ELSEVIER

Journal of Nuclear Materials 280 (2000) 151–161

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Comparison of nuclear irradiation parameters of fusion breeder materials in high flux fission test reactors and a fusion power demonstration reactor

U. Fischer [a,*], S. Herring [b], A. Hogenbirk [c], D. Leichtle [a], Y. Nagao [d], B.J. Pijlgroms [c], A. Ying [e]

[a] *Forschungszentrum Karlsruhe, Institut fur Kern- & Energietechnik, P.O. Box 3640, 76021 Karlsruhe, Germany*
[b] *Idaho National Engineering Laboratory (INEL), USA*
[c] *NRG Petten, P.O. Box 25, NL-1755 ZG Petten, Netherlands*
[d] *Department of JMTR, Oarai Research Establishment, JAERI, Japan*
[e] *University of California (UCLA), Los Angeles, CA 90095-1597, USA*

Received 22 December 1999; accepted 22 March 2000

Abstract

Nuclear irradiation parameters relevant to displacement damage and burn-up of the breeder materials Li_2O, Li_4SiO_4 and Li_2TiO_3 have been evaluated and compared for a fusion power demonstration reactor and the high flux fission test reactor (HFR), Petten, the advanced test reactor (ATR, INEL) and the Japanese material test reactor (JMTR, JAERI). Based on detailed nuclear reactor calculations with the MCNP Monte Carlo code and binary collision approximation (BCA) computer simulations of the displacement damage in the polyatomic lattices with MARLOWE, it has been investigated how well the considered HFRs can meet the requirements for a fusion power reactor relevant irradiation. It is shown that a breeder material irradiation in these fission test reactors is well suited in this regard when the neutron spectrum is well tailored and the ^{6}Li-enrichment is properly chosen. Requirements for the relevant nuclear irradiation parameters such as the displacement damage accumulation, the lithium burn-up and the damage production function $W(T)$ can be met when taking into account these prerequisites. Irradiation times in the order of 2–3 full power years are necessary for the HFR to achieve the peak values of the considered fusion power Demo reactor blanket with regard to the burn-up and, at the same time, the dpa accumulation.

1. Introduction

High flux fission reactors (HFR) are being used to investigate experimentally the behaviour of fusion reactor materials when exposed to high neutron fluences as anticipated for future fusion power reactors. The use of fission reactors for fusion material irradiation experiments necessitates, however, the proof that fusion reactor conditions can be properly simulated. In particular this is true for the nuclear parameters affecting the breeder material properties such as the lithium burn-up, the irradiation induced displacement damage and the gas production.

In the framework of an International Energy Agency (IEA) task agreement, high fluence breeder material irradiation experiments are currently under consideration with the objective to achieve both a high lithium burn-up and dpa accumulation. The considered fission test reactors include the HFR, Petten, the advanced test reactor (ATR) of INEL, USA and the Japanese material test reactor of JAERI (JMTR).

This work aims at investigating how well these HFR can meet the requirements for a fusion power reactor relevant irradiation of the candidate solid breeder materials Li_2O, Li_4SiO_4 and Li_2TiO_3. To this end, nuclear

* Corresponding author. Tel.: +49-7247 82 4837; fax: +49-7247 82 3407.
E-mail address: ulrich.fischer@iket.fzk.de (U. Fischer).

PII: S0022-3115(00)00049-0

irradiation parameters relevant to displacement damage and burn-up have been evaluated and compared. This includes detailed nuclear calculations for a fusion power demonstration reactor and the considered fission test reactors as well as a reliable assessment of the displacement damage in the breeder materials based on binary collision approximation (BCA) computer simulations of displacement cascades in the polyatomic ionic lattices. As a result, this proceeding enables to judge how well the fission reactor irradiation is suited to arrive at fusion reactor relevant irradiation parameters and, furthermore, guide the design and tailoring of the planned irradiation experiments.

2. Methodological approach

To meet the objective of this study, a detailed and reliable evaluation of the relevant nuclear irradiation parameters is required for both the considered fission test reactors and the fusion power reactor. As a prerequisite, reliable displacement damage data have to be provided for the three breeder materials. These are evaluated on the basis of BCA computer simulations of displacement cascades in the polyatomic ionic lattices of the solid breeders using an enhanced version of the MARLOWE-code [1]. Primary-knocked-on-atoms (PKA)-spectra as well as displacement damage cross-sections are provided for subsequent use with the neutron flux spectra to calculate the dpa accumulation. Detailed neutronic calculations have to be performed to provide the proper neutron flux spectra for irradiation in the fission test and the fusion power reactors. In this study, the neutronic calculations are being performed throughout with the help of the MCNP Monte Carlo code [2]. In any case, appropriate 3D models, developed for the respective reactors, are being applied. Based on the provided data, the lithium burn-up and damage related parameters such as the dpa accumulation and the damage production function $W(T)$ are evaluated.

The general proceeding is to define, on the basis of the fusion power reactor calculations, the target values for the relevant irradiation parameters and investigate, further-on, under which conditions these can be met in the fission test reactor irradiation considered. In detail, the applied procedure comprises the following steps:

- Evaluation of basic data required for the calculation of damage related parameters based on BCA computer simulations with the MARLOWE-code (PKA-spectra, displacement cross-sections).
- Calculations for the fusion power demonstration reactor.
  - 3D MCNP – calculations to provide proper neutron flux spectra for the considered breeder materials Li_2O, Li_4SiO_4 and Li_2TiO_3 in the helium-cooled pebble bed (HCPB) Demo blanket.
  - Lithium burn-up and dpa accumulation for a range of irradiation times and damage production function $W(T)$ to define target regions for these parameters.
- Calculations for fission test reactor irradiation.
  - 3D MCNP – calculations to provide proper neutron flux spectra in the considered material specimens.
  - Lithium burn-up and dpa accumulation for a range of irradiation times and damage production function $W(T)$.
- Comparison and evaluation of fission test and fusion power demonstration reactor results: neutron spectra, dpa accumulation vs. lithium burn-up, $W(T)$, PKA-spectra.

3. Basic data for displacement damage calculations

While the gas production and the lithium burn-up can be calculated in a straightforward and reliable way using state-of-the-art computational tools and data, methods superior to the standard NRT–dpa model [3] are required to properly assess the displacement damage in polyatomic light solids such as the breeder materials Li_2O, Li_4SiO_4 and Li_2TiO_3.

The NRT–dpa model shows fundamental deficiencies when being applied to polyatomic, low mass solids and high energy irradiation. These deficiencies are due to limitations of the underlying physics based on Lindhard's energy partition theory [4] (derived for medium mass, low energy ions in similar monoatomic targets) and the fact that the NRT model is not capable of treating crystalline and related material properties. To overcome these limitations, the BCA of collision cascades as implemented in the MARLOWE-code has been selected to assess the primary defect-state in the polyatomic crystalline solids. The BCA simulation method assumes that all collisions can be described in a series of sequential two-body encounters. MARLOWE simulates the formation of collision cascades by tracking deterministically ion trajectories in the polyatomic crystalline lattices. In addition, MARLOWE incorporates a sophisticated method for quasi-simultaneous encounters, which is required to take into account many body effects as well as the important channeling in crystalline solids.

3.1. Development of a refined binary collision model

In order to meet the requirements for the treatment of light mass and polyatomic materials, the MARLOWE BCA-code has been modified and enhanced [5,6]. The enhancements include the implementation of high energy projectile–target interactions (up to some MeV/amu), a refined and extended modeling of target materials, a revised scheme of BCA and quasi-simultaneous collisions as well as new routines for the defect identification and characterisation. Major effort was devoted to the elaboration of algorithms for the treatment of ionic compounds.

In ionic compounds like the lithium ceramics considered in this study, attractive and long range forces (partly screened Coulomb-potentials) have to be taken into account. In principle, this is unfeasible in a BCA-treatment due to the inherent limitation to solely binary collisions with a nearest neighbour target atom and the asymptotic calculation of particle trajectories. Therefore, a model has been developed and implemented into MARLOWE, which enables one to describe partly screened Coulomb-potentials. Besides the selection of a suitable parameterisation of the screening function, modifications of the BCA itself have to be performed including the determination of the apsis of the collision and the forced convergence of the time integral by using a cut-off distance.

The electronic energy losses have been extended to primary energies well above the stopping power maximum by interpolating the LSS [4] and Bethe–Bloch approaches. In addition, local energy losses in individual encounters have been modified by taking into account charge distributions according to AMLJ [7] and Coulomb-potentials. If not determined experimentally, then inelastic stopping powers in polyatomic solids are obtained by employing Bragg's additivity rule. In MARLOWE, we have adopted a semi-empirical procedure to correct Bragg values down to about 1 keV/amu.

According to the requirements presented above, the BCA-model in MARLOWE has been modified by introducing improved formulations for the collision integrals to take into account the inelastic kinematics of binary collisions, by incorporating attractive potentials, which can influence the trajectories of particles and, finally, by developing a new scheme for quasi-simultaneous collisions.

With these enhancements, MARLOWE is capable of providing reliable damage related parameters of collision cascades in lithium breeder ceramics. The outlined BCA approach is thus a substantial improvement over the standard NRT model for the kind of materials and irradiation under consideration in this study.

3.2. Deriving dpa cross-sections

Simulations of collision cascades in the lithium breeder materials Li_2O, Li_4SiO_4 and Li_2TiO_3 have been performed with the improved MARLOWE code. Microscopic material properties like crystalline structure and bond strength specifications (as derived by the heat of formation) have been included as well as thermal vibrations of lattice atoms and lattice expansion at elevated temperatures.

In order to obtain the damage functions of interest (the damage energy vs. PKA-energy and the number of defects vs. PKA-energy), a series of simulations has been performed for each species of PKAs covering the full possible energy range (up to 16 MeV for tritium from the ^{6}Li(n,t)α-reaction). By folding these damage functions with the related PKA-spectra, the dpa cross-sections are obtained. Note that there is no need to supply displacement threshold energies when calculating the dpa cross-sections in this approach. Effective threshold energies, however, can be derived from the MARLOWE simulations by forming the ratio of damage energy vs. number of defects. The threshold energies derived in this way are as follows: 19 eV (Li) and 57 eV (O) for Li_2O, 34 eV (Li), 18 eV (O) and 118 eV (Si) for Li_4SiO_4 and 45 eV (Li), 23 eV (O) and 76 eV (Ti) for Li_2TiO_3.

The dpa cross-sections were prepared and stored in the SPECTER 100 group structure [8] for use with subsequent dpa calculations along with the various neutron flux spectra provided for the considered fission and fusion reactor irradiation. With regard to the nuclear reactions initiating the collision cascade, all kinematically allowed neutron induced reactions contributing significantly are taken into account. The dpa cross-sections thus include all contributions from these reactions by considering as PKAs the recoil nuclei generated in elastic, inelastic and neutron absorbing reactions as well as secondary charged particles such as t and α resulting mainly from the ^{6}Li(n,α)t-reaction. The corresponding nuclear cross-section data have been taken from the ENDF/B-VI data library, whenever available. The NJOY-code [9] has been used to process the cross-sections with their secondary distributions (angle, energy–angle) to provide the recoil energy spectra.

When forming the total displacement cross-section for a lithium compound, it depends strongly on the ^{6}Li-enrichment as it consists only of the ^{6}Li(n,α)t-contribution below some 1–10 keV neutron incidence energy. This component decreases rapidly with increasing neutron energy. Figs. 1–3 show the calculated total displacement cross-sections for the three breeder materials Li_2O, Li_4SiO_4 and Li_2TiO_3 at selected ^{6}Li-enrichment levels.

The total displacement cross-sections of the three breeder materials are inter-compared in Fig. 4 at a ^{6}Li-enrichment of 30 at.%. For Li_2O, there is, in particular, a stronger ^{6}Li(n,α)t-contribution as compared to the other two breeders. Note, however, that different ^{6}Li-enrichment levels are required when using these materials as breeder in a fusion reactor blanket, see Section 4. As a consequence, the dpa cross-section below some 10 keV will not differ very much for such conditions. In the high-energy range, above some 5 MeV, the dpa cross-section of Li_2O is lower as compared to Li_4SiO_4 and Li_2TiO_3 due to the lower oxygen density and the

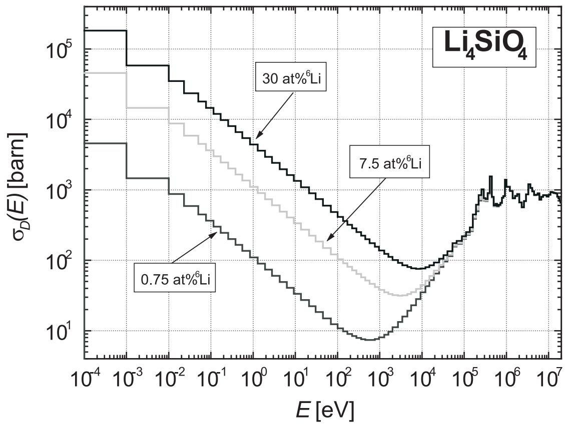

Fig. 1. Total displacement cross-section for Li_4SiO_4 at different ^{6}Li-enrichments.

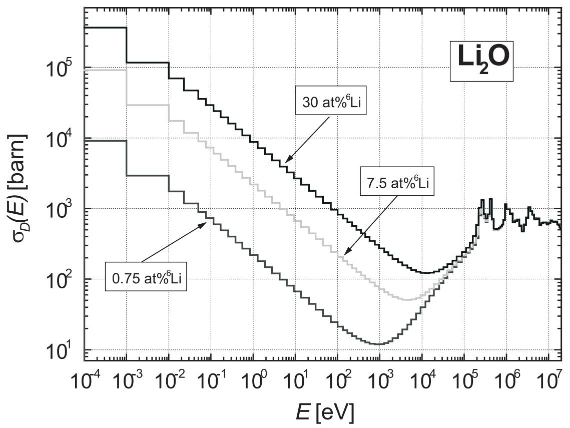

Fig. 2. Total displacement cross-section for Li_2O at different ^{6}Li-enrichments.

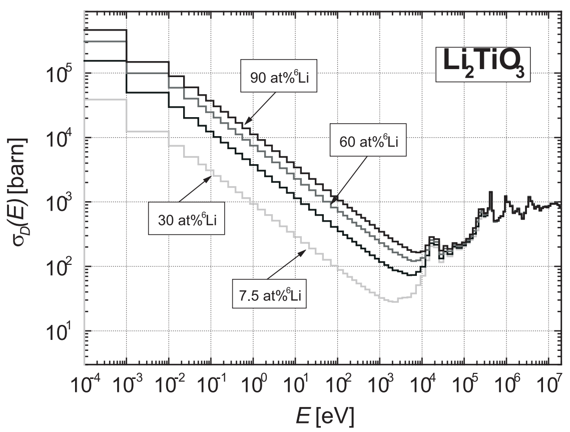

Fig. 3. Total displacement cross-section for Li_2TiO_3 at different ^{6}Li-enrichments.

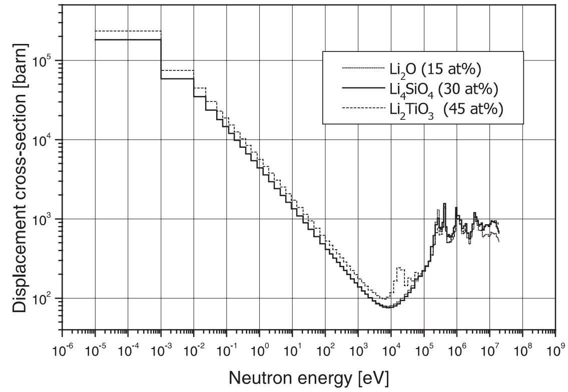

Fig. 4. Displacement cross-sections for Li_2O, Li_4SiO_4 and Li_2TiO_3 at 30 at.% ^{6}Li.

absence of heavier atoms (Si, Ti). When calculating the displacement cross-sections the stoichiometric compositions of the breeder ceramics have been assumed.

4. Fusion reactor blanket calculations

In this study, the EU HCPB blanket [10,11] is being used as reference design for a Demo-relevant solid breeder blanket. The HCPB Demo blanket makes use of ceramic lithium compound pebbles (Li_4SiO_4, Li_2ZrO_3 or Li_2TiO_3) as breeder material, beryllium pebbles as neutron multiplier and high pressure helium gas as coolant. The ceramics and beryllium pebbles are contained in 10–45 mm high poloidal layers, separated by 8-mm thick horizontal cooling plates assuming the martensitic steel MANET as structural material.

A suitable torus sector model, developed in the framework of the European blanket selection exercise for a Demo-type European tokamak reactor, has been used in the neutronic calculations performed with the MCNP code. The sector model takes into account the plasma vacuum chamber, blanket segments, the vacuum vessel, top and bottom divertor and the bottom divertor exhaust chamber with a pumping duct entrance. The fusion power of the related Demo reactor is at 2200 MW, resulting in an average neutron wall loading of 2.2 MW m^{-2}. The peak neutron wall loading amounts to 3.5 MW m^{-2} at the first wall of the central outboard blanket module in the torus mid-plane. At this location, the materials are subjected to the highest radiation loads. Therefore, the central outboard blanket module is considered when assessing the maximum irradiation loads with regard to displacement damage and lithium burn-up.

The neutron flux spectra have been accordingly calculated for the breeder materials in the central outboard blanket module. The breeder pebble layers with a total

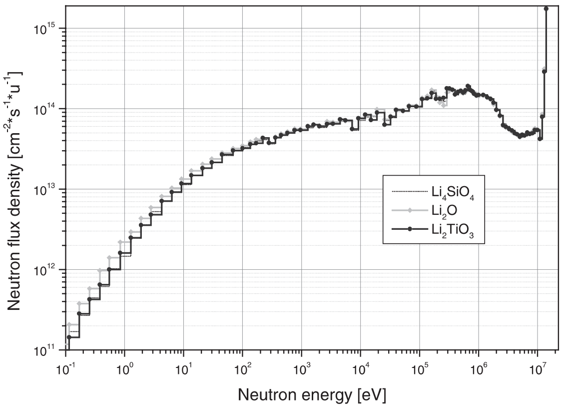

Fig. 5. HCPB Demo blanket: neutron flux spectra in Li_2O, Li_4SiO_4 and Li_2TiO_3.

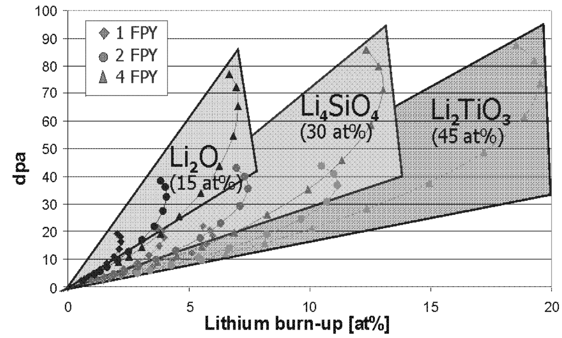

Fig. 6. DPA accumulation vs. lithium burn-up for the breeder materials Li_2O, Li_4SiO_4 and Li_2TiO_3 in the HCPB Demo blanket.

radial thickness of some 50 cm have been divided into 11 radial segments to obtain the radial profiles from the breeder front to the back region. For each of the considered breeder material a full 3D MCNP calculation was performed to provide the proper flux spectra in the breeder material. In these calculations, ^{6}Li-enrichment levels of 15, 30 and 45 at.% were used for the Li_2O, Li_4SiO_4 and Li_2TiO_3 breeder materials, respectively. These are required to achieve the requested global tritium-breeding ratio of 1.13. Fig. 5 shows the resulting spectra as calculated for the first radial segment of the breeder pebble bed layer. Note that there is no significant difference except for Li_2O in the low energy range (below some 10–100 eV). This is due to the lower ^{6}Li-density of Li_2O as compared to Li_4SiO_4 and Li_2TiO_3.

Maximum and minimum values of the neutron fluxes, the dpa accumulation and the lithium burn-up in the central outboard blanket module (front and back region of the blanket) are given in Table 1 for the three breeder materials. There is no significant difference in the dpa accumulation among the three breeder materials. (The 10% smaller dpa accumulation of Li_2O is due to the lower dpa cross-section in the high energy range, see Section 3.) On the other hand, there are large differences in the lithium burn-up. These are due to the different ^{6}Li-enrichment required for the different breeder materials.

When irradiating the breeder materials in the fission test reactors, target values must be defined for the irradiation parameters such as the required neutron fluence, lithium burn-up, dpa accumulation, etc. With regard to parameters affecting the material properties, the lithium burn-up and the dpa accumulation are the key parameters. To define suitable target values for these, irradiation times of one, two and four full power years are considered for the Demo-type fusion power reactor. The corresponding neutron fluence amounts to 3.5, 7 and 14 MW/m^2, respectively. Fig. 6 displays the resulting lithium burn-up and dpa accumulation for the three breeder materials in a dpa vs. burn-up representation. The displayed curves represent the dpa/burn-up ratios along the radial profile in the breeder layers at the given irradiation time. The shaded regions mark the target areas that have to be met for a material irradiation that aims at simulating fusion relevant irradiation conditions.

Table 1
Maximum and minimum nuclear responses in the HCPB Demo blanket module

	Total neutron flux (cm^{-2} s^{-1})	Dpa accumulation (dpa/FPY)	Lithium burn-up (at.%/FPY)
Li_2O [15 at.% ^{6}Li]			
Front	1.21×10^{15}	19.3	2.19
Back	1.54×10^{14}	2.22	0.56
Li_4SiO_4 [30 at.% ^{6}Li]			
Front	1.19×10^{15}	21.5	3.98
Back	1.49×10^{14}	2.21	0.96
Li_2TiO_3 [45 at.% ^{6}Li]			
Front	1.20×10^{15}	21.9	5.97
Back	1.51×10^{14}	2.45	1.45

With regard to the proper simulation of irradiation conditions affecting the material properties, it is not sufficient to meet the target dpa/burn-up ratio in an irradiation experiment. The same dpa level may be achieved by displacement cascades with different defect morphologies, which is dependent on the PKA spectrum (energy and species). In general, this is quite different when comparing irradiations in fission and fusion reactor spectra. This requires to take into account damage related parameters dependent on the PKA-spectrum. A suitable parameter is the *W*(*T*)-function indicating the (normalised) cumulative damage production by all PKAs up to the PKA energy *T*

$$W(T) = \frac{1}{\mathrm{dpa/s}} \int \Phi(E) \int^{T} \sigma_{\mathrm{PKA}}(E, T') N_{\mathrm{d}}(T')\, \mathrm{d}T'\, \mathrm{d}E. \qquad (1)$$

Here, $\sigma_{\mathrm{PKA}}(E,T)$ denotes the PKA-spectrum (dependent on the neutron incidence energy E and the PKA energy T) and $N_{\mathrm{d}}(T)$ the number of lattice defects caused by a PKA with energy T.

It is recalled that the total dpa accumulation in terms of dpa/s may be expressed as follows:

$$\mathrm{dpa/s} = \int \sigma_D(E) \cdot \Phi(E)\, \mathrm{d}E = \int \Phi(E) \int_{T_{\min}}^{T_{\max}} \sigma_{\mathrm{PKA}}(E,T) N_{\mathrm{d}}(T)\, \mathrm{d}T\, \mathrm{d}E, \qquad (2)$$

where $\Phi(E)$ is the neutron flux spectrum. The *W*(*T*)-function thus represents a spectral decomposition of the normalised dpa accumulation.

The *W*(*T*)-function of Li_4SiO_4 is displayed in Fig. 7 as calculated for the different radial locations in the central outboard HCPB blanket module. As a general trend, *W*(*T*) is smoothly increasing with the PKA-energy up to some 2 MeV. This part is formed by damage

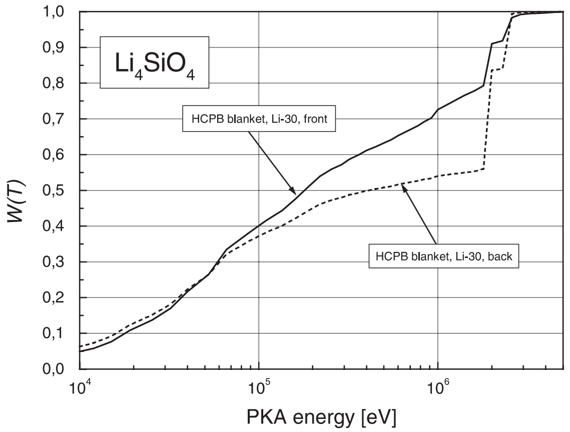

Fig. 7. *W*(*T*)-function of Li_4SiO_4 in the HCPB Demo blanket.

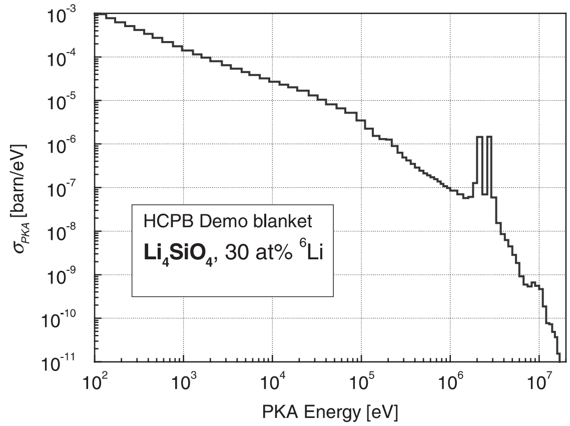

Fig. 8. Neutron spectrum averaged PKA spectrum for Li_4SiO_4 (30 at.% ^{6}Li) in the HCPB Demo blanket.

production of recoil nuclei from elastic and inelastic collisions. It adds up to some 75% and 50% of the total damage production in the front and back region of the HCPB blanket, respectively. Around 2 MeV, there is a steep increase caused by the contribution of the light α- and t-particles from the ^{6}Li(n,α)t-reaction. They are nearly monoenergetic with a relatively high PKA-energy around 2.0 and 2.6 MeV, respectively, as may be seen in the PKA-spectrum plot for Li_4SiO_4 shown in Fig. 8.

5. Fission test reactor calculations

Neutronic calculations have been performed with the MCNP-code for the considered HFR, JMTR and ATR. Appropriate 3D reactor models have been applied in each case with a proper representation of the irradiation test assembly including the investigated breeder material and the related ^{6}Li-enrichment as shown in Table 2. In either case, irradiation positions showing the highest neutron flux density have been considered. The specimen sizes and geometries, however, were different for the three investigated cases and no thermal and thermal-hydraulic considerations have been accounted for at this stage of the study. Spectral changes due to burn-up effects have not been considered in the neutronic calculations.

In the following is given a more detailed description of the three considered fission test reactors and the irradiation test assemblies along with the main results of the neutronic and damage calculations.

5.1. Japan materials test reactor

JMTR is a light water moderated and cooled HFR with a thermal power of 50 MW. It can be operated at 180 full power days per year and achieves a maximum

Table 2
Breeder materials and parameters considered in the fission test reactor calculations

Fission reactor	Breeder material	^{6}Li-enrichment (at.%)	Comments	
HFR, Petten	Li_4SiO_4	7.5, 30	No Cd shielding	Irradiation capsule, ∅38 mm, central position C5
		7.5, 30	0.8 mm Cd shield	
	Li_2TiO_3	7.5	0.8 mm Cd shield	
	Li_2O	7.5	0.8 mm Cd shield	
JMTR, JAERI	Li_2O	30	Irradiation capsule, ∅26 mm, 5 mm Cd shield, core position J-7, reflector position K-11	
	Li_4SiO_4	30		
	Li_2TiO_3	90		
ATR, INEL	Li_4SiO_4	7.5, 30, 60	Irradiation test vehicle (ITV), 0.51 cm Al–B alloy filter with 4.3 wt.% B-10, several capsules, ∅14.9 mm	

thermal neutron flux of 4.0×10^{14} cm^{-2} s^{-1}. The reactor core consists of 22 fuel elements (20 wt% ^{235}U) and five control elements surrounded by Be and Al reflector elements. In the fuel region of the core there are eight irradiation holes available for high flux irradiation. In this study, the positions J-7 in the fuel region and K-11 in the Be reflector region have been considered.

An irradiation assembly has been designed with a cylindrical breeder ceramics capsule (∅26 mm, height 7 mm) in between two beryllium pebble beds (∅26 mm, height 7 mm) and shielded by a 5-mm thick cadmium ring. In either case, the breeder ceramics was assumed to have a density of 85% of the theoretical value and a packing factor of 60% to simulate a single size breeder ceramics pebble bed.

Table 3 shows the lithium burn-up and the dpa accumulation achievable per full power year along with the neutron flux densities as calculated for the three breeder materials at the JMTR positions J-7 and K-11. Note that the dpa accumulation is at a relatively high level due to the high ^{6}Li-enrichment considered here. This is especially true for Li_2O which is more sensitive to the ^{6}Li-enrichment than are the other breeder materials (cf. the displacement cross-sections, Section 3). This means that a dominant contribution to the dpa accumulation comes from the ^{6}Li(n,α)t-reaction, which is not the case in the HCPB Demo blanket. As a consequence, the damage characteristics will not be typical for a fusion reactor irradiation. This can be improved, however, by simply applying a lower ^{6}Li-enrichment.

5.2. High flux fission test reactor, Petten

The HFR Petten is a light water moderated and cooled multipurpose materials testing reactor with a thermal power of 45 MW. The core lattice is a 9×9 array with 33 fuel assemblies, 6 control assemblies, 17 in-core experiment positions and 25 beryllium reflector elements. It is being operated at 280 full power days per year and achieves a maximum thermal neutron flux of 1.6×10^{14} cm^{-2} s^{-1}. The HFR central core position C5 has been considered for the high-fluence breeder material irradiation study.

The irradiation assembly considered is a TRIO type rig of 38 mm diameter. For the scoping nuclear calculations of this study, only a few breeder specimens were considered, typically 5.5 mm in diameter and 33 mm high, with an axial separation of 35 mm. Various ^{6}Li-enrichment levels and cadmium shielding (0.8 mm) have been considered for the purpose of spectral tailoring.

Table 4 shows the lithium burn-up and the dpa accumulation per full power year along with the neutron

Table 3
Neutron fluxes, dpa accumulation and lithium burn-up in JMTR

	Li_2TiO_3		Li_4SiO_4		Li_2O	
^{6}Li-enrichment (at.%)	J-7	K-11	J-7	K-11	J-7	K-11
	90	90	30	30	30	30
Li burn-up (at.%/FPY)	17.3	10.3	6.65	4.20	5.36	3.50
DPA/FPY	25.3	12.6	17.9	8.47	20.5	11.0
Fast (E > 1 MeV) neutron flux (cm^{-2} s^{-1})	1.88×10^{14}	6.52×10^{13}	2.01×10^{14}	6.11×10^{13}	1.92×10^{14}	6.09×10^{13}
Total neutron flux (cm^{-2} s^{-1})	7.30×10^{14}	3.28×10^{14}	7.54×10^{14}	3.44×10^{14}	7.19×10^{14}	3.47×10^{14}

Table 4
Neutron fluxes, dpa accumulation and lithium burn-up in HFR, central position C5

	Li_4SiO_4				Li_2TiO_3	Li_2O
Effective density (%TD)	62.3	62.3	62.3	62.3	53	53
^{6}Li-enrichment (at.%)	7.5	30	7.5	30	7.5	7.5
	Cd-shield	Cd-shield	No Cd	No Cd	Cd-shield	Cd-shield
Li burn-up (at.%/FPY)	2.45	8.87	7.0	22.6	2.47	2.43
DPA/FPY	15.5	23.2	33.4	54.5	14.1	17.2
Fast (E > 1 MeV) neutron flux (cm^{-2} s^{-1})	2.43×10^{14}	2.45×10^{14}	2.56×10^{14}	2.53×10^{14}	2.39×10^{14}	2.46×10^{14}
Total neutron flux (cm^{-2} s^{-1})	9.35×10^{14}	9.36×10^{14}	1.12×10^{15}	1.02×10^{15}	9.34×10^{14}	9.46×10^{14}

flux densities as calculated for the three breeder materials at the HFR position C5. The results for Li_4SiO_4 clearly show that an unshielded breeder sample gives too high dpa rates which are dominated by the contribution of the $^6Li(n,\alpha)t$-reaction. This is also true for the Cd shielded samples when a too high ^{6}Li-enrichment is applied. There is a clear indication that the enrichment must be lower than in the HCPB blanket to arrive at similar dpa to burn-up ratios.

5.3. Advanced test reactor, INEL

The ATR of the Idaho National Engineering Laboratory (INEL), USA, is a 250 MW light water moderated and cooled test reactor designed to study the effects of intense radiation on reactor materials. Forty fuel elements with highly enriched uranium are arranged in a serpentine pattern. A beryllium reflector containing also 16 control cylinders filled with plates of hafnium surrounds the core. It is being operated at an average availability of 70–80% and can achieve a maximum (unperturbed) thermal neutron flux of 1×10^{15} cm^{-2} s^{-1}. There are nine flux trap positions in the ATR. The centre flux trap C has been considered for the high-fluence breeder material irradiation study.

An irradiation test vehicle (ITV) has been previously developed for fusion materials irradiation at ATR [12]. It consists of three in-pile tubes running the length of the reactor vessel with the capability of providing neutron spectral tailoring and individual temperature control for up to 15 experiment capsules simultaneously. Thermal neutron filtering is achieved by applying a 0.51-cm thick aluminium–boron alloy filter with a 4.3 wt% ^{10}B loading. The considered breeder specimen capsules have a diameter of 1.49 cm and a height of 25.93, 27.41, 17.78 and 17.78 for capsules 3826, 3813, 1832 and 1807, respectively. Capsules 3826 and 3813 are surrounded by other breeder specimens with an inner diameter of 1.49 cm and an outer diameter of 2.24 cm.

Table 5 shows the lithium burn-up and the dpa accumulation per full power year along with the neutron flux densities as calculated for Li_4SiO_4 at different ^{6}Li-enrichments. In these calculations, the ATR was assumed to be operating at 120 MW_{th}. The results indicate again that in the fission test reactor irradiation a lower enrichment is required as compared to the HCPB Demo blanket in order to avoid a too high contribution to the dpa rate of the $^6Li(n,\alpha)t$-reaction. When using naturally enriched lithium, the tailored ATR-ITV spectra are in general well suited to arrive at a proper dpa to burn-up ratio.

6. Fission test reactor vs. fusion Demo reactor irradiation

6.1. Neutron spectrum comparison

For the Li_4SiO_4 breeder, a comparison of selected fission reactor spectra and the spectrum in the HCPB Demo blanket is provided in Fig. 9. It is revealed that the thermal spectrum is completely cut off when applying a Cd-shield (HFR, JMTR). The thermal neutron filter considered for the ATR on the other hand reduces the Maxwellian spectrum tail without cutting it off. This might be advantageous as it provides the needed lithium burn-up, which in case of the HCPB blanket takes place in the higher energy range.

6.2. Dpa vs. lithium burn-up

According to the proceeding for the HCPB Demo blanket, irradiation times of 1, 2 and 4 full power years were considered when calculating the lithium burn-up and the dpa accumulation during the breeder material irradiation in the considered fission test reactors.

For Li_4SiO_4, Fig. 10 shows a comparison plot of the dpa accumulation versus the lithium burn-up. As already indicated in Section 5, it is clearly revealed that a lower ^{6}Li-enrichment is required in the fission test reactor irradiation to arrive at the target dpa to burn-up ratio of the HCPB blanket. With the ATR-ITV and HFR, the flux spectra are well suited to achieve HCPB target values with naturally enriched lithium up to about 2 FPY. A slightly higher enrichment in the range 10–15

Table 5
Neutron fluxes, dpa accumulation and lithium burn-up in ATR-ITV, central position

	Li_4SiO_4				Li_4SiO_4			
Irradiation capsule	1807	1832	3813	3826	1807	1832	3813	3826
^{6}Li-enrichment (at.%)	7.5	7.5	7.5	7.5	30	30	30	30
Li burn-up (at.%/FPY)	3.12	4.73	3.88	2.67	5.67	9.79	5.55	3.32
DPA/FPY	8.99	17.8	17.9	10.4	11.7	21.5	17.8	10.3
Fast (E > 1 MeV) neutron flux (cm^{-2} s^{-1})	9.02×10^{13}	1.79×10^{14}	2.15×10^{14}	1.27×10^{14}	9.39×10^{13}	1.66×10^{14}	2.03×10^{14}	1.18×10^{14}
Total neutron flux density (cm^{-2} s^{-1})	4.17×10^{14}	8.53×10^{14}	1.0×10^{15}	5.73×10^{14}	4.08×10^{14}	7.42×10^{14}	8.54×10^{14}	4.97×10^{14}

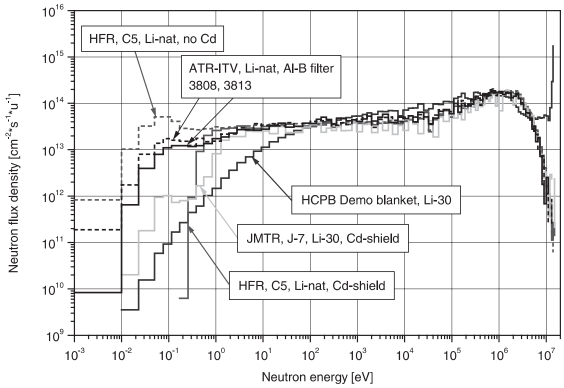

Fig. 9. Comparison of neutron flux spectra in Li_4SiO_4.

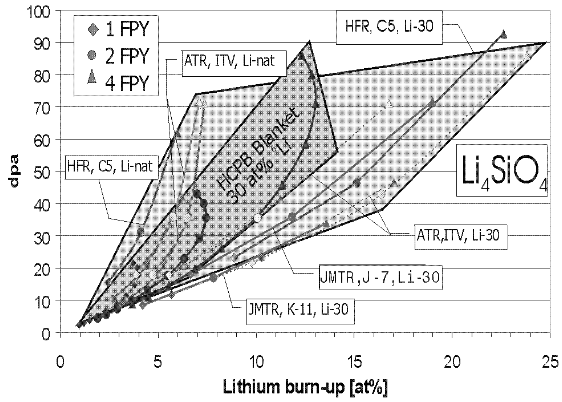

Fig. 10. Dpa accumulation vs. lithium burn-up for Li_4SiO_4.

at.% ^{6}Li would allow one to simulate an irradiation up to 4 FPY. The same is basically true for the irradiation in the JMTR as well.

For the Li_2O and the Li_2TiO_3 breeder materials, results are available for the HFR and JMTR reactors only. As revealed in Figs. 11 and 12, there is the same trend as being observed for Li_4SiO_4. Dependent on the ^{6}Li-enrichment required for the HCPB blanket, an enrichment of 7.5 at.% and 20–30% is well suited to meet the HCPB target area when irradiating Li_2O and the Li_2TiO_3 using Cd-shielding in, e.g., the HFR and JMTR reactors.

6.3. Damage production function $W(T)$

The agreement of the dpa accumulation and, at the same time, the lithium burn-up is an indication that the resulting damage characteristics do also agree. This can be better judged by comparing the damage production function $W(T)$ as defined in Section 3. Fig. 13 shows a corresponding comparison for Li_4SiO_4. As one can see for the HFR calculations, the PKA-spectrum is too soft

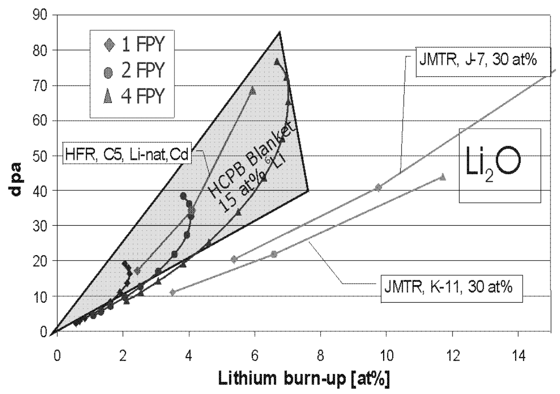

Fig. 11. Dpa accumulation vs. lithium burn-up for Li_2O.

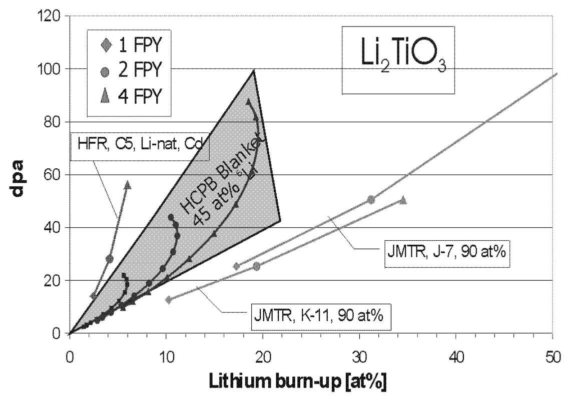

Fig. 12. Dpa accumulation vs. lithium burn-up for Li_2TiO_3.

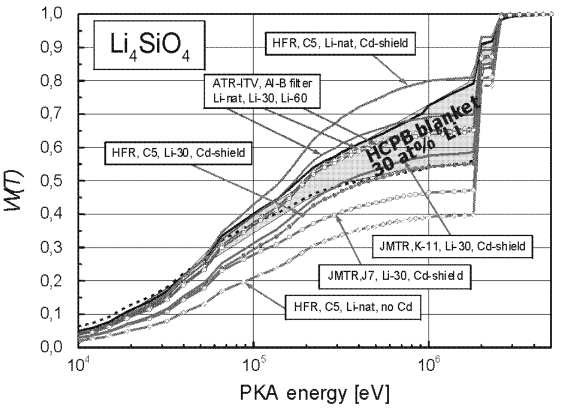

Fig. 13. Comparison of $W(T)$ damage production function for Li_4SiO_4.

with natural lithium but too hard for an enrichment at 30 at.%. As with the dpa to burn-up ratio, a ^{6}Li-enrichment of 10–15 at.% would allow a proper representation of $W(T)$-function typical for a HCPB Demo blanket. The same applies for the JMTR irradiation where also use is made of a Cd shield to cut off thermal neutrons. Spectral tailoring with boron requires a little lower enrichment as shown by the ATR cases. Note that without any neutron spectrum tailoring, the resulting PKA spectrum would be by far too hard, even with natural lithium (see the corresponding HFR-curve with no Cd shield in Fig. 13).

For Li_2O, a natural ^{6}Li-enrichment provides an optimal agreement with the HCPB $W(T)$-function in the HFR irradiation (Fig. 14). The same would apply for JMTR when reducing the enrichment to the same level. For Li_2TiO_3, a higher enrichment in the range 15–20% is required to arrive at a HCPB blanket typical $W(T)$-function when irradiating in the HFR and the JMTR test reactors (Fig. 15).

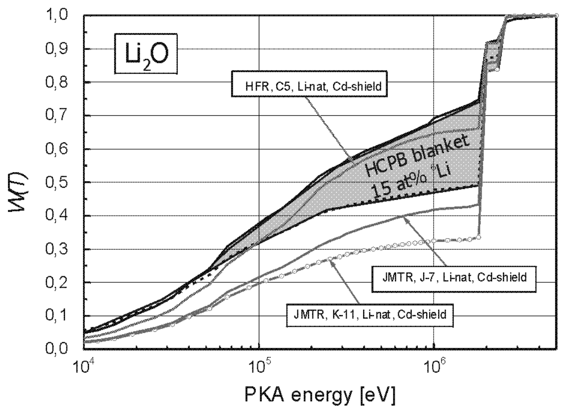

Fig. 14. Comparison of $W(T)$ damage production transfer function for Li_2O.

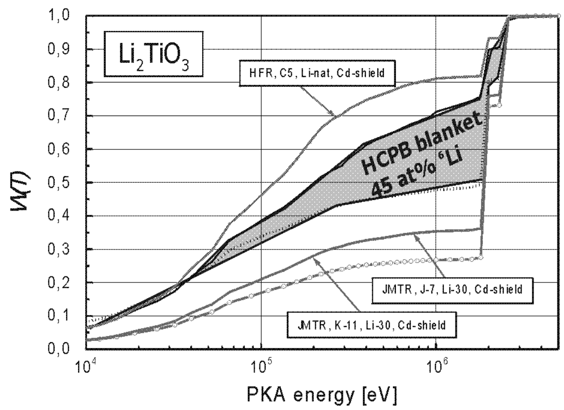

Fig. 15. Comparison of $W(T)$ damage production function for Li_2TiO_3.

Thus the $W(T)$ damage production function provides similar results as the dpa vs. burn-up comparison regarding the question if fusion relevant irradiation damage parameters can be achieved in HFR irradiations.

7. Conclusion

Nuclear irradiation parameters relevant to displacement damage and burn-up of the breeder materials Li_2O, Li_4SiO_4 and Li_2TiO_3 have been evaluated and compared for a fusion power demonstration reactor and the fission test reactors HFR Petten, ATR and JMTR. Based on detailed nuclear reactor calculations and BCA computer simulations of the displacement damage in the polyatomic lattices, it has been shown that breeder material irradiation in these fission test reactors are well suited to simulate fusion power reactor irradiation conditions provided the neutron spectrum is well tailored and the ^{6}Li-enrichment is properly chosen. In particular, it is required to reduce or cut off the thermal neutron spectrum and decrease, at the same time, the ^{6}Li-enrichment as compared to the fusion power reactor.

Requirements for the relevant nuclear irradiation parameters such as the displacement damage accumulation, the lithium burn-up and, furthermore, the damage production function $W(T)$ can be met when taking into account these prerequisites. Irradiation times in the order of 2–3 full power years are necessary for the considered HFRs and irradiation positions to achieve the peak values of a fusion power demonstration reactor blanket with regard to burn-up and, at the same time, the dpa accumulation. A high reactor availability is necessary to achieve these target values within a few calendar years. The detailed layout of the actual irradiation experiment requires further investigations taking into account thermo-mechanics, thermo-hydraulics, experiment operation and cost issues [13]. The present study has provided an analytical framework to arrive at a proper test-matrix for the irradiation experiment.

Acknowledgements

It is a pleasure to thank Dr R. Conrad (NRG), Dr H. Kawamura (JAERI), Dr J. van der Laan (NRG) and Dr S. Malang (FZK) for their active support involving many stimulating discussions on the scope of this activity.

References

[1] M.T. Robinson, Nucl. Instrum. and Meth. B 67 (1992) 396.
[2] F. Briesmeister (Ed.), MCNP – a general Monte Carlo N-particle transport code, version 4A, LA-12625-M, November 1993, version 4B March 1997.
[3] M.J. Norgett, M.T. Robinson, I.M. Torrens, Nucl. Eng. Des. 33 (1975) 50.
[4] J. Lindhard, V. Nielsen, M. Scharff, P.V. Thomsen, Mat-fys. Medd. 33 (10) (1963) 1.
[5] D. Leichtle, Strahlungsinduzierte Gitterschädigung leichter Materialien in Fusionsreaktorblankets, Report FZKA-6253, April 1999.
[6] D. Leichtle, U. Fischer, Fusion Technology 1998, in: Proceedings of the 20th Symposium on Fusion Technology, Marseille, France, 7–11 September 1998, vol. 2, p. 1179.
[7] S.T. Nakagawa, Y. Yamamura, Radiat. Eff. 105 (1988) 239.
[8] L.R. Greenwood, R.K. Smither, SPECTER: neutron damage calculations for materials irradiations, Argonne National Laboratory, ANL/FPP/TM-197, January 1985.
[9] R.E. MacFarlane, The NJOY nuclear data processing system, version 91, Los Alamos National Laboratory, Report LA-12740-M, 1994.
[10] M. Dalle Donne, et al., Fus. Eng. Des. 39&40 (1998) 825.
[11] U. Fischer, P. Norajitra, in: Proceedings of the 20th Symposium on Fusion Technology, Marseille, France, 7–11 September 1998, p. 1149.
[12] F.W. Ingram, A.J. Palmer, D.J. Stites, J. Nucl. Mater. 258–263 (1998) 362.
[13] J.G. van der Laan, et al., in: Proceedings of the Eighth International Workshop on Ceramic Breeder Blanket Interactions, 6–8 October 1999, Colorado Springs.