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# Comparison of material irradiation conditions for fusion, spallation, stripping and fission neutron sources

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**Abstract**

Selection and development of materials capable of sustaining irradiation conditions expected for a future fusion power reactor remain a big challenge for material scientists. Design of other nuclear facilities either in support of the fusion materials testing program or for other scientific purposes presents a similar problem of irradiation resistant material development. The present study is devoted to an evaluation of the irradiation conditions for IFMIF, ESS, XADS, DEMO and typical fission reactors to provide a basis for comparison of the data obtained for different material investigation programs. The results obtained confirm that no facility, except IFMIF, could fit all user requirements imposed for a facility for simulation of the fusion irradiation conditions.


## 1. Introduction

During the last few decades, significant efforts were spent on the design of a number of novel nuclear facilities. The major role among them belongs to the fusion prototype reactors ITER and DEMO aimed at demonstrating the technical feasibility of electrical power production by means of the (d,t) fusion reaction. On the other hand, several accelerator-based facilities have been designed either in support of the fusion material development program (IFMIF) or for other scientific purpose (ESS, XADS).

In the present work, several nuclear facilities are compared with respect to materials irradiation conditions. Different types of facilities have been considered: the intense stripping neutron source IFMIF, spallation sources ESS and XADS, fusion prototype reactor DEMO and typical fission reactors HFR and BOR60.

While the purposes of the facilities considered in this work are quite different, there is a common problem of development and testing of the structural materials capable of sustaining hard operating conditions. Assessment of the irradiation conditions for nuclear facilities is required by designers and material scientists to make an optimum and safe choice of the structural materials.

The *Future Demonstration Power Reactor, DEMO* [11], is a magnetically confined fusion prototype reactor with a power of 2–4 GW and an expected wall loading of the order of 2–3 MW/m$^2$. The first inner wall of the facility is exposed to high neutron flux, resulting in about 30 dpa per full-power year of operation. In this work material responses were calculated at the position of the maximum neutron irradiation wall load on the central outward segment of the DEMO Helium-Cooled Pebble Bed Blanket.

The *International Fusion Materials Irradiation Facility, IFMIF* [3], is the accelerator based deuterium–lithium (d–Li) stripping neutron source for production of high-energy neutrons at sufficient intensity to test samples of the fusion candidate materials up to about the full lifetime of anticipated use in fusion energy reactors. Two deuteron beams (40 MeV, $2\times125$ mA) are striking a common liquid lithium target and produce high-energy neutrons with a peak around 14–16 MeV permitting irradiation of material samples

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with a damage rate higher than 20 dpa/fpy in 0.5 l volume.

The description of the geometry model and the details of neutronics analysis for IFMIF high and medium flux test modules (HF & MFTM) can be found elsewhere [1–3].

The *European Spallation Source, ESS*, is a spallation neutron source driven by a proton linear accelerator (LINAC) with a beam energy of 1.33 GeV and a beam power of 10 MW [4]. It features two target stations, both equipped with a liquid mercury target and operating with 5 MW beam power. The short pulse target station is fed with proton pulses compressed by a factor of 800 to 1.4 μs duration in a double compressor ring (repetition rate 50 Hz). The long pulse target is fed directly with protons from the LINAC (proton pulse length 2.0 ms, repetition rate 16.6 Hz). Since it was suggested [5] to use spallation sources for fusion materials testing to bridge the time until the IFMIF source is available, a related feasibility study has been performed [6]. As a result, for material irradiation in the ESS a useful 'high flux' volume of about 0.83 l at the out-of-target reflector position of the short pulse target station has been identified [7]. The geometry model description and neutronics analysis of the ESS can be found elsewhere [6].

The *Experimental Accelerator Driven System, XADS*, is aimed at reduction of radiotoxicity of a spent nuclear fuel by means of their incineration in accelerator driven systems. The ADS reactor for nuclear waste transmutation is a sub-critical reactor and requires an external neutron source for maintaining a fission chain reaction. Neutrons are initially produced via the spallation reaction induced by a high-energy proton beam impacting on a liquid metal target. In the present work we are considering a liquid metal (lead–bismuth eutectic) cooled design variant with a hot beam window. In this design, the beam goes from the top of the reactor through a beam guide ending with a hemispherical beam window. The guide and the window tightly separate the vacuum of the accelerator from the liquid spallation target. Neutrons penetrating through the liquid target reach fuel assembles and induce fission and transmutation of the long-living radioactive isotopes. The hot window is subjected to a very high irradiation load by source protons and spallation neutrons and protons as well as by fission neutrons.

*Fission reactors*: The High Flux Reactor (HFR) at Petten is a light water moderated and cooled multipurpose materials testing reactor with a thermal power of 45 MW. The BOR-60 facility is a fast, sodium-cooled reactor designed to test fuel elements and structural materials. At present, both reactors are extensively used for the irradiation testing both in the fusion and in the XADS material programs [12].

## 2. Evaluation of irradiation conditions

### 2.1. Neutron spectra

The geometry models of the IFMIF, XADS and ESS were constructed by the authors and used as an input for the modified MCNP [8] code McDeLicious [9] and MCNPX [10] codes for neutral and charged particle transport calculations. The neutron spectra of the DEMO HCPB and fission reactors were taken from other sources [11,12]. High-energy neutron cross section library LA150 was used in our calculations.

The neutron spectra of the nuclear facilities considered in this work are presented in Fig. 1. The spectra shown as bands correspond to the high and medium flux test module in the case of IFMIF, and to the maximum and minimum fluxes at irradiation rigs in the case of ESS. The most important for the comparison is an energy range of neutrons covered by each spectrum. The spectra of spallation (ESS and XADS) and stripping (IFMIF) accelerator driven sources have some fraction of neutrons with an energy higher than the characteristic fusion neutron peak at 14.1 MeV. In the ESS the neutron flux in the energy range 5–14 MeV is a factor 4–5 lower than in the DEMO and a neutron tail with energies up to hundreds of MeV is present. The IFMIF spectrum reproduces quite well the shape of the DEMO fusion reactor spectrum already near the 14 MeV peak and at intermediate energies, while the ESS and XADS neutron spectra are an order of magnitude smaller in flux. It should be noted that for the XADS window and, to a lesser extent, for the ESS rigs at the reflector position a substantial proton flux has to be taken into ac-

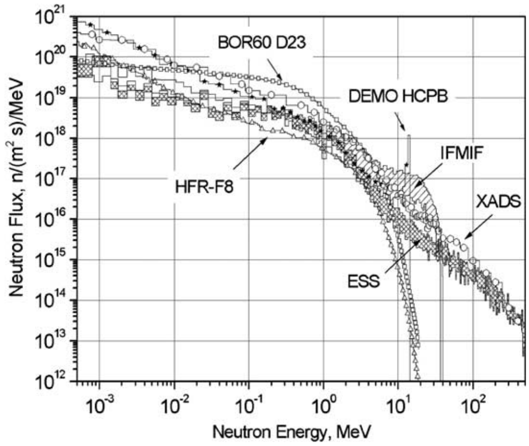


Fig. 1. Neutron spectra of the HCPB blanket of fusion DEMO reactor, the IFMIF high and medium flux test volumes, the spallation sources ESS and XADS as well as of fission reactors HFR and BOR-60.

count for the proper assessment of the material response.

### 2.2. Irradiation damage

The data on the displacement damage and gas production rates for all of the facilities are summarized in Table 1. The maximum values for the DEMO HCPB (at the first wall outboard midplane) are taken from Ref. [13]. For the ESS and IFMIF high flux test module (HFTM) maximum and minimum values in different irradiation rigs have been calculated. All the data refer to pure iron as a major component of reduced activated ferritic–martensitic steels presently considered as prime candidate for fusion structural materials.

The fission reactors are not adequate for the simulation of fusion irradiation conditions due to the very low gas production rates and low gas to dpa production ratios. The HFTM of IFMIF provides damage and gas production values exactly in the same range as the fusion DEMO reactor. In spite of the fact that the displacement damage produced at the ESS irradiation rigs is about two times lower than for DEMO and IFMIF, the gas to dpa ratios would be still acceptable for the fusion material irradiation. However, the lower damage rate in the ESS implies about two times longer irradiation campaigns to reach the same DEMO relevant irradiation dose (100–150 dpa). In the IFMIF high flux test module the neutron damage ranges from 55 to 20 dpa/fpy in a volume of 0.5 l. On the other hand, about two times higher damage is generated in the XADS window and the gas production is too high with respect to DEMO reactor, due to the simultaneous irradiation by high-energy neutrons and protons.

At the typical ESS irradiation position the total proton flux is about $2.5\times10^{12}$ p/cm$^2$ s (i.e. only 0.4% of the neutron flux which is about $6.5\times10^{14}$ n/cm$^2$ s). However, most of the protons (~97%) have energies far above 15 MeV and thus contribute significantly to the total H and He production. The gas production is increased due to spallation reactions, which produce numerous light elements as debris of the target elements.

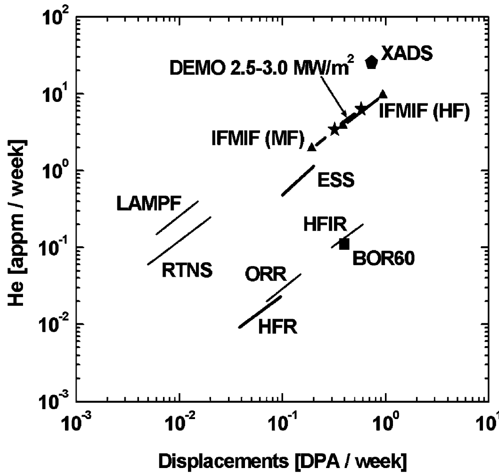


Fig. 2. Ranges of helium and damage production for the DEMO power reactor and for the accelerator driven neutron sources discussed in the paper. For comparison we presented also the data for several other irradiation facilities: Los Alamos Meson Physics Facility (LAMPF) at LANL, Rotating Target Neutron Source (RTNS) at UC Berkley, Oak Ridge Research Reactor (ORR) and High Flux Isotope Reactor (HFIR) at ORNL.

The He/dpa ratio in Fe based alloys in the ESS is between 5 and 6, about a factor of two lower than expected for DEMO, while the H/dpa ratio is about 33–36 which is only a factor of about 1.5 below DEMO. In IFMIF HFTM the He/dpa and H/dpa are 10–12 and 35–50 respectively and therefore practically identical to the related DEMO values (Fig. 2).

### 2.3. PKA spectra

Hard (fast neutron induced) and soft (e.g. electron irradiation induced) primary knock-on atom (PKA) spectra can produce very different damage morphologies. Low-energy recoils produce only Frenkel defects, that is, isolated pairs of vacancies and interstitials. A significant fraction of these defects survives recombination

Table 1
Displacement damage and gas production in iron for several neutron irradiation environments

| Irradiation parameter | | Demo FW 3 W/m$^2$ | IFMIF HFTM | ESS irr. rigs reflector | XADS 1 MW window | HFR position F8 | BOR60 position D23 |
|---|---|---|---|---|---|---|---|
| Total flux, | n | $1.3\times10^{15}$ | $5.7\times10^{14}$ | $6.5\times10^{14}$ | $1.2\times10^{15}$ | $3.8\times10^{14}$ | $2.3\times10^{15}$ |
| cm$^{-2}$ s$^{-1}$ | p | 0 | 0 | $2.5\times10^{12}$ | $2.7\times10^{14}$ | 0 | 0 |
| Damage, dpa/fpy | | 30 | 20–55 | 5–10 | 38 | 2.5 | 20 |
| H, appm/fpy | | 1240 | 1000–2400 | 160–360 | 16 250 | 1.9 | 14 |
| He, appm/fpy | | 320 | 250–600 | 25–60 | 1320 | 0.8 | 5.8 |
| H/dpa | | 41 | 35–54 | 33–36 | 430 | 0.8 | 0.70 |
| He/dpa | | 11 | 10–12 | 5–6 | 35 | 0.3 | 0.29 |

and can be involved in the further defect kinetics. On the other hand, high-energy recoils generate atomic collision cascades in which a high fraction of the defects recombine during collision and cooling phases. For a PKA with energy higher than some critical value (according to different authors it is in the range of 10–40 keV for Fe, see e.g. [14]), the formation of sub-cascades is more probable.

To characterize the entire PKA spectrum, we have used a cumulative damage production function $W(T)$, which represents the fraction of damage energy released by all PKA recoils with recoil energies less than given recoil energy $T$. According to the NRT standard [15] damage energy is the energy spent for displacement production and is defined as initial recoil energy minus energy spent for electron excitation and ionization by the initial and all secondary recoils produced in atomic collision cascade. The cumulative damage production function thus depends on neutron spectrum and can show a difference in damage morphology for different irradiation sources.

The $W(T)$ function usually increases smoothly without steps in fusion structural materials (with an exception for $^6$Li based tritium breeder materials [1]). The hatched area in Fig. 3 shows that the relevant test volume of IFMIF meets perfectly over the entire PKA energy range the DEMO reactor conditions in iron based alloys, because the shape of the $W(T)$ function can be adjusted by using an appropriate combination of $W$-moderator [2].

It is clear that computer simulation techniques need to be further developed to relate more precisely the relationship between neutron spectrum, damage morphology and mechanical properties of irradiated materials.

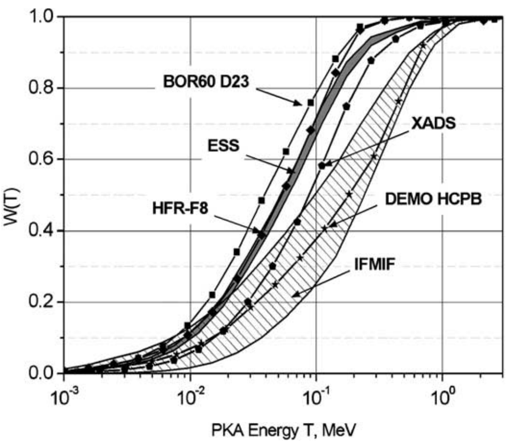


Fig. 3. Damage production function $W(T)$ in iron for HCPB blanket of DEMO reactor in comparison with the stripping neutron source IFMIF (hatched), neutron spallation sources ESS and XADS, and fission reactors HFR, Petten and BOR-60, Dimitrovgrad.

## 3. Conclusions

The main goal of the present study was to compare materials irradiation response in various irradiation facilities. The following conclusions can be drawn:

- Although the spallation neutron source spectra (ESS, XADS) possess a long high-energy tail, only the stripping source IFMIF is able to provide sufficiently high neutron flux around 14 MeV fusion peak.
- The shape of the IFMIF neutron spectrum nearly follows that of a HCPB DEMO reactor blanket over a wide range of neutron energies.
- *Displacement damage production in structural steels*: Compared to a HCPB blanket (‘first wall’ side), accelerated irradiation would be possible in the IFMIF HFTM. The irradiation damage in Fe based alloys at the chosen position of the fusion material ESS test module (outside the target, close to the target–reflector interface) is on average, one-third and one-fifth with respect to the DEMO fusion reactor and IFMIF high flux module respectively.
- *Gas production rates in structural steels*: Gas and damage production rates in the IFMIF HFTM as well as gas to dpa ratios are exactly in the same range as for the DEMO reactor making the IFMIF a very suitable test bed for fusion materials testing. The He/dpa and H/dpa ratios in the ESS are about one-half of both the DEMO and IFMIF. Nevertheless, the possibility to test fusion relevant materials in the ESS at relatively high appm He/dpa ratio (conditions that are not accessible with fission reactors) could be very interesting for the fusion community in anticipating results on one of the key issues related to irradiation damage in a typical fusion neutron spectrum. Extensive modelling and analysis would be required to carefully interpret the meaning of the acquired data.
- *PKA spectra in structural steels*: An appropriate arrangement of $W$ neutron spectral shifters allows a perfect adaptation of the damage production function $W(T)$ for the DEMO reactor conditions over the entire recoil energy range for structural steels in the medium and high flux test volumes of the IFMIF. The PKA spectrum in the ESS is softer than are those in the IFMIF and DEMO. The effects of PKA spectra on irradiated material properties should be a subject of future investigations.

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