A FIRST-WALL, BLANKET, AND SHIELD ENGINEERING TEST PROGRAM FOR MAGNETICALLY CONFINED FUSION POWER REACTORS

by

Victor A. Maroni

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Victor A. Maroni
Argonne National Laboratory
Argonne, Illinois

Summary

In December of 1979, the DOE/Office of Fusion Energy initiated work on a fusion reactor first wall, blanket, and shield (FW/B/S) engineering test program (ETP) and designated Argonne National Laboratory (ANL) as lead technical organization. Since the initiation of this program, a series of planning exercises has been conducted to develop near term and longer range scope, objectives, strategies, and goals for the engineering testing of FW/B/S components and integrated assemblies of components. The key engineering areas identified for early study relate to FW/B/S system thermal-hydraulics, thermomechanics, nucleonics, electromagnetics, assembly, maintenance, and repair. Programmatic guidance derived from planning exercises involving over thirty organizations (laboratories, industries, and universities) has indicated (1) that meaningful near term engineering testing should be feasible within the bounds of a modest funding base, (2) that there are existing facilities and expertise which can be profitably utilized in this testing, and (3) that near term efforts should focus on the measurement of engineering data and the verification/calibration of predictive methods for anticipated normal operational and transient FW/B/S conditions. The remainder of this paper discusses in more detail the planning strategies, proposed approach to near term testing, and longer range needs for integrated FW/B/S test facilities.

Introduction

Philosophies, strategies, designs, and analyses of magnetic fusion reactor first wall, blanket, and shield (FW/B/S) systems have been subjects of study in the U.S.A. and abroad for over ten years. The challenge of finding a credible combination of materials (coolant, breeder, structure, etc.), operating conditions (temperatures, pressures, etc.), and subsystem configurations has been great. Questions relating to systems and materials response in the environment of cyclic surface and bulk heat fluxes, time varying and steady magnetic fields, and high-energy neutrons (14 MeV) have continued to be studied. The understanding of these questions progressed considerably during the 1970s, but there is still more research and development required with respect to the overall design, engineering, and construction of a fusion FW/B/S system.

Although numerous FW/B/S concepts already exist, the task of completely determining their viability in the total fusion environment cannot be done by analytical and computational methods alone. From the long-standing awareness of this limitation, there has evolved, within the U.S. Department of Energy/Office of Fusion Energy (DOE/OFE) and the fusion community as a whole, a recognized need to embark on a test program that would seek to resolve the critical engineering issues concerning the design of FW/B/S systems. The urgency for such a program is further heightened by the committed intention of DOE/OFE to build and operate a D-T burning Engineering Test Facility (ETF) by the late 1980s or early 1990s. The design of the ETF, as it is currently evolving, represents a bold initiative for the magnetic fusion program, particularly in the FW/B/S area where the capability to accommodate the environment of a fusion power reactor will be fully tested for the first time. To fill these needs for the ETF and follow-on devices leading to commercialization of fusion energy, the DOE/OFE Division of Development and Technology (D&T) announced the establishment of the FW/B/S Engineering Test Program (ETP) in December of 1979, and designated Argonne National Laboratory (ANL) as the lead technical organization. This paper describes the planning methods and strategies that have been developed for initiating the FW/B/S ETP.

Definition of the FW/B/S System

The first wall, blanket, and shield (FW/B/S) portion of magnetic fusion reactors is most often taken to be inclusive of all those systems located inside the space bounded by the primary plasma-confining magnetic field coils (with the exception perhaps of plasma support systems or control devices therein). The exact nature of these systems is both concept and end-use dependent. The principal functions of the FW/B/S system are to

(1) provide the primary physical enshroudment of the plasma burn region, including in most designs the main vacuum boundary, (2) absorb and withstand the radiant and particle heat fluxes emanating from the plasma, (3) thermalize the fusion neutron and resulting gamma radiation that accompany the fusion reaction, (4) attenuate the penetrating radiation at shield boundaries to the levels required for magnet protection and personnel safety, and (5) supply the medium and interfaces for extraction of sensible heat and for production and recovery of tritium (in D-T reactors). In addition to the various penetrating (neutron and gamma) and non-penetrating (e.g., X-ray and ultraviolet) radiant fluxes and the particle bombardment, the first wall (including first wall-related components such as limiters, protective liners, disruption armor, etc.), the blanket, and to a lesser extent the shield, will be subjected to sizeable time varying thermal and mechanical stresses as well as to electromagnetic forces and torques. The combined effect of these conditions on component behavior has long been a key concern. The engineering and technology required to mitigate adverse reactions of FW/B/S subsystems to these conditions is clearly an attendant concern that represents an essential element in the successful development of fusion energy.

Description of FW/B/S System Features/Concerns

In developing a plan for addressing the critical engineering issues attendant to the FW/B/S system, emphasis has been placed on defining engineering studies that would be generally useful to all design efforts regardless of confinement concept or reactor approach. There are certain key features/concerns that characterize the environment of the FW/B/S system, and it is on these features/concerns that efforts have been focused to construct meaningful engineering analysis/test strategies. Those technological features/concerns that have created the most persistent FW/B/S related engineering issues and uncertainties in past fusion reactor design studies are discussed below.

Penetrating Radiation

The neutrons and secondary gammas produced as a result of the fusion reactions (e.g., D-T and D-D) constitute the means by which useful energy is extracted from the fusion process. These two forms of penetrating radiation are subsequently thermalized in the first wall, in the blanket, and to a limited extent, in the shield. The heat generated in the bulk of the first wall and blanket systems (including the structure, breeder, moderator, and coolant) is extracted from the reactor via the coolant(s) and (in most designs) used to drive a steam turbine. Although the neutrons and consequently the bulk thermal energy are deposited nonuniformly in the blanket, a uniform temperature profile is generally maintained throughout the blanket by adjusting the pitch of the coolant distribution system. The principal design objectives with respect to the penetrating radiation in a fusion FW/B/S system are (1) optimization of the neutron slowing-down process to maximize tritium production (for D-T reactors) and permit efficient extraction of the thermal energy, (2) attenuation of the penetrating radiation to acceptable levels at the outboard surface of the shield to protect vital reactor systems (e.g., magnets) from radiation damage and minimize induced activity at the perimeter of the nuclear island, and (3) accomplishment of objectives (1) and (2) in a minimum-thickness FW/B/S configuration. The meeting of these objectives requires detailed nuclear engineering data on cross sections, thermal energy production (Kerma) factors, nuclear performance of integrated materials configurations, and tritium breeding ratios.

Nonpenetrating Radiation/Energetic Particle Bombardment

The materials facing a fusion plasma (nominally, all the first wall components) are bombarded with a flux of charged and neutral energetic particles and a broad spectrum of nonpenetrating radiation. The particles strike the first wall structural materials, and together with the nonpenetrating radiation, deposit appreciable quantities of thermal energy at exposed first wall surfaces. In most fusion reactor designs, the recovery of this thermal energy as sensible heat is essential to an economically attractive power balance. The surface heat load during normal operation can be up to 25% of the total neutron wall loading for D-T reactors, depending on the extent to which plasma energy is removed via a particle divertor or related device. During plasma disruptions, the particle and radiant surface heat loads can exceed 100 MW/m^2 in localized areas of the first wall. Also, in nonsteady-state fusion devices, the cyclic heat load during normal operation can generate large time-varying thermal stresses in the first wall components. The design objectives for dealing with the nonpenetrating radiation and energetic particles are to recover the energy deposited on the first wall surfaces as sensible heat, accommodate the heat loads without disrupting the plasma or adversely affecting the integrity of the first wall, and identify first wall materials and configurations that can function reliably under normal and transient particle/heat load conditions.

Thermal-Hydraulics/Thermomechanics

The hydraulic and mechanical aspects of the FW/B/S system are crucial to developing a viable design concept. Temperature profiles, heat transfer characteristics, mechanical support, response to thermal and electromagnetic stresses, coolant system pressure, and possible reactions to transient conditions are studied early in conceptual design phases and play a major role in decisions concerning choice of structural materials and FW/B/S overall configuration.

Heat Transfer/Energy Conversion Coupling

The extraction of sensible heat (or some other useful form of energy) is of paramount importance to any fusion concept. The movement of coolant(s) from the FW/B/S system to a power generator or intermediate heat exchanger, the subsequent return of coolant to the reactor, and the manner in which energy conversion is accomplished (particularly in nonsteady-state devices) pose special problems to the design of fusion FW/B/S systems. Further, these problems must be resolved using methods that do not result in large releases of tritium or radioactive material to coolant systems, energy conversion systems, the plant facility, or the environment. Requirements related to coolant/heat transfer system interfacing and coolant processing also fall under this feature/concern.

Electromagnetic Reactions/Effects

The mechanical reactions of the electrically conductive portions of FW/B/S systems to large DC and, in some designs, time varying magnetic and electrical fields are an important area of concern in FW/B/S design. The fields generate large forces, torques, and other mechanical loads. Also, they can produce resistive (eddy current) heat loads, vibrations, and perturbations to FW/B/S instrumentation readings. Electromagnetic effects resulting from plasma disruptions can also induce large instantaneous mechanical loads. In addition, there are concerns related to magnetohydrodynamics of liquid metals and magnetization of ferritic steels in fusion magnetic fields.

Coolant Flow Transients

Perturbations to coolant flow (oscillations, depressurization, loss of flow) in various regions of a fusion FW/B/S system and the consequences to reactor component performance and integrity are beginning to receive attention in fusion design studies. The consequences of these types of transient effects are often difficult to predict, and some engineering simulations will be required. The principal impacts are on system integrity and worker safety.

Plasma/Confinement System Disruptions

Although the detailed nature, frequency, and potential impact of plasma disruptions and confinement system malfunctions for power reactors are difficult to gauge at the present time, it is well recognized that such events can seriously affect the integrity and subsequent performance of FW/B/S components. These events are likely to result in the local deposition of large quantities of energy on first wall surfaces and the creation of sizeable forces due to electromagnetic imbalances. While the elimination of the causes of this class of disruptions rests largely with the fusion physics community, much of the methodology to mitigate and withstand the consequences will likely be developed as part of FW/B/S engineering and materials R&D activities.

Assembly/Maintenance/Repair (AMR)

AMR features/concerns are pivotal to the successful operation of any fusion device and yet have remained one of the least well resolved of any considered herein. The strategies for dealing with AMR in fusion designs have been manifold in both approach and focus of emphasis. Although AMR affects all aspects of fusion system performance (including operability, integrity, and safety) the most frequent common denominator has been gross economic performance as reflected by cost of construction, cost of maintenance, and downtime for maintenance and repair. In all detailed reactor studies, AMR of the FW/B/S system is of prime concern; yet, only limited work has been done to date to develop generic criteria and approaches. In particular, the area of vacuum system integrity and leak detection poses many unique problems for fusion that will require extensive development and testing.

Tritium Breeding/Recovery

This feature/concern is specific to D-T fueled reactor concepts and involves the achievement of adequate tritium breeding (breeding ratio >1.0) and efficient tritium recovery from the breeder blanket under conditions of low steady-state tritium inventory (in the blanket and connected systems). Breeding questions relate for the most part to optimization of breeder/structure choice and materials configuration. Tritium recovery is dependent on the chemical characteristics of the breeding material over its operating range, and in the case of solid breeders, on blanket configuration.

Materials Compatibility/Response

The performance of materials in the fusion FW/B/S environment is a central issue to all features/concerns discussed here. Specifically, materials (depending on the particular FW/B/S application) must withstand penetrating and nonpenetrating radiation, energetic particle bombardment; corrosion by coolant, breeder, neutron multiplier, etc.; time varying thermal stresses; mechanical loads; large instantaneous forces; electrostatic and electromagnetic fields; and wear. Aspects of these problems for fusion that relate specifically to the response of materials to isolated phenomena (neutrons, ions, coolants, etc.) are addressed as part of the fusion materials program. The engineering performance of fabricated components will be studied in part by the FW/B/S ETP.

Instrumentation and Control

Instrumentation and control (I&C) issues have been a recognized but only sparsely probed feature/concern of FW/B/S design and analysis. The FW/B/S system requires a variety of instrumentation to measure temperature, coolant pressure and flow rate, stress, strain, vibration, deflection, neutron flux and fluence, etc. A unique feature of these I&C needs for magnetic fusion reactors is that the instruments and controls must respond reliably and accurately in modest time vary and steady magnetic and electric fields. Although I&C problems are seldom viewed as having up-front importance in most technology programs, in the case of the FW/B/S ETP, these concerns will have to be addressed early on to (1) assure that meaningful engineering data are recorded from the outset for each individual test program element, and (2) to begin to identify and resolve key I&C deficiencies in the FW/B/S area.

Feature/Concern Impacts

From an engineering point of view, the above described features/concerns generally have the greatest impact on reactor design credibility in the following ways.

1. They have impact on the operability of the reactor to a first order of approximation, i.e., the reactor would not operate at all if the engineering design were seriously inadequate.

2. They have impact on the integrity of FW/B/S components and of other reactor systems, either in the sense of basic short term operation (design adequacy) or long term operation (reliability).

3. They have impact on the overall safety of the device from the point of view of serious damage to systems and components, worker safety, and public safety.

4. They have impact on the overall economic performance of the reactor from the point of view of capital cost, cost of electricity, availability, and cost of recovery from off-normal occurrences.

The most obvious impacts (considering only the four given above) of each feature/concern on reactor design credibility are listed in Table 1 together with judgments about the importance of the particular feature/concern to the primary FW/B/S subsystems. Again, while these judgments are most assuredly concept dependent in many respects, they represent the type of thought that has motivated a vast majority of the fusion reactor conceptual designs carried out to date.

Proposed Approach to the FW/B/S ETP

The Planning Exercises

The planning exercises conducted by the FW/B/S ETP technical management center at ANL were carried out in two steps. Initially, a planning inquiry document was forwarded to over thirty organizations (laboratories, industries, and universities). The planning inquiry document (PID) described a set of five test program areas covering, respectively, (1) first wall thermal-hydraulics and thermomechanics; (2) blanket thermal-hydraulics and thermomechanics; (3) FW/B/S electromagnetic and eddy current effects; (4) FW/B/S assembly, maintenance, and repair; and (5) comprehensive design algorithms/equations for FW/B/S systems. The organizations receiving the PID were asked to respond to questions relating to the importance of each test program area to ETF and to reactors beyond ETF, the prospects for initiating meaningful engineering programs in each area in existing or readily established facilities at an initial funding level of $300 to $350 K/yr, the appropriateness of the scope and thrust proposed for each test program element, and the need for engineering tests in areas other than those covered in the inquiry document. The assimilated results of the responses to the PID revealed a strongly positive opinion concerning the importance of the proposed test program areas to ETF and reactors beyond ETF and the feasibility of initiating meaningful work at the $300 to $350 K/yr level. There was, however, a modest diversity of opinion concerning the scope of work and near term thrust (objectives) for each test program area. An FW/B/S ETP Planning Workshop, which followed the PID, was organized to focus on revised, prioritized work scopes, and improved definitions of near term technical objectives for each test program area. (The same organizations that responded to the PID also participated in the workshop.)

The combined output of the planning exercises may be summarized as follows:

1. In the area of first wall thermal-hydraulic and thermomechanical effects, the recommendation was made to focus approximately equally on normal operational and transient effects testing. The testing should be done in non-nuclear facilities using radiant heaters (or equivalent methods) to apply controlled heat fluxes to first wall component facsimiles. Bulk heating and related nuclear effects should be simulated to the extent possible. Armor, limiters, heat ejector panels and related first wall components should be examined separately, in appropriately constructed test facilities. The tests should address (i) normal condition thermal-hydraulics, (ii) the consequences of plasma and coolant system disruptions (including failure modes and effects), (iii) first wall instrumentation and control,

Table 1 - RELATIVE IMPORTANCE FACTORS FOR TESTING OF FW/B/S SYSTEMS

Technological Feature/Concern	Major Impacts[a]	Timing of Importance to Major FW/B/S Subsystems Design[b]		
		The First Wall	The Blanket	The Shield
Penetrating Radiation (n,γ)	S,E	I/CD	I/CD	I/CD
Non-penetrating Radiation (Σ,ν)	O,I	I/CD	-	-
Particle Bombardment (D,T,He)	O,I	I/CD	-	-
Thermal-Hydraulics/Thermomechanics	O,E	I/CD	I/CD	I/DD
Heat Transfer/Energy Conversion	E	I/CD	I/CD	-
Electromagnetic Reactions/Effects	O,I,S	I/CD	I/CD	I/CD
Coolant Flow Oscillations	I,S	I/CD	I/CD	I/DD
Confinement System Disruptions	I,S	I/CD	DOC	DOC
Assembly/Maintenance/Repair	E	I/CD	I/CD	I/CD
Tritium Breeding/Recovery	E,S	DOC	I/CD	-
Materials Compatibility/Response	E,I,S	I/CD	I/CD	I/DD
Instrumentation and Control	O,I,S	I/DD	I/DD	I/DD

[a] O = operability of device; I = device integrity; S = safety; E = economics.

[b] I/CD = a high level of importance of feature/concern to subsystem conceptual design.
I/DD = a high level of importance of feature/concern to detailed design phases.
DOC = onset of importance depends on design concept.

and (iv) simulated mechanical upsets. Members of the plasma physics community should be called upon to supply guidance in the planning of meaningful plasma disruption effects tests. The tests should also be geared to provide first wall design data (e.g., on component reliability, transient abatement requirements, configuration optimization, etc.), operational parameters (e.g., gross heat transfer coefficients), and computational method verification.

2. In the area of blanket thermal hydraulic and thermomechanical effects, there was a diversity of opinion concerning the need for extensive near term work in support of the ETF, since some viewed the present ETF blanket shield concept (low temperature/nonbreeding) as being devoid of serious hydraulic and mechanical uncertainities. Others, however, sensed a need for some work in this area to establish the capability for verification testing of an ETF blanket mockup and to begin the required development work on power and breeder blanket modules. It was recommended that near term work in this area be directed toward nonnuclear, separate effects tests and toward the planning of subsequent power and breeder blanket performance tests in fission reactors. The focus should be on development/testing of a predictive capability for analyzing effects of coolant oscillations, mechanical perturbations, and related transient phenomena.

3. In the area of electromagnetic and eddy effects testing, it was recommended that near term work be directed toward the establishment of design criteria for accommodating electromagnetic interactions in FW/B/S structures. Focus should be on (i) validation of computational models, (ii) correlation of pulsed field penetration characteristics with FW/B/S composition and geometry, (iii) analysis and experimental evaluation of forces and torques on FW/B/S components due to electromagnetic interactions, (iv) response of FW/B/S instrumentation to nonuniform pulsed and steady magnetization, and (v) reaction of FW/B/S components to electromagnetic transients. Work on ferromagnetic FW/B/S components and liquid metal MHD should be conducted when and as appropriate to fusion

FW/B/S development needs.

4. In the area of FW/B/S assembly, maintenance and repair (AMR), the recommendations were to (i) establish an expertise base for generic fusion AMR technology supported by experience from other advanced technologies (e.g., fission energy, aircraft technology, space exploration), (ii) develop AMR guidelines and criteria for near term and longer range fusion devices, (iii) evaluate and test failure detection, location, and repair methodologies, (iv) examine impacts of AMR operations and operation sequencing considerations on FW/B/S design approaches and reactor availability.

5. In the area of FW/B/S design algorithms/equations, it was recommended that the scope of work proposed in the PID be revised and that the activity be conducted within the purview of the FW/B/S ETP technical management center at ANL. The new scope should emphasize the potential utility of existing general purpose nuclear, hydraulic, and mechanical analysis codes, the development of fusion-specific transient analysis codes, and to a limited extent the concept of coupling pairs of codes to achieve some semblance of design data integration. The desirability of preparing fusion-dedicated preprocessor packages for existing general purpose codes, and the need for a code to model tritium transport/inventory in FW/B/S systems were also mentioned.

The Proposed Approach to FW/B/S Engineering Testing

Assimilation of the results of the planning exercises described above has led to improved definition of five technical areas for which there is a consensus of community-wide opinion that meaningful engineering studies can and should be undertaken at this point in time as part of the FW/B/S ETP. The five areas, hereafter referred to as test program elements (TPEs), were derived on the basis of their need by the magnetic fusion program, their character as engineering studies, and the absence of comprehensive, coordinated study by other OFE programs. These TPEs may be summarily described as follows:

TPE I: Thermal-hydraulic and thermomechanical testing of first wall heat reflecting and heat removing components (e.g., tube banks, panel coils, disruption armor, limiters).

- Performance and lifetime-limiting characteristics of individual first wall component concepts under conditions of normal (1-10 MW/m^2) and transient (10-100 MW/m^2) cyclic surface (radiant) heat flux.
- Effects of material thickness, fabrication method, configuration, stress condition, and fatigue pattern on component integrity.
- Hydraulic response of selected first wall coolants (e.g., water and helium) under normal and transient flow conditions.

TPE II: Blanket and shield component thermal-hydraulic, thermomechanical, and nucleonic testing.

- Nonnuclear testing of transient overheating and coolant flow oscillation effects in scaled-down facsimiles of conceptual blanket components.
- Nuclear (fission reactor) testing of normal and transient hydraulic and mechanical conditions (10-50 W/cc) in blanket component mockups.
- Nuclear engineering tests of blanket/shield radiation attentuation characteristics, including penetration design, afterheat effects, and residual radioactivity.
- Breeder blanket integral testing to examine the breeding potential of conceptual tritium breeder materials/configurations.

TPE III: First wall, blanket, and shield electromagnetic engineering.

- Functional dependence of pulsed field penetration/distortion on FW/B/S composition and configuration.
- Structural loads, torques, and other forces in FW/B/S assemblies under normal and transient electrical and magnetic conditions, including back-lash effects from plasma disruptions and magnet failures.
- FW/B/S instrumentation response in stationary and time-varying magnetic and electrical fields.
- Electromagnetic reactions in ferritic materials and in liquid metals.

TYPE IV: First wall, blanket, and shield assembly, maintenance and repair (AMR) concept development and testing.

- Development of a fusion-specific AMR information bank from existing nonfusion AMR technology.
- Exploration of fundamental approaches to the understanding and the fulfillment of AMR requirements.
- Performance of statistical and other soft engineering analyses to produce criteria for evaluating AMR sequencing strategies, time planning methods, and performance limitations.

TPE V: First wall, blanket, and shield design/data integration and analysis.

- Computational tools to benchmark and extend results of FW/B/S engineering tests to reactor operating conditions.

- Assimilation and integration of early FW/B/S ETP engineering effects data to prepare guidance for longer range integrated testing.

- Transfer of refined FW/B/S engineering test data and computational methods to the fusion design community.

During the coming year, the development of details for the engineering tests outlined above will be conducted through the FW/B/S ETP technical management center at ANL in conjunction with other participating organizations. In many instances, the participating organizations (laboratories, industries, and universities) will in turn be called upon to execute the engineering tests. Selection of the participating organizations will be based on organizational expertise, facilities, and other resources relevant to the proposed engineering test.

It is important to recognize that the first series of engineering experiments to be conducted within the FW/B/S ETP will not be comprehensive tests of the environment to which a typical FW/B/S component is likely to be exposed in a fusion reactor system. Rather, these first experiments will focus mainly on the study of isolated effects and, to a limited extent, groupings of two or three effects. The combined results of all tests will be used to (1) supply fundamental design data, (2) confirm and calibrate specific assumptions and selected aspects of computational models, (3) provide a cross correlation capability that can shed light on important feature/concern synergisms, (4) generate insights concerning dominant failure modes for specific component concepts, and (5) develop and test the instrumentation and control strategies required for meaningful FW/B/S experimentation. A key activity of the FW/B/S ETP (starting in FY 1981) will be to examine in detail the features, requirements, configurations, costs, and general feasibility of one or two comprehensive, integrated FW/B/S test facilities to be constructed and made operational by the mid-1980s. In the light of this goal, an additional purpose of the first series of engineering tests will be to provide the guidance and insight needed to bolster the planning and design of the integrated test facilities. A discussion of the perceived character of these facilities is included in the following section of this paper.

First Wall/Blanket/Shield Test Facilities

The Need for FW/B/S Test Facilities

Carrying out the test program described in the preceding section will clearly require many small (bench-scale) testing tools (FY 1981-1984), several intermediate-scale test stands (FY 1985-1987), and at least one large test facility (FY 1987 and beyond). The individual testing tools and the test stands will probably not be capable of replicating more than a few isolated conditions of the fusion FW/B/S environment. In fact, because of the inability to fully simulate the fusion environment in anything other than a reactor-grade fusion device, it seems reasonable to look towards an ETF-type device as a major FW/B/S development and verification facility. However, a cautionary argument that merits serious thought addresses the wisdom of inserting marginally qualified test segments and, for that matter, a marginally qualified low-temperature blanket/shield into a device (e.g., the ETF) that will probably represent an investment of about a billion dollars.

Even before fabrication is started on the FW/B/S system for the earliest stages of D-T operation on ETF, all concerns about serious failure of that system in the ETF will have to be comfortably laid to rest by a well-integrated series of tests. Furthermore, those tests, taken collectively, must cover the entire range of possible synergistic effects. This will not be a simple chore, but would be reduced in complexity if the number of integrated test facilities required to cover all such effects were limited to one or two. It seems prudent, therefore, that over the next few years the FW/B/S ETP engage in assessments to determine the feasibility of constructing a limited number of nonfusion-reactor test vehicles capable of collectively simulating (with overlaps) all of the fusion FW/B/S environment. Of course, the inception of ideas for, or approaches to, these comprehensive FW/B/S test facilities should be carried out in a manner that derives input from the entire fusion community. Such planning could well lead to the implementation of one or two facilities ($30 to $50 M each) in the latter half of the 1980s.

The Character of Near Term Test Stands

As part of the technical analysis and evaluation function of the FW/B/S ETP management center at ANL, an effort was made in FY 1980 to complete preliminary assessments of the characteristics of plausible near term FW/B/S test facilities. The sizeable effort on the part of ANL staff members that went into this activity will only be summarized here. Facility characteristics were analyzed for two of the proposed TPEs: the first wall thermal-hydraulic/thermomechanical testing (TPE I) and the electromagnetic effects testing (TPE III).

In the case of the first wall thermal-hydraulic/thermomechanical testing, an evaluation was made of existing heat flux generation tools and is summarized in Table 2. Since the existing tools appear to have capabilities that overlap with testing requirements as spelled out in a previous section, a conceptual design of a perceivable test facility was developed and is shown in Fig. 1. The type of test pieces that could be studied in such a facility are sketched out in Fig. 2 for purposes of example. A more detailed description of the assessment of this concept for a first wall heat flux test stand will appear in the FY 1981 version of the Program Plan[1] for the FW/B/S ETP.

A conceptual design of an electromagnetics test stand was also developed during FY 1980, primarily by L. R. Turner and co-workers in the ANL Accelerator Research Facility Division. A sketch of the facility is shown in Fig. 3, and facility-related parameters are listed in Table 3, together with paralleling parameter values estimated[2] for the ETF and STARFIRE conceptual designs. The facility is capable of studying many of the important electromagnetic effects related to field penetration electromagnetic transients, electromechanical reactions, FW/B/S instrumentation response, and validity of computational tools. More detailed description of this facility will be included in the FY 1981 version of the Program Plan[1] for the FW/B/S ETP.

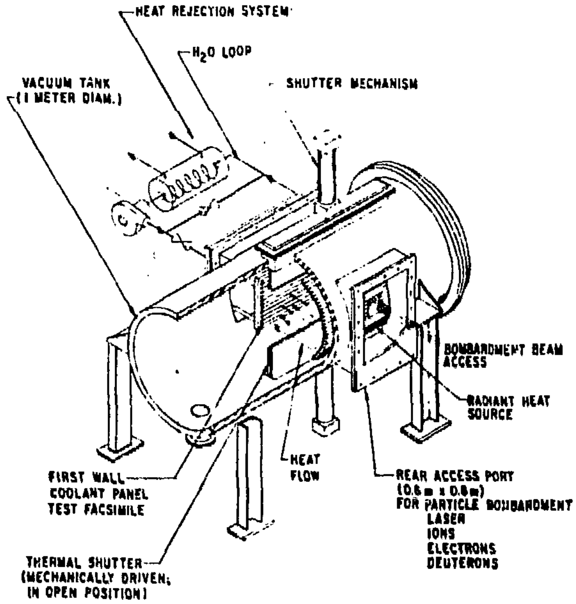

Fig. 1 Conceptual layout of a near term first

Table 2 - REPRESENTATIVE CHARACTERISTICS OF EXISTING HEAT FLUX TEST FACILITIES

Type of Facility	Typical Test Zone Area	Capability	Remarks
Arc Jet	100 cm^2	10-50 MW/m^2	- presents oxidizing environment
	10 cm^2	100-300 MW/m^2	- fusion vacuum conditions not readily achievable
	1 cm^2	→1500 MW/m^2	- long cycles possible
Continuous HP Laser	100 cm^2	1-5 MW/m^2	- in-vacuum testing feasible
	10 cm^2	10-50 MW/m^2	- adsorption of radiation by metal surfaces a problem
	1 cm^2	100-500 MW/m^2	- potential large facility operating costs
Radiant/Incandescent	1000 cm^2	<7 MW/m^2	- filament temperature limited (<3000°C)
	100 cm^2	<7 MW/m^2	- in-vacuum testing feasible
	10 cm^2	<7 MW/m^2	- long cycles possible

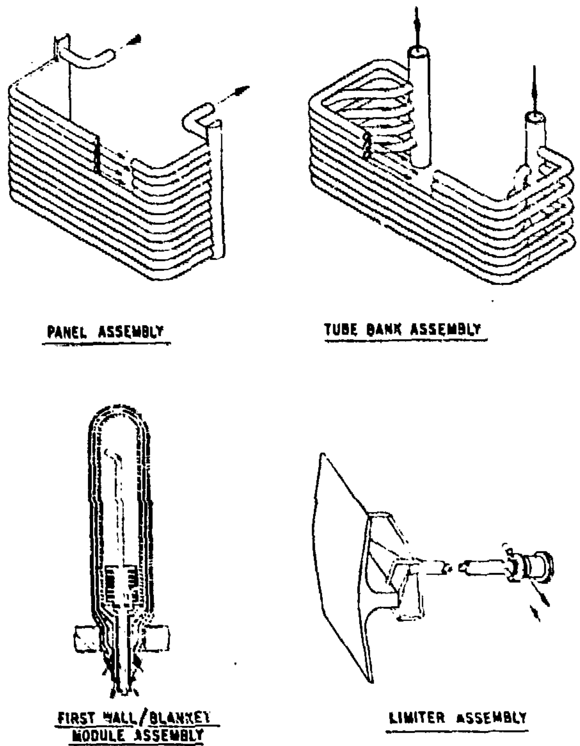

Fig. 2 Sketches of typical test pieces that could be examined in the test facility in Fig. 1.

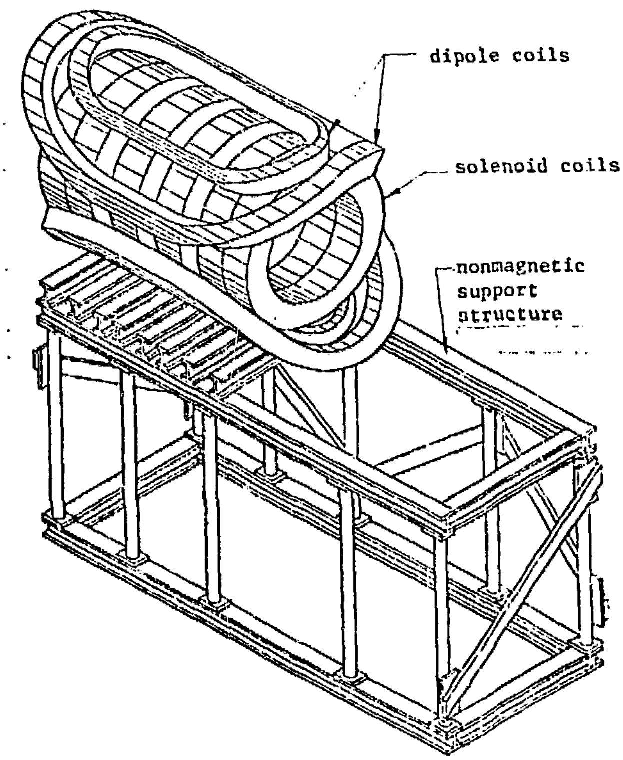

Fig. 3 Conceptual layout of a near term electromagnetic effects test facility.

Table 3 - PARAMETER RANGES APPLICABLE TO ELECTROMAGNETIC EFFECTS TESTING

Parameter	Test Facility		ETF	STARFIRE
	Initial	Upgrade		
Component Volume (m^3)	∿1	∿1	∿1	∿1
Typical Dimension (m)	0.9	0.9	2.0	1.0
Toroidal Field (T)	1.0	2.0	5	4.5
Plasma B (T/S)	0.5-100	1-200	10-700	6-100
Disruption Time (S)	0.005-1.0	0.005-1.0	0.001-0.025	0.01-1.0
Plasma Field (T)	0.5	1	0.7	1.0
Structural Material	Cu*	Cu*	SS	SS
Resistivity (Ωcm)	1.7	1.7	75	75
L/R Time (s)	0.004	0.004	---	0.001-0.003
Eddy Current (kA)	60	120	180	130
B Force (ksi)	5	20	60	30
B_T Force (ksi)	10	40	400	130
Torque (10^6 in-lb)	0.4	1.6	33	5

*Substitution of Cu for SS is only necessary for force and torque effect simulations. Other simulations (field penetration, MHD, instrumentation response, etc.) can be simulated directly.

A key conclusion of the facility analyses conducted during FY 1980 was that the establishment of technically meaningful test stands capable of accommodating separate-effects and limited combined-effects tests of FW/B/S engineering features/concerns was feasible and could be done within the confines of existing funding levels.

The Character of Integrated FW/B/S Test Facilities

It is difficult to accurately project the character of a comprehensive FW/B/S test facility that is not in itself a reactor-grade fusion device. However, some early consideration could be given to the following two-facility approach to comprehensive pre-ETF qualification testing. The principal demarcation between the two facilities would be the presence and absence, respectively, of a genuine neutron and gamma environment. One facility would be designed to permit simultaneous replication of as many as possible of the nonnuclear effects anticipated in the fusion FW/B/S environment, e.g., plasma chamber vacuum conditions, ion bombardment, simulated nuclear heating, electromagnetics, mechanical loads, limiter/armor/heat ejector interfacing, FW/B/S thermal-hydraulic/thermomechanical interfacing, heat-dump/power-conversion interfacing, assembly/maintenance/repair interfacing, and so on. The second facility would be an integral part of the core of an experimental fission test reactor (presumably an existing one). In this facility, the asymmetric nuclear heating and attenuating characteristics of FW/B/S prototype assemblies would be tested in the most comprehensive achievable fashion. Also, as many as possible of the nonnuclear effects cited for the first facility would be incorporated into the second facility as well. The combined results of tests (e.g., for normal operation and transient conditions) done in these two facilities could well provide the level of qualification of ETF FW/B/S design approaches that should be reached to minimize the possibility of adverse FW/B/S system response during ETF operations.

The ETF as a Major FW/B/S Test Facility

There is little doubt that the ETF, as presently envisioned, could and should represent the final critical link between the FW/B/S development efforts and the demonstration of the commercial viability of fusion energy. The extent of FW/B/S testing capability achievable with the ETF can best be summarized by the comparative listings in Tables 4 through 6. These tables[3] show that ETF operating parameters, such as the neutron wall loading, overall availability, test materials, and test-module conditions, could be close to and in many cases the "same" as those projected for commercial fusion reactors. This leaves little doubt that a device like the ETF can be looked upon to provide the type of verification and reliability testing that has been achieved with prototype reactors in the fission industry.

On the other hand, if the ETF evolves into a significantly less ambitious device than the one reflected by the parameters in Tables 4 through 6, then the FW/B/S development activity for magnetic fusion energy must begin to look at another device (beyond the ETF) which would provide the capability for comprehensive FW/B/S system verification and reliability testing. These considerations will have to be examined jointly by the DOE/OFE, the ETF Design Center and the FW/B/S ETP in the coming years to create the assurance that essential FW/B/S testing capability will be available to meet the development schedule for magnetic fusion energy.

Interfacing with Other FW/B/S-Related Programs

The FW/B/S ETP is but one of a number of ongoing OFE/D&T supported activities that is providing data relevant to FW/B/S system design and

Table 4 – COMPARISON OF FW/B/S-RELATED DESIGN PARAMATERS FOR ETF AND COMMERCIAL TOKAMAK FUSION REACTORS

Design Paramter	ETF Physics Phase	ETF FW/B/S Testing	Commercial Reactors
Length of burn, s	50-100	50-500	500-10^7
Duty factor	~50%	~50-90%	≥90%
FW/B/S Thickness, m	1.2	1.2	1.5
Availability	~25%	25-50%	≥75%
Neutron wall loading, MW/m^2	~2	~2	3-5

Table 5 - COMPARISON OF FIRST WALL MATERIALS AND OPERATING CONDITIONS FOR ETF AND COMMERCIAL TOKAMAK REACTORS

Materials/Conditions	ETF Physics Phase	ETF FW/B/S Testing	Commercial Reactors
Structural Material	SS/C	← SAME[b]	→
Structural Temperature, °C	$\leq$250	← SAME[b]	→
Coolant Operating Temperature, °C	$\leq$100	← SAME[b]	→
Fractional Area at Power Reactor Operating Condtions	0	20%[a]	100%

[a] Includes test and demonstration modules.

[b] "Same" indicates that conditions achievable during FW/B/S testing stages of ETF operation can in principal be identical to those projected for commercial reactors.

Table 6 - COMPARISON OF BLANKET MATERIALS AND OPERATING CONDITIONS FOR ETF AND COMMERCIAL TOKAMAK REACTORS[a]

Materials/Conditions	ETF Physics Phase	ETF FW/B/S Testing	Commercial Reactors
Structural Material	SS	← SAME[b]	→
Breeder Material	None	← SAME[b]	→
Multiplier Material	None	← SAME[b]	→
Structural Tempeature, °C	$\leq$200°C	← SAME[b]	→
Coolant Temperature, °C	$\leq$100°C	← SAME[b]	→
Fractional Area at Power Reactor Operating Condtions	0	~20%	100%

[a] Note: Shield operating conditions and materials should be much the same for all phases of ETF and follow-on reactors.

[b] "Same" indicates that conditions achievable during FW/B/S testing stages of ETF operation can in principal be identical to those projected for commercial reactors.

performance. These programs span a range of physics, engineering, and materials issues, each contributing vital information to the design and analysis of FW/B/S systems. Examples of some of these related program areas (including the FW/B/S ETP) are shown schematically in Fig. 4, in perspective with their perceived role as a source of information to the ETF and to devices beyond ETF. To avoid unnecessary overlaps, provide continuity in the development of test data, derive the maximum amount of information from all ongoing work, and assure that a complete technology/data base is on hand when needed to support ETF, it will be essential to establish recognized interfaces from one FW/B/S-related programmatic area to another.

As an aid to sorting out potential interprogram overlaps, the technical features/concerns for the total design and integration of the FW/B/S system have been divided into three basic categories of issues; these are engineering issues, materials issues, and physics issues. A listing of some specific technical issues that can be identified for each category of issues is given in Table 7. Although the listing is not considered complete and may require reshuffling of some issues to accommodate the perceptions of other programs, it does serve to delineate the nature of the three classes of issues from a programmatic viewpoint. The present scope of work proposed for the FW/B/S ETP is expected to directly cover only the engineering issues in Table 7, but may require input from or provide input relevant to the materials and physics activities. For example, the hydraulic, mechanical, and electromagnetic testing of first wall component facsimiles will require input from (1) the materials activities on choice of materials, fabrication requirements, materials properties, etc., and (2) the physics activities on test conditions, test parameter values (ranges, etc.). In turn, the component facsimile tests are expected to provide information on (1) materials reliability, failure mode, etc., and (2) performance impacts relative to the plasma systems. Other examples of issues that may tend to span two or more of the categories in Table 7 include, but may not be limited to, plasma impurity control, plasma chamber evacuation system topology, blanket processing technology, materials/component mechanics, and data base management activities. Coordinated planning of activities in all three categories of issues should provide the resolution of overlaps and information transfers required to assure the development of a timely and complete FW/B/S technology/data base.

An example of the type of interprogram planning that is currently being carried out by the FW/B/S technical management center involves the case of evaluating the prospects and plausible approaches for integrating neutron irradiation and surface effects data (from materials-related task areas) in with the results of proposed out-of-pile first wall and blanket engineering tests. During this evaluation, a clear need surfaced for continuous examination of the extent to which materials irradiation and surface effects data can be combined with FW/B/S ETP generated engineering data to derive a more comprehensive picture of FW/B/S component performance in the total fusion environment. Methods must be identified by which the effects of neutron and energetic particle bombardment can be incorporated or otherwise simulated in out-of-pile engineering tests of hydraulic and mechanical performance, particularly in cases where these effects are expected to have an impact on hydraulic and mechanical response. The types of approaches presently in use in the fusion materials programs and those planned for the FW/B/S ETP studies will have to be reviewed to determine whether and how overlapping features of isolated materials tests and component engineering tests can be extended and correlated. The principal objective of this type of endeavor would be to identify a means of bridging the gap between phenomenological testing of materials and engineering testing of FW/B/S components so that both activities can be effectively pursued in parallel.

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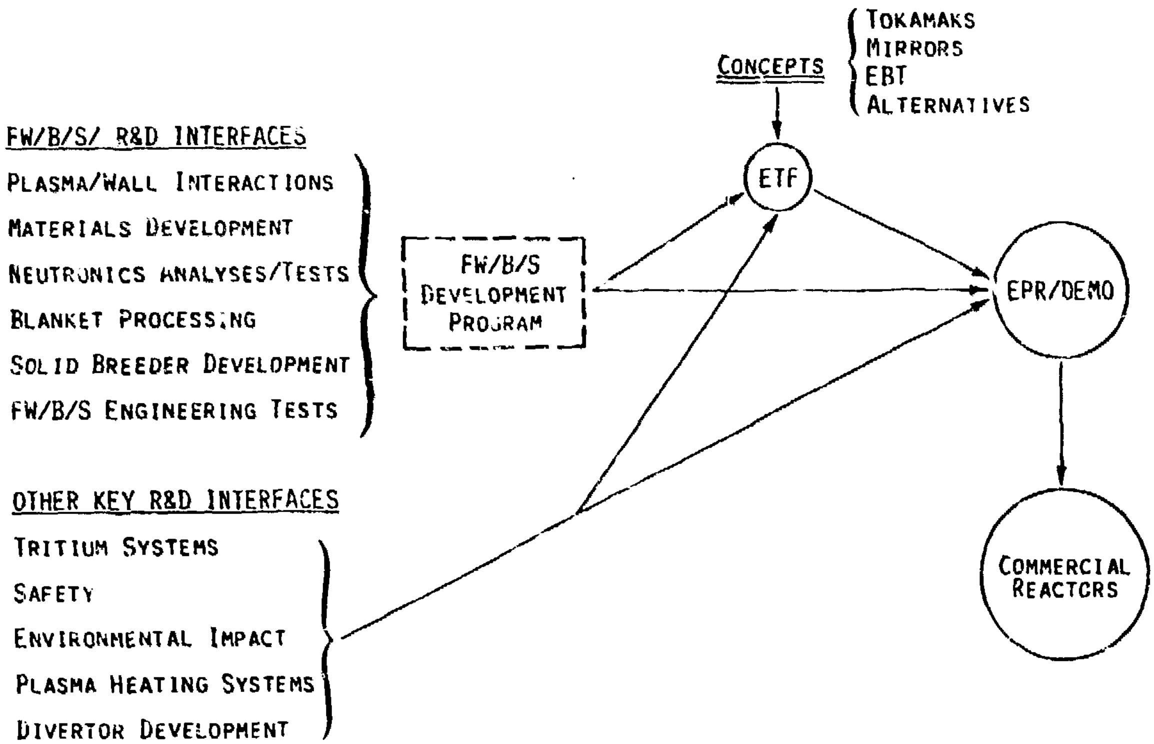

Fig. 4 OFE/D&T programmatic interconnections with the ETF and follow-on reactors

Table 7 - CATEGORIES OF ISSUES RELATED TO THE DESIGN AND DEVELOPMENT OF FW/B/S SYSTEMS

Engineering Issues	Materials Issues	Physics Issues
Nuclear Response	Radiation Damage/Effects	Plasma Confinement Systems
Thermalhydraulic Response	- all classes of materials	Plasma Fueling Systems
Thermomechanical Response	- includes dosimetry and damage analysis	Plasma Heating Systems
Electromechanical Response		Plasma Exhaust Systems
Assembly	Plasma Materials Interactions	Plasma Impurity Control
Maintenance	Corrosion	Plasma Diagnostics
Repair	- all classes of materials	Plasma Control Systems
System Integration	- all types of environments	Physics Data Base Management
Instrumentation Systems	Materials Property Data	
Control Systems	- mechanical properties	
Blanket Processing Technology	- chemical properties	
Vacuum System Topology	- physical properties	
Engineering Design Equations	- thermal properties	
Engineering Data Base Management	Materials Performance Equations	
	Materials Data Base Management	