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Journal of Nuclear Materials 359 (2006) 192–201

journal of nuclear materials

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On the radiation damage characterization of candidate first wall materials in a fusion reactor using various molten salts

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Received 17 February 2006; accepted 21 August 2006

Abstract

Evaluating radiation damage characteristics of structural materials considered to be used in fusion reactors is very crucial. In fusion reactors, the highest material damage occurs in the first wall because it will be exposed to the highest neutron, gamma ray and charged particle currents produced in the fusion chamber. This damage reduces the lifetime of the first wall material and leads to frequent replacement of this material during the reactor operation period. In order to decrease operational cost of a fusion reactor, lifetime of the first wall material should be extended to reactor's lifetime. Using a protective flowing liquid wall between the plasma and first wall can decrease the radiation damage on first wall and extend its lifetime to the reactor's lifetime. In this study, radiation damage characterization of various low activation materials used as first wall material in a magnetic fusion reactor blanket using a liquid wall was made. Various coolants (Flibe, Flibe + 4% mol ThF_4, Flibe + 8% mol ThF_4, $Li_{20}Sn_{80}$) were used to investigate their effect on the radiation damage of first wall materials. Calculations were carried out by using the code Scale4.3 to solve Boltzmann neutron transport equation. Numerical results brought out that the ferritic steel with Flibe based coolants showed the best performance with respect to radiation damage.

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1. Introduction

Fusion promises great prospects in supplying unlimited energy to mankind. A fusion energy system has attributes of an attractive product with respect to safety and environmental advantages compared to other energy sources. Moreover, fusion fuels are abundantly available in nature, contrary to relatively scarce fission fuel resources. Hence, it can be thought that commercial fusion energy reactors would create a revolution in the energy market. The main components of a fusion reactor are (1) the plasma chamber, (2) a first wall to confine the plasma, (3) a blanket to convert the fusion nuclear energy into heat, and finally (4) thermal and biological radiation shielding. Selection of structural materials to be used in the fusion blanket plays a very crucial role in design of fusion reactors by taking into account of the reactor performance. The general properties for the materials considered to be used in fusion reactors can be given as below [1,2]:

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doi:10.1016/j.jnucmat.2006.08.023

- Low activation property.
- Attractive high temperature physical and mechanical properties.
- Broad compatibility with coolants.
- Low atomic displacement and helium production cross-sections.
- High thermal conductivity.
- Low neutron absorption cross-sections.
- Low cost.

Low activation property is one of the most important parameters in selection of structural material for fusion reactors [3–6]. The primary low activation materials considered to be used in fusion reactors are: (1) ferritic/martensitic steels [7–9], (2) vanadium alloys [10–14] and (3) SiC_f/SiC composites [15–20].

In a fusion reactor, the highest material damage occurs in the first wall because it will be exposed to the highest neutron, gamma ray and charged particle currents produced in the fusion chamber. Nuclear radiation causes several types of defects and diverse nuclear reactions. There are two main material damage types causing failure: atomic displacement and helium gas production. Therefore, the radiation damage level should be lower than a certain value to prevent material failure during reactor operation. Material damage criteria must satisfy both the displacement per atom (dpa) and helium production limits in design of reactor structures. In order to decrease operational costs of a fusion reactor, replacement of first wall structural material should be eliminated during the reactor lifetime. By using a flowing liquid zone adjacent to plasma the lifetime of the first wall could be extended to the lifetime of the fusion reactor (~30 years) [21–24]. Different researchers investigated liquid walls for inertial fusion energy (IFE) reactors [25–29], whereas magnetic fusion energy (MFE) reactors with protective flowing layers were investigated in Refs. [30–32]. They found different wall thickness values to those of IFE reactors for protection of solid first wall, namely with a liquid wall thickness of 60 cm for Flibe, 160 cm for natural lithium and 170–180 cm for $Li_{17}Pb_{83}$ for a 1 GW_{el} fusion power output ($10^{21}n$/s) to extend the lifetime of the first wall made of SS-304 to 30 full power years (FPYs) with respect to material damage.

An advanced magnetic fusion reactor, namely APEX using flowing liquid wall was proposed by Abdou and his team [9]. A pure fusion reactor of the APEX design using Flibe as a liquid wall has

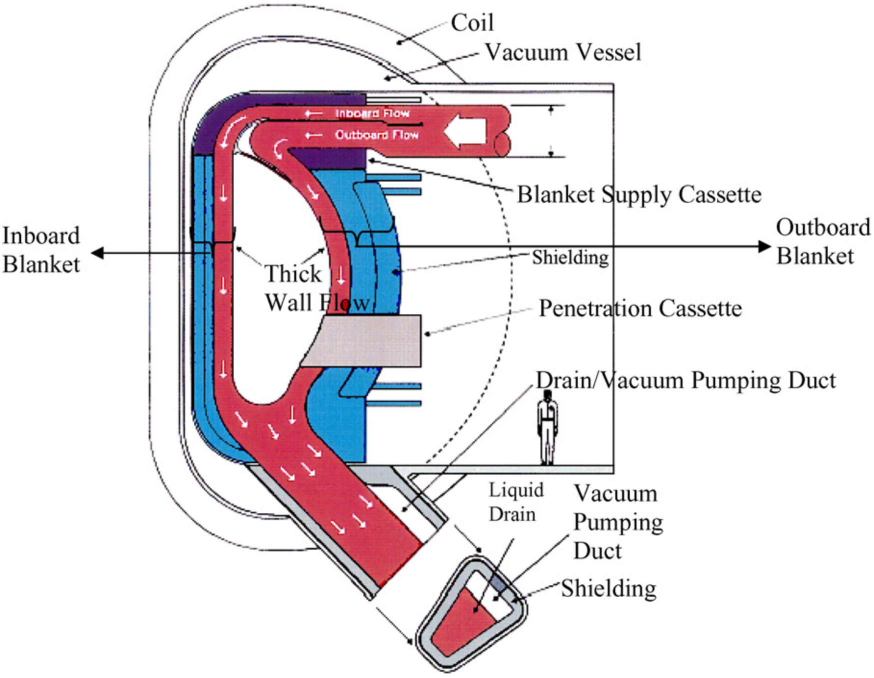

Fig. 1. Main components of the APEX fusion reactor design concept [35].

a fusion power of 4000 MWth. In a previous study [33], it was shown that using heavy metal molten salt (Flibe + UF_4 or ThF_4) improved the neutronic performance of the APEX fusion reactor with respect to energy multiplication and fissile fuel breeding. Youssef and Abdou [34] computed important radiation damage parameters for the ferritic steel first wall of the APEX fusion reactor using Flibe, LiSn, LiPb and Li with respect to liquid wall thickness. In this study, radiation damage behavior of the ferritic steel first wall structure in the APEX reactor using different salts, namely Flibe + 4% mol ThF_4 or Flibe + 8% mol ThF_4 to examine the effect of addition of ThF_4 into Flibe on the radiation damage behavior of ferritic steel. Moreover, radiation damage calculations of vanadium alloy V–4Cr–4Ti and SiC_f/SiC composite were carried out by using Flibe, Flibe + 4% ThF_4 or Flibe + 8% ThF_4 or $Li_{20}Sn_{80}$. Liquid wall thickness was chosen as a variable parameter for radiation damage calculations. The main aims of this study were to analyze the effect of using different molten salts in flowing liquid wall on the radiation damage behavior of the low activation materials and determine optimum wall thickness required to extend solid first wall lifetime to reactor's lifetime.

2. Blanket geometry

Schematic side view of the APEX fusion reactor with its main components is shown in Fig. 1 [35]. Fig. 2 depicts one-dimensional model for neutronic calculations that gives the order, thickness and name of separate zones at outboard part of the blanket [36]. The flowing liquid wall has a variable thickness (ΔR) where Flibe, Flibe + 4%ThF_4, Flibe + 8%ThF_4 or $Li_{20}Sn_{80}$ is considered between the plasma and solid first wall structure. Next, a backing solid wall of 4 cm thickness follows the liquid wall zone. A shielding zone of 50 cm thickness surrounds the backing solid wall for outboard build. It has the structure to breeder (molten salt) ratio of 60/40. At the solid first wall, low activation materials, ferritic steel (9Cr–2V–W–Ta), vanadium alloy (V–4Cr–4Ti) or SiC fiber reinforced SiC composite (SiC_f/SiC) were utilized. There were no changes made at the rest of the blanket. In this study, radiation damage behavior of ferritic steel first wall structure in the APEX reactor using heavy metal molten salts, namely Flibe + 4% ThF_4 or Flibe + 8%ThF_4 to examine the effect of addition of ThF_4 into the Flibe on the radiation damage behavior of ferritic steel and to make comparison with previous study [34] using pure Flibe with ferritic steel solid first wall. Moreover, radiation damage calculations of vanadium alloy V–4Cr–4Ti and SiC/SiC composite first walls were carried out by using the Flibe, Flibe + 4% ThF_4 or Flibe + 8%ThF_4 or $Li_{20}Sn_{80}$ salts in the blanket. Liquid wall thickness was chosen as a variable parameter for the radiation damage calculations.

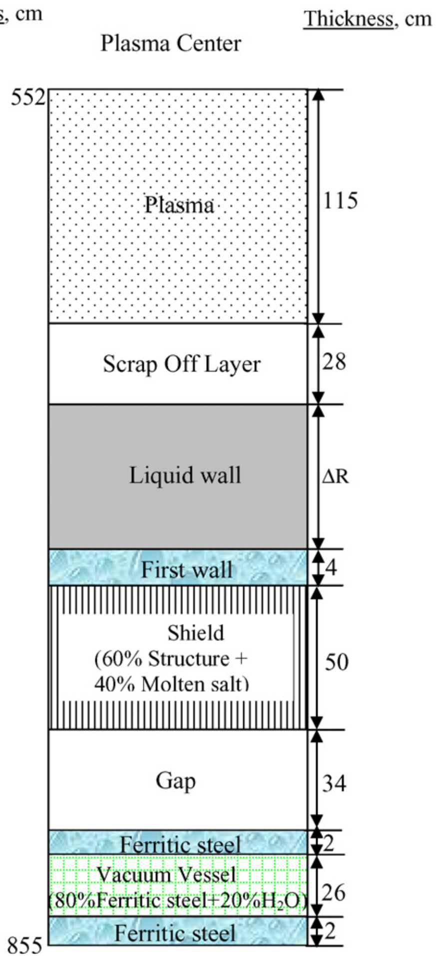

Fig. 2. One-dimensional outboard blanket model for calculation [36].

3. Calculation method

One-dimensional S_N calculations in cylindrical coordinates were performed with the help of the Scale4.3 System using the 238 groups library, derived from ENDF/B-V [37]. The neutron transport calculations were carried out by solving the Boltzmann transport equation with transport code

XSDRNPM [38] in S_8–P_3 approximation by using Gaussian quadratures [39] to obtain the neutron flux at the outer first wall of the investigated blanket.

The resonance calculations in the fissionable fuel element cell were carried out with BONAMI [40] for unresolved resonances and NITAWL-II [41] for resolved resonances. CSAS control module [42] was used to generate the resonance self-shielded weighted cross-sections for XSDRNPM. The numerical output of XSDRNPM was processed with XSCALC [43] to evaluate following reactor data. The highest radiation damage will be expected at outer first wall of the reactor. Therefore calculations were performed under a neutron wall load of 10 MW/m^2 for outboard first wall by using low activation materials and different coolants.

4. Numerical results

The displacement damage and helium generation limits for the structural materials are not certain due to the lack of an intense fusion neutron source at present. For this reason more work is necessary to clarify and define more realistic limit values. In an earlier study [44], higher limits for fusion reactors, namely 300–1000 dpa, were suggested. On the other hand, in more recent studies [29,45] a lower damage limit as 165 dpa was proposed. In this work, a more conservative limit of 100 dpa was chosen. Furthermore, a helium limit of 500 atomic parts per million (appm) was suggested by Blink et al. [45] and Perlado et al. [29]. This limit was also considered as the reference value in helium generation for this study.

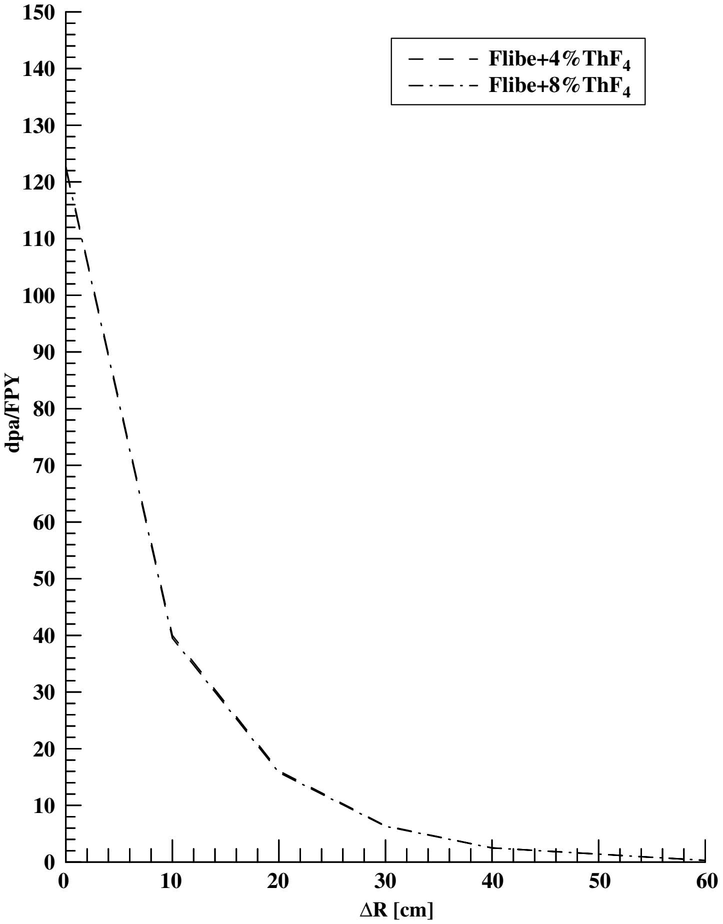

Fig. 3. Displacement damage at the ferritic steel first wall versus Δ*R* for the blanket using Flibe + 4% ThF_4 or Flibe + 8%ThF_4.

4.1. Displacement per atom

Displacement damage at the outer first wall was calculated for the investigated materials. Displacement per atom can be defined as follows:

$$\mathrm{dpa} = \iint \sum_{(n,\mathrm{dpa})} \cdot \Phi \cdot \mathrm{d}E \cdot \mathrm{d}t \tag{1}$$

where,

t = irradiation time,
$\sum_{(n,dpa)}$ = dpa macroscopic cross-section,
Φ = neutron flux,
E = neutron energy.

Fig. 3 shows the dpa rate at the outer first wall with respect to ΔR. It can be seen that the dpa decreases exponentially with the increased liquid wall thickness. The displacement damage is around 122 dpa/FPY when no liquid wall is assumed, but it drops down to 0.3 dpa/FPY when a liquid wall of 60 cm in thickness is used. The curves for the blanket using either the Flibe + 4% ThF_4 or Flibe + 8% ThF_4 are overlapped and no clear difference is observed. Lifetime of first wall can be extended to the reactor lifetime (~30 years) when ~38 cm of liquid wall containing either the Flibe + 4% ThF_4 or Flibe + 8% ThF_4 by taking into account of the dpa damage.

Fig. 4 illustrates the dpa per year at the V–4Cr–4Ti first wall for the blanket using various molten salts. For all case, the dpa decreases exponentially with increased thickness due to exponential softening character of neutron flux during deeper penetration through the blanket. The atomic displacement

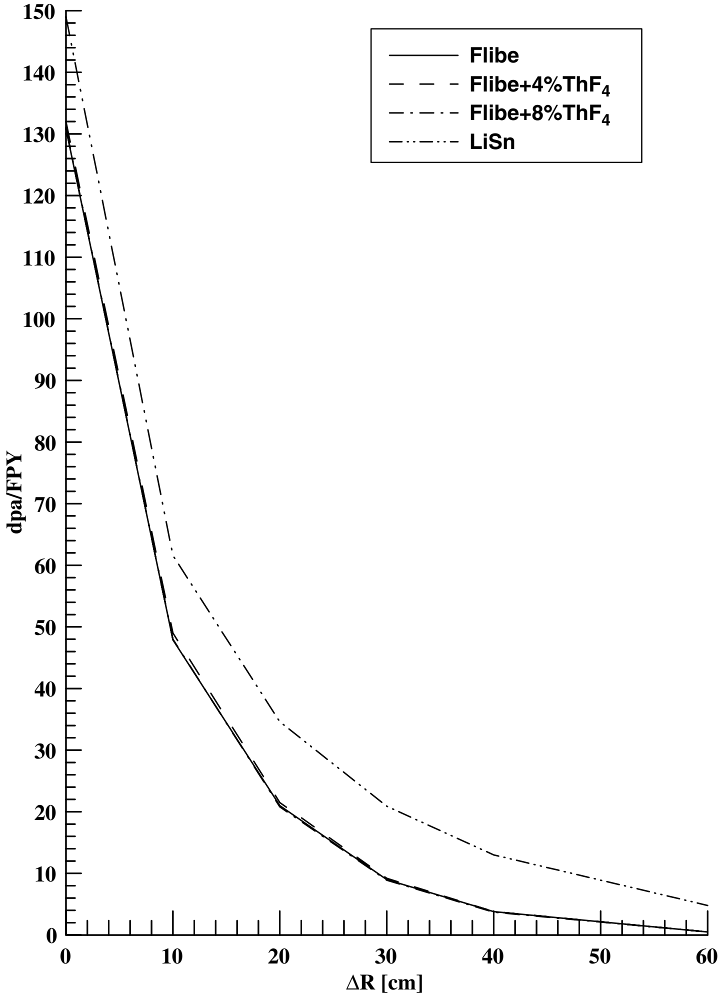

Fig. 4. Displacement damage at the V–4Cr–4Ti first wall versus ΔR for the investigated blanket using various molten salts.

values for the blanket using the Flibe, Flibe + 4% ThF_4 or Flibe + 8% ThF_4 are very close to each other and practically the same. However, at the first wall of the blanket using $Li_{20}Sn_{80}$ higher dpa values are found. Although a ΔR of 43 cm will be enough to satisfy the dpa limit for the blanket using the Flibe or Flibe + ThF_4, a $\Delta R > 60$ cm will be required for that with the $Li_{20}Sn_{80}$ for an operation period of 30 years.

Annual dpa profiles with respect to ΔR for the SiC_f/SiC composite first wall of the blanket with different coolants is represented in Fig. 5. Again, the blanket using the Flibe or Flibe + ThF_4 mixture is more effective in shielding the first wall with respect to the dpa than the $Li_{20}Sn_{80}$. Displacement damage decreases from 94 to 0.4 dpa/FPY when ΔR is increased from 0 to 60 cm for the blanket using the Flibe based salts. It drops from 100 to 3.6 dpa/FPY while a liquid wall of 60 cm in thickness is used for the blanket cooled by the $Li_{20}Sn_{80}$. In this case, a ΔR of ~40 and 60 cm will be necessary not to exceed dpa limit for the blanket using the Flibe based salts or the $Li_{20}Sn_{80}$ during the reactor lifetime of ~30 years, respectively.

4.2. Helium gas production

Helium gas production was calculated in a similar manner given below:

$$\text{He generation} = \int\int \sum_{(n,\alpha)} \cdot \Phi \cdot \mathrm{d}E \cdot \mathrm{d}t \qquad (2)$$

where $\sum_{(n,\alpha)}$is the macroscopic cross-section of helium generation.

Fig. 6 depicts the helium production rate at the ferritic steel first wall per year as a function of ΔR

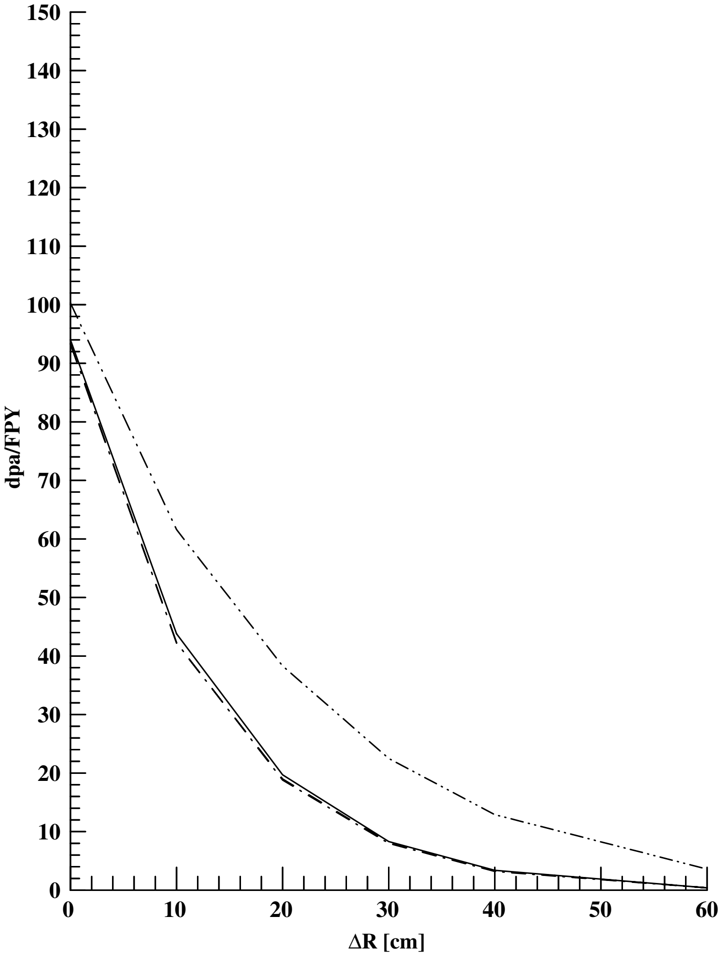

Fig. 5. Displacement damage at the SiC_f/SiC first wall versus ΔR for the blanket using various molten salts (Legend as in Fig. 4).

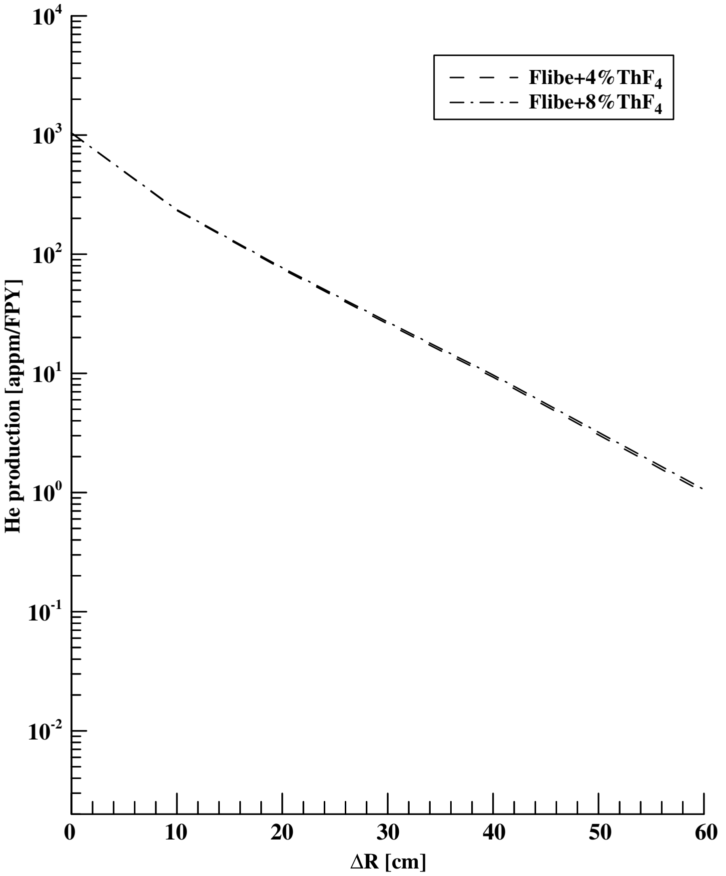

Fig. 6. Helium production rate at the ferritic steel first wall with respect to ΔR for the blanket using Flibe + 4% ThF_4 or Flibe + 8% ThF_4.

for the blanket using heavy metal molten salt (Flibe + 4% ThF_4 or Flibe + 8% ThF_4). The helium generation values decrease significantly with increased ΔR as expected. The helium production rate is ~1040 appm/FPY when no liquid wall is considered. It decreases down to ~1 appm/FPY when a liquid wall of 60 cm is utilized. As in the dpa curves, the helium generation curves are also overlapped. Only slight differences occur.

Fig. 7 shows the annual helium generation (appm/FPY) at the V–4Cr–4Ti first wall versus ΔR for the investigated blanket. It can be observed that the helium generation values decrease drastically with increased ΔR. When no liquid wall is used, the helium production rates at the first wall are ~1014 and 1039 appm/FPY for the blanket using the Flibe based salts or $Li_{20}Sn_{80}$ in the shielding zone, respectively. However, when a liquid wall of 40 cm is used, the helium generation rate drops down to 3.8 and 13 appm/FPY for the liquid wall consisting of the Flibe based salts or $Li_{20}Sn_{80}$, respectively. Even though there is no clear difference between the helium production profiles at V–4Cr–4Ti in the blanket using Flibe based coolants, lower helium generation values were computed for the blanket cooled by $Li_{20}Sn_{80}$. In order to keep the helium generation value below the limit for an operation period of 30 years, a ΔR of ~32 and 28 cm will be required for V–4Cr–4Ti first wall of the blanket using the Flibe based salts or $Li_{20}Sn_{80}$, respectively.

Fig. 8 illustrates helium production rate as a function of ΔR at the SiC_f/SiC first wall. The helium production values decrease sharply with the increased liquid wall thickness. In order to keep the helium generation values lower than the limit for an operation period of 30 years, a liquid wall thickness of ~52 cm and > 60 cm will be needed for the $Li_{20}Sn_{80}$ and Flibe based coolants, respectively.

In radiation damage criteria, both the dpa and helium generation must be considered together. In other words, a structural material must comply with both the dpa and helium production limits. Therefore, ~43 cm of liquid wall thickness would be needed for the ferritic steel first wall to fulfill

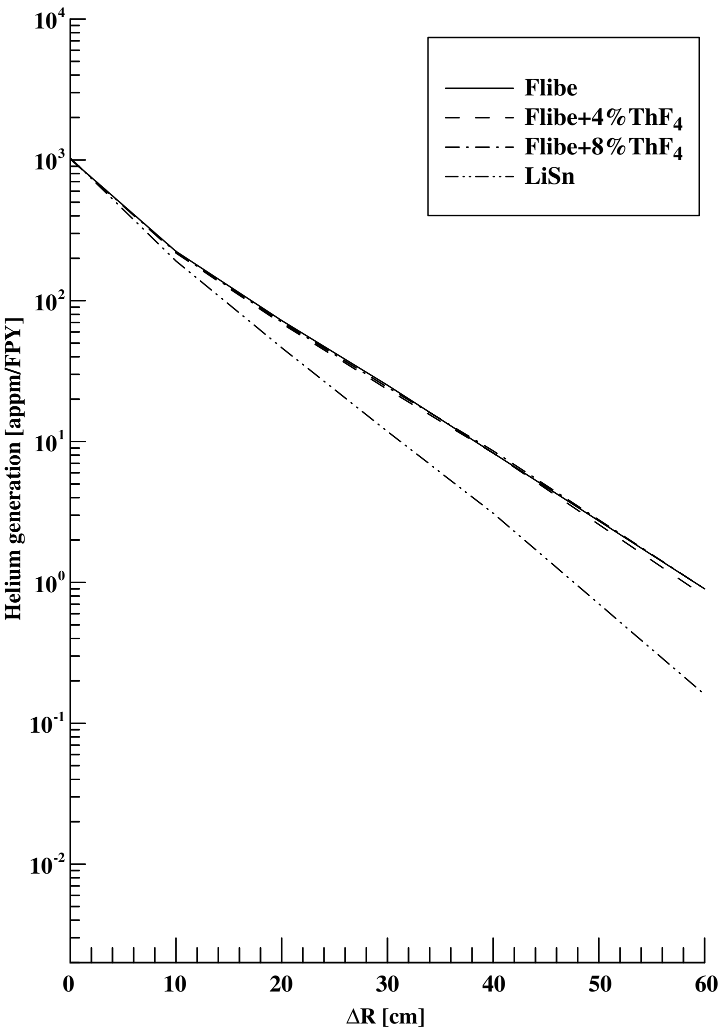

Fig. 7. Helium generation rate at the V–4Cr–4Ti first wall with respect to Δ*R* for the blanket with different coolants.

radiation damage criteria for an operation period of 30 years for the blanket using Flibe + 4% ThF_4 or Flibe + 8% ThF_4.

A first wall made up V–4Cr–4Ti would require a protective liquid wall thickness of ~43 cm and >60 cm for the blanket using the Flibe based coolants and $Li_{20}Sn_{80}$, respectively. If the SiC_f/SiC composite material is used as a first wall, then a liquid wall thickness of ~60 cm and >60 cm would be necessary to satisfy radiation damage criteria during reactor lifetime for the blanket using the $Li_{20}Sn_{80}$ or Flibe based salts, respectively.

5. Discussion

The primary neutrons coming from the fusion plasma dominate on the left side of the flowing liquid wall, whereas secondary neutrons (collided neutrons + fission neutrons) begin to dominate by deeper penetration into the liquid zone. The great reduction of neutron flux in the liquid eliminates a replacement of the first wall during the plant lifetime. When compared to a previous study [34], addition of 4% or 8% ThF_4 into the Flibe did not change the displacement damage and the helium generation values at a ferritic steel first wall practically. Radiation damage at the first wall was slightly affected due to heavy metal fluoride. The increase of heavy metal component along with the decrease of lithium has a mutual compensating effect on neutron absorption with very minor effects on the spectrum. So that, neutron spectrum was almost unchanged for the investigated Flibe based coolants. Furthermore, the same result was also valid for the Flibe

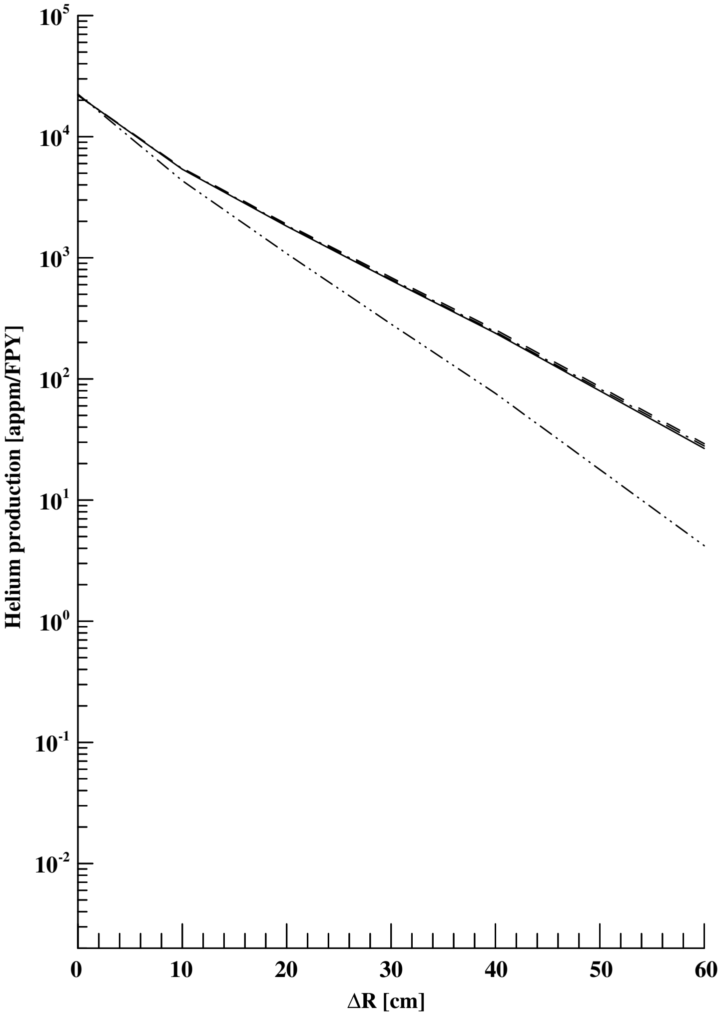

Fig. 8. Helium production rate at the first wall made up SiC_f/SiC composite as a function of ΔR for the blanket (Legend as in Fig. 7).

based coolants when the V–4Cr–4Ti or SiC_f/SiC composite first wall was used.

On the other hand, the Flibe based salts gave the lower dpa values compared to $Li_{20}Sn_{80}$ since the Flibe is very effective in softening the neutron flux by attenuating both high and low energy neutrons. However, they caused the higher helium productions compared to the $Li_{20}Sn_{80}$. This is mainly due to the higher moderation capability of the $Li_{20}Sn_{80}$ on high energy neutrons by both elastic and inelastic collisions of fusion neutrons with Sn atoms.

6. Conclusions

According to the numerical results, the main conclusions can be given as:

- Addition of 4 or 8 mol% ThF_4 into the Flibe salt slightly affected the radiation damage parameters of solid first wall when compared to a previous study [34].
- The best first wall material–coolant couple was the ferritic steel and Flibe based salts among the investigated material–coolant couples.
- Using the Flibe lowered dpa damage values due to its higher neutron flux attenuation characteristics compared to the $Li_{20}Sn_{80}$.
- Lower helium generation values at first wall were found for the blanket using the $Li_{20}Sn_{80}$ compared to that with the Flibe based salts.
- SiC_f/SiC composite exhibited the worst radiation damage performance due to its much higher helium production reaction cross-section.

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