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Role and contribution of ITER in research of materials and reactor components

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Abstract

ITER will be the first operating fusion reactor. Although operational conditions and the design of ITER in-vessel components may differ from the design for reactors producing electricity, the operation of ITER will provide a wide range of tests of materials and components under combined 14 MeV neutron, heat and particle fluxes within the available fluence. This paper discusses the possible tests in ITER in the following areas: tests of the materials with the goal of development of a fundamental understanding of fusion neutron irradiation effects, tests of breeding blanket materials and components, and tests of plasma facing materials and divertor components.
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1. Introduction

ITER will be the first operating fusion reactor. Its programmatic objective is 'to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes'. The overall ITER design is complete and ITER construction will start soon. The detailed description of the ITER design is published in the ITER Final Design Report, 2001 [1]. The present status of the project and future prospects are discussed in these proceedings [2].

Starting from the first ITER Conceptual Design Activities (1988), ITER was always considered as a test-bed for fusion reactor components and fusion reactor materials. Although operational conditions and the design of ITER in-vessel components may differ from the design for reactors producing electricity (different materials, pulsed operation, coolant temperature, etc.), the operation of ITER will provide an opportunity to conduct a wide range of tests of materials and components under combined 14 MeV neutron, heat and particle fluxes up to the maximum neutron fluence of $\sim$0.5 MWa/m^2. The results of these tests should provide valuable information for the next device, one which must finally produce electricity ('DEMO').

Taking into account the schedule for finalisation of the design of the ITER in-vessel components up to the start of manufacturing, there are several possibilities to include specific testing programs in the ITER operational plan. The preparation of the testing program is under way through a joint activity between the ITER International Team and the ITER Parties, which represent the future users of the ITER machine. The planned testing program in ITER is part of the worldwide fusion materials program, which include the modelling for the fundamental understanding of the radiation defects, required high dose irradiation in IFMIF [3] and other facilities, design and tests of blankets, studying of the plasma-materials interaction issues, etc.

This paper will briefly discuss the main operational parameters of ITER important for the in-vessel materials and component testing and will describe the main possible areas of tests in ITER.

2. ITER design features

The major parameters of ITER, which are important for materials and components testing, are shown in Table 1. ITER is an experimental facility and some

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parameters in Table 1 (e.g. maximum neutron fluence) could be reassessed based on the results of ITER operation.

In any case, ITER will provide the highly relevant testing features for the subsequent device:

- fusion neutron flux in a large test volume;
- fusion neutron spectrum (see as example Fig. 1);
- volumetric heat generation in first wall, blanket and divertor;
- surface heat flux to the first wall and divertor;
- typical magnetic field;
- sufficiently long power cycles.

The modular design of the ITER in-vessel components allows exchange/update of components during the operational phase, so that different elements can be tested.

The most restrictive factor is the low neutron fluence in comparison with DEMO.

A draft ITER operational plan has been developed for only the first 10 years of operation [1]. In accordance with this plan, the expected average neutron fluence after 10 years will reach values of approximately 0.1 MWa/m^2. The schedule for the next 10 years, during which the maximum neutron fluence will be achieved, will be discussed later and depends on the results of the first phase of ITER operation.

Table 1
Major ITER parameters

Fusion power	500 MW
Plasma volume	837 m^3
Plasma surface	678 m^2
Neutron flux	Av. 0.57 MW/m^2
	Max. 0.8 MW/m^2
Neutron fluence	Av. 0.3 MWa/m^2
	Max. 0.5 MWa/m^2
Heat flux on first wall	0.2–0.5 MW/m^2
Heat flux on divertor	10 (20) MW/m^2
Pulse length	400 s
Number of pulses	~30.000

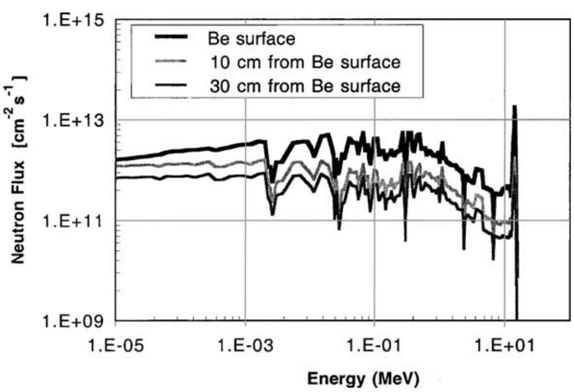

Fig. 1. Neutron spectrum of ITER in different locations related to the first wall.

3. Fusion materials tests in ITER

The calculated level of radiation damage (in dpa) and He production (in appm) for DEMO-relevant materials for ITER conditions (maximum fluence of 0.5 MWa/m^2) are shown in Table 2. Clearly, ITER cannot fully meet the materials testing needed for DEMO due to its maximum fluence limit. However, ITER can provide valuable understanding of fusion materials behaviour in a fusion neutron spectrum: dpa/gas production ratio, etc. Direct information about the effect of the fusion neutron spectrum on materials properties could be very important for the possible licensing of DEMO materials.

The main advantages of materials testing in ITER are:

- correct fusion spectrum;
- large volume (large samples and quantity);
- possibility to test materials under combined loads (synergetic effects);
- possibility for specific in-pile designed tests.

At the same time, the following ITER features have to be taken into account:

- pulsed operation;
- variable irradiation temperature.

In the immediate future only ITER will provide high flux and fluence of 14 MeV neutrons. The RTNS neutron source, which was the most powerful source available for testing of materials, provides a neutron fluence corresponded to 0.01 dpa [4]. A worldwide program to understand the fundamental features of radiation defects produced with fission and fusion neutrons is underway. Based on recent results on molecular

Table 2
The radiation damage and He production in DEMO materials for ITER conditions, neutron fluence −0.5 MWa/m^2, 1–10 cm below first wall surface

Material	dpa	He, appm
Ferritic steel	5.1–1.1	70–10
SiC/SiC	5–1.4	590–80
V alloy	5.1–1.2	20–3
Be	1.6–0.6	1670–300
W	1.5–0.3	1–0.1

dynamic simulations, it has been concluded that there is some similarity in defect production. However, the effect of He on the properties of materials is not yet well understood [4]. Specially designed simulation experiments using IFMIF and fission reactors could be designed and ITER could provide some data for the correct fusion neutron spectrum.

Another important feature of ITER is that ITER provides simultaneously the effects of different factors (neutrons, stress, heat flux, hydrogen atmosphere, etc.). The understanding of these effects first of all is important for ITER itself, because the prediction of the materials performance has been based on conventional experimental techniques. On the other hand, by combining these factors, the materials performance could be significantly different. Recently Singh [5] demonstrated that, combining neutron irradiation and tensile loading, the resultant properties of Cu alloy could be significantly different to standard properties after irradiation. Similar synergetic effects could be expected for DEMO materials must be tested in the IFMIF facility.

To validate the ITER design, especially for the high fluence phase, the properties of the ITER materials under combined loads have to be known. A possible solution is to establish a Materials Testing Program. This program has to include a materials test matrix, the design of possible irradiation rigs (irradiation temperature, etc.). Clearly, the coordination of the ITER test program and tests of the ITER materials in other facilities is still needed.

4. Test blanket module program

A key element of the worldwide fusion program is the development of breeding blankets for commercial fusion power stations. Among the various programmatic goals of ITER there is the 'test of tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency, the extraction of high grade heat and electricity production'.

To conduct this activity, the Test Blanket Working Group was established. This group represents the users of the ITER machine. The goal of this group is to develop the design of the test blanket modules (TBM) to be deployed in ITER and to establish the testing program to be implemented during ITER operation. The main objectivities of this program are quite ambitious and include [6]:

- validation of the accuracy of calculating the tritium generation rate for the tokamak configuration;
- study of tritium recovery process efficiency and tritium inventory in the blanket;
- study of breeder and beryllium multiplier temperature control;
- demonstration of ability of DEMO relevant blanket design to generate high temperature heat for electricity generation;
- validate structural integrity of TBM's under integrated thermal, mechanical, and electromagnetic loads under fusion neutron irradiation;
- validation of irradiation effects seen in a fission reactor spectrum with the aim to determine the impact of the fusion neutron spectrum at least for low fluence irradiation;
- validation of previously developed codes for thermomechanical calculations of integrated structures of blanket module including pebble beds, neutronics models, and nuclear libraries used in ITER and DEMO.

The detailed description of the ITER TBM program is described elsewhere [6,7]. ITER will provide three equatorial ports (size of $\sim 1310\times1760$ mm) for various types of TBMs. Each port can accommodates two types of TBM. Detailed design and integration of the TBMs have been started recently with the close cooperation of the ITER Team and the ITER Parties.

Testing of breeding blanket modules must not interfere with ITER availability or decrease ITER reliability and safety. This means that supporting R&D and finalisation of the TBM design must be completed soon. All materials used for TBMs must be qualified at least for the ITER operational conditions (neutron effect on properties of structural materials and breeding materials). All modules before installation in ITER must be qualified. The first TBMs must be installed in ITER at the start of operation. The ITER remote handling and maintenance will permit the exchange and servicing of the TBMs.

Reflecting the general direction of breeding blanket developments for fusion, the most developed blanket designs are under consideration for the ITER TBM program:

- He-cooled, ceramic breeder (Li_2TiO_3 or Li_2O or Li_4SiO_4), Be multiplier (pebble beds or others), reduced activated steels (F82H or Eurofer or ferritic steel 10Cr9MoMn);
- Water-cooled, ceramic breeder (Li_2TiO_3 or Li_2O), Be multiplier, reduced activated ferritic steel F82H;
- He-cooled, Pb–17Li, reduced activated steel Eurofer;
- Self-cooled Li blanket, V–4Cr–4Ti alloy.

Other advanced concepts are also under discussion. Depending on the readiness of these concepts they will be implemented in the ITER TBM program. It is planned that the ITER Parties will have the possibility to implement their blanket concepts in the ITER TBM program. However, taking into account the total possible number of blanket modules the joint participation of several Parties in implementation of specific TBM concepts could be most efficient.

The test conditions of TBMs in ITER are not fully representative of those with expected in DEMO or commercial reactors. The main differences are neutron flux, fluence, volumetric heat and surface heat flux. This means that the direct utilisation of the DEMO blanket designs is not appropriate. The 'act-alike' type of design has to be developed and implemented in the TBM program, that will allow testing of the main features of the of the blanket designs. Multiple designs of TBM for special test types, such as tritium production, beryllium pebble bed behaviour, etc. will be needed.

The TBM test strategy includes the following types of testing:

- electromagnetic testing of the blanket modules;
- neutronic and tritium production testing and code verifications;
- thermo-mechanic testing of specific components of the TBM;
- integrated testing, especially during the enhanced ITER phase.

The results of these tests will provide the confidence to support the design of the different blanket types. Depending on the general design requirements for DEMO type reactors and the results of these tests the selection of the specific blanket types will be made.

5. Plasma surface interaction and safety issues

A principle difference between ITER and the DEMO is fusion power ($\sim$2–3 GW vs. 0.5 GW for similar size) which leads to more challenging requirements to plasma facing materials and phenomena related to plasma surface interaction. The ITER plasma operational conditions are based on scaling from the conditions in current tokamaks, in a similar way, the ITER machine will be the most appropriate tool for investigation of the plasma operational scenarios for the next step machine.

The key issues, related to materials and their performance, which have to be studied during ITER operation and that are needed for the next step are:

- transient event (ELMs, disruptions) control;
- divertor power loads and power handling;
- tritium retention;
- erosion and erosion product behaviour.

Some of these issues (ELMs energy, tritium retention) have to be studied to permit the ITER operation too.

The selection of plasma-facing materials in ITER and DEMO is driven by the erosion lifetime. ITER is planning to use beryllium as a first wall armour, and tungsten and CFC as armour for the divertor. The assessment of the erosion lifetime for DEMO conditions shows that beryllium and carbon are not acceptable, only tungsten could provide the required lifetime [8].

5.1. ELMs and disruption control

ITER, as an experimental machine, is designed to withstand power transients such as disruptions and ELMs (Edge Localized Modes). The current predicted specification for Type I ELMs in ITER is:

- energy −0.5–5 MJ/m^2;
- pulse duration −0.2–1 ms;
- frequency −1–10 Hz.

Assessment of the thermal performance of the different materials shows that conditions with energy density more than 1 MJ/m^2 are not acceptable due to high thermal erosion [9]. An additional concern is the possible high cycle fatigue damage of armour materials. Extrapolation to DEMO conditions shows that the energy density per Type I ELM will be 3–5 time higher than in ITER and it is definitely unacceptable for reactors [10]. Either predictions have to be wrong or regimes without Type I ELMs and disruptions will have to be found during operation of ITER.

5.2. Divertor power loads

Due to higher fusion power the total heat flux going into the DEMO divertor will be several times larger than that in ITER. For ITER operational conditions (10 and 20 MW/m^2, 10 s transients) the power handling for the divertor design with copper alloy heat sink and water-cooling is easily realizable. However, for a DEMO type divertor with He cooling, tungsten armour and ferritic steel, the maximum heat flux should be less that 10 MW/m^2. ITER should investigate the different possible scenarios with a detached plasma with the goal to minimize the heat flux density on the divertor target.

5.3. Tritium retention and operational limitations

The main source of tritium accumulation in ITER is the codeposition of tritium with eroded carbon. To solve this problem, several ways are still under investigation [9]. For DEMO, without carbon armour, the problem with tritium retention will be of significantly less importance. But the tritium retention in the W armour, and tritium permeation to the coolant, especially under high doses of neutron irradiation could be issues. These phenomena could also be studied during ITER operation.

Another vital safety concern for ITER and for DEMO is the presence of large quantities of erosion products (dust), which potential release in case of accident could breach licensing limits. It is planned on ITER to investigate the main features of dust such as size distribution of particles, the amount and distribution in the machine. Methods of dust mobilization and removal have also to be developed.

The ITER divertor is experimental and hence exchangeable. It is foreseen in the future that different types of divertor design will be installed for testing. A divertor test program has to be established in a similar way to that for the test blanket program.

6. Conclusions

ITER will be the most important experiment in support of the design of a following power reactor, providing the vital information about plasma performance and operational conditions for key reactor elements. ITER, when built, will provide an unique opportunity to test different reactor components and reactor materials for the next step fusion reactor. Only with the success of the ITER project can future projects and future development of fusion reactors based on magnetic confinement be possible.

A consistent research program in ITER is being developed during finalisation of the design of ITER in-vessel components. It is proposed that this program should include tests on:

- materials;
- test blanket modules;
- plasma surface interaction and safety.

This program has to be coordinated with other programs such as IFMIF, materials tests in fission reactors, blanket developments, etc.

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