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Fusion Engineering and Design 27 (1995) 111–153

Fusion Engineering and Design

A volumetric neutron source for fusion nuclear technology testing and development

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Abstract

Research and development (R&D) needs to construct and operate fusion nuclear technology (FNT) components for DEMO have been investigated. Non-fusion facilities, i.e. non-neutron test stands, fission reactors and accelerator-based neutron sources, can and should play a role in FNT R&D because of their availability and low cost. However, none of the FNT critical issues will be resolved by testing in non-fusion facilities because of their serious limitations on simulating multiple integrated effects of the fusion environment and their lack of adequate test volume. Testing of FNT components, particularly blankets, in fusion facilities is necessary. The FNT requirements on fusion testing are a 1–2 MW m^{-2} neutron wall load, steady state plasma operation, a fluence of greater than 6 MW years m^{-2} and a test area greater than 10 m^2. Requirements on reliability growth and component engineering development are the most demanding. Calculations of both expected and tolerable failure rates and reliability growth testing requirements for the blanket lead to a number of important conclusions: (1) achieving a fluence of about 6 MW years m^{-2} at the test modules with about six to 12 test modules per blanket concept is crucial to achieving a DEMO reactor availability in the 40–50% range with 90% confidence, (2) achieving a DEMO reactor availability of 60% may not be possible with 90% confidence for any practical blanket test program with present design concepts. The required mean time between failure for the blanket is much longer than that achieved in other existing and perhaps less complex technologies, (3) the mean down-time to replace (MTTR) or to recover from a random failure in the blanket must be kept on the order of 1 week or less in order to achieve the required blanket and reactor system availabilities and (4) the length of MTTR must be by itself one of the crucial objectives for testing in fusion facilities. Scenarios for fusion facilities to provide the data base for DEMO have been evaluated. A strategy based on the International Thermonuclear Experimental Reactor (ITER) alone results in unacceptably high risk and long delays in DEMO operation. A plasma-based volumetric neutron source (VNS) facility is proposed for construction and operation parallel to ITER. VNS will serve as a dedicated facility to test and develop FNT components for DEMO. An attractive design envelope for a small-sized tokamak VNS exists with driven ($Q \approx 1$–3) steady state plasma and normal conducting copper toroidal field coils. Operation of VNS in parallel to ITER reduces the risk to DEMO and results in net savings in the overall R&D cost to DEMO.

Elsevier Science S.A.
SSDI 0920-3796(94)00383-1

1. Introduction

Fusion nuclear technology (FNT) includes those fusion system components responsible for energy conversion and extraction, tritium production and processing, high heat components (divertors, r.f. antennae etc.) and radiation shielding. Beyond plasma physics, FNT has most of the remaining feasibility and attractiveness issues in the development of fusion as an energy source. However, the development of FNT represents an extremely difficult problem because it requires facilities that do not currently exist. This paper is concerned with evaluation of the FNT needs for facilities.

The results of the evaluation show definite need for testing in fusion facilities. On the basis of the quantitative measures developed in this work, various scenarios for fusion facilities prior to DEMO have been evaluated. From the results, we propose that a plasma-based volumetric neutron source (VNS) be constructed and operated parallel to the International Thermonuclear Experimental Reactor (ITER). VNS will serve as a dedicated facility to test, develop and qualify FNT components, particularly blankets, for DEMO. The design options for VNS are explored. The range of parameters and characteristics of a small-sized tokamak with driven steady state plasma is investigated. More details based on the VENUS study carried out in the USA will be published in [1].

Table 1
Blanket options for DEMO (almost all concepts use beryllium as the neutron multiplier)

Breeder	Coolant	Structural material
Solid breeders		
Li_2O, Li_4SiO_4, Li_2ZrO_3, Li_2TiO_3	He or H_2O	Ferritic steel, V alloy, SiC composites
Self-cooled liquid-metal breeders		
Li, LiPb	Li, LiPb	Ferritic steel, V alloy with electric insulator, SiC composites with LiPb only
Separately cooled liquid-metal breeders		
Li	He	Ferritic steel, V alloy
LiPb	He or H_2O	Ferritic steel, V alloy, SiC composites

Table 2
Summary of critical research and development issues for fusion nuclear technology

(1) D–T fuel cycle **self-sufficiency**

(2) **Thermomechanical** loadings and response of blanket components under normal and off-normal operation

(3) Materials **compatibility**

(4) Idenitification and characterization of **failure modes, effects**, and **rates**

(5) Effect of imperfections in electric magnetohydrodynamic (MHD) **insulators** in self-cooled liquid metal blanket under thermal–mechanical–electrical–nuclear loading

(6) **Tritium inventory** and recovery in the solid breeder under actual operating conditions

(7) **Tritium permeation** and inventory in the structure

(8) Radiation shielding: accuracy of prediction and quantification of radiation production requirements

(9) Plasma-facing component thermomechanical response and lifetime

(10) **Lifetime** of first-wall and blanket components

(11) Remote maintenance with acceptable machine shut-down time

Table 3
Test categories for blanket research and development

Basic test
(1) Basic or intrinsic property data
(2) Single material specimen
(3) For example thermal conductivity; neutron absorption cross-section

Single-effect test
(1) Exploration of a single effect, a single phenomenon, or the interaction of a limited number of phenomena, in order to develop understanding and models
(2) Generally a single environmental condition and a "clean" geometry
(3) For example (a) pellet-in-can test of the thermal stress–creep interaction between solid breeder and clad, (b) electromagnetic response of bonded materials to a transient magnetic field and (c) tritium production rate in a slab of heterogeneous materials exposed to a point neutron source

Multiple-effect, multiple-interaction test
(1) Exploration of multiple environmental conditions and multiple interactions between physical elements in order to develop understanding and prediction capabilities
(2) Inclusion of identifying unknown interactions, and directly measuring specific global parameters that cannot be calculated
(3) Two or more environmental conditions; more realistic geometry
(4) For example testing of an internally cooled first-wall section under a steady surface heat load and a time-dependent magnetic field

Partially integrated test
(1) Partial "integration test" information, but without some important environmental condition to permit large cost savings
(2) All key physical elements of the component; not necessarily full scale
(3) For example liquid-metal blanket test facility without neutrons if insulators are not required (for concepts requiring insulators, tests without neutrons are a limited multiple effect)

Integrated test
(1) Concept verification and identification of unknowns
(2) All key environmental conditions and physical elements, although often not full scale
(3) For example blanket module test in a fusion test device

Component test
(1) Design verification and reliability data
(2) Full-size component under prototypical operating conditions
(3) For example (a) an isolated blanket module with its own cooling system in fusion test reactor and (b) a complete integrated blanket in an experimental power reactor

2. Fusion nuclear technology issues and types of testing

Among FNT components, blankets determine the critical path to DEMO. The primary blanket options at present being considered worldwide as candidates for DEMO are summarized in Table 1. These can be classified into (a) solid breeders, (b) self-cooled liquid-metal breeders and (c) separately cooled liquid-metal breeders. Both helium and pressurized water are considered as coolants for solid breeders. Two types of liquid metal are being considered: lithium and lithium–lead. In self-cooled concepts, the same liquid metal serves as the breeder and coolant. For separately cooled concepts, helium is considered as a coolant for both lithium and LiPb, while pressurized water is considered as a coolant only with LiPb. Only three classes of structural materials are at present considered as candidates for DEMO and commercial reactors: martensitic steels, V alloys and SiC composites.

FNT testing issues have been identified and characterized in previous studies (e.g. [2,3]). These issues include feasibility issues and attractiveness issues.

Feasibility issues are those whose negative resolution will have the following impact.

(a) They may close the design window.

(b) They may result in unacceptable safety risk.

(c) They may result in unacceptable reliability, availability or lifetime.

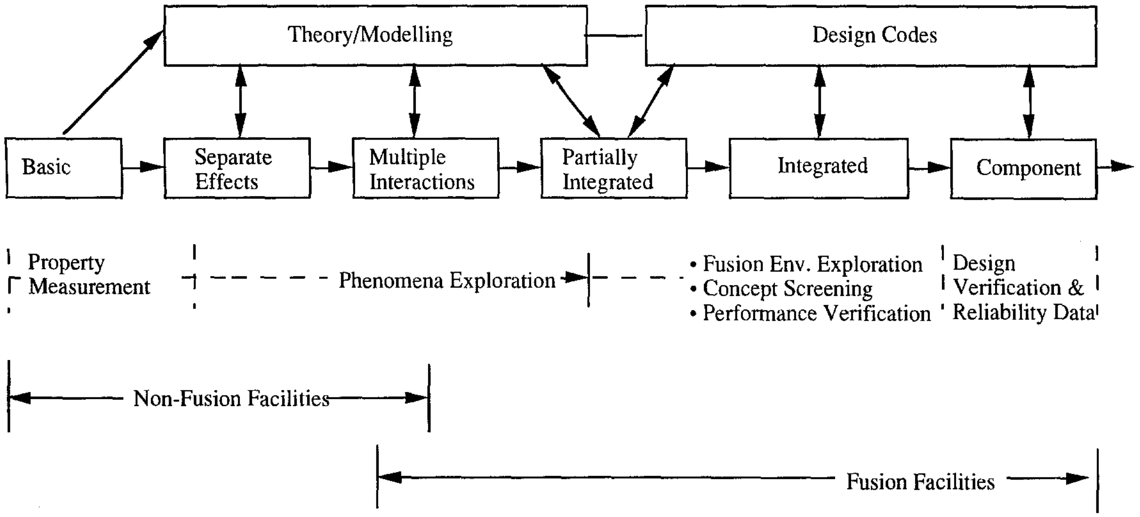

Fig. 1. Types and roles of experiment and facility for FNT.

Table 4
DEMO goals

(1) The DEMO must demonstrate through actual sustained operation of a fully integrated power plant system that fusion energy
  (a) is renewable (i.e. the fuel cycle can be closed with doubling time suitable for fusion power economy),
  (b) is safe,
  (c) has a small environmental impact,
  (d) has competitive economics (capital cost, plant availability, operation and maintenance costs) and
  (e) is reliable and maintainable

(2) The size, operation, performance and reliability of DEMO must be sufficient to demonstrate that there are no open questions about the fuel cycle, safety, environmental impact and economics of the first commercial reactor

Attractiveness issues are those whose negative resolution will have the following impact.

(a) They may reduce system performance.
(b) They may reduce component lifetime.
(c) They may increase system cost.
(d) They have less desirable safety or environmental implications.

A summary of the critical research and development (R&D) issues of FNT that stresses the key functional aspects of the fusion reactor that must be resolved through testing is given in Table 2.

FNT development up to the DEMO needs testing to resolve the many known issues as well as the currently unknown issues. The term "test" is used here in a generic sense to mean a process of obtaining information through physical experiment and measurement, i.e. not through design analysis or computer simulation. The testing needs for FNT have also been addressed in previous studies (e.g. [2,3]). However, these studies focused more on testing in non-fusion facilities, while here we are more concerned with testing in fusion facilities.

The testing needs are distinguished by the relevant components and by the level of integration of the test. For each component, there is a set of tests ranging from property measurements to component verification. The test categories adopted here are as follows: basic, single effect, multiple effect–multiple interaction, partially integrated, integrated and component tests. Table 3 summarizes the description of these categories. Note that the level of integration provides a rough measure of test complexity and an approximate indication of the chronological order.

Fig. 1 illustrates a loose chronological order of tests for a major nuclear component such as the blanket, although some overlap will occur. For example, some

Table 5
DEMO parameters and characteristics suggested by most studies

	Value
Neutron wall loading (average)	2–3 MW m^{-2}
Tritium fuel cycle	Self-sufficient (with 5–10 year doubling time)
Plasma mode of operation	Steady state
Net plant availability	>50% [a]
Reactor availability (assuming a balance-of-plant availability of 85%)	>60%[a]
Thermal conversion efficiency	>30%
Overall plant lifetime (design)	30 years
Blanket lifetime	10–20 MW years m^{-2}

[a] A scenario in which the availability of a DEMO plant during its initial years of operation (stage I) is 25% (i.e. a DEMO reactor availability of 30%) may be acceptable provided that the availability increases (in stage II) to about 50% (i.e. greater than 60% for the DEMO reactor) and such final availability goals are sustained over many years of operation.

multiple-effect tests can continue in parallel to integrated tests. A very important conclusion from the results given later in this paper that must be stressed here is that integrated and component tests can be performed only in fusion devices. However, tests in the fusion environment do not have to be of the fully integrated type. For example, a test article simulating a portion of the blanket to examine a particular group of multiple effects can be designed for testing in the fusion environment.

3. DEMO characteristics and blanket goals

A number of studies worldwide [4–10] have examined the general requirements and desired characteristics of a DEMO in the pathway to a commercial fusion power plant. There were several international meetings in which the DEMO was discussed [6]. There appears to be general agreement worldwide on the DEMO goals and range of major parameters. Table 4 summarizes the goals of DEMO while Table 5 shows the major parameters and characteristics that can be currently stated for the DEMO. The assumption is made here that the DEMO is based on the tokamak concept. Most world programs (see for example [11]) specify the year 2025 as the goal for the beginning of DEMO operation.

A key parameter for DEMO is a reactor availability of 60% or better. On the assumption of a balance-of-plant availability of 85%, which is representative of average performances of conventional power plants, the DEMO plant availability goal is about 50%. This goal remains much lower than the 75–80% availability required in commercial power plants. Therefore previous studies stated 50% as a lower limit for the DEMO plant availability goal. However, our results discussed later in this paper suggest that this 50% requires very high blanket availability (above 95%), which may be a very difficult goal to achieve with any foreseeable development program. Therefore we introduce here the notion that DEMO could operate in two stages. The plant availability goal for the first stage is reduced to 25%, while that for the second stage remains at 50%. Obviously, this scenario of staged operation defers achieving the demonstration goals required by utility and industry. However, the compelling need to consider such a scenario will be evident later in this paper.

We attempted to derive specific technical goals for the performance parameters of the blanket in DEMO. The results are shown in Table 6. Note that the blanket and first-wall development, including the choice of blanket concept and the extent of testing, is influenced considerably by the power density. Commercial power reactors [12–14] will probably operate at a much higher wall load than with the DEMO. Ideally, the goals for blanket development should be those of the ultimate commercial reactor. However, we selected here more modest goals for the blanket derived directly from the DEMO requirements. The ratio of peak to average neutron wall load in typical tokamak designs is about 1.2–1.5. The surface heat flux has tremendous impact on the selection of materials and designs for first wall. However, since the first-wall surface area is about an order of magnitude larger than that of the diverter plates, it appears prudent to radiate most of the α-power to the first wall. In developing Table 6, we required that the first would be able to handle up to 80% of the α-power including a peaking factor of about

Table 6
Specific technical goals for DEMO blanket performance parameters and availability

Neutron wall load	
Average	2–3 $MW\,m^{-2}$
Peak	3–4 $MW\,m^{-2}$
Surface heat flux	
Average	0.6 $MW\,m^{-2}$
Peak	1.0 $MW\,m^{-2}$
Peak magnetic field (in blanket region)	11 T
Blanket availability [a]	
System	97.6%
Module (assuming 80 modules)	99.97%
Blanket mean time between failure (MTBF)	See Table 22
Blanket mean down-time to replace (MTTR)	See Table 22
Blanket lifetime	10–20 MW years m^{-2}
Non-vulnerable tritium inventory	<500 g
Decay heat/operating power at shut-down	<0.4%
Radioactivity level per watt of thermal power	<1 Ci
Material long-term radioactivity	Recyclable within 100 years
(surface γ dose 100 years after shut-down)	<25 $\mu Sv\,h^{-1}$

[a] For the initial stage of operation, if the DEMO reactor availability is 30%, then the blanket system and module availabilities are 37.4% and 97.9% respectively.

Table 7
Requirements on blanket system availability as a function of reactor availability

Reactor availability (%)	Blanket system availability (%)
75	>99
59	97.6
56	90
52	80
37	50
31	40

1.67. The peak magnetic field in the blanket region of about 11 T is consistent with recent tokamak designs for ITER, DEMO and power reactors which require high toroidal field in the coils [5,12,15–17].

Table 6 indicates the goal blanket availability. This parameter will be shown later to be the most demanding on blanket development. Bünde [18,19] analyzed the availability allocation among components of a fusion reactor system. Similar studies were also performed in INTOR [20,21], STARFIRE [13] and DEMO [4]. The requirements on blanket availability as a function of reactor availability are given in Table 7. For a DEMO with reactor availability of 60%, the blanket system availability needs to be about 98%. The implications of these availability requirements on the MTBF and MTTR of a failed component will be addressed later.

The required MTBF for a blanket module as a function of MTTR will be calculated in Section 6 for two cases of DEMO reactor availability: 60% and 30%. The MTBF requirements are long and will be shown later (in Section 6) to be a major driver on testing and development requirements.

The last group of parameters in Table 6 relates to goals in the safety and environmental impact areas. The decay heat limits are set so that, with proper design, no damage of any part of the blanket will occur under loss of coolant conditions. The long-term radioactivity limits are obtained by requiring that all materials, particularly structural materials, can be recycled within 100 years after final shut-down. Other important goals can be set in this area, but they will not significantly change our requirements for testing.

4. Role and limitations of non-fusion facilities

Non-fusion facilities can and should play a role in FNT R&D because of availability and low cost. Information from testing in non-fusion facilities can help to reduce the risks and costs of the more complex inte-

Table 8
Capabilities of available fission reactors for blanket tests

Reactor	Location	Reactor power (MW)	Fast flux (neutrons $cm^{-2} s^{-1}$)	Thermal flux (neutrons $cm^{-2} s^{-1}$)	Dimension of irradiation channel (cm)	Effective core height (cm)
ATR	USA	250	3.7×10^{13}	2.48×10^{14}	3.81 (circular)	122
			5.25×10^{14}	4.64×10^{14}	1.59 (circular)	
			1.9×10^{14}	8.8×10^{14}	6.05 (7 flux traps)	
HFIR	USA	100	1.5×10^{15}	2.3×10^{15}	3.7 (circular)	51
EBR-II	USA	62	2.0×10^{15}		7.4 (circular)	36
RBT-10	Russia	10	4.4×10^{13}	2.3×10^{13}	15.8 × 23.7	35
IVV-2M	Russia	20	9.3×10^{13}	5.5×10^{13}	14.7 × 25.5	50
SM-3	Russia	100	2.2×10^{14}	8.8×10^{13}	16 (circular)	35
					6 (circular)	
OSIRIS	France	70	5.0×10^{14}	1×10^{14}	8.4 (circular)	60
SILOE	France	35	5.0×10^{14}	4.0×10^{14}	8.0 (circular)	60
BR-2	Belgium	60	6.0×10^{14}	1.0×10^{15}	20 (circular)	96
HFR	Netherlands	20	5.0×10^{14}		14.5 (cricular)	60
KNK	Germany	60	2.0×10^{15}	2.0×10^{14}	10 (circular)	60
JRR-2	Japan	10	1.0×10^{14}	1.0×10^{14}		
NRU	Canada	125	4.0×10^{13}	2.4×10^{14}	10 (circular)	300

grated tests in the fusion environment. However, a major point to be stressed here is that tests in non-fusion facilities have very serious limitations. Blanket concepts cannot be verified in non-fusion facilities, not to mention component engineering development and reliability growth. Non-fusion facilities tests cannot replace the need for a comprehensive testing program in fusion facilities; they can only help to reduce the costs and risks of the early stages of this program. Non-fusion facilities can be classified into (a) non-neutron test stands, (b) fission reactors and (c) point neutron sources. Each of these is disucssed briefly below.

4.1. Non-neutron test stands

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 the neutron field is not important. Since neutrons are the only practical source of nuclear heating in a large volume as well as radiation effects, the value of non-neutron test stands is limited. Studies in the early 1980s have assumed that MHD tests without neutrons for liquid-metal concepts are possibly able to perform concept verification tests. Such an assumption is no longer valid. It is clear now that the toroidal magnetic field in tokamaks will most likely be high (greater than 12 T at the coils). Therefore electrical insulators must be used inside the blanket to reduce the MHD drop to an acceptable level. Concepts for self-healing coatings (e.g. aluminum oxide with LiPb) have been proposed. One of the fundamental feasibility issues relates to the imperfections in such coatings: (a) the speed at which they occur, (b) the speed at which they heal and (c) their effect on MHD pressure drop. These problems are strongly dependent on nuclear heating effects (e.g. temperature and stress magnitude and gradient) as well as radiation damage effects. Therefore an experiment with a prototypical test section in an environment that combines neutrons and a magnetic field is necessary to establish the feasibility of self-cooled liquid-metal concepts. Such a combination with the large test volume required is practically available only in a fusion test facility as will be clear from Sections 4.2 and 4.3.

The above examples do not argue against tests in a non-neutron environment. They only emphasize the fact that feasibility of blanket concepts cannot be established prior to testing in the fusion environment. Experiments in non-neutron test stands are relatively low in cost and they are important and useful in reducing the large costs and risks associated with future tests in the fusion environment.

Table 9
Key limitations of fission reactors

- (1) Small test volume:
  - (a) small size per location;
  - (b) small number of existing locations
- (2) Lack of fusion-related (non-neutron) conditions:
  - (a) magnetic field;
  - (b) surface heat;
  - (c) particle flux;
  - (d) mechanical forces
- (3) Different radiation damage simulation:
  - (a) neutron spectra;
  - (b) He-to-displacements-per-atom (dpa) ratio;
  - (c) types and rates
- (4) Power density:
  - (a) magnitude;
  - (b) spatial profile
- (5) Lithium burn-up rate:
  - (a) magnitude
  - (b) spatial profile
- (6) Reactivity considerations limits on size and type of experiments
- (7) Availability of fission test reactors for testing (rapid downward trend)

4.2. Fission reactors

Fission reactors provide neutrons in a limited volume and are thus suited to some FNT experiments. Table 8 summarizes the capabilities of fission reactors available in the USA, Canada, Russia and Europe for blanket tests. Testing in fission reactors suffers from serious limitations which are listed in Table 9. Most serious is the small test volume. For example, there is no fission reactor operating now anywhere in the world that can provide a test location with 15 cm or greater equivalent circular diameter at a fast neutron flux equivalent to 1 MW m^{-2} wall loading (1×10^{15} neutrons cm^{-2} s^{-1} or greater). This limitation, together with some safety aspects of fission reactors, also makes the simulation of non-nuclear effects such as magnetic field and mechanical forces very difficult or impossible. Another set of problems arises from the difference between the fission and fusion reactor neutron and secondary γ-ray spectra. These differences lead to difficulties in simulating the magnitude, profile and time-dependent behavior of reaction rates such as helium and tritium production, as well as power density and atomic displacements.

Despite these limitations, fission reactor testing is extremely useful for near-term FNT experiments. It is suitable for some multiple-effect tests that depend on nuclear effects and are less sensitive to non-nuclear effects. Examples are tests of a unit cell of a solid breeder blanket to investigate tritium release behavior and some aspects of breeder–structure interactions.

4.3. Accelerator-based neutron sources

Accelerator-based neutron sources produce neutrons in such a small volume that they are normally called "point neutron sources". Deuterium–tritium point sources produce 14 MeV neutrons, and hence the correct fusion spectra, but their yield is limited technologically to about 10^{13} neutrons s^{-1}. Such a yield results in a very low neutron flux. Even at a small distance as close as 5 cm to the target, the neutron flux is more than five orders of magnitude lower than that in a fusion reactor with 1 MW m^{-2} wall load. Furthermore, the life of the target is limited to less than 100 h irradiation. Therefore the usefulness of DT point neutron sources is limited to neutronics experiments, e.g. measurements of tritium production rates. The flux is too low to produce nuclear heating or reactions at a rate that would permit other engineering experiments,

Table 10
Comparison of the present DT point neutron source (FNS) with the present plasma-based device (TFTR)

	TFTR	FNS
Neutron yield	2×10^{18} neutrons per shot	5×10^{12} n s^{-1}
Pulse length	≈ 1 s	Variable
Irradiation frequency	≈ 10 cycles day^{-1}	≈ 10 h day^{-1}
Neutron flux	At the first wall, 2×10^{12} neutrons cm^{-2} s^{-1}	At 5 cm from target, 6.4×10^{9} neutrons cm^{-2} s^{-1} At 1 m from target, 1.6×10^{7} neutrons cm^{-2} s^{-1}

Table 11
Neutron generation rate and average neutron energy from D–Li source

	Value for the following incident deuteron energies		
	30 MeV	35 MeV	40 MeV
Total neutron generation rate for a 250 mA D beam (neutron s^{-1})	6.46×10^{16}	8.36×10^{16}	1.035×10^{17}
Average neutron energy (MeV)	5.36	6.06	6.71
Neutrons (%) generated in the following ranges			
0–15 MeV	91.9	88.1	84.3
15–50 MeV	8.1	11.9	15.7

e.g. thermomechanics testing or measurements of significant radiation effects. An example of a state-of-the-art DT point neutron source is the FNS facility in Japan [22]. The capabilities of FNS are compared in Table 10 with those from recent DT shots in The Tokamak Fusion Test Reactor (TFTR) [23]. The Joint European Torus (JET) [24] provides performance comparable with the TFTR. It is interesting to note that even present plasma physics devices could provide a neutron flux several orders of magnitude higher than DT point neutron sources. The key problem with present tokamaks is obviously the plasma pulse length as well as the number of plasma cycles per day.

Other proposals for accelerator-based neutron sources have been made. The most prominent is a proposal for a (D, Li) source in which neutrons are produced by bombarding a flowing lithium target with high energy (about 30–40 MeV) deuterons. The deuterons interact with the lithium jet atoms, either losing part of their energy through coulomb interactions or producing nuclear reactions some of which produce neutrons: $^7\mathrm{Li}(d, np)^7\overset{*}{\mathrm{Li}} \rightarrow \mathrm{T} + \alpha$, $^7\mathrm{Li}(d, 2n)^7\overset{*}{\mathrm{Be}} \rightarrow {}^3\mathrm{He} + \alpha$, $^7\mathrm{Li}(d, n)^8\mathrm{Be}$, $^7\mathrm{Li}(d, 3n)^6\mathrm{Be}$ and other reactions.

Design of a D–Li source (FMIT) was started [25,26] in the late 1970s in the USA and was later terminated during construction owing to a combination of funding problems and technological issues. Recently, an international activity under the auspices of the International Energy Agency (IEA) was started [27–29] to examine the need and issues for a D–Li source called the International Fusion Material Irradiation Facility (IFMIF). Examples of analysis of neutronics characteristics of IFMIF-type facilities are given in [29–31].

One advantage of such a source is the existing experience with accelerators. Another potential advantage is the possibility to perform accelerated testing of radiation damage effects in material specimens if a high neutron flux can be produced at a reasonable cost. However, there are a number of technical issues that severely affect the usefulness of a D–Li source for FNT and material development. These include (1) neutron spectrum, (2) steep flux gradient and (3) the surface area and volume available for testing.

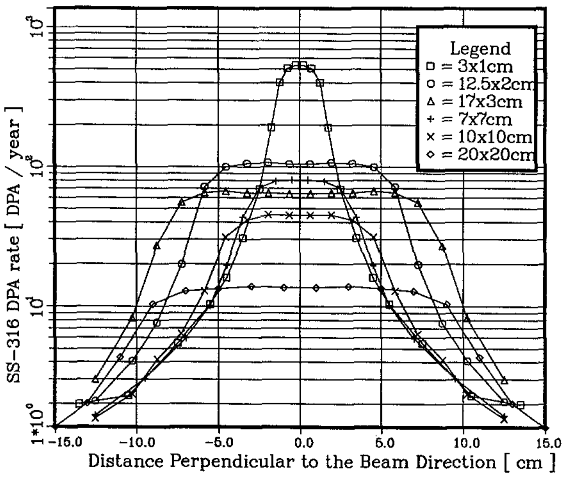

Fig. 2. Gradient of the type 316 stainless steel dpa rate perpendicular to the beam (current, 250 mA; deuteron energy, 35 MeV).

The D–Li neutron source produces neutrons with energies from the electronvolts up to about 50 MeV. This is compared with the fusion D–T reaction where neutrons are produced within a narrow energy range around 14 MeV. The neutron spectrum from the D–Li

Table 12
Surface area available for testing with a D–Li neutron source (35 MeV, 250 mA deuteron beam) to simulate first-wall conditions of a fusion reactor

(Equivalent) neutron wall load ($MW\,m^{-2}$)	Maximum surface area available for testing [a] (cm^2)	Comments
1	200	Possible with a beam spot area of 20 cm × 20 cm
3	50	Possible with a beam spot area of 10 cm × 10 cm

[a] Area perpendicular to the beam direction.

Table 13
Test volume available with dpa rate per year greater than a specified threshold for D–Li neutron source with a 35 MeV, 250 mA deuteron beam

$dpa\ year^{-1}$ [a]	Test volume (cm^3) for the following beam cross-sectional area	
	10 cm × 10 cm	20 cm × 20 cm
30	10	0
20	100	0
10	300	7

[a] Assuming a plant factor of 70% and stainless steel as typical material.

reaction varies with the incident deuteron energy. As shown in Table 11 [30], the fraction of the neutrons above 15 MeV increases from 8% to 15.7% when the incident deuteron energy is increased from 30 to 40 MeV. The average neutron energy is about 6 MeV for a 35 MeV deuterium beam. The low energy component of the D–Li source may be able to simulate qualitatively the neutron spectrum created by back scattering into a fusion reactor first wall. However, the high energy (greater than 15 MeV) component in the D–Li neutron spectrum is of concern. There, high energy neutrons can induce reactions with a high energy threshold which are not accessible to the lower energy neutrons of the D–T fusion reactor spectra. Furthermore, the accuracy of nuclear data above 14 MeV is generally poor. So, the concern here is whether radiation effects observed with D–Li neutron spectra can be accurately correlated to those in a fusion reactor. Available models to correlate neutronics parameters such as dpa, helium production rates etc. to observed macroscopic behavior of materials are not reliable.

An accelerator-based neutron source produces a neutron yield that is highly anisotropic. Furthermore, the neutron spectra are dependent on the angle (relative to the beam direction). This leads to gradients in the neutron flux in all directions at the test sample. Of particular concern are the directional gradients in the plane perpendicular to the direction of the deuteron beam. Fig. 2 from [31] shows the dpa rate in a direction perpendicular to the beam. Gradients in the direction along the beam are much steeper. At the first wall of the tokamak, the gradients in the toroidal direction are very small, and in the poloidal direction are typically less than $0.1\%\,cm^{-1}$. The flux gradient at the test samples with a D–Li source can be reduced for a given test area by increasing the beam focus area. However, this reduces the magnitude of local neutron flux.

The most serious issue that severely limits the usefulness of a D–Li source is the available space for testing and the type of test that can be performed. This problem has not received in the literature the comprehensive analysis required to judge the merits of a D–Li source. Key points related to this testing space issue are treated briefly below.

Optimization studies for the D–Li source suggest a 250 mA beam with 35 MeV deuterons. Fig. 2 shows the dpa rate per full power year in the direction perpendicular to the beam. Tables 12 and 13 show the test area and test volume respectively obtainable with a 35 MeV, 250 mA D–Li source. Table 12 shows the maximum surface area available for testing with rates of radiation damage indicators, e.g. dpa equivalent to that attainable with a given neutron wall load at the first wall of a tokamak reactor. Results show that the maximum surface area available for testing is 200 cm^2 (obtainable with a beam spot area of 20 cm × 20 cm) at an equivalent neutron wall load of 1 $MW\,m^{-2}$. The maximum test area with equivalent neutron wall load of 3 $MW\,m^{-2}$ is only 50 cm^2 (obtainable with a beam spot area of 10 cm × 10 cm).

Table 14
Space requirements for material property specimen tests for “material science” information on radiation effects on four candidate structural materials

Test description	Specimen configuration	Size (mm × mm × mm)	Material variables	Irradiation environment				Multi-plicity	Total number of specimens	Volume per specimen (cm^3)	Total volume (cm^3)
				Temp-erature	Fluence	Flux	Stress				
Charpy-V	$\frac{1}{3}$ CVN	(3.3 × 3.3 × 23.6)	4	7	4	1	0	8	896	0.26	235
Tensile	Flat	(0.76 × 25.4 × 5.0)	4	7	4	1	0	15	1680	0.10	162
Creep	Tube	(4.57 diameter × 23.0)	4	7	1	1	6	1	168	0.38	63
Swelling	Disc	(3.18 diameter × 0.25)	144	7	4	1	0	6	24192	0.002	48
Fracture toughness	Compact tension	(16 diameter × 2.5)	4	7	4	1	0	16	1792	0.5	901
Stress corrosion cracking	CERT SS-3	(0.76 × 25.4 × 5.0)	4	7	4	1	0	24	2688	0.10	259
Fatigue	Constant amplitude high cycle	(6.35 diameter × 38)	4	7	4	1	0	3	336	1.2	404
Total for all specimens (does not include volume for coolant and support)								—	31752	—	2072

Clearly, such a test area is not suitable for module or even submodule testing. Therefore D–Li sources cannot play a role in engineering development of FNT components and compatible material combinations. The question to be addressed here is whether such a source can fulfil the "material science irradiation" needs.

Irradiation testing of material specimens is a useful tool to supplement component tests. However, irradiation of small specimens alone without parallel component tests is not useful for component development because specimens will not simulate the critical environmental conditions such as material interfaces (e.g. coolant–breeder–structure), temperature and stress gradients, and joints. If component tests are carried out, then parallel tests on specimens are useful when a large number of specimens are irradiated to investigate the response of a number of candidate materials under a variety of conditions. Table 14 summarizes the space requirements for material specimen tests. Information in this table was first developed in INTOR [32,33] and subsequently improved in FINESSE [14,15,34,35] and ITER conceptual design activity studies [36–39]. The table is limited to structural materials and assumes that four candidate metallic alloys are to be investigated. Some observations are in order here. First, non-structural materials such as breeder and multiplier materials are not suitable for specimen tests because their issues (e.g. tritium transportation in solid breeders) require large volumes. Second, silicon carbide composites represent a leading candidate for structural materials in DEMO. It is only one of two materials (the other being vanadium alloy) that can meet the low activation and low decay heat requirements for attractive safety and environmental impact. The test volume required for ceramic matrix composites is much larger than that for metallic alloys because the fiber matrix behavior is not uniform, e.g. it is very different at a bend section from that in a straight section. Therefore requirements for testing SiC composites are excluded from this table. Third, for specimen tests to be useful, they have to be irradiated in a controlled environment, e.g. well-defined temperature. Controlling the temperature of the specimen requires cooling. Therefore the irradiation volume required for the test matrix is much larger than that obtained by summing up only the volume of the specimens. Practical requirements of cooling, support and instrumentation will considerably increase the test volume requirements.

On the basis of the above points, one concludes that the test volume defined in Table 14 is a minimum for the "material science irradiation" specimen matrix. Table 14 shows that more than 30 000 specimens are needed with a volume greater than 2000 cm^3. This volume does not include the additional space needed for cooling, support, instrumentation and other functions.

Table 13 shows the test volume available with a dpa rate greater than a specified threshold for a D–Li source. With a 20 cm × 20 cm beam focus, only 7 cm^3 is available with a dpa rate of 10 per year. With a 10 cm × 10 cm beam focus area, higher dpa rates are possible but still at very small test volume. The maximum test volumes at 30, 20 and 10 dpa year^{-1} are 10, 100 and 300 cm^3 respectively. These volumes are to be compared with the requirements of greater than 2000 cm^3 in Table 14 for four candidate structural material science specimen irradiation. Note that the DEMO has 2–3 MW m^{-2} as discussed earlier, while commercial fusion reactors will need about 3–5 MW m^{-2}. Also note that the dpa rate per full power year of operation in a tokamak first wall is about 11–12 for typical candidate structural materials. On the assumption of 70% plant availability for the D–Li source, dpa rates much greater than 50 dpa per full power year are needed if "accelerated" testing is to be possible.

Several important conclusions can be reached regarding the usefulness and limitations of a D–Li neutron source.

(1) Present concepts for the source are clearly limited in both neutron flux/power density and test area/volume; representative maximum test area/volume are 200 cm^2/300 cm^3 at an equivalent neutron wall load of 1 MW m^{-2}. This wall load is comparable only with ITER and is a factor of 3–5 lower than that for DEMO and power reactors.

(2) It is clearly not suitable for testing submodules of components.

(3) It is not suitable for testing important non-structural materials such as breeder and multipliers as the key issues for such materials require testing in a volume (e.g. tritium release and transport in solid breeders).

(4) It can be used for some structural material irradiation specimen testing; the major advantage relative to ITER is expected to be higher availability (about 70% compared with less than 10% in ITER); however, the test volume is not sufficient to do all the required material science specimen irradiation tests for one material. Since the flux in the D–Li source test region is not high, considerations of the test space–test time matrix need to be carefully analyzed.

(5) Results from specimen irradiation tests are generally meaningful only if performed in parallel to com-

Table 15
Capabilities of non-fusion facilities for simulation of key conditions for fusion nuclear components experiments

	Neutron effects [a]	Bulk heating [b]	Non-nuclear [c]	Thermal–mechanical–chemical–electrical [d]	Integrated synergistic
Non-neutron test stands	No	No	Partial	No	No
Fission reactor	Partial	Partial	No	No	No
Accelerator-based neutron source	Partial	No	No	No	No

[a] Radiation damage, tritium and helium production.

[b] Nuclear heating in a significant volume.

[c] Magnetic field, surface heat flux, particle flux, mechanical forces.

[d] Thermal–mechanical–chemical–electrical interactions (normal and off normal).

Table 16
Contribution of non-fusion facilities to resolving critical issues for fusion nuclear technology

Critical issues	Non-neutron test stands	Fission reactors	Accelerator-based neutron sources	
			D–T	D–Li
D–T fuel cycle self-sufficiency	None	None	Partial	None
Thermomechanical loadings and response of blanket components under normal and off-normal operation	Small	Small	None	None
Materials compatibility	Some	Some	None	Small
Identification and characterizations of failure modes, effects and rates	None	None	None	None
Effect of imperfections in electric (MHD) insulators in self-cooled liquid-metal blanket under thermal–mechanical–electrical–nuclear loading	Small	Small	None	None
Tritium inventory and recovery in the solid breeder under actual operating conditions	None	Partial	None	None
Tritium permeation and inventory in the structure	Some	Partial	None	None
Radiation shielding: accuracy of prediction and quantification of radiation protection requirements	None	Small	Partial	Small
Plasma-facing component thermomechanical response and lifetime	Some	Some	None	Some
Lifetime of first-wall and blanket components	None	Partial	None	Partial [a]
Remote maintenance with acceptable shutdown time	None	None	None	None

[a] Partial; substantial contribution when supplemented by fusion test; not meaningful in the absence of fusion tests.

ponent tests; therefore an IFMIF-type facility will be useful only if submodule tests and module tests are carried out in parallel in fusion facilities.

4.4. Summary of role and limitations of non-fusion facilities

It is important to assess the overall contribution of non-fusion facilities to the development of fusion nuclear technology. Table 15 summarizes the capabilities of non-fusion facilities for simulation of key conditions for fusion nuclear component experiments. The most important conditions are (1) neutron effects (radiation damage, tritium and helium production), (2) bulk heating (nuclear heating in a significant volume), (3) non-nuclear conditions (e.g. magnetic field, surface heat flux, particle flux and mechanical forces), (4) conditions for simulating thermal–mechanical–chemical–electrical interactions and (5) conditions for integrated tests and synergistic effects. A very important conclusion is that non-fusion facilities are not able to simulate partially integrated or integrated conditions. Their capabilities are limited mostly to single environmental conditions and some multiple-effect multiple-interaction experiments.

From the FNT development viewpoint, the most important question is the contribution of facilities to resolving the critical issues, which were presented earlier in Table 2. Table 16 shows the contribution of non-fusion facilities to resolving the FNT critical issues. The most striking result is that there is no critical issue that can be fully resolved by testing alone in non-fusion facilities. The second most striking conclusion is that there are critical issues for which no significant information can be obtained from testing in non-fusion facilities. An example is the identification and characterization of failure modes, effects and rates. Therefore the feasibility of blanket concepts cannot be established prior to testing in fusion facilities.

The word "partial" in Table 16 designates a contribution which is substantial when supplemented by fusion tests; otherwise, in the absence of fusion tests, no judgment can be rendered on the resolution of the critical issue.

It should be emphasized here once again that the above conclusions do not suggest that non-fusion facilities should not be used. They only suggest that their usefulness in resolving the critical issues is severely limited. Non-fusion facilities can and should be used to narrow materials and design concept options and to reduce the costs and risks of the more costly and complex tests in the fusion environment. The cost of tests in non-fusion facilities tends to be much smaller than that expected in the fusion environment; the only possible exception is tests in a D–Li source since none

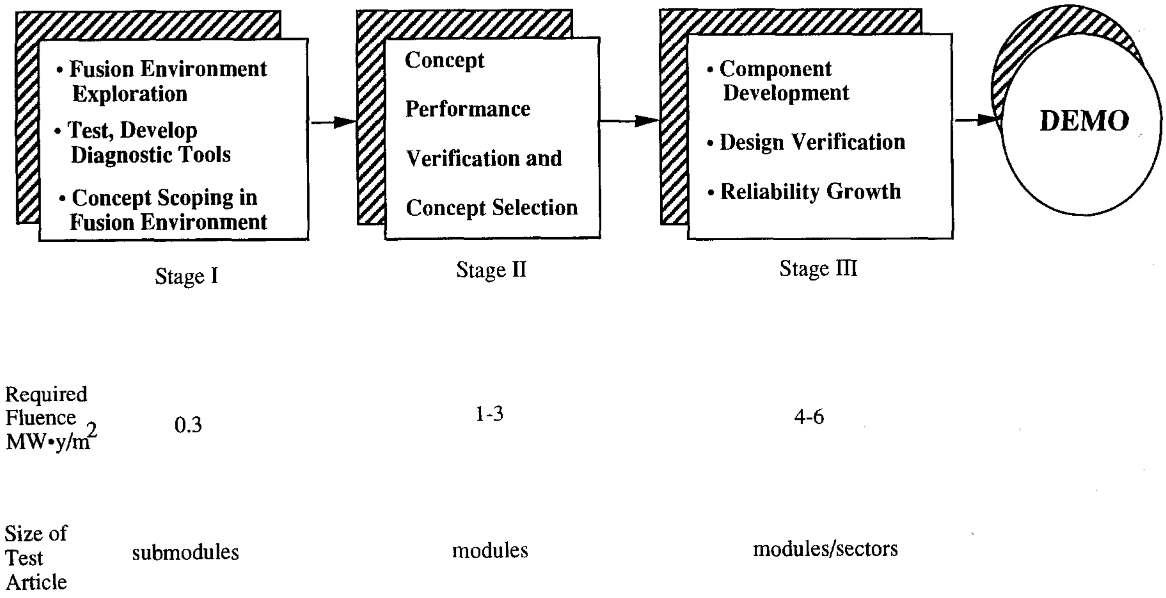

Fig. 3. Stages of fusion nuclear testing in fusion facilities.

exists at present and both the capital and operating costs are substantial.

The key conclusion from here is that fusion nuclear technology development does require fusion testing facilities.

5. Fusion nuclear technology requirement for testing in fusion facilities

The preceding section has shown that non-fusion facilities, albeit useful, are severely limited in simulating the key conditions for fusion nuclear component experiments and development (see Table 15). From the results in Table 16, it is clear that non-fusion facilities are unable to resolve any of the critical FNT issues. It is therefore very clear that testing in fusion facilities is an absolute necessity to develop fusion nuclear components. The key questions are as follows.

(1) What are the different stages of tests in the fusion environment required to qualify fusion nuclear components for DEMO operation?

(2) What are the requirements of FNT tests on the major parameters and characteristics of suitable fusion test facilities?

5.1. Testing stages and framework

Fig. 1, shown earlier, illustrated a loose chronological order of tests for a major nuclear component such as the blanket. Tests in non-fusion facilities are limited to single-effect and some multiple-interaction tests. Fusion tests need to cover several multiple-interaction tests, integrated tests and component tests.

In partial analogy to experience from technology development in other fields, we propose that testing and development of FNT (primarily the blanket) in fusion facilities proceed in three stages: stage I is the concept scoping in the fusion environment; stage II is the concept performance verification; stage III is the component engineering development and reliability (CEDAR) growth as illustrated in Fig. 3. Note that FNT components such as the blanket have never been tested before on any fusion facility. Therefore the first stage should be focused on calibration and exploration of the fusion environment as well as testing and development of experimental techniques and diagnostic tools (e.g. how we measure, collect data, and interpret and extrapolate results, and effects of the fusion environment on instrumentation tools). Submodules, rather than modules, should be used to save cost in this stage. Part of the fusion environment exploration is screening a number of candidate design concepts. Only a limited number of concepts are tested in the second stage which aims at performance verification. Modules should be used in this stage to ensure that all the key aspects of subsystem interactions are tested. Results of tests in stage II should permit selection of a very small number of concepts. This number should be two or three. It is risky to select one concept before performing reliability growth tests in stage III. In the meantime, since stage III tests are complex, costly and time consuming, the number of concepts should not exceed three. Stage III tests focus on true engineering development where actual prototypical components are tested to verify the final component design and to obtain data on reliability. As shown in a later section, tests (particularly reliability tests) result in failure and/or unacceptable performance. Therefore an aggressive design–test–fix iterative program is needed. More details on failure rates and reliability growth testing will be given in the next section. The extensive reliability testing required to achieve the goals for blanket availability is one of the primary reasons why blanket testing determines the critical path for FNT development.

5.2. Testing requirements on major parameters of fusion facilities

Satisfactory testing of the blanket in the fusion environment imposes important requirements on the design

Table 17
Fusion nuclear technology requirements on major parameters for testing in fusion facilities, with emphasis on testing needs to construct a DEMO blanket

Parameter	Value
Neutron wall load (MW m^{-2})	1–2
Plasma mode of operation	Steady state
Minimum continuous operating time (weeks)	1–2
Neutron fluence (MW years m^{-2}) at test module	
Stage I: scoping	0.3
Stage II: concept verification	1–3
Stage III: CEDAR growth	4–6
Total neutron fluence for test device (MW years m^{-2})	>6
Total test area (m^2)	>10

of the fusion testing facility in at least two areas: (1) major parameters and (2) engineering design. The major parameters of concern are those that have major impact on both the usefulness of the tests and the cost of the device. The requirements on the engineering design include providing capabilities for fast insertion and removal of test modules, access to the many coolant, tritium-processing and instrumentation lines, and suitably located space and facilities for ancillary equipment to support the test program (e.g. heat rejection system, tritium-processing facility, purification and chemical control systems, and instrumentation systems).

The FNT testing requirements on the major parameters for fusion facilities have been analyzed in several major studies [2,3,34–41]. International workshops have also helped to develop consensus on many of these requirements. However, recent interest in scenarios for fusion development facilities and the evolution of the ITER design during the engineering design activity (EDA) have made it necessary to investigate in more detail the FNT testing requirements. A summary of our results for the FNT requirements on major parameters for testing in fusion facilities is given in Table 17. The requirements given in Table 17 are driven by the goal of providing the database necessary to construct the blanket for DEMO.

There are other important requirements that are not given in Table 17, such as the value of the magnetic field in the blanket test region (e.g. to test liquid-metal blankets or effects of ferritic steel in magnetic performance), surface heat flux, and minimum test area per module. We limited Table 17 to those requirements that appear to be a major discriminating factor in the selection among options for fusion testing facilities. Other parameters not given in Table 17 are either implied or can be deduced from those already given or do not appear to be a crucial discriminating factor in the selection among options for fusion testing facilities. The technical basis for the values given in Table 17 are briefly summarized in the following subsections.

5.2.1. Neutron wall load

The minimum acceptable neutron wall load is derived from two factors: (1) engineering scaling considerations and (2) trade-offs between device availability and wall load for a given testing fluence and testing time.

Volumetric heating in the blanket is directly proportional to the wall load. Most thermomechanical and tritium-related phenomena in the blanket strongly depend on the temperature and stress profiles, which in turn are directly dependent on the heating rates. Since the wall load in a fusion test facility is likely to be much lower than that in DEMO (about 3 MW m^{-2}) and commercial plants (about 4–5 MW m^{-2}), engineering scaling considerations [2,3,40] are crucial. Useful testing at reduced wall load, relative to DEMO and reactor conditions, is possible by altering the design and operating parameters of the test modules. Test modules must "act like" rather than "look like" a DEMO module. Generally, bulk average temperatures are easy to maintain by varying the coolant speed and flow rate. Temperature distributions within components are much more difficult to maintain. Some control over temperature distributions can be obtained by changing the thickness of blanket elements within the blanket as well as the overall dimensions of the test module. However, very large changes in sizes lead to new effects and an overall geometry that is much less representative than a real DEMO or commercial blanket. It is found that engineering scaling techniques are useful, particularly in simulating individual effects. However, two important conclusions are reached: (1) engineering scaling techniques require that, for any one given blanket design, several test modules must be designed, each focusing on a different group of phenomena, effects and technical issues; (2) the confidence in extrapolation of test results to the DEMO and commercial reactors drops sharply when the wall load in the test facility is reduced by a factor of more than 2–3 relative to that in DEMO and commercial power plants. Therefore a neutron wall load of 1–2 MW m^{-2} is necessary in the fusion test facility. The confidence level in extrapolating the test results is higher for higher wall load. The surface heat flux has a major influence on blanket thermomechanics, particularly for the first wall. Thus prototypical ratios of the surface to bulk heating should be preserved.

Table 18
Neutron wall load and availability required to reach 6 MW years m^{-2} goal fluence in 12 calendar years

Neutron wall load (MW m^{-2})	Availability [a] (%)
1	50
1.5	33
2	25
2.5	20

[a] For pulsed plasma operation, this becomes the product of availability and plasma duty cycle. Therefore, at any given wall load, a higher availability would be required.

Another requirement on the wall load is the need to achieve a reasonable fluence in a given calendar time. The integrated neutron wall load I is given by $I = P_{nw}At$, where P_{nw} is the neutron wall load, A is the device availability and t is the operating period. As discussed later, the goal of FNT testing should be to reach about 6 MW years m^{-2} in 12 calendar years. Table 18 shows the relationship between wall load and availability. The device availabilities required at wall load of 1 and 2 MW m^{-2} are 50% and 25% respectively. The present ITER EDA design [17] plans on achieving less than 10% availability. Consequently, a higher wall load is needed. Since the fusion device size and cost increases with wall load (at present the ITER reference wall load is about 1 MW m^{-2}), improvements in achievable device availability are also necessary.

5.2.2. *Fluence and test area*

One of the most critical parameters of primary interest to testing is fluence. The required fluence for testing blankets prior to DEMO also has substantial impact on the selection scenarios and design of fusion testing facilities.

Fluence requirements for FNT were developed by considering the following factors: (1) time required to perform basic and multiple effects experiments to observe groups of phenomena and to resolve technical issues associated with particular aspects of the blanket design (e.g. tritium release in solid breeders, and thermomechanical interactions); (2) time required to observe integrated behavior past the beginning of life and during periods of significant radiation-induced changes in material properties and component behavior; (3) time required to obtain data on key issues related to long-term component and system behavior such as corrosion and mass transfer, chemical reactions, stress relaxation, breeder burnup and tritium build-up and containment; (4) time required to obtain data on failure modes, effects and rates; (5) time required to perform the three stages, namely stage I (scoping), stage II (concept verification) and stage III (component engineering development and reliability growth tests), where the reliability growth testing phase is the most demanding on fluence requirements.

Before we proceed further, some definitions are necessary to ensure clarity.

The machine lifetime fluence I_d refers to the time-integrated neutron wall load at the first wall during the machine lifetime:

$$I_d = P_{nw} A_d t_d$$

where P_{nw} (MW m^{-2}) is the average neutron wall load at the first wall of the fusion testing facility, A_d is the machine availability averaged over t_d and t_d (years) is the machine lifetime. The test module fluence I_m is the time-integrated wall load as received at the front (first) wall of the test module:

$$I_m = P_{nw} A_m t_m T$$

where P_{nw} is as above, A_m is the machine availability integrated over t_m, t_m (years) is the time during which

Table 19
Summary of expected radiation-induced effects on blankets in the 0–3 MW years m^{-2} fluence range

0–0.1 MW years m^{-2} (at test module)
Some changes in thermophysical properties of non-metals occur below 0.1 MW years m^{-2} (e.g. thermal conductivity)

0.1–1 MW years m^{-2} (at test module)
Several important effects become activated in the range 0.1–1 MW years m^{-2}:
(1) radiation creep relaxation;
(2) solid breeder sintering and cracking;
(3) possible onset of breeder–multiplier swelling;
(4) He embrittlement
Correlation of materials data with fission reactors can probably be done with about 1 MW years m^{-2}

1–3 MW years m^{-2} (at test module)
Numerous individual effects and component (element) interactions occur here, particularly for metals, e.g.
(1) changes in ductile-to-brittle transition temperature;
(2) changes in fracture toughness;
(3) He embrittlement;
(4) breeder and burn-up effects;
(5) breeder and multiplier swelling;
(6) breeder–clad interactions

a test module is placed in the machine and T is the transmission factor (equivalent fraction of neutron wall load that reaches the test module).

In the literature, the integral wall load is quite often referred to as fluence. Despite the obvious misnomer here (fluence can be obtained from the expressions above for I_d and I_m by replacing P_{nw} with the total neutron flux), we shall occasionally follow the literature, relying on the units to make the distinction clear (megawatt years per square metre for I and reciprocal square metres for the true fluence).

The machine lifetime fluence can be much greater than the test module fluence because normally no test module is inserted for the entire lifetime t_d of the machine, and because the transmission factor T is always less than unity. In the test program as currently envisaged, there are three stages of nuclear testing: scoping, concept verification and reliability growth. Different test articles may be used in each stage. During testing, some test articles are likely to fail or require replacement, also limiting the time any single test article can be irradiated.

Tests may be specified with isolation from the plasma for reasons of safety, reliability and ease of maintenance. The existence of plasma-facing components, first-wall and multiple-containment structures for some tests reduces the neutron flux and energy spectrum at the test module. Reductions in neutron effects may be a factor of as much as 2 at the location of the tests owing to a typical 1–2 cm steel and water enclosure.

The scoping phase cumulative fluence at the test articles has been derived by considering several aspects. One of these is the testing time required for individual and multiple-effects tests at the beginning of life. Examples include thermomechanical and tritium release tests. Rapid changes occur in the beginning of life under irradiation in the range of 0–0.3 MW years m^{-2} (beyond this fluence, important changes still occur, but at a slower rate). This is one reason for selecting 0.3 MW years m^{-2} as the fluence goal for the scoping test stage. Another reason is derived from the time to reach equilibrium for certain phenomena. Many phenomena such as tritium release and tritium permeation to the coolant, which will be discussed later, reach equilibrium in about 1–2 weeks. Therefore each test campaign must be performed with continuous machine operation (100% availability) for about 1–2 weeks. About ten test campaigns are needed to perform tests under different conditions (temperature, flow rate, chemistry etc.) to explore relevant phenomena and submodule behavior fully. On the assumption that P_{nw} in the fusion testing facility is about 1–2 MW years m^{-2}, the scoping phase requires a fluence in the range 0.2–0.7 MW m^{-2}. Consequently, the 0.3 MW years m^{-2} specified for the scoping tests is at the lower end of what is needed.

Concept performance verification is aimed at verifying performance beyond the beginning of life and in the regime where changes in properties nearly saturate. Since concept verification testing results will be used to reduce sharply the number of specific blanket design concepts to only two or three, it is necessary that testing in this stage is sufficiently long to observe behavior under near steady state conditions. It is essential that the system behavior be observed when long-equilibrium-time phenomena, such as corrosion and mass transfer, tritium permeation and containment, stress relaxation and a variety of radiation effects, have reached some type of equilibrium. Table 19 presents a summary of expected radiation induced effects in blankets in the 0 to 3 MW years m^{-2} fluence. Changes in mechanical properties of structural materials start to saturate around 2 MW years m^{-2}. During the concept verification stage, it is not necessary nor practical to test components to their design end of life. However, it is desirable to test for a sufficiently long time, e.g. one third to one half of the projected life in order to provide confidence in concept selection. Therefore a fluence of 1–3 MW years m^{-2} is suggested for the concept verification phase.

Stage III consisting of CEDAR tests is concerned with integrated behavior and endurance tests. The focus here is primarily on failure modes, effects and rates. Because these tests are very demanding and require integrated component tests, the number of concepts to be tested should be limited. However, selecting one design concept at the end of concept verification, i.e. the beginning of the reliability testing stage, involves unacceptable risks because attaining the desired reliability goals may not be possible for a given concept regardless of how much testing and modifications in the design are made. Therefore, the number of blanket concepts at the beginning of stage III should be two or three.

The required fluence during the CEDAR stage can be derived in several ways. One simple method is that experience from other technologies require testing to more than one half the lifetime. Since the goal for DEMO is 10–20 MW years m^{-2}, the CEDAR fluence goal should be about 5–10 MW years m^{-2}. This argument is too simplistic because (1) reliability growth testing is concerned with failure rates during service, which may be fairly independent of the lifetime (failure is defined as the ending of the ability of a design element to meet its function before its allotted lifetime is achieved, i.e. before reaching the operating time for which the element was designed) and (2) the fluence requirement for testing will have major consequences on the design and cost of the testing facility and therefore a more quantitative investigation of fluence needs is necessary.

As a point of departure for this study, we have attempted to derive quantitative guidelines for testing requirements, including fluence, by applying available reliability analysis and statistical methods to the fusion blanket reliability testing problem.

The results are given in the next section and can be briefly summarized for our purposes here. The results show that attaining a DEMO reactor availability of 60% which implies blanket system availability of 98% requires greater than 20 MW years m^{-2} testing fluence. Such a high testing fluence is practically unattainable because (1) it greatly exceeds the estimated lifetime expected for any blanket to be developed in the time frame of interest and (2) it cannot be achieved in a reasonable time with a fusion testing device that has 1–2 MW years m^{-2} wall load and 30% availability. The results also show that benefits increase with increasing neutron fluence at a relatively high rate up to a testing fluence of about 5 MW years m^{-2}. Beyond this fluence, the rate of increase in benefits becomes much slower. Therefore we have selected about 4–6 MW years m^{-2} as a target for fluence testing, which makes it possible to achieve a DEMO reactor availability of 50% with the optimistic assumptions of an MTTR of 1 week and the simultaneous testing of 12 modules for a given blanket concept. The subject is examined in more detail in Section 6.

Considering the fluence requirements of the three stages of testing, i.e. scoping (0.3 MW years m^{-2}), concept verification (1–3 MW years m^{-2}), and reliability growth (4–6 MW years m^{-2}), the total fluence required for FNT testing is greater than 6 MW years m^{-2}.

The minimum surface area at the first wall for a test module is about 0.36 (60 cm × 60 cm) based on engineering scaling considerations. Some blanket concepts, e.g. those with self-cooled liquid-metal breeders or ceramic matrix composite structure, might require a larger test module area. Assuming two to three blanket concepts to be tested in parallel during the reliability testing stage and 12 test modules per concept, the total testing area required at the first wall is greater than 10 m^2. This area is also sufficient for the scoping stage and concept verification stages. The scoping stage will have a larger number of concepts but the size of the test submodules can be smaller. During concept verification, four to six concepts may be tested but the number of modules per concept can be only four to five.

Table 20
Characteristic time constants in solid breeder blankets

Process	Time constant
Flow processes	
Solid breeder purge residence time	6 s
Coolant residence time	1–5 s
Thermal processes	
Structure conduction (metallic alloys 5 mm)	1–2 s
Structure bulk temperature rise	
5 mm austentic steel, water coolant	≈1 s
5 mm ferritic steel, He coolant	5–10 s
Solid breeder conduction	
Li_2O (400–800 °C)	
10 MW m^{-3}	30–100 s
1 MW m^{-3}	300–900 s
$LiAlO_2$ (300–1000 °C)	
10 MW m^{-3}	20–100 s
1 MW m^{-3}	180–700 s
Solid breeder bulk temperature rise	
Li_2O (400–800 °C)	
10 MW m^{-3}	30–70 s
1 MW m^{-3}	80–220 s
$LiAlO_2$ (300–1000 °C)	
10 MW m^{-3}	10–30 s
1 MW m^{-3}	40–100 s
Tritium	
Diffusion through steel	
300 °C	150 days
500 °C	10 days
Release in the breeder	
Li_2O, 400–800 °C	20–30 h
$LiAlO_2$, 300–1000 °C	20–30 h

5.2.3. Plasma cycle parameters and continuous operating time

There are two areas of time-related parameters that have a major impact on testing. The first is the plasma mode of operation, specifically the plasma burn time and dwell time. The second is the minimum continuous operating time (COT), i.e. the minimum time required for continuous operation of the device with 100% availability.

At present, the designs for DEMO and commercial reactors are based on steady state plasma operation because pulsing increases the capital cost [8,12,13,42,43] and has a large negative impact on reactor component

Table 21
Characteristic time constants in liquid-metal breeder blankets

Process	Time constant
Flow processes	
Coolant residence time	
First wall ($V = 1$ m s^{-1})	≈30 s
Back of blanket ($V = 1$ cm s^{-1})	≈100 s
Thermal processes	
Structure conduction (metallic alloys, 5 mm)	1–2 s
Structure bulk temperature rise	≈4 s
Liquid breeder conduction	
Li	
Blanket front	1 s
Blanket back	20 s
LiPb	
Blanket front	4 s
Blanket back	300 s
Corrosion processes	
Dissolution of Fe in Li	40 days
Tritium processes	
Diffusion through	
Ferritic steel	
300 °C	2230 days
500 °C	62 days
Vanadium	
500 °C	47 min
700 °C	41 min
Release in the breeder	
Li	30 days
LiPb	30 min

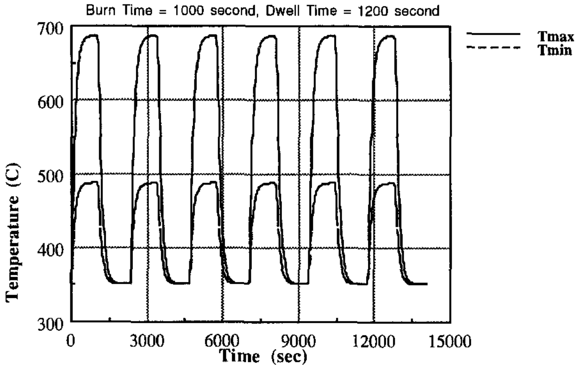

Fig. 4. Scaled-up Li_2O breeder temperature response to 1 MW m^{-2} pulsed wall load (blanket front position; $q''' = 9.4$ MW m^{-3}).

reliability and failure rate. Therefore steady state plasma operation is desirable for FNT testing in order to simulate well the DEMO reactor environment. However, devices such as ITER are based on pulsed plasma mode of operation. We have examined the effects of plasma pulsing on blanket testing and we attempted to derive requirements on the plasma burn time t_b, dwell time t_d and plasma duty cycle $t_b/(t_b + t_d)$.

Pulsing results in time-dependent changes in the environmental conditions for blanket testing, such as volumetric nuclear heating, surface heating, poloidal magnetic field and the production of tritium and other neutron-induced reactions. Key blanket test issues to be affected by these time-dependent environmental changes include thermal and fluid processes, structural response and tritium release, diffusion and inventory. The characteristic time constants calculated for these processes are shown for typical solid breeder and liquid-metal blankets in Tables 20 and 21 respectively. The characteristic time constant provides an indication of how fast a response will rise during the plasma start-up and burn, and how quickly it will decay during plasma shut-down and dwell time. For a given response F, such as temperature, the time dependence can be approximated during the burn as

$$F = F_0\left[1 - \exp\left(-\frac{t}{\tau}\right)\right]$$

and during the dwell as

$$F = F_0 \exp\left(-\frac{t}{\tau}\right)$$

where τ is the time constant. The allowable variation in a response during a specific test should be no greater than 5% because (a) small changes in some fundamental quantities result in large changes in important phenomena, i.e. 5% change in solid breeder temperature results in a factor of 5 change in the tritium diffusion time constant, and (b) the goal of a test is not just reaching equilibrium but it is to stay at equilibrium long enough to observe behavior. If we are to preserve a response within 95% of equilibrium value, the guidelines should be

$$t_b > 3\tau \qquad t_d < 0.05\tau$$

Tables 20 and 21 show that the time constants vary from a few seconds for thermal processes in the structure to several weeks for tritium processes and corrosion. A critical point to note is that most blanket issues and phenomena are temperature dependent. Therefore preserving temperature in the test modules is necessary.

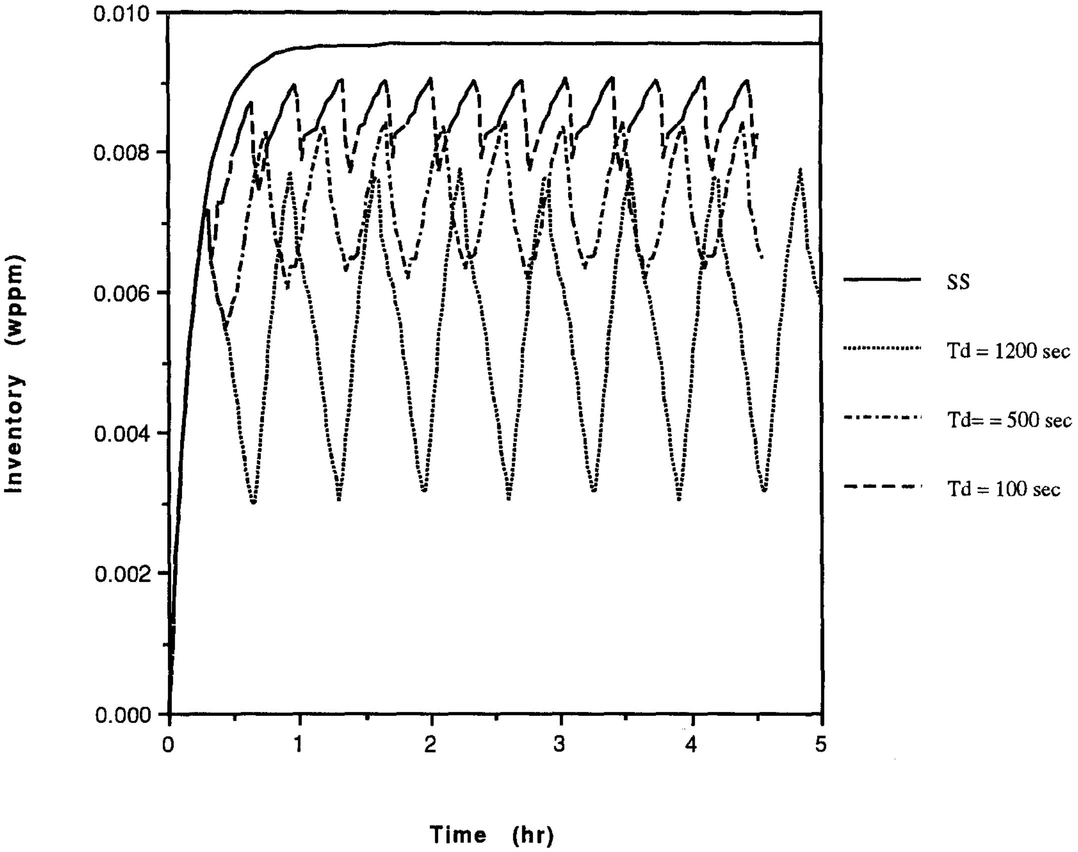

Fig. 5. Effect of dwell time on tritium release and inventory in Li_2O (blanket front; $q''' = 15\ \mathrm{MW\ m^{-3}}$; burn time, 1000 s).

This makes the requirements on burn time and dwell time difficult. A process with a long time constant, e.g. tritium release in solid breeders requires a long burn time ($\tau > 20$ h) to reach 95% of equilibrium value but during the dwell time it will be quickly affected by the rapid temperature drop since the temperature in high power density regions has $\tau \approx 30$ s.

Desirable values for the burn time can be derived from the time constant approximations. The burn time must be longer than 3τ for important processes with the longest time constants. The dwell time should be shorter than 0.05τ for the processes with the shortest time constants. From calculations in Tables 20 and 21 the burn time needs to be several days and the dwell time should not exceed a few seconds. Clearly, this is a very difficult requirement to meet in a tokamak designed strictly for pulsed operation. The dwell time is determined by many considerations including the time to evacuate the plasma chamber and more importantly the time to cool down and reset the poloidal coils. Obtaining a long burn time in a relatively small size machine with pure inductive current drive is not possible. For example, ITER EDA [17] has 1000 s burn and 1200 s dwell time.

Fig. 4 shows the maximum and minimum temperature response of Li_2O in a position inside a breeder blanket test module under the ITER pulsed conditions of $t_b = 1000$ s and $t_d = 1200$ s with plasma start-up and shut-down times of 50 s and 100 s, respectively [44]. The figure shows that the breeder temperature barely reaches steady state during the burn and drops to the inlet coolant temperature during the dwell time (the coolant inlet temperature was kept constant during the dwell by external means). Fig. 5 shows the effect of the dwell time on the tritium release and inventory in Li_2O. Long dwell times will make interpretation of tritium release very difficult and could lead to occurrence of phenomena not otherwise accessible in steady state operation.

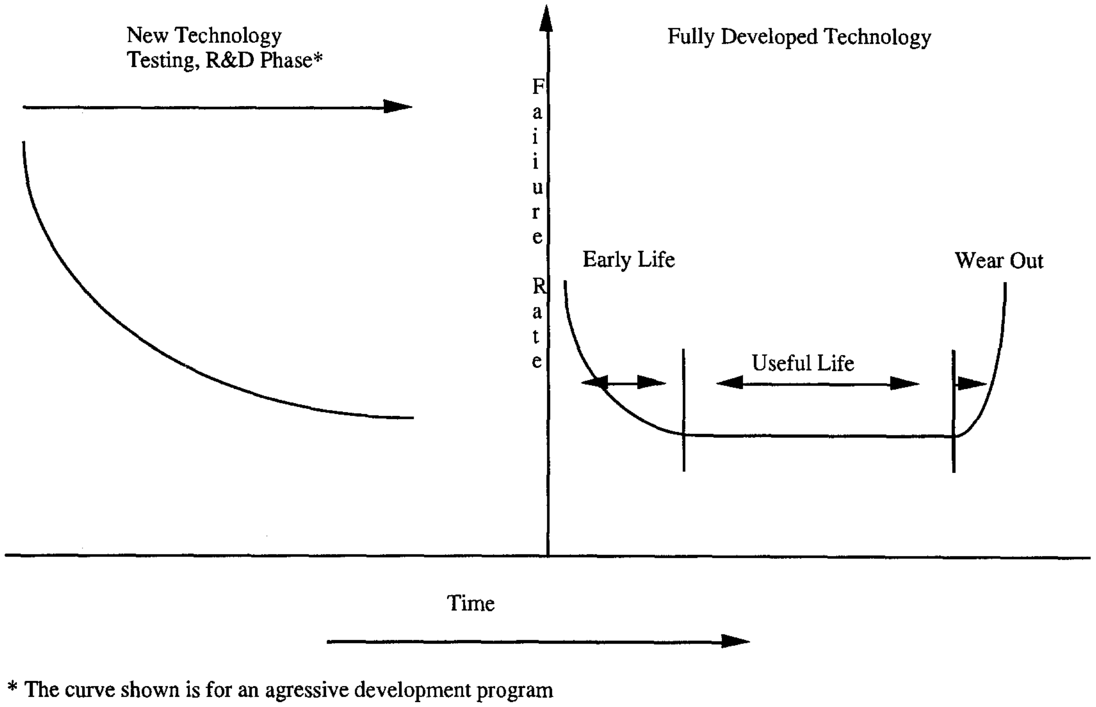

Fig. 6. Schematic failure rate vs. time during development and after development.

There is a need to provide many periods for test campaigns. During each period the device must operate continuously (i.e. at 100% availability or load factor). This COT is for steady state plasma operation or back-to-back plasma cycles in a pulsed system. The COT allows continuous operation of test modules to reach equilibrium and to observe cumulative effects, e.g. some radiation-induced changes, failures and other nuclear phenomena. This COT is calculated to be about 1–2 weeks. On the basis of the time constants shown earlier, shorter periods will result in a loss of substantial test information.

We conclude that steady state plasma operation is very highly desirable for FNT testing. If pulsing is unavoidable, then the plasma duty cycle should be greater than 80% with the burn time greater than 1000 s in order to achieve quasi-equilibrium for the most important processes.

6. Failures and reliability testing in fusion facilities

One of the most serious concerns in the engineering development of a component, particularly for new technology, is failure. Failure is defined here as the ending of the ability of a design element to meet or continue its function before its allotted lifetime is achieved, i.e. before reaching the operating time for which the element is designed.

Causes of failures include (1) errors in design, manufacturing, assembly and operation, (2) inadequate design codes, (3) lack of knowledge and experience, (4) insufficient prior testing and (5) random occurrence despite available knowledge and experience.

Experience from other technologies shows [45] that the failure rate λ during the lifetime of a component for fully developed technology generally looks like a "bathtub" curve as shown schematically in Fig. 6. High failure rates are experienced during early life, which decrease with time until it reaches a "steady state" value λ_b at the "bottom of the bathtub". This steady state value λ_b remains generally constant with time until near the end of the component life when the failure rate increases with time during the "wear-out" period. The value of λ_b may actually decrease or increase moderately during operation. A key question for FNT development is the vlaue of λ_b for the blanket, what the goal value is for λ_b and how to achieve it through testing.

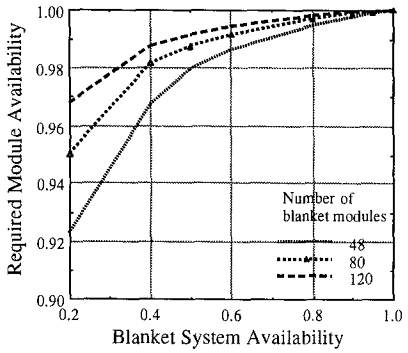

Fig. 7. Required blanket module availability as a function of blanket system availability for different numbers of blanket modules.

Table 22
Required DEMO blanket module mean time between failure as a function of mean time to replace for two values of DEMO reactor availability (A = 30% and A = 60%)

MTTR	MTBF_n (full power years)	
	A (reactor) = 60%	A (reactor) = 30%
1 week	62	0.92
2 weeks	125	1.84
1 month	271	3.98
2 months	542	7.96

Note that we assume that there are 80 modules in the blanket system and that $\mathrm{MTBF}_{\mathrm{BS}} = \mathrm{MTBF}_n/80$.

Experience shows that the value of λ_b for new technology is high and decreases with testing during the R&D phase as illustrated on the left-hand side of Fig. 6. Such a reduction in failure rate λ, or equivalently an increase in MTBF $1/\lambda$ is achieved through a reliability growth program that involves a test–analyze–fix strategy.

The term reliability here implies that a component satisfies a set of performance criteria while under specified conditions of use over a specified period of time. The objective of this section is to quantify the reliability goals for the DEMO blanket and to derive quantitative requirements of reliability growth testing in fusion facilities prior to constructing the DEMO blanket. Such a testing program proceeds from measurements of unexpected performance, investigation of failure modes and consequences, and identification of the optimum product and ends with demonstration of satisfactory performance [18,19,46]. While the component lifetime is mainly determined by the fluence limitation (i.e. damage level) which leads to performance degradation, the MTBF represents an arithmetic average life of all units in a population. As we shall shortly see, the MTBF requirements are much more demanding on the blanket test program than on the design lifetime.

Our approach here to evaluating the requirements of the reliability growth program for fusion blankets is as follows:

(1) Determine the DEMO reactor availability goal.

(2) Determine a corresponding goal for the availability of the blanket system and for the blanket modules.

(3) Determine a target MTBF for blanket modules.

(4) Quantify both the test times and the number of test articles that would be required to ensure that the specified target MTBF is met.

6.1. Goal mean time between failures (and mean down-time to replace) for the DEMO blanket

We dealt with the subject briefly in Section 3. We add here several additional points. The blanket system availability goals were shown in Table 7 to be about 97.6% and 40% for DEMO reactor availability goals of 59% and 31% (which will be approximated here as 60% and 30%) respectively. The availability of the blanket system as defined is

$$A_{\mathrm{BS}} = \frac{\text{up-time}}{\text{up-time} + \text{down-time}}$$

The down-time includes the cumulative time during a given period to replace (or fix) the blanket. This includes time for replacement at the end of the blanket life and replacement of one or more modules due to failure.

We make the assumption here that the down-time to replace the blanket at the end of life will not reduce the blanket availability. We assume that end-of-life blanket replacement will always be planned to occur during the annual routine maintenance for the balance of the plant, which is typically about 6 weeks per year. This requires careful scheduling but, with a blanket life of about 3 years or more, one third of the blanket could be replaced each year during the annual plant routine maintenance. Thus we assume that only down-time due to failure of one or more blanket modules will reduce plant availability. This assumption permits the following relationships to be developed (with subscripts BS and n referring to blanket system and blanket module respectively):

$$\lambda_{\mathrm{BS}} = n\lambda_n$$

$$\mathrm{MTBF}_{\mathrm{BS}} = \frac{\mathrm{MTBF}_n}{n}$$

where n is the number of modules

$$A_{\mathrm{BS}} = \frac{1}{1 + n\lambda_n \,\mathrm{MTTR}} = \frac{A_n}{A_n(1-n) + n}$$

$$A_n = \frac{1}{1 + \lambda_n \,\mathrm{MTTR}} = \frac{n}{(n-1) + 1/A_{\mathrm{BS}}}$$

The MTTR is the down-time to recover from a failure. We use the same value of MTTR in the expressions for A_{BS} and A_n since the most likely failure mode is a failure in a single module. Blanket MTTR for simultaneous failures in more than one module can be kept the same as that for a single module failure since parallel operations are possible.

Fig. 7 shows the required availability A_n as a function of blanket system availability A_{BS} for different numbers of blanket modules. It is striking that A_n needs to be greater than 90% for $A_{\mathrm{BS}} = 20\%$. Notice that many failures are dependent on the size. Therefore changing the number of modules will not drastically change the failure rate requirements for the total blanket system; it only changes the failure rate per module since the size and number of modules are changed.

Let us focus on two goal values for DEMO reactor, as discussed in Section 3; one is 30% and the other is 60%. The corresponding goals for the blanket system availability are 97.6% and 40%. For these, the target MTBF per module is shown in Table 22 for MTTR values of 1 week, 2 weeks, 1 month and 2 months. For the 30% DEMO reactor availability, the MTBF (module) varies from 0.92 to 7.96 full power years for an MTTR of 1 week to an MTTR of 2 months. For 60% DEMO reactor availability, the MTBF (module) is very long and is about 62 full power years for an MTTR of 1 week and becomes much longer for MTTR longer than 1 week.

The results in Table 22 have serious implications, particularly for the DEMO reactor availability of 60%, which is commonly assumed worldwide. For this A (reactor) = 60%, the required MTBF per blanket module is much longer than the design life of the blanket (10–20 MW years m^{-2} which is about 3–7 full power years at $P_{\mathrm{nw}} \approx 3\ \mathrm{MW\,m^{-2}}$). For an MTTR of 1 week and 80 modules, the goal MTBF for the blanket needs to be about 0.8 full power years, i.e. about only one failure anywhere in the 80 blanket modules is permissible per calendar year. For an MTTR of 1 month, MTBF (module) is 271 full power years and MTBF (blanket system) is 3.4 full power years. This means only one failure in the entire blanket system is allowed every 4 years. These are extremely ambitious goals compared with the state of the art discussed in Section 6.2. As also shown later, the testing requirements to achieve such a long MTBF appear to be extremely demanding. This is why we are considering here a different scenario for the DEMO, as discussed in Section 3, which assumes that DEMO will have two stages. The first has initial target availability of 30% and it reaches 60% only in the second stage.

One additional observation can be made on the results of Table 22. The MTTR (failed blanket module)

Table 23
Estimated failure rate for typical blanket based on data from non-fusion technologies (failure rates given here do not include fusion-specific failure modes)

Blanket element	(Unit) failure rate [a]		Failure rate per blanket module (h^{-1})	
	Mean	High	Mean	High
Longitudinal welds of length 66 m	$5.0 \times 10^{-8}\ \mathrm{h^{-1}\,m^{-1}}$	$5.0 \times 10^{-7}\ \mathrm{h^{-1}\,m^{-1}}$	3.3125×10^{-6}	3.3125×10^{-5}
Butt welds of pipe (number of elements per blanket module, 462)	$5 \times 10^{-9}\ \mathrm{h^{-1}}$ per weld	$1 \times 10^{-7}\ \mathrm{h^{-1}}$ per weld	2.31×10^{-6}	4.62×10^{-5}
Pipes (straight) of length 2.75 km	$5 \times 10^{-10}\ \mathrm{h^{-1}\,m^{-1}}$	$1 \times 10^{-8}\ \mathrm{h^{-1}\,m^{-1}}$	1.375×10^{-6}	2.75×10^{-5}
Pipe bend (number of elements per blanket module, 28)	$1 \times 10^{-8}\ \mathrm{h^{-1}}$ per bend	$3.5 \times 10^{-7}\ \mathrm{h^{-1}}$ per bend	2.8×10^{-7}	9.8×10^{-6}
Overall failure rate per module (h^{-1})		7×10^{-6}–1×10^{-4}		
Calculated MTBF per module (years)		1–16		
Calculated MTBF for blanket system (years)		0.01–0.2		

[a] From Ref. [47] (failure rates are based on experience from non-fusion technologies).

has tremendous influence on the target blanket MTBF for a given availability. We considered the MTTR range from 1 week to 2 months. Analysis shows that it is difficult to reduce the MTTR to significantly less than 1 week. The operations required to replace a failed blanket module are many and complex (de-energizing the magnets, filling the vacuum vessel with inert gas, breaking seals in the vacuum vessel, disconnects, removal, insertion, reconnect etc.) In addition, when a module fails, one needs to identify the failure consequences (e.g. the distortion of module geometry) on the maintenance operation. There are also many safety-related precautions and operations (maintenance operations that require warming up the superconducting toroidal field coils (TFCs) must be avoided because about 3–4 weeks may be required to warm up and cool these coils). Therefore 1 week appears a low value for the MTTR. However, values of 1–2 months have very serious impact on the required MTBF and achievable availability. The results here and in other sections suggest that achieving a short MTTR is crucial to the ultimate economic viability of the tokamak system. A key conclusion here is that all aspects related to MTTR must be addressed in machine design and in fusion testing. Data on achievable MTTR needs to be obtained from fusion test facilities.

Table 24
Comparison of expected blanket mean time between failures with that required in DEMO

	MTBF (years)	
	Blanket module	Blanket system
Expected (for fully developed technology based on steam generators and fission reactors data) [a]	1–16	0.01–0.2
Required		
DEMO availability, 30%		
MTTR, 1 week	0.92	0.01
MTTR, 1 month	3.98	0.05
MTTR, 2 months	7.96	0.1
DEMO availability, 60%		
MTTR, 1 week	62	0.78
MTTR, 1 month	271	3.4
MTTR, 2 months	542	6.8

[a] Estimates here do not account for additional failure modes specific to the fusion environment.

6.2. Estimates of failure rates

Given the target MTBF values for blanket DEMO in Section 6.1, a key question is what we expect the failure rate to be, based on current knowledge. Unfortunately, our current database from fusion systems is non-existent since no blanket was ever tested or operated. An indication of expected failure rates can be obtained from using data in other technologies. Data from steam generators and fission reactors appear relevant and have recently been used by Bünde [18,19] in assessing failure rates in fusion systems. We considered in this study a range of blanket options for the DEMO, particularly those with high pressure coolant. We assumed that the size of DEMO is similar to that of ITER EDA [17], with a first-wall surface area of about 1200 m^2. We assumed 80 blanket modules. The number of modules affects only the failure rate per module but does not have a major influence on the total failure rate for the blanket system.

Table 23 shows the estimated failure rates using data compiled by Bünde et al. [47] from steam generators and fission reactors. Mean and high values for unit failure rate units (i.e. per unit length of weld or pipe) are given in Table 23. The estimated length and number of elements per blanket module are also given in the table. The overall failure rate per blanket module is estimated to be in the range 7×10^{-6}–1×10^{-4} h^{-1}. Thus the MTBF (module) is in the range 1–16 years and the MTBF for the overall blanket systems 0.01–0.2 years, i.e. there will be about five to 80 failures somewhere in the blanket per year. It should be noted that Cadwallader [48] estimated the MTBF for a previous ITER helium cooled concept due to coolant leakage to be about 200 h (about 0.02 years) based on coolant failure leak data compiled from the TFTR.

It is instructive to compare MTBF estimates based on what has been achieved to date in mature non-fusion technologies with those that must be achieved in fusion DEMO. Table 24 presents a comparison of what is expected vs. what is required for the blanket mean time between failure. The MTBF values are shown for the blanket module and the blanket system, which consists of 80 modules. The expected MTBF is based on results in Table 23, i.e. based on those failure modes and failure rates that we know from the mature technologies of steam generators and fission reactors that are likely to exist in fusion DEMO blankets. The expected MTBF values in Table 24 do not account for the additional failure modes for the fusion specific system, as will be discussed later. The required values of MTBF in Table 24 are those that must be achieved in order to meet certain availability goals for the blanket. We show the required MTBF in Table 24 for two cases of DEMO reactor availability: 30% and 60%. For each case, MTBF values are given for different values of the MTTR, i.e. the down-time to recover from a blanket failure.

The results in Table 24 are striking and have very serious consequences for many aspects of fusion R&D. Required MTBF values for the DEMO blanket module are in the range 0.9–8 years for an MTTR in the range 1 week–2 months for the case of a DEMO reactor availability of 30%. These are within the range of expected values, which is 1–16 years. However, for the DEMO reactor availability goal of 60%, the MTBF per blanket module is 62 years at an MTTR of 1 week and increases to 542 years at an MTTR of 2 months. These values are much greater than the 1–16 year range of expected values. In other words, assuming the shortest time estimated for the MTTR of 1 week, the MTBF values required to achieve DEMO reactor availability of 60% are much longer than those expected to be achievable. This suggests that a blanket with a sufficiently low failure rate to achieve a DEMO reactor availability goal of 60% appears to be an unrealizable goal. This dramatic conclusion seems to be a quantitative measure that reflects the complexity of the reactor system. While the tokamak system is the one being considered here, the results may be applicable to other types of systems, e.g. those with a similarly large first-wall surface area, geometrical configuration, and maintenance features. However, it should be emphasized here that this conclusion is correct only to the extent to which the assumptions for our calculations here are correct. So, evaluating these assumptions is in order.

First, let us examine the expected values derived here based on data from steam generators and fission reactors. The primary failure rate in steam generators appears to come from failures in welds. Since steam generators represent mature technologies with tens of thousands of components in operation, the failure rate per unit length of weld in fusion systems cannot be expected to be any lower, particularly when the radiation environment is considered. Consequently, the only prudent method to reduce the failure rate in fusion blankets is to reduce the number and length of welds. This should be a key factor in the design of blankets and in selection among blanket concepts. However, reducing the number and length of welds in the blanket—first wall may not be possible in the complex fusion environment, particularly in the tokamak geometry which requires a very large surface area (the first-wall surface area is about 1200 m^2 in ITER).

Table 25
Some possible failure modes in blanket–first wall system (for solid and liquid breeder blanket concepts)

(1) Cracking around a discontinuity or weld

(2) Crack on shut-down (with cooling)

(3) Breeder (solid) disintegrates or cracks

(4) Cracks in electrical insulators (for liquid-metal blankets)

(5) Cracks, thermal shock, vaporization and melting during disruptions

(6) First-wall or breeder structure swelling and creep leading to excessive deformation of first-wall or coolant tube failure

(7) Environmentally assisted cracking

(8) Excessive tritium permeation of coolant tubes

(9) Cracks in electrical connections between modules

Another serious concern is that the failure rates in Table 23 account only for the very limited number of known failures modes. Very little work has been done to date to identify failure modes in first-wall–blanket systems. Table 25 lists some of the possible failure modes that should be of concern. For example, in self-cooled liquid-metal blankets, cracks or other imperfections in insulator coatings may prove to be a failure mode that occurs at high frequency, and the large flow channel area in the tokamak geometry will magnify the problem. On the contrary, self-heating insulator coatings may function perfectly with a very low failure rate. The problem is that we do not know. There has been little FNT R&D. Fusion testing can provide the answer to such critical questions.

It is reasonable to ask whether the failure rate in fusion blanket systems can be expected to be lower or higher than in steam generators and fission reactors. A quantitative answer is beyond the scope of this work but must be seriously addressed in the future, most importantly by generating a database from actual tests of blankets in the fusion environment. Our concern is that failure rates may be much higher in fusion blankets because they appear to be much more complex than steam generators and the core of fission reactors because of the following points.

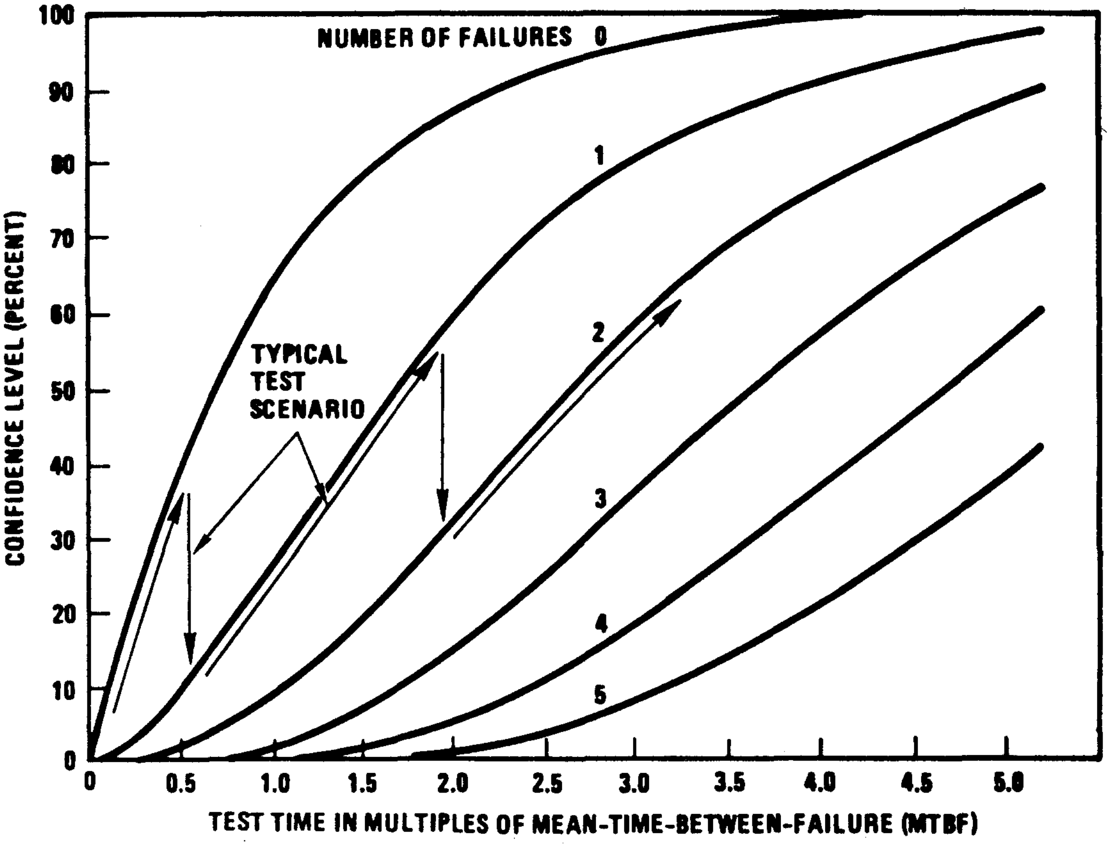

Fig. 8. Confidence level as a function of test time in multiples of MTBF and the number of failures that occur during the tests.

(1) There are a larger numbers of subcomponents and interactions (tubes, welds, breeder, multiplier, coolant, structure, insulators, tritium recovery etc.).

(2) More damaging, higher energy neutrons are used.

(3) Other environmental conditions must be considered: magnetic field, vacuum, tritium, etc. (e.g. a leak from the first-wall or blanket module walls into the vacuum system results in failure while, in steam generators, continued operation with leaks is often possible; typically, fission reactors are permitted to continue operation with 1% of fuel-rod clad failure).

(4) Reactor components must penetrate each other; many penetrations have to be provided through the blanket for plasma heating, fueling, exhaust etc.

(5) Ability to have redundancy inside the first-wall–blanket system is almost impossible.

Some important concluding remarks regarding this topic of failure modes, failure rates and reliability growth testing are as follows.

(1) Capability to replace first wall and blanket (individual modules as well as the entire first-wall–blanket system) in a reasonable time must be a design goal for fusion devices.

(2) Design concepts for the first-wall–blanket system (and other components) must aim at improving reliability. One of the most effective directions is to minimize features that are known to have a high failure rate (e.g. to minimize or eliminate welds, brazes, joints and total tube length).

(3) A serious reliability and availability analysis must be an integral part of the design process.

(4) The R&D program must be based on quantitative goals for reliability (type of tests, prototypicality of test, number of tests, test duration).

(5) Reliability growth testing in fusion devices will be the most demanding (particularly on number of tests and time duration of tests). Reliability testing should include (a) identification of failure modes and effects, (b) aggressive iterative design–test–fix programs aimed

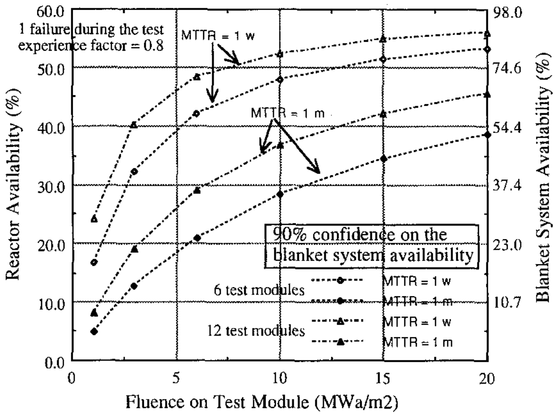

Fig. 9. Achievable DEMO reactor and blanket system availability as a function of fluence on test module (results are given for an MTTR of 1 week and an MTTR of 1 month and for six and 12 test modules).

at improving reliability and (c) obtaining failure rate data sufficient to predict the MTBF.

6.3. Reliability testing requirements

The term "reliability" is defined as the ability of an item to perform for a stated period of time. The principal purpose of reliability testing is to determine whether the product meets a specific reliability goal from experience in other technologies. There are several methods that provide guidelines and procedures for reliability testing (e.g. [18,19,49–56]. A more detailed description of reliability testing is given in [46]. Here, we are concerned with determining the blanket test time and test area in fusion facilities which are required to meet certain goals for MTBF.

Fig. 8, based on data discussed in [35], shows the upper statistical confidence level as a function of test time in multiples of MTBF and the number of failures experienced during the tests for a Poisson distribution. This test plan requires that only equipment "on time" may be used in MTBF determination, and the minimum test time per piece of equipment should not be less than one half the average operating time of all equipment on a test. Based on this test plan, we calculated (1) the confidence level achieved in meeting specific goals for DEMO reactor availability as a function of test time and number of test articles and (2) the achievable DEMO reactor availability as a function of fluence on test module and number of modules tested. For all cases, we used that data in Tables 6 and 7 that correlate reactor availability, blanket availability, MTBF and MTTR. In all cases, we assumed the number of blanket modules in DEMO to be 80.

Table 26
Achievable blanket system availability (at 90% confidence) vs. testing scenario (one failure during the test; number of blanket modules in the blanket system, 80, neutron wall load in DEMO, 3 MW m^{-2})

Fluence[a] (MW years m^{-2})	Experience factor[b]	Number of test modules	Module MTBF (fluence)	Module MTBF (full power years)	Blanket system availability	
					MTTR, 1 week	MTTR, 1 month
1.1	0.5	6	0.5	0.167	0.097	0.0244
1.1	0.5	12	0.712	0.237	0.133	0.0343
1.1	0.8	6	0.862	0.287	0.157	0.0413
1.1	0.8	12	1.5	0.5	0.245	0.0698
3.1	0.5	6	1.761	0.587	0.276	0.0809
3.1	0.5	12	2.49	0.83	0.35	0.111
3.1	0.8	6	3.018	1.006	0.395	0.131
3.1	0.8	12	5.25	1.75	0.532	0.208
6	0.5	6	3.587	1.196	0.437	0.152
6	0.5	12	7.174	2.391	0.6084	0.264
6	0.8	6	6.1439	2.048	0.5698	0.235
6	0.8	12	10.697	3.565	0.6985	0.348

[a] Within a given fluence, 0.3 MW years m^{-2} is dedicated to the concept scoping test.

[b] A factor to account for the fact that similar failure causes may be seen in different blanket modules. The actual cumulative test time in a parallel test of duration T (per test module) with N test modules is estimated as $N^{n-1}(NT)$, where n is the experience factor.

Fig. 9 shows the DEMO reactor availability achievable with 90% confidence, and assuming one failure during the test, as a function of fluence on test modules. Results are shown for two cases of six and 12 modules and for two cases of an MTTR of 1 week and an MTTR of 1 month. Several important observations can be made from the results. The MTTR is again clearly a critical parameter. If the MTTR is 1 month or longer, the DEMO reactor availability will be below 40% even for a fluence of 10 MW years m^{-2}. Increasing the number of modules provides an opportunity to possibly observe different failure modes and to improve statistics. However, the same failure may occur in more than one module. Therefore, the increase in experience from testing with the number of test modules is less than linear. We can use an experience factor of 0.8 [35]. The effect of the experience factor is shown in Table 26.

The fluence requirement on the test modules is critical. From Fig. 9, it is clear that the achievable DEMO blanket availability, and hence the DEMO reactor availability, increases substantially with testing fluence. For an MTTR of 1 week, increasing the testing fluence from 1 to 6 MW years m^{-2} increases the DEMO availability from 25% to 48% with 12 test modules and from 17% to 42% for six test modules. For an MTTR of 1 month, a testing fluence of 1 MW years m^{-2} leads to reactor availability of only 8% with 12 test modules, but increasing the testing fluence to 6 MW years m^{-2} increases the DEMO reactor availability to 30%.

Notice that, as the test fluence increases beyond about 5 MW years m^{-2}, the rate of increase in reactor availability per unit of additional testing fluence decreases. The rate of improvement in reactor availability becomes even smaller at higher fluences, greater than 10 MW years m^{-2}. Since the blanket design lifetime may be limited to about 10 MW years m^{-2}, testing will become difficult at such high fluences.

A number of key conclusions are important from the results here.

(1) Achieving a fluence of about 5-6 MW years m^{-2} at the test modules with about six to 12 test modules is crucial to achieving DEMO reactor availability in the 40-50% range with 90% confidence.

(2) Achieving DEMO reactor availability of 60% may not be possible with 90% confidence for any practical blanket test program.

(3) The MTTR (blanket) must be of the order of 1 week or less in order to achieve the required blanket and reactor system availabilities.

(4) The length of the MTTR must be by itself one of the critical objectives for testing in fusion facilities.

7. Role of the International Thermonuclear Experimental Reactor and need and options for a volumetric neutron source

The preceding sections have clearly shown that testing in non-fusion facilities, albeit useful, cannot resolve the critical issues for FNT. Fusion facilities are required to test, develop and qualify FNT components and to demonstrate short MTTR for DEMO. These testing requirements have also been quantified for the three stages of fusion testing: stage I (scoping), stage II (concept verification) and stage III (CEDAR growth), Table 17 and Fig. 3 summarized the FNT primary requirements on the major parameters for testing in fusion facilities. The key requirements are 1-2 MW m^{-2} neutron wall load, steady state plasma operation, many periods of continuous operation (100% availability) with each period 1-2 weeks, at least 6 MW years m^{-2} of neutron fluence, and greater than 10 m^2 of test area at the first wall.

7.1. The International Thermonuclear Experimental Reactor alone strategy

The key question now is how to satisfy these FNT requirements for fusion testing, and specifically what

Table 27
Comparison of parameters for present plasma devices TFTR-JET, ITER and DEMO

	TFTR-JET	ITER	DEMO
Neutron wall load (MW m^{-2})	<0.2	1	2-3
Plasma burn length (s)	1	1000	Steady state (or hours)
Plasma dwell time (s)	Very long	1200	0 (or <100 s)
Fuel cycle	None	Partial (fuel consumer)	Complete, self-sufficient
Thermal conversion efficiency	0	0	>30%
Net plant availability	<1%	1-10%	>50%
Fluence (MW years m^{-2})	$\approx 10^{-4}$	0.1 BPP; 1.0 EPP	10-20

Table 28
Major research and development tasks to be accomplished prior to DEMO

(1) Plasma:
  (a) confinement;
  (b) diverter;
  (c) disruption control;
  (d) current drive

(2) System integration

(3) Plasma support systems:
  (a) magnets;
  (b) heating

(4) FNT components and materials (blanket, first wall, high performance diverters):
  (a) materials combination selection:
  (b) performance verification and concept validation;
  (c) show that the fuel cycle can be closed;
  (d) failure modes and effects;
  (e) remote maintenance demonstration;
  (f) reliability growth;
  (g) component lifetime;
  (h) mean time to recover from failure

ITER will address most of (1)–(3)

FNT components and materials require dedicated fusion-relevant facilities parallel to ITER

fusion facilities can best serve the FNT development needs. Since ITER is already in the EDA phase, it is prudent to examine first whether ITER can satisfy the FNT testing needs. Parameters of ITER [17] are compared with those of present devices TFTR [23]–JET [24] and DEMO in Table 27.

Table 28 summarizes the major R&D tasks to be accomplished prior to DEMO: (1) plasma performance, (2) system integration, (3) plasma support systems and (4) materials and FNT components performance and reliability and change-out cycle. ITER as designed in EDA [17] will accomplish tasks (1)–(3) with the possible exception of non-inductive current drive and steady state plasma operation. Task (4) will not be addressed adequately in ITER. This should be clear from comparing the FNT requirements in Table 16 with the ITER parameters listed in Table 27. The primary reasons that ITER cannot satisfy the FNT fusion testing and development requirements are (1) pulsed operation with a low duty cycle, (2) low device availability and low fluence, (3) short continuous operating time, and (4) project time schedule.

As shown in Section 5, FNT testing requires steady state plasma operation and, if this cannot be realized, the plasma duty cycle must be greater than 80%. From Table 27, ITER has a burn length of 1000 s, a dwell time of 1200 s and plasma duty cycle of about 45%. Therefore, on the basis of the analysis in Section 5, the ITER plasma mode of operation does not meet the FNT testing requirements.

The neutron fluence at the first wall of the ITER is 0.1 MW years m^{-2} during 12 years of a basic performance phase (BPP) and 1 MW years m^{-2} during an additional 12 year extended performance phase (EPP). Therefore the ITER fluence is 1.1 MW years m^{-2} compared with almost 6 MW years m^{-2} required for FNT testing (see Table 17). Consequently, ITER alone cannot provide a database sufficient enough for construction of FNT components in DEMO. The risk to the DEMO of relying on only ITER's low fluence is unacceptably large and will be quantified in the next section.

FNT requires many (about 100) periods of COT, i.e. at 100% availability each period is 1–2 weeks. In ITER, the 0.1 MW years m^{-2} during the 12 year of BPP means that the total operating time is less than 5 weeks, i.e. only about 3 full power days per year.

As shown in Section 6, the MTTR (blanket), particularly the down-time to recover from a random failure in the blanket is crucial to attaining availability goals for DEMO. This MTTR needs to be on the order of 1 week (or less). Obtaining data on MTTR and demonstrating all the technologies and engineering and safety procedures associated with recovery from blanket failure require a major focus of the engineering, configuration, remote maintenance and other aspects of the blanket design and testing facility design. At present, such aspects are not a major focus in ITER design. In contrast, ITER EDA design assumes replacing the blanket to be a major operation that requires a year or longer. Our results on failure rates in the previous section shows the need to change this aspect of ITER design to ensure that ITER operates adequately even if it is only to satisfy the plasma physics mission. However, it appears unlikely that an entirely different design approach for ITER that can fully assess the MTTR-related issues will emerge.

The time schedule issue can be characterized readily by comparing the DEMO time schedule discussed in Section 3 to the ITER time schedule. Such a comparison is shown schematically in Fig. 10. To start DEMO operation by the year 2025 as stated in most of the plans for the world major programs (see Section 3), the DEMO design needs to start the year 2013 allowing 5 years for design and 7 years for construction. ITER will

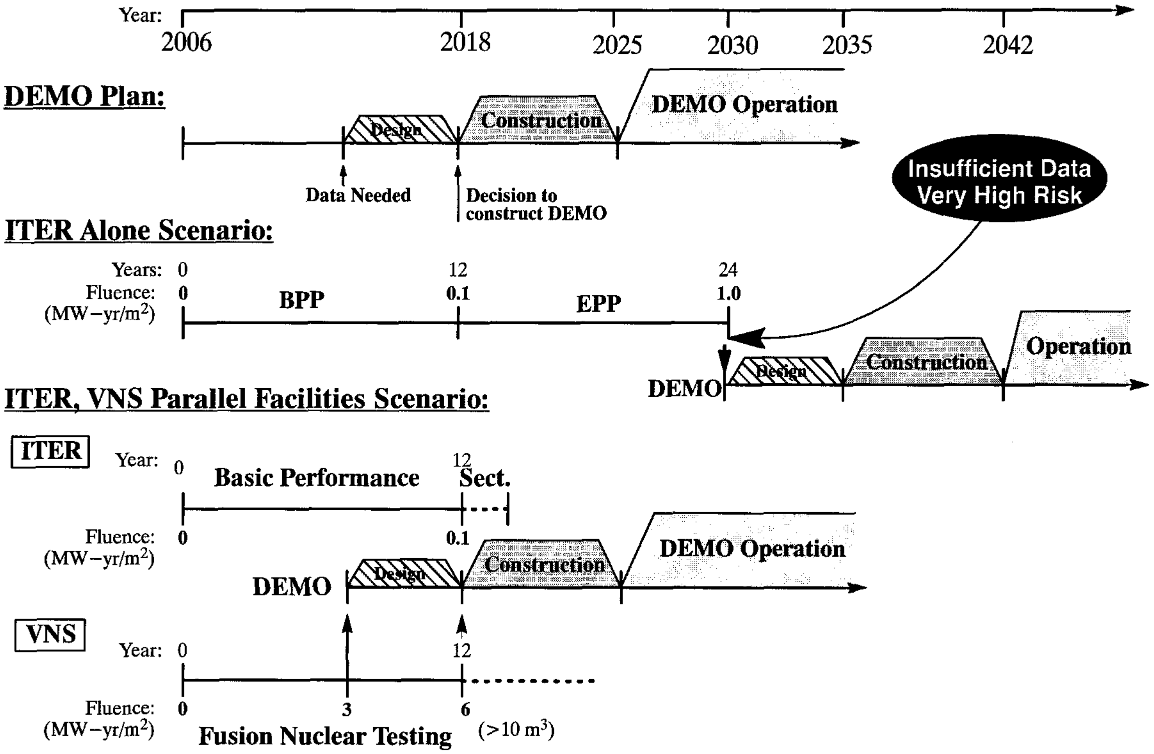

Fig. 10. Comparison of time schedule with DEMO for two scenarios: ITER alone; VNS and ITER as parallel functions.

achieve about 1.1 MW years m^{-2} by the year 2030. This fluence is not sufficient for FNT design and results in high risk, which will be quantified shortly. On the assumption that such a major risk is accepted, the earliest a DEMO can operate, using ITER data alone, is the year 2042. So, in addition to the high risk to DEMO, an ITER-alone strategy delays DEMO operation by at least 17 years.

It should be very clear now that an ITER-alone strategy will not provide the FNT database required for DEMO. Furthermore, even if very high risk to the DEMO is accepted, ITER-alone strategy cannot meet the program plan time schedule for DEMO.

7.2. Definition and objectives of the volumetric neutron source

From the above conclusions it is clear that ITER alone cannot provide the database for DEMO. There is a definite need for another fusion facility to test, develop and qualify fusion nuclear technology components and material combinations for DEMO. We shall call such a facility the VNS. Such a facility must be a fusion facility to provide prototypical environment and since plasma-based neutron sources are the only ones capable of providing neutrons in an appropriate test volume as discussed in Section 4.

The VNS mission is to complement ITER as a dedicated fusion facility to test, develop and qualify FNT components and materials combinations required for DEMO. The blanket determines the critical path for FNT development and is a major focus for FNT testing in VNS. The design and material combination options to be tested are those that have a high potential for meeting the DEMO goals in safety, environmental impact, economics, reliability and dependability. More detailed objectives and testing strategy for VNS can be defined as follows.

Stage I: scoping.

(1) Calibrate non-fusion tests against performance in the fusion environment.

(2) Carry out initial check on codes and data.

(3) Test and develop experimental techniques and instrumentation.

(4) Screen and narrow material combinations and design concepts in the fusion environment.

Table 29
Comparison of physics and nuclear technology requirements for testing and impact on required tritium supply

Scenario	Fusion power	Integrated burn time	Tritium consumption
(a) Separate facility for plasma ignition	1500 MW	15 days	3.5 kg
(b) Separate facility for FNT	20 MW	5 years	5.6 kg
Combined[a] (a) + (b) in one facility	1500 MW	5 years	420 kg

Note that the physics and FNT requirements are very dissimilar.
[a] Combining large power and high fluence leads to large tritium consumption requirements.

Table 30
Suggested ground rules for evolving volumetric neutron source design concepts

Plasma operation	Steady state
Low fusion power to keep cost low and to avoid the need for a breeding blanket	<150 MW
Surface area at first wall for testing	>10 m^2
Neutron wall load	1–2 MW m^{-2}
Design for maintainability and higher availability: duty cycle × availability	>0.3
No breeding blanket to avoid use of unproven technologies	
Maximum site power requirements	<700 MW
Cost	<0.3 ITER

Stage II: concept verification.

(1) Obtain data on performance under normal operating conditions (temperature, stress, pressure drop etc.).

(2) Obtain data on initial failure modes and effects.

(3) Select two or three concepts for further development.

Stage III: CEDAR growth.

(1) Identify failure modes and effects.

(2) Implement iterative design–test–fix programs aimed at improving reliability and safety.

(3) Failure rate data: obtain a database sufficient to predict MTBF with sufficient confidence.

(4) Obtain data to predict MTTR for both planned outage and random failure.

(5) Obtain a database to predict overall availability of FNT components in DEMO.

The next question is what type of fusion facility VNS should be and what are the major parameters of VNS. From Table 17, it is clear that VNS must have the following parameters in order to meet FNT development requirements: (1) neutron wall load, 1–2 MW m^{-2}; (2) steady state plasma operation; (3) COT of 1–2 weeks; (4) total neutron fluence of 6 MW years m^{-2} or more; (5) total test area at the first wall greater than 10 m^2. One observation that can be made here is that FNT testing requires about 10 m^2 of test area at 1–2 MW m^{-2} neutron wall load, i.e. total fusion power of only about 20 MW. In contrast, plasma ignition in tokamaks requires greater than 1500 MW of fusion power. In Table 29, the plasma ignition physics in tokamaks and FNT testing requirements are compared. Plasma ignition physics requires about 1500 MW fusion power with toal integrated burn time of about 15 days. The tritium consumption, and hence the tritium supply requirement, for ignition physics is only about 3.5 kg. In contrast, FNT testing requires only about 20 MW of fusion power but a long test time of about 5 full power years. Because of the low fusion power, the tritium supply required for 5 full power years of FNT testing remains modest, about 5.6 kg. If one combines the missions of (a) plasma ignition testing and (b) FNT testing in one facility, this leads to combining the large power requirements of (a) with the long test time of (b), and therefore the tritium supply requirement becomes very large, about 420 kg. To put the magnitude of this tritium supply in perspective, consider the cost. At today's price of US$20 million kg^{-1}, the cost of tritium for the combined (a) + (b) scenario is US $8.4 billion, which is clearly unaffordable (and not justifiable). A more serious issue is the availability of the tritium supply. Since tritium production facilities for weapons have been shut down in the USA and Russia, and since the half-life for tritium radioactive decay is only 12.3 years, it is reasonable to deduce that no supply will be available from such a source in the 2006 to 2020 time frame. The only known supply is from operation of heavy-water-moderated CANDU reactors in Canada. This supply is estimated [57] at 2.5 kg year^{-1}, which is clearly not sufficient for the combined (a) + (b) scenario but is more than adequate for the two separate facilities of (a) and (b).

If a combined (a) + (b) facility were to be built, a tritium-producing blanket must first be constructed to produce tritium internally in such a facility. The problem here is that such a scenario assumes that a breeding blanket can be designed, constructed and operated reliably and safely before obtaining the required database. The technical logic in such a scenario is flawed. This is actually one of the fundamental reasons why attempts to design an acceptable next-step ITER-type device for the past 20 years have not been successful.

The above discussion leads to the following points.

(1) Although we derived the need for VNS from detailed examination of FNT technical issues and evaluation of facilities capabilities, there is another way to arrive at the need for VNS. This is based on comparative evaluation of a scenario of two separate facilities, one for FNT testing and the other for plasma ignition testing, with another scenario that combines ignition and FNT testing. It is worth noting that such a comparative evaluation was performed in earlier work [2,3] and led to a conclusion in favor of the two-separate-facilities approach.

(2) A key requirement that should be imposed on VNS is that the fusion power should be kept small to minimize the tritium supply requirements. This suggests that the fusion power of VNS should be less than 150 MW to keep the annual tritium consumption to 2 kg year^{-1} or less assuming the VNS overall availability is 30% and that about 20% of the wall area will be used by blanket test modules. Implicit in this guideline is that a base breeding blanket whose sole function is to produce tritium should not be used in VNS. Use of unproved technologies on VNS should be avoided to the maximum possible extent.

Designing for maintainability and high availability is both an objective and a requirement on VNS. To achieve the required testing fluence of about 6 MW years m^{-2} in 12 years with wall loads in the range 1.5–2 MW m^{-2}, the device availability must be in the range 25–30% (see Table 18). As discussed earlier, achieving such a range of availability is by itself an important objective as a step towards DEMO. Involved in such a task is developing the failure recovery and remote maintenance techniques and safety procedures in order to reduce the device down-time.

Table 30 summarizes the ground rules suggested for evolving VNS design concepts.

Table 31
Key design configuration and engineering features for volumetric neutron source tokamaks

Configuration and features	Superconductivity TFC	Multi-turn normal-conductivity TFC [a]	Single-turn normal-conductivity TFC [b]
Total inboard shield thickness (cm)	72	23	3
Total outboard shield–blanket thickness (cm)	100	100	100
Number of outboard TFC legs	12	8	8
Number of removable diverter modules	12	8	8
Elevation of outboard poloidal field coils	X-point	X-point	X-point
Jointed demountable TFCs	No	Yes	Yes
Average toroidal field inner winding current density (kA cm^{-2})	3.7	3.0	1.9–2.1 [c]
Average toroidal field outer winding current density (kA cm^{-2})	3.7	1.0	1.0
TFC load path through radiation shield	No	Yes	Yes
Poloidal field coil location vs. TFC bore	External	Internal	Internal

[a] With standard aspect ratio $A > 2.5$.

[b] With low aspect ratio $A < 2$.

[c] Averaged over the entire center leg, which is hourglass shaped at the midsection.

Table 32
Key parameters for volumetric neutron source tokamaks, compared with the Internaitonal Thermonuclear Experimental Reactor

	ITER [a]	Superconductivity	Multi-turn normal-conductivity	Single-turn normal-conductivity
Average neutron wall load (MW m^{-2})	≈1.0	1.0	1.0–2.0	1.0–2.0
Major radius R_0 (m)	7.75	4.64	1.53–1.62	0.79–0.81
Minor radius a (m)	2.8	1.05	0.6	0.6
Plasma current I_p (MA)	24	6.4	6.0–7.1	9.4–10.4
Externally applied toroidal field B_{t0} (T)	6.0	7.7	4.3–5.5	2.0–2.4
Volume-averaged density $\langle n_e \rangle$ ($\times 10^{20}$ m^{-3})	1.1	1.4	1.3–1.7	0.95–1.3
Density-averaged temperature T_n (keV)	11	12	13–15	16
Divertor heat flux factor f_{div} (MW $T^{1/2}$ $m^{-3/2}$)	20	17 [b]	14–24 [b]	12–21 [b]
Drive power P_{drive} (MW)	0	135	30–46	19–29
Fusion power P_{fusion} (MW)	1530	400	82–172	32–65
Electric power consumption [c], peak/s.s. (MW)	200	300	740	155–200
Outboard accessible wall area (m^2)	TBD	56	30–31	20
Number of ports for plasma drive	N/A	3	2	2
Plasma volume (m^3)	≈2000	150	21–22	10–11
Plasma surface area (m^2)	≈1150	250	56–59	27–28
First-wall area, including inboard (m^2)	≈1300	290	66–70	26

TBD, to be determined; NA, not available.
[a] Parameters chosen for the BPP of the ITER outline design.
[b] Double-null poloidal diverters assumed.
[c] Further design optimization is required to reduce electric power consumption.

7.3. Types of confinement concepts for the volumetric neutron source

There are two types of magnetic confinement concept that can be considered for plasma-based VNS, namely mirrors and tokamaks. One option, proposed in [58] for a mirror-type facility is called the gas dynamics trap (GDT). This concept has the advantage of reasonable confidence in its technical feasibility. Unfortunately, the maximum testing area available with GDT is about 0.5–0.75 m^2. Thus, it cannot provide the surface area required for FNT testing (greater than 10 m^2; see Table 16); hence it is not suitable for VNS. Examining such a concept suggests that it might be an attractive alternative to accelerator-based neutron sources for "material science irradiation" specimen tests. GDT appears to overcome some of the difficulties of accelerator-based neutron sources discussed in Section 4. Designs with more "conventional" mirrors that provide a larger test area have been proposed by others, e.g. [59]. Unfortunately, important physics feasibility issues (e.g. electron temperature) will have to be resolved prior to considering these mirror concepts for VNS.

Tokamaks appear to offer the most attractive approach to VNS at present. A driven plasma is acceptable for VNS since FNT testing requires only that neutrons be produced steadily over a large area, regardless of whether neutrons are produced by ignited or driven plasmas. This fact is a key reason, as will be shown in the next section, why an attractive design envelope can be identified for VNS. At a Q (ratio of fusion power to plasma input power) of about 1–3, it can be shown that a tokamak with TFTR–JET-type devices supplemented by non-inductive current drive and a diverter can satisfy FNT requirements and provide a VNS at a relatively low cost.

The design options for VNS were investigated in [1] and have been examined in other studies (e.g. [2,3,34,35,60–62]. Here, we summarize options for a tokamak VNS.

The basic variations of tokamak VNS designs include (1) superconducting TFCs and adequate inboard radiation shield to protect the superconducting magnets, (2) multiturn normal-conducting TFCs and adequate inboard radiation shield to limit damage to TFC insulators and normal conductor requiring standard aspect ratios ($R_0/a \geqslant 2.5$) and (3) single-turn normal-conducting TFCs and essentially no inboard nuclear shielding, permitting $R_0/a \leqslant 2$. These design options have been considered recently [60–62] for application in fusion

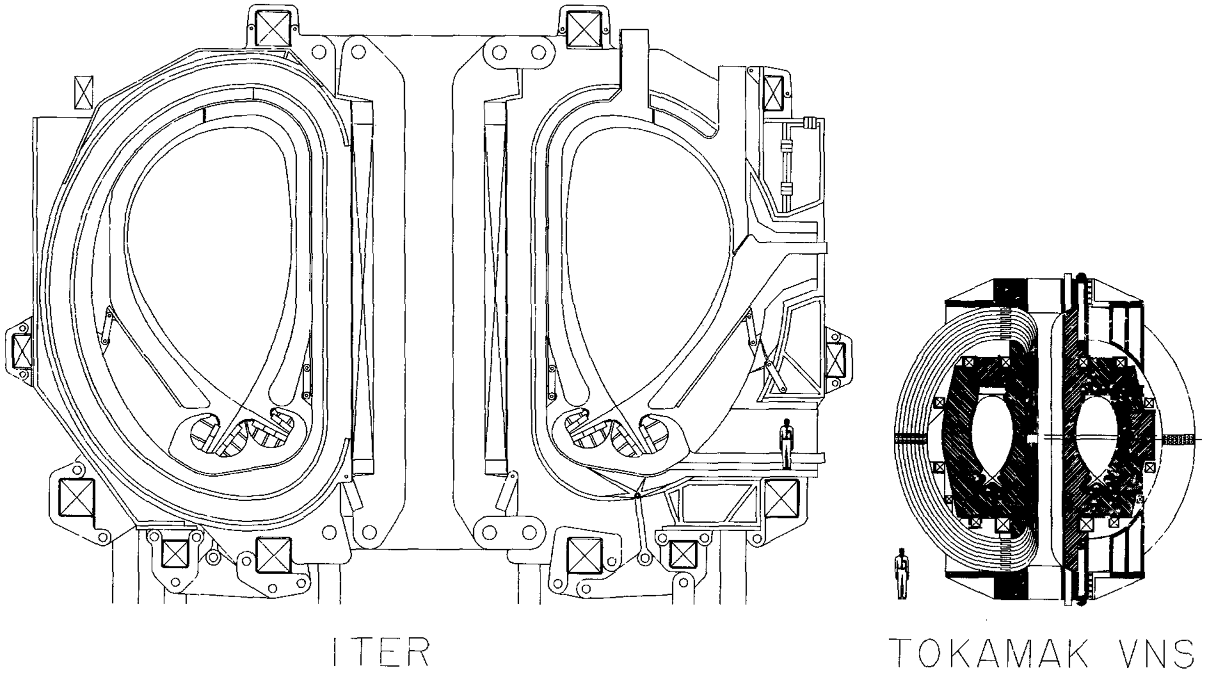

Fig. 11. Elevation views for ITER and a typical tokamak VNS built with multiturn normal conducting toroidal field coils in same scale.

development. The present study utilizes common assumptions to define the envelope for VNS, and to produce information useful in comparing the merits of these options in future studies. An updated version of the SuperCode [63] has been utilized.

Table 31 shows the key design configuration and engineering features for VNS tokamaks. Table 32 shows the key parameters calculated for VNS with superconducting TFCs, normal-conducting TFCs with standard aspect ratio $A > 2.5$ and the very low aspect ratio ($A < 2$) designs with copper TFCs.

The superconducting TFCs option results in a device with a major radius about half that of ITER. However, the device size appears to be too large for VNS. In addition, superconducting TFCs may not be suitable for a testing facility in which rapid replacement of test articles and failed components is essential.

Tokamak designs with normal-conducting TFCs (possibly with demountable joints) and standard plasma aspect ratio offer a very attractive option for VNS. The major radius is less than 2 m; the fusion power is about 80–170 MW and it satisfies well all the FNT requirements. The first-wall surface area is smaller by a factor of about 20 than that of ITER. Fig. 11 shows a comparison of the relative size of this type of VNS with that of ITER.

The small-aspect-ratio tokamak designs provide the smallest tokamak size. It appears to satisfy the FNT testing requirements but further work is necessary to evaluate configurations, maintenance and physics issues.

The key issues for VNS Tokamaks are (1) steady state current drive at densities around $1 \times 10^{20}\,\mathrm{m}^{-3}$, (2) divertor heat and particle loads and engineering design and (3) configuration and component engineering design to achieve high availability (about 30%). The first two issues must be resolved soon because they have tremendous impact on the viability and attractiveness of tokamaks as an energy source in general. The third deserves by itself to be an R&D goal on the path to DEMO because achieving high availability in tokamak systems, as discussed earlier, is one of the most critical goals for DEMO. Therefore VNS does not pose any major R&D issue which is not on the path to DEMO.

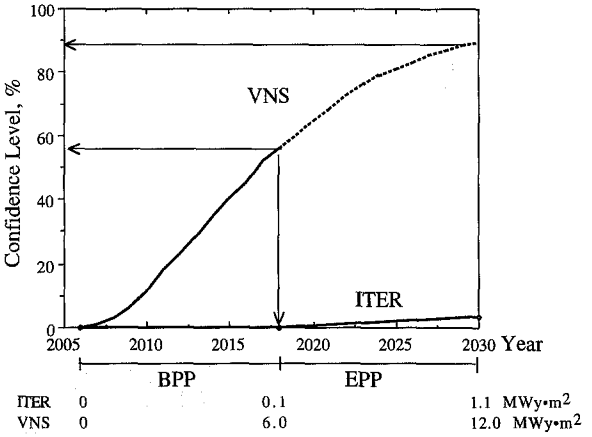

Fig. 12. Confidence level in DEMO obtainable with FNT testing in VNS and ITER (MTTR$_n$, 1 week; MTBF$_n$, 6.1 years).

8. Time schedule, risks and costs with and without a volumetric neutron source

In the previous sections we established the technical need for VNS and we showed that an attractive design envelope exists for a tokamak VNS. It is now necessary to consider when a VNS should be constructed. Furthermore, since an expected reaction to the VNS proposal is whether it is affordable, it is prudent to examine the impact of VNS on the time schedule, risks and costs of the world R&D program which has the DEMO as its goal.

We have investigated several scenarios for fusion development towards DEMO. The one practical scenario that appears to improve the time schedule best and to reduce costs and risks is one in which VNS starts operation about the same time as ITER, i.e. about the year 2006. This scenario of parallel ITER and VNS operation is illustrated in Fig. 12. In this scenario, both ITER and VNS start operation abut the year 2006 and operate for about 12 years. For ITER, this corresponds to the BPP in which only 0.1 MW years m^{-2} fluence is accumulated. The ITER mission during this period is to demonstrate plasma performance (except for steady state operation), plasma support technologies (superconducting magnets and heating) and system integration (except for breeding blanket). During the same 12 year period, VNS achieves 6 MW years m^{-2} fluence and is used as a dedicated facility to test, develop and qualify material combinations, blankets and other fusion nuclear components.

Now, let us compare the ITER–VNS parallel facilities scenario to the ITER-alone scenario. Areas of comparison are (a) time schedule, (b) risks and (c) costs of the R&D program to develop DEMO. The time line diagram is shown for both scenarios in Fig. 10.

The ITER-alone scenario was shown earlier to delay the DEMO operation to the year 2042 at the earliest even with the major assumption that the risk of using only 1.1 MW years m^{-2} data were acceptable (the risk is unacceptable as shown shortly). In contrast, with VNS, DEMO operation by the year 2025 becomes possible. VNS will provide FNT testing data by the year 2013, when DEMO design begins, and 6 MW years m^{-2} in the year 2018 when DEMO construction starts. Of course, both ITER and VNS can continue to operate beyond the 12 years indicated to provide additional confirmatory data during DEMO construction. An attractive possibility is to use the high fluence FNT data from VNS to construct and test full sectors for about 1 year on ITER. These sector tests do not need high fluence but they can provide additional data on module-to-module interactions and on system integration, which would also be useful during the construction of DEMO.

Therefore the VNS–ITER scenario reduces the time schedule to DEMO by at least 17 years relative to the ITER-alone scenario in addition to substantially reducing the risk to DEMO.

The risk to the DEMO in the two scenarios can be quantified in at least one critical area: the DEMO reactor availability. Using the methods and data developed in Sections 3 and 6, we use two approaches.

(I) Calculate with 90% confidence the achievable blanket system availability and the corresponding DEMO reactor availability for the ITER-alone and the ITER–VNS scenario.

(II) Calculate the confidence level in achieving the DEMO blanket system and reactor availability goals given earlier, i.e. DEMO reactor availability of 60% and the alternative case of 30%.

The results for approach I can be readily estimated from calculations given in Section 6 and summarized in Table 26 and Fig. 9. Strictly speaking, the ITER-alone scenario provides fluence that is barely sufficient for the FNT testing stages of scoping and concept verification and therefore does not provide any real CEDAR growth testing. However, let us assume that the concept verification testing of 0.8 MW years m^{-2} counts towards reliability growth testing. To facilitate the comparison, consider an experience factor of 0.8 and 12 test modules in both VNS and ITER. With the ITER-alone

Table 33
Available confidence level at the end of testing vs. DEMO reactor availability (assuming one failure during the test, an experience factor of 0.8 and a DEMO neutron wall load of 3 MW m^{-2})

DEMO reactor availability	Blanket availability	MTTR$_n$	MTBF$_n$	Confidence level (%) in DEMO after testing ends		
				BPP	EPP	VNS
0.52	0.8	1 week	6.1 years	0	3.6	56.3
		1 month	26.6 years	0	0	7.7
0.37	0.5	1 week	1.5 years	0	29	100
		1 month	6.6 years	0	3.0	53.2

scenario provides fluence that is barely sufficient for the FNT testing stages of scoping and concept verification and therefore does not provide any real CEDAR growth testing. However, let us assume that the concept verification testing of 0.8 MW years m^{-2} counts towards reliability growth testing. To facilitate the comparison, consider an experience factor of 0.8 and 12 test modules in both VNS and ITER. With the ITER-alone scenario, the achievable DEMO reactor availability at the 90% confidence level is about 24% for an MTTR of 1 week and about 8% for an MTTR of 1 month. In contrast, with the VNS–ITER scenario, the DEMO availability is about 50% for an MTTR of 1 week and 30% for an MTTR of 1 month. Therefore VNS makes it possible to come close to achieving the DEMO goals from the beginning of its operation if the MTTR is 1 week or the staged DEMO operation (see Section 3) if the MTTR is 1 month. Without VNS, the achievable DEMO availability is too low to be acceptable.

Approach II of determining the risk in achieving the DEMO availability goals provides another useful perspective. Fig. 12 shows the confidence level in DEMO obtainable with FNT testing in VNS and ITER, assuming an MTTR of 1 week. The ITER-alone scenario provides nearly zero confidence by the year 2018 (end of BPP) and about 1% confidence by the year 2030 (end of EPP). In contrast, VNS achieves about 58% confidence by the year 2018. If the VNS continues to operate until the year 2030, it would provide about 90% confidence. This means that without VNS, i.e. an ITER-alone scenario, there is no appreciable level of confidence that the DEMO will achieve its availability goal. With VNS, there is substantial confidence (about 58%) in achieving the DEMO availability goal. Note, however, that the 90% level is generally required for major and critical projects such as DEMO. This is particularly alarming since we made optimistic assumptions about an MTTR of 1 week.

The results here show that the DEMO time schedule and availability goals for DEMO defined in earlier studies are not attainable with ITER alone, and the area attainable with VNS at some risk. To reduce the risk to DEMO further, one may consider several options: reduce the availability goal for the early years of DEMO and assume staged DEMO operation, or operate VNS for FNT testing longer than 12 years. The calculations presented in Table 33 help to provide additional quantification of the issue. Two cases for DEMO reactor availability are considered; 52% and 37%. For each case, two values of MTTR of 1 week and 1 month are assumed. The confidence level in DEMO availability is then calculated after the end of FNT testing. For the 52% DEMO availability case, the confidence level is zero with ITER and 56% with VNS after 12 years of testing if the MTTR is 1 week. For the same 52% case, if the MTTR is 1 month, the confidence level with ITER testing remains zero and decreases dramatically even with VNS. If the DEMO reactor availability goal is reduced to 37% and the MTTR is 1 week, the confidence level after 12 years of operation is still zero with ITER but becomes almost 100% with VNS. If the MTTR is 1 month, the confidence level remains zero with ITER and decreases to about 53% with VNS.

Key conclusions on risk can be summarized here. With ITER alone, the risk to DEMO is unacceptably high even if the DEMO availability goal is reduced to 30%. With VNS, the risk is very low for a DEMO availability goal of about 30%. However, even with VNS, there remains some risk to the DEMO with the magnitude of such risk increasing for higher values of DEMO availability goals and/or longer machine downtime for recovery from failure.

Table 34
Comparison of costs, schedule and confidence level in DEMO for three scenarios

	(A) ITER-alone strategy (with 1.1 MW years m^{-2})	(B) ITER-alone strategy (with 3.3 MW years m^{-2})	(C) ITER BPP with parallel VNS
Capital cost (US$ billion)			
ITER	8	8 [a]	8
VNS	—	—	2
Operating cost (US$ billion)			
ITER BPP (12 years)	4.8	4.8	4.8
ITER EPP (12 years)	4.8	4.8 [a]	—
VNS (12 years)	—	—	3.0
Tritium supply cost (US$ billion)			
ITER BPP	0.17	0.50	0.17
ITER EPP	1.68	5.04 [b]	—
VNS	—	—	0.48
Total cost (US$ billion)	19.45	23.14	18.45
Confidence level in DEMO at the year 2025	<1%	<10% [a]	>70%
Year of DEMO operation	After 2042 (??)	After 2042 (??)	2025

[a] Note that no additional capital or operating costs are included for operating ITER at the high fluence. Therefore the cost presented here for this scenario is likely to be an underestimate.

[b] Tritium supply availability is an issue.

8.1. Costs

All the above considerations clearly indicate that VNS is not only desirable but is a necessary element in the world fusion R&D program toward DEMO. The question is whether it adds a substantial financial burden. We shall address cost considerations which show that VNS is affordable and most probably will result in savings in the overall cost of R&D toward DEMO.

There are two aspects of financial considerations that will be addressed: (1) the total cost of fusion R&D from now until the DEMO, and (2) expenditure profile, i.e. the annual cost and whether it peaks to an unaffordable level in certain years.

We shall make approximations here regarding the cost estimate. They are for comparative and illustrative purposes and are not meant to be precise numbers. Table 34 shows a comparison of costs for three scenarios: (A) ITER-alone strategy with the fluence goals as in EDA, i.e. 0.1 and 1.0 MW year m^{-2} for BPP and EPP respectively; (B) ITER-alone strategy with the fluence increased to 3.3 MW year m^{-2} assuming that ITER would be modified and operated to its full potential of the present design; (C) ITER with VNS as parallel facilities. Note that VNS may eliminate the need for EPP in ITER since the fluence achievable with VNS during the ITER BPP already far exceeds that planned for the ITER EPP.

The capital cost for ITER is about US$8 billion (1994 dollars). Relative to ITER, VNS has a smaller first wall surface area by a factor of about 20. The VNS design envelope with normal copper coils shown in the previous section has an estimated capital cost in the range of 15% to 25% of that of ITER. We use here the 25% upper value to yield US$2 billion for VNS capital cost. ITER has an estimated operating cost of about US$400 million $year^{-1}$. Relative to this, we estimate VNS operating cost to be about US$250 million $year^{-1}$ including the power consumption cost. The tritium supply cost is calculated at US$20 million kg^{-1}.

The results in Table 34 show that the total capital, operating and tritium supply costs are US$19.45, 23.14 and 18.45 billion for scenarios (A), (B) and (C) respectively. The lowest cost strategy for fusion R&D is with VNS parallel to ITER. The uncertainties in the cost estimate are not critical here. The key point is that VNS, besides being necessary from a technical standpoint, does not really add a cost burden; it actually provides cost savings. Another indication of the cost savings of operating VNS parallel to ITER is a minimum 17 year reduction in the period from now to DEMO. At the present world expenditure on fusion

Table 35
Construction cost by party for the International Thermonuclear Experimental Reactor and the volumetric neutron source (assuming that the host party pays 50%)

Facility	Total cost (US$ billion)	ITER at X site (US$ billion)	VNS at Y site (US$ billion)
ITER	8	4	1.33
VNS	2	0.33	1.0
IFMIF	0.8	0.13	0.13
Other	2	0.5	0.5
Total	12.8	4.96	2.96

R&D of US$1.2 billion, this shortening of time to DEMO made possible by VNS provides additional savings of about US$20 billion. This cost saving becomes possible with VNS even if the high risk to the DEMO with ITER alone strategy is ignored.

Table 34 shows the confidence level in achieving the DEMO availability goal with FNT testing data accumulated up to one specific point in time, i.e. the year 2025. The confidence level with the ITER alone scenario is less than 1%, which implies too high a risk to be acceptable. Introducing VNS allows a confidence level in the DEMO of greater than 70%, which means that the risk is still significant but it is low enough that it could be accepted.

It should be obvious that, if the ITER-alone strategy is to be compared with the ITER–VNS parallel facilities strategy on the same risk, one should consider another facility (pre-DEMO) between ITER and DEMO. This scenario results obviously in very large additional capital and operating costs of DEMO, it delays DEMO operation to the year 2054 and results in improving the confidence level only to the level achievable with VNS for a DEMO by the year 2025.

The final point on costs is whether constructing and operating VNS in parallel to ITER will impose a substantial financial burden during the years of construction. Such a burden will be substantial if one country builds both ITER and VNS. However, in the context of an international fusion program, VNS will not impose a significant burden if two key points are realized: (1) ITER and VNS will be sited in two different countries, instead of in the same country, and (2) the host party for a facility will pay 50% or more of the capital cost for this facility, as presently being discussed for ITER. Table 35 summarizes the construction costs for party X that hosts ITER and for party Y that hosts VNS. The ITER host party X will pay US$4.96 billion of which only US$0.33 billion, i.e. less than 10%, is the additional burden due to VNS. The VNS host Y will pay a total cost of US$2.96 billion which is substantially lower than that to be paid for hosting ITER. The benefits to both parties X and Y cannot be quantified at present but they appear comparable. Since VNS will deal with the FNT components and engineering issues that are most critical to DEMO, the experience gained from hosting VNS is tremendous. Finally, from a programmatic viewpoint, the scenario with parallel ITER and VNS should make it easier to agree on siting by providing more than one opportunity to the parties.

9. Conclusions

This paper has addressed and quantified the R&D needs for the design, construction and operation of FNT components for DEMO with emphasis on the type and characteristics of a fusion testing facility. The most important overall conclusion is that there is a compelling and quantifiable need for the construction of VNS, a dedicated fusion facility to test, develop and qualify FNT components and materials for DEMO. VNS should start operation at the same time as ITER.

The analysis presented in this paper led to many important scientific and broad technical conclusions that have critical implications to fusion development in general and to tokamak blankets in particular. These conclusions were derived from analysis and evaluation of many complex and interrelated technical areas. These conclusions are clearly stated in various parts of the paper where they can best be understood in the context of the supporting analysis. Below, we briefly summarize some of the key conclusions.

(1) FNT development has most of the remaining feasibility and attractiveness issues for realizing fusion power. A serious R&D program with clear strategy and goals for FNT development does not now exist and needs to be established.

(2) Industry and utility requirements for fusion demonstration power plants (DEMO) make it possible to define a narrow range of parameters and characteristics for a tokamak DEMO. Such a DEMO is now the stated goal of most of the world's fusion R&D program. The DEMO goals for fuel self-sufficiency, safety, environmental impact and plant availability permit deriving quantitative goals for FNT R&D. The blanket is found to determine the critical path to FNT development.

(3) The feasibility of blanket concepts cannot be established prior to extensive testing in the fusion envi-

ronment. None of the critical issues can be resolved by testing in non-fusion facilities. Non-neutron test stands, fission reactors and accelerator-based neutron sources (including the D–Li source) are unable to simulate the multiple effects of the fusion environment and they cannot provide adequate space per test article nor sufficient volume for a significant part of the test matrix. However, non-fusion facilities can and should play a role in blanket R&D because of availability and low cost and in order to reduce the cost and risk of the more complex fusion experiments.

(4) FNT testing in fusion facilities should proceed in three stages: stage I, scoping; stage II, concept verification; and stage III, CEDAR growth. The FNT fusion testing requirements are 1–2 MW years m^{-2} neutron wall load, steady state plasma operation, 1–2 week periods of continuous operation (i.e. 100% device availability), greater than 6 MW years m^{-2} fluence and greater than 10 m^2 of test area.

(5) Component engineering development and reliability growth stage is the most demanding on FNT testing.

(6) Reliability and availability analysis reveals critical concerns in fusion power development, some of which can be addressed by changes in blanket and machine design, some can be addressed by extensive testing, but some points raise questions about the ultimate practicality and economics of tokamak power systems. For a DEMO reactor availability goal of 60%, the blanket availability needs to be about 98%. The MTTR and MTBF are interrelated. For MTTRs of 1 week and 1 month, the blanket MTBFs must be greater than 0.8 full power years and 3.4 full power years respectively, i.e. only one failure anywhere in the blanket is allowed about every 1 year or four years of operation respectively. For a blanket that has 80 modules, the corresponding MTBFs per module are 62 full power years and 271 full power years. These are too ambitious. Experience from non-fusion technologies shows that the longest MTBF that can be achieved per blanket module is likely to be about 1–16 years.

(7) Some of the important conclusions regarding failure modes, failure rates and reliability growth testing are as follows.

(a) Capability to replace first wall–blanket system in a reasonable time (less than 1 week) must be a design goal for fusion devices.

(b) Design concept selection and improvement for the first wall–blanket system must aim at improving reliability (e.g. minimize welds, brazes, joints or total tube length).

(c) A serious reliability and availability analysis must be an integral part of the design process.

(d) R&D program must be based on quantitative goals for reliability (type and number of tests, test duration, prototypicality).

(e) Reliability growth testing in fusion devices will be the most demanding, particularly on number of tests and time duration of tests (greater than 10 m^2 and about 6 MW years m^{-2} for blankets).

(f) Reliability testing should include: (1) identification of failure modes and effects, (2) aggressive iterative design–test–analyze–fix programs aimed at improving reliability and (3) obtaining failure rate data sufficient to predict the MTBF.

(8) ITER alone cannot satisfy the FNT fusion testing requirements because of (1) pulsed operation with low duty cycle, (2) low fluence, (3) short continuous operating time and (4) low device availability.

(9) An ITER-alone strategy delays DEMO operation by more than 17 years and results in unacceptably high risk (greater than 99%) of not achieving the DEMO availability goals.

(10) A prudent optimum path to fusion DEMO involves two parallel fusion facilities: (1) ITER to provide data on plasma performance, plasma support technology, and system integration (except blanket) and (2) VNS to test, develop and qualify fusion nuclear components and materials combinations and to demonstrate an acceptable MTTR for DEMO.

(11) An attractive design envelope for VNS exists. A small-size ($R < 2$ m) tokamak with normal-conducting TFCs and driven ($Q \approx 1$–3) steady state plasma meets the FNT testing requirements with capital cost expected to be less than 25% of that of ITER.

(12) A parallel ITER–VNS strategy makes it possible to meet the DEMO operation by the year 2025 and increases the confidence level in achieving DEMO availability from less than 1% with ITER-alone strategy to about 60% with VNS.

(13) A scenario with VNS parallel to ITER provides cost savings in the overall R&D towards DEMO compared with an ITER-alone strategy. The near-term cost burden is small in the context of an international fusion program with VNS and ITER sited in two different countries.

Acknowledgments

Part of this research was carried out in the context of a US study, called VENUS, led by the University of California Los Angeles (UCLA), with support from the

Oak Ridge National Laboratory (ORNL) and Lawrence Livermore National Laboratory (LLNL) and other organizations. The efforts of many scientists and engineers, particularly Dr. A. Ying, Dr. F. Tehranian, Dr. M.S. Tillack, Dr. S. Sharafat, Dr. M.Z. Youssef and Dr. L. Zhang from UCLA, Dr. M. Peng from ORNL and B. Hooper from LLNL are greatly acknowledged. Sincere thanks are also due to Dr. I. Gomes from Argonne National Laboratory for providing a reprint of his neutronics calculations for the D–Li source. The assistance of Ms. Whitney Hinman and Ms. Rachel Holmes in the typographical preparation of the manuscript is greatly appreciated. This research was supported in part by the US Department of Energy.

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