11TH SYMPOSIUM FUSION ENGINEERING

PROCEEDINGS

Volume 2

November 18-22, 1985
Austin, Texas

EDITORIAL STAFF
Jennifer Evans
Dianne Jones
D. Cheryl Wilkins
Center for Fusion Engineering
The University of Texas at Austin

SPONSORS
Institute of Electrical and Electronics Engineers
The University of Texas at Austin
U.S. Department of Energy
Electric Power Research Institute
American Nuclear Society
Texas Atomic Energy Research Foundation

FUSION NUCLEAR TECHNOLOGY EXPERIMENTS AND FACILITIES

M. A. Abdou, P. J. Gierszewski, and M. S. Tillack
Mechanical, Aerospace, and Nuclear Engineering Department
University of California
Los Angeles, California 90024

Fusion nuclear technology poses critical issues related to feasibility, economics, safety and environmental impact of future fusion reactors. Resolving these issues requires a careful plan of experiments and facilities. The types of experiments and the environmental conditions that must be provided in these experiments have been assessed. The capabilities and limitations of existing facilities and the need for new facilities have been evaluated.

Introduction

Technical planning of experiments and facilities is an important activity in the development of a complex technology. A methodology has been developed for the planning of experiments and facilities for fusion nuclear technology (FNT), referred to as the FINESSE process. The primary input to the process is a set of promising design options and the major output is a technical test plan that identifies and quantifies the role, timing and characteristics of major experiments and facilities. The process, as shown in Fig. 1, consists of four primary elements: 1) characterization of issues, 2) quantification of experimental needs, 3) evaluation of facilities, and 4) development of a test plan. The process has been applied to a number of FNT components, with emphasis on the blanket and first wall.

In order to generate the data and models needed to judge the feasibility and attractiveness of FNT components, a number of experiments must be performed in new and existing facilities. There is a general need for basic measurements, including irradiated properties of materials. Non-neutron test stands are most suited for exploration of liquid metal blanket phenomena and there is a need for new facilities to address momentum, heat and mass transport issues. Fission reactors can provide the volumetric bulk heating, radiation damage and transmutation necessary to address many of the solid breeder blanket issues. Concept verification requires integrated tests in the fusion environment.

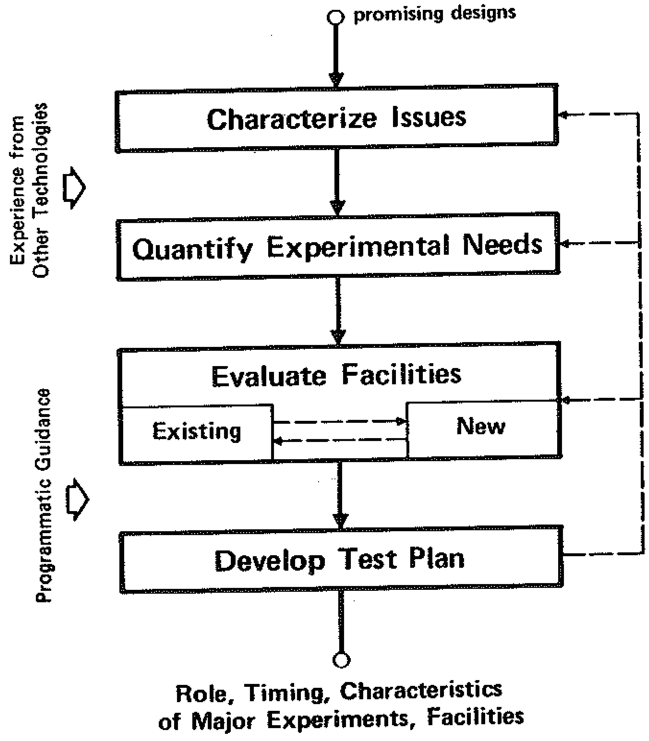

Figure 1 The FINESSE Process for Experiment Planning

This paper provides a summary of the required experiments and facilities for the blanket/first wall subsystem. Further details are provided in Ref. 1. Issues, experiments, and facilities for other fusion nuclear components are also discussed in Ref. 1.

Issues and Testing Needs

Key fusion nuclear issues have been identified and characterized in FINESSE. The issues have been classified according to their potential impact, level of concern, and importance of operating environmental conditions such as neutrons and magnetic field. A range of generic design concepts for liquid metal and solid breeder blankets were considered with reactor parameters and conditions typical of those for tokamaks and mirrors.

Achieving tritium fuel self-sufficiency requires that the achievable tritium breeding ratio be greater than the required breeding ratio. The latter suffers from uncertainties related to performance of plasma (e.g. tritium fractional burnup) and technology components. The uncertainties in the achievable breeding ratio are more serious for solid breeder than liquid metal blankets.

The major issues for liquid metal blankets include: 1) MHD effects, particularly on fluid flow characteristics, pressure drop, and heat transfer; 2) compatibility, e.g. corrosion of structural materials by liquid metals and strong reactivity with air and water; 3) structural response under irradiation; 4) tritium extraction and control; and 5) failure modes and effects.

In addition to tritium self-sufficiency, the major issues for solid breeder blankets include: 1) tritium recovery and inventory; 2) solid breeder temperature window and control; 3) irradiation effects on structure, breeder, and multiplier; 4) thermal and mechanical interactions among breeder, structure, mul-

Table 1 Critical Issues for Blankets

liquid metal	solid breeder
• MHD effects	• tritium recovery & inventory
• compatibility	• temperature window & control
• structural response under irradiation	• irradiation effects on structure, breeder, multiplier
	• thermomechanical interactions

- tritium fuel self-sufficiency
- tritium extraction and control
- failure modes and effects

tiplier and coolant; 5) tritium control; and 6) failure modes and effects.

Resolving the above issues requires a carefully planned program of experiments supported by theory and model development. In FINESSE, both the type of experiments and the environmental conditions that must be met in these experiments to resolve the key issues have been addressed.

The type of experiments required can be classified into: 1) basic; 2) separate effect; 3) multiple effect, multiple interaction; 4) partially integrated; and 5) integrated tests. Basic tests are designed to obtain property data. Separate effect experiments are performed to understand basic phenomena. Multiple interaction/multiple effect tests are aimed at exploring the combined benefits of two or more environmental conditions and the interactions among two or more physical elements of a component. In integrated tests, all environmental conditions and physical elements of the components are simulated, but not necessarily at full size scale. The purpose of integrated tests is to verify concepts and to obtain engineering design data.

The required experiments and facilities have been organized according to the classes of issues they resolve and their level of integration. Figures 2 and 3 show the matrices of tests required to fully address the key issues for liquid metal and solid breeder blankets respectively, including a number of experiments which are already in progress. A test matrix represents a complete list of major experiments which are desirable, but all of them will not necessarily be performed. Depending on funding constraints, choices of blanket materials and configurations, results of prior experiments, and time-dependent testing goals, only some of the proposed experiments may actually be performed. In addition, a complete testing program designed around these major experiments may include a number of smaller experiments and a complementary theory development program. The logic behind these choices is discussed elsewhere.[1]

Liquid Metal Blanket Experiments and Facilities

Liquid metal blankets include several generic design variations and materials combinations. The existance and seriousness of the major issues vary considerably between blanket concepts and expected operating conditions, such as power density, magnetic field, and surface heat flux. Generic issues have been defined to encompass the most promising blanket designs being considered today. These include MHD effects, thermomechanical response under irradiation, tritium extraction and control, DT fuel self-sufficiency, and safety. In the following, the existing and required experiments are briefly reviewed for each type of experiment - basic, separate and multiple effects, partially integrated, and integrated tests.

Basic Materials Data

Most basic unirradiated materials data is known accurately enough to judge the feasibility of the blanket, although the required accuracy for design purposes may be greater. A major exception is lithium-lead eutectic, for which several basic thermal, physical, and chemical properties are unknown.[1] Facilities for performing unirradiated properties measurements generally exist and the experiments themselves are not usually complicated.

The state of information on irradiated properties

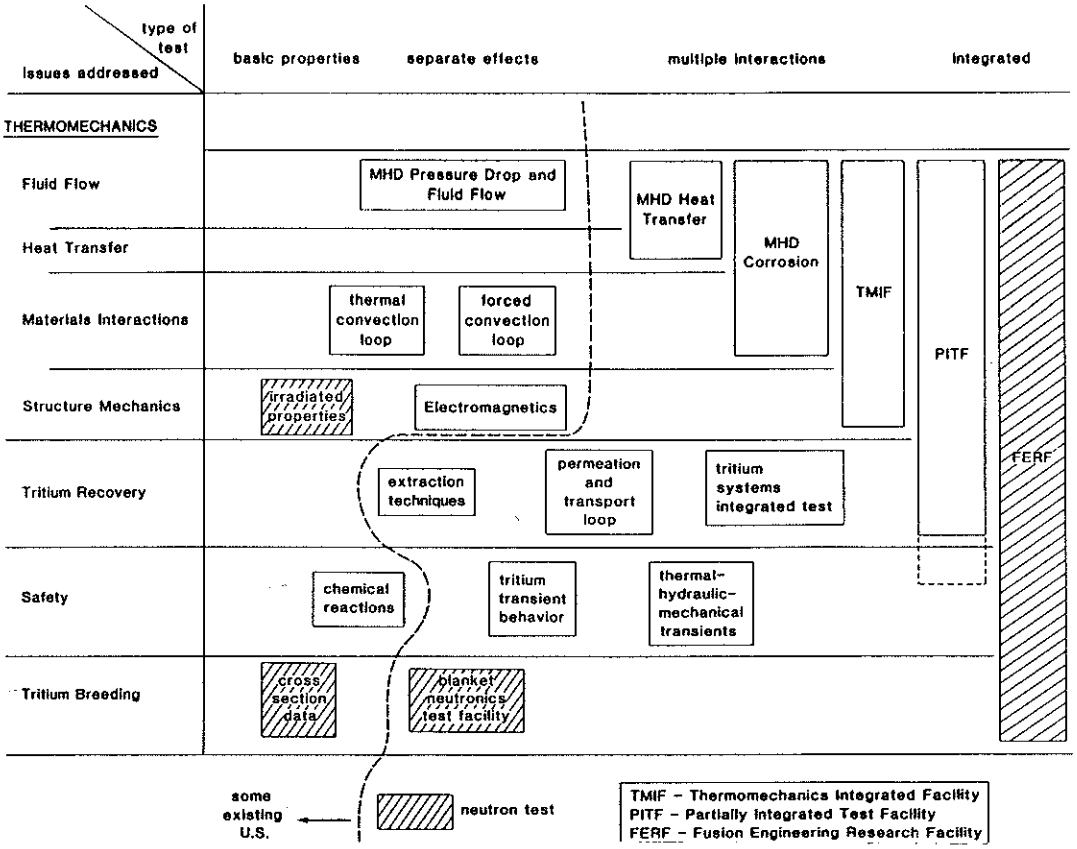

Figure 2 Test Matrix for Liquid Metal Blankets

is far worse; however, an organized materials development program (ADIP) exists for structural alloys. Data currently being accumulated includes swelling, creep, loss of ductility, and others. Facilities specifically devoted to high fluence irradiation measurements are not anticipated within the next 5-10 years. However, many experiments can be performed in existing fission reactors if spectral and isotopic tailoring, and other techniques for improving He/dpa ratios are applied. The first benchmark test of materials in a 14 MeV spectrum might not occur until a fusion test facility is constructed.

In addition to mechanical and thermophysical properties, there is also a need to refine neutron cross-sections for some materials - particularly at high energy - in order to improve predictions of tritium breeding, volumetric heat deposition, and transmutation rates.

Separate Effects and Multiple Interactions

Phenomena which determine the overall component behavior - such as heat transfer, mass transfer, tritium transport, and structural behavior - are also important in defining the existance and extent of a design window. The uncertainties in the individual phenomena are large for liquid metal blankets; when these individual uncertainties are considered together with interactive effects, the overall level of uncertainty can easily rule out present liquid metal designs.

MHD Effects: The largest uncertainties in liquid metal blankets relate to MHD, including effects on velocity profiles, heat transfer, pressure drop, and mass transfer. MHD effects are present to some extent in most designs, but are most critical for self-cooled uninsulated designs. Experimental data on MHD fluid flow and pressure drop under fusion relevant conditions are very scarce.

The principal element in the current U.S. MHD program is the ALEX facility, which is expected to provide information on single channel pressure drops and velocity profiles in straight channels, bends, and magnetic field entrance regions. Further experiments with more complex design geometries and with improved scaling to fusion reactor conditions will be necessary in order to develop an ability to predict fluid flow and pressure drop behavior in some self-cooled blanket designs with more complex flow paths.

One of the primary consequences of MHD effects on velocity profiles is altered heat transfer characteristics. MHD heat transfer can be predicted if the velocity profiles are sufficiently well known, but in some designs the velocity profiles may not be entirely predictable. In this case, it will be necessary to empirically verify the actual temperature profiles which exist. The need for a MHD heat transfer experiment depends on both the results of fluid flow experiments and on design selection.

Materials Interactions: Materials interactions phenomena include both mass transfer and structural changes due to interactions between the coolant, breeder, and structural materials within the primary cooling loop. Compared to heat transfer and fluid flow, additional environmental conditions are important, such as materials, impurity levels, absolute temperature, out-of-blanket geometry, and long term exposure. Because of the complexity and materials dependence, general models for predicting materials interaction phenomena will likely be deficient. Thus, a number of experiments will be needed to develop correlations and empirically bound the expected behaviors under relevant temperatures, impurity levels, etc.

A small number of thermal convection and forced convection corrosion loops already exist in the U.S.; however, the amount and depth of the data is insufficient to adequately establish the temperature and impurity levels required to meet minimum lifetime standards for fusion structural materials. More corrosion loops will be required for thorough studies of fusion relevant materials, especially for refractory metals and bi-metallic systems.

The presence of a strong magnetic field may significantly alter mass transfer in certain materials systems due to its dominating influence on the fluid hydrodynamics inside the blanket. Consequently, corrosion experiments under a magnetic field, called MHD corrosion experiments, may be required.

Structural Mechanics: Structural issues involve uncertainties in both the loading conditions and the response to those loads. The principal loading conditions include pressure stresses, thermal stresses, electromagnetic forces, and radiation swelling. Many of these are already considered in the test matrix, except for electromagnetics. Currently, the major U.S. facility for electromagnetics testing is FELIX, which complements testing in existing and planned confinement experiments.

Many of the issues relating to structural behavior are dominated by the materials response under irradiation. These issues can be partially addressed in small, subscale test elements placed in fission reactors and other available neutron sources. The most desirable test facility for structural response issues is clearly a fusion reactor, in which the fluence, spectrum, and key thermomechanical conditions can all be achieved simultaneously.

Tritium Recovery: At present, tritium recovery is considered a critical issue for LiPb, but not for lithium. Acceptable extraction schemes have been proposed for lithium (for example, molten salt extraction), although experimental verification is still required. For LiPb, the tritium solubility is so low that high partial pressures exist, which may result in unacceptable tritium permeation and release rates. An extremely high required extraction efficiency is required, but not yet convincingly demonstrated. This is further complicated by a general lack of tritiu-related data in LiPb.

Safety: Safety is listed as a separate issue, however it can also be considered an aspect of all other issues. In cases where it is possible, experiments should be run under transient and off-normal conditions to gather data relevant to safety analysis, including predictions of probabilities and consequences. It is only in cases for which the presence of safety issues would endanger or otherwise grossly complicate the experiments that a separate test must be performed. These unusual circumstances exist for hard transients, chemical reactions, some tritium behavior (e.g., transient tritium release), and radionuclide release. The need for separate safety facilities depends to a large extent on the design of the other tests in the test matrix.

Tritium Breeding: Tritium breeding is not usually considered a feasibility issue for liquid metal blankets. Self-cooled designs show the highest breeding ratios of any blanket design, but in separately cooled designs, the breeding margin is much smaller. Partial coverage may be required in some reactor designs (such as the tokamak inboard side), which would result in poor breeding characteristics. The uncertainties in tritium self-sufficiency can be reduced through a program of cross-section measurements, integral neutronics experiments, and numerical code improvement. The primary experimental vehicle for tritium breeding experiments is the point neutron source. A cooperative program with Japan is currently in place in the area of neutronics, using the JAERI Fusion Neutron Source (FNS).

Partially Integrated and Integrated Experiments

Fully integrated testing in the fusion environment will be a costly step in the development of fusion nuclear components. In order to maximize the availability of the fusion device and the benefit of fusion testing, it may be cost effective to build a small set of partially integrated experiments first. This class of experiments is intended more as concept verification, rather than phenomena exploration (as with separate and multiple effects experiments). For liquid metal blankets, the omission of neutrons results in large cost savings, with many of the critical issues still addressed.

Partially integrated tests with different missions have been considered. Since their operation would occur after 5-10 years of more fundamental testing, it is difficult to anticipate the exact features of the facilities. A thermomechanical integrated test is one particularly attractive concept. It combines thermal, hydraulic, materials, and structural issues in a system which includes the blanket, chemical control systems (inhibition and impurity control), primary cooling system components, and possibly even the tritium extraction systems.

Solid Breeder Blanket Experiments and Facilities

The issues and testing needs for solid breeder blankets differ from liquid metal blankets in several important respects. First, there is a much wider range of possible materials to consider. Secondly, the influence of geometry on the primary uncertainties is not as important and there are only a limited number of basic forms - breeder-outside-tube, breeder-inside-tube and plate. Thirdly, the behavior and the issues are dominated by the effects of radiation. And fourthly, much of the important functional behavior of the solid breeder is not described by classical equations, but rather the controlling phenomena must be determined by experiments. The major testing needs are briefly discussed below.

Materials Development and Characterization

The basic material in solid breeder blankets is a tailored material, since a wide variety of lithium-bearing compounds can be formed. The development of a suitable material involves more than choosing between the known materials such as Li_2O or $LiAlO_2$. A variety of compounds have been or are under consideration, including also silicates, zirconates, titanates and beryllates. More complex combinations can also be considered. The characteristics of the material are important, including grain size, porosity and pore size, sphere-pac or sintered form, and impurity or additives content. The result is that there is a large range of materials variables that can be explored. The development of suitable materials is a significant and near-term task, with a larger investment in time and manpower than in equipment.

Although some solid breeder blankets may not need a multiplier, the breeding margin is generally small compared to the uncertainties and will probably not be resolved until fusion device testing. It is prudent to assume that some multiplier will be needed. While beryllium is the preferred material, the form of incorporating it into the blanket is uncertain (e.g., separate or mixed with breeder). Questions related to mechanical behavior, tritium retention and compatibility with the breeder need to be resolved, and again the material characteristics affect the behavior.

The structural material options include primarily austenitic and ferritic steels; the development program was described in the liquid metals section. The possible use of high-temperature refractory materials depends on the development of suitably compatible alloys and an understanding of the acceptable interface conditions.

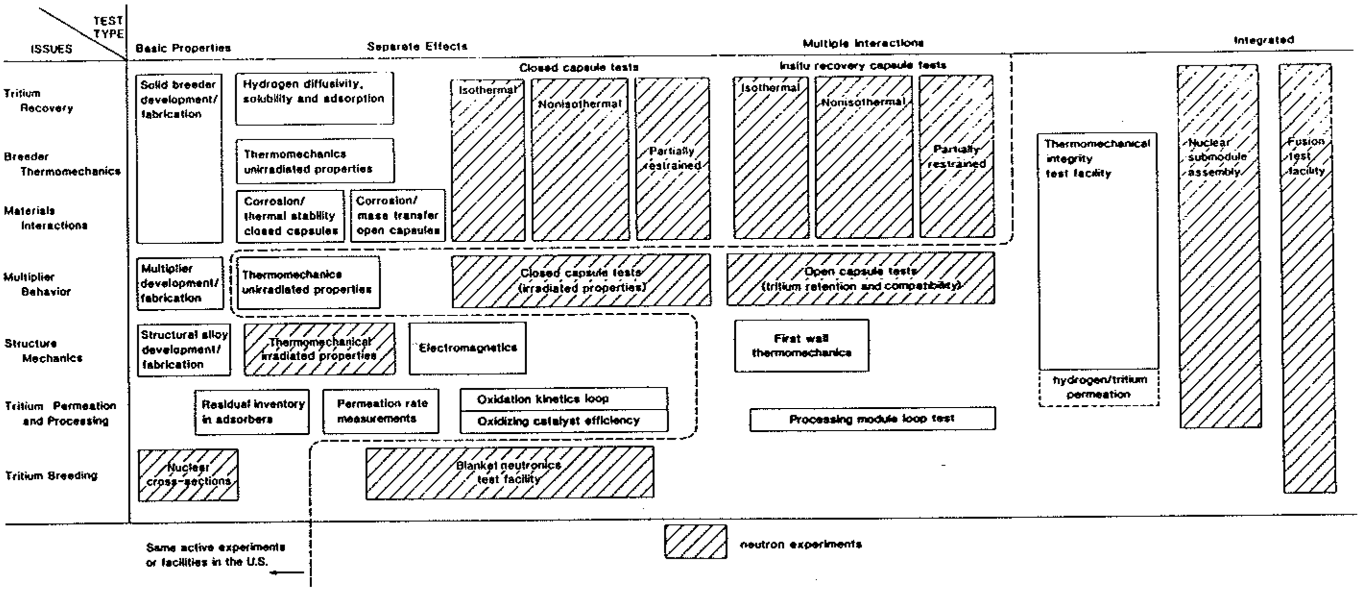

Figure 3 Test Matrix for Solid Breeder Blankets

Separate Effects and Multiple Interactions

The selection of the appropriate materials will depend largely on the results of separate effect and multiple interaction experiments, which explore and quantify the phenomena occuring in the material. Small open or closed capsule tests, many with radiation effects, will be needed to address the issues. Larger module-related geometry effects are not important for differentiating among the materials.

Tritium Recovery: Compared to liquid breeders, solid breeders offer the potential for adequate tritium production with much reduced chemical reactivity. However, the difficulties in extracting a gas from an irradiated solid make this the primary feasibility concern for solid breeders.

The needed data includes the basic tritium transport properties of diffusivity, solubility and surface adsorption. These measurements can be performed on unirradiated (or pre-irradiated) specimens using relatively standard equipment. However, accurate measurements of these properties requires careful characterization of the material and calibration and operation of the experiment.

The most important tests involve irradiation to provide internal tritium generation, heating and fluence effects. These can be either closed or open capsule tests, using (essentially) isothermal specimens, pellets large enough to support reactor-relevant temperature gradients (or to achieve peak temperatures that could not be supported in contact with the container walls), and/or pellets with significant mechanical interactions with the container walls. The importance of an actively-controlled flowing gas environment has been demonstrated in recent experiments such as TRIO, however closed capsule experiments are cheaper and have proved useful for providing scoping data and irradiated specimens for subsequent properties measurement.

A number of such tests are presently underway, including FUBR-1 (closed) in the US; VOM (open) in Japan; CREATE (closed) and CRITIC (open) in Canada; and LILA (open), LISA (open), ALICE (closed), DELICE (closed) and EXOTIC (closed) in Europe. These tests will explore a range of temperatures, temperature gradients, materials (primarily Li_2O, $LiAlO_2$, and some silicates and zirconates), material characteristics (grain size, porosity, form, impurity content, fabrication process), container material, burnup and sweep gas composition and flow rate. As a result of these tests, a fairly wide-ranging data base will be available around 1990. This data will support modeling of solid breeder behavior and selection of a much more limited set of materials and material characteristics to form the basis for subsequent research.

However, the planned tests will not address the combination of high burnup with a flowing purge gas under temperature gradients and breeder/clad interactions. Although these effects will be considered to some degree separately, synergistic effects and modeling inadequacies will make extrapolation to this reactor-relevant combination uncertain. Consequently, the next major class of tests should address these concerns. Such advanced in-situ tritium recovery experiments could still be performed with relatively small capsules, allowing multiple specimens at a given site or a distributed set of tests at different irradiation facilities. The importance of achieving significant burnup while limiting self-shielding in a fission reactor neutron spectrum leads to relatively long irradiation times. Consequently the test facilities must be high flux and have enough test volume to be able to dedicate the space for the duration of these tests.

Breeder Thermomechanics: Although unirradiated tests of mechanical properties can be performed relatively easily with standard equipment, the important breeder/clad interactions and breeder thermomechanical behavior are affected by radiation (swelling, creep) and larger geometrical/operating effects (settling, cyclic cracking). The radiation effects can be determined in the same tests as those monitoring tritium recovery described above. Some scoping tests with temperature gradients and breeder/clad interaction are underway (e.g., FUBR-1B). However, some closed capsule tests dedicated to thermomechanical effects might be performed in order to allow complete instrumentation (e.g., thermocouples distributed inside the solid breeder) and to provide scoping data to plan more complex in-situ recovery tests.

Materials Interactions: Although there are no major chemical reactivity concerns, temperature limits will exist based on materials interactions leading to changes in composition, mechanical integrity or mass transfer. The associated experiments involve long-term tests of relevant materials and impurities at temperature, which is the conditions in many of the tritium recovery experiments (including those presently underway). However, for new and/or more reactive materials, separate unirradiated testing at temperature for long-time periods may provide cost-effective data to judge the feasibility of the material or to provide well-defined test conditions for model development. Possible examples include mass transfer within and from Li_2O in a purge stream with hydrogen, the thermal stability and clad compatibility of lithium beryllates, and the interaction kinetics of beryllium with solid breeders.

Multiplier Behavior: For beryllium or other solid multipliers, the mechanical behavior and tritium retention are significant uncertainties under reactor conditions. Experiments to address these would include unirradiated properties measurements, and irradiated closed and open capsule experiments as with the solid breeder material. Fission reactors such as FFTF can provide reactor-relevant simulation of the helium and tritium production in beryllium. The safety costs associated with the chemical toxicity of beryllium powder should constrain the number of locations which can provide fabrication and testing capabilities. It may be noticed from Figure 3 that there is relatively little work presently planned or underway on multipliers, either in the US or elsewhere (other than neutronics).

Structure Mechanics: Many of the issues associated with structural behavior can be addressed by determining the irradiated properties of the materials through specimen tests in suitable irradiation facilities. The modeling basis for structural behavior is reasonably well-established from the fission (and breeder) program, although some further model development is needed to provide simpler design tools, for particular phenomena or to establish design limits.

Separate unirradiated experiments could usefully address electromagnetic effects (such as steady-state forces on ferritic steels or transient forces on any alloy) and the behavior of the first wall under high heat flux and cycling conditions. In the long-term, full geometrical effects need to be verified by operation of submodules and/or full modules under reactor-relevant temperatures, pressures and irradiation effects. These more integrated tests are discussed later.

Tritium Breeding: The tritium breeding uncertainties range from cross-section uncertainties (particularly ^{7}Li at higher energies), to the achievable tritium breeding ratio and heating profile in blankets. The more important questions at present require the measurement of neutron spectra and reaction rates (tritium, heating, transmutations) under progressively more relevant blanket geometries to provide for verification of the cross-section data, data libraries and neutronics analysis techniques. A well-calibrated 14-MeV neutron source is important, although high fluence is (fortunately) not. Existing facilities such as the Fusion Neutron Source in Japan are able to address the major issues, and the present US/JAERI cooperative agreement should allow addressing these issues to the extent possible in a non-fusion test facility.

Tritium Permeation and Processing: Uncertainties associated with controlling tritium permeation and in recovering the tritium efficiently from the purge stream are not as critical as other issues but are still important. Many of the issues associated with inventory, permeation rate and oxidation kinetics can be addressed in separate glove-box-scale experiments. The use of tritium provides finer accuracy, which may be particularly important for addressing issues at the low tritium partial pressures relevant to some applications. Processing system loop tests (including molecular sieves, oxidizers, getters, etc.) can be performed with reactor-relevant modules to explore holdup, efficiency, cycling and general operations. This still leads to a reasonably small-sized experiment because of the modularity and size of the components.

Partially Integrated and Integrated Experiments

Three classes of more integrated tests can be considered for providing concept verification information: non-nuclear, non-fusion nuclear and fusion based tests. Only a fusion device can provide fully integrated testing.

The non-nuclear thermomechanical tests involve heat sources such as microwaves and resistive wires to simulate bulk heating, and particle beams or radiant arcs for surface heating. The tests can range in size from single unit cells to full blanket modules. Although there are clearly limitations on the ability to simulate reactor heating profiles and irradiation effects, these tests provide an opportunity to explore complex thermomechanical behaviors (e.g., gap conductance, flow distribution, thermal cycling), to benchmark design codes, and to study severe transients. The ability to perform such tests in irradiation facilities is limited by available test volume, by the costs of irradiation tests, and by reactor safety constraints. The value of non-nuclear large-geometry tests is dependent on the degree to which geometrical details have been defined, on the importance of the related issues, and on the extent of the planned nuclear experiments.

Nuclear test assemblies designed for fission reactors (assuming no large point source is built in the next 15 years) would also provide concept verification information. These would include the important nuclear effects but be limited in several respects, primarily test volume. A full-blanket module test would need about 1 m^3 of test volume, require extensive modifications to any operating fission reactor core, and still only achieve the equivalent of (at most) a 1 MW/m^2 heating rate. In-core assemblies could be placed in existing fission reactors like FFTF at reactor-relevant heating rates (2-5 MW/m^2), but would be limited to about 10 cm diameter. These would provide a reasonable amount of concept verification prior to fusion testing.

Fusion Integrated Testing

Some issues simply cannot be tested outside the fusion environment, such as failure modes, reliability, and some thermomechanical interactions under irradiation. In addition, most issues are affected in some way by the combination of all relevant environmental conditions. Without fusion testing, the risk in proceeding to a high availability reactor experiment is very high.

The minimum requirements for scaled fusion testing have been estimated by analyzing the behavior of representative blankets and are given in Table 2.

Table 2 Requirements for fusion integrated testing

Parameter	Reference reactor	Minimum
Neutron wall load (MW/m^2)	5	1
Surface heat load (MW/m^2)	1	0.2
Fluence (MW/yr-m^2)	15-20	1-2
Test port size (m^2 x m deep)	—	0.5 x 0.3
Total test surface area (m^2)	—	5
Plasma burn time (s)	Continuous	500
Plasma dwell time (s)	None	< 100
Continuous operating time	Months	Days
Availability (%)	70	20
Magnetic field strength (T)	7	1

Reference:

1. M. A. Abdou et al., "FINESSE Phase I: Technical Issues and Requirements of Experiments and Facilities for Fusion Nuclear Technology", UCLA, to be published.