OVERVIEW OF FINESSE EFFORT ON FUSION NUCLEAR TECHNOLOGY

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ABSTRACT

FINESSE is a study concerned with technical planning of experiments and facilities for fusion nuclear technology research and development. The effort is focused on: a) understanding the key issues, b) developing the scientific basis for engineering scaling and experimental planning, and c) identifying the characteristics, role and timing of major facilities required. Fusion nuclear technology is found to have many of fusion's remaining unresolved feasibility and attractiveness issues. Resolving these issues requires new knowledge from experiments and theory. Non-neutron test stands can play an important role in liquid metal blanket experiments. Fission reactors have some limitations, but they provide the bulk heating and radiation effects necessary for many solid breeder blanket experiments. Concept verification for fusion nuclear components may not be possible prior to testing in fusion devices.

I. INTRODUCTION

The development of a new technology, such as fusion energy, involves several types of activities. The development of a technology starts by a proposed application of a scientific principle and, if successful, ends with a commercial product. In between, three important activity elements take place, as indicated in Fig. 1.

The first element involves conceptual design studies. In these studies, design options are examined and compared based generally on a very limited data base.

The product of design studies is an identification of promising design concepts together with a preliminary description of such designs and their estimated performance. Information from design studies is necessary but not sufficient to implement a research and development (R&D) program. R&D implementation which is the third activity element in Fig. 1, refers to the construction of experimental facilities and performing experiments.

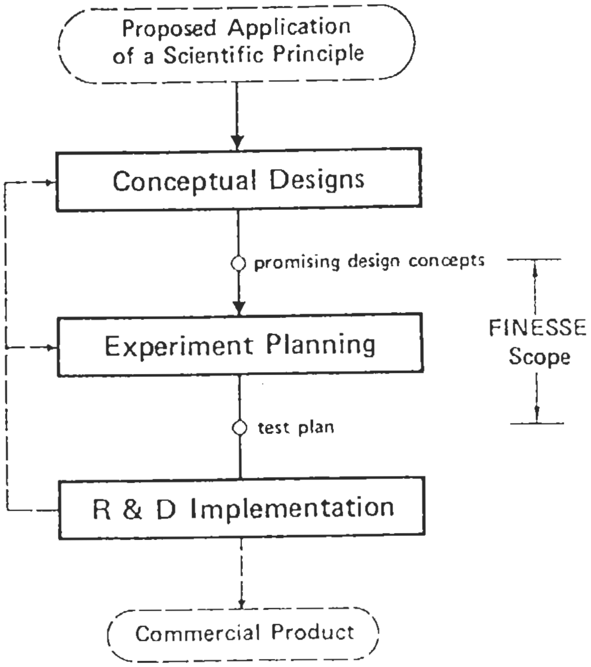

Fig. 1. Role of experiment planning in technology development and scope of FINESSE.

Experiment Planning (EP), as indicated in Fig. 1, is an important activity element in technology development. The purpose of EP is to investigate the technical and programmatic issues of the technology R&D and recommend a sound strategy based on detailed technical evaluation of key R&D issues and required experiments and testing facilities.

FINESSE is concerned with EP for Fusion Nuclear Technology (FNT). The primary fusion reactor components included in FNT are those whose main functions are: 1) fuel production and processing, 2) energy extraction and use, and 3) radiation protection of personnel and components. These include blanket, plasma interactive components (such as first wall, limiter and divertor), radiation shield and tritium system. Other components affected by the nuclear environment include instrumentation and control, magnets, remote maintenance, and heat transport systems.

FINESSE was initiated in November 1983 by the U.S. Department of Energy (DOE) with UCLA as the lead technical organization. The study is carried out by a number of organizations from the US and involves significant participation by technical experts from Canada, Europe and Japan. This paper presents an overview of the FINESSE scope and highlights technical results obtained during 1984. Detailed results are documented in Ref. 1. A number of specific topics are treated in depth in Refs. 2-11.

2. FINESSE APPROACH

An approach for EP has been developed in FINESSE. The main elements of this approach, i.e., the FINESSE process, are shown in Fig. 2.

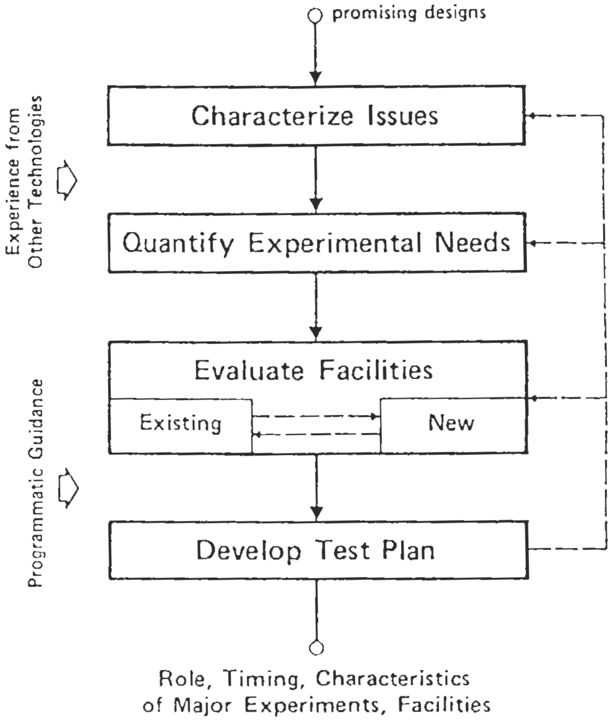

Fig. 2. FINESSE process for experiment planning.

The primary input to the process is a set of promising design options for a particular technology component. The major output from the process is a technical test plan that identifies and quantifies the role, timing and characteristics of major experiments and facilities. The FINESSE process consists of four primary elements indicated in Fig. 2, namely: 1) characterization of issues, 2) quantifying experimental needs, 3) evaluation of facilities, and 4) development of a test plan. Experience from other technologies is an important input to the process, particularly in quantifying experimental needs and developing engineering scaling options. Programmatic considerations provide important input to the process primarily for the last process element concerned with the development of a test plan. The four elements in Fig. 2 are generally carried out sequentially, but considerable feedback and iterations among the elements have proved necessary. A brief summary of the focus of the technical effort in each process element is given below.

The process element concerned with characterization of issues involves the following technical investigations:

- assessment of accuracy and completeness of existing data and models;
- analysis of scientific/engineering phenomena to determine (anticipate) behavior, interactions and governing parameters in fusion reactor environment;
- evaluation of effect of uncertainties on design performance; and
- comparison of tolerable and estimated uncertainties.

This process element provides quantified understanding of the important issues.

The process element of quantifying experimental needs involves:

- survey of needed experiments;
- exploration of engineering scaling options (engineering scaling is a process to develop meaningful tests at experimental conditions and parameters less than those in a reactor);
- evaluation of effects of scaling on usefulness of experiments in resolving issues;
- development of technical test criteria for preserving design-relevant behavior; and
- identification of desired experiments and key experimental conditions.

In evaluating facilities, the effort is focused initially on existing facilities to: a) survey available facilities, b) evaluate their capabilities and limitations, c) define meaningful experiments to be performed in such facilities, and d) estimate costs for such experiments. Issues that cannot be resolved in existing facilities require the construction of new facilities. In evaluating the need for and in identifying new facilities, the effort is focused on: 1) exploring innovative testing ideas; 2) assessment of the feasibility of obtaining the desired information, e.g., examination of instrumentation limitations; 3) development of preliminary conceptual designs of facilities and their costs; and 4) performing tradeoffs among experiments and facilities including many complex aspects of technical usefulness, time and cost.

In developing a test plan, a number of test program scenarios are defined based on information from the process elements described above. These scenarios are then compared as to risk, usefulness and cost.

The rest of this paper briefly summarizes the results from FINESSE obtained to date. More details are given in Refs. 1-11.

3. FUSION NUCLEAR ISSUES

The development of fusion nuclear components are found to present new, unique and challenging questions to many fields of science and technology that have not been encountered before in the development of other technologies. One reason is the unique fusion environment experienced by the nuclear components which involves the simultaneous presence of plasma particles, neutrons, gamma rays, magnetic field, surface and bulk heating, tritium and vacuum. A second reason is that the fusion nuclear components perform new and unique functions, e.g., simultaneous tritium production/extraction and energy conversion/extraction in the blanket and heat removal and plasma ash removal in the impurity control and exhaust system. A third reason is that the integration of the fusion components into a fusion system results in many interactions among components.

These new and unique functions for and the environmental conditions and interactions experienced by the fusion nuclear components result in new phenomena and a substantial change in the characteristics of previously known phenomena. The R&D effort on FNT in the world fusion programs has been so limited that presently we do not have a data base nor an understanding sufficient to characterize these new phenomena or the major changes in the nature of old phenomena. Thus, attempts to select material and design options and to predict the performance of fusion nuclear components suffer from the large uncertainties caused by insufficient knowledge. These large uncertainties result in many critical issues for fusion that relate to: 1) feasibility, which is the ultimate acceptance criterion for technologies; 2) economic potential, which is the crucial acceptance criterion for industry and utilities; and 3) safety, which is the uncompromised acceptance factor by the public.

In FINESSE, key fusion nuclear issues have been identified and characterized. The issues are classified according to their potential impact, level of concern, and importance of operating environmental conditions (e.g., neutrons, magnetic field, etc.). The details are in Refs. 1 and 2. Table 1 lists briefly some of the critical fusion nuclear issues.

4. EXPERIMENT REQUIREMENTS

Understanding and resolving the known and unknown fusion nuclear issues require new knowledge that must be acquired through carefully planned experiments, theory and models. In FINESSE, we have analyzed[1,3] both the type of experiments and the environmental conditions that must be met in these experiments in order to resolve the fusion nuclear issues.

The type of experiments required in FNT development can be classified into 1) basic, 2) single effect, 3) multiple effect/multiple interaction, 4) partially integrated, and 5) integrated tests. The types of facilities suited for FNT can be classified into: a) non-neutron test stands and b) neutron-producing facilities. There are only three types of neutron-producing facilities: accelerator-based neutron sources, fission reactors and fusion devices.

Basic tests are to obtain property data and can be performed in available standard laboratory facilities. Single effect experiments are to explore phenomena and are aimed at a single effect, e.g., electromagnetic response of bonded materials to a transient magnetic field. Some of the required experiments can be performed in present facilities, but others require new facilities.

Multiple effect/multiple interaction experiments are aimed at exploring the combined effects of two or more environmental conditions and the interactions among two or more physical elements of a component. The new and unique fusion environment results in many new multiple effects and multiple interactions that require exploration. For example, corrosion is known to depend on temperature and velocity of the fluid, but in the fusion environment strong dependence of corrosion on the magnetic and neutron fields is predicted. Thus, reliable data on the corrosion of structural materials by liquid metals in the fusion environment cannot be obtained merely from "classical" corrosion loops but requires new experiments in which magnetic field, surface heating, velocity and geometry are properly simulated.

Another example is MHD effects on self-cooled liquid metal blankets. Results obtained in FINESSE predict complex interrelations among magnetic field, fluid flow, heat

Table 1. Critical fusion nuclear technology issues.

1. DT Fuel Cycle Self-Sufficiency:
   - Achievable Tritium Breeding
     - e.g., Effects of Blanket Material Choices and Internal Details
     - Extent of Plasma Coverage (Choice of RF v. Neutral Beams, Limiter or Divertor)
     - Uncertainties in Neutronics Methods and Data
   - Required Tritium Breeding
     - e.g., Dependence on Plasma Recycling (Limiter vs. Divertor, Pumping Efficiency)
     - Tritium Inventory in the Blanket, Plasma Exhaust, Storage, etc.
     - Tritium Extraction and Processing System Inventories and Efficiencies

2. Thermomechanical Peformance of Blanket Components under Normal and Off-Normal Operation:
   - Liquid Metal MHD Effects: Relationship of Fluid Flow, Heat Transfer and Structural Reponse in the Presence of Magnetic Fields, Bulk Heating, Surface Heating, and Full Geometic Complexity
   - Interaction of Primary and Secondary Stresses and Deformation
   - Effect of Swelling and Creep on Stress Concentrations
   - Consequences of Plasma Disruptions
   - Sources and Consequences of Hot Spots

3. Materials Compatibility:
   - Effect on Design Limits
     - e.g., Liquid Metal Corrosion Temperature Limits
     - LiOT and Lithium Burnup Effects
   - Influence on Failure Modes
     - e.g., Liquid Metal Embrittlement and Stress Corrosion Cracking
   - Impact on Safety and Reliability
     - e.g., Transport of Radioactive Isotopes
     - Oxidation/Volatility of Vanadium
     - Lithium Chemical Reactivity
     - Blocking of Coolant or Purge Streams

4. Identification and Characterization of Failure Modes and Rates:
   - Crack Growth and Brittle Fracture with Irradiation
   - Vulnerability at Welds and Discontinuities
   - Discovery of Unforseen Failure Modes

5. Tritium Inventory in the Solid Breeder under Actual Operating Conditions:
   - Radiation Effects on Tritium Diffusivity and Solubility
   - Variability in Temperature due to Radiation Effects and Mechanical Interactions (Gap Conductance, Cracking, Swelling, Creep, etc.)

6. Tritium Permeation and Inventory
   - Magnitude in In-Vessel Components Under Actual Operating Conditions (Including Effects of Plasma Side Conditions, Radiation, etc.)
   - Form of Tritium (T_2,T_2O) Released from Solid Breeder
   - Effectiveness of Control Methods Such as Permeation Barriers

7. In-Vessel Component Thermomechanical Response and Lifetime
   - Erosion and Redeposition Mechanisms and Rates under Various Plasma Edge Conditions
   - Heat Removal Techniques
   - Structural Integrity of Components and Bonds
   - Leading Edge Design of Limiters

8. Radiation Shielding
   - Accuracy of Prediction
   - Data on Radiation Protection Requirements

9. Accuracy and Survivability of Instrumentation and Control:
   - Accuracy and Decalibration in the Fusion Environment
   - Lifetime Limits due to Radiation Effects

transfer, bulk heating, surface heating, geometry, pressure drop and stresses. Thus, MHD pressure drop data cannot be obtained from simple "classical" types of experiments in which the magnetic field is the only imposed environmental condition. Rather, fusion needs experiments in which the various interactions just mentioned are simulated.

Multiple effect/multiple interaction experiments generally require relatively larger size and are generally much more costly than single effect experiments. New facilities and upgrades of present facilities are required for these multiple effect experiments.

Some of the multiple effect tests require neutrons as part of the experiment environment. These are experiments in which bulk heating, radiation effects, and/or specific reactions, e.g., Li(n,t), are important. The size of such experiments is relatively large, at least orders of magnitude larger than the size of samples normally used with point neutron sources. The only two types of "bulk" neutron-producing facilities are fission reactors and fusion devices.

In integrated tests, all environmental conditions and physical elements of the components are simulated but not necessarily at full size scale. The purposes of integrated tests are to verify concepts and to obtain engineering design data. Integrated tests for FNT require fusion-type devices.

5. NON-NEUTRON TEST STANDS

Facilities in which no neutrons are provided as part of the test environment are referred to as "non-neutron" test stands. The identified issues and testing needs clearly indicate that non-neutron test facilities can and should serve an important role in FNT R&D. The role of non-neutron test stands is in the area of basic property data, single-effect experiments, and some of the multiple-effect/multiple-interaction tests for which radiation effects and extensive bulk heating are not important. Examples are mechanical properties and corrosion of unirradiated structural materials, sputtering of plasma-side material surfaces, and some liquid metal MHD experiments. The cost of non-neutron experiments and facilities is generally much lower than those involving neutrons. Therefore, information from non-neutron tests is important for at least two reasons. First, they permit early scoping of some material and design options. Second, they provide information that make more useful and less risky irradiation experiments possible.

A survey of the U.S. facilities indicates the availability of some test stands that are potentially useful for some fusion technology experiments. However, multiple-effect test stands appropriate for fusion are not, as might be expected, available from other technologies. Thus, there is a definite need to upgrade existing non-neutron facilities and to build new ones.

In evaluating the blanket component, it is found that non-neutron test stands are very useful for liquid metal blankets, while they are of limited value for solid breeders. The dominant issues in solid breeders relate to the thermal state (temperature gradient) of the system, tritium retention and release and clad-breeder interaction which require neutrons for generating bulk heating, tritium and radiation effects. In contrast, liquid metal blanket issues are dominated by MHD effects on momentum, heat and mass transfer.

Three non-neutron test stands have been identified as necessary to resolve key issues for liquid metal blankets. The important testing conditions in each of these facilities are indicated in Table 2.

Table 2. Three key facilities and testing conditions required for liquid metal blankets.

	1	2	3
Testing Condition	Momentum Transfer	Heat Transfer	Mass Transfer
Velocity Profile	x	x	x
Magnetic Field	x	x	x
Geometry	x	x	x
Temperature Gradient	—	x	x
Temperature Level	—	—	x
Material	—	—	x
Time	—	—	x
Impurity Level	—	—	x
Outside B Field	—	—	x

x = Important — = Not Important

6. POINT NEUTRON SOURCES

Point neutron sources are attractive for irradiation testing because of their easy access, simplicity and relatively low cost. In reality, point sources often suffer from limited neutron intensity, inappropriate neutron spectra, and difficulties associated with operating very high technology machines. It should also be noted that as the level of neutron exposure is increased, the cost associated with utilization of point sources increase dramatically. These increased costs are associated primarily with shielding and remote handling.

Table 3 shows the neutron flux and testing volume capabilities of operational or

Table 3. U.S. point neutron sources.

Facility	Comments	Flux	Testing Volume
RTNS-II	In use for materials testing	5×10^{12} n/cm^2 sec	0.1 cm^3
LAMPF A-6	Operational spallation source High energy tail	1×10^{13} n/cm^2 sec	0.02 m^3
INS	Conceptual design completed - project terminated	1×10^{14} n/cm^2 sec	1 cm^3
FMIT	Design completed - project deferred	1×10^{15} n/cm^2 sec	10 cm^3
Multiple Beam Test Facility	Scoping study	1×10^{15} n/cm^2 sec	0.016 m^3

proposed point neutron sources in the U.S. It is concluded that existing sources are very limited in flux and volumes. They are suited only for: a) neutronics studies (e.g., tritium breeding measurements) that do not require significant fluence, and b) limited miniature specimen irradiation. Proposed sources, e.g., FMIT, provide high flux needed for fluence data but are still limited to material specimen testing and, therefore, are not capable of addressing the many multiple effect tests required for FNT R&D. Scoping studies aimed at increasing the testing volume for accelerator-based neutron sources show that the capital cost for such facilities is high (several hundred million dollars).

7. FISSION REACTOR UTILIZATION

The issues related to the benefits and limitations of utilizing fission reactors for fusion nuclear tests were evaluated. The first issue is the difference between the fusion and fission spectra. There is presently no adequate model to correlate radiation damage with spectrum. The special difference is considered a limitation for those tests that require accurate simulation of radiation damage in the structure. Simulation of radiation damage in solid breeders in fission spectra is likely to be more successful than that in structural materials.

The second issue is power density. Fission reactors provide sufficient neutrons and gamma rays to bulk heat all materials of an element test, a capability that does not exist anywhere else except fusion devices. The fact that ^{6}Li has a high cross section for the exothermic reaction (n,a)t makes simulation of tritium production and heating profiles in a blanket test possible. However, there are limitations on the magnitude of the power density obtainable in existing fission reactors. In addition, since most of the heat generation and tritium production are via interactions of low energy neutrons with ^{6}Li, the power density and tritium production profiles will continually deviate from those in fusion reactors during irradiation. This places limitations on the maximum achievable lithium burnup.

Closely related to the power density limitation are the issues of 1) the maximum size of a test element that can be accommodated in fission reactors, and 2) the number of test locations available in existing fission reactors. Table 4 shows the number of in-core test locations in U.S. and foreign reactors as a function of the minimum flux required and the maximum dimension of a test assembly. Table 5 shows the same information for slab-type tests on the side of fission reactors. The fluxes shown in Table 5 are the unperturbed values. Calculations show a flux depression of ~ 80% for thermal neutrons (energy < 0.4 eV) and ~ 30% to 40% for fast neutrons (energy > 900 keV). To simulate bulk heating corresponding to 1 MW/m^2 fusion neutron wall load requires a flux of ~ 5×10^{14} n cm^{-2} s^{-1} for in-core and ~ 1×10^{15} n cm^{-2} s^{-1} for core-side locations. Simulation of helium production rate in non-nickel materials requires about two orders of magnitude higher flux because of the soft spectrum in fission reactors. From Table 4, there are some existing in-core locations that can provide power density equivalent to ~ 2 MW/m^2 fusion neutron wall load. However, there are considerable size limitations. First, the maximum size (the most limiting dimension) of the entire test assembly cannot exceed ~ 10 cm, which is useful for many test types but is inadequate for many others, particularly those involving interactive effects. Second, the total number

Table 4. Number of existing relevant in-core test locations in U.S. (U.S. and foreign) reactors.

Minimum Required Flux (n/cm^2 sec)	Test Assembly Maximum Dimension (cm)				
	5	7.5	10	12.5	15
5×10^{12}	180 (315)	119 (168)	33 (79)	16 (45)	2 (27)
5×10^{13}	167 (292)	106 (145)	30 (66)	15 (44)	1 (26)
5×10^{14}	49 (69)	13 (30)	13 (30)	10 (27)	0 (16)
5×10^{15}	40 (40)	4 (4)	4 (4)	1 (1)	0 (0)

Table 5. Numbers of existing relevant slab test locations in U.S. (U.S. and foreign) reactors.

Minimum Required Flux (n/cm^2 sec)	Test Assembly Maximum Dimension (cm)				
	25	50	75	100	150
5×10^{13}	7 (11)	1 (4)	0 (2)	0 (1)	0 (1)

of test locations available (i.e., the total number of simultaneous experiments) is limited.

Core-side locations were explored because of flexibility in accommodating relatively large size experiments. However, as shown in Table 5, the flux is limited to $\sim 5 \times 10^{13}$ n cm^{-2} s^{-1}, which results in power density equivalent to less than that needed for 0.05 MW/m^2 fusion neutron wall load. Even at this very low wall load equivalence, the number of test locations available is severely limited.

Fission reactors are useful for some FNT experiments and their use should be maximized as they are the only facilities available now to provide: a) bulk heating in significant volume experiments, and b) significant fluence. These capabilities are crucial for tests related to the dominant issues for solid breeder blankets. However, the limitations on fission reactor utilization must be clearly recognized. The important limitations relate to: a) different neutron spectrum, b) simulation of fusion environment, and c) size of test element (< 15 cm).

8. FUSION DEVICES

The identified testing needs for fusion nuclear technology include a number of critical multiple interaction and integrated experiments. These particular experiments have the following characteristics: 1) they require simulating many of the fusion environmental conditions, particularly the neutrons; 2) the size of a typical experiment is large, typically on the order of 1 m^3; and 3) the total testing volume requirements for the important needs is large, in the range of 10-20 m^3.

Multiple interaction experiments for which the neutron field is not critical may be performed in non-neutron test stands, even if they require a large size. Although suitable test stands are not readily available, the construction of new ones at a reasonable cost may be justified. One particular problem here that must be considered is that many of these multiple interaction experiments require bulk heating. Even if neutrons are not critical in certain tests to simulate radiation effects, they may be the only practical source of bulk heating.

Neutrons are needed to simulate radiation effects, to provide bulk heating, and to induce specific nuclear reactions, e.g., Li(n,t). The only presently available source of neutrons for a significant experimental volume is while useful for some multiple interaction tests, cannot satisfy critical needs for other multiple interaction and integrated tests.

Thus, concept verification and obtaining engineering design data for fusion nuclear technology components requires experiments in fusion devices. Therefore, part of the effort in FINESSE focused on: 1) investigating the

Table 6. Key requirements on parameters of fusion devices based on fusion nuclear technology testing needs.

Wall Load
- Minimum: > 1 MW/m^2
- Substantial benefits: 2-3 MW/m^2
- Much higher wall loads can be extremely beneficial and will alter strategy (accelerated testing, more ambitious technology performance gaols for fusion, (etc.)

Surface Heat Load
- Critical for tests of first wall, solid breeder blankets, liquid metal blankets
- Tokamak blankets: > 20 W/cm^2
Mirror blankets: < 20 W/cm^2
- Methods to enhance surface heat flux in fusion test facilities, are important

Plasma Burn Cycle
- Pulsing sharply reduces the value of many tests
- Minimum burn time: > 500 s
- Maximum dwell time: < 100 s
- Prefer steady state

Minimum Continuous Time
- Many periods with 100% availability
- Duration of each period:
  - Critical: several days
  - Important: several weeks

Availability
- Minimum: 20%
- Substantial benefits: 50%

Fluence
- Fluence requirements will depend on whether a point neutron source or other means is available for high fluence material testing.
- In general, component tests in the early stages of development are carried out to fluences lower than those for specimen tests.
- In all cases, higher fluences are desirable but costly; modest fluences are still extremely valuable.
- For component tests:
  - Critical: 1-2 MW yr/m^2
  - Very important: 2-4 MW yr/m^2
  - Important: 4-6 MW yr/m^2
  - Desirable: 6-10 MW yr/m^2

Minimum Size of Test Assembly
- Interactive tests:
  0.2 m x 0.2 m x 0.1 m
- Integrated tests:
  1 m x 1 m x 0.5 m
  (Some liquid metal blanket designs tend to require larger size, sector scale)

Test Surface Area
- Critical: > 5 m^2
- Very Important: > 10 m^2
- Important: 15-20 m^2

key requirements on parameters of FNT experiments, and 2) evaluating fusion facility concepts for FNT testing.

Table 6 shows preliminary requirements on parameters of fusion devices in order to perform meaningful experiments for FNT components. These parameters were derived based on trade-offs between increased cost of the device at high performance parameters and reduction in the benefits obtained from FNT experiments at scaled-down conditions.

A number of options for next-generation fusion devices were evaluated. One option is a tokamak facility in which both physics and nuclear technology experiments are performed. An example of such a device for tokamaks is INTOR.[12] A fundamental problem is found with such devices that are based on the conventional tokamak approach. They require large fusion power (~ 300-600 MW) to have ignited plasmas. Physics testing alone requires low fluence (< 0.01 MW y/m^2). On the other hand, nuclear technology testing requires only low fusion power (~ 20-50 MW) but needs high fluence (~ 2-6 MW y/m^2). The combination of high power for physics testing and high fluence for nuclear technology testing in a single device leads to high tritium consumption (> 100 kg). Such large amounts of tritium can be provided only if the device has its own tritium breeding blanket. Construction of such a breeding blanket in the next generation fusion device without prior fusion testing is found to result in high risks of not attaining reasonable device availability.

One option that appears attractive is: 1) to limit the mission of the next-generation tokamak device to physics testing, and 2) to perform fusion nuclear technology experiments in another type of more suitable device. The most suitable facility for FNT testing is a device in which the total fusion power and the power density (or wall load) are decoupled. A device that produces 20-50 MW of fusion power at 1-2 MW/m^2 wall load is most suited for nuclear technology testing. The plasma can serve only as a neutron producer and there are no requirements on the plasma except long burn or steady-state operation. Options for such a device are presently being evaluated based on a number of plasma confinement concepts, e.g., mirror, reversed field pinch, and innovative tokamak approaches.

9. SUMMARY

A process for technical planning of experiments has been developed and applied for fusion nuclear technology as part of FINESSE.[1] The process involves four elements: a) characterization of issues; b) quantifying testing requirements; c) evaluation of facilities; and d) development of a test plan to identify role, timing and characteristics of major experiments and facilities.

FNT is found to pose critical issues related to feasibility, economics, safety and environmental impact of fusion reactor systems. Resolving these issues requires new knowledge that can be acquired only through new experiments accompanied by theoretical and modelling efforts. The types of experiments and the environmental conditions that must be provided in these experiments have been assessed. In addition, the capabilities and limitations of existing facilities and the need for new facilities have been evaluated.

Figure 3 shows a summary of the type of experiments required for FNT R&D and the role of various facilities in fulfilling the experimental needs.

Basic tests for measurement of material properties are performed primarily in non-neutron test stands. Radiation-related properties (e.g., neutron reaction cross section of material) can be measured using accelerator-based (point) neutron sources. Effects of radiation on basic material properties (e.g., thermophysical or mechanical properties) can also be made using point neutron sources. Fission reactors are utilized whenever there is a need for larger irradiation volume and higher fluence than those available with point neutron sources, but extrapolation of results to the different fusion spectrum is necessary.

A critical phase of FNT R&D involves multiple effect/multiple interaction experiments. In these experiments, a number of environmental conditions (e.g., magnetic field, bulk heating) and a number of component physical elements (e.g., breeder material, clad and coolant of a unit cell for solid breeder blanket) are simulated. These experiments are for phenomena exploration, and they should proceed from the simplest (least number of environmental conditions and least number and smallest size of physical elements) to the more complex experiments.

Non-neutron test stands can and should play an important role in phenomena exploration in a number of areas. In particular, they are well suited for liquid metal blanket experiments to address key issues related to momentum, heat and mass transfer. A number of relatively small-scale facilities are needed to address individual groups of issues or phenomena (e.g., a facility for MHD pressure drop and a facility for heat transfer in the presence of magnetic field). A partially integrated test facility (PITF) which simulates all environmental conditions of a fusion reactor except neutrons can be built later to provide maximum information on liquid metal blankets prior to fusion testing. Non-neutron test stands are less useful for solid breeder blankets.

The role of point neutron sources in phenomena exploration is limited because of the relatively large volume required for multiple effect/multiple interaction experiments. Fission reactors can and should play a major role in the development of solid breeder blankets. Fission reactors are the only facilities at present that can provide the neutrons necessary for producing bulk heating and radiation effects in experiments with significant volume. Fission reactors are less useful for liquid metal blanket experiments.

First generation DT fusion devices will permit more complete phenomena exploration. In addition, they will provide the first opportunity to perform integrated tests for concept verification. Identifying the type and characteristics of the first DT fusion device for nuclear technology testing requires further investigation. Subsequent (pre-demonstration and demonstration) fusion devices will be used for component testing and obtaining data on component reliability.

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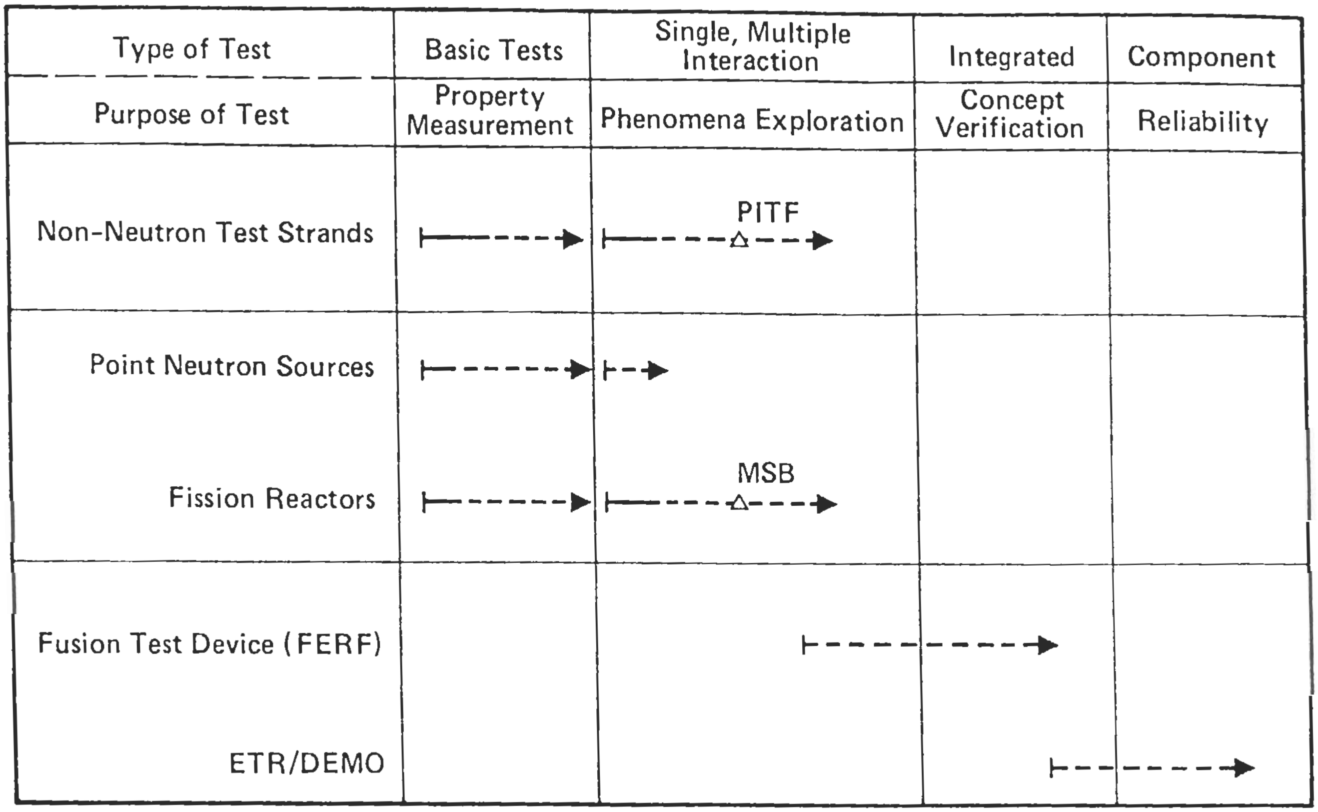

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