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Activation properties of tungsten as a first wall protection in fusion power plants

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Abstract

Tungsten is a candidate material for protective armour on the plasma-facing first wall of a fusion power plant. In order to assess the radiological implications of this use of tungsten, two power plant models from the European Power Plant Conceptual Study (PPCS) have been extended by the addition of a 2 mm tungsten layer on the ferritic–martensitic first wall. Neutronics and activation modelling have shown that there is no significant impact on the favourable conclusions regarding long-term disposal of materials, but that earlier activity levels could potentially be of importance on the timescale of maintenance operations. The short-term activity and decay are expected to have only a minor impact on the consequences of postulated accidents.

Keywords: Neutron activation; Tungsten; First wall armour; Dose rate; Decay heat; Fusion power plant

1. Introduction

Studies of future fusion power plant design concepts in the European Power Plant Conceptual Study (PPCS) [1] have been based on four design concepts. Three of these assume as structural material the reduced activation ferritic–martensitic steel Eurofer. This material is employed as blanket structure, including the plasma-facing first wall surface. It may be desirable to protect this Eurofer surface from erosion by provision of a protective armour layer, either as a coating or as tiles. One candidate for such armour is tungsten, attractive by virtue of its expected low sputtering and erosion rate. But exposure to a high flux of 14 MeV neutrons from the plasma, as well as lower energy neutrons returning from the blanket after moderation, raises the issue of activation of this tungsten layer and the possibility of radiological consequences.

In this work, the neutron activation has been calculated in a tungsten-armour layer added to two of the PPCS plant models, and the implications for safety, environmental impact and operation are assessed. The

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two models, labelled Plant Models A and B in the PPCS study are chosen to represent a water-cooled and a helium-cooled concept, in order that any influence of the different blanket neutron spectra can be observed.

2. Calculations performed

The activation behaviour of a 2 mm-thick layer of tungsten has been studied by extending existing neutronic models of PPCS Plant Models A and B. Both assume Eurofer structure, which will have a similar influence on the neutron spectra in the vicinity of the first wall for both models, but whereas Model B has helium-cooled first wall and blanket, Model A is water-cooled, which could lead to a softer neutron spectrum through greater moderation.

The neutronics calculations were performed with the MCNP code (version 4C3) and ENDF/B-VI cross section data, using 3D models previously generated for PPCS safety and environmental analyses using the in-house HERCULES code system [2], as illustrated in Fig. 1. An additional layer of tungsten, 2 mm thick, was added on the plasma-facing surface of the entire first wall, divided into poloidal sectors as with the rest of the geometrical model. For both Models A and B, the neutron flux spectra in all these tungsten armour cells were computed in 175 energy groups, and transferred to the FISPACT neutron activation code for the inventory calculations, with EAF-2003 activation cross section data in the EASY-2003 system [3]. In the FISPACT calculations, the tungsten composition was assumed to include a full set of impurities, as shown in Table 1.

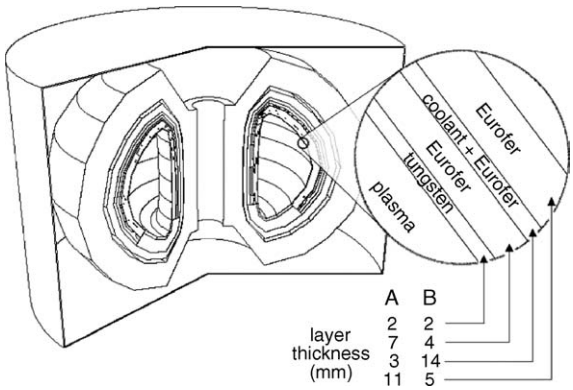

Fig. 1. Illustration of the model geometry with the thicknesses of first wall layers for Plant Models A and B.

Special care was taken to correctly calculate the contribution of the reaction $^{186}W(n,\gamma)^{187}W$, which has

Table 1
Assumed composition of tungsten with impurities

Element	wt.%	Element	wt.%	Element	wt.%	Element	wt.%
H	1.00E−02	Ti	1.00E−02	Ru	1.00E−03	Dy	5.00E−05
He	1.00E−02	V	1.00E−02	Rh	3.00E−04	Ho	4.00E−05
Li	1.00E−04	Cr	1.00E−02	Pd	1.00E−03	Er	1.00E−03
Be	6.00E−03	Mn	6.00E−03	Ag	5.00E−04	Tm	1.00E−02
B	2.00E−03	Fe	7.00E−03	Cd	5.00E−04	Yb	1.00E−02
C	6.00E−02	Co	3.00E−03	In	1.00E−02	Lu	1.00E−03
N	9.00E−04	Ni	1.00E−03	Sn	5.00E−03	Hf	2.00E−03
O	1.00E−01	Cu	2.00E−03	Sb	1.00E−02	Ta	2.00E−03
F	3.00E−03	Zn	1.00E−02	Te	1.00E−04	W	9.94E+01
Ne	1.00E−02	Ga	1.00E−02	I	1.00E−02	Re	3.00E−02
Na	4.00E−03	Ge	1.00E−02	Xe	3.00E−03	Os	2.00E−02
Mg	1.00E−02	As	1.00E−02	Cs	6.00E−04	Ir	1.00E−03
Al	1.00E−04	Se	1.00E−03	Ba	1.00E−02	Pt	9.00E−04
Si	1.00E−02	Br	1.00E−02	La	1.00E−02	Au	1.00E−02
P	1.00E−02	Kr	1.00E−03	Ce	1.00E−02	Hg	1.00E−02
S	1.00E−02	Rb	1.00E−02	Pr	1.00E−02	Tl	3.00E−03
Cl	2.00E−03	Sr	1.00E−02	Nd	1.00E−02	Pb	5.00E−03
Ar	1.00E−02	Y	1.00E−02	Sm	7.00E−04	Bi	5.00E−05
K	7.00E−05	Zr	8.00E−04	Eu	5.00E−05	Th	5.00E−05
Ca	5.00E−05	Nb	5.00E−04	Gd	1.00E−03	U	5.00E−05
Sc	1.00E−02	Mo	4.00E−03	Tb	5.00E−05		

a giant resonance at about 20 eV. Due to resonance self-shielding, the use of multigroup cross sections and group fluxes is likely to lead to an over-estimation of ^{187}W production via this resonance capture. To ensure a correct evaluation, the ^{186}W(n,γ) reaction rate was computed directly in the MCNP continuous-energy calculation, and this value transferred to the FISPACT code for the inventory calculation. The magnitude of the effect is geometry-dependent, with thicker tungsten regions leading to more pronounced self-shielding; nevertheless, even in a 2 mm layer, the effect was found to be significant.

A comparison was made of the total activation results for tungsten with this correct procedure and with a purely multigroup calculation. Fig. 2 shows the factor by which three results for Plant Model A tungsten armour have been affected, i.e. this is the factor by which these results would have been over-estimated if the proper treatment of resonance self-shielding had not been done. At early times, the results are over-estimated due to over-production of ^{187}W, even though this is only one of many nuclides contributing to the total results. The over-estimation of gamma dose-rate and decay heat is initially more than 50%, and falls to zero after a few days. At later times, the effect becomes even more important. After about 500 years, the factor rises until the activity is over-estimated by more than 100%. This is also due to the over-prediction of ^{187}W, and thereby to that of ^{186m}Re via a multi-step reaction. ^{187}W β-decay leads to ^{187}Re(n,2n)^{186m}Re, and this metastable state has a 2×10^5 year half-life.

In the FISPACT calculations, the irradiation history assumed that the first wall lifetime is five full power years—the armour was also assumed to be exposed for this period. At the end of the first 2.5 years operation, there is a shutdown for 2 months for divertor replacement, followed by a further 2.5 years operation. After the end of this lifetime, the inventory, activation and all related quantities were calculated at decay times from 1 s up to 10,000 years.

3. Results

3.1. Activation results

The specific activity of the tungsten material after the end of operation is shown in Fig. 3 for both Plant Models A and B. For comparison, this figure also shows results obtained previously for PPCS Plant Model D, which assumes silicon carbide composite blanket structure and first wall, and includes 2 mm tungsten armour as standard.

The gamma dose-rate in contact with the tungsten material, evaluated by FISPACT using an approximate formula for a semi-infinite slab, is plotted in Fig. 4. For comparison, similar calculations were performed with no armour, and the results for the bare plasma-facing Eurofer in Plant Model A are also shown (Model B results, not plotted, are almost coincident). This dose rate is an important parameter in the criteria for categorisation of active material at end of life (see next

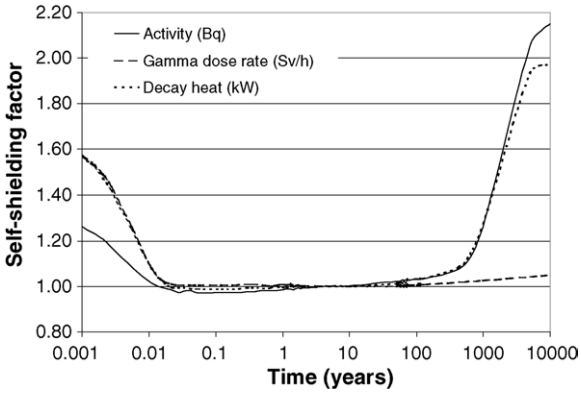

Fig. 2. Factor by which activation results are over-estimated if resonance self-shielding is not correctly allowed for in tungsten armour of Plant Model A.

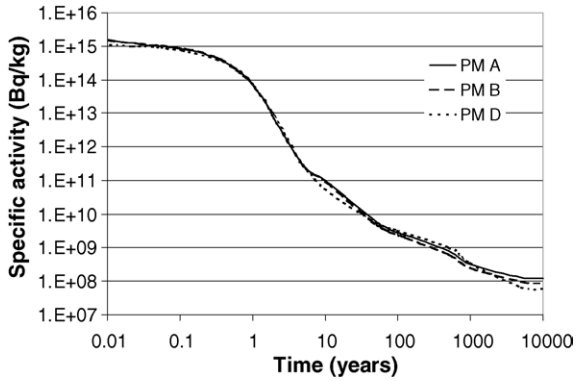

Fig. 3. Specific activity in tungsten armour of Plant Models A, B and D at the outboard mid-plane position (where the values are maximum).

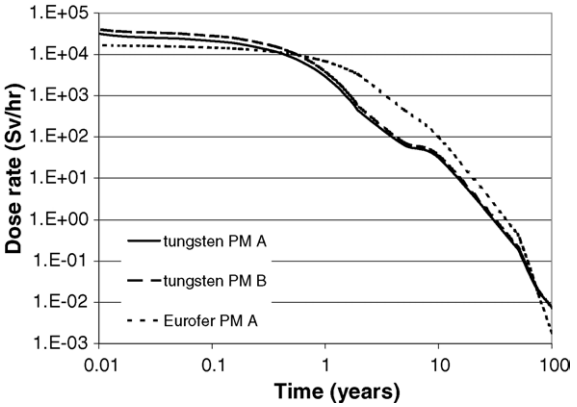

Fig. 4. Contact gamma dose-rate of tungsten armour of Plant Models A and B, and of Eurofer in Plant Model A with no armour.

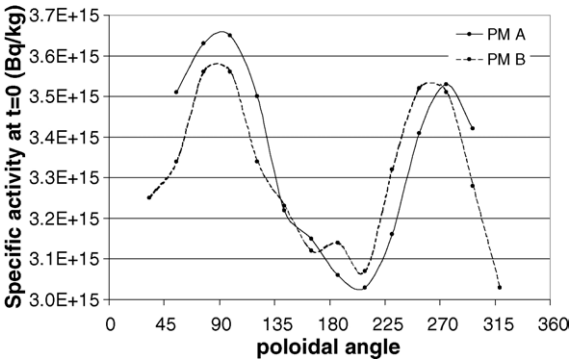

Fig. 6. Poloidal variation of initial tungsten armour activity in Plant Models A and B. Relative variation at later times is similar. *Note*: angle 90° = outboard mid-plane, angle 180° = vertically upwards, angle 270° = inboard mid-plane.

section), and the very high dose rate at early times could also have an impact on maintenance operations. The contact gamma dose rate is above 10,000 Sv/h for around 6 months after shutdown, which could be a challenge for some remote handling equipment. Although this result for tungsten is initially around three times that for Eurofer, beyond this 6 months point it falls to lower values—however, this is too late to be of benefit for maintenance procedures.

The decay heat density of the tungsten after the end of operation is shown in Fig. 5 for both Plant Models A and B. For the first 12 h, the value is between 0.2 and 0.3 kW/kg, compared with about 0.1 kW/kg in the Eurofer first wall itself. The small additional heat in this thin tungsten layer is unlikely to promote significantly

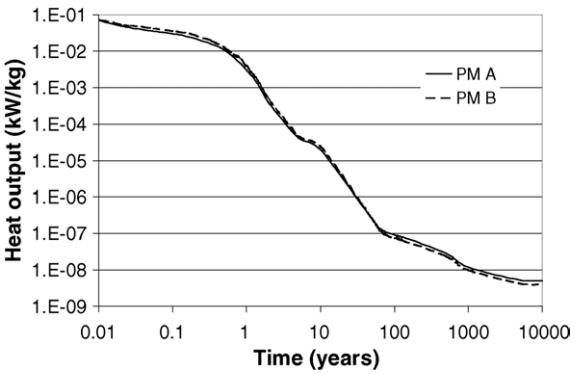

Fig. 5. Decay heat density in tungsten armour of Plant Models A and B at the outboard mid-plane.

higher temperatures in postulated loss-of-coolant accidents, but this will be confirmed in future work. In accident scenarios, which postulate a release of material from within the vessel, dust generated from the plasma-facing tungsten could be a part of the source term. The three times higher dose from tungsten compared with Eurofer at early times after shutdown, as noted above, could be important to potential consequences. The calculated biological hazard through inhalation is higher by a similar factor, with a dose after 1 day of 1.78 Sv/mg of tungsten compared with 0.55 Sv/mg of Eurofer. But since in-vessel dust is only one component of the total source term in postulated accidents [4], this increase is expected to have only a minor impact on the overall consequences.

A notable feature of all these results, Figs. 3–5, is that the values for Plant Models A and B are very similar. In Fig. 3, the earlier results for the tungsten armour of model D are also shown, and these too are close to those of A and B. This illustrates that details of the neutron spectra in the blanket have little influence on the activation of tungsten armour.

Figs. 3–5 each show maximum values from the poloidal distribution, which occur at the outboard mid-plane. At other poloidal locations, the values are a little lower, dropping by 14% (Model A) or 17% (Model B) to a minimum near the top of the torus. The poloidal distributions of the specific activity at time zero are shown in Fig. 6, for both Plant Models. The shape of this distribution is similar at later decay times, as are

those of the distributions of the other quantities, dose rate and decay heat.

3.2. Waste categorisation

Based on the results of the activation calculations presented above, it is possible to categorise the active tungsten according to the criteria adopted in PPCS and earlier European studies [5]. These define categories for non-active waste (below clearance limits), simple and complex recycling material, and permanent disposal waste. The clearance level is never reached by the tungsten armour material and the simple recycling level only after several hundreds of years. So the only relevant categories are complex recycling material and permanent disposal waste. The material is categorised for permanent disposal, if the contact gamma dose-rate is above 20 mSv/h or the decay heat is above 10 W/m^3. These limits are somewhat arbitrary, and the 20 mSv/h limit is now believed to be conservative, but it has been adopted by PPCS in common with earlier European fusion safety and environmental assessments [5], pending a re-evaluation.

The tungsten armour falls below the 20 mSv/h level after about 75 years (Fig. 4) and the decay heat below 10 W/m^3 (in tungsten, 5×10^{-7} kW/kg), before 50 years (Fig. 5), so it is the gamma dose rate, not the heat output, that determines the time at which recycling becomes a possibility on the adopted criteria. The breakdown of the categorisation of tungsten material from each Plant Model, at 50 and 100 years after end of plant life, is given in Table 2. These masses include all tungsten removed at each routine blanket replacement during operation.

Table 2
Categorisation of mass (tonnes) of tungsten armour material after end of plant life

	Plant Model A		Plant Model B	
	50 years	100 years	50 years	100 years
Permanent disposal waste				
Inboard	86	0	81	0
Outboard	187	0	180	0
Total	273	0	261	0
Complex recycling material				
Inboard	11	97	5.5	86
Outboard	9.2	196	2.4	183
Total	20	293	7.9	269

The total mass of tungsten, less than 300 tonnes, is only a relatively minor addition to the total masses of material arising from Plant Models A and B. The presence of the 2 mm tungsten armour has an insignificant effect on the activation levels in other components due to neutron absorption in the tungsten itself; comparison of the MCNP results with and without the armour layer showed that the total neutron flux at the back of the first wall is reduced by just 0.7%, when the tungsten is added.

4. Conclusions

The addition of a 2 mm tungsten armour layer to the plasma-facing surface of the Eurofer first wall has been analysed for its neutron activation behaviour. The decay heat in the short term (∼1 day) following shutdown is modest, and unlikely to give rise to any problems in postulated accidents. The relatively high activity at these early times may be significant for accident scenarios in which in-vessel dust, formed mainly of material from the plasma-facing surface, is a potential source term. The dose rates from tungsten armour, both direct and through inhalation, are initially around three times higher than those from an equivalent mass of Eurofer first wall exposed without tungsten armour.

For the first few months after shutdown, the contact gamma dose rate remains relatively high, but falls below that of Eurofer after 6 months. The high dose at the times that maintenance operations would be in progress could conceivably be an issue for some remote handling equipment that is sensitive to operation in a radiation field.

After the end of plant life and up to 50 years later, the activation properties of the tungsten material are such that only a small proportion is categorised as suitable for recycling. But some 75 years after end of plant life, all of the tungsten material has a contact gamma dose-rate that has fallen below the 20 mSv/h level, allowing it to be categorised as complex recycling material. A key outcome of the earlier studies in PPCS was that for all four Plant Models, there is no material requiring permanent disposal after 100 years [1], as all active material from operation of the plant has fallen into one of the recycle categories by this time. These new results show that the addition of tungsten armour does not alter this important conclusion.

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