.6.5.2 Reactor Power Levels

Neutron wall loadings >2 MW/m^2 will be required to evaluate reactor-level radiation effects adequately.

A.6.5.3 Operations and Maintenance

Access will be required for both scheduled and unscheduled removal and replacement of test modules. Materials test units consisting of an entire station/module will be removed for maintenance outside the reactor cell. One to three days is proposed as the maximum time for this operation. A limited number of tests (e.g., of first wall and limiter samples) can possibly be handled inside the reactor cell. Access for visual inspection of components is also desirable.

A.6.5.4 Additional Facilities

Hot cell facilities outside the main reactor cell will be required for routine maintenance and assembly of the test modules. However, equipment for postirradiation testing is not considered a necessary part of the ETF. Laboratory facilities for hot surface analysis will be required.

Heat transfer systems will be required for a range of coolants and operating temperature conditions.

A.6.6 TESTING SCHEDULE REQUIREMENTS

Estimates of the time required to achieve the missions defined in Appendix A.6.4 are listed in Table A.6.8.

Table A.6.8. Testing schedule requirements

Milestones	Testing time[a]
First examinations and correlations	1 year of full power D-T operation
One-half design lifetime of candidate materials for EPR/DEMO	6 years
Qualification of materials for CPR	>10 years
Post-mortem test	Not applicable

[a] Because of the continuous nature of materials testing, an overall operating schedule chart is not shown.

APPENDIX A.7

ALTERNATE CONCEPTS

A.7.1 INTRODUCTION

The base fusion concept for the ETF, the tokamak, satisfies the urgent need to achieve a D-T burning device that can provide the test environment necessary to establish engineering designs and component qualification. An examination of the applicability of the tokamak ETF test results to the needs of any of the alternate magnetic fusion concepts shows that the ETF can make a significant contribution to most of their major engineering and technology needs. (The physics issues are to be addressed by the planned alternate concept research devices.)

The alternate magnetic fusion concepts considered at the ETF Mission Workshop are listed in Table A.7.1 and include the tandem mirror concept and those concepts discussed in Ref. 1. Participants in the alternate concepts subgroup are listed in Table A.7.2.

A.7.2 KEY ISSUES

The key issue relating to the alternate fusion concepts is to identify the manner in which the ETF can advance the development of the alternate fusion concepts. General conclusions reached regarding the contributions of the ETF to the alternate concepts include the following:

(1) Information obtained in the ETF on first wall and blanket engineering, on radiation effects on materials and reactor components, on plasma/wall interaction, and on tritium handling and processing is pertinent and relevant to all alternate concepts.

(2) Beam and fueling technologies required for the ETF are of general interest and will advance the entire fusion program.

(3) Licensing issues and environmental and safety constraints satisfied in the ETF will benefit the alternate concepts program by setting guidelines for future fusion reactors.

(4) Operational and maintenance experience gained on the ETF will benefit the broader fusion programs.

Table A.7.1. Alternate fusion concepts considered in ETF Mission Workshop

- Tandem Mirror Reactor (TMR)
- ELMO Bumpy Torus (EBT)
- Reverse Field Pinch (RFP)
- Stellarator/Torsatron
- Linear magnetic fusion (LMF) devices:
  - Linear theta pinch
  - Laser-heated solenoid
  - Electron-beam-heated solenoid
  - Multiple mirror
- Multipole

Table A.7.2. Participants in alternate concepts subgroup

R. E. Aronstein, Chairman	Bechtel Corporation
S. L. Bogart	Science Applications, Inc.
C. C. Damm	LLL
D. A. DeFreece	McDonnell Douglas Astronautics Company
B. K. Jensen	Public Service Electric and Gas Research Corporation
R. A. Krakowski	LASL
N. A. Krall	JAYCOR
R. L. Reid	ORNL
N. A. Uckan	ORNL

(5) The actual operation of a fusion device as demonstrated by the ETF will establish credibility for fusion and instill confidence in the reality of fusion in general.

(6) The ETF will provide an established facility containing equipment and structures common to many fusion devices, e.g., power supplies, a vacuum system, cryogenic plants, tritium-processing units, a heat rejection system, test cells, and administration buildings. Some of these facilities could be shared with alternate concept devices, thus reducing the time and investment required to bring an alternate concept experiment on-line.

(7) The ETF will not answer many of the plasma physics questions of the alternate concepts. A strong basic program for the alternate concepts is required.

A.7.3 ASSUMPTIONS

In Table A.7.3 the component technology requirements for the alternate concepts are compared to those of the ETF in 1990. The programs to achieve the level of technology assumed in 1990 for the alternate concepts are listed in Table A.7.4. It is assumed that the results of the various programs are all positive and budget restrictions are not imposed. In some cases (e.g., linear magnetic fusion and multipole), both the programs and data base relative to 1990 are extremely speculative. The areas in which the ETF might advance the technology of the alternate concepts beyond the assumed data base presented in Table A.7.3 are presented in the following section.

A.7.4 ACHIEVEMENTS/MILESTONES

The achievements of the ETF relative to the alternate fusion concepts lie primarily in the area of materials testing, with some simulation of the interaction of fueling with the plasma and of beam heating with the plasma. Materials to be tested, in addition to the stainless steels, include conducting first wall materials, direct converter materials, and normal magnet materials. Some of the linear magnetic fusion devices

Table A.7.3. Technology and operational requirements of alternate concepts compared with those of ETF in 1990

Component	Concept					
	TMR	EBT	RFP	Stellarator/ Torsatron	LMF	Multipole[a]
First wall	Similar	Similar	Conducting wall required	Similar	Higher wall loading	
Blanket/shield	Similar	Similar	Similar	Similar	Short, rapid burn cycles	
Magnets	Higher fields, no $\dot{B}$	Lower fields, no $\dot{B}$	Lower fields, similar $\dot{B}$	Similar fields, helical winding required	More radiation danger in some concepts	
Plasma heating	Higher beam energy, more beam power, negative ion injectors, and steady-state beams	Similar beams, rf heating required	Compression heating, higher plasma current than ETF	Similar	Lasers, electron beams, etc.; different requirements	
Fueling	Similar	Similar	Batch burn	Similar; interaction with plasma has many common elements	Batch burn for pinches and solenoids; similar for multiple mirrors	
Vacuum chamber exhaust processing	Similar technology. Throughput varies according to device.					
Instrumentation and control	Some similar instrumentation. Control unique to each device.					
Power supplies	Higher voltage, steady-state; no pulsed energy requirement	No poloidal field pulsed power	Similar	No pulsed power		
Blanket processing	Similar	Similar	Similar	Similar	Similar	
Heat transport		Similar	Steady-state devices do not require thermal storage			
Power conversion	Direct converter required	Similar	Water-cooled, direct cycle steam system	Similar	Direct converter required	
Divertor	No divertor required	Similar or less severe requirement	Unknown	Poloidal or helical divertor required		

[a] Not enough information available to make assessment.

Table A.7.4. General assumptions for data base at beginning of ETF operations

TMR	EBT	RFP	Torsatron	LMF	Multipole[a]
TMX, MFTF-B, and Phaedras operated	EBT-S, EBT-II, and proof-of-principle experiment operated	ZT-40, reverse field experiment, and near-ignition proof-of-principle experiment operated	Continued operation of existing devices; PLT-size device in early 1980's	Existing program too speculative to ascertain	
Scaling and physics understood	Scaling and physics understood				
15-T magnet technology tested					
High energy, steady-state neutral beam injection tested	Heating understood				
Ready for ETF/EPR-type device before 1990	Ready for ETF/EPR-type device before 1990	Ready for ETF/EPR-type device by 1990	Ready for TFTR-type device by 1990		

[a] Not enough information available to make assessment.

require compression coils near the plasma; hence, there is a need for evaluating material damage properties of normal magnets in a high neutron flux environment. Some answers relative to the fueling and heating of plasmas unique to the alternate concepts (e.g., penetration, pellet size, pellet speed) could possibly be achieved by tailoring the plasma of the ETF to simulate the conditions of the density, temperature, and impurity levels of the alternate concept. This simulation could perhaps be modeled for toroidal devices such as the ELMO Bumpy Torus (EBT) and Torsatron. Table A.7.5 lists achievements for each alternate concept that might be derived from the ETF.

A.7.5 DEVICE/FACILITY REQUIREMENTS

A.7.5.1 Device Requirements

The materials testing program for the alternate concepts is expected to be integrated into the overall materials program of the ETF. Requirements listed in Appendix A.6 are also relevant to the alternate concepts. A portion of the materials test volume of the ETF should be allocated to testing materials specifically for the alternate concepts.

Provisions should be made for varying the injection angle of the neutral beams and the size and speed of the pellets in order to test neutral beam and pellet-fueling interaction with plasmas. If helical control windings are used on the ETF (to mitigate plasma disruption), a crude simulation of a Torsatron plasma might be provided.

The reverse field pinch (RFP) reactor assumes near-reversible magnetic field energy recovery. This mechanism could be demonstrated by the PF system of the ETF if provision is made for recovering this energy (as opposed to dumping it). Also, information relative to rapidly changing fields in superconducting magnets required by the RFP reactor will be provided by the PF system of the ETF.

The divertor option for the ETF has not yet been selected. If a bundle divertor is selected, operational experience relative to EBT could be obtained. A poloidal divertor would yield information of interest to Torsatron operation. Changing divertor types to provide

Table A.7.5 Necessary milestones to be achieved during ETF mission

TMR	EBT	RFP	Torsatron	LMF
Demonstrate fueling of mirror central cell	Simulate neutral beam/plasma operation for reactor-grade EBT	Test conducting first wall materials	Simulate neutral beam ignition (non-perpendicular)	Conduct irradiation test of pinch and solenoid first wall material
	Simulate fueling/plasma operation for reactor-grade EBT	Demonstrate near-reversible PF energy recovery	Simulate fueling	Conduct irradiation tests of magnet materials
				Conduct irradiation tests of direct converter materials
Test direct converter materials		Demonstrate $\dot{B}$ requirement in PF winding	Test poloidal or helical divertor	Test near-reversible field energy recovery for application to linear theta pinch

operational simulation for the alternate concepts would require a major modification of the ETF device, and this would have to be considered in the initial design of the ETF device.

A.7.5.2 Facility Requirements

Hot cells, power supplies, cryogenics, heat dissipation systems, etc., provided for the ETF should be adequate for conducting specific tests for the benefit of alternate concept reactors. However, if a second load assembly were constructed at the ETF exclusively for alternate concept testing, facility requirements (land, electrical power, water, etc.) would be affected.

A.7.6 TESTING SCHEDULE REQUIREMENTS

As previously indicated, the major contribution of the ETF to the alternate concepts is in the area of materials testing. Test modules in the ETF should be allotted to alternate concepts materials, and testing should be integrated into the overall materials test program. At least a 15-year duration is estimated for the testing of conducting first wall material, copper and aluminum magnet material, and materials used in direct converter components. An overall operating schedule for the ETF pertinent to alternate concepts developmental activities is shown in Fig. A.7.1.

Poloidal or helical divertor operation and gas blanket fueling are included on this schedule as desirable tests relative to some of the alternate concepts. However, if the ETF does not have such components in its initial design, major modification of the device would be required in order to perform these tests; this may not be programmatically or economically feasible.

The impact on the schedule (either construction or operation) of providing a second load assembly on the ETF site was not addressed.

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ETF MISSION/OPERATION SCHEDULE

(25-year operation)

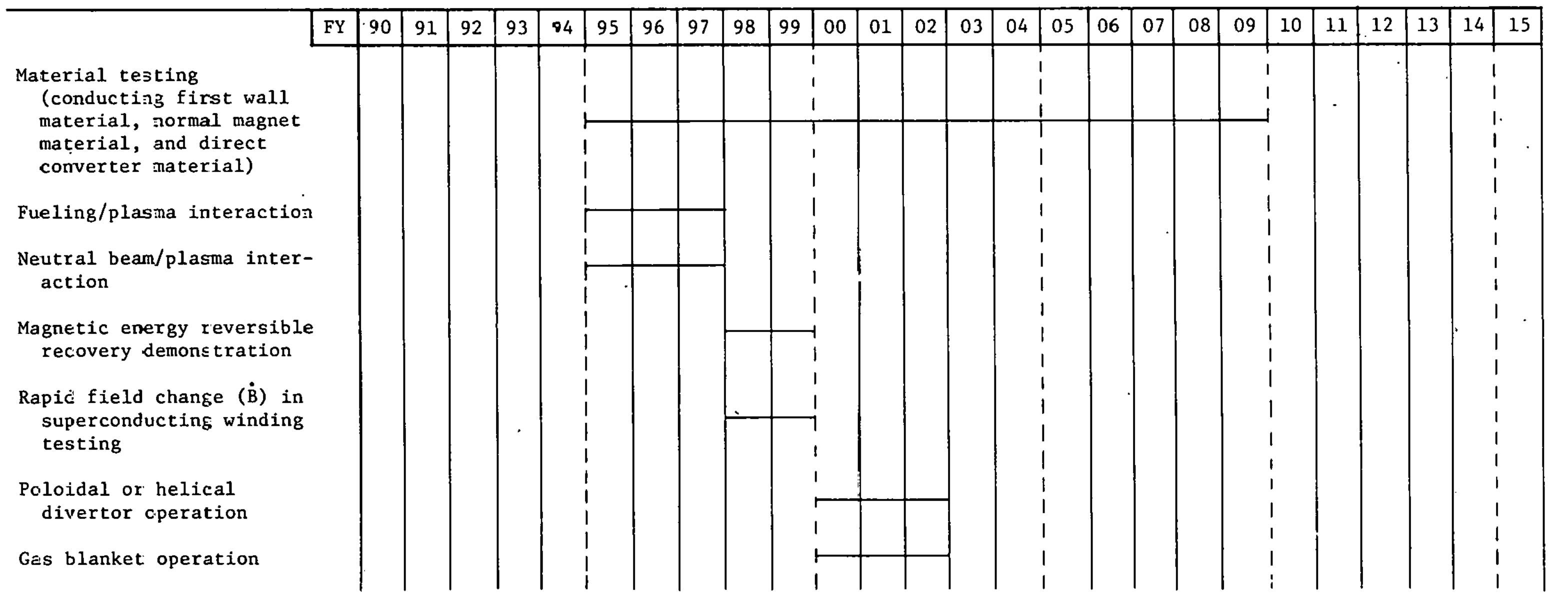

Fig. A.7.1. Alternate concepts.

REFERENCE

1. James F. Decker (DOE), Levels 1 and 2 of "Report on the Concept Review Committee Recommendations on Proof of Principle Alternate Concepts Program (Draft)," letter to Alternate Concepts Subgroup participants (January 15, 1979).

APPENDIX A.8

ETF MISSION WORKSHOP

A.8.1 PRELIMINARY MISSION DESCRIPTION FOR THE ETF[1]

A.8.1.1 Design Philosophy

The underlying philosophy for the ETF design should be to produce a skeletal, basic framework machine designed to include a series of pre-planned upgrades that will allow progressing from a short hydrogen/deuterium check-out phase to the high Q, high duty cycle, D-T plasma phase. The objectives in general should be as follows:

(1) Investigate the plasma engineering of alternative startup, burn, and shutdown scenarios for both low Q and high Q toroidal fusion reactors.

(2) Serve as a test-bed for fusion reactor technologies, including thermal hydraulics, first wall performance, radiation damage, tritium and fissile breeding, synfuel production, support systems, and maintenance techniques.

(3) Generate a data base on the operational reliability, safety, and ease of repair of fusion reactor subsystems.

(4) Serve as a national facility for experiments that require an intense source of 14-MeV neutrons.

A.8.1.2 Experimental Plan

Figure A.8.1 outlines a possible plan for utilization of a proposed ETF based on the tokamak concept. The basic structure of the program plan is defined by a set of project milestones that are directly related to the stated purposes of the device. Actual times required to complete particular engineering and physics tasks requisite to the achievement of each milestone will be sensitive to the allocation of personnel and budgetary resources to each task at various phases of the program. Resources would be allocated toward the earliest practical attainment of

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ENGINEERING TEST FACILITY: MISSION DESCRIPTION

Phase

I. Hydrogen plasma (OH) shakedown

II. Hydrogen plasma (auxiliary heating)

- Low Q,[c] quasi-steady state
- High Q,[a] ≥30-s pulse length
- Torus heat removal
- Demonstrate remote handling
- Test advanced diagnostics

III. Deuterium and D-T burning plasma

- Test neutron shielding and dosimetry with D_2
- ≥1.5-MW/m^2 wall loading with D-T
- Investigate startup, burn, and shutdown
- Near ignition, ≥30-s pulse length

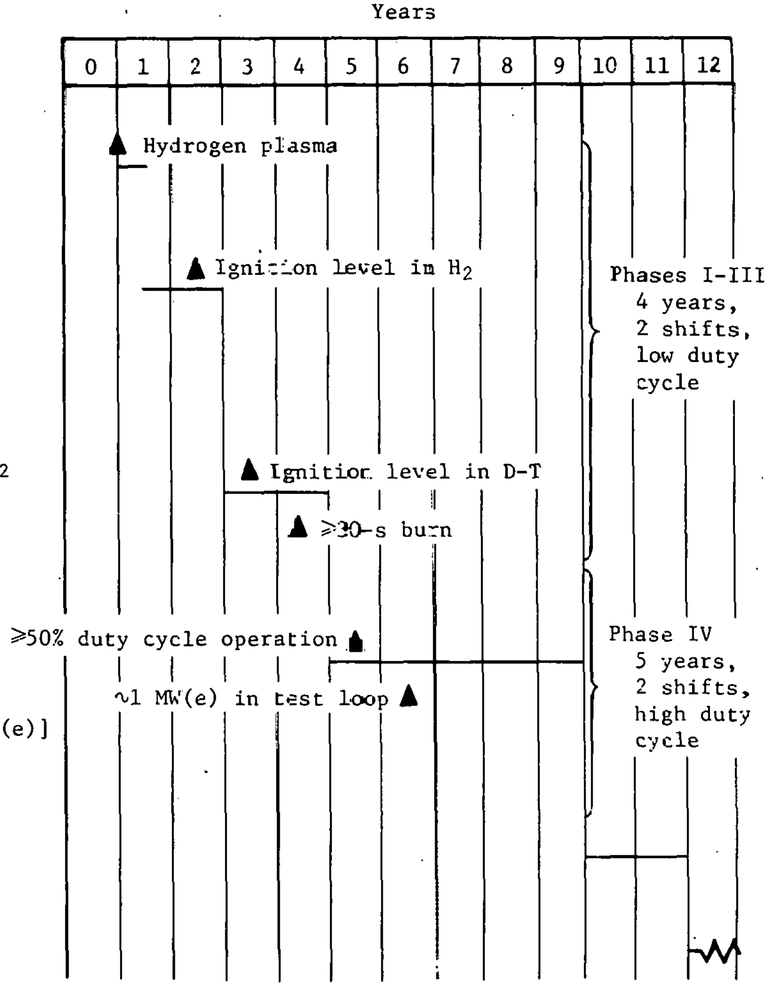
IV. Nuclear and thermal engineering (15-25 blanket modules, 1 m^2 each)

- ≥50% duty cycle, two-shift operation
- Test tritium and fissile breeding blankets
- Test electrical power-producing loop [~1 MW(e)]
- Test synfuel-producing blankets
- Radiation damage studies (total neutrons, 10^{22} neutron/cm^2)

V. Advanced plasma engineering tests

- Test advanced auxiliary heating
- Test near-ignition steady-state techniques

VI. Major overhaul or decommission



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[a] Calculated equivalent for D-T operation.

Fig. A.8.1. Engineering Test Facility mission description.

near-thermonuclear ignition, consistent with the need for considerable engineering and plasma physics tests in hydrogen, before neutron activation precludes convenient access to the device.

A.8.1.3 Design Objectives

The ETF is intended to bridge the gap between TFTR and a full-scale EPR. In order to fulfill the engineering test role, the ETF should produce a near-ignition plasma and achieve a stable (or controllable) extended burn state for a substantial length of time (⩾30 s). In order to attain these goals, a number of subsidiary physics questions must be addressed, including plasma position, shape, and current profile control in the presence of internal alpha particle heating; impurity control; fueling; alpha particle physics (confinement, thermalization, and instabilities); and the control of burn thermal equilibrium.

The technology demonstration aspect of the ETF objectives will be achieved if the machine can be operated reliably and routinely for extended periods of time. Preliminary program milestones related to technology demonstration are the achievement of the design point 50% duty cycle (∿4.5 years after initial startup) and successful generation of electrical power (∿5.5 years) in one or more test loops.

At some point, the first wall of the ETF must be replaced because of limits imposed by cyclic fatigue and radiation damage. Prior to this point, but after the nuclear engineering mission of the ETF has been accomplished, testing of advanced plasma technology such as higher energy neutral beams or higher frequency rf generators could be performed. Techniques for driving steady-state tokamak currents, if demonstrated on small-scale experiments, might be tested on the ETF during this period.

REFERENCE

1. This material appeared as Section 5 of Enclosure 3 of a letter from E. E. Kintner (Office of Fusion Energy, Department of Energy, Washington, DC) to M. Gottlieb, T. Ohkawa, and L. A. Berry, October 2, 1978.

A.8.2 ETF MISSION WORKSHOP: REFERENCE PARAMETERS

The reference case for the ETF Mission Workshop consisted of the preliminary mission statement, included as Sect. A.8.1; the TNS design parameters, listed in Tables A.8.1 and A.8.2; and the current EPR/DEMO parameters, listed in Tables A.8.3 and A.8.4.

A.8.3 SUGGESTED GUIDELINES, AGENDA, AND PARTICIPANTS

A.8.3.1 Suggested Guidelines for Subgroup Deliberations

The initiation of the ETF mission or facility operations is assumed to be ∿1990. In order to define a meaningful testing program for the ETF, we must establish the scope of data base in physics, technology, and engineering expected at the initiation of the testing program. This difficult task requires assumptions concerning the program achievements that will be realized during the next decade. It is suggested that only those machines now planned (plus modest upgrades) be considered in this exercise. The forthcoming data base/R&D needs assessment will provide guidance and recommendations for modifying the assumptions adopted in developing the ETF Mission Statement. The following guidelines are proposed as a means for achieving the Workshop objectives.

(1) Divide subgroup areas into a workable number of key technical components that have a minimum of overlap. Each component can then be addressed separately in all aspects of the subgroup deliberations, thereby helping to ensure that all key components are considered.

(2) Develop a consensus of general assumptions for the technology/physics data base available at the <u>beginning</u> of ETF operations. It is from this base that the advancements required from the ETF operations can be described. Each key component should be discussed and assumptions for each delineated.

(3) Using the EPR/DEMO characteristics, prepare a descriptive list of necessary advancements or milestones that should be achieved for each key component during the ETF mission. These advancements should build on the assumed base of knowledge developed in response to item (2) above.

Table A.8.1. TNS design parameters — plasma and device

	ORNL TNS	GA TNS	PPPL SLPX-III	ANL EPR
Operating mode				
Power	1140 MW(t)	650 MW(t)	534 MW(t)	600 MW(t)
Operating period	560 s	60 s	762 s	75 s
Burn time	500 s	30 s	86 s	60 s
Number of pulse/lifetime	0.45×10^6	0.2×10^6	4.0×10^3	1.0×10^6
Dimensions				
Major radius	5.0 m	3.6 m	4.5 m	4.7 m
Plasma radius/elongation (σ)	1.2 m/1.6	0.95 m/2.7	1.2 m/1.6	1.34 m/1.64
Plasma volume	225 m^3	180 m^3	205 m^3	337 m^3
Plasma				
Ion temperature	12 keV	12 keV	13 keV	8 keV
Ion density	2×10^{20} m^{-3}	1.9×10^{20} m^{-3}	3.0×10^{20} m^{-3}	1.4×10^{20} m^{-3}
Effective charge (Z_{eff})	1.5	2	<2	1.7
Energy confinement time	1.2 s	1.4 s	1.4 s	2.5 s
B_T on axis	5.3 T	5.0 T	6.0 T	4.5 T
Safety factor (q)	3.8	2.5	3.0	3.0
β_p		1.2	2.8	
β_T	7%	6-9%	3.7%	7%
Plasma current	5 MA	11.6 MA	5.4 MA	7.3 MA
TF coils				
Number of coils	12	12	16	16
Conductor	Nb_3Sn	NbTi	Nb_3Sn	NbTi
Bore (height/width)	9.8 m/6.2 m	9.2 m/5.8 m	6.8 m/5.15 m	8.7 m/5.6 m
Maximum field	10.9 T	10 T	12 T	9 (10) T
PF coils				
Conductor (EFC/OHC)	(Cu/NbTi)/NbTi	Cu/NbTi	Cu/NbTi	NbTi/NbTi
Position	(Inside/outside)/outside	Inside/outside	Inside/outside	Outside
Neutral beams				
Beam energy	150 keV	150 keV	150 keV	180 keV
Injection power	50 MW	60 MW	35 MW	40 MW
Injection time	6 s	2-5 s	6 s	4-6 s
Vacuum vessel				
Position	Containment building	First wall	Outside shield	Outside blanket
Material		Inconel 625	Stainless steel	Stainless steel
First wall				
Type and material	Stainless steel tubes	Carbon coating on Inconel 625	Stainless steel	Coolant panel, beryllium coated on 316 stainless steel
Neutron wall loading	2.4 MW/m^2	1.8 MW/m^2	1.4 MW/m^2	1.3 MW/m^2
Wall lifetime (efp yr)	5			2.5
Blanket				
Structure	None	None	None	316 stainless steel
Coolant				H_2O/steam
Breeding material				None
Thickness				0.2 m
Bulk shield				
Material	Stainless steel, Pb	W, Pb, stainless steel, borated H_2O	Stainless steel, Pb, Cu, borated H_2O	Stainless steel, B_4C, Pb, Al
Thickness	0.60 m	0.40/1.1 m	0.66 m	0.5/1.0 m
Coolant	Borated H_2O	H_2O	H_2O	H_2O

Table A.8.2. TNS design parameters — systems

	ORNL TNS	GA TNS	PPPL SLPX-III
Fueling system			
Type	Pellet injection via centrifugal slinger	Plasma-gas blanket with gas puffing at the plasma boundary or pellet injection	Pellet injection
Fueling rate (during burn)	0.185 g/s, provided by ∿0.5-cm-diam pellets with a velocity of 1000–2000 m/s and a 1-s particle confinement time		0.046 g/s, with a 1.92-s particle confinement time
Pulsed power supplies			
Energy conversion systems	AC motor-generator flywheel (MGF) system with transformer/12-pulse thyristor bridge; 1200 MVA; 4.3-GJ deliverable energy for 35-s pulse	0.5-GJ homopolar motor-generator (HMG) system plus a 200-MVA MGF system, providing 0.8 GJ of storage capacity for neutral beams	AC MGF system
Initiation	RF heating	Pulse field coils from 1-MJ capacitor bank	
Coil connection	Series	Parallel	Parallel with voltage sources connected in series
Torus maintenance			
Segmentation	16 sectors, each consisting of a 22.5° module of first wall and shield	30° plasma chamber segments, 48 blanket modules located between the plasma chamber and the outboard field coils, and shield segments encompassing the plasma chamber and the field coils	8 sectors, each consisting of 2 TF coils and including a 45° module of first wall and shield
Replacement technique	Each sector removed between stationary TF coils	Blanket and shield segments removed between TF coils; plasma segment remotely cut in situ and removed	Complete sector removed
Sealing technique	Vacuum building with mechanical seals between sectors	Welded plasma chamber	Secondary vacuum enclosure with mechanical seals
PF coil access	Raise (or lower) coils	Disconnect outboard field coils at joints	Disconnect PF coils at joints
Plasma purity control	Bundle divertor with 3% ripple at plasma centerline, 3×10^{23} particles/s flux, 226-MW maximum heat load, water-cooled copper coils, lithium droplet cloud collector system, and 10-MW/m^2 collector heat flux	Flow reversal (requires use of low Z materials in vacuum chamber)	Poloidal divertor
Vacuum pumping system			
Torus high vacuum pumps	Cryosorption pumps with Zr-Al gettering system for pump regeneration; base pressure of 10^{-6} torr; specific pumping speed of 2×10^{5} liters/s; pumpout time of 25 s	Cryocondensing vacuum pumps with turbomolecular forepumps	
Secondary enclosure vacuum pumps	Mechanical diffusion pumps with base pressure of 10^{-4} torr		
Tritium handling	On-site batchwise processing of plasma exhaust; maximum on-site storage of 10 kg; isotopic separation by cryodistillation; tritium separation from lithium via sorption of tritium on solid yttrium or via permeation-diffusion process using niobium	On-site batchwise processing of plasma exhaust; 1.63-kg tritium inventory including 1.49 kg as basic standby and 0.10 kg in fueling system; impurities removed by cryogenic trapping and hot gettering; helium removed by a cryostripping column; isotopic separation by cryodistillation	On-site batchwise processing of plasma exhaust; 0.64-kg tritium inventory including 0.38 kg as basic standby, 0.038 kg in fueling system, 0.065 kg in cryodistillation complex, and 0.16 kg in processing equipment; uranium hot and cold traps for impurity removal and storage of hydrogen, deuterium, and tritium; isotopic separation by cryodistillation

Table A.8.3. EPR/DEMO design parameters — plasma and device

	ORNL DEMO	GA DOUBLET	MIT/PPPL HFCTR-DEMO	University of Wisconsin NUMAK-CPR
Operating mode				
Power	1930 MW(t)	2350 MW(t)	2440 MW(t)	2097 MW(t)
Operating period	1260 s	197 s	588 s	245 s
Burn time	1200 s	168 s	500 s	224 s
Number of pulses/lifetime (20 years)	0.5×10^6	3.6×10^6	1×10^6	
Dimensions				
Major radius	6.2 m	6.8 m	6.0 m	5.1 m
Plasma radius/elongation (σ)	1.5 m/1.6	2.1 m/2.8	1.2 m/1.5	1.13 m/1.64
Plasma volume	460 m^3	2015 m^3	317 m^3	312 m^3
Plasma				
Ion temperature	13 keV	16 keV	12.4 keV	13 keV
Ion density	$1.7 \times 10^{20}\ m^{-3}$	$1.8 \times 10^{20}\ m^{-3}$	$5.2 \times 10^{20}\ m^{-3}$	$2 \times 10^{20}\ m^{-3}$
Effective charge (Z_{eff})	1.1	1.7	1.2	1-1.5
Energy confinement time	1.5 s	0.6 s	1.0 s	1.0 s
B_T on axis	3.4 T	3.7 T	7.4 T	6.1 T
Safety factor (q)	3.0	2.5	3.0	2.6
β_p		1.49		3.7
β_T	10.0%	10%	4.0%	6.0%
Plasma current	3.8 MA	22 MA	6.7 MA	7.0 MA
TF coils				
Number of coils	18	16	16	8 (plus 16 copper trim coils)
Conductor	NbTi	NbTi	Nb_3Sn	NbTi
Bore (height/width)	11 m/7 m	18 m/11 m	6.8 m/5.2 m	9.5 m/6.3 m
Maximum field	8.0 T	8.6 T	13.1 T	11.9 T
PF coils				
Conductor (EFC/OHC)	(Cu/NbTi)/NbTi	Cu/NbTi	(Cu/NbTi)/NbTi	(Cryo Al/NbTi)NbTi
Position	(Inside/outside)/outside	Inside/outside	(Inside/outside)/outside	(Inside/outside)/outside
Neutral beams		None	Ripple injection	None
Beam energy	150 keV		120 keV	
Injection power	95 MW		100 MW	
Injection time	5 s		6.4 s	
RF heating	None		None	
Frequency		2 GHz		92 MHz
Injection power		25 MW		75-80 MW
Injection time		7.3 s		1.0 s
Vacuum vessel				
Position	Containment building	Secondary vacuum enclosure (inside TF coil)	First wall	Secondary vacuum enclosure (inside TF coil)
Material			Molybdenum alloy (TZM)	
First wall				
Type and material	Stainless steel tubes	None	Molybdenum alloy (TZM)	None
Neutron wall loading	2.7 MW/m^2		3.4 MW/m^2	
Wall lifetime (efp yr)	5		3	
Blanket				
Structure	Stainless steel	Inconel 718	Molybdenum alloy (TZM)	Ti-6Al-4V
Coolant	Helium	Helium	$2LiF \cdot BeF_2$	Boiling H_2O
Breeding material	Lithium	Li_7Pb_2/Li_4SiO_4	Lithium	LiPb
Thickness	0.75 m	0.4 m	0.6 m	0.5 m
Bulk shield				
Material	Stainless steel, Pb	Stainless steel, B_4C	Stainless steel, B_4C	B_4C, Pb
Thickness	0.6 m	0.26 m	0.6 m	0.85 m
Coolant	Borated H_2O	H_2O		H_2O

Table A.8.4. EPR/DEMO design parameters — systems

	ORNL DEMO	GA DOUBLET	MIT/PPPL HFCTR-DEMO	University of Wisconsin NUMAK-CPR
Fueling system	Pellet injection or gas puffing	Plasma-gas blanket with gas puffing at the plasma boundary or pellet injection	Plasma-gas blanket with gas puffing at the plasma boundary	Plasma-gas blanket with gas puffing at the plasma boundary (may be supplemented with pellet injection)
Pulsed power supplies				
Storage systems	AC MGF system	HMG system		2-MW HR superconducting storage coil system
Coil connection	Series	Parallel		
Torus maintenance				
Segmentation	54 primary vacuum sectors with attached first wall and 18 segmented shield modules	408 blanket modules mechanically attached through vacuum-sealed penetrations in the blanket support structure	8 sectors, each consisting of blanket and shield modules plus 2 TF coils	24 blanket/shield segments and 16 normal TF trim coils
Replacement technique	Remove outboard shield and primary vacuum sectors between stationary TF coils	Remove each blanket module individually between stationary TF coils	Remove complete sector	Remove outboard vertical shield, TF trim coil, and blanket module between stationary TF coils
Sealing technique	Vacuum building with mechanical seals between primary vacuum sectors	Secondary vacuum enclosure inside TF coils with mechanical seals	Secondary vacuum enclosure at unspecified location with mechanical seals between sectors	Secondary vacuum enclosure inside shield with high vacuum area inside blanket area
PF coil access	Relocate exterior OH coils and disconnect interior EF coils at joints	PF coils do not obstruct blanket access	Disconnect interior EF coils at joints	Lower exterior PF coils; interior PF coils do not obstruct blanket access
Plasma purity control	Bundle divertor plus a plasma-gas blanket	Impurity gas reversal	Plasma-gas blanket plus a limiter to remove alpha ash	Plasma-gas blanket

(4) Based on the above list of technical advancements, a set of functional and performance requirements should be established for the ETF device and facilities.

(5) Each specific technical advancement/milestone should now be allocated testing time. The resulting testing schedule should include best estimates for operating time requirements and downtime requirements for component changeouts.

(6) Using the TNS characteristics and the preliminary ETF mission statement as the basis, list and comment on the major device, facility, and schedule impacts that may result from following the recommendations of the subgroup; i.e.:

- Must the device characteristics be altered?
- Must other facilities be available on-site?
- Must the schedule be changed significantly?

(7) Each attendee is asked to prepare some comments on the subgroup areas of key interest to him and to which he feels best able to contribute. It is encouraged that "going around the table" for comments and short presentations be allowed initially to get all pertinent inputs that may add to the effectiveness of the subgroups' activities.

(8) Each subgroup is requested to consider the issues of remote maintenance, reliability, and safety relative to their area and to provide comments and recommendations for preparing for these needs.

(9) During the last morning of the meeting, each chairman will present his subgroup's findings, conclusions, and recommendations to the plenary session. Approximately 30 min per group is planned. The presentation material will constitute the key part of the initial ETF Mission Statement that is to be prepared by the Design Center.

A.8.3.2 ETF Mission Workshop Agenda

February 13 — Tuesday

8:30 AM	Introduction 1. ETF Activity Logic 2. ETF → EPR → DEMO 3. ETF Design Center Staffing 4. IAEA/ETF Interface 5. Role of Workshop	D. Steiner
9:30 AM	TNS Reviews 1. Physics Assumptions/Issues 2. Technology Assumptions/Issues 3. Engineering Design/Assembly/Maintenance	
9:30 AM	GA TNS	J. Rawls
10:15 AM	Coffee Break	
10:30 AM	PPPL-SLPX-III	P. Reardon
11:15 AM	ORNL TNS	T. Shannon
12:00 noon	Lunch	
1:00 PM	Subgroup Operations Suggestions and Meeting Guidelines	D. Steiner
1:30 PM	Subgroup Meetings	
3:00 PM	Coffee Break	
3:15 PM	Reconvene	
5:30 PM	Adjourn for the Day	
6:30 PM	Cash Bar	
7:30 PM	Banquet	
8:30 PM	Banquet Speaker — J. F. Clarke, Deputy Director Office of Fusion Energy Department of Energy	

February 14 — Wednesday

8:30 AM	Continue Subgroup Meetings
10:15 AM	Coffee Break
10:30 AM	Reconvene in Subgroups
12:00 noon	Lunch
1:00 PM	Reconvene in Subgroups
3:00 PM	Coffee Break
3:15 PM	Reconvene in Subgroups
5:30 PM	Adjourn for the Day

February 15 — Thursday

8:30 AM	Plenary Session	D. Steiner
	Presentations by Subgroup Chairmen	
12:00 noon	Adjourn Workshop	

A.8.3.3 ETF Mission Workshop Participants

Subgroup chairmen and invited key contributors

(1) Plasma Operations Testing

J. M. Rawls, Chairman	GA
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D. Cohn	MIT
R. W. Conn	University of Wisconsin
Y-K. M. Peng	ORNL
J. A. Schmidt	PPPL
S. Yoshikawa	PPPL

(2) Heating/Fueling Technology Testing

J. Sheffield, Chairman	ORNL
R. L. Freeman	GA
H. H. Haselton	ORNL
J. C. Hosea	PPPL
S. L. Milora	ORNL
P. Parks	GA
R. V. Pyle	LBL
J. Scharer	University of Wisconsin
T. J. M. Sluyters	BNL
L. D. Stewart	Exxon Nuclear Company
K. E. Wright	PPPL

(3) Tritium/Particle Collection Technology Testing

V. A. Maroni, Chairman	ANL
J. L. Anderson	LASL
T. H. Batzer	LLL
M. H. Dandridge	Grumman Aerospace Corporation
J. S. Watson	ORNL
W. M. Wells	ORNL
W. R. Wilkes	Monsanto Research Corporation
T. F. Yang	Westinghouse Electric Corporation

(4) Blanket/First Wall/Shield Technology Testing

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M. Stauber	Grumman Aerospace Corporation
C. Trachsel	McDonnell-Douglas Astronautics Company

(5) Remote Maintenance and Engineering Operations Testing

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K. E. Wakefield	PPPL
N. E. Young	EBASCO Services

(6) Materials Testing

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R. Gold	Westinghouse Electric Corporation
R. Micich	Grumman Aerospace Corporation
S. N. Rosenwasser	GA
D. L. Smith	ANL

(7) Alternate Concepts

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