

BLANKET MATERIAL AND ENGINEERING ISSUES, AND REQUIREMENTS FOR EXPERIMENTS AND FACILITIES*

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Fusion nuclear technology components face a new and tougher environment than experienced by any previous nuclear application: The development of feasible and attractive fusion nuclear components will require a broad research effort including experiments, model development and innovative designs. In order to provide an efficient strategy, the important issues must be identified and characterized, and required experiments and facilities must be defined.

This paper considers the experiments needed to solve the uncertainties associated with liquid breeder and solid breeder blankets. Many of these uncertainties are strongly material-related and involve a number of areas ranging from basic material properties under irradiation to highly interactive phenomena involving several materials, components and/or environmental conditions. They can be addressed in a number of progressively more integrated experiments.

Test facilities to investigate these uncertainties range from simple bench-top experiments, to large non-nuclear tests, fission reactors and point neutron sources, and fusion test facilities. Possible experiments and facilities have been analyzed in a timeframe consistent with the present US goal of supporting an assessment of the feasibility and attractiveness of fusion around the year 2000.

1. Introduction

Three important activities always take place in the development of a new technology, such as fusion energy: (a) the study and comparison of design options with the aim of identifying the most promising design concepts; (b) the planning of experiments with a view toward developing a cost-effective research strategy; and (c) the implementation of a research and development (R&D) program with the objective of constructing experimental facilities and performing experiments. The second activity, experiment planning, has been performed for the fusion nuclear technology area (i.e., blanket, tritium and vacuum systems, plasma interactive components, and radiation shield) as part of the FINESSE study [1]. The FINESSE process consists of four steps: (1) characterization of issues, (2) quantification of experimental needs, (3) evaluation of facilities, and (4) development of a test plan. The principal objective is to recommend the types, sequences and characteristics of major experiments and facilities which maximize technical benefits and minimize cost in a logically consistent path for fusion nuclear technology development.

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This paper describes the experiment planning process for the blanket which is a particularly important fusion nuclear component having a number of critical feasibility and attractiveness concerns. Blanket issues are highly interrelated to material issues and material uncertainties can strongly affect the feasibility of a blanket concept. The range of experiments and test facilities needed to investigate these material uncertainties are also described in this paper, but the implementation of a particular set of experiments and facilities depends on the overall fusion program goals and strategy, time frame and funding level. The results presented here focus on the R&D effort for the next fifteen years, with the goal of supporting an assessment of the feasibility and attractiveness of fusion around the year 2000.

2. Leading blanket concepts

Blanket concepts can be divided into liquid breeders and solid breeders. Within each class, there are a number of distinct material and design options, as shown in fig. 1. Although the functional requirements (e.g., tritium breeding) and reactor operating conditions (e.g., neutron wall load) are similar for both classes of blankets, the critical issues are generally not alike. Since it is not now possible to make a choice between solid or liquid breeder blankets within the uncertainties, it appears prudent for the fusion program to retain both options. The technical issues, associated experiments,

and key technical considerations for the test plan for each class of blanket concepts are presented separately in the following sections.

3. Technical issues and testing needs

3.1. Solid breeder blankets

Table 1 shows the general classes of issues for solid breeder blankets, based on the characteristics of solid breeder concepts from recent studies such as the Blanket Comparison and Selection Study (BCSS) [2,3]. It can be seen that they are all strongly material oriented. The most important uncertainties are related to tritium breeding, tritium recovery, and breeder thermomechanical behavior. These are particularly large for solid breeder blanket because: (1) there is limited understanding of gas transport in irradiated solids, (2) complex designs are used to keep the low thermal conductivity solids within their temperature limits under substantial nuclear heating and neutron damage rates, and (3) the resulting designs have a significant amount of non-breeding structure, coolant, and other materials.

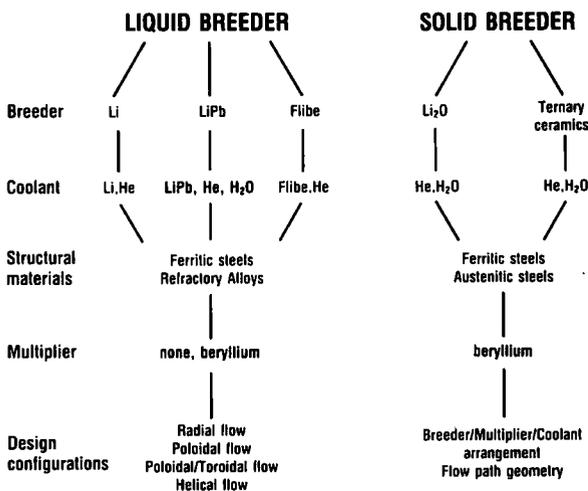


Fig. 1. Primary options for blanket materials and configurations.

Table 1
Generic solid breeder blanket issues

Tritium self-sufficiency	
– achievable breeding ratio	
– required breeding ratio	
Breeder/multiplier tritium inventory and recovery	
Breeder/multiplier thermomechanical behavior	
Corrosion and mass transfer	
Structural response and failure modes in fusion environment	
Tritium permeation and processing from blanket	

Each of the generic solid breeder issues is discussed in more detail below.

Most solid breeder blankets (with the possible exception of Li₂O) require ⁶Li enrichment and a neutron multiplier for adequate tritium breeding. However, within present uncertainties in data, modeling methods and design definitions, it is not clear that present solid breeder blanket concepts provide reactor self-sufficiency in tritium. In blankets with multipliers, the tritium breeding is affected by the form in which the multiplier is incorporated – which also affects the tritium and thermal behavior. An accurate assessment of the tritium breeding margin would thus indicate whether a multiplier is needed (for the Li₂O case in particular) and, if so, what multiplier form and level of physical separation from the solid breeder is acceptable.

The prediction of tritium behavior in solid breeder blankets requires understanding tritium transport, retention and chemical form in the breeder and multiplier material under the influence of the fusion environment. The major contributors are the diffusivity, solubility and surface adsorption processes. Tritium diffusion is anticipated to be a rate-controlling step in LiAlO₂ and other ternary ceramics while the solubility inventory is believed to be large only for Li₂O. The surface inventory could be large for all breeder materials and is sensitive to surface conditions and the chemical environment. In all cases, the uncertainties are still large. Sufficient tritium is produced in the beryllium multiplier to require a better understanding of the importance of the tritium transport processes in beryllium. The permeation of tritium outside of the breeder and into the coolant is an important safety issue, but the nature and effects of the surface and environmental conditions are uncertain.

Mechanical interactions between the solid breeder, multiplier and structure arise due to swelling and thermal expansion and can lead to restructuring of the solid breeder, creep, deformation and/or rupture of the structure, and changes in the heat transfer across the breeder/cladding interface. There are no completed experiments which indicate the extent and consequences of mechanical interactions or temperature gradients within the breeder. The solid breeder thermal behavior is dependent on the thermal conductivity (which is temperature dependent) and the upper temperature limits, which are not well-defined for most candidate solid breeders. A separate issue is the structural response of the blanket to the loading conditions, which in effect will determine the blanket lifetime. The mechanisms for component failure must be identified in order to determine and improve blanket reliability and safety.

3.2. Liquid breeder blankets

A number of large uncertainties exist in the behavior of liquid breeder blankets and they can be classified

under a list of generic issues, which are shown in table 2 and described below. These issues directly affect the feasibility and attractiveness of liquid breeder blankets and are strongly material dependent. Table 3 indicates the effect of material choices on the dominant near-term issues. The existence and seriousness of the major issues depend not only on the particular blanket concept, but also on the operating conditions, such as the magnetic field and surface heat flux.

Some of the largest uncertainties in self-cooled liquid metal blankets relate to magnetohydrodynamic (MHD) effects which impact many aspects of blanket behavior such as coolant pressure drop, heat and mass transfer, and structural behavior. The existing MHD theory has established some general features of the flow but large uncertainties remain in predicting key parameters, such as the velocity and temperature pro-

files, for the complex geometries of fusion blankets.

Most of the existing experimental data have been accumulated in very simple geometries for relatively low values of the Hartmann number (M = ratio of magnetic to viscous forces) and of the interaction parameter (N = ratio of magnetic to inertia forces), as indicated in fig. 2. More data are needed for higher values of M and N and for more reactor-relevant geometries. Measurements of velocity and temperature profiles are needed in each case to help develop the MHD flow theory but separate heat transfer and pressure drop measurements, which would require scaling to reactor conditions, should also be considered as an important supplement. MHD pressure drop and stress problems can be alleviated by electrical insulation, but the effectiveness and survivability of such insulations are of concern and must be experimentally determined.

Material interaction issues include a large number of phenomena, such as mass transfer and structural degradation. The most important issues are shown in

Table 2
Generic liquid metal blanket issues

Tritium self-sufficiency
Magnetohydrodynamic (MHD) effects
– fluid flow (including pressure drop)
– heat transfer
Material interactions (e.g., corrosion)
Structural response in the fusion environment
– irradiation effects on material properties
– response to complex loading conditions
– failure modes
Tritium recovery and control

Table 3
Effect of coolant, breeder and structural material choices on dominant issues for liquid breeder blankets

<i>Liquid metal cooling</i>	
Li or 17Li-83Pb	MHD effects (including viability of insulators)
	corrosion (including viability of inhibitors)
<i>Coolant or breeder</i>	
Lithium	chemical reactivity
17Li-83Pb	tritium containment
Flibe	tritium containment
Helium	tritium containment
<i>Structural material</i>	
Vanadium alloys	bimetallic mass transfer
	DBTT ^{a)} (due to impurities, radiation, He)
Ferritic alloys	DBTT

^{a)} Ductile-to-brittle transition temperature.

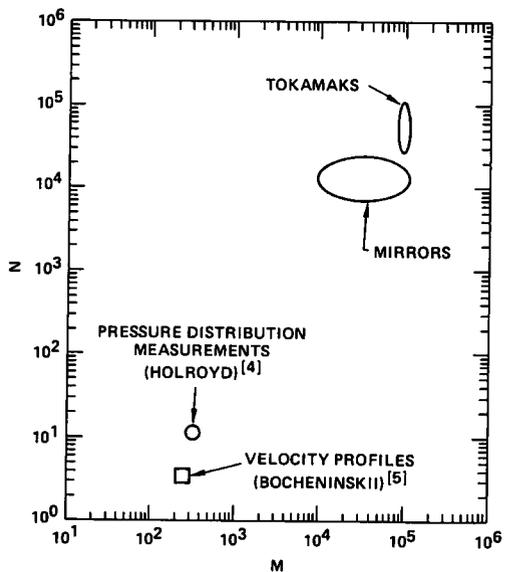


Fig. 2. Hartmann number (M) and interaction parameter (N) ranges for existing data and reactor conditions.

Table 4
Material interaction issues

- A. Mass transport
 1. Wall erosion from dissolution and spalling
 2. Erosion/redeposition phenomena, including tube plugging and activation product transport
- B. Structural property degradation
 1. Liquid metal embrittlement
 2. Removal of alloying elements
 3. Embrittlement and surface chemistry changes due to interstitial element transport
 4. Stress-corrosion interactions
 5. Radiation-corrosion interactions

table 4. Because of the complexity and material dependence, general models for predicting material interaction phenomena will likely be deficient and experiments are needed to develop empirical correlations. Temperature and impurity limits have to be adequately established and methods to control impurity and corrosion explored.

Structural response uncertainties relate to the loading conditions caused by pressure, thermal gradients, electromagnetic forces and swelling. MHD effects have a strong effect on the loading conditions and MHD experiments should also address this issue. The structural response to the loads is dominated by material behavior under irradiation. Small, subscale test elements placed in fission reactors can provide important information in this regard before fully integrated testing in a fusion reactor can take place.

Tritium issues include two major categories: permeation rates and extraction techniques. Permeation is affected by the partial pressure, temperature, surface condition and hydrogen isotopic composition. Tritium extraction issues are highly dependent on the choice of breeding material and on recovery schemes. For example, the tritium solubility is high and the partial pressure is relatively low in lithium. However, the situation is reversed for ^{17}Li - ^{83}Pb (LiPb) and LiF/BeF₂ salt (Flibe) and a very efficient extraction system must be developed to prevent large quantities of tritium from escaping the system. The situation is complicated by a general lack of tritium-related data for LiPb and Flibe; better measurements of tritium solubility and diffusivity in these materials are needed. Tritium self-sufficiency is not usually considered a feasibility issue for liquid breeder blankets, particularly for self-cooled designs, which show a high breeding ratio. Separately cooled designs have smaller breeding margins and are more affected by the uncertainties in tritium breeding.

The importance of feasibility issues is well characterized by the design window concept, as illustrated by fig. 3, which shows a design window for the feasibility of a self-cooled blanket with poloidal manifolds and

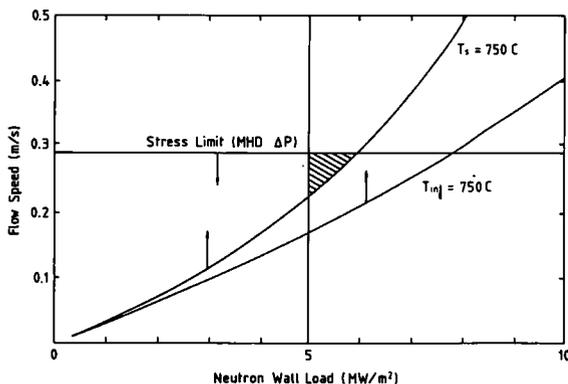


Fig. 3. Thermomechanical design window.

toroidal first wall cooling channels under typical reactor design conditions. The importance of heat transfer, fluid flow, corrosion and pressure stresses is demonstrated. In the inboard blanket of the reference design, where the magnetic field is 7 T, the maximum allowable pressure stress under irradiation (105 MPa at 150 dpa) limits the coolant velocity to about 30 cm/s. Also shown are the maximum interface and structure temperature limits, T_{int} and T_s , for vanadium (both assumed to be 750°C in this calculation) imposed by corrosion mass transport and material property degradation at high temperature and irradiation. The resulting design window, shown as the shaded area, is quite small and can be closed if uncertainties (e.g., in structure temperature limit) are included.

4. Required experiments and facilities

Solid breeder and liquid breeder blanket issues can be addressed by a range of possible experiments, as discussed below. The actual experiments will depend on particular test program assumptions and funding constraints. It must be noted that one of the major reasons for performing experiments is to aid in the development of predictive capabilities and, consequently, the development of modeling capabilities is an essential complement to the experimental program.

4.1. Solid breeder blankets

Fig. 4 shows the required tests for addressing solid breeder issues organized according to their level of integration, from basic properties to phenomena exploration in separate and multiple effect tests, to concept verification in integrated fusion tests.

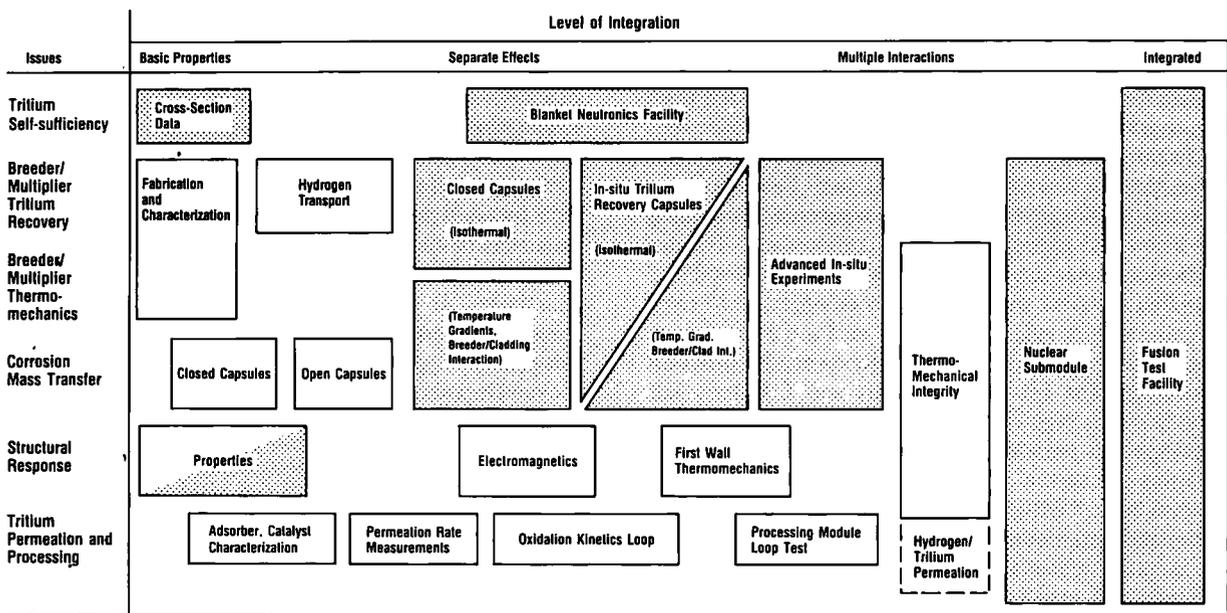
Since there is no general theoretical basis for scaling solid breeder behavior, the significant phenomena must be quantified by conducting tests at fusion reactor relevant conditions. Among the most important parameters are the tritium generation and heating rates. The ability of thermal reactors (e.g., ORR and ETR) and fast reactors (e.g., FFTF) to match fusion conditions is shown in figs. 5 and 6 for Li₂O and LiAlO₂, respectively. By appropriate ⁶Li enrichment in the breeder material, it is possible to simulate fusion tritium generation and heating rates, which makes existing fission reactors an important resource for solid breeder testing. The fast reactors are superior to thermal reactors in simulating the fast neutron spectrum in the Li₂O blanket without a neutron multiplier. The LiAlO₂ blanket must have a neutron multiplier for adequate tritium breeding, and the neutron spectrum is much softer and the burnup rate is much higher in the breeder region behind the multiplier. Fast reactors are less advantageous in such designs.

As shown in fig. 4, the objective of early experiments for the solid breeder and multiplier materials is

to fabricate the materials and to characterize and improve their properties. The near-term material goal is to provide basic material data to support blanket design and, in the case of the breeder materials, to provide a basis for the selection of materials. For beryllium, which is the primary candidate multiplier material, near-term tasks also include the measurement of irradiation effects (such as swelling, creep and ductility) on different material forms and porosity. In the long term, the aim in both cases is to optimize the properties of selected materials for the particular applications and to

develop fabrication techniques which can be extrapolated to commercial operation.

The measurement of tritium recovery and thermal behavior in closed and open capsule irradiation of material specimens is an important complement to the basic property measurement task and there are already a number of active or recently completed solid breeder fission reactor irradiation experiments carrying out this task. Detailed references for these experiments are available in ref. [1]. As a result of these experiments, a fairly wide-ranging data base for a range of tempera-



^a Some Experiments and Facilities Exist

Neutron Test

Fig. 4. Types of experiments and facilities for solid breeder blankets^a).

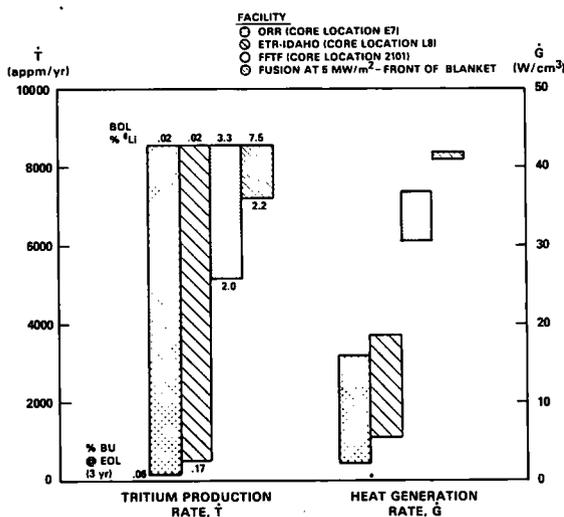


Fig. 5. Fission/fusion irradiation comparison for $\text{Li}_2\text{O}/\text{He}/\text{HT-9}$ system.

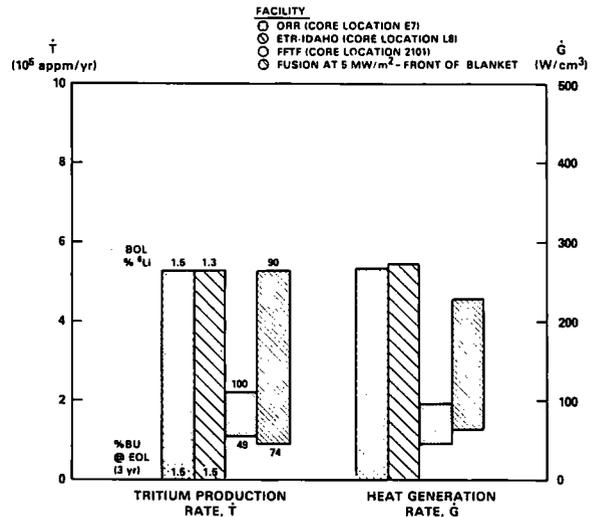


Fig. 6. Fission/fusion irradiation comparison for $\text{LiAlO}_2/\text{H}_2\text{O}/\text{HT-9}/\text{Be}$ system.

tures, temperature gradients, breeder materials, container materials, burnups and sweep gas composition and flow rates, will be available around 1990. However, the planned tests will not address the combination of high burnup with a flowing purge gas under temperature gradients and breeder/clad interactions. The next major class of tests, the advanced in-situ tritium recovery experiments, should address these interactions. Note that the effects of radiation on the breeder thermomechanical behavior can be determined in the same tests as those planned for monitoring tritium recovery.

Development and characterization of structural alloys under irradiation is also an important and active material task which is not specific to solid breeder blankets.

The objective of the neutronics and tritium breeding experiments is to measure the tritium production rate and heating rate distributions in order to verify and improve nuclear data, design methods and models. Testing would be done in two stages: the simple geometry mock-up stage with a geometrically simplified blanket module, and the blanket mock-up stage with a geometrically detailed mock-up of a blanket module design. Both stages require a wellcalibrated 14 MeV neutron source with sufficient strength (about 10^{12} n/cm² s).

Other tests include the closed capsule and open capsule irradiated testing at relevant temperatures to determine the temperature limit based on material interactions and corrosion, the glove box-scale experiments for tritium permeation and the tritium processing system loop tests using a reactor relevant modules.

As shown in fig. 4, additional integrated tests with more relevant geometries, size and environmental conditions are required in the longer term to provide some concept verification information. These tests could be done in different facilities serving different purposes. Non-neutron test stands with non-nuclear heat sources such as microwaves or resistive wires can be used to test up to full blanket modules. Fission reactors can provide the maximum concept verification possible in non-fusion devices and would include the important nuclear effects, but would be limited with respect to test volume. Ultimately, a fusion device is a necessity, as only a fusion reactor can provide fully integrated testing.

A test plan has been developed, based on the above considerations, as a method to optimally resolve the issues and develop blankets whose feasibility and attractiveness can be predicted with adequate certainty. In addition to providing focus to the research effort, the test plan defines a framework which spans the entire time period from the present to the time when a decision can be made on the ultimate attractiveness of fusion. Fig. 7 shows the solid breeder blanket test plan. It structures the experiments according to the four phases of a proposed test program. In the first phase

(0–10 years), the primary goal is to explore phenomena and develop an understanding of material behavior. The purpose of the second phase (5–15 y) is to quantify local design-related behavior under fusion relevant conditions. The third phase (10–20 y) provides concept verification to the maximum extent possible in non-fusion facilities, and the fourth phase relates to the testing of components in a fusion device. Note that the four phases overlap in practice because the distinction between the experiments is not abrupt and because further data might be needed from early-phase tests.

4.2. Liquid breeder blankets

Examination of the key issues and test requirements for liquid breeder blankets has led to the development of the matrix of tests shown in fig. 8. The required experiments and facilities are organized according to the classes of issues which they resolve and their level of integration. Depending on funding constraints, choices of blanket materials and configurations, results of prior experiments, and time-dependent testing goals, only a subset of the proposed experiments may actually be performed. Some of the early experiments are already in progress, including the measurements of liquid metal corrosion in thermal and forced convection loops and the characterization of liquid metal flow in simple geometry with MHD effects. Detailed references for these experiments are available in ref. [1].

A range of experiments has been explored to fulfill the need for further testing of MHD-related effects. The base program for MHD fluid flow and heat transfer should be complemented by tests to develop instrumentation and MHD insulators. Beyond the simple geometry experiments, experimentation on MHD effects should progress to more complex geometries and conditions closer to the fusion reactor environment. This is particularly important in order to develop the ability to predict fluid flow, heat transfer, and pressure drop behavior in self-cooled blanket designs with complex flow paths. Two advanced Liquid Metal Flow Facilities, LMF1 and LMF2, have been examined. In LMF1, the emphasis is on developing a better understanding of “microscopic” MHD behavior, especially the velocity profiles, in basic elements of relevant geometries. As a complement to LMF1, it is suggested that another facility, LMF2, be devoted to the purpose of measuring “macroscopic” parameters such as the pressure drop and heat transfer coefficient for relevant geometries.

Results from the existing experiments in corrosion/mass transport will not provide enough information for the development of fusion blankets. More corrosion loops will be required for thorough studies of fusion relevant materials, especially for refractory metals and bimetallic systems. The most critical information includes dependence on temperature and impurities, loop

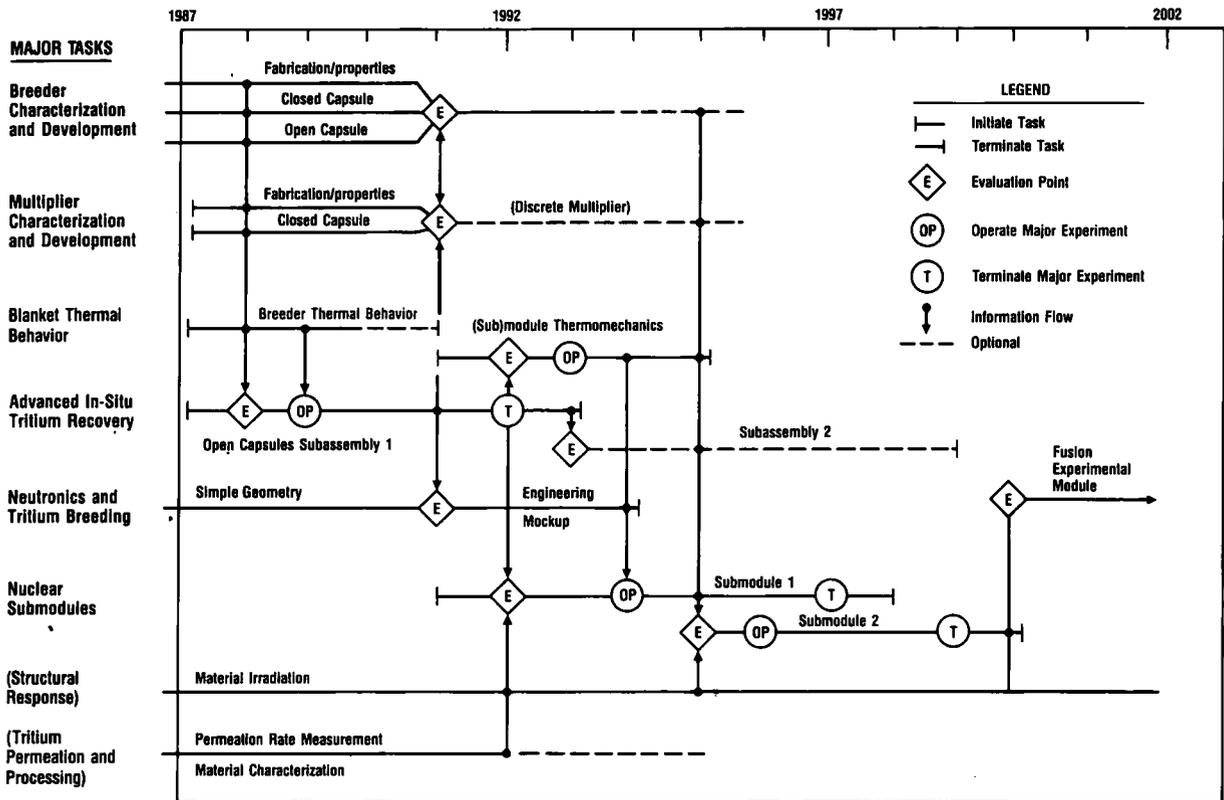
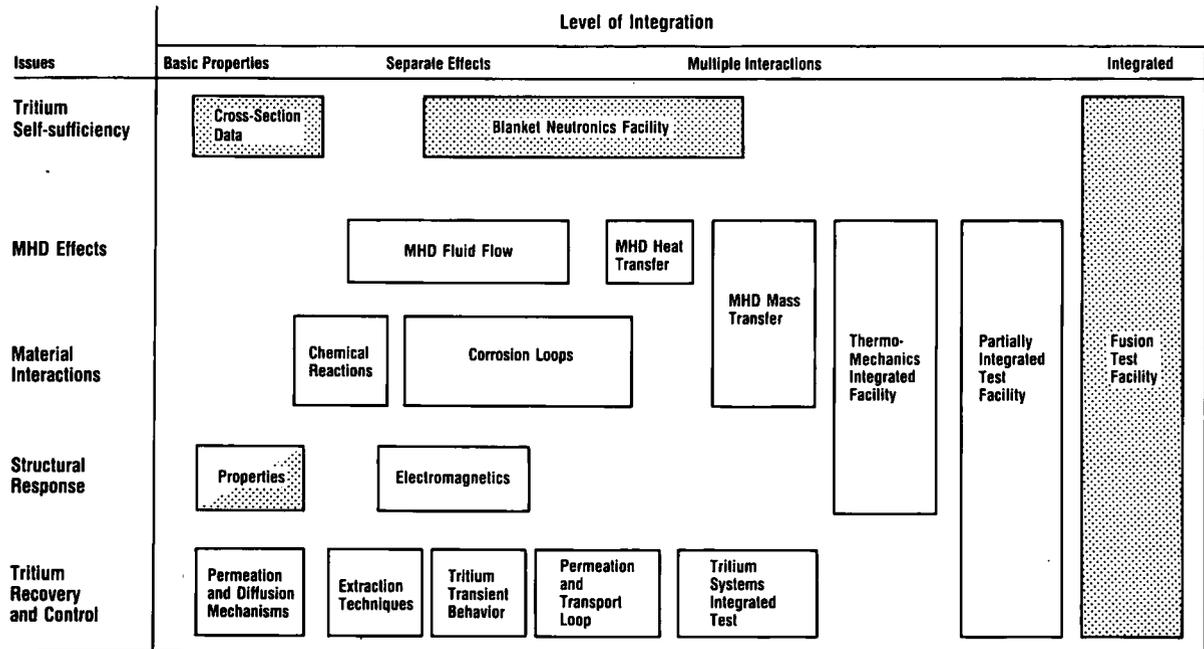


Fig. 7. Solid breeder blanket test plan.



^aSome experiments or facilities already exist

Neutron test.

Fig. 8. Types of experiments and facilities for liquid metal blankets^a.

effects, dependence on magnetic field, and methods of controlling corrosion/mass transport. At a later stage, experiments with strong magnetic fields will also be needed to explore the effects of magnetic fields on mass transport. A particular facility, called the MHD Mass Transfer Facility (MHDM) was defined for the purpose.

Needed experiments related to tritium recovery and control cover varying levels of integration and are concerned with: (1) measurement of basic properties and mechanisms, (2) development of tritium extraction techniques, (3) measurement of tritium permeation and transport in the coolant loop, and (4) integration of extraction and tritium processing systems. Blanket neutronics experiments are required in order to establish tritium self-sufficiency for liquid breeder blankets. However, the uncertainty in tritium self-sufficiency for most liquid breeder blankets is much less than for solid breeder blankets and this issue is less critical.

The major uncertainties in structural response include material behavior under irradiation, mechanical response under complex loading conditions, and failure modes. Structural response under complex loading conditions can be addressed, to a large extent, by the

MHD-effect experiments since most of the loading condition uncertainties involve magnetic field effects. However, fully adequate testing involving the integrated effects of irradiation, material choices, configurations and correct loading conditions requires a fusion test facility.

Beyond the first 5–10 y of testing, experiments will become progressively more integrated as they treat a larger number of environmental conditions and components resembling actual reactor blankets. Two types of tests with different missions have been considered for providing concept verification engineering data. The first is a Thermomechanical Integration Facility (TMIF), whose aim is to aid in the selection of a small number of leading configurations and to begin to develop empirical relations describing the global blanket behavior. It would test the combined influence of heat, mass and momentum transport issues as well as some structural issues in a non-neutron environment. Another type of facility is the Partially Integrated Test Facility (PITF), which would be a full or near-full scale test which simulates all environmental conditions except neutrons. In addition to the blanket, the primary cooling system, chemical control systems, and tritium

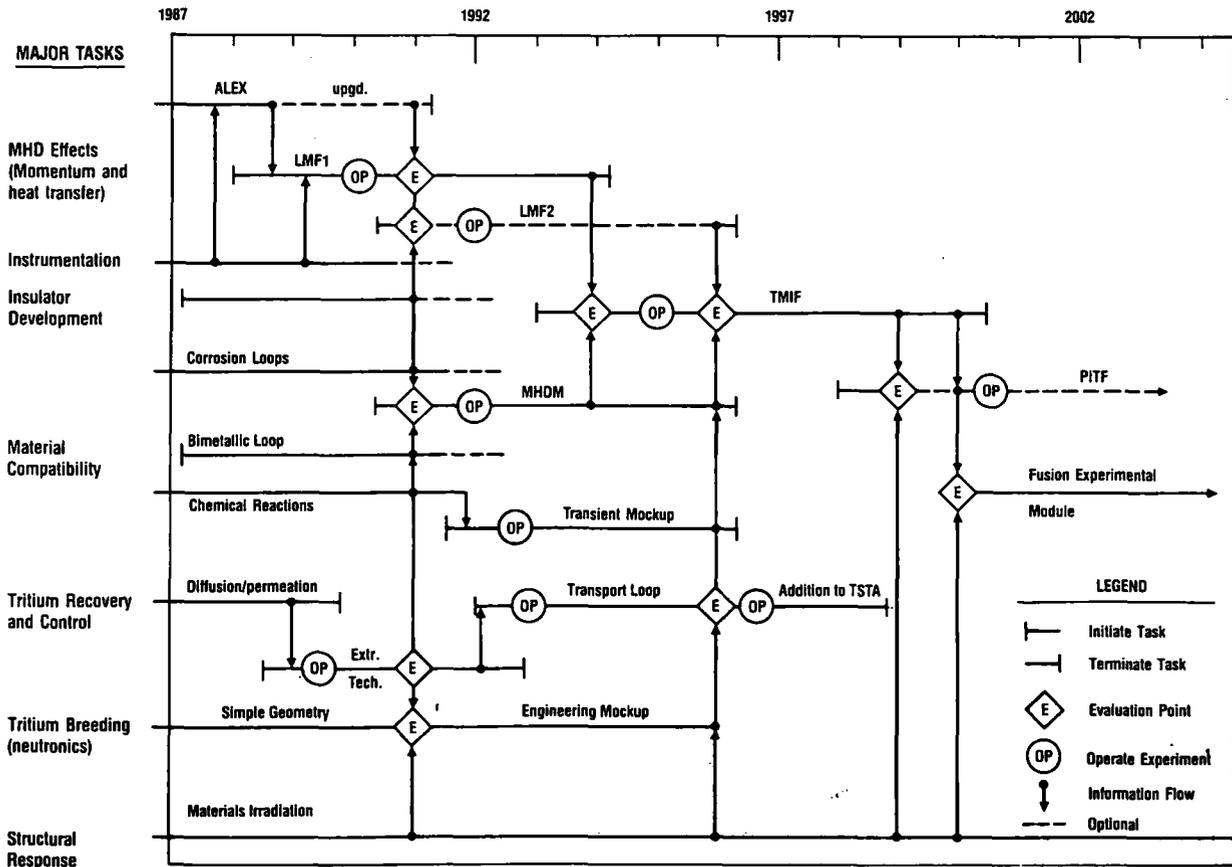


Fig. 9. Liquid breeder blanket test plan.

extraction system would be present. Since PITF has characteristics similar to the TMIF, it could be built as an upgrade to that facility.

A test plan, similar to the one for the solid breeder blanket, has also been developed for the liquid breeder blanket. The same phasing is used, with the three early phases leading up to fourth and final phase of fusion testing for prototypic blanket test modules under full fusion conditions around the year 2000. Fig. 9 shows the test plan. The first phase (0–10 y) includes a variety of MHD fluid flow tests, material compatibility loops, and tritium recovery and tritium breeding experiments in simple geometries. In the second phase (5–15 y), more integrated facilities such as the TMIF are initiated and more advanced experiments on tritium recovery and control are performed. In the third phase (10–20 y), partially integrated tests will be carried out to verify prototypic designs under non-fusion conditions and finally, in the fourth phase, integrated testing will be done under full fusion conditions.

5. Summary

A number of blanket uncertainties exist, ranging from basic material properties under irradiation to highly interactive phenomena involving several materials, components and/or environmental conditions. These uncertainties include several material-oriented issues such as corrosion of structure by liquid metals, tritium recovery and thermomechanical behavior of solid breeders, and tritium permeation rates.

These blanket uncertainties can be addressed in a

range of experiments from separate-effect experiments with simple geometries and limited number of environmental conditions, to more integrated multiple interaction experiments involving more complex geometry, to fully integrated fusion testing. Test facilities needed to investigate these uncertainties also range in complexity according to the experiment, from simple bench-top experiments, to large non-nuclear tests, fission reactors and point neutron sources, and fusion test facilities.

Based on quantifying the technical requirements for these experiments and facilities, test plans have been developed for both the solid breeder and the liquid breeder blankets for a desired timescale. It provides a method for focusing the research effort and defines a planning framework which spans the entire time period from the present to the time when a decision can be made on the ultimate attractiveness of fusion.

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