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Users' requirements for IFMIF

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Abstract

The International Fusion Materials Irradiation Facility (IFMIF) is a high energy neutron irradiation facility which generates an intense neutron flux with D–Li stripping reactions for fusion materials testing. The role of IFMIF is (1) development of various fusion reactor materials, (2) determination of design-relevant engineering databases for the DEMO fusion reactor, (3) calibration and validation of data generated from fission reactor irradiations and the other simulation experiments, etc. The conceptual design activity (CDA) of IFMIF was initiated in February 1995 as an IEA collaborative activity to complete a reference conceptual design of IFMIF in December 1996. Users' requirements for the conceptual design of IFMIF were developed for materials to be tested, types of experiments, small specimen test technology and irradiation conditions. Furthermore, the neutron irradiation field characteristics (spectrum, flux/volume, etc.) of IFMIF were evaluated for the conceptual design parameters and were shown to meet the essential requirements of the users.

1. Introduction

Fusion reactor materials will be exposed to neutrons with energies up to 14 MeV. Radiation damage of materials in a fusion reactor environment is characterized by synergistic effects of the cascade damage, due to displacement by PKAs (primary knock-on atoms) in a wide energy range, and nuclear transmutation products such as hydrogen and helium. Helium and hydrogen effects can be examined to some extent with spectrum tailoring and isotope tailoring methods using fission reactors for limited kinds of materials [1,2] or at lower displacement dose levels with light ion implantation techniques using accelerators [3]. With respect to damage production, materials test reactors and fast neutron reactors are valuable tools for phenomenological studies and materials screening. However, due to difference in neutron spectra between fusion and fission reactors, their applicability to generating data for fusion reactor components remains uncertain. That is, none of the existing irradiation sources combines a sufficiently large volume with high fluence and suitable neutron spectrum to develop a variety of materials for advanced D–T fusion reactors like DEMO and to qualify within a realistic time window the materials up to end-of-life conditions. Hence, a high energy neutron source has been identified as a critical need for these purposes [4,5].

An extensive design study on a high energy neutron source known as the Fusion Materials Irradiation Test Facility (FMIT) was previously performed in the USA, and engineering R&D required for construction of the D–Li stripping type neutron irradiation facility with deuteron beam current of 100 mA was carried out in the period 1978 to 1985 [6]. After cancellation of the FMIT project, an assessment of several neutron source concepts for the International Fusion Materials Irradiation Facility (IFMIF) was performed in terms of technical feasibility and suitability for fusion materials irradiation testing under IEA collaboration from 1989 to 1993 through several international workshops and IEA neutron source working group activity [6–8]. In the same period, a technical evaluation of a neutron source with an energy selectivity based on the D–Li stripping reaction, i.e., Energy Selective Neutron Irradiation Test Facility (ESNIT), was performed at Japan Atomic Energy Research Institute (JAERI) to demonstrate the

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usefulness of energy selectivity for fusion materials testing, especially for avoiding the influence of a high energy tail (neutrons with energy exceeding 14 MeV) on materials properties [9].

Based on these activities, a D–Li stripping type neutron source with neutron energy selectivity was selected for the IFMIF concept, and requirements for IFMIF were developed based on currently available miniaturized specimens and recent advances in accelerator and target technology [10]. The requirements are shown in Table 1. The conceptual design activity (CDA) of IFMIF was initiated in February 1995 as a collaborative activity under the IEA Implementing Agreement for a Programme of R&D on Fusion Materials, to complete a reference conceptual design by December 1996 [11]. The roles of IFMIF were identified to include: (1) development of various fusion reactor materials with emphasis on studies of materials radiation behavior, (2) determination of design-relevant engineering databases for DEMO fusion reactors, (3) calibration and validation of data generated from fission rector irradiations and the other simulation experiments using ion irradiations, etc. Based on IEA activities on a neutron irradiation facility for fusion materials carried out prior to IFMIF-CDA [12], users' requirements for the conceptual design of IFMIF were made for materials to be tested, types of experiments, small specimen test technology, and irradiation conditions including neutron irradiation spectrum characteristics. Several important differences were developed for the IFMIF versus FMIT. In the FMIT project, interest in materials testing focused on radiation damage data of fusion materials irradiated with high energy neutrons at high fluence in order to provide fission–fusion correlation [13]. Irradiation test matrices for post irradiation examination (PIE) were mainly considered for high and low flux regions. For the very high flux (the maximum flux;100 dpa/fpy), the test volume was small and the test matrix of metallic structural materials was based on using miniaturized specimens for limited materials properties. In contrast with this, users' requirements for IFMIF include (1) both irradiation for PIE and various in situ experiments, (2) miniaturized specimens with sufficient size to evaluate materials properties including fracture toughness, (3) a large test volume with a moderate flux gradient to accommodate extensive test matrices to support essentially the development of a materials database for fusion reactor design. In this paper, users' requirements for IFMIF and the characteristics of neutron irradiation field are described.

2. Materials

2.1. Structural materials

At present the three leading candidates for the first wall and blanket structural materials of DEMO fusion reactors are considered to be ferritic/martensitic steels, vanadium alloys, and SiC/SiC composites. A least two to three variants of each of these materials are expected to be investigated in IFMIF. Some space should also be reserved for a limited number of unspecified innovative alloys which may be developed in the coming decades. In addition, some irradiation experiments are needed for conventional "reference" alloys which have been extensively studied in fission reactors over the past two decades in order to identify and qualify any differences between high energy and fission neutron irradiations.

2.2. Breeding materials

Although ceramic breeders have excellent materials properties in tritium recovery, safety etc. in comparison with liquid breeder materials, the ceramic breeders are subjected to radiation damage in fusion blanket environments. Consequently, irradiation tests are indispensable to evaluate degradation of tritium release performance, irradiation durability, thermal properties, compatibility with structural materials, etc. The ceramic breeder materials expected to be tested in IFMIF are Li_2O, Li_2ZrO_3, $LiAlO_2$, Li_4SiO_4, Li_2TiO_3 and some innovative lithium-based ceramics.

2.3. Special purpose materials

Many ceramics such as Al_2O_3, MgO, $MgAl_2O_4$, AlN, diamond, etc. will be used in fusion reactors as materials for electrical insulation of in-vessel components, rf-windows, diagnostics, etc. For the materials, high

Table 1
Requirements for IFMIF

1.	Neutron flux/volume relation: equivalent to 2 MW/m^2 [a] in 0.4 l.
2.	Neutron spectrum: should meet neutron spectrum at first wall as near as possible.
3.	Neutron fluence: DEMO-relevant fluences of 150 dpa_{NRT} for a reasonable test period.
4.	Neutron flux gradient: $\leqslant 10\%$/cm.
5.	Machine availability: 70%.
6.	Time structure: quasi continuous operation.
7.	Good accessibility of irradiation volume for experimentation and instrumentation.

[a] 1 $MWy/m^2 \approx 10$ dpa_{NRT} for Fe.

electrical resistivity, low dielectric loss, adequate thermal conductivity, and good optical properties are required in the fusion reactor environment as well as the high irradiation durability. Ceramics coatings are proposed for self-cooled liquid metal breeder blankets, in order to minimize the magneto-hydrodynamic pressure drop. These materials are needed to be tested in IFMIF. Some additional irradiation testing may be also carried out for cryogenic materials, e.g., superconducting magnet materials, polymer insulation, and window materials for electron cyclotron heating systems.

3. Types of experiments

3.1. Irradiation for PIE

The majority of the structural materials irradiations will be performed in the high-flux region and will be followed by post irradiation examination (PIE). The PIE would include examinations for microstructural change/swelling, tensile properties, fatigue strength, fracture toughness, crack growth and creep. Due to the limited test volume of the high-flux region, small specimen test technology (SSTT) must be applied for the irradiation tests. A special attention must be given to the correct control of irradiation temperatures and monitoring the neutron flux and dose, since temperature variations can strongly influence the development of radiation-induced defects and the radiation effects on materials properties. Some conventional instrumented low-dose capsules for PIE are expected to utilize the medium and low flux regions.

3.2. In situ experiments

In situ tests are required to establish the design database of materials and are in some cases mandatory for characterizing the materials during irradiation. For structure materials, in situ tests are expected for creep fatigue behavior under irradiation and IASCC (Irradiation Assisted Stress-Corrosion Cracking) phenomena. IASCC is important for water-cooled blanket designs. During the first phase of IFMIF, these in situ experiments would be performed in the medium-flux region, because the high-flux region has limited volume and will be occupied by specimens for PIE.

Most of the fusion blanket designs utilize continuous tritium recovery during operation. In situ tritium release experiments with helium or hydrogen-containing helium sweep gas up to the expected lifetime are very important for ceramic breeder materials. These in situ tests should be followed by PIE to evaluate tritium inventory, the irradiation durability including swelling, degradation of thermal properties, microstructure change, etc.

Radiation Induced Conductivity (RIC) occurs in ceramic insulators during irradiation and disappears after irradiation [14]. With respect to a permanent decrease of the electrical resistivity of ceramic insulators, i.e., "Radiation Induced Electrical Degradation (RIED)", fusion materials community has recently made a consensus of view that RIED does not appear to be an issue for ITER [15]. It is, however, considered that RIED needs to be evaluated in irradiation conditions of DEMO or prototype fusion reactors which are more severe than that of ITER. For an investigation of RIED, the dose dependence of data is very useful. Consequently, in situ experiments for electrical resistivity are required for ceramic insulators including ceramic coatings of self-cooled liquid metal breeder blankets. For the liquid metal breeder blankets, in situ experiments to evaluate irradiation effects on self-healing capability are also important. In addition, in situ experiments for dielectric loss, optical properties and thermal conductivity of insulator ceramics, etc., are useful in terms of contribution of RIC/RIED to dielectric loss, luminescence under irradiation and post-irradiation annealing of point defects, respectively.

4. Small specimen test technology

4.1. Structural materials

Extensive use of miniaturized specimens is essential in order to fully utilize the irradiation volume of IFMIF, especially for the high flux region which is limited in volume. The tentative reference geometries of the structural materials specimens for IFMIF are shown in Fig. 1 for an evaluation of swelling and microstructure, tensile properties, fatigue strength, fracture toughness, crack growth, impact behavior, and irradiation creep. The specimen geometries are based on an initial set of recommendations by the IEA Neutron Source Working Group [12], and they are similar to specimens that are currently used in fission reactor irradiation programs, except some modifications for the fracture toughness and fatigue crack growth rate tests. Small specimen test technology (SSTT) has been extensively investigated [16–18] and recently several slightly different specimen geometries have been proposed by a separate international group of scientists [19]. However, further R&D is necessary to reach a final decision on the best miniaturized specimen for IFMIF. In addition, consideration on a special geometric restriction should be given for SiC/SiC-composites.

4.2. Ceramic breeder materials

For ceramic breeding materials, the tritium inventory and irradiation durability characteristics depend on the

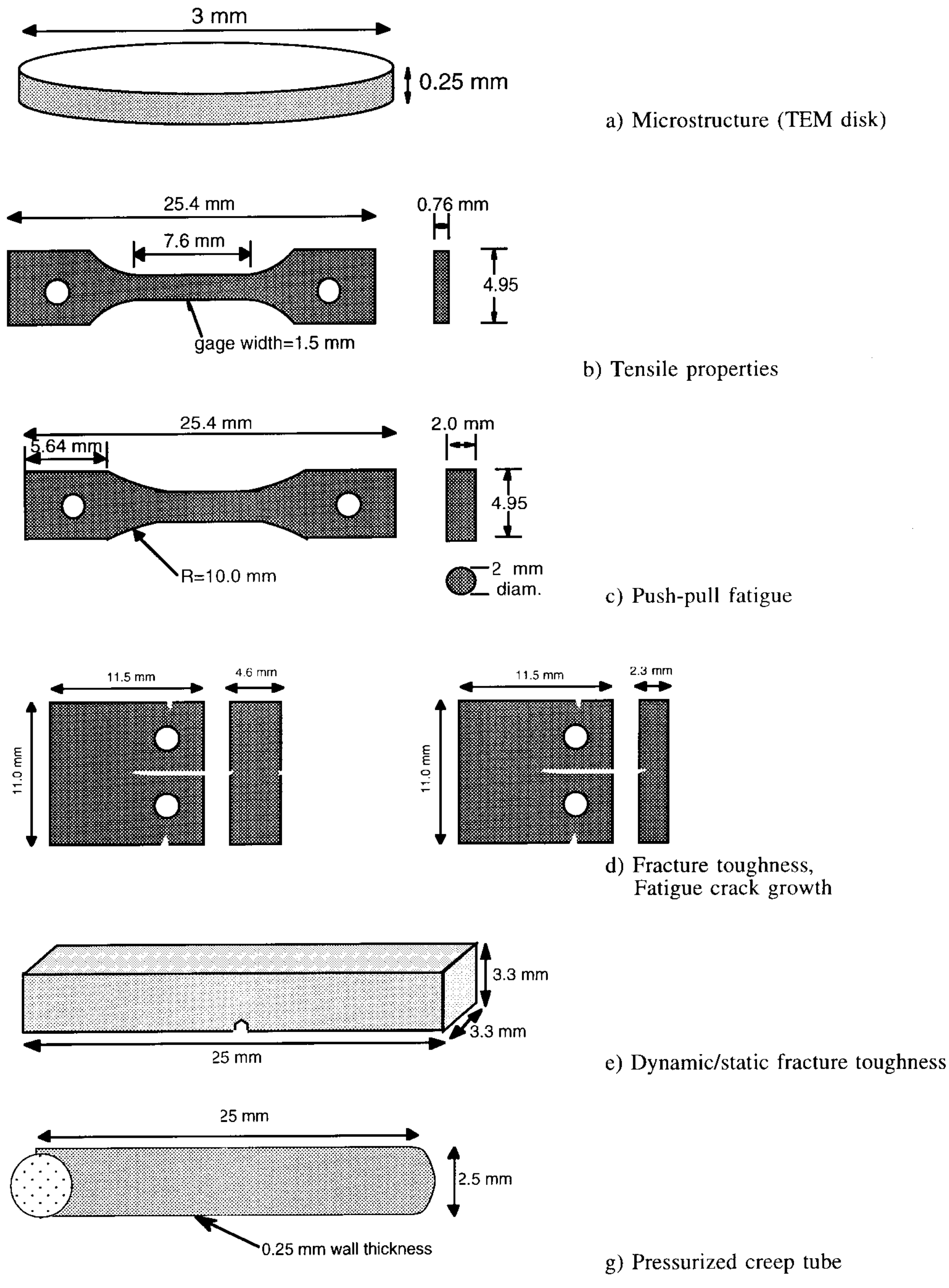


Fig. 1. Proposed reference geometries of structural material specimens for the high flux region of IFMIF [11].

temperature and temperature gradient during irradiation. In fusion breeding blanket designs with ceramic breeders, blocks, pebble beds and tubes of ceramic breeders have been proposed. Therefore, the following four types of specimens of various ceramic breeders are proposed for irradiation tests in IFMIF; (a) disks (10 mm in diameter $\times$ 2 mm in thickness) for which the temperature gradient is small and the irradiation behavior at various temperatures can be examined, (b) pellets (10 mm in diameter $\times$ 10 mm in length) for which the temperature gradient is large, (c) pebbles (1 mm in diameter) with which irradiation behavior of pebble bed concepts can be tested, (d) specimens for compatibility tests (breeders; 5 mm in diameter $\times$ 1.5 mm in thickness, structural materials; 5 mm in diameter × 0.5 mm in thickness) for which the compatibility with structural materials during irradiation can be examined. Furthermore, in situ electrical testing of insulating coatings in contact with flowing liquid metal breeder could be performed to verify liquid breeder blanket concepts.

5. Irradiation conditions

5.1. Neutron spectra

Neutron spectra may affect the radiation response of materials through effects of displacement damage and nuclear transmutation products. The defect reaction kinetics, the spatial distribution of produced defects, their mobility, accumulation and stability as well as their relationship to materials properties depend in a nontrivial way on the PKA energy spectrum. Such a PKA spectrum effect has been primarily observed for swelling at higher temperatures, e.g. [20]. Hence, the PKA spectra for materials tested in IFMIF should closely reflect those ones of the fusion reactor. Recently the impact of the recoil spectra on the displacement damage energy has been calculated for IFMIF, a typical mixed spectrum reactor and a first wall position of DEMO reactor [21].

The production of nuclear transmutation products, especially light elements, i.e., hydrogen (H) and helium (He), can have large influences on materials irradiation behavior such as embrittlement, swelling, etc. H/dpa and He/dpa ratios are considered to be suitable parameters to characterize neutron spectra in terms of effects of H and He produced by nuclear transmutation reactions. Such parameters close to DEMO relevant conditions are required to be realized for irradiation tests using IFMIF.

5.2. Neutron flux/fluence, test volume and the other conditions

Irradiation conditions, i.e., neutron flux and fluence (dpa), irradiation temperature, test volume, etc. depend on materials to be tested with IFMIF. With respect to first wall and blanket structure materials, irradiation tests up to 150 dpa in the temperature range 520–770, 570–870 and 670–1270 K are needed for ferritic-martensitic steels, vanadium alloys and SiC/SiC-composites, respectively. For the structural materials, irradiation for PIE will be mainly performed at damage rates higher than 20 dpa/fpy (full power year) in the high flux region. In addition, fully instrumented in situ tests on irradiation creep fatigue and IASCC are required in the medium flux region in the range 1–20 dpa/fpy.

For ceramic breeder materials, in situ tritium release tests in the fluence range 1–30 dpa at the temperatures in the range 570–970 K, followed by PIE are required. These can be performed in the medium-flux region (1–20 dpa/fpy). For special propose materials, in situ irradiation tests for RIC/RIED, dielectric loss, luminescence/optical absorption, etc., and some irradiation tests for PIE are needed. Such irradiation tests for ceramic insulator materials, RF-window materials and diagnostic materials are expected to be performed in the temperature range 300–720, 80–670 and 300–670 K at fluences in the range 0.1–10, 0.01–10 and 0.001–1 dpa, respectively.

A test volume of 0.5 l is required for the high-flux region to accommodate the proposed test matrices of the structural materials; these include two to three heats of ferritic/martensitic steels, vanadium alloys, SiC/SiC composites and an innovative material, for seven test specimen geometries (microstructural change/swelling, tensile test, fatigue test, fracture toughness test, crack growth test, creep test, etc.), three irradiation temperatures, and reasonable test periods. The likely operation scheme for the high-flux region of IFMIF utilizes alternating "low-temperature" (520–770 K) and "high-temperature" (870–1270 K) campaigns in 10–20 dpa segments. Achievement of DEMO-relevant lifetime doses of ∼150 dpa in a comprehensive set of mechanical property specimens would require an irradiation test period of 20 yr for the above-mentioned test matrices.

A typical test matrix for various ceramic breeder specimens and irradiation conditions requires a test volume of about 3 l in the medium flux region to achieve the irradiation tests at three dose levels (e.g., 10, 20, 30 dpa) within 15–20 yr.

Neutron flux gradients to metallic structural materials are requested to be less than 10%/cm for the gauge length portion of the specimens. Similar conditions have to be fulfilled for ceramic breeder materials, insulators and other ceramic materials.

6. Evaluation of characteristics of neutron irradiation field in IFMIF

6.1. Neutron spectra

Neutron source models for D–Li reactions were made for evaluation of neutron irradiation field characteristics in IFMIF. The models were developed on the basis of existing codes from the FMIT project in the USA and the ESNIT program at JAERI (Japan Atomic Energy Research Institute) in Japan, and at FZK (Forschungszentrum Karlsruhe) in Germany [22–24]. The total neutron yield depends on the model, and the difference in the yield evaluated with the three models is less than ±20%. Neutron spectra of these models agree with the neutron spectra experimentally measured by Sugimoto et al. [25] for D–Li reactions, except the high energy region above 20 MeV in which neutron flux levels are negligibly small in comparison with those of the region below 20 MeV.

Table 2
Characteristics of the neutrons generated from the D–Li reaction for a few incident deuteron energies (FMIT data) [16]

Energy interval (MeV)	% of neutrons born in each energy interval		
	30 MeV D-beam	35 MeV D-beam	40 MeV D-beam
0–15	91.94	88.12	84.33
15–21	5.51	7.63	9.28
21–32	2.12	3.54	5.39
32–43	0.42	0.66	0.90
43–50	0.0022	0.059	0.10

Table 2 shows fraction of numbers of neutrons generated with 30, 35 and 40 MeV deuterons versus neutron energy range, which was evaluated using the cross section data developed for the FMIT project. The neutrons with energies above 20 MeV account for less than 7% of the total number of neutrons produced, and most of the neutrons are generated with energies between zero and 15 MeV (>84%).

H/dpa and He/dpa ratios calculated for iron, vanadium and chromium at deuteron beam energies of 30, 35 and 40 MeV are compared for those at the typical positions of ITER and DEMO fusion reactor in Table 3. The H/dpa and He/dpa ratios for a 40 MeV deuteron beam approximate the calculated values for a fusion reactor. Furthermore, despite the 40-MeV deuteron beam having a considerably larger number of neutrons with energy above 20 MeV it approaches the D–T fusion environment better than deuteron beams with lower energy.

Table 3
Gas production/dpa ratios for three deuteron beam energies compared with fusion reactor values (the distance (d) indicated in the table refers to the distance from the point where the flux was calculated to the back-plate [16])

	Iron	Vanadium	Chromium
Helium to dpa ratio			
30 MeV – $d = 0$ cm	6.87	3.30	6.05
30 MeV – $d = 5$ cm	7.92	4.29	7.79
35 MeV – $d = 0$ cm	8.02	4.52	8.03
35 MeV – $d = 5$ cm	9.12	5.70	10.12
40 MeV – $d = 0$ cm	9.09	5.82	10.12
40 MeV – $d = 5$ cm	10.16	7.16	12.44
ITER-inboard	11.26	5.50	17.86
DEMO-outboard	10.40	4.85	16.11
Hydrogen to dpa ratio			
30 MeV – $d = 0$ cm	39.6	14.2	14.1
30 MeV – $d = 5$ cm	44.9	16.6	15.2
35 MeV – $d = 0$ cm	45.7	17.8	15.4
35 MeV – $d = 5$ cm	51.9	21.4	16.1
40 MeV – $d = 0$ cm	52.0	21.6	16.4
40 MeV – $d = 5$ cm	58.4	25.4	16.7
ITER-inboard	44.1	23.0	44.8
DEMO-outboard	41.0	20.4	41.3

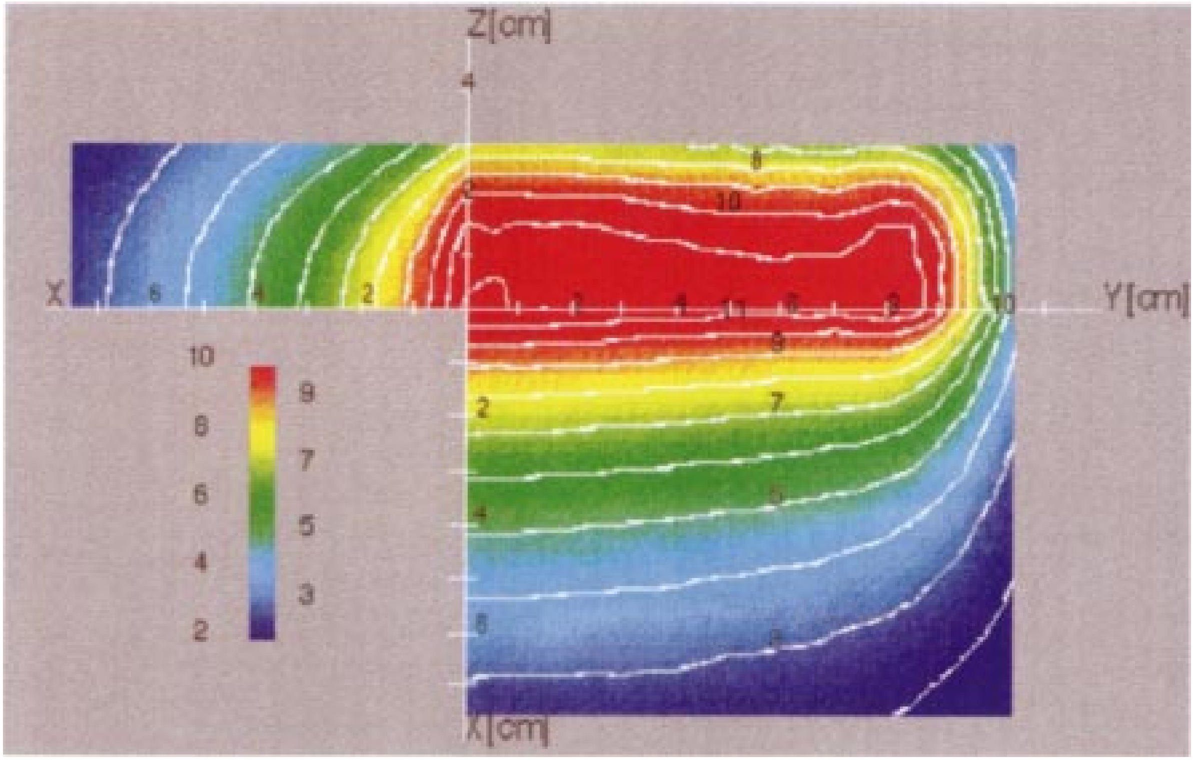
With respect to PKA spectra, it was roughly shown in the early work by the IEA Neutron Source Working Group that for the high-flux region in IFMIF the PKA spectra agree rather well with the DEMO-first wall position for nearly all elements with some deviations for carbon [8]. The unfavorable influence of neutrons with energies exceeding 14 MeV is expected to be reduced to acceptable levels by decreasing deuteron beam energy to 30 MeV and irradiating at special locations in the irradiation field of IFMIF. There is, however, an uncertainty of these calculations due to the lack of neutron cross sections for energies above 20 MeV. Further evaluation of effects of PKA spectra should be performed precisely using nuclear data in the energy range up to 50 MeV.

6.2. Neutron flux/test volume and flux gradient

Fig. 2 shows a cross-sectional collided neutron flux contour map at the deuteron energy of 40 MeV for the ^{56}Fe-loaded (Fe: 50%, void: 50%) area near the Li target, which was evaluated by MCNP (Monte Carlo Neutron and Phonon) transport code calculation using the FZK neutron source model [24]. In the figure, the contours in the one quarter of the region near the target are indicated in three dimensional coordinates (x axis: beam direction, y axis: width, z axis: height).

The test volumes for the ^{56}Fe-loaded area were evaluated in the same deuteron beam condition for annual dpa rates higher than threshold values of 20, 30 and 40 dpa/fpy using the above-mentioned MCNP calculation, and a three-dimensional layout of test area for the threshold values of dpa level is shown in Fig. 3. It is seen that a test volume of more than 0.5 l for annual dpa rate higher than 20 dpa/fpy can be attained for an Fe loading fraction of 50%, a typical material-loading fraction for a He gas cooled test module.

The special contours of dpa for the ^{56}Fe-loaded area in 40-MeV and 250-mA deuteron beam case were also evaluated for the medium and low flux regions [11,16]. The material loading fractions for the medium and the low flux regions were assumed to be 30% iron + 70% void and 20% iron + 80% void, respectively. The test volumes for the medium (1–20 dpa/fpy) and the low flux



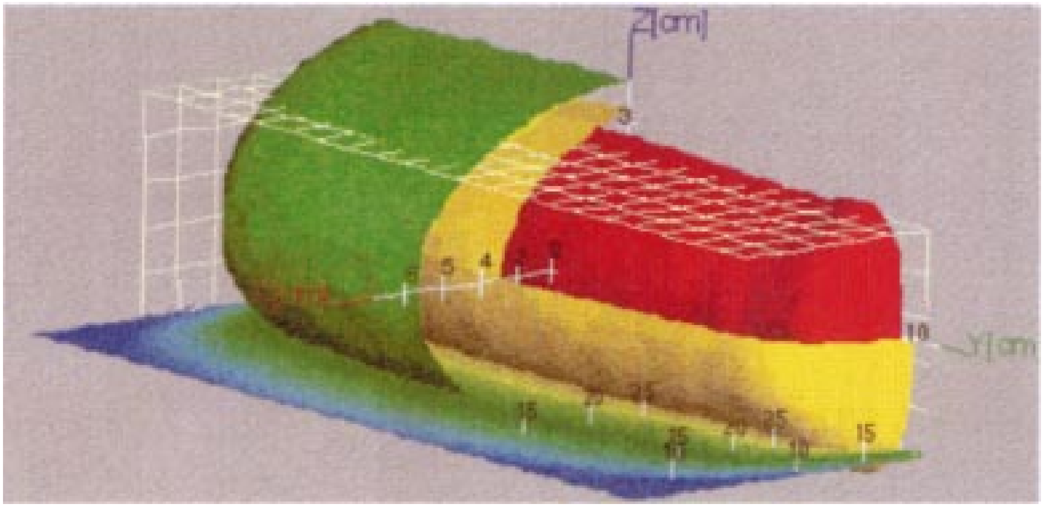


Fig. 2. Three-dimensional layout of test area for threshold dpa value (20, 30, 40 dpa/fpy) at deuteron energy of 40 MeV for Fe-loaded area (Fe: 50%, Void: 50%) [24]. Green = 20 dpa/fpy, yellow = 30 dpa/fpy and red = 40 dpa/fpy.

Fig. 3. Cross-sectional collided neutron flux contour map at deuteron energy of 40 MeV for Fe-loaded area (Fe: 50%, Void: 50%) [24]. The unit is 10^{14} n/cm^2/s.

(0.1–1 dpa/fpy) regions are evaluated to be much larger than 6 and 7.5 l, respectively.

Neutron flux gradients were found to be strongly dependent on the beam cross section area [16]. For the IFMIF reference beam cross sectional area (20×5 cm^2), the gradients in the high, medium and low flux regions were evaluated to be 15–20%/cm, 10–15%/cm and below 10%/cm, respectively [16,24,26]. Fig. 4 shows the flux as

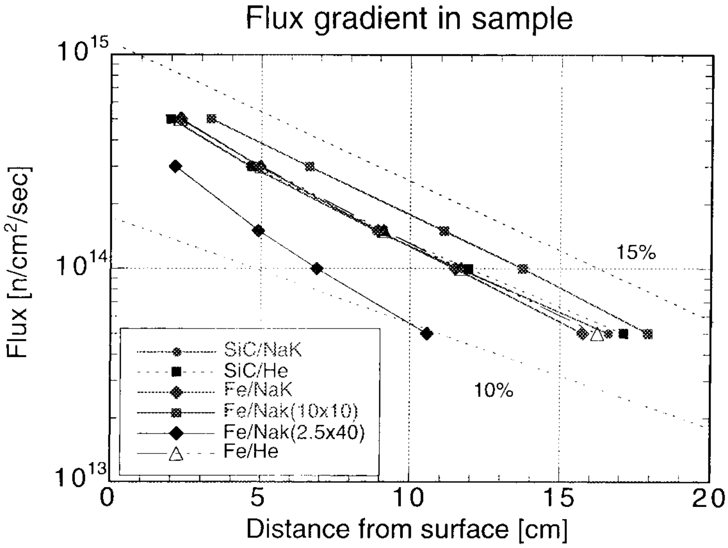


Fig. 4. Neutron flux gradient inside the test cell for different beam shapes and material loading [16,26].

a function of distance along beam direction from the Li target backwall surface for different material loading and beam cross-section shapes, which was evaluated using the JAERI neutron source model [16,26]. The influence of the material loading is relatively small while beams with rectangular cross sections have larger gradients than the ones with square cross-sections. Although the neutron flux gradient along the beam direction is larger than 10%/cm for the high flux region, the gradients in the vertical plane perpendicular to the beam direction are fairly flat (see gradient in *Y–Z* plane in Fig. 2). This means that the neutron flux gradient for the gage parts of specimens can meet the requirement by orienting the axis of the specimen in the direction orthogonal to the beam.

7. Conclusions

Users' requirements for conceptual design of IFMIF have been established for candidate materials, experiments, small specimen test technology, and irradiation conditions; these include requirements necessary for obtaining materials data for development of the variety of fusion reactor materials and design-relevant engineering database for DEMO fusion reactors. The neutron irradiation field characteristics for the conceptual design parameters of IFMIF meet the users' requirements for a high-energy neutron source. Furthermore, the irradiation field of IFMIF has been shown to be able to accommodate potential test matrices based on the above requirements within reasonable test periods.

However, the following efforts should be made to further improve the design of IFMIF.

1. Preparation of test matrices which reflect the strategy to achieve efficiently fusion materials development and acquisition of design-relevant engineering materials database.
2. Further improvement of small specimen test technology.
3. Improvement of neutron source models and preparation of high energy nuclear data to evaluate more precisely neutron irradiation field characteristics, PKA spectra, H/dpa and He/dpa ratios.
4. Obtain knowledge on neutron spectrum effects on various materials properties for proper and effective use of irradiation field of IFMIF.

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