Paper submitted to 6th Topical Meeting on the Technology of Fusion Energy, San Francisco, March 3-7, 1985.

IDENTIFICATION AND CHARACTERIZATION OF THE KEY ISSUES OF FUSION NUCLEAR TECHNOLOGY[a]

M. Tillack, M. Abdou, P. Gierszewski,[b]
K. Kleefeldt,[c] Y. Seki[d]
University of California, Los Angeles, CA

D. Berwald, W. Steele
TRW, Inc., Energy Development Group, Redondo Beach, CA

J. Davis, D. Morgan
McDonnell Douglas Astronautics Co., St. Louis, MO

G. Deis, S. Piet
EG&G, Inc., Idaho Falls, ID

G. Hollenberg, J. Straalsund
Westinghouse Hanford Company, Richland WA

Y. Liu
Argonne National Laboratory, Chicago, IL

DRAFT
Submitted February 1985

[a]Work supported by U.S. Department of Energy under contract DE-AM03-76SF00034.
[b]On attachment from the Canadian Fusion Fuels Technology Project.
[c]On leave from Kernforschungszentrum Karlsruhe GmbH (IRE), FRG.
[d]On leave from JAERI Fusion Research Center, Japan

IDENTIFICATION AND CHARACTERIZATION OF THE KEY ISSUES OF FUSION NUCLEAR TECHNOLOGY[a]

M. Tillack (UCLA), M. Abdou (UCLA), D. Berwald (TRW), J. Davis (MDAC), G. Deis (EG&G), P. Gierszewski (UCLA/CFFTP), G. Hollenberg (HEDL), K. Kleefeldt (UCLA/KfK), Y. Liu (ANL), D. Morgan (MDAC), S. Piet (EG&G), Y. Seki (UCLA/JAERI), W. Steele (TRW), J. Straalsund (HEDL)
University of California Los Angeles
6288 Boelter Hall
Los Angeles, CA 90024
(213) 206-1230

ABSTRACT

Fusion nuclear technology testing issues are reviewed, covering the technical disciplines of materials science, structural mechanics, MHD, thermal hydraulics, tritium recovery, and others. These issues represent the largest uncertainties whose resolution will require new knowledge through experiments, models, and theory in order to demonstrate the feasibility and attractiveness of the entire fusion nuclear system. Needed tests range in complexity, including basic materials property data, exploration of individual and interactive phenomena, and fully integrated tests. By addressing the complete array of testing issues, this work helps to define needed engineering research which should prove useful in future fusion program planning.

1. INTRODUCTION

Many uncertainties exist in the actual operation of present day fusion reactor conceptual designs. The expected consequences of these uncertainties vary greatly in magnitude: on one extreme the uncertainties are so large that the feasibility of the reactor design is at stake, and on the other extreme the uncertainties may simply reduce performance, increase cost, or require modest redesign. This paper summarizes the results of FINESSE[1] on the most important testing issues for fusion reactor nuclear components, including primarily those components listed in Table 1. In particular, the issues are characterized by the nature and magnitude of the uncertainties and the potential consequences for fusion reactor operation.

The issues serve to identify the testing needs which are also discussed here. These testing needs range from simple experiments for isolated issues to complex, integrated tests to examine the interaction of many different phenomena. The most critical issues

Table 1 Reactor Components Affected by the Nuclear Environment

1. Blanket
2. Plasma Interactive Components
   A. First Wall
   B. Limiter/Divertor
   C. Vacuum Systems
   D. RF Components (Auxiliary Heating)
3. Shield
4. Tritium Processing System
5. Magnets
6. Instrumentation and Control

dominate the determination of the required test conditions for integrated testing.

Generic examples of blankets were used to focus the effort to identify the issues. The number of blanket options was limited to liquid metal (Li and LiPb) and solid breeder (Li_2O and ternary ceramics) concepts. Other concepts (e.g., molten salt) are not likely to substantially change the test requirements for a fusion facility. However, they do need to be considered in determining near-term experimental programs.

Long term, integrated testing issues are the most difficult to define because near term experiments and analysis may result in the resolution of some issues or the elimination of certain blanket designs. The uncertainties we define today may no longer remain five or ten years from now. Special effort has been made to emphasize those issues thought to be generic or long-lasting.

In addition, most of the precise technical issues of fusion nuclear technology can only be understood in the context of the overall system operation, including the many interactions of phenomena and design trade-offs which

[a]Work funded under DOE contract number DE-AM03-76SF00034.

are involved. For example, in the liquid metal blanket, first wall thermal stresses are an important issue since they are a primary contributor to structural failures. The thermal stresses are a function of temperature distributions, which depend on velocity profiles and MHD eddy current paths, which in turn are strongly dependent on geometry and magnetic field. Structural failures are also affected by the primary stresses resulting from the MHD pressure drop, by materials properties changes due to irradiation, by cyclic operation, corrosion, plasma erosion, etc.

It is sometimes difficult to appreciate the importance of individual aspects of the overall behavior of the nuclear components, since their impact is inherently part of an interactive phenomenon. The only real issue for the reactor is the demonstration of tritium self-sufficiency and energy conversion at economical and safe conditions, i.e. thermal conversion efficiency, reliability, etc. At the same time, specific technical problems must be identified in a form which leads to well defined tests.

The issues are presented here in a general format with specific examples of the problems and interactions as we know them today. The general areas of concern are listed in Table 2.

Table 2. Critical Issues for Fusion Nuclear Technology Development

a. DT Fuel Cycle Self-Sufficiency

b. Thermomechanical Performance of Blanket Components under Normal and Off-Normal Operation

c. Materials Compatibility

d. Identification and Characterization of Failure Modes and Rates

e. Tritium Inventory and Recovery in the Solid Breeder under Actual Operating Conditions

f. Tritium Permeation and Inventory in the Structure

g. In-Vessel Component Thermomechanical Response and Lifetime

h. Radiation Shielding

i. Accuracy and Survivability of Instrumentation and Control

2. CRITICAL NUCLEAR TECHNOLOGY ISSUES

a. DT Fuel Cycle Self-Sufficiency

Fuel self-sufficiency is a necessary goal for fusion as a long-term, renewable energy source. Attaining fuel self-sufficiency in DT fusion reactors cannot be assured prior to resolving present uncertainties in both the required and the acheivable tritium breeding ratios, TBR.

The required tritium breeding ratio is uncertain due to lack of data and models to reliably predict the tritium behavior throughout the fuel cycle. One example of such uncertainties is the magnitude of the achievable tritium fractional burnup in the plasma. A low fractional burnup results in large tritium inventories in the plasma fueling and processing systems, and results in a high required TBR. The burnup fraction depends on the characteristics of the plasma and the impurity control and exhaust system, which presently are not well known.

Another example is the magnitude of tritium inventory in the blanket. Blanket tritium inventory is particularly uncertain for solid breeders for which there is a lack of adequate data, for example on tritium release and retention under irradiation. All of these effects result in uncertainties in determining the required excess in the tritium breeding ratio above unity.

The achievable tritium breeding ratio is also uncertain. Some of the uncertainties in the tritium production rate are due to alternatives in specifying reactor design choices, such as the type of impurity control and plasma heating system, and the details of material constituents, geometry, and other characteristics of the blanket and other components. Other uncertainties in the prediction of the acheivable TBR exist due to limitations in both neutronics computational methods and available nuclear data. For all the leading concepts, the estimated value for the achievable TBR does not have enough margin to cover present uncertainties in both the achievable and required TBR's.

b. Thermomechanical Performance of Blanket Components under Normal and Off-Normal Operation

The environment of a fusion reactor blanket is very demanding on materials and structures. This includes a combination of high temperatures, particle and heat fluxes, neutron irradiation, and high magnetic fields. These result in thermal and mechanical loads in all components under normal and off-normal conditions that must be kept within acceptable engineering limits. In addition, nuclear components must survive changes in these loads and in material properties for adequate life under the radiation environment. At present, there are large uncertainties in estimating both the various thermomechanical loads and the resulting response in blanket components.

Liquid metal blankets appear to have greater uncertainties than solid breeder blankets in this area. The most serious concerns arise from MHD effects, which couple the fluid and structural responses in a way that is very sensitive to geometry and which depends on magnetic and neutron fields. Many of the phenomena occuring in liquid metal blankets are new and virtually unexplored.

The principal problem with liquid metal cooled blankets is their ability to maintain the entire blanket within allowable temperature ranges. There is an upper limit imposed on the coolant flow rate due to the MHD pressure drop. In addition to large pumping powers required, a large MHD pressure drop leads to high pressure stresses in the structure which can contribute to structural failure.

Large uncertainties exists in the magnitude of the MHD pressure drop. Both experiments and well developed theories exist for simple geometries, such as a single channel in a uniform field, but many reactor designs contain geometrically complicated features which are poorly understood. If the pressure drop is significantly larger than the single channel estimates, then the ability of the liquid metal to remove heat is greatly reduced and the pressure stresses are increased.

In addition to the MHD pressure drop, the fluid velocity profiles are strongly affected by the presence of the magnetic field. The velocity profiles are critical in determining the heat and mass transfer characteristics of the blanket. If the velocity is not uniform, then the first wall or other surfaces in the blanket may be much hotter than predicted. This further limits the ability of the liquid metal to cool the structures.

The high temperatures normally present in liquid metal blankets result in high thermal stresses and also tend to reduce the mechanical properties of the structural materials. In addition to pressure stresses and thermal stresses, other sources of thermomechanical loading are present in both liquid metal and solid breeder blankets. Two of these which are poorly known include plasma disruptions and hot spots. Hot spots can occur due to poor coolant flow distribution, plasma variations, and nonuniformities due to in-vessel components and penetrations.

Plasma disruptions, and electromagnetic loads in general, cause currents to be induced in the structures. (In liquid metal blankets, the induced currents can flow in both the structures and the coolant itself.) The induced currents interact with the magnetic fields to induce electromagnetic pressures and pressure stresses. These forces are very difficult to calculate, as they depend strongly on the details of the structure. The most serious stresses are likely to occur near structural discontinuities. Furthermore, since plasma disruptions occur over a time scale of approximately tens of milliseconds, the impact loading can excite structural resonances which may further increase the stresses.

Besides body forces, plasma disruptions can cause thermal shock loading and possibly melting in the first wall and in-vessel structures. The thermal effects are difficult to predict, primarily due to the unknown temporal evolution and spatial distribution of the heat loads.

In solid breeder blankets, there are uncertainties in thermomechanical loading which are different from those in liquid metal blankets. These special concerns result from the higher coolant velocities, larger number of flow paths, and the relatively small channel dimensions. For example, the relatively complicated geometry in some blankets leads to uncertainties in flow distribution. When a large number of parallel flow paths are present and the flow rate is high, the flow may become unstable. Instability in the flow may induce vibrations in the structure in addition to causing hot spots.

Another concern in solid breeder blankets results from the sometimes small spacings between the structures. The flow distribution may be sensitive to small dimensional changes, resulting in localized hot spots.

For all blankets, large uncertainties exist in the structural response resulting from the complex loading conditions described above. The interaction of large primary and secondary stresses with irradiation effects such as creep and swelling is largely unknown. The first walls of some blankets are designed to operate with significant plastic deformations. It is allowable under ASME codes that secondary stresses exceed the yield stress, since they relax out after the initial loading. However, ASME codes do not deal with the special conditions present in a fusion reactor blanket. Time dependent responses to thermal and irradiation creep together with cycling are not well known, particularly for high cycle devices. Determination of allowable temperature and stress limits in the fusion environment represents a fundamental testing need.

In general, materials properties under irradiation have not been sufficiently well characterized. Although an extensive data base has been developed in fission reactors for some materials, there are many new materials which will be used in fusion reactors and the data at 14 MeV are scarce.

c. Materials Compatibility

All combinations of materials present compatibility problems to some degree, such as corrosion mass transport, degradation of materials properties, and chemical reactions. The selection of materials and determination of operating limits for selected combinations require new data and understanding of the interactions among candidate materials in the presence of the fusion environment.

One area of uncertainty is the effects of coolant, breeder, and purge on the structural material and its failure modes. Stress corrosion cracking in water cooled systems and embrittlement in liquid metal systems are two examples which may limit the lifetime and reliability of the blanket.

Other aspects of the fusion environment can alter the corrosion process in ways which are not presently understood. One good example is the influence of magnetic field on corrosion in liquid metal blankets. The velocity profiles near the walls can be very different than those normally encountered in nonconducting fluids. On the one hand, the magnetic field laminarizes the flow in liquid metals, which would be expected to reduce cross channel mass transport. However, the thickness of the boundary layer is simulaneously reduced at high magnetic field strength to values which are comparable to the mass diffusion boundary layer thickness.

The influence of these processes in the reactor blanket is very difficult to understand due to the simultaneous importance of the loop chemistry and temperatures.

Besides magnetic field, the radiation environment is expected to affect corrosion. For example, it is not certain how the combination of radiation-induced segregation and impurity interactions in the lithium-vanadium system combine to cause embrittlement. In a more indirect example of radiation effects, burnup products in Li_2O blankets are expected to be transported and interact with the cladding material.

One of the most important implications of materials selection is the safety risk and consequences. Some of the most serious risks associated with the blanket include: lithium and LiPb chemical reactions with air and water, structural material oxidation and volatility at high temperature (especially for vanadium), and activation, mobilization and transport of radioactive isotopes. Many of the experimental needs in this area are for basic measurements to aid in materials selection; however, after materials have been chosen, the need remains to investigate the safety related aspects of the design.

Materials compatibility plays an important role in the selection of materials and the blanket operating conditions. In some cases it represents a critical feasibility limit. Materials compatibility problems are generally resolved by imposing temperature limits; for example, to limit the corrosion rate and reduce the radioactive mass transfer and structure thinning to acceptable limits. At present, available data on corrosion of liquid lithium and lithium leads result in low temperature limits for steels. These limits rule out liquid metals with austenitic steels and provide only a narrow design window with ferritic steels. Therefore, reliable data on corrosion of structural materials by liquid metals in the fusion environment is a critical requirement to establishing the feasibility of liquid metal blankets. Similarly, adequate data is needed on the compatibility of breeder with the structure and tritium recovery fluid with breeder and structure for solid breeder blankets.

d. Identification and Characterization of Failure Modes and Rates

Knowledge of failure modes and rates is necessary in the research and development of engineering components because of their critical impact on economic potential and safety. There is virtually no data on failure modes and rates of the nuclear components in the fusion environment. Prudent selection of feasible and attractive designs is extremely difficult without such data. For example, pressurized water coolant/solid breeder blankets presently offer substantial savings in the capital cost of a tokamak reactor, but the primary issue with such blankets is whether the failure rates and modes can result in acceptable operational economics and safety.

Analysis has identified some possible failure modes; for example, those listed in Table 3. Most failures result from either cracking, melting, or plastic rupture. Experiments are required to examine these potential failure modes. However, the most important information from experiments is expected to be the identification of unforseen failure modes in the unique fusion environment. These unknowns place severe requirements on the test conditions, because it is not clear which environmental conditions are the most important.

Table 3. Anticipated Structural Failure Modes

Cracking Around a Discontinuity or Weld
Crack on Shutdown (with cooling)
Breeder Disintegration or Cracking
First Wall, Breeder, or Structure Excessive Deformation due to Swelling and Creep, Leading to Tube Failure
Cracking During Operation
Environmentally Assisted Cracking
Cracking on Start-up
First Wall, Structure, or Breeder Melting
Manifold Tube Breaks

e. Tritium Inventory and Recovery in the Solid Breeder under Actual Operating Conditions

Tritium inventory and recovery in the solid breeder is important for two reasons. First, as mentioned above, the feasibility of solid breeder blankets depends on whether or not they can breed enough tritium to satisfy DT fuel self-sufficiency conditions. The required breeding ratio increases with the breeder tritium inventory. Secondly, this tritium inventory may be a large safety risk, depending on its magnitude and mobility.

Uncertainties are very large; in some cases there are orders of magnitude of uncertainty associated with some of the tritium transport processes. These relate to both fundamental tritium transport mechanisms and to the actual behavior in the fusion environment, such as consequences of structural and breeder mechanical interactions. Within the solid breeder material, transport depends on intragranular diffusion, surface kinetics, and porosity. These processes are very sensitive to the fabricated microstructure and operating conditions, particularly the radiation environment.

The breeder temperature profile is particularly crucial because a relatively narrow window of operation is predicted, based on unreasonably high inventory at low temperature and sintering and materials properties changes at high temperature. Reliable data to accurately define these temperature limits does not exist.

There are several areas of uncertainty in the thermal behavior of solid breeder blankets which could have a large impact on the temperature window, include breeder/cladding gap size changes, swelling and creep interactions with the structure, thermal expansion, etc. In addition, there are materials and radiation effects in the solid breeder material which may alter the temperature and/or diffusivity, for example, thermal conductivity changes, cracking, and LiOT corrosion effects.

f. Tritium Permeation and Inventory in the Structure

Tritium permeation is primarily a safety concern, but the attempt to control it can have a large impact on design and operation. The problem is thought to be most critical for in-vessel components where tritium passes from the plasma chamber into the coolant streams. The magnitude of permeation depends on the plasma edge conditions, on trapping in the structure (which may depend strongly on irradiation), and on the effectiveness of techniques for controlling permeation such as coatings. In the bulk of the blanket, permeation can be significantly altered by the form of the tritium -- either gas or oxide -- and by the presence of protium (H_1). The form of tritium as it is released from the breeder is uncertain, as well as its chemistry and kinetics as it moves through the structure, coolant and purge streams.

Recently, concern has arisen over the mechanisms of tritium permeation at very low tritium pressure. Most estimates of tritium permeation rate are extrapolated from data at high tritium pressure. It is still uncertain whether the processes of diffusion, solubility, and surface reactions remain unchanged at very low pressure (10^{-10} atm).

In liquid metal blankets, the method of tritium extraction is closely related to the tritium permeation rate. Especially for LiPb, which is characterized by a very low solubility for tritium, the extraction process must be very efficient in order to minimize permeation in the primary coolant loop. At the same time, chemicals used in the extraction process must be well confined, since the presence of impurities in the primary coolant can seriously affect corrosion of the structures.

g. In-Vessel Component Thermomechanical Response and Lifetime

In-vessel components have special problems with thermomechanical performance in addition to those in the bulk blanket. In-vessel components include the first wall, limiters and divertors, RF antennas, beam dumps, and others. These special problems stem from the very high heat and particle fluxes that these components are exposed to under normal operating conditions, and from the potentially high thermal loads and electromagnetic forces under off-normal conditions.

Erosion and redeposition is one of the largest uncertainties. This issue has far-reaching implications on lifetime, failure modes, and design choices. Several surface damage mechanisms will influence in-vessel components, including physical sputtering, arcing, chemical/thermal erosion, and melting due to plasma disruptions. Plasma edge conditions are critical parameters in determining these processes. This area is linked to the plasma physics of the device, and therefore entails large uncertainties.

The structural integrity of in-vessel components is uncertain due to the high thermal stresses and presence of local hot spots (for example at the limiter leading edge). Bonds may be necessary if the surfaces are protected by coatings or composite structures. The structural response of these bonds is a particular concern.

h. Radiation Shielding

Shielding must protect both personnel and sensitive reactor components. Components with the most stringent protection requirements include superconducting magnets, some elements of plasma heating and exhaust systems (for example, RF windows or cryopanels), and instrumentation and control. Any component which must contain ceramics or any other material with a high sensitivity to radiation will also cause concern. In some cases, for example, the inboard region of a tokamak, the thickness and materials of the shield have substantial impact on the economics of the reactor. Establishing accurate radiation protection requirements is necessary, particularly for components whose shielding is either physically difficult or results in substantial economic penalty. This requires quantitative knowledge of the effect of radiation on components.

Sophisticated neutronics techniques exist for the prediction of the radiation field and associated nuclear responses. But uncertainties in accuracy remain due to modeling complexities, nuclear data uncertainties, limitations of calculational methods in void regions and deep radiation penetration problems, and time dependent behavior of materials and structures. For example, it is likely that components will deform during operation, which may lead to unpredictable streaming paths. Improvements in methods, data, and experimental verification of predictive capabilities are needed.

i. Accuracy and Survivability of Instrumentation and Control

Failure of instrumentation and control will have a negative impact on the safety and operation of the reactor. The vulnerability of these components depends to a large extent on radiation shielding as described above. However, because of the added effects of all of the environmental condition present in a fusion reactor (e.g., magnetic field), this category is considered as a separate issue. Instrumentation and control components often contain materials which are sensitive to radiation, electromagnetic effects, and corrosion. It is necessary in a number of key cases to develop new measurement techniques because presently available instruments will not function properly in high fields, with bulk heating, or in corrosive environments. In addition, innovative techniques for measurements related to new phenomena in the fusion environment are needed in order to obtain meaningful information from experiments.

3. FUSION NUCLEAR TECHNOLOGY TESTING NEEDS

The development of fusion to the commercial reactor stage will require resolving the many known issues, as well as the many presently unknown ones. The first step is to identify these concerns, the second is to identify the tests that are needed to resolve these concerns, and the third is to implement a test program to perform these tests. In this section, the fusion nuclear technology testing needs up to the engineering demonstration stage are identified.

The word "test" is used in the generic sense to mean a process of obtaining information through physical experiment and measurement - i.e., not through design analysis or computer simulation. A "testing need" refers to a need for a certain type of information that must be obtained through testing. There are different kinds of testing needs, including:

- developing a property data base (to allow quantitative predictions and quantitative modelling);
- understanding underlying phenomena (to make predictions, interpret component behavior, and allow design improvements);
- verifying component performance.

In FINESSE, the tests are classified into 6 types as described in Table 4: basic tests, single effects tests, multiple effect/multiple interaction tests, partially integrated tests, integrated tests, and component tests. There is a clear differentiation in the test condi-

Table 4. Test Categories

Basic Test
- Basic or intrinsic property data
- Single material specimen
- Examples: thermal conductivity; neutron absorption cross section

Single Effect Test
- Single phenomenon or the interaction of a limited number of phenomena to develop understanding and models
- Generally a single environmental condition and a "clean" geometry
- Examples: 1) thermal stress/creep interaction between solid breeder and clad; 2) electromagnetic response of bonded materials in a transient magnetic field; 3) tritium production rate in a heterogeneous slab due to a point neutron source

Multiple Effect/Multiple Interaction Test
- Multiple environmental conditions and multiple interactions among physical elements to develop understanding and predictive capabilities
- Includes identifying unanticipated interactions, and directly measuring global parameters that cannot be calculated
- Two or more environmental conditions; more realistic geometry
- Example: testing of an internally cooled first wall section under a steady surface heat load and a time-dependent magnetic field

Partially Integrated Test
- Partial "integrated test" information, but without some important environmental condition to permit large cost savings
- All key physical elements of the component; not necessarily full scale
- Example: liquid metal blanket test facility without neutrons

Integrated Test
- Concept verification and identification of unknowns
- All key environmental conditions and physical elements, although often not full scale
- Example: blanket module test in a fusion test device

Component Test
- Design verification and reliability data
- Full-size component under prototypical operating conditions
- Examples: 1) an isolated blanket module with its own cooling system in a fusion test reactor; 2) a complete integrated blanket in a demonstration power reactor

---

tions for the different test categories. Basic tests require only the state conditions (e.g., temperature, fluence, pressure) necessary to the intrinsic properties being measured. Single effect tests include a single environmental condition (e.g., neutron flux, surface heat flux, or magnetic field) that is necessary for the phenomena of interest. Multiple effect/multiple interaction tests include several environmental conditions (e.g., both surface heat flux and magnetic field) in order to explore the interactions between the effects of each environmental condition. Partially integrated tests supply all conditions except some key environmental condition, generally absent due to the large cost of providing this condition (e.g., neutron flux). Integrated tests provide the full environmental conditions, although often scaled from the commercial operating values. Component tests are conducted in a complete prototypical environment.

There is also a progression in the geometry of the tests. Basic tests are performed on small coupons or specimens, since intrinsic properties generally apply down to microscopic dimensions. Single effect tests are idealized tests with "clean" geometry so that the phenomena of interest are not obscured by complex geometrical effects. Multiple effect/multiple interaction tests begin to explore the interactions between different physical regions of a component, and so have more realistic geometries such as multiple unit cells. The partially integrated and integrated test categories contain all key physical elements of the hardware, although possibly scaled in size. The component tests involve full components with the complete geometry and structure.

Table 5 lists the tests identified in FINESSE which require fusion neutrons. Along with the tests, estimates are given for the size and required number of the test articles. While tentative, the numbers in Table 5 point to the need for a considerable amount of irradiation testing space for fusion research and development. A more complete list and discussion of the tests can be found in Ref. 1.

SUMMARY

As in the development of any complex new technology, fusion nuclear technology must proceed through stages of R&D. In the early stages, fusion has emphasized basic and single effect tests. Now, there is a need to begin performing many interactive tests; some of which will require upgrades of existing non-neutron test stands or construction of new ones, while others require designing and constructing experiments for use in available fission reactors and point neutron sources. In the early 1990's, more complex interactive

Table 5. Fusion Nuclear Technology Tests Requiring Fusion Neutrons

Tests	Typical Test Article Size (cm x cm x cm)	Number of Test Articles[a]
BASIC TESTS		
Structural material irradiated properties	1 x 1 x 2	20,000
Solid breeder irradiated properties	1 x 1 x 2	1,200
Plasma interactive materials irradiated properties	1 x 1 x 5	900
Radiation damage indicator cross-sections	1 x 1 x 0.5	500
Long-lived isotope activation cross-sections	1 x 1 x 0.1	200
Neutron sputtering rate cross-sections	1 x 1 x 0.1	30
SINGLE EFFECT TESTS		
Structure thermomechanical response experiments	10 x 10 x 10	50
Weld behavior experiments	10 x 10 x 5	50
Shield effectiveness in complex geometries	50 x 50 x 100	50
Optical component radiation effects	2 x 2 x 2	20
MULTIPLE EFFECT/MULTIPLE INTERACTION TESTS		
Submodule thermal and corrosion verification	LB[b]:100 x 100 x 30	5
	SB[b]:10 x 50 x 30	5
PARTIALLY INTEGRATED AND INTEGRATED TESTS		
Verification of neutronic predictions	50 x 50 x 100	4
- Tritium breeding, nuclear heating during operation, and induced activation		
Full module verification	LB[c]:100 x 100 x 50	5
- Thermal and corrosion	SB:100 x 100 x 50	5
- Module thermomechanical lifetime		
- Tritium recovery		
Instrumentation transducer lifetime	1 x 1 x 2	70
Insulator/substrate seal integrity	1 x 1 x 2	20
Biological dose rate profile verification	DT device	1
Afterheat profile verification	DT device	1
COMPONENT TESTS		
Blanket performance and lifetime verification	SB:30 x 100 x 80	3
	LB:900 x 300 x 80	3
Radiation effects on electronic components	1 x 1 x 1	20
Instrumentation performance and lifetime	5 x 5 x 5	100

[a] A test article is defined as one physical entity tested at one set of conditions. Duplication of tests for statistical purposes, off-normal conditions, data at several time intervals, for high fluence tests, etc., are not included in the number of test articles.
[b] LB = liquid breeder blankets, SB = solid breeder blankets
[c] Some designs require larger test volume.

experiments will have to be carried out. In cases such as self-cooled liquid metals, it appears plausible to construct a new facility that simulates all aspects of the fusion environment except neutrons. Such a facility will cost under $50M and will provide much needed information on the complex fluid flow, MHD, corrosion and other aspects of the thermomechanical loading and response. In the mid to late 1990's, the construction of a fusion facility for engineering experiments will provide the necessary transition to more complex interactive and integrated tests.

The number and detailed design of the experiments for each stage of fusion nuclear technology development involves considerations of benefit, cost and risk. In an accelerated fusion R&D program, higher risks can be acceptable in moving more rapidly from the lower cost simple experiments to the more costly and more complex tests which provide engineering design data. The degree of risk in an accelerated program can, of course, be reduced by providing additional funds to perform more experiments in a shorter time period. On the other hand, a normal pace R&D program will take lower risk by emphasizing the understanding of phenomena and development and verification of models in each stage.

It must be clearly recognized, however, that there are large uncertainties introduced by the many new phenomena and the substantial change in the characteristics of old ones brought about by the unique and complex fusion environment. It is possible that definitive data to establish the feasibility and judge the safety and economic potential of concepts may come only from the more elaborate interactive and integrated tests. Such a possibility will demand more rapid transition from the simple to the more representative types of experiments.

Reference

1. M. A. Abdou, et al., "FINESSE: A Study of the Issues, Experiments, and Facilities for Fusion Nuclear Technology Research and Development (Interim Report)," University of California, Los Angeles, PPG-821, also UCLA-ENG-84-30, October 1984.