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Transmutation and activation analysis for divertor materials in a HCLL-type fusion power reactor

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A B S T R A C T

The activation and transmutation of tungsten and tantalum as plasma facing materials was assessed for a helium cooled divertor irradiated in a typical fusion power reactor based on the use of Helium-cooled Lithium Lead (HCLL) blankets. 3D activation calculations were performed by applying a programme system linking the Monte Carlo transport code MCNP and the fusion inventory code FISPACT through an appropriate interface. Special attention was given to the proper treatment of the resonance shielding of tungsten and tantalum by using reaction rates provided directly by MCNP on the basis of continuous energy activation cross-section data. It was shown that the long-term activation behaviour is dominated by activation products of the assumed tramp material while the short-term behaviour is due to the activation of the stable Ta and W isotopes. The recycling limit for remote handling of 100 mSv/h can be achieved after decay times of 10 and 50 years for Ta and W, respectively. The elemental transmutation rates of Ta and W were shown to be on a moderate level for the HCLL-type fusion power reactor.

1. Introduction

Within the European Power Plant Conceptual Study (PPCS) [1] a helium gas cooled divertor with challenging material performance has been suggested for removing the anticipated heat loads in the order of 10–15 MW/m^2 [2]. The selection of suitable alloys that can withstand the high loads and thermal stresses during operation in a power reactor is a key issue in the engineering design of the divertor. Primary candidates for the divertor tiles are tungsten and tantalum alloys as well as oxide dispersion strengthened (ODS) refractory alloys. Activation issues of different divertor designs and configurations have been recently investigated by Taczanowski et al. [3]. In this work, the activation and transmutation characteristics of tungsten and tantalum are assessed as materials of the plasma-facing divertor tiles employed in a fusion power reactor (FPR) based on the HCLL (Helium-cooled Lithium–Lead) conceptual design of the PPCS reactor. A dedicated computational approach has been applied which enables coupled 3D neutron transport and activation calculations as required for a reliable assessment of the divertor activation in a real FPR configuration.

2. Computational approach

A code system for activation calculations in full 3D geometry has been previously developed by linking the Monte Carlo transport code MCNP [4] to the fusion inventory code FISPACT [5] through an appropriate (automated) interface [6]. Neutron flux spectra are calculated with MCNP5 in a standard 175 energy group structure using nuclear cross-sections from the Fusion Evaluated Nuclear Data Library FENDL-2.1 [7] and a dedicated model of a HCLL-type PPCS reactor with integrated helium cooled divertor. The neutron flux spectra are calculated in the material zones of the divertor as specified in Section 4 below. FISPACT uses these spectra to collapse the 175 group activation cross sections from the recent FENDL-2.1 activation data library [8] into effective one-group sections. These are then used to calculate the nuclide inventories and related quantities for the material and geometry cell under consideration. Special attention is given to the proper treatment of the resonance shielding of tungsten and tantalum by using reaction rates provided directly by MCNP on the basis of continuous energy activation cross-sections.

3. Helium cooled divertor outline

A vertical cut of the helium cooled divertor design is included in Fig. 1. The plasma-facing surface of the divertor consists of hexagonal tiles made of tungsten (or tantalum) serving both as thermal shield and erosion layer. These tiles are brazed to a thimble forming a cooling finger unit. Each finger is cooled with high pressure He supplied through a manifold system. The cooling finger units are fixed to the front plate of the supporting structure made of ODS reduced activation ferritic steel.

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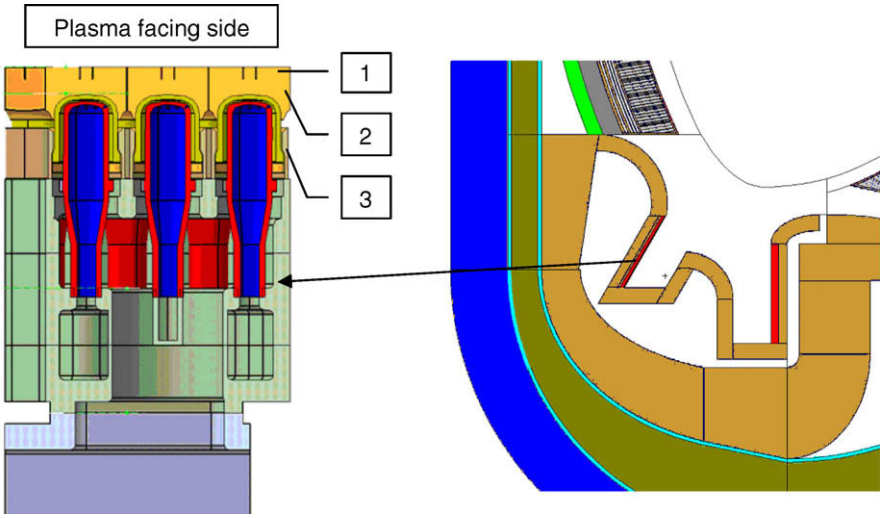

Fig. 1. Sketch of the modular multiple-jet design for a helium cooled divertor (left) [2] and section of the HCLL reactor model for MCNP calculations showing the divertor region with the plasma target plate indicated (right). The three zones for which the neutron flux spectra and the activation were calculated are marked (left).

4. MCNP model

A suitable MCNP model of a 20° HCLL PPCS reactor (4000 MW fusion power) torus sector with integrated gas cooled divertor was developed in the frame of the PPCS study. This model was adapted to the requirements for coupled 3D neutron transport and activation calculations of the divertor, see Fig. 1 for a vertical cut. The engineering design model of the divertor was simplified for the neutron transport calculations with MCNP assuming four homogenised layers: a plasma-facing layer for the tiles (6 mm thickness), a layer representing the finger units (44.6 mm) and two layers representing the in- and outlet helium supply manifolds (28 and 78.5 mm, respectively). The homogenised material composition of each layer has been calculated on the basis of the volume fractions as given in the engineering CAD design model.

5. Material composition for activation calculations

The activation behaviour of materials under irradiation is affected to a large extent by impurities and other minor elements. For the activation and transmutation calculations, it is therefore mandatory to take proper account of impurities and minor constituents of the materials considered. Table 1 show the chemical compositions assumed in this work for the plasma-facing protecting layers made of tungsten or tantalum. The elemental compositions shown are based on specifications by a commercial manufacturer of tungsten [9] and tantalum [10].

6. Activation and transmutation calculations

The activation calculations for the divertor materials were performed with the FISPACT inventory code assuming a continuous irradiation time of one calendar year. Decay times were considered from 1 s to 1×10^6 years after irradiation. Special attention was given to a proper treatment of neutron capture reactions such as $^{186}W(n,\gamma)^{187}W$ and $^{181}Ta(n,\gamma)^{182}Ta$. The nuclear cross-sections of these reactions show very pronounced resonances which cannot be represented in the 175 group structure without taking into account resonance self-shielding in an appropriate way. To this end, the $^{186}W(n,\gamma)$ and $^{181}Ta(n,\gamma)$ reaction rates were calculated directly with MCNP using continuous energy nuclear cross sections. Thus the resonance shielding is properly taken into account. The reaction rates provided by MCNP were then passed to FISPACT via the input files thus overwriting the incorrect reaction rates calculated by FISPACT on the basis of group cross-sections.

Due to the pronounced resonances for neutron induced reactions in Ta and W, the neutron flux spectrum, and thus the reaction rates, can vary very rapidly with the radial depth. To take into account this effect, neutron flux spectrum and activation calculations were performed for three different zones as indicated in Fig. 1. The zones have thicknesses of 1, 1 and 2 mm, respectively. These zones were selected to encompass the full range of possible responses in

Table 1
Chemical composition of tungsten and tantalum according to the specifications by Plansee SE [8,9].

Element	Tungsten (μg/g)	Tantalum (μg/g)
Ag	10	–
Al	15	–
As	5	–
Ba	5	–
Ca	5	–
Cd	5	10
Co	10	–
Cr	20	10
Cu	10	–
Fe	30	50
K	10	–
Mg	5	–
Mn	5	–
Na	10	–
Nb	10	100
Ni	5	50
Pb	5	10
Ta	20	99.94%
Ti	5	10
Zn	5	–
Zr	5	–
Mo	100	50
W	99.96%	20
C	30	50
H	5	15
N	5	50
O	20	150
P	20	–
S	5	–
Si	20	50
Hg	–	10

Table 2
Transmutation rates for tungsten and tantalum (at%/year) at the three different divertor locations shown in Fig. 1.

Location	W	Ta
1	0.70	1.48
2	0.59	1.21
3	0.63	1.29

the tungsten/tantalum layer. The first zone is at the front of the tiles (0–1 mm), the second zone is located at 5–6 mm depth and the third one at 16–18 mm from the surface.

Table 2 shows the transmutation rates calculated for tungsten and tantalum in the three different divertor zones. The transmutation rates for tantalum are about two times higher than for tungsten because of the higher neutron absorption of Ta in the resonance region of the (n,γ) reactions. Note that the differences of the transmutation rates in the different zones are only minor. This is due to the fact that both the neutron spectra and the flux levels do not differ very much for these locations, see Fig. 2. There is just a slight decrease of the transmutation rates from zones 1 to 2 according to the neutron flux reduction and a slight increase from zones 2 to 3 due to the spectral degradation resulting in a higher effective capture cross-section. Actually, the transmutation rates depend in a very sensitive way on the shape of the neutron spectrum. Significantly higher transmutation rates are expected for a FPR with a beryllium containing solid breeder blanket such as the Helium-cooled Pebble Bed (HCPB) blanket [11]. The neutron spectrum in such a configuration is much softer thus enhancing the neutron captures in the resonance region and, consequently, the transmutation rates in W and Ta.

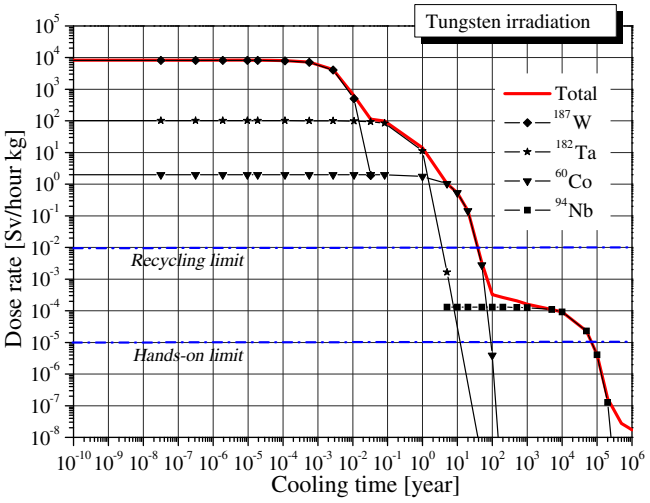

Fig. 4. Specific contact dose rate of tungsten in zone 1 of the divertor.

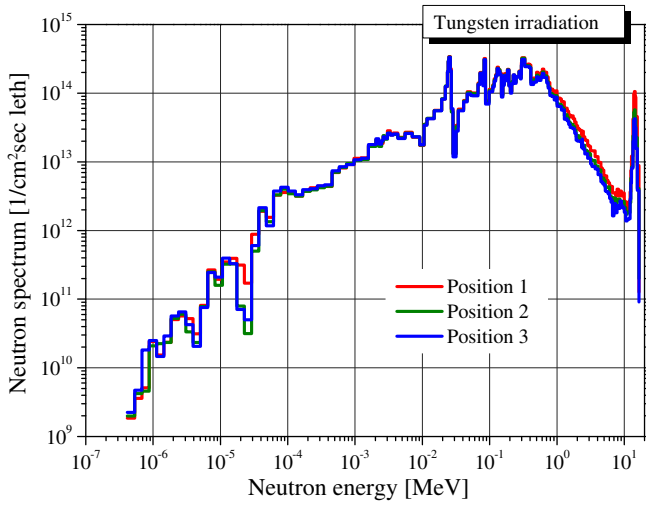

Fig. 2. Neutron spectra at different locations in the tungsten protection layer of the divertor.

Results of the FISPACT activation calculations are shown in Figs. 3 and 4 for tungsten irradiated in the first zone of the divertor. The tungsten specific activity is dominated by radioactive W isotopes until about 1 year decay time. The long term activity is mainly due to the activation of tramp elements (^{60}Co, ^{93m}Nb). Only four radio-nuclides contribute significantly to the contact dose rate, namely: ^{187}W and ^{182}Ta, ^{60}Co, ^{94}Nb coming from impurities. The recycling limit for the irradiated tungsten is achieved after about 50 years of decay time.

It is noted that both considered materials, W and Ta, are very effective neutron absorbers due to their pronounced resonances in the neutron capture reaction cross-sections. Fig. 5 compares the neutron spectra for both materials in the plasma facing layer.

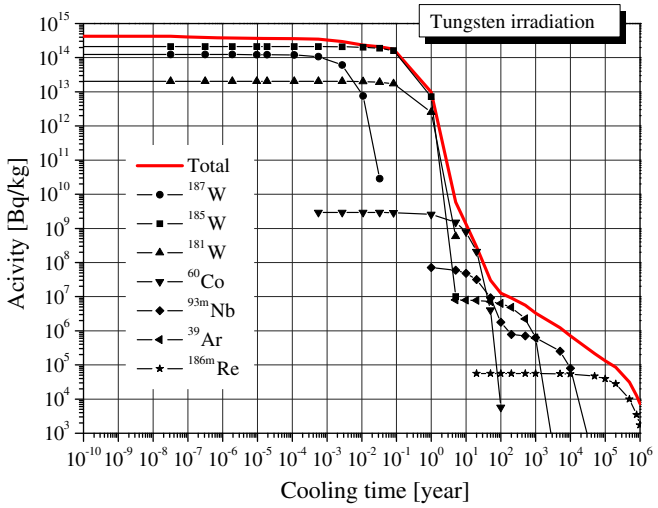

Fig. 3. Specific activity of tungsten in zone 1 of the divertor.

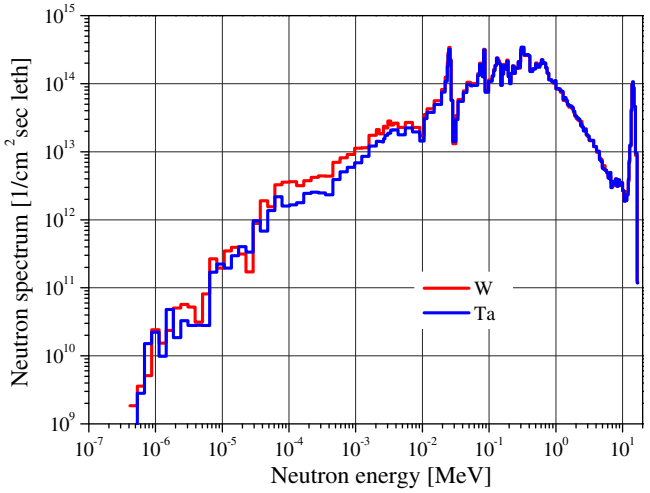

Fig. 5. Neutron spectra for tungsten and tantalum in zone 1 of the divertor.

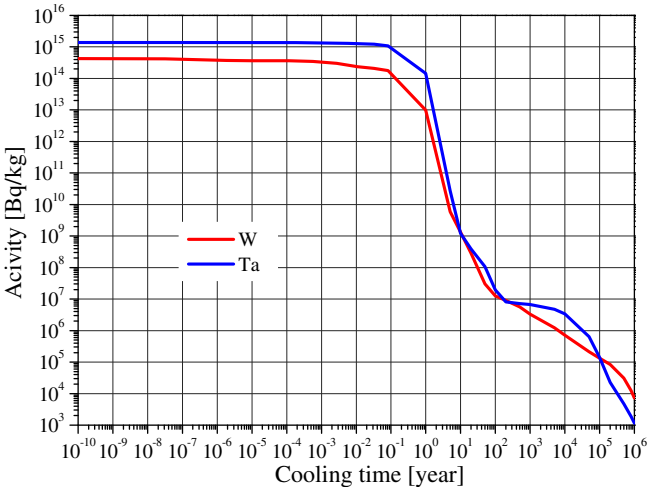

Fig. 6. Specific activities of tungsten and tantalum in zone 1 of the divertor.

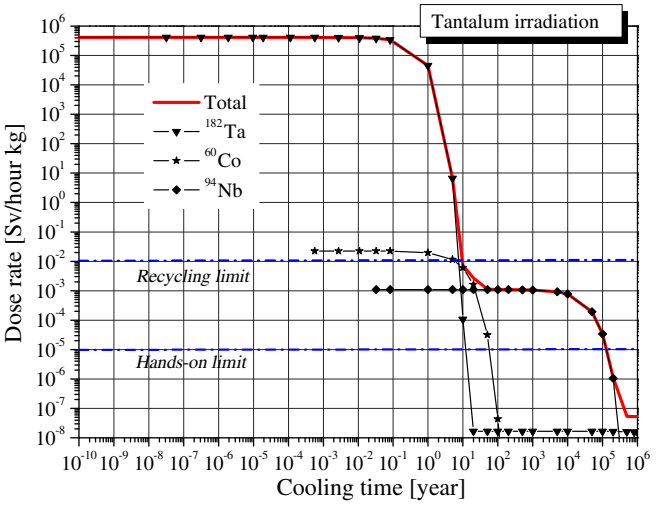

Fig. 8. Contact dose rate of tantalum in zone 1 of the divertor.

In the energy range below 100 keV, tantalum shows a higher neutron absorption than W as can be taken from the lower neutron populations in this energy domain. For decay times up to one year, the specific activity of tantalum is about three times higher as compared to tungsten, see Fig. 6. Only three radio-nuclides contribute significantly to the he total tantalum activity: ^{182}Ta, ^{93m}Nb and ^{94}Nb, see Fig. 7. The contact dose rate of tantalum is dominated by the two radio-nuclides ^{182}Ta and ^{94}Nb, see Fig. 8. The first nuclide dominates the contact dose rate until one year decay time while the second one is responsible for the long-term dose rate of tantalum. Note that the recycling limit for Ta is already achieved after 10 years decay time.

7. Summary

The activation and transmutation of tungsten and tantalum as plasma facing materials was assessed for a helium cooled divertor irradiated in a typical fusion power reactor based on the use of Helium-cooled Lithium Lead (HCLL) blankets. 3D activation calculations were performed by applying a programme system linking the Monte Carlo transport code MCNP and the fusion inventory code FISPACT through an appropriate interface. Use was made of a fusion power reactor model with integrated helium cooled divertor developed in the frame of the European Power Plant conceptual study (PPCS) for MCNP calculations. Special attention was given to the proper treatment of the resonance shielding of tungsten and tantalum by using reaction rates provided directly by MCNP on the basis of continuous energy activation cross-section data. It was shown that the long-term activation behaviour is dominated by activation products of the assumed material impurities while the short-term behaviour is due to the activation of the stable Ta and W isotopes. The recycling limit for remote handling of 100 mSv/h can be achieved after decay times of 10 and 50 years for Ta and W, respectively. The elemental transmutation rates of Ta and W were shown to be on a moderate level for the HCLL-type fusion power reactor. The maximum transmutation rates amount to 1.5 and 0.7 at.% for Ta and W, respectively. Significantly higher transmutation rates are expected for a power reactor with a beryllium containing solid breeder blanket resulting in a softer neutron spectrum.

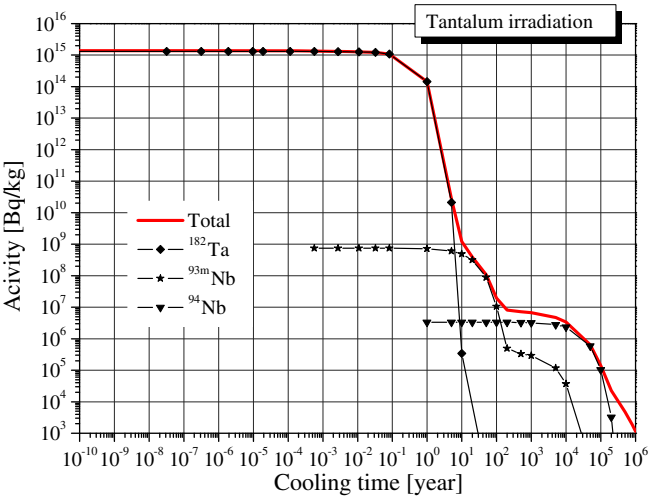

Fig. 7. Specific activity of tantalum in zone 1 of the divertor.

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