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Summary

To understand the impact of radiation damage in fusion reactor ceramic breeder materials sample irradiations in fission reactors are foreseen. But the two main radiation damage sources - fast neutron elastic scattering and the $^{6}Li(n,\alpha)T$-reaction - may lead to different damage chacteristics. Thus, the contributions of the two have to be adjusted in sample irradiations or should be varied. Therefore radiation damage calculations in dpa were performed for a variety of fusion reactor blanket concepts as well as for fission reactor irradiations. To do this it was necessary to generalize the dpa concept to composite materials.

The calculations showed:

1) the damage rate obtainable in fission reactors corresponds to the one in fusion reactor blankets (at least for NET), 2) the contributions of the two main damage sources varies by more than a factor of ten between different blanket concepts, 3) sample irradiations in a fast and a thermal fission reactor cover this range. Thus, in order to identify differences in radiation damage characteristics parallel irradiation of identical samples in a fast (KNK II) and a thermal (OSIRIS) reactor are recommended.

Anforderungen und Möglichkeiten der Bestrahlung keramischer Brutmaterialien für Fusionsreaktoren

Zusammenfassung

Um die Veränderung keramischer Brutstoffe bei der Neutronenbestrahlung in Fusionsreaktor-Blankets kennenzulernen, sind Probenbestrahlungen in Spaltungsreaktoren vorgesehen. Da die elastische Streuung schneller Neutronen und die $^{6}Li(n,\alpha)T$-Reaktion andersartige Strahlenschäden hervorrufen können, muß das Verhältnis richtig eingestellt oder variiert werden können. Daher wurden für einige Blanketkonzepte und Bestrahlungseinrichtungen die beiden Arten von Strahlenschäden in dpa berechnet. Dazu mußte zuerst das dpa-Konzept auf zusammengesetzte Materialien erweitert werden.

Es zeigte sich: 1) Die Schädidungsraten bei Bestrahlung in Spaltungsreaktoren entsprechen denen von Fusionsreaktor-Blankets (zumindest für NET), 2) das Verhältnis der beiden Schädigungsraten variiert um mehr als einen Faktor 10 zwischen verschiedenen Blanketkonzepten, 3) durch Bestrahlungstests in einem Schnellen und Thermischen Reaktor wird der Bereich abgedeckt. Um festzustellen, ob unterschiedliche Strahlenschäden auftreten, wird eine Parallelbestrahlung identischer Proben in einem Schnellen Reaktor (KNK II) und einem Thermischen Reaktor (OSIRIS) empfohlen.

Content

1. Introduction

Feasibility assessment and concept selection of a ceramic breeder blanket implies the assurance that blanket performance is not jeopardized by radiation damage effects. Two main contributions to radiation damage in ceramic breeder materials can be distinguished:

a) fast neutron elastic scattering leading to a cascade of atoms displaced from their lattice positions, as it is the case for structural materials;

b) the $^{6}Li(n,\alpha)T$ process which generates a 2.08 MeV α-particle and a 2.78 MeV triton. These particles produce a similar cascade of recoil atoms as the neutron scattering but in addition helium and tritium gas implementation is formed.

α-particles are also formed in the $^{16}O(n,\alpha)$ process, but this is a threshold reaction and in a typical blanket spectrum the α-yield is about 4% of the yield from the $^{6}Li(n,\alpha)T$ reaction. Similarily $^{7}Li(n,n'\alpha)T$ contributes to about 1% to the tritium and α-particle production. Inelastic scattering and other transmutation reactions have even smaller effects.

The elastic scattering and $^{6}Li(n,\alpha)T$ contributions are of the same order of magnitude but the partition strongly depends on the neutron spectrum.

Only neutrons with energies above 100 keV contribute significantly to radiation damage by elastic neutron scattering whereas the $^{6}Li(n,\alpha)T$ reaction is primarily induced by low energy neutrons (1/v-cross section).

As a consequence of the radiation damage tritium release may be drastically inhibited due to tritium trapping in lattice defects or closure of open porosity by swelling. The two above mentioned contributors to radiation damage may or may not have different impacts on tritium release characteristics and material property changes. Eventually the whole effect is very small. These questions can only be answered by sample irradiations.

There are two principle possibilities to select the irradiation environment:

a) irradiate samples in a neutron spectrum which is as similar as possible to the one of the blanket under consideration and use the results directly.

b) Irradiate samples in two neutron spectra with significantly different contributions of elastic scattering and the $^{6}Li(n,\alpha)T$ reaction to radiation damage, try to identify the differences in the damage pattern, and find the radiation pattern of the blanket by proper interpolation.

Procedure b) has the advantage to give more insight and the results are applicable to a variety of blanket concepts and locations in the blanket. Moreover, in case there is no difference in the damage pattern future irradiations could be done in the most convenient and cheap irradiation facility, what would generally be a thermal reactor.

In order to assess the possibilities of fission reactors to simulate irradiation conditions of a fusion reactor blanket in the way described above, radiation damage calculations were performed for ceramic breeder materials in different reactor spectra.

As a measure of radiation damage effects the displacements per atom were chosen. It is not evident that this quantity is simply correlated to the material properties and tritium release characteristics. But there is no alternative available and identification of the radiation damage effects for given dpa-levels is one of the main subjects of the irradiation experiments.

However, the dpa-concept implies (already in the wording) that there is only one kind of atoms in the materials. Thus, for the solid breeder materials the concept has to be generalized first.

2. The methods applied for dpa calculations

2.1 The displacement rate for mono-atomic materials

We first consider fast neutron elastic scattering only. Radiation damage by the triton and α-particle is treated in Sect. 2.3.

Fast neutron scattering can remove by recoil an atom from its lattice position. The primary knock on atom (PKA) removes other atoms from their place which again hit other atoms so that a cascade is formed which propagates until the energy of the atoms is too small to transfer the displacement energy E_d. E_d is typically in the range of 20 eV - 80 eV.

The total number of displaced atoms per cm^3 and second $\dot{D}$ is then given by the fast neutron scattering rate $R_s(E)$ times the number of displaced atoms per scattering event (or per cascade) $N_D(E)$ integrated over the neutron energy E.

$$\dot{D} = \int_0^\infty N_D(E)\ R_S(E)\,dE \qquad (1)$$

where

$$R_S(E)dE = N\ \sigma_S(E)\phi(E)dE \tag{2}$$

σ_S = elastic neutron scattering cross section
$\phi(E)dE$ = flux of neutrons with energies between E and E+dE
N = number of atoms per cm^3 in the lattice

so that

$$\dot{D} = \int_0^\infty N_D(E)\ N\ \sigma_S(E)\phi(E)dE \tag{3}$$

and the displacements per atom per second

$$dpa/s = \dot{d} = \frac{\dot{D}}{N} = \int_0^\infty N_D(E)\sigma_S(E)\phi(E)dE \tag{4}$$

By introduction of the displacement cross section

$$\sigma_d = \sigma_s \cdot N_D \tag{5}$$

we get

$$\dot{d} = \int_0^\infty \sigma_d\ \phi(E)dE = \langle\sigma_d\rangle\ \phi_{tot} \tag{6}$$

where

$$\langle\sigma_d\rangle = \frac{\int_0^\infty \sigma_d(E)\phi(E)dE}{\int_0^\infty \phi(E)dE} \tag{7}$$

$$\phi_{tot} = \int_0^\infty \phi(E)dE$$

The scattering cross section $\sigma_s(E)$ is mostly well known and available in data liberaries, $\phi(E)$ is obtained by neutronics calculations of a specific reactor and irradiation position. Thus the dpa-calculation is reduced to the determination of $N_D(E)$.

If E_D is the energy to remove an atom from its lattice position, because of momentum conservation, the kinetic energy of an atom to just displace an atom of the same kind has on the average to be 2 E_d. Thus, one could think that the total number of displaced atoms is given by $E/2E_d$. This is not correct, however, for several reasons:

First, the neutron can not transfer its full energy in one collision but on the average isotropic scattering only the fraction

$$E_{PKA} = \frac{1-\alpha}{2} E \tag{8}$$

with $$\alpha = \left(\frac{A-1}{A+1}\right)^2$$

A = atomic mass number.

Second, not all of the energy of the primary knock on atom E_{PKA} is available for elastic scattering. For kinetic energies above 10 keV an increasing fraction is consumed in inelastic scattering resulting in electron excitation. Our calculations are based on the so called NRT-model /1,2/ which uses the method of Lindhard et al. /2,3/ to account for this effect. In the NRT-model the available damage energy E_{Dam} is obtained from the primary knock on energy by

$$E_{Dam} = E_{PKA} \frac{1}{1 + k \cdot g(\varepsilon)} \tag{9}$$

with

$$k = 0.1337\ Z_1^{1/6} \cdot \sqrt{\frac{Z_1}{A_1}} \qquad \text{(Thomas-Fermi-factor)}$$

$$\varepsilon = \frac{E_{rel}}{E_L}$$

$$E_{rel} = \frac{A_2}{A_1+A_2} E_{PKA}, \quad E_L = \frac{Z_1 Z_2 e^2}{a_s}$$

$$a_s = 0.8853\, a_H\, (Z_1^{2/3} + Z_2^{2/3})^{-1/2}$$

$$a_H = 0.5292 \cdot 10^{-8} \text{ cm (Bohr's radius)}$$

$$g(\varepsilon) = 3.4008\, \varepsilon^{1/6} + 0.40244\, \varepsilon^{3/4} + \varepsilon$$

The indices 1 and 2 refer to the primary and secondary atom in a collision. For a monoatomic material $A_1 = A_2$ and $Z_1 = Z_2$.

The so called "damage efficiency" $1/1+kg(\varepsilon)$ accounts for all inelastic energy losses in the cascade.

Third, a so called cascade factor β has to be taken into account. β essentially describes the deviation of the interatomic potential from the ideal hard sphere. In the NRT-model $\beta=0.8$ is taken which seems to be a good approximation /1,2/. Thus we have

$$N_D = \frac{\beta}{2E_d} \cdot E_{Dam} \tag{10}$$

$$N_D = \frac{E}{2E_d} \cdot \beta \frac{1}{1+kg(\varepsilon)} \cdot \frac{1-\alpha}{2}$$

In addition, somewhat arbitrarily independent of the material E_d is set to E_d=40 eV. This is good enough for the relative statements in which we are interested. Then

$$N_D = 0.01\, E_{Dam} \qquad (E_{Dam} \text{ in eV})$$

A programme was written which calculates the displacement cross section and the dpa-rates based on these equations. The calculation is performed in a multigroup representation where the scattering cross sections and the neutron spectrum have to be given as inputs.

2.2 The displacement rate for a mixture of different atoms

In a mixture of atoms the energy transfer process in more complicated: First the neutron can be scattered at any one of the different kinds of atoms constituting the lattice, secondly the primary knock on atom can collide with anyone of the different atoms and so on. This leads to an enormous number of potential combinations of binary collisions which in principle have to be treated in following the cascade. Therefore it is more meaningful to look for an adequate approximation.

A simple way to transform the problem to a monoatomic one consists in using an effective atom for treating the cascade. This effective atom should be an average over the different kinds of atoms in the lattice.

Inspection of Equ. 3 and Equ. 10 reveals that the different kinds of atoms contribute in a totally different manner to the neutron scattering events and to the collisions after the primary knock on. In case we would mix this all up in one avereging process the mass of the effective atom would depend on the neutron spectrum.

It is much better to treat the neutron scattering process up to the primary knock on energy separately for the different kinds of atoms and to use the average atom approximation only for treating the cascade.

This was done and the average atom was specified by

the atomic number $$Z = \sum_i n_i Z_i \qquad (11)$$

the atomic weight $$A = \sum_i n_i A_i \qquad (12)$$

with n_i = fraction of atoms of type i in the lattice or molecule.

This approximation would be exact if the damage efficiency $1/1+kg(\varepsilon)$ would be a linear function of both A_i and Z_i. In reality the dependence is less than linear (more like a square root). But for the silicates considered here the contribution of oxygen is so much dominating that the impact of the nonlinearity in the weighting is supposedly quite small.

In addition a second, completely different approximation was used for comparison. In this second approximation not only the neutron scattering but also the collision between the primary knoøk on and the secondary knocked on atoms (SKA) is treated exactly (i.e. each constituent of Li_2SiO_3 is treated separately) but it is assumed that each following cascade atom is of the same kind as the SKA. Afterwards the different contributions of the constituents are averaged corresponding to their abundancies. This approximation means that we use a superposition of sublattices (of equal kind) for treating the SKA and the following cascade.

In Table 1 results from the two approximations are compared. The case refers to Li_2SiO_3 in a Phenix reactor spectrum. As can be seen the two approximations yield quite similar values for the displacement cross section. This was also observed for the energy dependence of the damage efficiency. Thus, the "average cascade atom approximation" should be good enough and it is used here for the calculation of the displacement cross section of mixtures.

2.3 The displacement cross section for tritium and α-particles

The governing transmutation process in ceramic blanket materials is the $^{6}Li(n,\alpha)T$ reaction (see Sect.1). Because of the 1/v behaviour of the $^{6}Li(n,\alpha)T$ cross section the reaction takes place primarily with low energy neutrons and the kinetic energy of the reaction products is 4.86 MeV. From this energy 3/7 (=2.083 MeV) are transferred to the α-particle and 4/7 (=2.777 MeV) to the triton.

The α-particle and the triton can be treated as if they were primary knock-on atoms from neutron elastic collisions what allows to apply the whole formalism of Sect. 2.1 and Sect. 2.2. The main differences are:

a) The primary reaction rate is not elastic scattering but the tritium production rate.

b) The primary knock-on particles do not have an energy spectrum but a single energy value.

To this single energy value corresponds for a given material a fixed number of displacements $N_D(\alpha+T)$. Thus, with the tritium production rate C (T-atoms/cm^3 s) we get for the damage rate

$$\dot{D}_{\alpha+T} = N_D(\alpha+T) \cdot C \tag{13}$$

or

$$\dot{d} = (dpa/s)_{\alpha+T} = \frac{N_D}{N} C \tag{13a}$$

with $N = \sum_i N_i$ = number of atoms per cm^3 ceramic material

one gets for Li_2SiO_3

$$N_D(\alpha) = 115.7$$
$$N_D(T) = 72.6$$
$$N_D(\alpha+T) = 188.3$$

Values for other ceramic materials are summarized in Table 2. These values are obtained with the average cascade atom approximation. Marginally different values result for the superimposed sub-lattice approximation (see Sect. 2.2).

Alternatively one can also use the cross section notation. With

N_i = number of type i atoms per cm^3

N_1 = number of ^6Li atoms per cm^3

and $< >$ = symbol for average over neutron energy

one gets

$$C = N_1 \int_0^\infty \sigma_{n\alpha}\, \phi(E)\, dE$$
$$C = N_1 \langle\sigma_{n\alpha}\rangle \phi_{tot} \qquad (14)$$

$$\dot{d} = \frac{N_D}{\sum_i N_i} \cdot C = N_D \cdot \frac{N_1}{\sum_i N_i} \langle\sigma_{n\alpha}\rangle \phi_{tot} \qquad (15)$$

and by definition (Eq.6)

$$\dot{d} = \langle\sigma_d\rangle \phi_{tot}$$

Thus,

$$\langle\sigma_d(\alpha,T)\rangle = N_D \frac{N_1}{\Sigma N_i} \langle\sigma_{n,\alpha}\rangle \qquad (16)$$

where $N_D \frac{N_1}{\Sigma N_i}$ is a constant for a given material and ^{6}Li enrichment. The total damage cross section is

$$\langle\sigma_d\rangle = \langle\sigma_d(n)\rangle + \langle\sigma_d(\alpha,T)\rangle \qquad (17)$$

For low ^{6}Li concentrations the damage cross section varies linearly with the ^{6}Li-enrichment, for higher values a flux depression occurs, especially in the thermal and low epithermal neutron energy range and the dependence is less than linear. In the following tables the flux depression is already included and the data refer to the ^{6}Li-enrichment indicated.

3. Irradiation Test Requirements

Primary objective of the irradiation tests is a qualification of breeder materials for NET. Therefore we first have to identify the radiation environment of the breeder materials in a NET blanket together with other conditions such as atomsphere, temperature, heat generation rate, thermal cyling effects, and other materials in contact with the breeder.

Here the problem is that in the moment no reference concept for a ceramic breeder blanket exists. All are undergoing rapid modifications and it will take some time before final specifications are available. But also in the area of breeder materials a number of options are still open, the fabrication process is not yet fixed and important characteristics such as grain size, open porosity and specific surface can only be decided on the basis of the ongoing tritium release experiments.

On the other hand irradiations have a long lead time, long irradiation time, and post irradiation examination and interpretation also need time. Thus, preparations should start as soon as possible, since behaviour under irradiation may be the crucial point for final material selection and the critical path in the blanket development.

Therefore we used a variety of blanket concepts and breeder materials to identify a range for the irradiation conditions to be expected. This will be compared with what is available in fission reactor irradiations.

Some of the concepts considered here are already cancelled because of poor performance or lack of feasibility. But they still may help to identify a possible parameter range. The following concepts were included in the study:

B1 Poloidally arranged pressure tubes filled with helium cooled rods of ceramic breeder material behind a first wall with lead multiplier which also is helium cooled (NET-Team proposal November 1983).

B2 Poloidally arranged pressure tubes filled with a mixture of beryllium and Li_2SiO_3 pebbles, helium coolant tubes penetrating the pebble bed, a helium cooled first wall and 5 cm beryllium layer between first wall and pressure tubes /4/. (Previous KfK proposal, cancelled for poor breeding performance, high pressure drop, and Be/Li_2SiO_3 compatibility problems).

B3 Toroidally arranged canisters filled with Li_4SiO_4 pebbles, helium coolant tubes with radial flow direction penetrating the pebble bed. Behind the first wall inside the canisters is first a 2 cm to 3 cm layer of breeder material followed by a 10 cm beryllium layer, (KfK, presently preferred solution).

B4 Radially arranged short pressure tubes filled with helium cooled rod bundles. The rods consist of $LiAlO_2$ pellets sandwiched between thick beryllium pellets, coolant flow in radial direction.
(CEA proposal, in a more recent proposition the tubes are arranged in toroidal direction, for our aspect this difference is marginal).

B5 Radially arranged short pressure tubes filled with a mixture of Li_4SiO_4 pebbles and beryllium pebbles, helium pressure tubes penetrating the pebble bed.
(KfK modification of CEA proposal).

For all concepts except B1 lithium with 60% ^6Li-content was used. In B1 the value was 30%.

A detailed description of the concepts, their merits and problems is beyond the scope of this report. No water cooled concepts were included. They seem to have very serious problems in keeping the breeder material temperature high enough under all operating conditions and are not followed any more.

For all concepts radiation damage in the front part of the breeder was calculated where both fast neutron flux and tritium production rate are highest. Some calculations for other positions confirmed this.

The values refer to a wall load of 1.3 MW/m^2 which is the average of the NET II design. According to Ponti /5/ the maximum could be 2.1 MW/m^2.

From the neutronics calculations the total neutron flux and the neutron spectrum at the position of interest are taken. With these values the dpa per second from elastic neutron scattering and from the $^{6}Li(n,\alpha)T$ reaction are calculated with the methods outlined in Sect.2. The calculations were made for Li_2SiO_3, Li_4SiO_4, $LiAlO_2$ and Li_2O.

In Table 3 the results are summarized. For the case of Li_2SiO_3 a graphical representation is given in Fig.1 and Fig.2 together with data for test reactor irradiations. The same representation is given for Li_2O in Fig.3 and Fig.4. The results will be discussed in Sect.5.

Although the focus is on NET design it is not very meaningful to plan an extensive material and blanket development program unless the concept has a potential for application in DEMO and fusion power reactors as well. Thus materials testing has to include conditions which are expected to occur in fusion power reactors.

In the moment it is not clear, however, which containment principle will be used on the long term and what will be the wall load and power density of fusion power reactors. In the USA a wall load of 5 MW/m^2 (14 MeV neutrons) is generally considered as typical for a power reactor and we adopted this value /6/.

Although the NET blanket concepts investigated here are not directly applicable at such a wall load, simple upscaling of the data of Table 3 by a factor of $\frac{5}{1.3} = 3.85$ was used to get a first indication of the irradiation requirements (Fig.5 and Fig.6).

In addition to the radiation damage rate other parameters have also to be simulated in irradiation tests, these include:

- tritium production rate
- gas atmosphere
- heat generation rate
- temperature
- thermal cycling effects

Tritium production rate is connected with the α+T damage rate by Equ. 13a, the quantities for conversion from one unit to the other are included in Table 2.

The tritium release properties seem to depend very sensitively on the atmosphere of the sample, whether it is oxidizing or reducing and what the partial pressures are. But also the moisture content is important. The atmosphere again is influenced by the capsule wall material and temperature.

A very important parameter is the sample temperature. It can be controlled in irradiation tests by the coolant gas and capsule surface temperature.

For small sample irradiations the heat generation rate in the sample is not a very critical parameter. It determines the temperature profile in the sample. But in view of the relatively low power density the temperature profile is rather flat. For some concepts the temperature gradient may be very important, however. It could lead to cracks in the sample which would prevent the purge flow from passing through the material as foreseen in the design.

The impact of thermal cycling effects on the breeder material has not yet been investigated. Simulation in fission reactor irradiations would be difficult and separate thermal cycling tests may be needed.

4. Irradiation Test Possibilities

In order to assess the potential of fission reactors to simulate radiation damage in fusion blankets calculations were done for some typical reactors available in the European Community.

As an example for a high performance thermal reactor OSIRIS in Saclay was used. A four group spectrum from /7/ was taken which refers to a position inside the Li_2SiO_3 sample irradiated in the COLIBRI-loop in the core center. With the help of a typical spectrum of a light water moderated research reactor the spectrum was converted to a 26 group representation which then was used for the dpa calculation.

As an example for a fast reactor Phenix was selected and the spectrum of an intermediate core zone was used. No irradiation capsule has been designed yet and the unperturbed flux was taken. Inelastic scattering in the capsule may degrade the spectrum somewhat what would lead to a slight reduction in the fast neutron induced radiation damage. But the core position and that means the flux was somewhat arbitrarily selected anyway.

As a third test facility the reactor KNK was taken. A special feature of this reactor is the radial variation of the neutron spectrum: In the core center the spectrum is similar to that of a fast breeder but at the core periphery are elements which contain zirconium hydride so that a moderated spectrum is obtained. This allows to find a position where the ratio of fast neutron induced radiation damage to the (α+T)-induced radiation damage is nearly equal to the value in a fusion reactor blanket. In these calculations the real irradiation capsule is included and the spectrum at the sample position was taken. The sample itself was not contained in the calculation but a correction for the neutron self shielding in the lower energy groups was applied.

Two irradiation positions close to the core periphery were considered. These are immediately available for blanket material tests. The core center is still occupied for tests in the frame of the breeder project.

Again the neutron spectrum and total neutron flux from the reactor calculations were used as input for radiation damage calculations as described in Sect. 2. The results are summarized in Table 4.

The data in Table 4 refer to natural lithium where the ^{6}Li-content is 7.5%. In Phenix increase of ^{6}Li enrichment would lead to a linear increase of the dpa-rate from the ^{6}Li(n,α)T-process. For KNK it is nearly linear, the flux depression at 60% ^{6}Li-content in Li is a few percent for 1 cm diameter test samples. In OSIRIS, however, we have already a flux depression factor of 0.85 for natural lithium and only an increase in ^{6}Li by about a factor of two could be tolerated. But the (α+T)-contribution to radiation damage is already high for natural lithium.

5. Discussion of Results

In Fig. 1 the results from Table 3 and Table 4 are presented in a graphical form to compare the fission reactor potential with the breeder blanket conditions. The figure refers to Li_2SiO_3 which is typical for the mixed oxides. The dotted lines represent the case of 60% Li-enrichment in KNK samples. The same representation for Li_2O is shown in Fig.3. One can draw the following conclusions:

1. The blankets show a large variation in the damage rate contribution from the ^{6}Li(n,α)T-process. For B1 with lead multiplier it is rather small, for B2 with beryllium admixed to Li_2SiO_3 and an additional beryllium layer behind the first wall it is quite large. Here the small volume fraction of breeder material in the blanket (8.57 vol%) also plays a role. All the tritium has to be produced in that small volume, what makes the tritium production rate per cm^3 breeder high.

2. The reactors KNK and OSIRIS are well within the damage rates occuring in the front part of a NET blanket. The (α+T)-contribution in KNK is on the low end that of OSIRIS on the upper end of the NET blanket concepts.

Parallel irradiations in the two facilities seems extremely important and useful to cover a variety of concepts and to clarify the role of helium and tritium produced on tritium release characteristics and material properties.

The way these reactors cover the range gets even clearer from Fig.2 and Fig.4 where the neutron induced damage rate is plotted versus the (α+T)-induced damage rate for Li_2SiO_3 and Li_2O, respectively. The blanket concpets are lying more or less on a diagonal straight line. The dotted lines for the reactors again represent increase in ^6Li-enrichment. Connection of the end-points of these lines would give an area which covers the points calculated for the various blanket concepts.

Locations more inside in a blanket or closer to the shield correspond to lower damage rates both from neutrons and (α+T). Calculations for such blanket positions would fill the triangle to zero. This was checked for a few cases.

KNK and OSIRIS satisfy the neutron flux requirements for NET blankets with a 1:1 time scale for irradiations. But, as already mentioned above, higher fluence levels are needed to assess the long term potential of ceramic breeder materials and solid breeder blanket concepts. To extend the irradiation time by a factor of $\frac{5}{1.3} = 3.85$ seems not very reasonable and in addition rather long breeder residence times are envisaged for power reactors. Therefore only irradiations in the Phenix reactor or in facilities with similar neutron flux values are realistic.

Fig.5 and Fig.6 show in the same representation as the previous ones dpa-rates in Li_2SiO_3 in the Phenix reactor and for the blanket concepts when they are scaled up to 5 MW/m^2. Phenix covers the blanket test requirements for all concepts even when

we take into account a slight reduction from the presently ignored test device.

When Phenix is used to qualify materials only for NET conditions the irradiation time could be reduced by a factor of four. That means one full power year in NET is equivalent to three full power month's in Phenix. It is not clear whether such a time compression would shift the damage-annealing equilibrium in a way that the results are not prototypic any more. Supposedly this is not the case.

In all facilities it seems possible to adjust and control the temperature in the required range. Phenix and KNK only allow capsule irradiations with a stagnant atmosphere. A sweep flow of controlled composition and purity can be installed in the thermal research reactors which are equipped with loops.

There are some tricks to mitigate the disadvantage of capsule irradiations by adding a gas plenum and zirconium for trapping the tritium generated. But the conditions remain nonprototypic and not well known.

Some questions on the usefulness of capsule irradiations will be answered when a comparison is made between the tritium release characteristics of samples irradiated in OSIRIS capsules and of samples used for in-situ tritium recovery experiments at SILOE.

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Table 1: Comparison of Models to Calculate the Displacement Cross Section of Composit Materials. Example: Li_2SiO_3 in a Phenix Reactor Spectrum

superimposed lattice approximation					average cascade atom appr.	
PKA i	SKA j	$\langle\sigma_d^{ij}(E)\rangle$ barn	$\frac{N_j\sigma_d^{ij}}{\sum_j N_j}$	$\frac{N_i\sigma_d^i}{\sum_i N_i}$	SKA with $\bar{A} = 14.995$ $\langle\sigma_d^i\rangle$	$\frac{Ni\langle\sigma_a^i\rangle}{\sum_i N_i}$
Li^6	Li^6	89.8	2.23			
	Li^7	84.7	26.1			
	Si	232.3	38.7			
	O	161.2	80.6			
			147.7	3.69	151.7	3.79
Li^7	Li^6	87.3	2.18			
	Li^7	82.2	25.3			
	Si	209.6	34.9			
	O	149	74.5			
			136.96	42.2	140.8	43.4
Si	Li^6	298.3	7.46			
	Li^7	288.5	88.95			
	Si	348.1	58.0			
	O	325.7	162.9			
			317.3	52.9	321.5	53.6
O	Li^6	348.3	8.71			
	Li^7	331.3	102.2			
	Si	497.1	82.85			
	O	429.8	214.9			
			408.6	204.3	418.8	209.4
			$\langle\sigma_d\rangle^{Phenix}_{Li_2SiO_3}$ =	303.1		310.2

$\bar{A} = 14.995$ $\qquad$ $\bar{Z} = 7.333$

$$\langle\sigma_d^{ij}\rangle = \frac{\int\sigma_d^{ij}(E)\,\phi(E)\,dE}{\int\phi(E)\,dE} \qquad \langle\sigma_d^i\rangle = \frac{\sum_j N_j\langle\sigma_d^{ij}\rangle}{\sum_j N_j}$$

$$\langle\sigma_d\rangle = \frac{\sum_i N_i\langle\sigma_d^i\rangle}{\sum_i N_i}$$

1	2	3	4	5	6	7	8	9	10	11
Material	molecular weight	theor. density	ΣN_i	N_{Li}	Li-nat N_1	60% ^{6}Li N_1	Li-nat $\frac{N_1}{\Sigma N_i}$	60% ^{6}Li $\frac{N_1}{\Sigma N_i}$	N_D	$c/\dot{d} = \frac{\Sigma N_i}{N_D}$
		g/cm^3	$10^{24} cm^{-3}$	$10^{24} cm^{-3}$	$10^{24} cm^{-3}$	$10^{24} cm^{-3}$				$\frac{10^{13}\ T\text{-}At/cm^3 s}{10^{-7}\ dpa/s}$
Li_2SiO_3	89.96	2.53	0.1016	$3.387 \cdot 10^{-2}$	$0.254 \cdot 10^{-2}$	$2.032 \cdot 10^{-2}$	0.025	0.2	188.3	5.40
γLi_4SiO_4	119.84	2.21	0.0999	$4.44 \cdot 10^{-2}$	$0.333 \cdot 10^{-2}$	$2.664 \cdot 10^{-2}$	0.0333	0.2666	164.7	6.066
$\gamma LiALO_2$	65.92	2.55	0.0931	$2.33 \cdot 10^{-2}$	$0.175 \cdot 10^{-2}$	$1.398 \cdot 10^{-2}$	0.01875	0.15	210	4.43
Li_2O	29.88	2.01	0.1215	$8.1 \cdot 10^{-2}$	$0.608 \cdot 10^{-2}$	$4.86 \cdot 10^{-2}$	0.05	0.40	119	10.21

N_1 = ^{6}Li-Atom density

The numbers in columns 4,5,6,7 and 11 are proportional to the density

Table 2 Data to calculate the dpa-rate and tritium production rate from the ^{6}Li(n,)T-reaction.

$$C = N_1 \langle \sigma_{n,\alpha} \rangle \phi_{tot} \qquad T\text{-Atoms/cm}^3\ s$$

$$\dot{d} = \frac{N_D}{\Sigma N_i} N_1 \langle \sigma_{n,\alpha} \rangle \phi_{tot} \qquad dpa/s$$

Table 3 Displacement cross sections σ_d and Displacements per Atom $\dot{d}$ in breeder blanekts (description page 12 and 13).

Blanket	B1	B2	B3	B4	B5
ϕ_{tot} (10^{14}n/cm^{2}s)	5.64	5.64	5.79	6.51	6.27
$\langle \sigma(n,\alpha) \rangle$ (barn)	1.035	11.2	1.715	4.80	3.69
$\frac{N_1}{N_{Li}}$ (^{6}Li enrichm.)	0.3	0.6	0.6	0.6	0.6
Li_2SiO_3					
σ_d(neutron) barn	539,9	368,5	538,6	355,0	455,1
σ_d(α+T) barn	19,49	421,1	64,6	180,5	138,7
$\dot{d}$(neutr.) 10^{-7}dpa/s	3,04	2,08	3,11	2,31	2,85
$\dot{d}$(α+T) 10^{-7}dpa/s	0,108	2,38	0,374	1,17	0,87
C 10^{13} T-atoms/cm^{3}s	0,583	12,85	2,02	6,32	4,70
Li_4SiO_4					
σ_d(neutr.) barn	462,3	313,0	452,7	372,2	384,5
σ_d(α+T) barn	22,67	419,2	75,3	210,7	162,0
$\dot{d}$(neutr.) 10^{-7}dpa/s	2,61	1,76	2,62	2,42	2,41
$\dot{d}$(α+T) 10^{-7}dpa/s	0,128	2,77	0,44	1,37	1,02
C 10^{13} T-atoms/cm^{3}s	0,776	16,80	2,67	8,31	6,19
$LiAlO_2$					
σ_d(neutr.) barn	618,9	430,4	634,6	514,9	532,4
σ_d(α+T) barn	16,30	352,8	54,0	151,2	116,2
$\dot{d}$(neutr.) 10^{-7}dpa/s	3,49	2,43	3,67	3,35	3,34
$\dot{d}$(α+T) 10^{-7}dpa/s	0,092	1,99	0,31	0,98	0,73
C 10^{13} T-atoms/cm^{3}s	0,408	8,81	1,37	4,34	3,23
Li_2O					
σ_d(neutr.) barn	306,4	203,2	285,1	238,2	245,8
σ_d(α+T) barn	24,63	533,1	81,6	228,5	175,6
$\dot{d}$(neutr.) 10^{-7}dpa/s	1,73	1,15	1,65	1,55	1,54
$\dot{d}$(α+T) 10^{-7}dpa/s	0,139	3,01	0,47	1,49	1,10
C 10^{13} T-atoms/cm^{3}s	1,419	30,72	4,80	15,21	11,23
Li-burn up % per FPY	0,55	10,8	1,84	5,6	4,2

$$\text{Li-burnup} = \frac{N_1}{N_{Li}} \left(1-e^{-\langle\sigma\rangle\phi t}\right)$$

Table 4 Displacement cross sections σ_d and Displacements per Atom $\dot{d}$ for Breeder Materials with Natural Lithium in Irradiation Reactors

	OSIRIS	Phenix	KNK 4.16	KNK 5.7
ϕ_{tot} (10^{14}n/cm^{2}s)	4.59	50	8.57	6.95
$\langle\sigma_{n,\alpha}\rangle$ barn	74.27	1.50	1.893	6.27
Li_2SiO_3				
σ_d(neutr.) barn	314.4	310.2	464.9	397.1
σ_d(α+T) barn	350	7.2	8.91	29.5
$\dot{d}$(neutr.) 10^{-7}dpa/s	1.44	15.5	3.98	2.76
$\dot{d}$(α+T) 10^{-7}dpa/s	1.60	0.36	0.076	0.205
C 10^{13} T-atoms/cm^{3}s	8.64	1.94	0.41	1.11
Li_4SiO_4				
σ_d(neutr.) barn	267.8	273.3	402	344.8
σ_d(α+T) barn	404	8.25	10.38	34.38
$\dot{d}$(neutr.) 10^{-7}dpa/s	1.23	13.7	3.44	2.40
$\dot{d}$(α+T) 10^{-7}dpa/s	1.85	0.41	0.089	0.24
C 10^{13} T-atoms/cm^{3}s	11.22	2.49	0.54	1.46
$LiAlO_2$				
σ_d(neutr.) barn	362.9	352.1	529.3	451.2
σ_d(α+T) barn	292	5.9	7.46	24.7
$\dot{d}$(neutr.) 10^{-7}dpa/s	1.67	17.6	4.53	3.13
$\dot{d}$(α+T) 10^{-7}dpa/s	1.34	0.30	0.064	0.171
C 10^{13} T-atoms/cm^{3}s	5.94	1.33	0.284	0.758
Li_2O				
σ_d(neutr.) barn	174.2	195.9	273.6	237.5
σ_d(α+T) barn	442	8.92	11.26	37.29
$\dot{d}$(neutr.) 10^{-7}dpa/s	0.800	9.80	2.34	1.65
$\dot{d}$(α+T) 10^{-7}dpa/s	2.03	0.45	0.183	0.259
C 10^{13} T-atoms/cm^{3}s	20.7	4.59	1.87	2.64
Li-burn up % per FPY	4.94	1.77	0.38	1.03
^{6}Li-burn up % per FPY	65.83	23.6	5.1	13.7

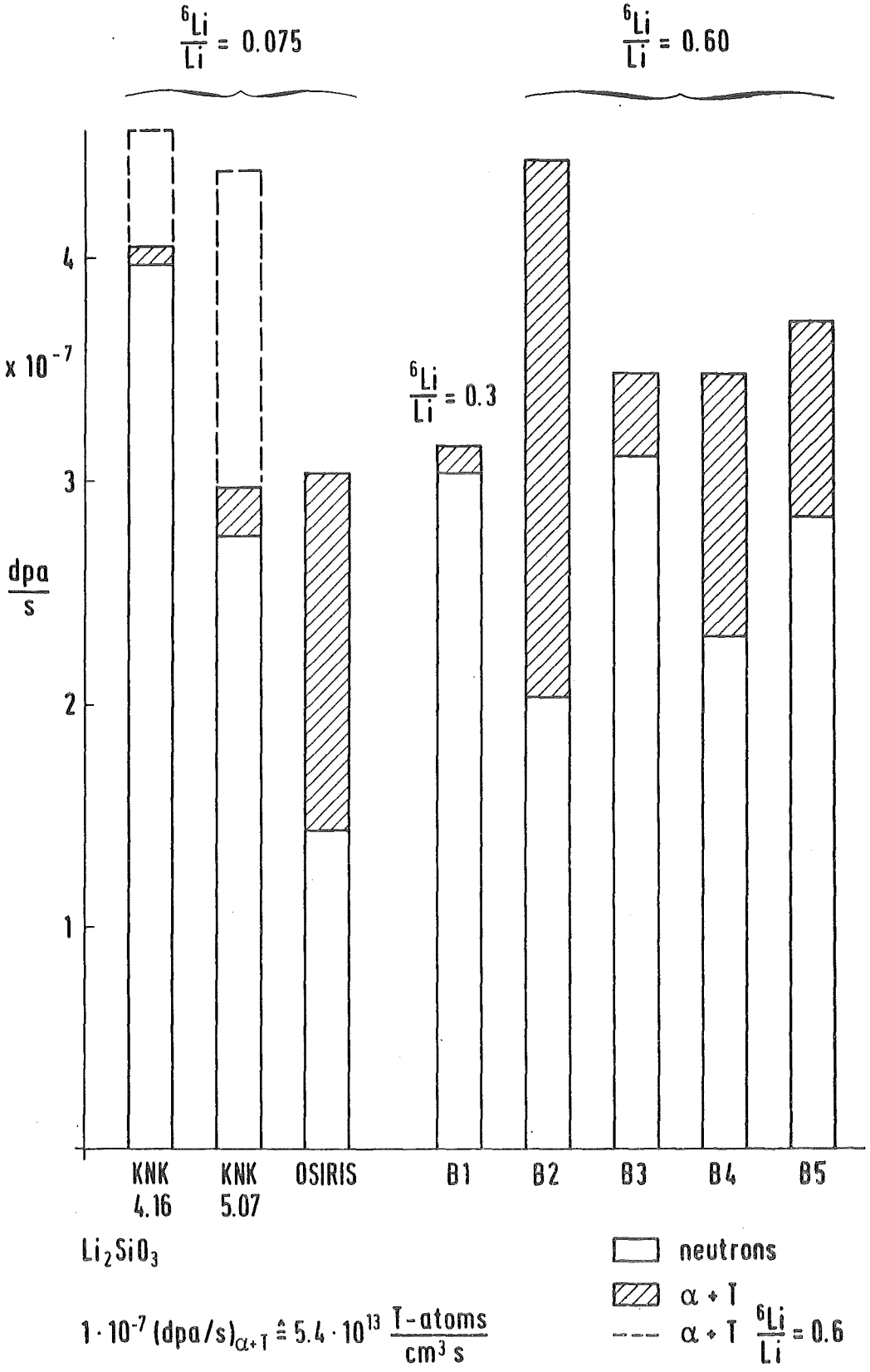

Fig.1: Radiation damage in various blankets (B1...B5) with 1.3 MW/m^2 and in fission reactor irradiations.

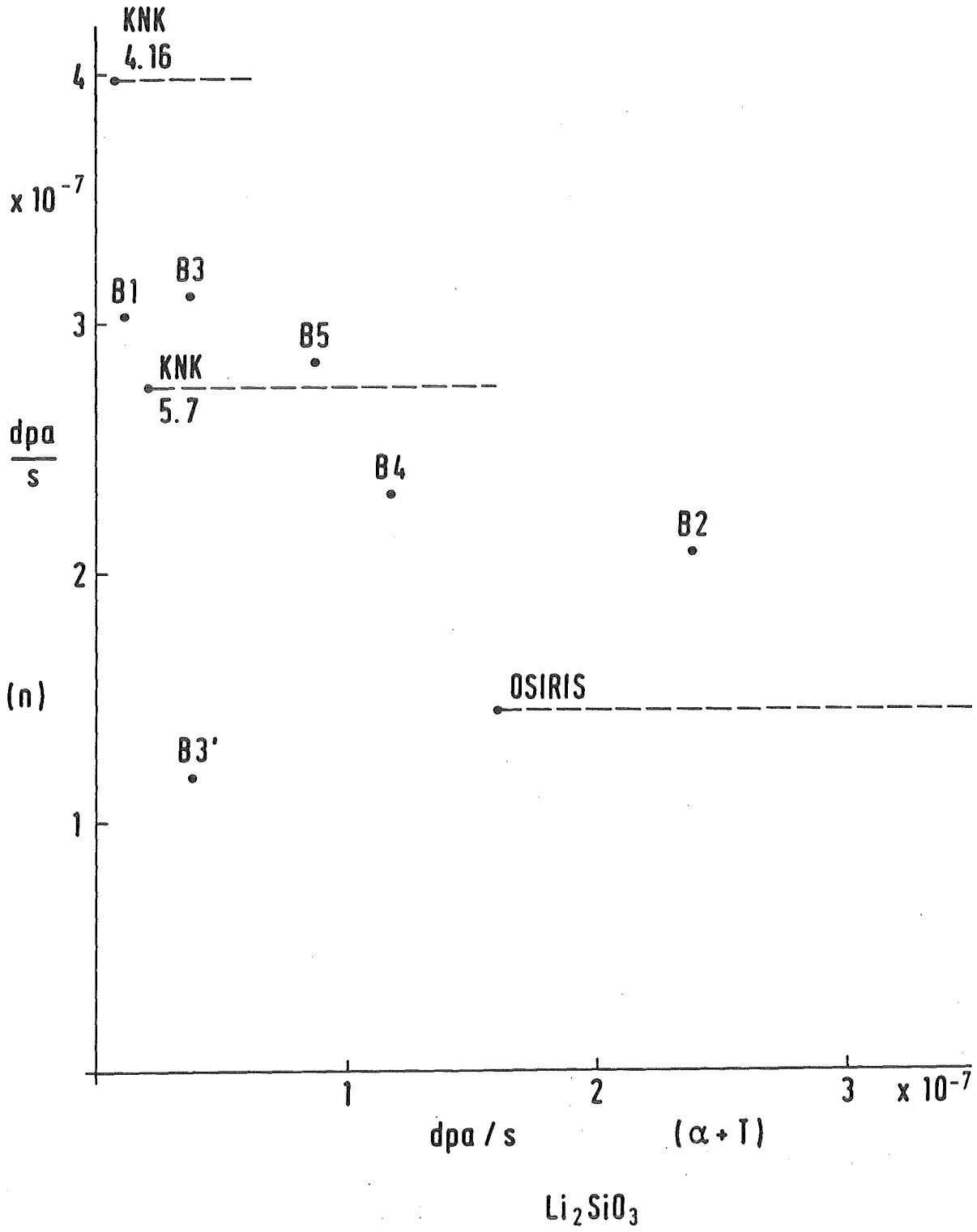

Fig. 2: Radiation damage from neutron scattering (n) versus radiation damage from the $^{6}Li(n,\alpha)T$-reaction (α+T) in blankets B1...B5 with 1.3 MW/m^2 and in fission reactor irradiations.

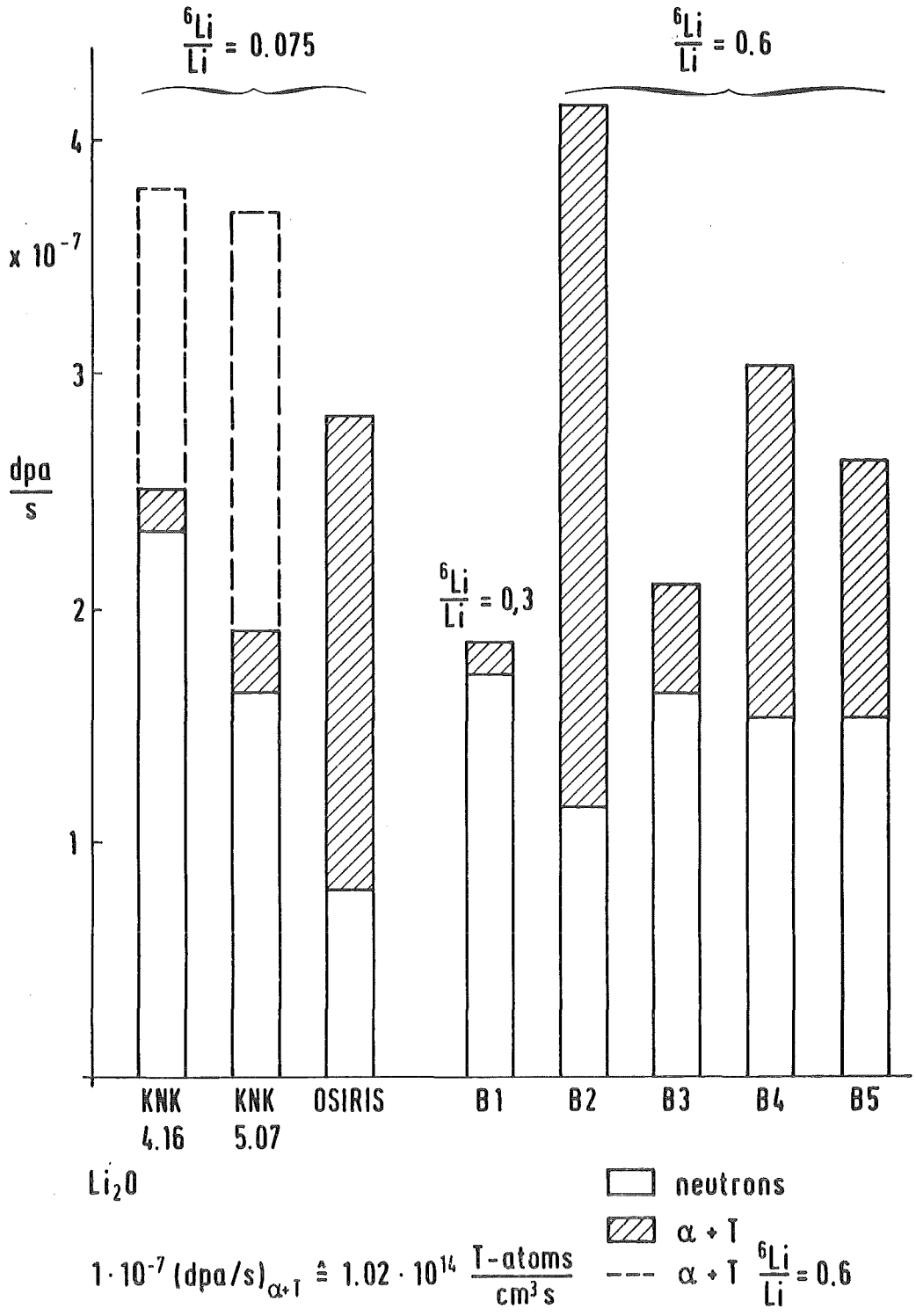

Fig.3: Radiation damage in various blankets (B1...B5) with 1.3 MW/m^2 and in fission reactor irradiations.

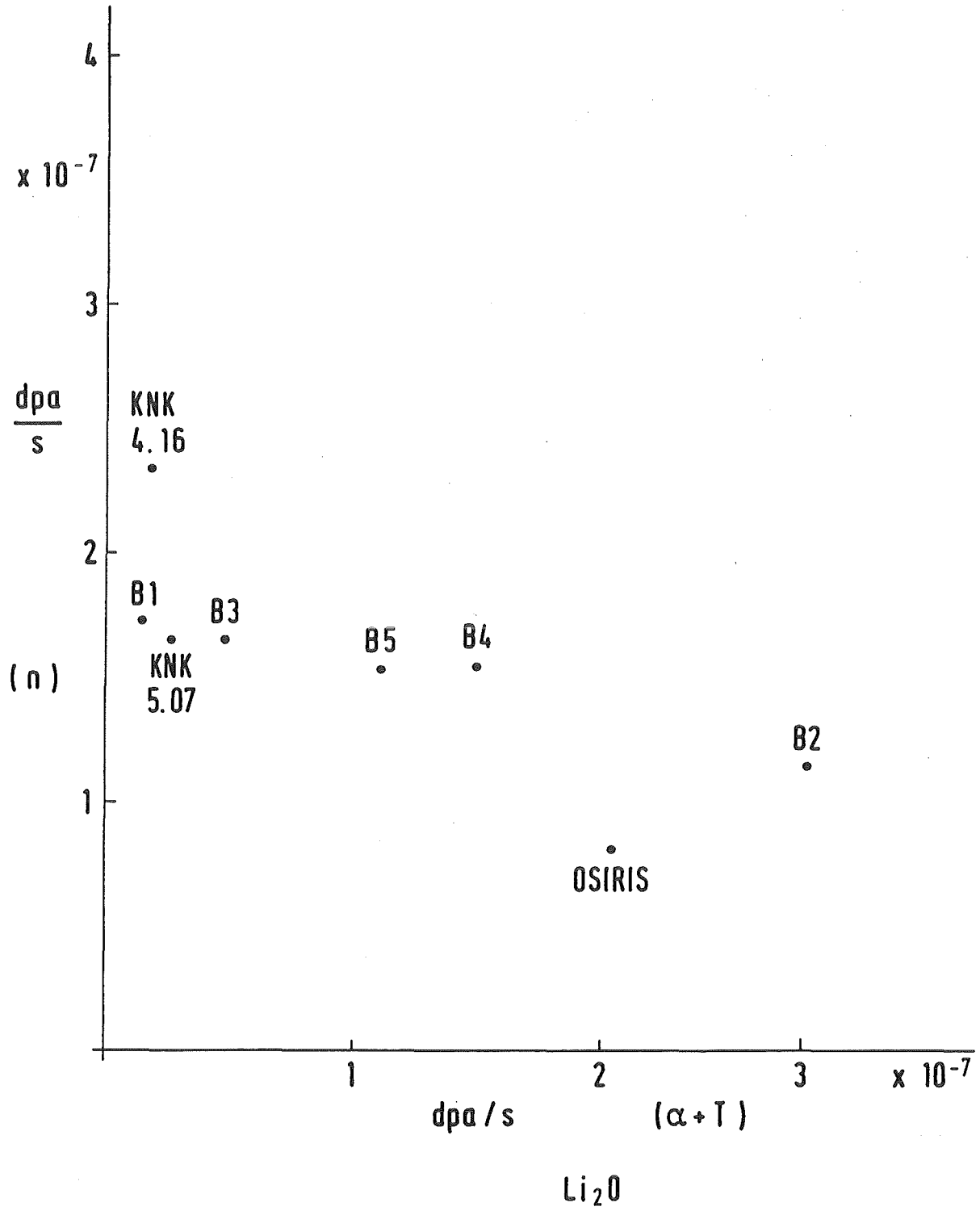

Fig. 4: Radiation damage from neutron scattering (n) versus radiation damage from the $^{6}Li(n,\alpha)T$-reaction (α+T) in blankets B1...B5 with 1.3 MW/m^2 and in fission reactor irradiations.

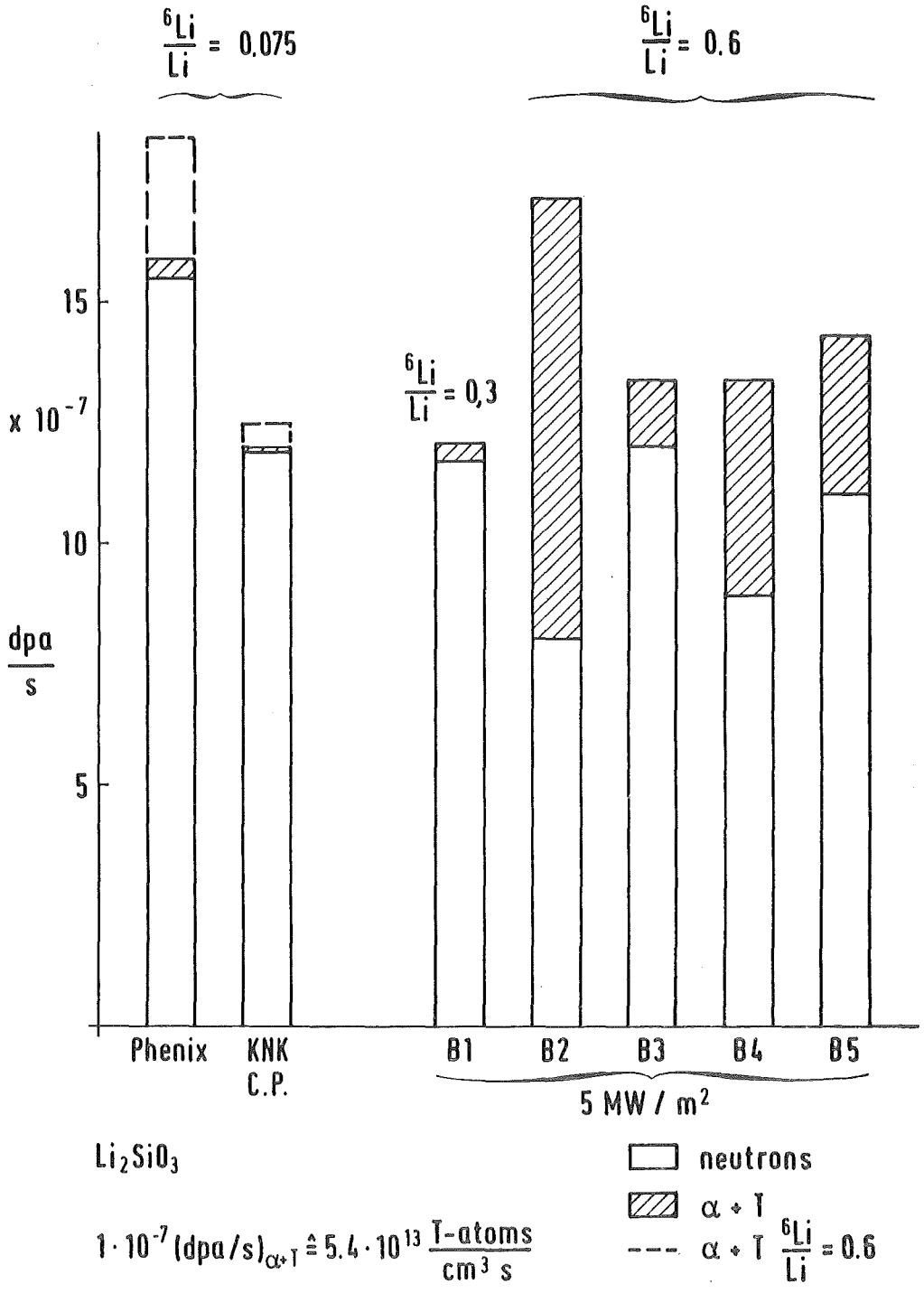

Fig.5: Radiation damage in various blankets B1...B5 with 5 MW/m^2 and in fission reactor irradiations.

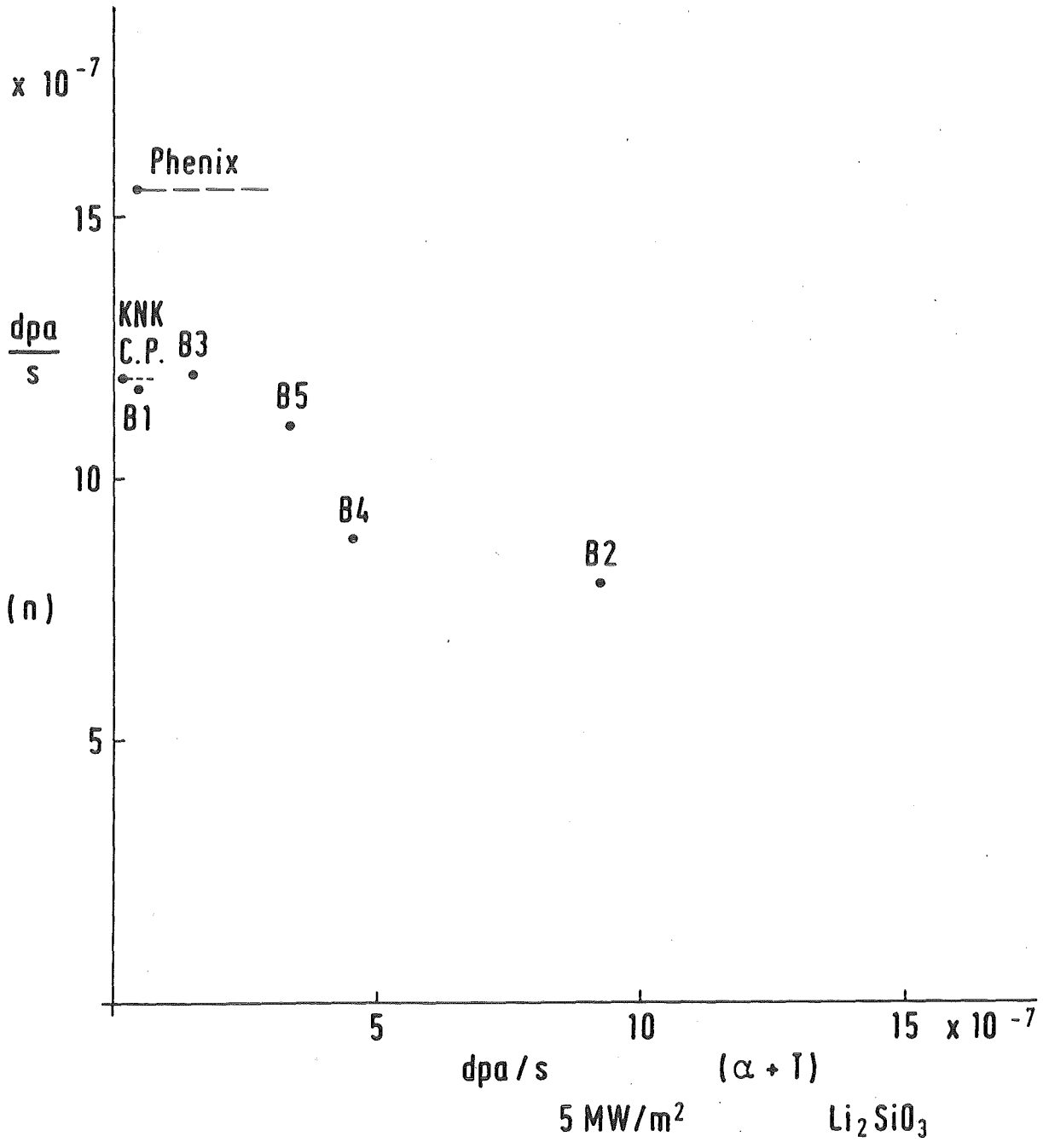

Fig. 6: Radiation damage from neutron scattering (n) versus radiation damage from the $^{6}Li(n,\alpha)T$-reaction (α+T) in blankets B1...B5 with 5 MW/m^2 and in fission reactor irradiations.