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Activation characteristics of a solid breeder blanket for a fusion power demonstration reactor

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Abstract

Activation characteristics have been assessed for a helium cooled solid breeder blanket on the basis of three-dimensional activation calculations for a 2200 MW fusion power demonstration reactor. FISPACT inventory calculations were performed for the beryllium neutron multiplier, the Li_4SiO_4 breeder ceramics and the Eurofer low activation steel. Neutron flux spectra distributions were provided by a previous MCNP calculation. Detailed spatial distributions have been obtained for the nuclide inventories and related quantities such as activity, decay heat and contact dose rate. These data are available form the authors upon request. On the basis of the calculated contact gamma dose rates, the waste quality was assessed with regard to a possible re-use of the activated materials following the remote or the hands-on handling recycling options.

1. Introduction

The blanket of a future fusion reactor is a key component with the main functions to breed the tritium required for self-sufficiency and to convert into heat the kinetic energy of the neutrons released in the (d,t) fusion reaction. The blanket has to be designed with suitable materials for the breeder, neutron multiplier, structure and coolant arranged in a suitable geometrical configuration to meet the essential objective of tritium-self-sufficiency. The materials are being selected primarily to fulfil their main functions and withstand, at the same time, the mechanical, heat and irradiation loads during reactor operation.

Elemental transmutation and nuclide activation under irradiation deteriorate the material properties and lead to a radiation hazard potential both under normal and off-normal operation conditions. Major sources of the radiation hazard are the tritium and the activation products of the structural material. The activation behaviour of the structural material can be controlled to some extent through the material selection and optimisation of its elemental composition. The development of low activation (LA) structural materials such as the Eurofer steel is being conducted to reduce the amount of activated material mainly with regard to the long-term hazard potential. The use of LA structural materials in the blanket is an essential contribution to the development of environmentally benign fusion power reactors. In this context, the assessment of the material activation is an important safety and environment related issue which requires qualified activation calculations for the complete fusion reactor.

In this paper, we present the activation characteristics of a solid breeder blanket developed in the framework of the European Fusion Technology Programme. The assessement of the activation characteristics is performed on the basis of three-dimensional activation calculations for a 2200 MW fusion power demonstration reactor. The paper includes a short description of the blanket concept and the methodological approach applied in the activation analyses, and discusses the

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activation results and their consequences for the waste management.

2. Blanket concept

The helium-cooled pebble bed (HCPB) blanket [1] has been developed in the framework of the European Fusion Technology Programme with the main objective to design a demo relevant solid breeder blanket [2]. It is characterised by the use of Li_4SiO_4 pebbles as breeder material, beryllium pebbles as neutron multiplier and high pressure helium gas as coolant. Breeder and multiplier are contained in a closed steel box whose plasma facing side is formed by the first wall. The blanket structure consists of an heterogeneous array of alternating beryllium and ceramics pebble bed layers separated by thin cooling plates arranged in toroidal–radial planes. In the reference design, the poloidal thickness of the cooling plates, the beryllium and the ceramics pebble bed layers amounts to 8, 45 and 10 mm, respectively [3]. An advanced version of the HCPB blanket has been recently developed for employment in a fusion power plant [4]. The martensitic–ferritic LA steel Eurofer [5] is employed as the structural material. The required ^{6}Li-enrichment is 40 at.% for Li_4SiO_4 while alternative breeder ceramics such as Li_2ZrO_3 and Li_2TiO_3 would require 75 and 65 at.%, respectively [3].

3. Methodological approach

Three-dimensional computational procedures are required for a reliable assessment of the activation inventory and the derived quantities. A suitable code system has been previously developed to enable activation calculations for a reactor system in full 3D geometry by linking the Monte Carlo transport code MCNP [6] to the inventory code FISPACT [7] through automated interfaces [8].

Neutron flux spectra are calculated with MCNP in the standard VITAMIN-J 175 group structure using a 3D torus sector model of the fusion power demonstration reactor with HCPB blanket modules as shown in Fig. 1. The neutron flux spectra are calculated in all material zones as defined in the MCNP model. They are passed to FISPACT for the inventory calculations in each material zone. FISPACT uses these spectra to collapse the 175 group activation cross sections of the EAF-99 data file [9] into effective one-group cross sections. These are then used to calculate the nuclide inventory and the related quantities for the material and the geometry cell under consideration. This procedure is repeated automatically for all geometry cells and materials of the reactor model. At the end, the individual results are merged to obtain the spatial (radial–poloidal) distribution and the total inventories for all materials and components.

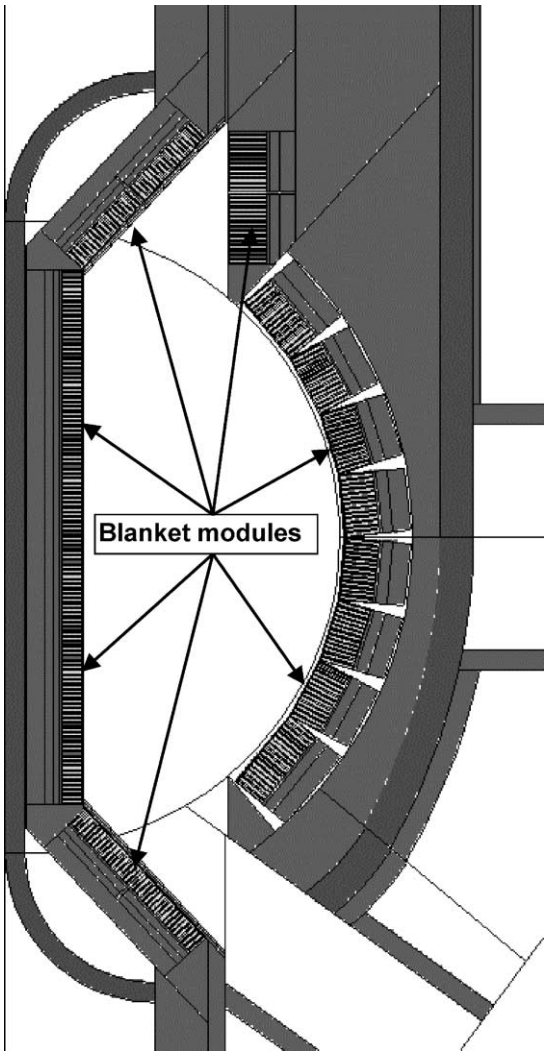

Fig. 1. MCNP model of Demo fusion reactor with HCPB blanket modules (vertical cut).

4. Irradiation conditions

The activation calculations assume a continuous irradiation at 2200 MW fusion power over a period of 20 000 h in accordance with the requirements for the full power lifetime of the demo-relevant blanket. With an average neutron wall load of 2.2 MW/m^2, the resulting first wall fluence is about 5 MWa/m^2.

For activation calculations, it is mandatory to take proper account of tramp elements and impurities of the materials considered. Table 1 displays the elemental composition of the blanket materials Eurofer, beryllium

Table 1
Elemental composition of the materials in the HCPB Demo reactor blanket

Element	Eurofer	Beryllium	Li_4SiO_4
Fe	88.983	0.09	0.0106
Li	–	–	22.345
O	0.010	0.14713	53.302
Be	–	99.583	–
C	0.105		0.113
Ca	–		0.0037
K	–		0.0041
Mg	–	0.03	0.0020
Na	–		0.0020
Si	0.050	0.02	24.179
Mn	0.400		0.00025
P	0.005		–
S	0.005		–
Cr	9.000		0.003
Ni	0.005		0.001
Mo	0.005		–
V	0.200		–
Nb	0.001		–
B	0.001		–
N	0.030		–
Al	0.010	0.04	0.006
Co	0.005	0.001	0.0004
Cu	0.005		0.0003
Zr	–		0.0066
Zn	–		0.0006
Sc	–	0.005	–
Ta	0.070		–
Ti	0.010		0.0206
W	1.100		–
U	–	0.01	–

and the Li_4SiO_4 breeder ceramics as assumed for the activation calculations. The Eurofer composition has been adopted from the specification for Eurofer 97 [5]. Yield data of manufactured Eurofer 97 largely agree with the specified elemental compositions. The elemental compositions of beryllium and Li_4SiO_4 have been recently compiled in the material assessment report on the Be and ceramics breeder pebble beds of the HCPB test blanket module in ITER [10].

5. Activation analysis: calculations, results and discussion

5.1. Activation calculations

The activation calculations were performed with the FISPACT-99 inventory code and EAF-99 activation cross sections [9] making use of the MCNP model demonstration reactor described above. A fine radial–poloidal segmentation scheme was employed to obtain the nuclide inventories for the beryllium neutron multiplier, the Li_4SiO_4 breeder ceramics and the Eurofer LA steel in the different spatial locations of the reactor. The poloidal segmentation scheme consists of nine inboard and eight outboard sections, two sections in the divertor region, each top and bottom, and one section in the upper outboard port region. The radial segmentation scheme consists of 10 segments for the beryllium and the breeder ceramics (breeder zone), and 20 for the Eurofer steel (first wall, breeder zone, back wall, helium pipe connections and manifolds). This results in 220, 220 and 406 material cells for the beryllium, the breeder ceramics and the Eurofer steel, respectively. Accordingly, a total number of 846 FISPACT runs is performed employing in either case the neutron flux spectrum provided by the preceding MCNP calculation for the considered geometry cell.

5.2. Activity inventories and afterheat

The total activity inventories and the afterheat power are displayed in Figs. 2 and 3. It is noted that both the activity and the afterheat power are largely dominated by Eurofer. There is one exception in the time period 10–100 years after shutdown where the activity is dominated by the tritium generated in beryllium through $^9Be(n, t)^7Li$ and the two-step reaction $^9Be(n,\alpha)^6He \rightarrow {}^6Li(n, \alpha)t$. The total tritium inventory accumulated in the beryllium amounts to some 4.4 kg at reactor shut-down. Mass inventories, afterheat power and direct nuclear power generation are displayed in Table 2. The afterheat power at reactor shutdown typically amounts to 1–2% of the nuclear power generation during operation.

5.3. Contact gamma dose rates

The surface gamma dose rate is a suitable quantity to qualify irradiated material for potential waste management strategies. The option of re-using activated fusion reactor material requires that specific dose rate limits must not be exceeded. These have been specified both

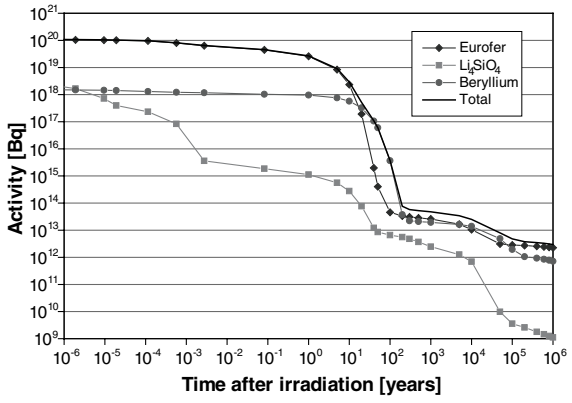

Fig. 2. Activity inventory of the HCPB Demo reactor blanket as function of the cooling time.

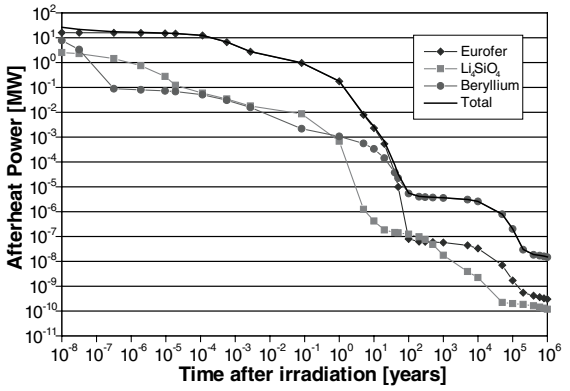

Fig. 3. Afterheat power of the HCPB Demo reactor blanket as function of the cooling time.

Table 2
Mass inventory, afterheat and direct nuclear power generation of the HCPB Demo reactor blanket

	Eurofer	Beryllium	Li_4SiO_4
Mass inventory (t)	1150	306	77
Afterheat power at shutdown (MW)	16.3	7.3	2.47
Direct nuclear power at operation (MW)	957	745	673

for hands-on and remote handling recycling at levels of 10 μSv/h and 10 mSv/h, respectively. Following this strategy, the activated material has to be stored in an interim repository until the dose rate has reached the recycling level. The required wait times are in the order of 50–100 years for the remote handling and hundreds to thousands years for the hands-on recycling option.

For assessing the recycling options for the different materials, the spatial variation of the activation level in the reactor has to be taken into account. To this end, the contact dose rate was calculated for the beryllium, the breeder ceramics and the Eurofer in all 220, 220 and 406 spatial segments, respectively, and then averaged over the total number of cells by using the associated masses as weighting factors. The resulting average contact dose rate is then used as useful quantity for assessing the waste quality when considering recycling options for the activated materials. In addition to the average, we also consider the maximum contact dose rates which is obtained in the reactor zones where the considered material is subjected to the highest radiation level. Figs. 4–6 display the corresponding dose rate graphs for beryllium, the Li_4SiO_4 breeder ceramics and the Eurofer steel, respectively.

It is revealed that a wait time of no more than 50–100 years is required for all materials to ensure the required

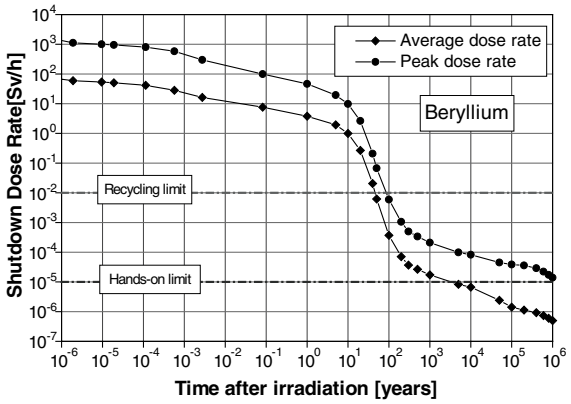

Fig. 4. Shutdown dose rate of beryllium in the HCPB Demo reactor blanket.

dose rate limit when considering remote handling. The associated waste volumes amount to 167, 32 and 148 m^3 of beryllium, Li_4SiO_4 and Eurofer, respectively. Hands-on recycling, on the other hand, appears to be a feasible option for the breeder material whereas prohibitively long wait times would be required for Eurofer and beryllium.

The major contributor to the contact dose rate in the time period up to 50 years after shutdown is ^{60}Co originating from the ^{59}Co impurity. This applies to beryllium, Li_4SiO_4 and Eurofer. A further reduction of the ^{59}Co impurity content would result in shorter recycling times if remote handling is adopted. In the case of Eurofer, ^{94}Nb, originating from the ^{93}Nb impurity (10 wppm) dominates the dose rate for decay times greater than 50 years. The hands-on recycling option for Eurofer is thus affected by the ^{93}Nb impurity content: wait times in the order of 10^4 years are required to reach the 10 μSv/h dose rate limit. For Li_4SiO_4, the long-lived ^{26}Al dominates the contact dose rate at decay times greater than 50 years. It is revealed, however, that a wait time of

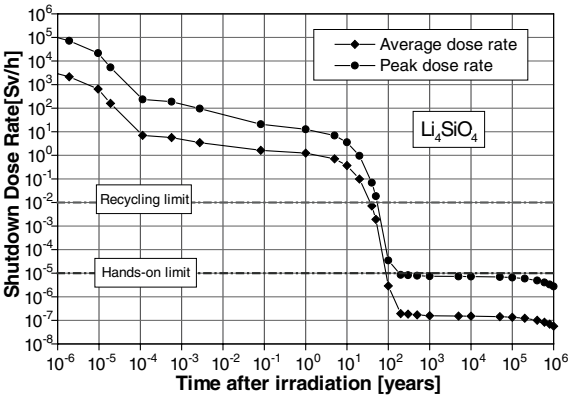

Fig. 5. Shutdown dose rate of Li_4SiO_4 in the HCPB Demo reactor blanket.

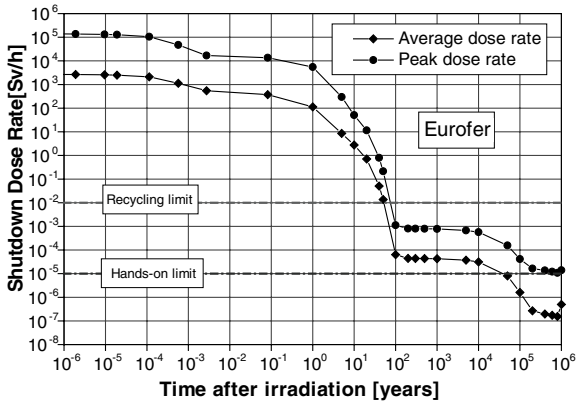

Fig. 6. Shutdown dose rate of Eurofer in the HCPB Demo reactor blanket.

no more than 50–100 years is sufficient for Li_4SiO_4 to enable hands-on recycling. In the case of beryllium, the contact dose rate at decay times greater than 50 years is dominated by fission products and actinides such as ^{137m}Ba and ^{241}Am, respectively, originating from the uranium impurity (100 wppm). Again this affects the hands-on recycling option requiring a wait time in the order of 10^4 years.

6. Conclusion

Activation characteristics have been assessed for a helium cooled solid breeder blanket on the basis of three-dimensional activation calculations for a 2200 MW fusion power demonstration reactor. The activation calculations included 846 FISPACT runs to obtain the nuclide inventory for beryllium, Li_4SiO_4 and the Eurofer in all associated material zones. Neutron flux spectra were provided in the 406 geometry cells of the applied reactor model by a preceding MCNP calculation. Detailed spatial distributions have been obtained for the nuclide inventories and related quantities such as activity, decay heat and contact dose rate. These data have been stored in computer files and are available from the authors upon request.

On the basis of the calculated contact gamma dose rates, the waste quality was assessed with regard to a possible re-use of the activated materials following the remote and the hands-on handling recycling option. It was shown that wait times are required in the order 50–100 years for the remote handling recycling option and hundreds (Li_4SiO_4) to thousands (Eurofer) years for hands-on handling. For all materials considered, the wait time for the remote handling recycling is determined by the ^{60}Co dose rate originating from the ^{59}Co impurity content.

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