Fusion Engineering and Design 10 (1989) 95–102
North-Holland, Amsterdam

NEUTRONICS TESTS IN A FUSION ENGINEERING FACILITY

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Many important neutronics issues will require testing in a fusion facility such as NET, FER, TIBER, OTR, or ITER. These neutronics issues include demonstration of tritium self-sufficiency, verification of adequate radiation protection of components and personnel, and validation of calculational methods and nuclear data. This paper examines the extent to which these issues can be resolved in a fusion testing facility, and discusses the technical interrelationships between the specialized neutronics tests and other tests for the blanket (e.g., fluid flow, tritium recovery). The most difficult issue appears to be the demonstration of DT fuel self-sufficiency. Direct demonstration requires a complete fuel cycle including full blanket and integrated tritium processing systems. This appears unlikely in the next fusion facility. Therefore, indirect demonstration through synthesis of information from various tests appears to be the only option.

Tests for verification of other neutronics parameters can be classified into three categories: (1) dedicated tests; (2) supplementary measurements; and (3) measurements for the basic device. Dedicated tests aim at examining the accuracy of present neutron transport codes, basic nuclear data, and geometrical modeling in predicting key neutronics parameters. These tests would be carried out in large modules specifically designed for that purpose to maintain the appropriate boundary conditions. In addition, these tests would also be performed in various breeding material/coolant test modules to estimate the uncertainties in predicting their key neutronics parameters. Most of these tests require only low fluence (< 0.1 MW y/m^2) and short plasma pulses (< 30 s) and are best suited for the early phases of the device operation. Supplementary neutronics measurements are intended to be performed in test modules used for other non-neutronics tests (e.g., tritium-recovery, thermo-mechanics tests, etc.). Goals of this category of tests are to: (1) provide the source terms and their associated uncertainties for the non-neutronics tests, and (2) provide additional supporting information to the dedicated tests. The overall test matrix schedule for the above-mentioned neutronics tests has been defined and the measuring techniques to perform these tests have been identified.

1. Introduction

Unlike the neutronics integral experiments that are currently in progress worldwide, and are utilizing D–T point sources (e.g., the FNS experiments at JAERI [1], the LOTUS experiments in Switzerland [2]), the future test reactor of the ITER type will offer a volumetric D–T neutron source (plasma) representative of the one found in a realistic fusion environment. The consequence is to have an external neutron source incident on a test module(s) that has an energy and angle distribution similar to those expected in future Demo or Commercial plants. As such, many of the neutronics parameters in the First Wall/Blanket/Shield (FW/B/S) system will have characteristics (absolute levels and profiles) that are different from the ones based on a simplified geometrical arrangement with a point source.

In this paper, we present an investigation of the role and requirements of neutronics tests in the next fusion engineering facility. This work was carried out in the context of TIBER [3]. However, the results are of much broader applicability. The key neutronics issues to be resolved in an experimental test facility are generic in nature and are important for each major blanket type to be tested in this facility. These include, (1) the demonstration of tritium self-sufficiency for a particular FW/B/S system, (2) verification of the adequacy of current neutron transport codes and nuclear data in predicting key parameters such as local (and zonal) tritium production rate (TPR), heating rate, gas production, and activation, and (3) verification of adequate radiation protection of machine components (e.g., magnets) and personnel. In the next fusion experimental reactor, several sectors will be devoted to technology testing on several blankets of various breeder/coolant types. For example, in TIBER-II [3], there are eight intercoil spaces available for nuclear test modules with a first wall area of 2 m (poloidal) × 1.2 m (toroidal). The other eight intercoil spaces consist of the basic device. Neutronics tests are intended to be performed in the test modules as well as the basic machine and behind the shield. In addition, the early stage of operating the test reactor will be mainly for physics tests. In TIBER-II, for example, the first Phase (Phase I) consists of one year for checkout with hydrogen plasma and 15% availability, followed by another year with D–T plasma and 10% availability. Phase II is for physics tests on D–T plasmas for three years with ~10% availability. A nuclear testing mission phase (Phase III) is scheduled for seven years on a D–T plasma with 30% availability. The integrated neutron fluence during the 12 years of TIBER-II operation is thus ~4 MW y/m^2. As discussed in the text, the tests intended to resolve important neutronics issues require much lower fluence and thus can be performed during the early stage of operation. These neutronics issues are discussed in Section 2. Classification of various neutronics tests intended to resolve these issues are given in Section 3, while Section 4 discusses the component test size required to carry out these tests along with the required instrumentation.

2. Key neutronics issues

2.1. Self-sufficiency demonstration

Achieving a tritium self-sufficiency condition [5,6] for fusion reactors operated on the DT cycle requires that the *achievable* tritium breeding ratio (Λ_a) be equal to or greater than the *required* breeding ratio (Λ_r). The Λ_a is the net tritium production per fusion neutron. It is a function of many variables, such as:

(a) blanket material,
(b) blanket design,
(c) blanket coverage of the region surrounding the plasma
(d) first wall and in-vessel components materials and design,
(e) characteristics of penetrations, and
(f) presence of non-breeding materials in the blanket region (e.g., passive copper coils).

The Λ_r is equal to the tritium consumption per fusion reaction plus the margin necessary to compensate for tritium decay and to supply the initial tritium inventory to other reactors for a specified doubling time. The Λ_r is also a function of many system parameters and features, such as:

(1) fractional tritium burnup in the plasma,
(2) tritium inventory retained in the blanket and other components,
(3) efficiency of tritium extraction from streams flowing from various components, particularly plasma exhaust,
(4) frequency of failure and downtime to repair tritium extraction systems, and
(5) desired doubling time.

At present, there are large uncertainties associated with estimating Λ_a and Λ_r. Preliminary analysis indicates that the uncertainty in extrapolation may be larger than the available tritium breeding margin with many leading blanket concepts in typical fusion reactor conceptual designs. It is therefore necessary that self-sufficiency be demonstrated at the earliest possible time, as it will definitely impact selection of concepts and operating regime for many parts of fusion reactors.

Direct demonstration of tritium self-sufficiency requires a fully integrated reactor system, including the plasma and all reactor prototypic nuclear components. This does not appear possible in ITER (e.g., basic tritium-producing blanket type, coverage and interface with tritium processing may not be prototypic). It may thus be necessary to rely on indirect demonstration through synthesis and extrapolation of information obtained from the operation of both basic components and test elements in ITER. One important finding is that, for at least one blanket type, testing an entire sector, fully integrated with a tritium processing system, is required as part of fuel self-sufficiency demonstration. A sector test, rather than only a module test, is necessary because

(1) there are strong poloidal variations in tritium production rates due to variations in wall load, geometry, penetrations, etc. Thus, the extrapolation of results from each module to reactor conditions will be different, and
(2) the uncertainties arising from specifying the boundary conditions for the modules are large and make extrapolation difficult.

Direct measurement of tritium breeding from a sector is possible by measuring all the tritium released and processed in the tritium processing system for that particular sector once equilibrium (or near equilibrium) is reached. This tritium processing system will also give direct measurements of parameters important to the required breeding ratio (λ_r), such as tritium mean residence time and any inefficiency in tritium processing. It is suggested that a module of the same type of blanket used in the sector also be tested in parallel to the sector in various poloidal locations. This would be useful in developing correlations for extrapolation from module to sector to reactor. Other blanket types can then be tested in modules and the module-reactor correlation can be used for extrapolation of testing results.

2.2. Other neutronics issues

Other neutronics issues to be addressed in the next fusion test facility are:

(a) *Nuclear heating*: This issue is related to power multiplication and deposition in the FW/B/S system. Local heat generation and associated profiles, can, in principle, be measured, and confirmation to analytical predictions can be made. Many of the thermomechanical behaviors and tritium recovery are strongly dependent on the accuracy in estimating this heat generation source;

(b) *Activation*: Activation levels in the FW/shield structure and behind the shield both during operation and after shutdown comprises an important neutronic issue. Neutron and gamma ray leakage will determine dose levels behind the shield and through penetrations during operation. Afterheat level is important in determining emergency cooling scenarios after shutdown; and

(c) *Radiation damage*: material properties and component lifetime under prolonged irradiation can be inferred from radiation damage indicators such as the rates of displacement and helium and hydrogen production. For component integrated testing, it is desirable to retain, as closely as possible, those levels and profiles of radiation damage parameters that are anticipated in a typical fusion reactor environment in a particular test module dedicated for material testing, especially in the first wall structure. However, the accumulated levels may not be prototypical of those needed for lifetime testing due to the low fluence in a fusion test reactor (4–5 MW y/m^2) and some interpolation may be required.

3. Classification of neutronics tests

For the above issues, the neutronics tests to be carried out in the next fusion test facility can be broadly classified under three categories of tests. These categories are:

3.1. Dedicated neutronics tests

These tests aim at examining the present state-of-the-art neutron cross-section data, various methodologies implemented in neutron transport codes, and system geometrical modeling as to the accuracy in predicting key neutronics parameters in a realistic fusion environment. This examination can be achieved by comparing predictions to measurements. The goal of this category of tests is to identify the source of discrepancies between the analytical predictions (by using various codes, such as the MCNP Monte Carlo Code and the DOT discrete ordinates code, and various data bases such as ENDF/B and JENDL) and the experimental data and hence actions can be taken to improve a particular cross-section type and/or numerical methods and their associated approximations. These tests will provide, among other information, the overall uncertainties in predicting important neutronics parameters such as the tritium production rate. Since these uncertainties are dependent on the test module type, such tests can be performed on the various blanket/coolant types planned for testing in the facility (e.g., He-cooled test modules with either solid breeder or liquid metal, water-cooled solid breeder, etc.).

The measurements that will be performed for the dedicated neutronics tests include neutron yield and external DT source characterization, local tritium production and heating rates, neutron (and gamma rays) spectra, and several reaction rate measurements using various foils of specific materials [e.g., ^{27}Al(n, 2n), ^{27}Al(n, α), ^{197}Au(n, γ), ^{58}Ni(n, p) etc.]. These multi-foil activation (MFA) measurements are performed to extract information on the neutron spectrum.

Included in this class of tests is the global TBR verification from a sector of a specific FW/B/S type discussed in subsection 2.1 with the objective of obtaining information on the uncertainties in prediction and attempting to extrapolate this uncertainty to commercial reactor conditions. Examples of other dedicated neutronics tests are shown in table 1. Except for neutron yield and source characterization, these measurements are performed at several locations inside the test modules. Other out-of-module measurements will include dose measurements behind the test module and they can be concurrently performed with other measurements. As stated earlier, these measurements require very low fluence (1 W s/m^2–1 MW s/m^2) and thus are suited for early stages of the reactor operation. The only exception is for hydrogen and helium production rate, and activation rate measurements which require a larger fluence (> 0.1 MW y/m^2) in order to accumulate enough measurable products.

3.2. Supplementary neutronics measurements

These neutronics measurements are intended to be performed in test modules (or submodules) used for other non-neutronics tests. Goals for this category are to: (1) provide additional supporting information to the dedicated neutronics tests in examining the prediction

Table 1
Examples of dedicated neutronics test

	Source characterization	In-module parameters		Out-of-module parameters
Parameters:	Neutron yield	TPR, heating rate, neutron spectrum, gamma spectrum, reaction rates	H, He, dpa rates, activation	Dose behind shield
Test type:	Out-of-module	In-module, integrated (at a location)	In-module, integrated (at a location)	Out-of-module, integrated
Test module conditions: Material, Geometry, Test module size	N/A	A submodule ($0.3 \times 0.3 \times 1$ m^3) or module ($2 \times 1 \times 1$ m^3) is sufficient to perform these tests provided the geometrical details surrounding the test module are accurately considered in modeling (module is preferable). Various materials and configuration (prototypical FW/B/S) are needed.		
Device operating conditions:				
Fluence	← 1 W s/m^2 to 1 MW s/m^2 → Any linear combination of wall load and operating time which leads to this range of fluence is acceptable. Typically, 20 s of operation of @ 5×10^{12} n/cm^2 s is adequate.		< 0.1 MW y/m^2 (Fluence is required to accumulate reasonable level of damage/activation)	1 MW s/m^2 Same as for in-module parameters
Operation scenario	← Steady-state or pulsed operation →			
Operation phase (TIBER-II)	Phase IB, Phase II, Phase III	Phase IB: Checkout Phase Phase II: Physics Mission Phase	Phase II or III	Concurrent with in-module tests

capabilities of various computational methods, and (2) provide the source terms and their associated uncertainties (e.g., heat generation and tritium production rate) for other non-neutronics tests devoted to predictive behavior and engineering performance verification (e.g., tritium recovery tests, thermo-mechanics tests, afterheat removal safety tests, etc.). Since these engineering performance tests will most likely be scheduled during the technology test phase after the early phases and checkout phases, these measurements can first be performed on the test submodule (module) since they require a very short time (typically 20 s to 1 min at 5×10^{12} n/cm^2 s neutron yield), then other non-neutronics tests can follow. As needed, these measurements can be repeated at any specific time during the technology phase of the reactor operation. Measurements that require longer times are those related to the first wall and breeder damage parameters such as H, He, and dpa production rates. These measurements will require a full operation period of 0.5–1 y before they can be performed.

Included in these supplementary measurements are those related to safety tests. Afterheat level measurements are performed on a selected test module type and comparison is made to prediction. These tests will also determine the accumulated radioactivity levels in the test module after prolonged operation (3 months to 1 y). Measurements of the test module environment (e.g., spectra, heat generation rate and profile) during transient effects tests could be performed toward the end of the technology phase. Examples of the supplementary neutronics measurements that are related to safety tests are shown in table 2.

3.3. *Neutronics measurements for the basic device*

The purpose of these measurements is to obtain useful information from measurements for other key parameters at important locations of the basic device. These include measurements of the afterheat level, accumulated activation level, and personnel exposure level

Table 2
Supplementary neutronics measurements in modules for other non-neutronics tests (safety related tests)

Parameters:	Afterheat level	Accumulated radioactivity	Test module characteristics (e.g., heat generation) under transient conditions
Related issues:	- LOC and LOF scenarios - Passive cooling system and heat dump	Waste classification and management	Safety control of test module under transient conditions
Test type:	Integrated, out-of-module	Performed after removing test module(s)	Integrated, in-module
Approach:	Predictions are made to the build-up of radionuclides in the breeder and structure after prolonged period of operation. Level of integrated decay heat is compared to measurements		Changes in local and zonal volumetric heat generation under transient conditions are measured. Comparison to prediction is made.
Test module conditions:			
Material, geometry, size, etc.,	Since a single coolant path is most likely to be deployed for all submodules that constitute a test sector ($2\times1.2\times1.2$ m^3), a full sector is preferred to perform these tests. Equally well performed on solid breeder or liquid metal breeder test module types.		
Device operating conditions:			
Fluence	Requires prolonged operation before performing tests. Operation for 3 months to 1 y is required to reach radioactivity saturation level. Fluence requirement $\approx$ 0.3–1 MW y/m^2		Transient effects tests are performed after reaching fluence of ~ 1.5 MW y/m^2 for dose after shutdown
Phase of operation (TIBER-II)	← Phase III →		← Near end of Phase III →

behind the shield during operation and after shutdown as well as the radiation levels around the penetrations for fueling and heating, etc. Of interest are the measurements of neutrons and gamma ray leakage behind the inboard (I/B) and outboard (O/B) shield of the device during operation. In particular, the level of fast neutron fluence ($E_n > 0.1$ MeV) behind the I/B shield is a measure of the radiation damage to the inner leg of the TF magnet. The monitored nuclear field (leakage spectra, dose) can be compared to the predicted values. Since these measurements could be viewed as monitoring processes, they could be carried out during all phases of operation.

4. Test component description and instrumentation

Neutronics parameters are sensitive to conditions such as the surface area of the test module and the geometrical arrangement and materials surrounding the test modules. Fig. 1 shows, for example, a test module placed in a tokamak device that is surrounded by a non-breeding blanket filled with stainless steel. The local tritium production rates from ^{6}Li(T_6) and from ^{7}Li(T_7), as a function of the poloidal angle at the front edge of the breeding zone, and for a given front surface test area determined by the angle θ, are shown in fig. 2 relative to the case where the test module fully surrounds the plasma. As shown, T_6 values are higher by a factor of 4–5 than those found in the full-coverage case. The deviation is more pronounced for smaller sized test modules [7,8]. While, in principle, a small size test submodule (~ 0.3 m $\times 0.3$ m) could be used for predictive capability verification, a full test module (2 m $\times$ 1.2 m $\times$ 1.2 m) is preferred since the derived uncertainties in the prediction of the local values of those parameters considered in the dedicated neutronics tests will be more representative of those anticipated in the full coverage blanket case. In addition, it is preferable to carry out the dedicated neutronics measurements in the innermost portion of the test module away from the test module boundaries where large spectrum changes are encountered.

As for a global parameter such as the tritium breeding ratio (TBR), it is necessary to use an entire sector for predictive capability verification. To illustrate the possibility of carrying out this global test, we refer to a proposed helium-cooled solid breeding blanket for the basic device of ITER [9]. In this blanket type, the canisters that include the solid breeder (Li_4SO_4) and multiplier (Be) rods are placed poloidally at the outboard. There are sixteen sectors in the device, some of them are devoted to nuclear testing on various breeder/coolant blanket concepts. Helium purge gas is also used to collect the released tritium. In principle, one can isolate a dedicated sector for the TBR verification. In this regard, a separate purge gas circuit can be assigned to that sector. Tritium released from the sector to the purge gas will vary with time during operation until the temperature profiles across the blanket are established. Thus, a saturation (or near saturation) in the amount of tritium released will occur. The time required to reach saturation depends on the type of breeder and its physical properties. Once saturation is reached, the amount of tritium generated in the entire sector will be equal to the amount of tritium released in the purge gas stream, regardless of the tritium inventory (trapped) in the sector. One can, in principle, measure the total amount of tritium in the purge gas emerging from the sector and comparison can be made to the integrated predicted value based on various transport codes and nuclear data. The calculated-to-measured value (C/E) indicates the uncertainty involved in the prediction of the TBR (after accounting for errors associated with measurements). This uncertainty is for the TBR of the blanket used for the basic machine, but in general test modules based on other breeder/coolant types can be designed to occupy also a whole sector in order to neutronically examine the uncertainty of the TBR in that particular blanket design concept. Note that the above method of verifying the predictive capability for the TBR could be viewed as an on-line method and thus could be applied during any phase of operation of the test device, provided that saturation in the tritium released to the purge gas is reached.

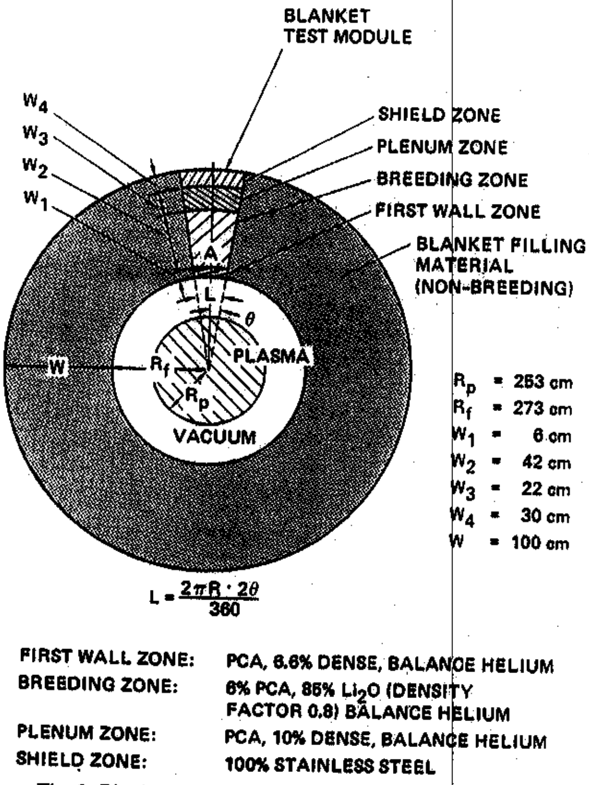


Fig. 1. Blanket test module placed in a tokamak reactor.

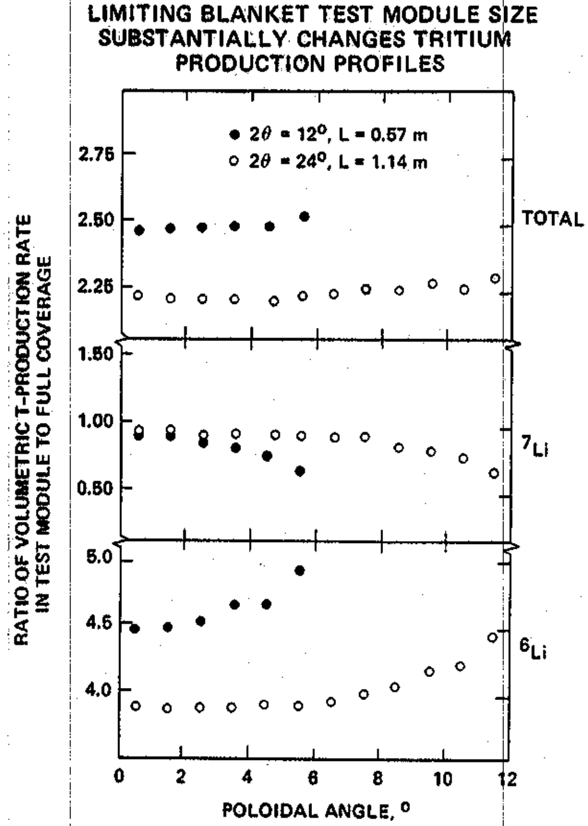
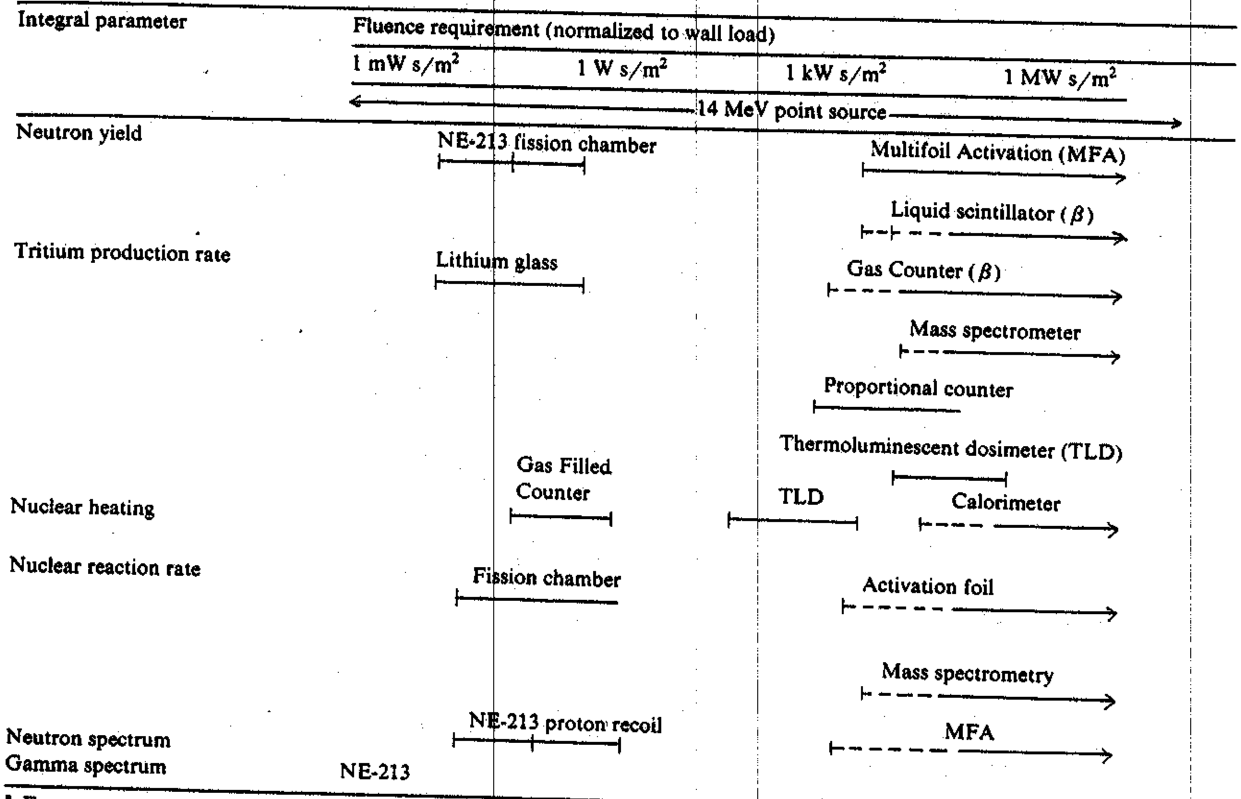


Fig. 2. Ratio of local tritium production for $^6Li(T_6)$ and $^7Li(T_7)$ in the poloidal direction at the front surface of the test module to the corresponding values in the full coverage case.

The neutronics measurements aimed at providing the source term(s) required for other non-neutronics tests will be performed in test modules whose size is governed

Table 3
Fluence requirements for various measuring techniques [a,b]



[a] For counter methods, the measuring time is assumed to be 10 to 100 s.

[b] Table taken from ref. [8].

basically by the requirements for these tests. To simulate a particular phenomenon that would take place in a full size reactor under the scaled down test conditions of the next fusion test facility, the size of the test module of a particular type may be different from these to be considered in a full-size reactor. For example, the first wall thickness of the test module may be larger at the reduced power of the test reactor to achieve the same level of thermal stress in a thin first wall subject to larger power. Also, the breeder zone thickness of the test module may be smaller than in an actual module to be placed in a commercial fusion reactor. The impact of such design changes on the neutronics parameters in the test modules is as follows:

(a) an increase by a factor of three in the first wall thickness can lead to 20–30% increase in the heat deposition rate in the first wall. Since damage parameters (e.g., He and H production rate) depend strongly on fast neutron flux, an increase in the first wall thickness leads to a decrease in these parameters everywhere in the breeding region.

(b) The shape of the profiles of tritium and heat generation rates across the breeding zone is insensitive to the thickness of the breeding zone except near the reflector. A variation in the local heating rate of ~ 10–15% is expected for a change in the breeding zone thickness from ~ 10 cm to 50 cm. This deviation is larger (~ 20%) for tritium production rates, especially near the reflector. A good simulation to these profiles can be obtained with a breeding zone of ~ 20 cm-thick as long as the reflector/shield zone is retained. Blankets which utilize enriched ^{6}Li are more sensitive to changes in the breeder thickness.

During the operation of the next fusion test facility, additional information about measuring techniques and instrumentation will be gained. Nuclear field and neutron yield measurements will be performed inside the plasma chamber using a multi-foil activation method.

Tritium production rate measurements can be spatially performed with liquid scintillation counters with samples made of Li, Li_2O or Li_2CO_3. Gas proportional counters can also be used for high fluence. In principle, thermoluminescent dosimeters (TLDs) and calorimeters can be used for heat generation rate measurements, but specially-designed, small-size detectors are necessary. Neutron spectrum measurements at selected locations inside the test module can be best performed by using the multi-foil activation method (MFA) that utilizes ^{197}Au, ^{58}Ni, ^{27}Al, and ^{93}Nb foils. The MFA method is an indirect technique and should be previously confirmed in various neutron fields [10]. Dose levels behind the shield of the test module will be performed using neutron and gamma ray dosimeters. In addition, confirmation of the acceptable damage limits to the TF magnets behind the shield can be achieved by performing fast neutron ($E_n > 0.1$ MeV) flux measurements using NE213 counters at various locations. Fluence requirements to perform the above mentioned measurements are summarized in table 3. The main concern with some of the instrumentation shown in this table is the radiation damage to the detector components (e.g., photomultiplier) under prolonged irradiation (e.g., NE213 detectors), but in general, further development is needed in the area of neutronics instrumentation for fusion applications.

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