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Abstract

Fusion devices offer the great advantage that the main source of radioactivity is generated from the activation of the plasma surrounding components (first wall, blanket and divertor). This process is dependent on the careful selection of the irradiated materials, alloying elements and impurities, which could effectively influence the radioactive inventory in any fusion device. It is crucial to limit the volume of materials that ultimately become classified as radioactive, long-lived waste, requiring long-term storage or disposal in a deep geological repository. This will be important in order to reduce the burden on future generations and to maintain a positive perception of fusion in competition with other energy sources.

Tungsten and its alloys are currently considered as prime candidates for plasma facing components in many fusion experimental devices and power plants, but some issues regarding the environmental impact of these materials remain to be clarified. This study addresses the activation of seven candidate structural W alloys (W-W composites, W-La_2O_3, W-TiC, W-Ta, W-K, VM-W and W-Re) that could be used for W-based divertors. We examined these alloys as well as W armors under the operating conditions of the international ITER experimental facility, the US ARIES-ACT power plant, and the EU PPCS power plant, assessing the waste management options (disposal, recycling, and clearance) and the sensitivity of W transmutation to soft and hard neutron spectra of several divertor and blanket concepts.

1. Introduction

ITER (International Thermonuclear Experimental Reactor) [1], currently under construction in France, aims to demonstrate the scientific and technologic feasibility of energy production from fusion. This machine is expected to produce an amount of energy from fusion reactions ten times greater than the energy used to initiate it. If ITER is successful, it will pave the way to a more evolved generation of fusion devices. The PPCS (Power plant conceptual studies) in Europe [2] and ARIES (Advanced Research Innovation and Evaluation Study) in the US [3] represent commercial fusion power plant designs with the objective of confirming that a fusion power plant can be economically competitive offering major safety and environmental advantages.

Fusion devices are considered environmentally friendly because they generate only short-lived radioactive waste, which is favorable in the long term. But even if fusion produces no long-lived waste, special attention should be paid to reducing the impact of materials activation. In fact the activation of materials in fusion machines is due to the interaction of the neutrons with the constituents of the fusion devices. The deuterium-tritium (D-T) fuel is currently considered to be the preferred energy source for first generation fusion facilities because it offers an easy way to reach ignition. In this D-T reaction, α particles and 14 MeV neutrons are generated. The energetic 14 MeV neutrons leave the plasma, interact with all components surrounding the plasma, and activate them at different degrees depending on their location. In other words, all components in a fusion device will be activated in relationship to their proximity to the plasma.

The activation of materials within a fusion device represents a significant advantage because the plasma-surrounding components are the main source of radioactive waste. This process is dependent on the careful selection of the irradiated materials, alloying elements and impurities, which could be carefully monitored to effectively reduce the radioactive inventory in any fusion device. It is crucial to limit the volume of materials that ultimately becomes classified as active waste, requiring long-term storage or disposal in deep geological repositories. In fact, the geological disposal is not an environmentally attractive option as the amount of low activated materials generated by a fleet of fusion power plants during operation and after decommissioning would rapidly fill up the available space in commercial repositories. That is why it would be necessary to develop an integrated management strategy for fusion radioactive materials and avoid the geological disposal option. Clearance and recycling would be a potential solution to reduce the volume of radioactive waste assigned for disposal. Clearance is the unconditional release of slightly radioactive materials to the commercial market. This approach applies mainly to the biological shield as all plasma-facing components are not clearable. Recycling calls for reusing the radioactive waste within the nuclear industry, if technically and economically feasible. The recycling technology is rapidly maturing in many countries around the world. It is crucial to be able to handle the fusion radioactive materials through recycling without imposing a radwaste burden on future generations.

One of the most challenging tasks for the first wall (FW) and divertor designers is to develop radiation-resistant materials to sustain the harsh fusion environment. At present, tungsten alloys are being considered as the primary

candidates for plasma facing components. Over the past 10 years, experts in EU, Japan, and US developed several W alloys for advanced He-cooled divertors that can handle heat fluxes in excess of 10 MW/m^2 and operate at high temperature of 800-1200^oC [4]. Since surface phenomena (such as erosion and blistering) will alter the surface morphology and properties of plasma facing components, the application of a sacrificial W armor was judged mandatory to protect the surface of both FW and divertor during operation.

We examined the seven candidate W alloys that have been proposed as structural materials for ARIES and PPCS divertor designs and for the W-based component of the ITER divertor dome. We considered the three radwaste handling scenarios (disposal, recycling and clearance) in order to clarify the technical issues associated with W activation and the potentiality of each scenario.

The W transmutation results from the process of neutron absorption by the W nucleus and a subsequent emission of a particle (alpha or beta), implying a change in the nucleus structure and leading to the formation of different isotopes (Re, Ta, Os, etc.). In most cases, W transmutes into its neighbor elements in the periodic table and this process could degrade the original W properties. Indeed, plasma-facing components (such as the FW and divertor) operate in a severe fusion environment; consequently their performance could be sensitive to any change in their composition. Therefore, it is necessary to assess the degree of transmutation during component operation until the end-of-life (3-5 full powers years for a typical first wall). Since W activation byproducts are highly sensitive to the neutron spectrum [4,5], we examined the sensitivity of the W transmutation to the ARIES and PPCS divertor designs and also to the PPCS blanket concepts. This assessment represents an important element of the study as a high level of W byproducts may have an adverse effect on the original properties of any W alloy.

2. Codes and analysis

Three codes have been used in this activation analysis:

- DANTSYS discrete ordinate neutral particle transport code (developed by Los Alamos National Laboratory) [6] and its multi-group FENDL-2.1 cross section data library [7] to calculate the neutron flux throughout the components,
- SPECTRUM code (developed by the University of Wisconsin) [8] to generate the data necessary to plot the neutron energy spectra at any radial location,
- ALARA activation code (developed by the University of Wisconsin) [9,10] with the IAEA FENDL-2.1 data library [11].

The activation analysis determines:

- Specific activity with time after shutdown
- Clearance index for all components
- Recycling dose to equipment
- Radioactive waste classification for disposal
- W transmutation products
- Percentage of W transmutations and variation with irradiation schedule
- Pathway from parent nuclide to radioisotope of interest.

3. Activation analyses for ITER, ARIES and PPCS W-based divertors

3.1. Introduction

In this section the activation of the divertor designs of the international ITER experiment facility, the US ARIES-ACT power plant and the EU PPCS power plant were studied. The activation analyses were performed using a 1-D model either based on information found in the literature or obtained from the divertor designers. The impurities were taken into account for all materials used to develop the radial builds of the three divertors (refer to Table 1). The activation and the transmutation of seven candidate W alloys were examined within the cooling channels of the ARIES and PPCS divertors. These seven alloys are W-W composites, W-La_2O_3, W-TiC, W-Ta, W-K, VM-W and W-Re. Pure W was also examined as a reference case representing the lower bound for the examined parameters. For the three designs the activation analysis involved:

- Defining the irradiation schedule based on the reference divertor lifetime
- Determining the neutron spectrum in the W armor

- Examining the specific activity, clearance and recycling
- Classifying the divertor radioactive waste according to both US and French regulations
- Performing transmutation calculations for W alloys (ARIES and PPCS divertor only)
- Extending the operational time for higher fluences up to 25 MWy/m² (ARIES and PPCS divertor only)
- Determining the contribution of the parent nuclides to the radioisotope of interest.

3.2. Definitions and classifications

3.2.1. Clearance and recycling

Clearance is the unconditional release of slightly radioactive materials to the commercial market to fabricate as consumer products. This means solid materials containing traces of radioactivity can be reused or recycled into a consumer product without restrictions. All organizations, including the International Atomic Energy Agency (IAEA) [12], recommended an individual dose standard of 10 μSv/year for clearable materials. This is very low in comparison with the variation in natural background radiation (2.4-3.6 mSv/year) representing less than 1% of the allowable [13]. By definition, the clearance index (CI) for any material is the ratio of the specific activity (in Bq/g) of the individual radioisotope to the allowable clearance limit summed over all radioisotopes. A component qualifies for clearance if the CI drops below one at any time during a defined storage period.

Recycling is the reuse of radioactive materials within the nuclear industry, if technically and economically feasible. In this analysis, the technical feasibility of recycling is based on the dose rate to the remote handling (RH) equipment. This dose determines the RH needs (hands-on, conventional and advanced tools) and the interim storage period necessary to meet the dose limit.

Figure 1 depicts the essential elements of the recycling/clearance process [14]. Examining the various steps, one could envision the following:

1. After extraction from the power core, components are taken to the Hot Cell to disassemble and remove any parts that will be reused, separate into like materials, detritiate, and consolidate into a condensed form. This is one of the most challenging steps.
2. Ship materials to a temporary onsite or centralized facility to store for a period of ~ 1 year or less.
3. If the CI does not reach unity in less than e.g. 100 years, transfer the materials to a recycling center to refabricate remotely into useful forms. Fresh supply of materials could be added as needed.
4. If the CI can reach unity in less than e.g. 100 years, store the materials for 1-100 years, then release to the public sector to reuse without restrictions.

3.2.2. US regulations

According to US regulations, the waste disposal rating (WDR) is by definition the ratio of the specific activity (in Ci/m^3) to the allowable limit summed over all radioisotopes. At 100 years after shutdown, a WDR higher than unity means high-level waste (HLW) and a WDR lower than unity means low-level waste (LLW). A radioactive material classified as HLW requires disposal in deep geological repositories (> 600 m below ground level) while LLW can be disposed of ~8 m below ground surface.

We evaluated the volumetric average WDR for a fully compacted waste using the most conservative waste disposal limits developed by Fetter [15] for fusion radwaste and by NRC-10CFR61 [16] for Class C waste for fission, medical, and industrial radwastes. Although Fetter's calculations carry no regulatory acceptance, they are useful because they include a range of limits for fusion-specific radioisotopes. We require all components to meet both NRC and Fetter's limits until the NRC develops official guidelines for fusion waste.

Table 1. Elemental compositions of materials (in wt.%) used in radial builds. Same impurities of Eurofer are considered for ODS Eurofer. Same impurities of W are considered for W-1%La_2O_3, W-26%Re, W-1.1%TiC, W-K (with 40 wppm K) and W-Ta (with 5%Ta and 1%Ta). Composition of W-VM is taken from PLANSEE (http://www.plansee.com/en/Materials-Tungsten-403.htm#WVM). W(1) is the tungsten elemental composition used in the ARIES and PPCS divertors analyses and W(2) is the tungsten elemental composition used in the ITER divertor dome analysis.

	W(1)	W-Re	W-La_2O_3	W-TiC	W-VM	W-K	W-1%Ta	W-5%Ta	ODS-FS	ODS Eurofer	Eurofer	W(2)	316-SS	Cu	CuCrZr	Water
h	0.0002	0.0002	0.0002	0.0002	0.0005	0.0002	0.0002	0.0002				0.0005	0.001			11.111
b									0.0003		0.001					
c	0.001	0.001	0.001	0.221	0.003	0.001	0.001	0.001	0.04	0.12	0.11	0.003	0.0225			
n	0.0002	0.0002	0.0002	0.0042	0.0005	0.0002	0.0002	0.0002	0.005		0.03	0.001	0.07			
o	0.0005	0.0005	0.1475	0.0205	0.002	0.0005	0.0005	0.0005	0.13	0.11	0.01	0.003	0.002	0.0005	0.03	88.889
na	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002				0.001				
mg	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002				0.0005				
al	0.0005	0.0005	0.0005	0.0005	0.0015	0.0005	0.0005	0.0005	0.01	0.008	0.008	0.0015	0.05			
si	0.0005	0.0005	0.0005	0.0005	0.002	0.0005	0.0005	0.0005	0.24	0.06	0.05	0.002	0.5		0.011	
p	0.001	0.001	0.001	0.001		0.001	0.001	0.001	0.005		0.005	0.005	0.025	0.0003	0.0003	
s	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002	0.002		0.003	0.0005	0.0075	0.0015	0.0015	
k	0.0005	0.0005	0.0005	0.0005	0.008	0.004	0.0005	0.0005			0.0002	0.001	0.0005			
ca	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002			0.0002	0.001				
ti	0.0002	0.0002	0.0002	0.8802		0.0002	0.0002	0.0002	0.09		0.01	0.001	0.15			
y									0.7	0.39						
v									0.29	0.19	0.2		0.004			
cr	0.0005	0.0005	0.0005	0.0005	0.002	0.0005	0.0005	0.0005	8.7	8.87	9	0.001	17.5		0.75	
mn	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002	0.45	0.42	0.4	0.0005	1.8	0.0001	0.0001	
fe	0.001	0.001	0.001	0.001	0.003	0.001	0.001	0.001	87.89	88.5761	88.949	0.003	64.938	0.001	0.001	
co	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002	0.0028	0.005	0.005	0.001	0.05		0.06	
ni	0.0002	0.0002	0.0002	0.0002	0.002	0.0002	0.0002	0.0002	0.0474	0.005	0.005	0.002	12.25	0.001	0.001	
cu	0.0005	0.0005	0.0005	0.0005	0.001	0.0005	0.0005	0.0005	0.01	0.0037	0.0037	0.001	0.1	99.9	99.039	
zn	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002				0.0005		0.0001	0.0001	
as	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002	0.002		0.02	0.0005		0.0005	0.0005	
se														0.0003	0.0003	
zr	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002			0.0001	0.001	0.002		0.11	
nb	0.0005	0.0005	0.0005	0.0005		0.0005	0.0005	0.0005	0.00033	0.001	0.001	0.001	0.01			
mo	0.002	0.002	0.002	0.002	0.01	0.002	0.002	0.002	0.0021	0.0012	0.0012	0.01	2.5			
ag	0.0005	0.0005	0.0005	0.0005		0.0005	0.0005	0.0005	0.00001			0.0005		0.0025	0.0025	
cd	0.0002	0.0002	0.0002	0.0002	0.0005	0.0002	0.0002	0.0002	0.00004			0.001		0.0001	0.0001	
ru											0.001					
sn									0.001		0.003		0.002	0.0002	0.0002	
sb									0.0005		0.01			0.0004	0.0004	
nd											0.003					
hf											0.0002					
te											0.0001			0.0002	0.0002	
ba	0.0002	0.0002	0.0002	0.0002		0.0002	0.0002	0.0002				0.001				
la			0.853													
ta	0.001	0.001	0.001	0.001		0.001	1	5	0.08	0.14	0.07	0.001	0.01			
w	99.99	73.99	98.99	98.866		99.99	98.99	94.99	2	1.1	1.1	99.96	0.001			
re		26									0.0001					
hg					0.0001											
pb	0.0002	0.0002	0.0002	0.0002	0.0005	0.0002	0.0002	0.0002	5E-06			0.001	0.0008	0.0005	0.0005	
os									5E-06							
ir									5E-06							
bi									0.00002				0.0008	0.0001	0.0001	
eu									5E-06							
tb									2E-06							
dy									5E-06							
ho									5E-06							
er									5E-06							
u									5E-06							

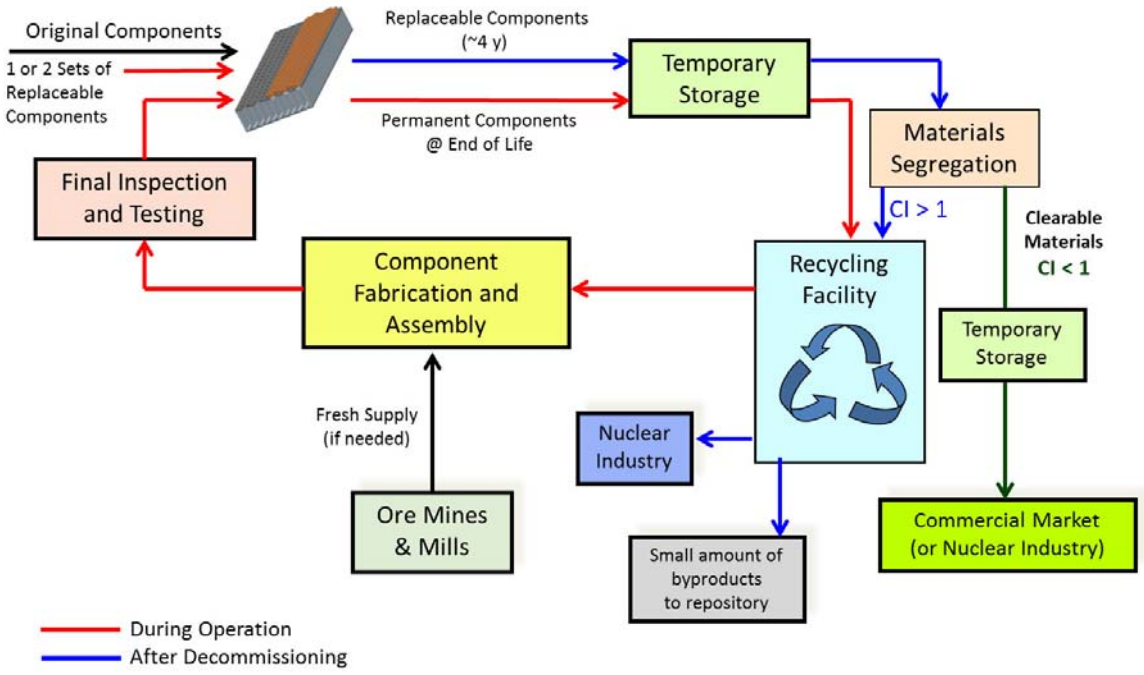


Figure 1. Recycling and clearance flow diagram.

3.2.3. French regulations

According to ANDRA (French national agency for radioactive waste management) classification, the radioactive waste can be classified into four categories:

- TFA (French abbreviation for "Très Faible Activité," meaning very low level waste)
- FMA-VC (French abbreviation for "Faible et Moyenne Activité à Vie Courte," meaning low and intermediate-level short lived)
- MA-VL (French abbreviation for "Moyenne Activité à Vie Longue," meaning intermediate-level long-lived) waste
- HAVL waste (French abbeviation for "Haute Activité à Vie Longue," meaning high level long-lived waste). Such a high-level waste will not be produced in fusion devices.

The maximum acceptability limit per package, defined in ANDRA specifications for CSA (Aube Storage Center) is used to determine if a waste can classify as TFA or FMA-VA. If one radioisotope exceeds the LMA in Bq/g ("Limites Maximales d'acceptabilité" meaning acceptable maximum limits) of CSA, the radioactive waste classifies as MA-VL. If a radioactive material classifies as MA-VL, it will be disposed of in deep geological repositories at 500 m depth (such a repository is still under development in France; commissioning is planned for 2025). In our analysis, the classification was established by considering the current list of radioisotopes with a LMA at CSA, knowing that there are still missing radioisotopes for which LMA will be developed in the near future.

Here is the status of clearance and recycling in France. At present, clearance is not considered in France; French regulators just started mentioning the possibility of recycling low-level radioactive waste within the nuclear industry. There is no possibility for recycling MA-VL radioactive waste, which means the ITER waste will be disposed of in geological repositories. Nevertheless, in this analysis, we examined non-disposal options to assess the feasibility of recycling and clearance of the W armor and other 316-SS structural components of the ITER divertor.

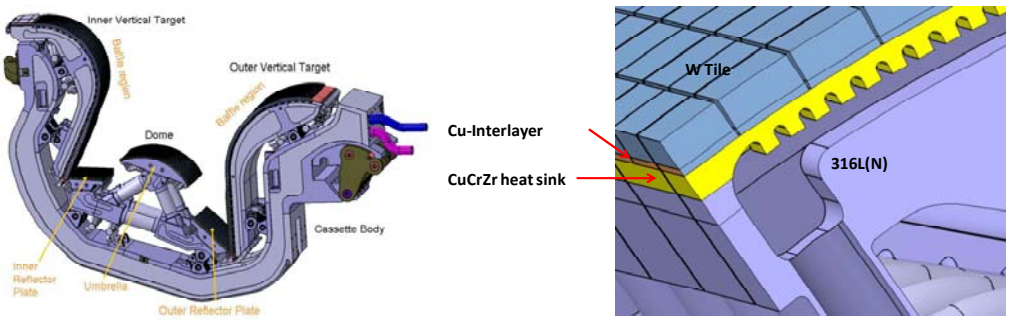


Figure 2. ITER divertor cassette (picture on the left) and detail of the dome components (picture on the right).

3.3. *ITER divertor*

3.3.1. Methodology

The ITER divertor design is shown in Fig. 2. We only considered the dome part of the divertor as it contains 0.8 cm W armor. Before conducting the activation analysis, we developed a radial built of the ITER divertor dome backed with a thick shield in order to provide the appropriate neutron reflection, as detailed in Figure 3 and Table 2. The compositions of all materials with their impurities have been taken into account in the activation calculations (refer to Table 1).

According to the ITER irradiation history for the assumed safety operational scenario [17], given in Table 3, ITER will operate for 2 years with D-D plasma (not considered in this analysis) and for 12 years with D-T plasma. The first ten of those 12 years are represented as a constant power at the level to accumulate 0.231 MWy/m² (FW fluence) and the final two years consist of 8 months of major shutdown and 16 months of operation with a total of 1.9 months of plasma pulses corresponding to a total fluence of 0.062 MWy/m² (FW fluence). The maximum lifetime of the divertor cassette is 7 years before replacement. Therefore the divertor dome irradiation schedule is based on the last 7 years of the safety operational scenario.

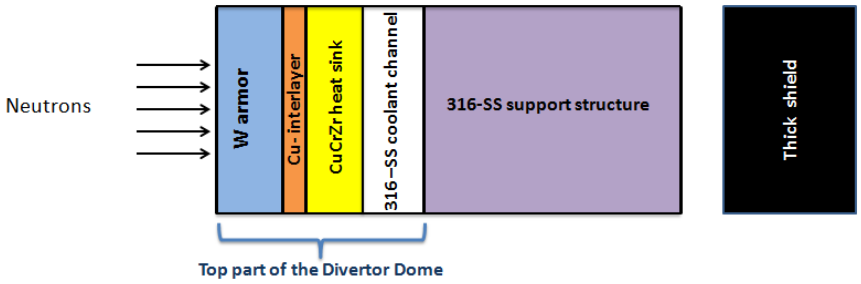


Figure 3. ITER 1-D model.

Table 2. Dimensions and compositions of ITER divertor dome.

	Average Thickness	Composition (in vol%)
W armor	8 mm	100% W
Cu interlayer	2 mm	100% Cu
CuCrZr heat sink	7 mm	100% CuCrZr
316-SS coolant channel	7 mm	23.6% 316-SS, 76.4% Water
316-SS support structure	350 mm	85% 316-SS, 15% Water

Table 3. ITER irradiation history for assumed safety operational scenario.

Duration	Machine Average Neutron Wall Loading (MW/m²)	Fusion Power (MW)	Repetition
2 y	0.003	2.68	once
10 y	0.0231	20.6	
0.667 y	0	0	
1.325 y	0.0465	41.5	
3920 s	0	0	17 times
400 s	0.56	500	
3920 s	0	0	3 times
400 s	0.784	700	

Table 4. Divertor irradiation schedule.

D-T Phase	FW (Total Fluence in MWy/m²)	Divertor Dome (Total Fluence in MWy/m²)
Last 5 yr of the first 10 y	0.116	0.089
Last 2 y	0.062	0.048
Total = 7 y	0.178 + 0.015 (Final Day)	0.137 + 0.011 (Final Day) ≃ 0.15

The fluence at the divertor dome, given in Table 4 and Figure 4, was calculated by multiplying the operation time (given in the assumed safety operational scenario) by the average neutron wall loading (NWL) over the divertor dome (0.43 MW/m^2) for 500 MW fusion power. Note that the NWL at the divertor dome is ~77% the machine average NWL.

As shown in Figure 4 all pulses were modeled with the ALARA code in a single run and the NWLs used in different phases have been normalized in order to be consistent with the fluence at the divertor dome and the operating schedule.

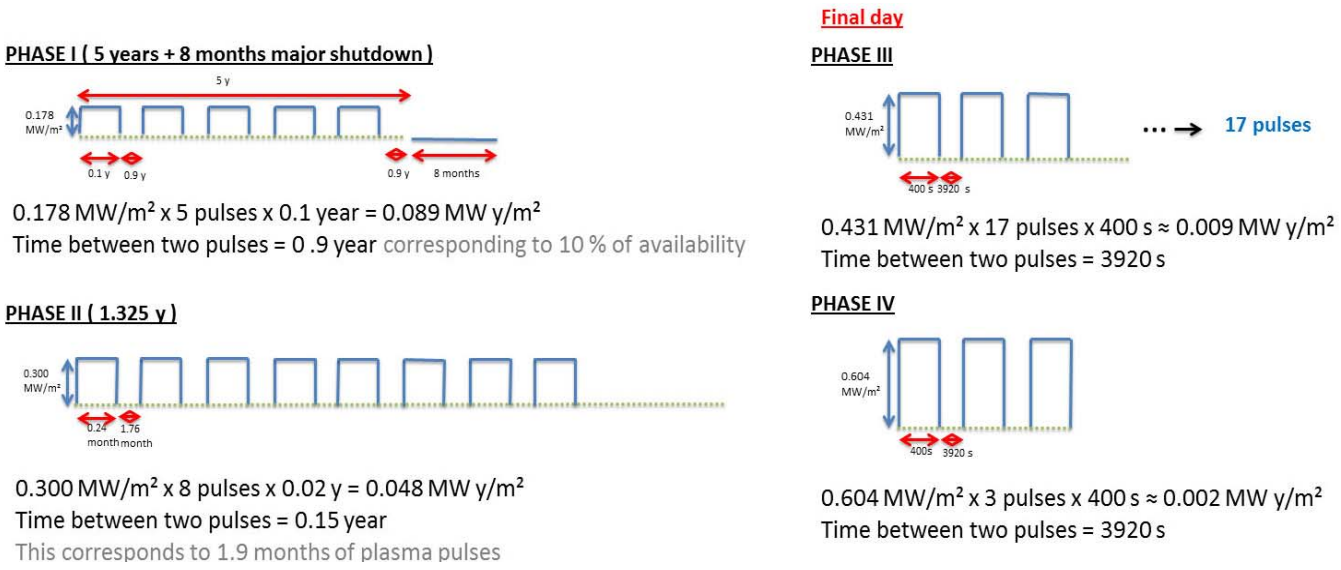


Figure 4. Divertor irradiation schedule considered in 1-D analysis.

3.3.2. Results

Two cases were considered in the analysis of the ITER divertor dome: the 2.4 cm thick top part of the divertor dome (consisting of W armor, Cu-interlayer, CuCrZr heat sink and 316-SS water coolant channel (refer to Figure 3)) and the entire divertor dome (the 2.4 cm thick top part combined with the 35 cm thick 316-SS support structure).

3.3.2.1. Spectrum

Figure 5 represents the neutron spectum at the W armor of the ITER divertor dome normalized to 0.6 MW/m² NWL of the last phase of the divertor irradiation schedule. The spectra normalized to lower NWLs used in the other phases would perfectly fit the shape of the sprectum of Fig. 5 but with lower neutron fluxes. This is a very soft spectrum mainly due to the use of water to cool the components behind the W armor. The water acts as a neutron moderator and most of the neutron thermalization is caused by hydrogen atoms.

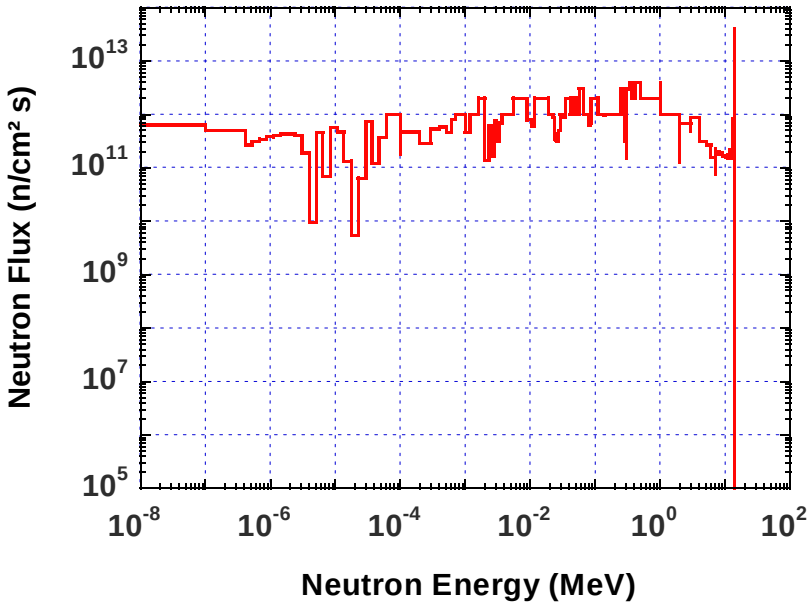


Figure 5. Spectrum in W armor normalized to 0.6 MW/m² NWL.

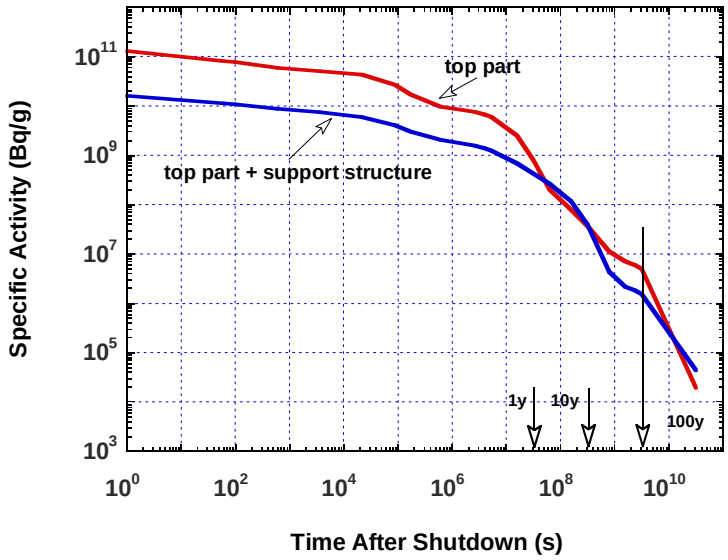


Figure 6. Specific activity versus time after shutdown of the top part of the divertor dome and the entire divertor dome (top part + support structure).

3.3.2.2. Specific activity

The specific activities in Figure 6 were calculated by mass averaging over the ITER divertor dome components.

3.3.2.3. Clearance and recycling

Figure 7 indicates that none of the divertor dome components could be cleared even after 100 years cooling period after being exposed to a fluence of 0.15 MWy/m². There is another option that could reduce the amount of ITER radioactive materials assigned to permanent repositories, that is recycling. In fact, Fig. 8 shows that the divertor could be handled and eventually recycled immediately after shutdown with advanced remote handling equipment that could withstand a dose of 10000 Sv/hr or after a 30-80 y cooling period with conventional remote handling equipment that could withstand a dose of 10 mSv/hr. However, the divertor cannot be handled/recycled by hands-on because the dose does not fall below the 1 μSv/hr limit.

As mentioned earlier, the ITER host country (France) does not consider clearance and has just started mentioning the possibility of recycling the low-level radioactive waste (TFA and FMA-VC) within the nuclear industry. Because the ITER divertor dome classifies as MA-VL (see Section 3.3.2.4 below), recycling is not applicable to the ITER divertor.

3.3.2.4. ANDRA classification of ITER divertor

The French national agency for radioactive waste management (ANDRA) classifies a radioactive waste MA-VL when a radioisotope exceeds the acceptable maximum limits of the Aube storage center. Table 5 shows that in both cases the radioactive waste ultimately classifies as MA-VL. The reason is that for the top part of the divertor dome, the SA/LMA for both H-3 (from neutron interaction with materials) and Ni-63 exceed 1. For the entire divertor dome, the SA/LMA of Nb-94 exceeds 1.

Reversed activation analyses were then performed to identify the parent radioisotopes responsible for the production of the main contributors to the ANDRA classification (see Tables 6-8). Ni-63 is mainly produced from Cu contained in the Cu-interlayer and CuCrZr heat sink. It is also produced from Ni in the coolant channel which is an alloying element for 316-SS. H-3 is produced from numerous neutron interactions with many elements such as W, Cu, Cr, etc. Nb-94 is mainly produced from Nb (which is an impurity in all components of the divertor dome) and from Mo (which is an alloying element in 316-SS). This confirms that the choice of materials and alloying elements

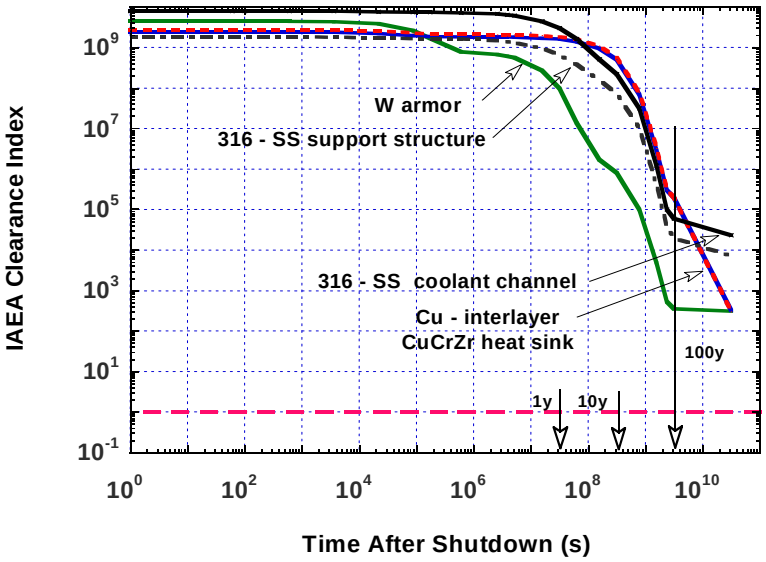


Figure 7. IAEA clearance index versus time after shutdown for the components of the ITER divertor dome after being exposed to a total fluence of 0.15 MWy/m² – the end of the divertor service lifetime.

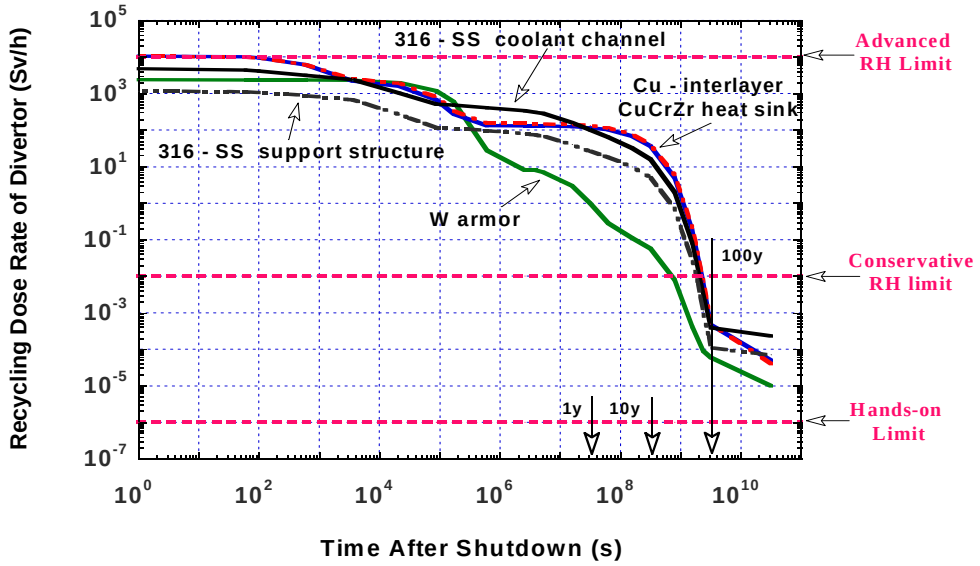


Figure 8. The recycling dose to the components of the ITER divertor dome versus time after shutdown after being exposed to a total fluence of 0.15 MWy/m² – the end of the divertor service lifetime.

as well as controlling the impurity content is determinant to the waste classification. Interestingly, even though the ITER divertor dome is exposed to a small fluence of 0.15 MWy/m², it is sufficient to classify the divertor as MA-VL requiring disposal in a geological repository, mainly because of the use of materials such as Cu and 316-SS.

3.3.2.5. Waste classification of ITER divertor at 100 years based on US regulations

The classification of the ITER divertor dome radioactive waste was examined according to US regulations just to compare it with the official ANDRA classification (see Section 3.3.2.4). Table 9 summarizes the ITER divertor WDR calculated using the NRC Class C and Fetter's limits and the main contributors to the WDR of each components. The maximum value for the WDR (volume averaged at 100 years after shutdown) is considered to classify the radioactive waste which is:

WDR (top part) = 0.65
WDR (top part + support structure) = 2.11.

Thus the top part of the divertor dome ultimately classifies as LLW while the entire dome classifies as HLW. The use of 316-SS in the coolant channel and in the support structure is responsible for such a high value for the WDR where the main contributor to the WDR is Tc-99 (produced by Mo – an alloying element of 316-SS).

3.3.2.6. Tritium inventory

The reported T inventory results from (n,t) nuclear reactions within the divertor structure (with W, Cu, Cr, etc.) and assumes the T does not diffuse out of the materials during irradiation. Tritium from the plasma will increase divertor T inventory near the divertor surface through various trapping phenomena (implantation, permeation, recombination, etc.). This may cause problems for the final disposal of the divertor (due to absorption, transfer to environment, etc.) unless the divertor materials are detritiated to recover the majority of T before disposal.

Table 5. ANDRA classification of the top part of the divertor dome and entire divertor dome after being exposed to a fluence of 0.15 MWy/m². The values in red (SA/LMA > 1) represent the radioisotopes that would not be accepted at the Aube storage center.

Top part of divertor dome		Top part of divertor dome + support structure	
	Relative mass		Relative mass
W-armor	48670.8	W-armor	48670.8
Cu-interlayer	5627.18	Cu-interlayer	5627.18
CuCrZr heat sink	16648.1	CuCrZr heat sink	16648.1
316-SS coolant channel	4221.58	316-SS coolant channel	4221.58
		316-SS support structure	774153
	SA/LMA		SA/LMA
h-3	2.91E+00	h-3	8.14E-01
co-60	4.95E-01	co-60	2.33E-01
ni-63	3.10E+00	ni-63	9.25E-01
zn-65	3.26E-04	zn-65	2.91E-05
c-14	7.89E-03	c-14	4.17E-02
mn-54	6.79E-02	mn-54	1.98E-01
ni-59	2.88E-02	ni-59	1.67E-01
sr-90	1.01E-06	sr-90	9.86E-08
zr-93	8.62E-05	zr-93	1.54E-05
nb-94	3.68E-01	nb-94	1.32E+00
mo-93	5.42E-02	mo-93	1.89E-01
tc-99	2.06E-03	tc-99	1.15E-02
sn-119m	2.95E-06	sn-119m	6.22E-06
sn-121m	7.54E-05	sn-121m	1.29E-04
po-210	2.63E-04	po-210	9.91E-04
be-10	1.27E-06	be-10	1.74E-06
na-22	2.66E-05	na-22	2.36E-06
cl-36	7.21E-02	cl-36	1.24E-02
ca-41	5.54E-07	ca-41	4.90E-08
fe-55	1.91E-02	fe-55	5.58E-02
ag-108m	2.07E-01	ag-108m	1.83E-02
ag-110m	2.05E-03	ag-110m	1.82E-04
cs-135	4.05E-10	cs-135	3.58E-11
cs-137	7.06E-07	cs-137	6.25E-08
se-79	6.55E-06	se-79	5.79E-07
pd-107	2.28E-09	pd-107	2.02E-10
i-129	4.06E-07	i-129	3.60E-08

Table 6. Reversed activation analysis for Ni-63 (one of the main contributors to ANDRA classification (MA-VL) for the top of the divertor). In the W armor, Cu, Ni, and Zn are impurities. In 316-SS, Ni is an alloying element.

Target: ni-63							
W armor		Cu-interlayer		CuCrZr heat sink		SS-316 coolant channel	
SA (Bq/g)	7.83E+02	SA (Bq/g)	3.44E+07	SA (Bq/g)	3.16E+07	SA (Bq/g)	6.34E+06
Parent	% Contribution to SA	Parent	% Contribution to SA	Parent	% Contribution to SA	Parent	% Contribution to SA
cu-63	49.62	cu-63	99.96	cu-53	99.96	ni-62	92.53
ni-62	33.53					ni-64	7.00
ni-64	13.96						
zn-66	2.66						

Table 7. Reversed activation analysis for H-3 (one of the main contributors to ANDRA classification (MA-VL) for the top of the divertor). Contributors to < 0.1% are not included.

Target: h-3							
W armor		Cu-interlayer		CuCrZr heat sink		SS-316 coolant channel	
SA (Bq/g)	6.34E+04	SA (Bq/g)	1.82E+06	SA (Bq/g)	1.64E+06	SA (Bq/g)	7.72E+05
Parents	% Contribution to SA	Parents	% Contribution to SA	Parents	% Contribution to SA	Parents	% Contribution to SA
w-183	67.27	cu-63	98.10	cu-63	96.92	cr-53	50.91
n-14	9.34	cu-65	1.90	cu-65	1.87	n-14	36.53
w-186	7.72			cr-53	1.16	mn-55	6.30
w-182	7.20					ni-58	1.36
w-184	6.27					fe-54	1.04
p-31	0.63					al-27	0.91
na-23	0.54					b-10	0.67
al-27	0.52					fe-57	0.58
						ni-61	0.38
						b-11	0.25
						si-29	0.23
						cu-63	0.18
						p-31	0.17
						ni-60	0.13

Table 8. Reversed activation analysis for Nb-94 (one of the main contributors to ANDRA classification (MA-VL) for the divertor dome). In the W armor, Nb and Mo are impurities. In 316-SS, Nb is an impurity and Mo is an alloying element.

Target: nb-94									
W armor		Cu-interlayer		CuCrZr heat sink		SS-316 coolant channel		SS-316 support structure	
SA (Bq/g)	2.01E+01	SA (Bq/g)	-	SA (Bq/g)	3.06E-04	SA (Bq/g)	5.54E+02	SA (Bq/g)	1.70E+02
Parent	% Contribution to SA	Parent	% Contribution to SA	Parent	% Contribution to SA	Parent	% Contribution to SA	Parent	% Contribution to SA
nb-93	93.25			zr-96	100.00	nb-93	60.41	nb-93	79.37
mo-94	5.26					mo-94	31.08	mo-94	16.36
mo-95	1.49					mo-95	8.52	mo-95	4.28

Table 9. Waste disposal ratings of the top part of the divertor dome and the entire divertor dome after being exposed to a fluence of 0.15 MWy/m² calculated at 100 years after shutdown using NRC Class C and Fetter's limits and the main contributors to the WDR of each components of the ITER divertor dome.

WDR at 100 y after shutdown						
	Relative Volume					
W-armor	2515.18					
Cu-interlayer	629.45					
CuCrZr heat sink	2205.05					
316-SS coolant channel	529.951					
316-SS support structure	97182.2					
	Fetter-Lo		Fetter-Hi		NRCC	
W armor	0.12		0.08		0.05	
	Isotope	%	Isotope	%	Isotope	%
	Nb-94	42.05	Nb-94	60.55	Nb-94	98.63
	Tc-99	37.49	Ag-108m	27.53	-	-
	Ag-108m	18.21	Tc-99	5.67	-	-
	Nb-91	1.74	Nb-91	2.63	-	-
Cu-interlayer	0.05		0.05		0.59	
	Isotope	%	Isotope	%	Isotope	%
	Ag-108m	88.06	Ag-108m	98.14	Ni-63	100.00
	Ni-63	11.38	Ni-63	1.27	-	-
CuCrZr heat sink	0.04		0.04		0.46	
	Isotope	%	Isotope	%	Isotope	%
	Ag-108m	88.39	Ag-108m	98.19	Ni-63	100.00
	Ni-63	10.98	Ni-63	1.23	-	-
316-SS coolant channel	6.44		1.32		0.79	
	Isotope	%	Isotope	%	Isotope	%
	Tc-99	88.17	Nb-94	44.90	Nb-94	75.30
	Nb-94	9.24	Tc-99	42.86	Ni-63	12.29
	Nb-91	2.21	Nb-91	8.97	Ni-59	6.97
	Ni-59	0.21	Ni-59	2.10	Tc-99	1.44
316-SS support structure	2.2		0.41		0.25	
	Isotope	%	Isotope	%	Isotope	%
	Tc-99	90.36	Tc-99	48.59	Nb-94	72.43
	Nb-94	8.28	Nb-94	44.53	Ni-63	13.88
	-	-	Nb-91	5.43	Ni-59	7.73
	-	-	Ni-59	1.16	Tc-99	1.58
WDR (TOP)	0.65		0.17		0.33	
WDR (TOP + SS)	2.11		0.4		0.26	

3.4. ARIES and PPCS divertors

3.4.1. Methodology

Two W-based, He-cooled advanced divertor designs for power plants were considered in this assessment. Figure 9 displays isometric and cross sectional views of ARIES-ACT [18] and PPCS [19] divertors. As in the case of the ITER divertor, a radial built backed with a thick shield (to provide the appropriate neutron reflection) was developed for both designs before conducting the analyses, as detailed in Figure 11. The compositions are given in Table 10 and Table 11. Impurities for all materials have also been taken into account in the activation calculations (refer to Table 1).

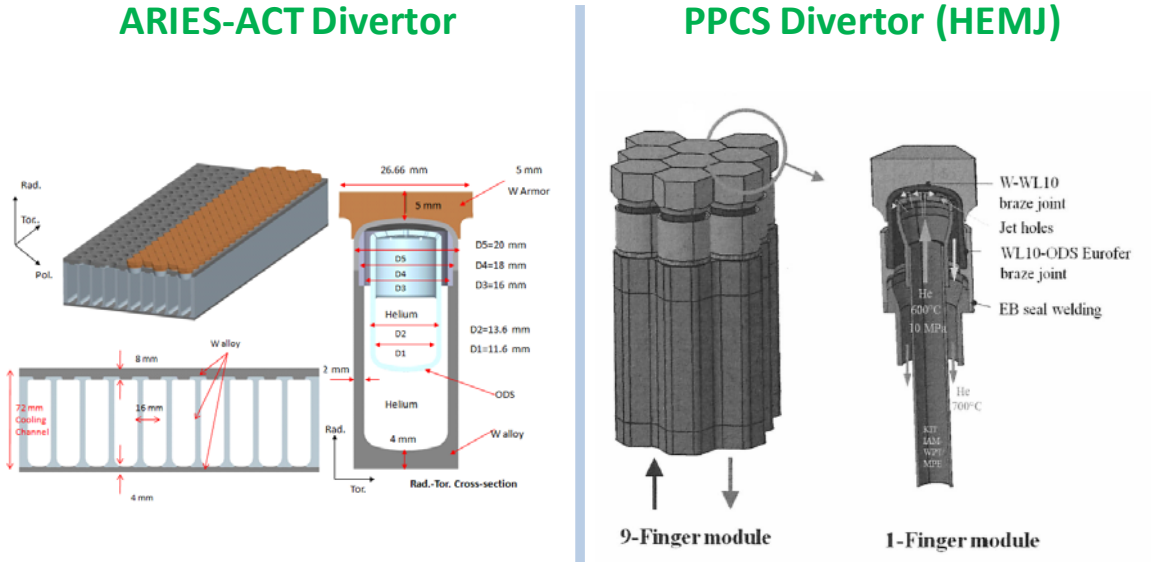


Figure 9. W-based divertor designs.

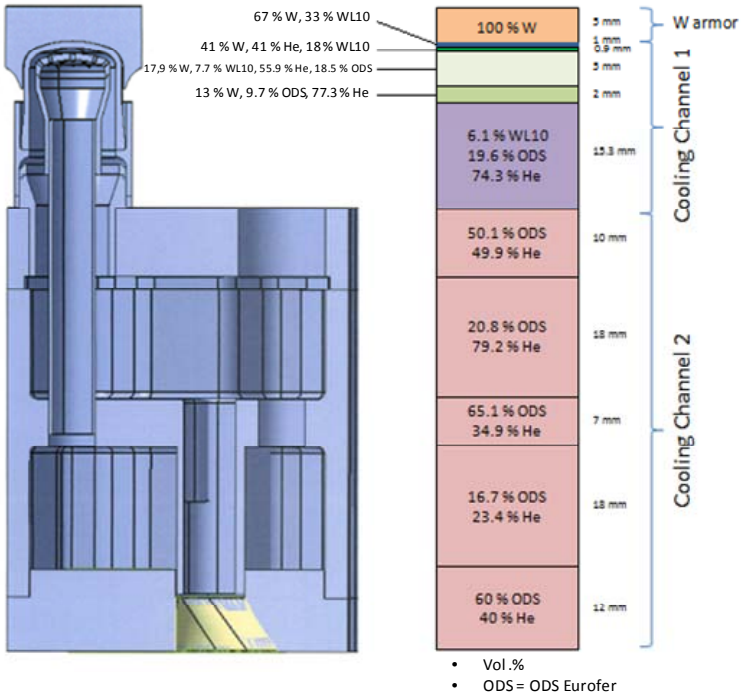


Figure 10. Details of the PPCS divertor (HEMJ).

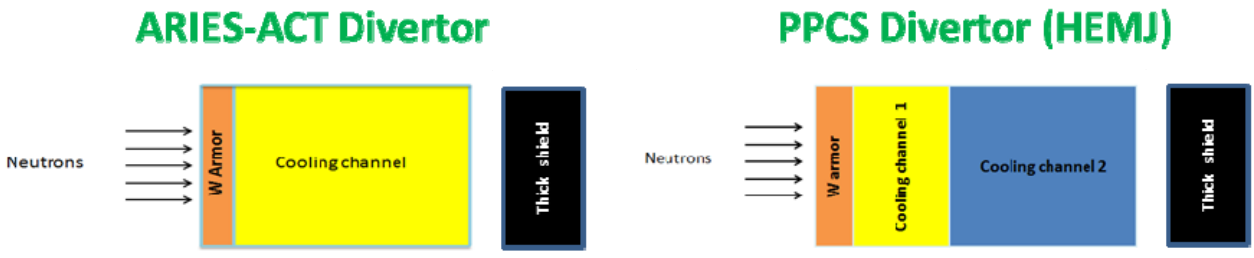


Figure 11. Divertor 1-D model.

Table 10. Dimensions and compositions of ARIES-ACT divertor.

	Average Thickness	Composition (in vol.%)
W armor	5 mm	88.4% W 11.6% void
Cooling channel	72 mm	29.6% W alloy 2.6% W 11.6% ODS FS 56.2% He

Table 11. Dimensions and compositions of PPCS divertor (HEMJ).

	Average Thickness	Composition (in vol.%)
W armor	5 mm	100% W
Cooling channel 1	24.2 mm	7.48% W alloy 9.07% W 17.02% ODS EUROFER 66.44% He
Cooling channel 2	65 mm	36.18% ODS EUROFER 63.82% He

Table 12. Irradiation schedule considered in the 1-D analysis.

ARIES Divertor	PPCS Divertor
Reference lifetime for divertor is ≈ 3.8 full power years, corresponding to ≈ 3 MWy/m² fluence	Reference lifetime for divertor is 2.5 full power years, corresponding to 1 MWy/m² fluence
Operational schedule reflects 85% availability	Operational schedule reflects 94% availability
Consider possibility of extending divertor lifetime (up to 25 MWy/m²) representing a situation where divertor can be operate for ≈ 35 FPY without failure	Consider possibility of extending divertor lifetime (up to 25 MWy/m²) representing a situation where divertor can operate for ≈ 60 FPY without failure
Pulses	**Pulses**
0.7 MW/m² x 5 pulses x 0.85 y = 3 MWy/m² Time between pulses = 0.15 y (reference ARIES divertor lifetime)	0.4 MW/m² x 1 pulses x 2.5 y = 1 MWy/m² Time between pulses = 0.17 y (reference PPCS divertor lifetime)
0.7 MW/m² x 12 pulses x 0.85 y = 7.1 MWy/m² Time between pulses = 0.15 y	0.4 MW/m² x 8 pulses x 2.5 y = 8 MWy/m² Time between pulses = 0.17 y
0.7 MW/m² x 24 pulses x 0.85 y = 14.3 MWy/m² Time between pulses = 0.15 y	0.4 MW/m² x 16 pulses x 2.5 y = 16 MWy/m² Time between pulses = 0.17 y
0.7 MW/m² x 42 pulses x 0.85 y = 25 MWy/m² Time between pulses = 0.15 y	0.4 MW/m² x 25 pulses x 2.5 y = 25 MWy/m² Time between pulses = 0.17 y

The following neutron wall loadings were considered in the analysis. The average NWL at the PPCS divertor was obtained by taking the same ratio for ARIES-ACT between the average NWL at FW and the average NWL at the divertor. The irradiation schedules used for both designs in the 1-D analyses are outlined in Table 12.

ARIES-ACT divertor [20]:

Average NWL at FW = 3.75 MW/m²
Average NWL at divertor = 0.7 MW/m²

PPCS divertor:

Average NWL at FW = 2.2 MW/m² (parameters for PPCS-Model C are considered in this analysis)
Average NWL at divertor ≈ 0.4 MW/m²

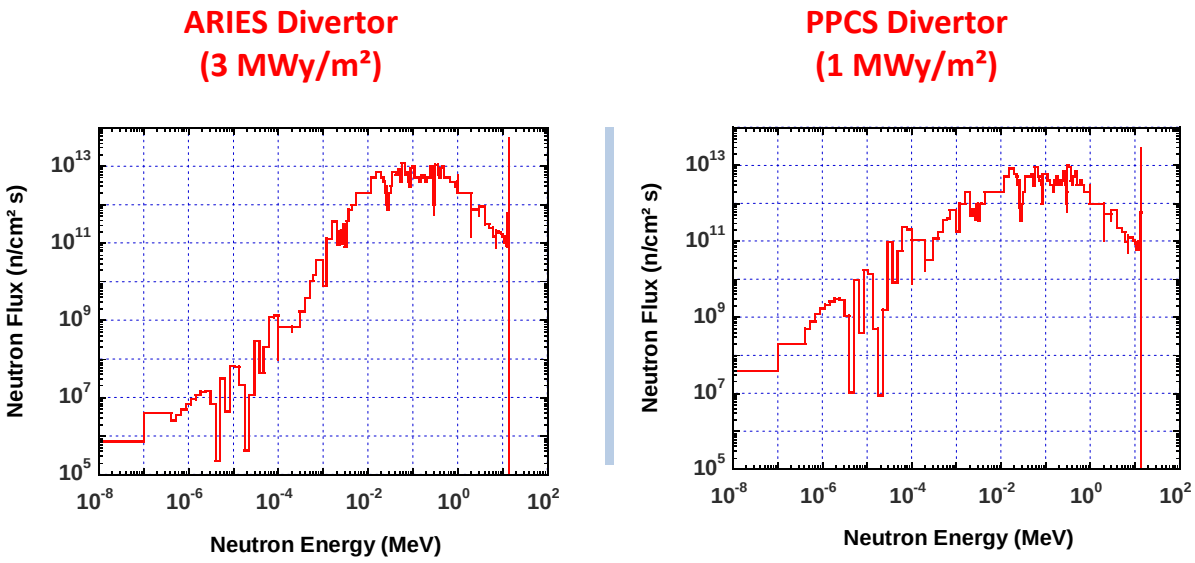


Figure 12. Neutron spectrum in the W armor

3.4.2. Results

The results for both divertor designs are presented side-by-side on the same figure to facilitate comparing the ARIES-ACT divertor results (on the left side) to the PPCS divertor results (on the right side). Seven W alloys were examined within the cooling channels of both divertors: W-W composites, W-La_2O_3, W-TiC, W-Ta, W-K, VM-W and W-Re. Pure W was also examined as a reference case representing the lower bound for the examined parameters.

3.4.2.1. Neutron spectrum at divertor surface

The W content in the ARIES divertor cooling channel is much larger than that in the PPCS divertor cooling channel. This has a significant impact on neutron slowing down and absorption. As a result, the neutron energy spectrum is harder in the W armor of the ARIES divertor than in the W armor of the PPCS divertor (refer to Figure 12). The difference in spectrum has a more profound impact on the production of some radioisotopes, as will be shown shortly.

3.4.2.2. Specific activity

The specific activity of the W alloys in cooling channels was analyzed for both ARIES and PPCS divertors after being exposed respectively to a fluence of 3 MWy/m² and 1 MWy/m². W-TiC, W-Ta and W-La_2O_3 look promising because their specific activities (not shown in the figure) match very closely the specific activity of W-W composites (same as W with nominal impurities) at all times after shutdown. This indicates that the alloying elements of these alloys have a reduced activation characteristic that make them very interesting. W-K and W-VM alloys exhibit a slightly higher activity at t > 50 y after shutdown while W-Re becomes the most activated alloy at 100 years after shutdown.

3.4.2.3. Clearance

Both divertors do not qualify for clearance. Even pure W does not fall below the clearance limit of one after a 100 y cooling period (refer to Fig. 14). Therefore divertors have to be recycled or disposed of in repositories.

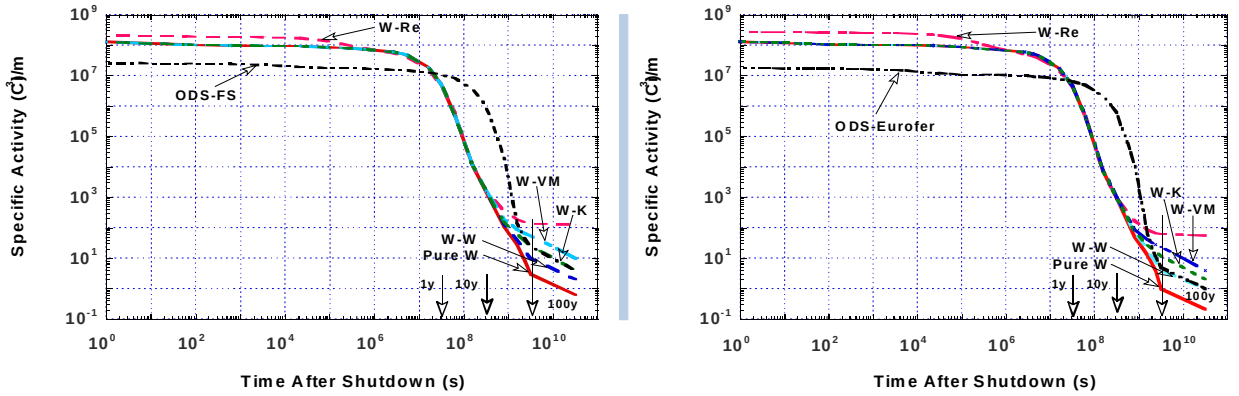


Figure 13. Specific activity of the W-alloys in cooling channels.

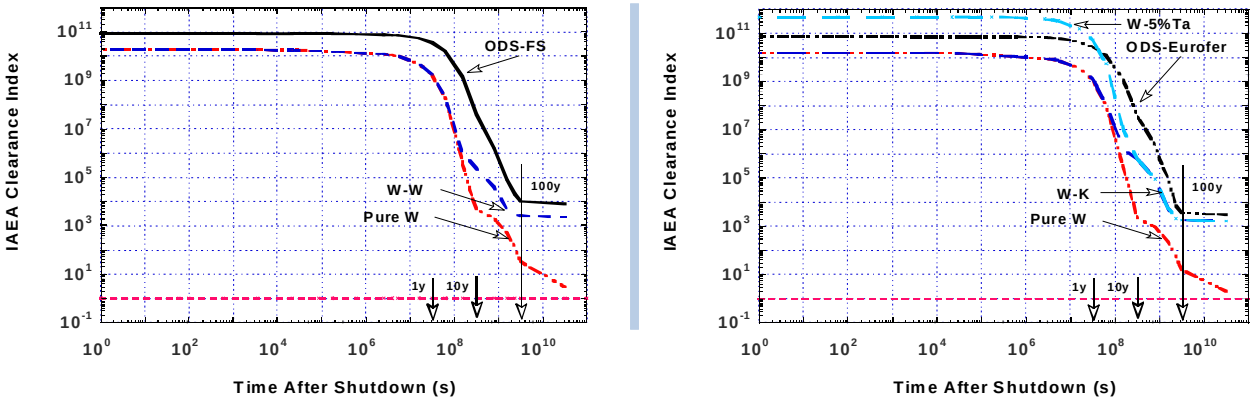


Figure 14. IAEA clearance index for W alloys of cooling channels.

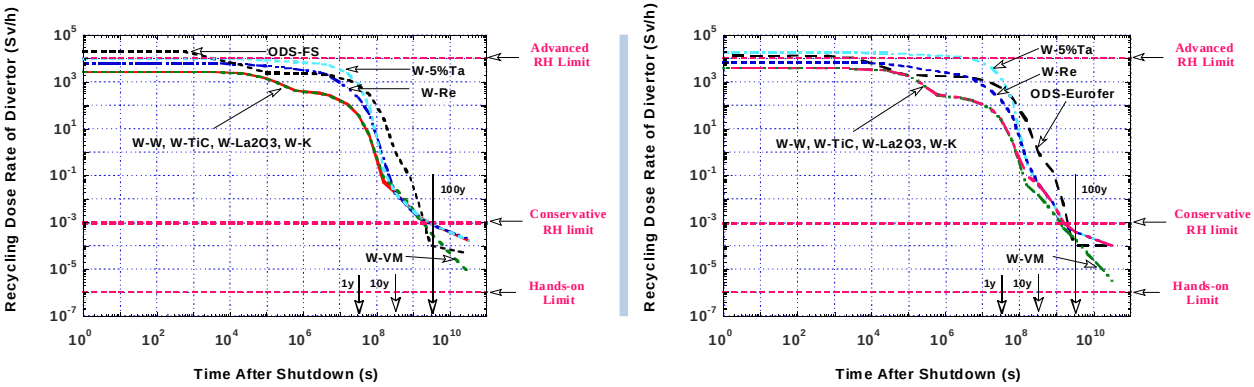


Figure 15. Recycling dose rate for W alloys of cooling channels.

3.4.2.4. Recycling

As Fig. 15 indicates, the hands-on recycling of W is not feasible even 100 years after shutdown because the dose does not fall below 1 μSv/hr. Advanced remote handling equipment capable of withstanding a dose of 10000 Sv/hr could be used immediately after shutdown to handle and eventually recycle all W alloys except W-5%Ta for the PPCS divertor case. W-5%Ta alloy would need a cooling period of about 4 months before handling/recycling with advanced equipment as shown in Fig. 16.

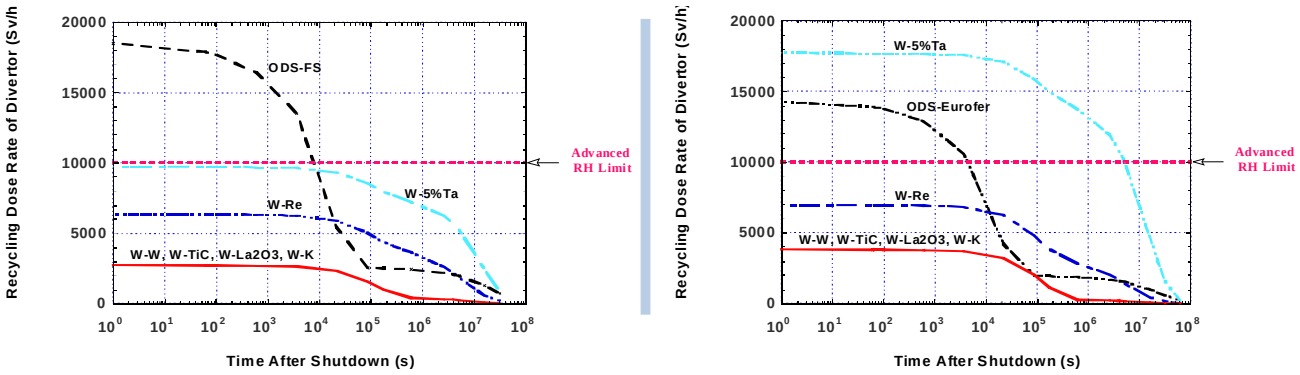


Figure 16. Recycling of W-alloy of cooling channels using a semi-log scale.

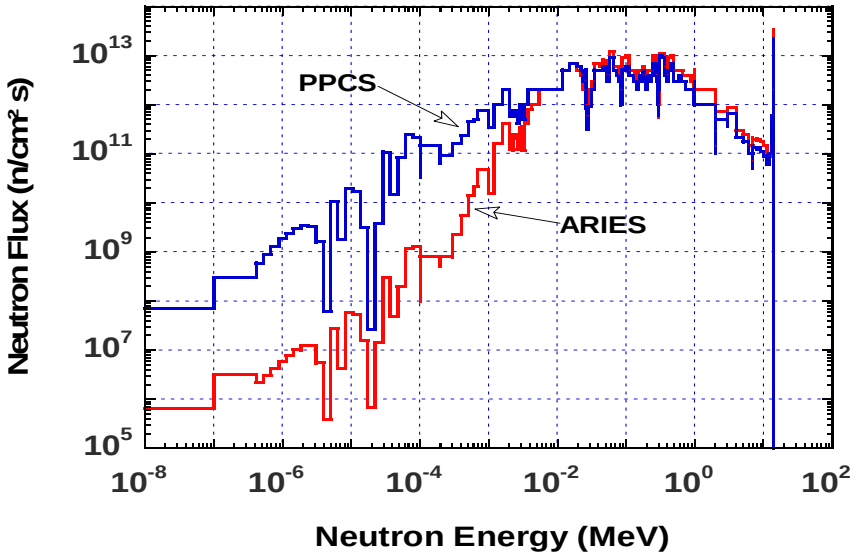


Figure 17. Comparison of neutron spectra in PPCS cooling channel 1 and front 2.4 cm of ARIES cooling channel.

Figure 16 shows that the PPCS recycling dose rate for W-5%Ta is higher immediately after shutdown even though the ARIES divertor was exposed to a fluence three time higher than that of the PPCS divertor. It turned out that the main contributor to the recycling dose of W-5%Ta is Ta-182 ($T_{1/2}$ = 114.7 d) produced from Ta-181 (n, γ) reaction with low-energy neutrons. The production of Ta-182 is sensitive to the neutron energy spectrum shown in Figure 17 for the cooling channel 1 of the PPCS divertor. It is much softer than the spectrum in the front 2.4 cm cooling channel of the ARIES divertor. As mentioned before, the harder spectrum of ARIES is due to the higher W content in the divertor coolant channel. Further investigation indicated that reducing the Ta content from 5 to 1% allows the W-1%Ta alloy of the PPCS divertor to be handled and recycled immediately after shutdown with advanced RH equipment.

3.4.2.5. W transmutation analysis

The transmutation of W and its alloying materials as structural materials in the divertor may affect the properties of W alloys as they undergo a change in the original composition [4]. That is why the degree to which the W and its alloying materials transmute in the cooling channels has been examined in the past [21,23] and is assessed here for both divertor designs. Figure 18 shows the percentage of W (in any of the seven W alloys) and Re (in the W-Re alloy) transmuted versus fluence for both ARIES and PPCS divertors. The transmutation is very sensitive to the neutron spectrum and the end of life fluence. Note the difference in the slope for the buildup of the W and Re

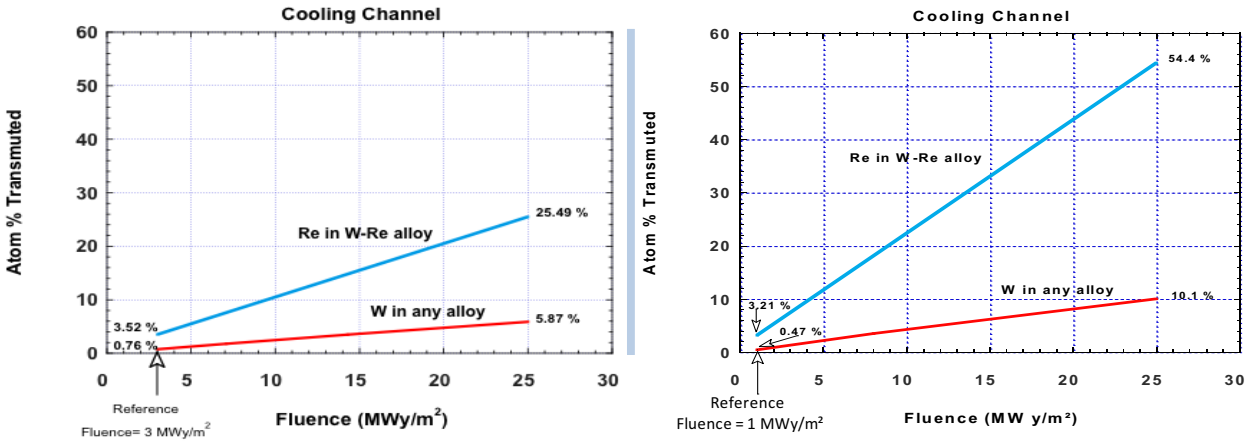


Figure 18. Percentage of W (in any W alloy) and Re (in W-Re) transmuted in cooling channels versus fluence for ARIES divertor (left) and PPCA divertor (right).

transmutation versus fluence which is a strong function of the neutron energy spectrum (harder in the ARIES divertor). At the reference 3 MWy/m² fluence for the ARIES divertor, about 4 at.% of W-Re alloy transmute while the W transmutation is very low (< 1 at.%). At the reference 1 MWy/m² fluence for the PPCS divertor, about 3.5 at.% of W-Re transmute while the W transmutation is very low (< 0.5 at.%). In both designs, the W in the cooling channels transmutes into Re, Ta, Os and other elements (see Table 13). Such a low W transmutation (< 1 at.%) will not degrade the bulk properties of the candidate W alloys except W-Re. Re transmutes at a much faster rate than W which could at a certain point degrade the bulk properties of the W-Re alloy.

The possibility of extending the divertor lifetime up to 25 MWy/m² was considered to represent a situation where the divertor can operate for about 35 FPY (ARIES divertor) and 60 FPY (PPCS divertor) without failure. In the ARIES divertor case, after being exposed to a fluence of 25 MWy/m², 5.9% of the W and 25.5% of the Re transmute within the cooling channel. In the PPCS divertor case, after being exposed to a fluence of 25 MWy/m², 10.1% of the W and 54.4% of the Re transmute within the cooling channel.

Table 13. W transmutation products within cooling channels at the reference fluences of ARIES (left) and PPCS (right).

at.% transmuted	0.76
Radioisotope	Contribution to at.% transmuted
re 185,187	0.5
ta 181	0.2
w 185,181	0.05
os 186,188	0.007
h-1	0.001

at.% transmuted	0.47
Radioisotope	Contribution to at.% transmuted
re 185,187	0.34
ta 181	0.08
w 185,181	0.05
os 186,188	0.005
h-1	0.001

3.4.2.6. ANDRA classification for ARIES and PPCS divertors

We selected the W-La_2O_3 alloy to evaluate the ARIES and PPCS divertors using the French regulations. According to the French national agency for radioactive waste management (ANDRA), both ARIES and PPCS divertors ultimately classify as MA-VL (intermediate-level long-lived waste) (refer to Table 14). In the ARIES divertor case, the SA/LMA exceeds the limit of one for H-3 (from neutron interaction with many elements), Mn-54,

Fe-55, Nb-94 and Ag-108m. In the PPCS divertor case, the SA/LMA exceeds 1 for H-3 (from neutron interaction with many elements), Mn-54, Fe-55, and Nb-94.

Reversed activation analyses were also performed to identify the parent radioisotopes responsible for the creation of the main contributors to the ANDRA classification (see Tables 15-18). Fe-55 and Mn-54 are mainly produced from Fe in the cooling channels of both designs. Both Nb-94 and Ag-108m originate from impurities in all components of both divertors. Once again the analyses show that the contribution of the impurities can be determinant to the classification. Nevertheless, in both cases, even without strict impurity control, the classification would be the same because of the activation of iron in ODS-FS of ARIES and ODS-Eurofer of PPCS.

We also examined the W-Ta alloy for the PPCS divertor. Table 14 is still valid for the W-Ta case and the PPCS divertor classifies as MA-VL for both W-5%Ta and W-1%Ta alloys. The same classification is expected for the W-K alloy.

Table 14. ANDRA classification (W-La_2O_3 case) of the ARIES divertor (left) and the PPCS divertor (right) after being exposed respectively to a fluence of 3 MWy/m² and 1 MWy/m². The values in red (SA/LMA > 1) represent the radioisotopes that would not be accepted at the Aube storage center.

	Relative mass
W-armor	21508.9
Cooling channel 1	130251
	SA/LMA
h-3	7.39E+00
be-10	4.45E-05
c-14	1.31E-02
na-22	1.39E-04
cl-36	7.30E-01
ca-41	2.98E-06
mn-54	2.42E+00
fe-55	1.09E+00
co-60	3.62E-03
ni-59	1.38E-03
ni-63	5.82E-03
zn-65	3.27E-04
sr-90	1.75E-06
zr-93	1.71E-05
nb-94	1.65E+00
mo-93	1.89E-02
tc-99	3.76E-04
pd-107	3.02E-08
ag-108m	1.47E+00
ag-110m	8.65E-04
sn-121m	1.02E-03
sb-125	3.11E-06
cs-134	2.97E-07
cs-135	6.07E-08
cs-137	5.84E-04
sm-151	8.82E-07
eu-152	1.27E-05
eu-154	2.57E-05
tl-204	1.99E-09
po-210	1.26E-04

	Relative mass
W-armor	31929.9
Cooling channel 1	36412.1
Cooling channel 2	61810.9
	SA/LMA
h-3	6.18E+00
be-10	1.10E-04
c-14	1.15E-03
na-22	3.94E-05
cl-36	1.66E-01
ca-41	8.08E-07
mn-54	7.10E+00
fe-55	2.38E+00
co-60	5.43E-02
ni-59	3.31E-04
ni-63	2.36E-03
zn-65	1.55E-04
sr-90	2.01E-06
zr-93	5.43E-06
nb-94	2.24E+00
mo-93	6.68E-03
tc-99	1.84E-04
pd-107	6.03E-09
ag-108m	3.46E-01
ag-110m	6.26E-04
cs-134	4.60E-08
cs-135	2.16E-09
cs-137	4.22E-05

Table 15. Reversed activation analysis for Mn-54 – one of the main contributors to ANDRA classification (MA-VL) for ARIES divertor (left) and PPCS divertor (right). In the W armors, Fe, Mn and Ni are impurities while in cooling channels, Fe is the main constituent and Mn is an alloying element.

Target: mn-54			
W armor		Cooling channel	
SA (Bq/g)	8.62E+05	SA (Bq/g)	1.02E+09
Parents	% Contribution to SA	Parents	% Contribution to SA
mn-55	84.92	fe-54	86.46
fe-54	14.67	mn-55	12.17
fe-56	0.39	fe-56	1.37

Target: mn-54					
W armor		Cooling channel 1		Cooling channel 2	
SA (Bq/g)	4.82e+05	SA (Bq/g)	1.74e+09	SA (Bq/g)	4.35e+09
Parents	% Contribution to SA	Parents	% Contribution to SA	Parents	% Contribution to SA
mn-55	85.14	fe-54	88.17	fe-54	89.11
fe-54	14.77	mn-55	11.47	mn-55	10.66
		fe-56	0.35	fe-56	0.23

Table 16. Reversed activation analysis for Fe-55 – one of the main contributors to ANDRA classification (MA-VL) for ARIES divertor (left) and PPCS divertor (right). In the W armors, Fe, Mn and Ni are impurities while in cooling channels, Fe is the main constituent and Mn is an alloying element.

Target: fe-55			
W armor		Cooling channel	
SA (Bq/g)	1.22E+06	SA (Bq/g)	7.74E+09
Parents	% Contribution to SA	Parents	% Contribution to SA
fe-56	94.34	fe-56	97.46
ni-58	4.14	fe-54	2.52
fe-54	1.50		

Target: fe-55					
W armor		Cooling channel 1		Cooling channel 2	
SA (Bq/g)	5.27e+05	SA (Bq/g)	1.04e+10	SA (Bq/g)	2.44e+10
Parents	% Contribution to SA	Parents	% Contribution to SA	Parents	% Contribution to SA
fe-56	93.54	fe-56	96.98	fe-56	95.52
ni-58	4.18	fe-54	3.01	fe-54	4.48
fe-54	2.26				

Table 17. Reversed activation analysis for Nb-94 – one of the main contributors to ANDRA classification (MA-VL) for ARIES divertor (left) and PPCS divertor (right). In the W armors and cooling channels, Nb and Mo are impurities.

Target: nb-94			
W armor		Cooling channel	
SA (Bq/g)	2.08e+02	SA (Bq/g)	1.96e+02
Parents	% Contribution to SA	Parents	% Contribution to SA
nb-93	97.03	nb-93	98.12
mo-94	2.31	mo-94	1.47
mo-95	0.66	mo-95	0.41

Target: nb-94					
W armor		Cooling channel 1		Cooling channel 2	
SA (Bq/g)	1.42e+02	SA (Bq/g)	1.00e+02	SA (Bq/g)	3.74e+02
Parents	% Contribution to SA	Parents	% Contribution to SA	Parents	% Contribution to SA
nb-93	98.53	nb-93	99.27	nb-93	99.82
mo-94	1.14	mo-94	0.56	mo-94	0.14
mo-95	0.33	mo-95	0.16		

Table 18. Reversed activation analysis for Ag-108m – one of the main contributor to ANDRA classification (MA-VL) for ARIES divertor. In the W armor and the cooling channel, Ag is an impurity.

Target: ag-108m			
W armor		Cooling channel	
SA (Bq/g)	3.40e+03	SA (Bq/g)	1.83e+03
Parents	% Contribution to SA	Parents	% Contribution to SA
ag-109	94.08	ag-109	90.77
ag-107	5.89	ag-107	9.20

Table 19. Waste disposal ratings and main contributors for each component of ARIES divertor (left) and PPCS divertor (right) using various W alloys after being exposed to a fluence of 3 MWy/m² and 1 MWy/m², respectively.

WDR at 100 years after Shutdown					
	Relative Volume				
W-armor	1111.56				
Cooling Channel	8007.1				
Pure-W	WDR		W-W	WDR	
W armor	0.03		W armor	1.26	
	Isotope	%		Isotope	%
	re-186m	98.51		nb-94	42.88
	hf-182	0.92		ag-108m	39.70
	hf-178n	0.57		tc-99	14.30
	-	-		re-186m	2.04
	-	-		nb-91	0.79
Cooling Channel	0.07		Cooling Channel	0.80	
	Isotope	%		Isotope	%
	nb-94	52.80		nb-94	53.94
	tc-99	21.44		ag-108m	28.51
	re-186m	15.91		tc-99	14.60
	al-26	2.91		re-186m	1.43
	ho-166m	2.22		nb-91	0.62
WDR (CC)	0.07		WDR (CC)	0.80	
WDR (W armor + CC)	0.07		WDR (W armor + CC)	0.86	
W-Re	WDR		W-La203	WDR	
W armor	1.26		W armor	1.26	
	Isotope	%		Isotope	%
	nb-94	42.88		nb-94	42.88
	ag-108m	39.70		ag-108m	39.70
	tc-99	14.30		tc-99	14.30
	re-186m	2.04		re-186m	2.04
	nb-91	0.79		nb-91	0.79
Cooling Channel	2.94		Cooling Channel	0.80	
	Isotope	%		Isotope	%
	re-186m	72.75		nb-94	53.88
	nb-94	14.91		ag-108m	28.47
	ag-108m	7.89		tc-99	14.58
	tc-99	4.03		re-186m	1.41
	-	-		nb-91	0.62
WDR (CC)	2.94		WDR (CC)	0.80	
WDR (W armor + CC)	2.73		WDR (W armor + CC)	0.86	
W-TiC	WDR		W-VM	WDR	
W armor	1.26		W armor	1.26	
	Isotope	%		Isotope	%
	nb-94	42.88		nb-94	42.88
	ag-108m	39.70		ag-108m	39.70
	tc-99	14.30		tc-99	14.30
	re-186m	2.04		re-186m	2.04
	nb-91	0.79		nb-91	0.79
Cooling Channel	0.76		Cooling Channel	0.66	
	Isotope	%		Isotope	%
	nb-94	53.77		tc-99	74.67
	ag-108m	28.26		nb-94	15.59
	tc-99	14.59		nb-91	3.18
	re-186m	1.40		ag-108m	2.92
	nb-91	0.62		re-186m	1.74
	c-14	0.53		-	-
WDR (CC)	0.76		WDR (CC)	0.66	
WDR (W armor + CC)	0.82		WDR (W armor + CC)	0.73	
W-5%Ta	WDR		W-K	WDR	
W armor	1.26		W armor	1.26	
	Isotope	%		Isotope	%
	nb-94	42.88		nb-94	42.88
	ag-108m	39.70		ag-108m	39.70
	tc-99	14.30		tc-99	14.30
	re-186m	2.04		re-186m	2.04
	nb-91	0.79		nb-91	0.79
Cooling Channel	0.79		Cooling Channel	0.80	
	Isotope	%		Isotope	%
	nb-94	53.98		nb-94	53.84
	ag-108m	28.51		ag-108m	28.45
	tc-99	14.61		tc-99	14.57
	re-186m	1.36		re-186m	1.43
	nb-91	0.62		nb-91	0.62
WDR (CC)	0.79		WDR (CC)	0.80	
WDR (W armor + CC)	0.85		WDR (W armor + CC)	0.86	

WDR at 100 years after Shutdown					
	Relative Volume				
W-armor	1650.12				
Cooling Channel 1	2690.95				
Cooling Channel 2	7853.00				
Pure-W	WDR		W-W	WDR	
W armor	0.01		W armor	0.65	
	Isotope	%		Isotope	%
	re-186m	97.89		nb-94	57.10
	hf-182	1.26		ag-108m	27.29
	hf-178n	0.85		tc-99	14.00
	-	-		re-186m	0.91
	-	-		nb-91	0.52
Cooling Channel 1	0.18		Cooling Channel 1	0.50	
	Isotope	%		Isotope	%
	nb-94	91.34		nb-94	73.40
	tc-99	6.06		ag-108m	14.28
	re-186m	1.56		tc-99	11.03
	al-26	0.80		re-186m	0.57
	-	-			
Cooling Channel 2	0.42		Cooling Channel 2	0.42	
	Isotope	%		Isotope	%
	nb-94	94.01		nb-94	94.01
	tc-99	5.40		tc-99	5.40
	al-26	0.45		al-26	0.45
WDR (CC1)	0.18		WDR (CC1)	0.50	
WDR*	0.31		WDR*	0.47	
W-Re	WDR		W-La203	WDR	
W armor	0.65		W armor	0.65	
	Isotope	%		Isotope	%
	nb-94	57.10		nb-94	57.10
	ag-108m	27.29		ag-108m	27.29
	tc-99	14.00		tc-99	14.00
	re-186m	0.91		re-186m	0.91
	nb-91	0.52		nb-91	0.52
Cooling Channel 1	0.81		Cooling Channel 1	0.50	
	Isotope	%		Isotope	%
	nb-94	45.00		nb-94	73.39
	re-186m	38.99		ag-108m	14.27
	ag-108m	8.79		tc-99	11.03
	tc-99	6.78		re-186m	0.56
	-	-		al-26	0.33
Cooling Channel 2	0.42		Cooling Channel 2	0.42	
	Isotope	%		Isotope	%
	nb-94	94.01		nb-94	94.01
	tc-99	5.40		tc-99	5.40
	al-26	0.45		al-26	0.45
WDR (CC1)	0.81		WDR (CC1)	0.50	
WDR*	0.54		WDR*	0.47	
W-TiC	WDR		W-VM	WDR	
W armor	0.65		W armor	0.65	
	Isotope	%		Isotope	%
	nb-94	57.10		nb-94	57.10
	ag-108m	27.29		ag-108m	27.29
	tc-99	14.00		tc-99	14.00
	re-186m	0.91		re-186m	0.91
	nb-91	0.52		nb-91	0.52
Cooling Channel 1	0.49		Cooling Channel 1	0.46	
	Isotope	%		Isotope	%
	nb-94	73.53		nb-94	60.48
	ag-108m	14.12		tc-99	29.03
	tc-99	10.97		ag-108m	8.43
	re-186m	0.56		nb-91	0.86
	al-26	0.34		re-186m	0.61
Cooling Channel 2	0.42		Cooling Channel 2	0.42	
	Isotope	%		Isotope	%
	nb-94	94.01		nb-94	94.01
	tc-99	5.40		tc-99	5.40
	al-26	0.45		al-26	0.45
WDR (CC1)	0.49		WDR (CC1)	0.46	
WDR*	0.47		WDR*	0.46	
W-5%Ta	WDR		W-K	WDR	
W armor	0.65		W armor	0.65	
	Isotope	%		Isotope	%
	nb-94	57.10		nb-94	57.10
	ag-108m	27.29		ag-108m	27.29
	tc-99	14.00		tc-99	14.00
	re-186m	0.91		re-186m	0.91
	nb-91	0.52		nb-91	0.52
Cooling Channel 1	0.50		Cooling Channel 1	0.50	
	Isotope	%		Isotope	%
	nb-94	73.43		nb-94	73.36
	ag-108m	14.27		ag-108m	14.28
	tc-99	11.03		tc-99	11.03
	re-186m	0.55		re-186m	0.57
	al-26	0.33		al-26	0.33
Cooling Channel 2	0.42		Cooling Channel 2	0.42	
	Isotope	%		Isotope	%
	nb-94	94.01		nb-94	94.01
	tc-99	5.40		tc-99	5.40
	al-26	0.45		al-26	0.45
WDR (CC1)	0.50		WDR (CC1)	0.50	
WDR*	0.47		WDR*	0.47	

Table 20. Summary of waste disposal ratings at 100 years after shutdown of a compacted ARIES divertor (W-armor + cooling channel) and PPCS divertor (W-armor + cooling channel 1 + cooling channel 2) using different W alloys in the cooling channels.

	WDR	Classification
Pure W	0.07	Class C LLW
W-W (W with impurities)	0.86	Class C LLW
W-La2O3	0.86	Class C LLW
W-TiC	0.82	Class C LLW
W-VM	0.73	Class C LLW
W-K	0.86	Class C LLW
W-5%Ta	0.85	Class C LLW
W-Re	2.73	HLW

	WDR	Classification
Pure W	0.31	Class C LLW
W-W (W with impurities)	0.47	Class C LLW
W-La2O3	0.47	Class C LLW
W-TiC	0.47	Class C LLW
W-VM	0.46	Class C LLW
W-K	0.47	Class C LLW
W-5%Ta	0.47	Class C LLW
W-Re	0.54	Class C LLW

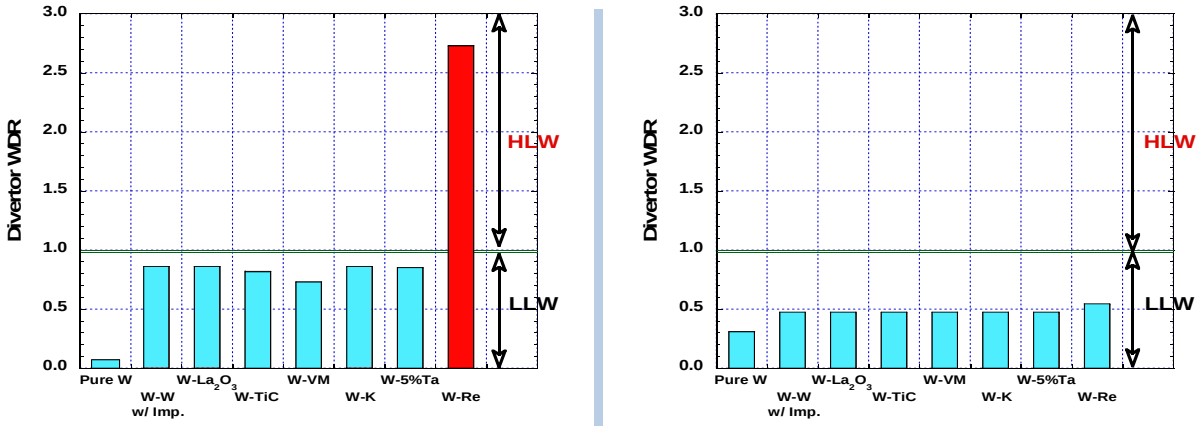


Figure 19. Waste disposal ratings of compacted ARIES and PPCS divertors at the end of 3 MWy/m² and 1 MWy/m² fluences, respectively.

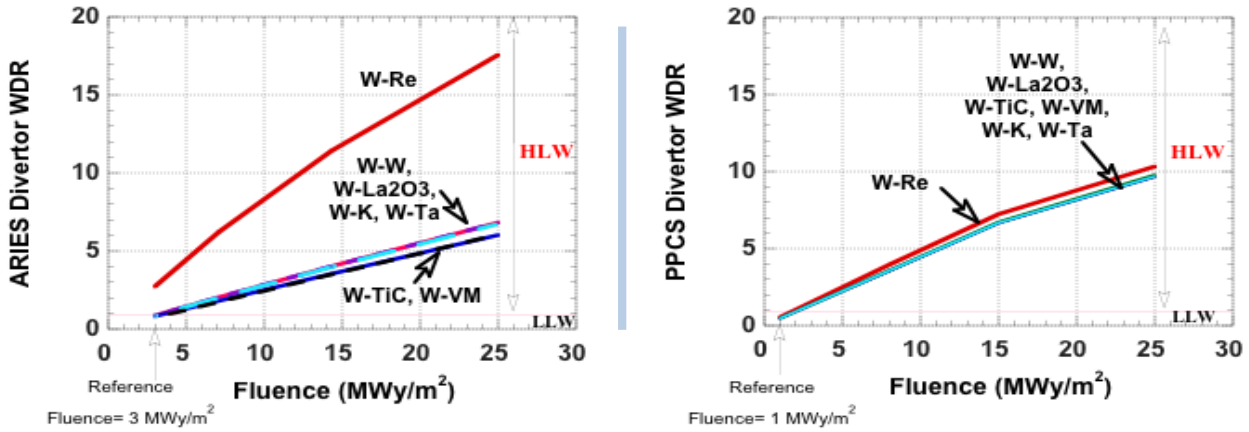


Figure 20. Waste disposal ratings of W-based alloys versus fluence for the ARIES and the PPCS divertors.

3.4.2.7. Waste classification of ARIES and PPCS divertors at 100 years based on US regulations

As detailed in Table 19, Table 20, and Figure 19, the ARIES divertor with any W alloy, except W-Re, classifies as low-level waste (LLW) and the PPCS divertor with any W alloy classifies as low-level waste (LLW). Interestingly, both the ARIES and PPCS divertors classify as low-level waste according to the US regulations, but as intermediate-level long-lived waste according to the French regulations.

Excluding W-Re alloy for the ARIES divertor, Figure 20 shows that divertors made with any alloy cannot be exposed to a fluence greater than ≈ 3.5 MWy/m² for ARIES and ≈ 2 MWy/m² for PPCS to avoid generating high-level waste.

3.5. Conclusions

The following points can be made:

ITER divertor:

- None of the divertor dome components could be cleared even after 100 years.
- The divertor dome could be handled immediately after shutdown with advanced remote handling equipment or after 30-80 y cooling period with conventional remote handling equipment.
- According to US regulations, the divertor dome ultimately classifies as high-level waste because of the use of 316-SS.
- At present, clearance is not considered in France and there is no possibility for recycling MA-VL radioactive waste. This means ITER waste will be disposed of in geological repositories.
- According to the French National Agency for Radioactive Waste Management (ANDRA), the divertor dome ultimately classifies as MA-VL (intermediate-level long lived waste) due to a high level of T, Ni-63, or Nb-94, depending on the component.
- Tritium from the plasma will increase the divertor T inventory further. This may cause problems for final disposal unless divertor materials are detritiated to recover the majority of T.

ARIES and PPCS divertors:

- From an activation viewpoint, the most attractive alloys appear to be W-TiC, W-1%Ta, W-K and W-La_2O_3 because their specific activity and recycling dose closely match that of W with nominal impurities.
- Both ARIES and PPCS divertors do not qualify for clearance, consequently they have to be recycled or disposed of in repositories.
- Advanced remote handling equipment could be used immediately after shutdown to handle and eventually recycle all W alloys, except W-5%Ta in the PPCS divertor case that requires a 4 month cooling period. More radiation resistant RH equipment could handle W-5%Ta immediately after shutdown.
- At the end of divertor service lifetime and according to US regulations:
    - ARIES divertor classifies as LLW for all W alloys, except W-Re.
    - PPCS divertor classifies as LLW for any W alloy.
    - The impact of the softer PPCS neutron spectrum on transmutation products is more pronounced for:
        - The WDR of pure W (see Fig. 19). It is three times higher for the PPCS divertor even though the fluence is three times lower.
        - Higher slope for the WDR vs. fluence curves of the PPCS divertor for all alloys, except W-Re (see Fig. 20).
    - Unlike ARIES-ACT, a PPCS divertor could afford a larger fluence (almost 2 times the reference fluence) before generating HLW.
    - ARIES-ACT could not adopt a PPCS divertor as it generates HLW under ARIES operating conditions of 3 MWy/m^2.
    - PPCS designs could employ an ARIES divertor to allow operating with higher fluences (up to 3.5 MWy/m^2), if desirable.
- At the end of divertor service lifetime and according to French regulations, both ARIES divertor (utilizing W-La_2O_3) and PPCS divertor (utilizing W-La_2O_3 and W-5%Ta) classify as MA-VL (intermediate-level long lived waste).
- French classification for W-K and W-1%Ta expected to be the same as for W-5%Ta and W-La_2O_3 alloys.
- W transmutation at the reference fluence is low (< 1%) and does not expect to degrade bulk properties of the W alloys:
    - ARIES divertor (at 3 MWy/m²) = 0.8%.
    - PPCS divertor (at 1 MWy/m²) = 0.5%.

4. Sensitivity of transmutations in tungsten armor to PPCS blanket concept

4.1. Introduction

We studied the transmutation of a 2 mm thick tungsten protective armor on the plasma-facing surface of five PPCS blankets of Models A, AB, B, C, and D. The plasma boundary for each model is shown in Figure 21. Models A, AB and B are so-called near-term models whose concepts are close to the current technological feasibility. Models-C and D represent the most advanced models for which some physics and engineering issues remain to be solved or developed [24].

The transmutation results are quite sensitive to the first wall and blanket materials because of neutron back-scattering which softens the spectrum producing high reaction rates in W resonance regions. Therefore, the efficiency of transmutation depends on the neutron absorption cross-sections that can be very important when an incident neutron energy equals an excitation energy of W. Thus, the neutron spectrum at the W armor is very dependent on the blanket concept and will have a notable impact on the W transmutation.

4.2. Methodology

The analysis was conducted for a simplified radial build with FW and blanket materials following the W armor (refer to Table 23) of the PPCS 5 models (see Fig. 22). For a fair comparison between results, the transmutation calculations for all blankets are based on Model-C plasma dimensions which represents an intermediate dimension between the 5 PPCS models shown in Figure 21 and Table 21. Thus, the simplified 1-D model presented in Figure 22 is common to all 5 PPCS models considered in this analysis. Moreover, the transmutation calculations for all models are based on a common outboard neutron wall loading peak value of 3 MW/m² which also represents the average value between PPCS models shown in Table 22. In addition, pure W is considered for the 2 mm thick W armor as impurities will not impact the W transmutation.

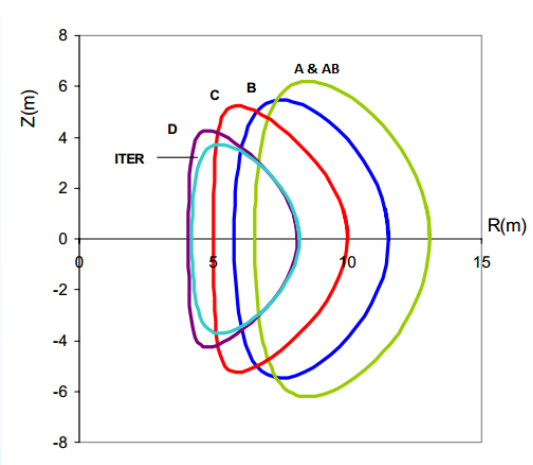


Figure 21. Sizes and shapes of plasma in PPCS models.

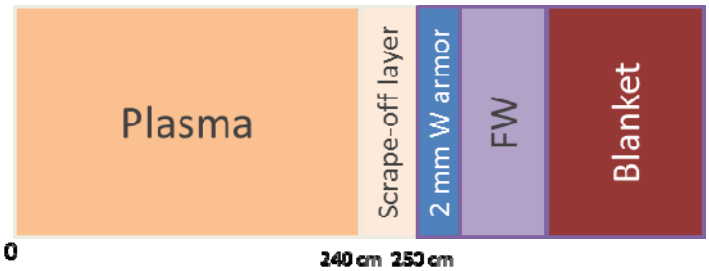


Figure 22. Simplified 1-D model used in the analysis.

Table 21. Dimensions of PPCS models.

	Model A	Model AB	Model B	Model C	Model D
Major radius (m)	9.55	9.56	8.6	7.5	6.1
Minor radius (m)	3.2	3.2	2.8	2.5	2.03
Plasma elongation	1.7	1.7	1.7	1.9	1.9

Table 22. Neutron wall loading for PPCS models.

	Model A	Model AB	Model B	Model C	Model D
Inboard peak value	2.69	?	1.99	2.69	2.94
Outboard peak value	3.05	?	2.41	3.10	3.44
Average value	2.56	1.90	1.94	2.23	2.59

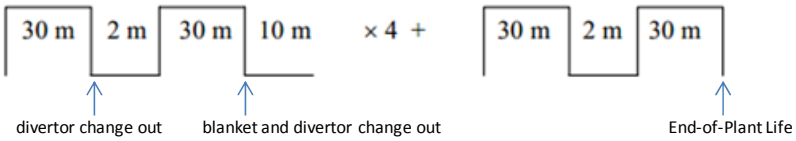
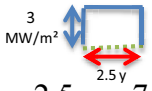
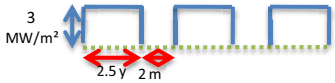


Figure 23. Reference PPCS operational scheme [25].



3 MW/m² x 1 pulses x 2.5 y = 7.5 MW y/m²

3 MW/m² x 2 pulses x 2.5 y = 15 MW y/m² (reference component lifetime)



3 MW/m² x 3 pulses x 2.5 y = 22.5 MW y/m²

3 MW/m² x 4 pulses x 2.5 y = 30 MW y/m²

Figure 24. Irradiation schedule considered in 1-D analysis.

Table 23. Detailed PPCS radial builds [24]. Thicknesses in cm.

PPCS plant model A (WCLL)				
	Outboard		Composition	
component	thickness	cumul.	Material	Vol. Frac.
W armor	0.2	0.2	W	1
FW front	0.7	0.9	Eurofer	0.444
FW middle	0.3	1.2	Eurofer	0.35
			Water	0.65
FW back	1.1	2.3	Eurofer	1
Blanket breeder front	15.9	18.2	Eurofer	0.09
			LiPb	0.89
			Water	0.08
Blanket structure	0.8	19	Eurofer	1
Blanket breeder	15.9	34.9	Eurofer	0.037
			LiPb	0.93
			Water	0.033
Blanket structure	0.8	35.7	Eurofer	1
Blanket breeder middle	15.9	51.6	Eurofer	0.037
			LiPb	0.93
			Water	0.033
Blanket structure middle	0.8	52.4	Eurofer	1
Blanket breeder	15.9	68.3	Eurofer	0.048
			LiPb	0.92
			Water	0.038
Blanket structure	0.8	69.1	Eurofer	1
Blanket breeder back	15.9	85	Eurofer	0.048
			LiPb	0.91
			Water	0.042
Blanket backplate	6	91	Eurofer	0.997
			Water	0.003
Manifold	10.9	101.9	Eurofer	0.56
			Water	0.4
Shield	15	116.9	Eurofer	0.56
			Water	0.4
Vacuum vessel	78	194.9	SS-316	0.614
			Boron	0.016
			Water	0.37
TF coil	245.8	440.7	SC coil	0.95

PPCS plant model B (HCPB)				
	Outboard		Composition	
component	thickness	cumul.	Material	Vol. Frac.
W armor	0.2	0.2	W	1
FW front	0.4	0.6	Eurofer	1
FW middle	1.4	2	Eurofer	0.27
			He	0.73
FW back	0.5	2.5	Eurofer	1
Blanket breeding zone	46.5	49	Eurofer	0.098
			Be	0.692
			Li_4SiO_4	0.154
			He	0.055
Blanket back wall	2	51	Eurofer	1
HT shield	27	78	Eurofer	0.6
			He	0.4
gap	2	80	void	1
LT shield	25	105	Eurofer	0.6
			ZrH	0.3
			Water	0.1
Manifold	25	130	Eurofer	0.15
			He	0.85
gap	44	174	void	1
Vacuum vessel	5	179	SS-316	1
Vacuum vessel	65	244	SS-316	0.6
			Water	0.4
Vacuum vessel	5	249	SS-316	1
gap	10	259	void	1
Inner TF-coil case	10	269	SS-316	1
TF coil	60	329	SC coil	0.95
Outer TF-coil case	10	339	SS-316	1

PPCS plant model AB (MCNP)				
	Outboard		Composition	
component	thickness	cumul.	Material	Vol. Frac.
W armor	0.2	0.2	W	1
Blanket FW	2.5	2.7	Eurofer	0.7
			He	0.3
Blanket breeder	77.5	80.2	Eurofer	0.1
			LiPb	0.8
			He	0.1
Blanket manifold	25.4	105.6	Eurofer	0.5
			He	0.5
HT shield	40	145.6	Eurofer	0.5
			He	0.5
LT shield	30	175.6	Eurofer	0.1
			WC	0.65
			Water	0.25
Vacuum vessel	102	277.6	SS-316	0.2
			Boron	0.6
			Water	0.2
TF coil	270	547.6	SC coil	0.95

PPCS plant model C (SCLL)				
	Outboard		Composition	
component	thickness	cumul.	Material	Vol. Frac.
W armor	0.2	0.2	W	1
FW	4.4	4.6	Eurofer	0.45
			He	0.65
Blanket	77.1	81.7	SiC	0.0904
			CC	0.1025
			LiPb	0.7716
			He	0.0355
Structure	4	85.7	Eurofer	1
He in/out	9	94.7	He	1
Structure	1.5	96.2	Eurofer	1
He in/out	9	105.2	He	1
Structure	3	108.2	Eurofer	1
HT shield	25	133.2	Eurofer	1
LT shield	30	163.2	Eurofer	0.6
			Water	0.4
Vacuum vessel	75	238.2	SS-316	0.614
			Boron	0.016
			Water	0.37

PPCS plant model D (SCLL)				
	Outboard		Composition	
component	thickness	cumul.	Material	Vol. Frac.
W armor	0.2	0.2	W	1
SiC FW	0.9	0.9	SiC	0.1
			LiPb	0.8
			He	0.1
Blanket	69.1	1.2	SiC	0.0904
			CC	0.1025
			LiPb	0.7716
			He	0.0355
HT shield	33	18.2	SiC	0.1
			WC	0.8
			LiPb	0.1
LT shield	35	18.2	Borated Steel	0.2
			WC	0.6
			He	0.2
Vacuum vessel	42	18.2	Borated Steel	0.2
			WC	0.6
			He	0.2

The reference PPCS operational scheme described in Figure 23 consists of 2.5 years at full power, then 2 months shutdown for divertor replacement, another 2.5 y of full power, then 10 months for blanket and divertor replacement. The scheme is repeated to accumulate an operating time of 25 FPY – the end of plant life. The maximum lifetime for W-armor/FW/blanket is taken to be 5 FPY.

The irradiation schedule considered in the 1-D analysis is described in Figure 24. The reference lifetime for the W-armor/FW/blanket is 5 FPY and the NWL is ~3 MW/m^2, corresponding to a fluence of 15 MWy/m². The possibility of extending the FW/blanket lifetime up to 10 FPY was considered if more radiation resistant structure becomes available.

4.3. Neutron spectra in W armor

PPCS Model-A utilizes a water cooled blanket, whereas the other four models are helium-cooled. The Model-B blanket concept uses lithium orthosilicate (Li_4SiO_4) as breeder and beryllium as neutron multiplier, whereas Model-A, AB, C, and D use LiPb as the breeder . The different blanket concepts are summarized in Table 24.

Figure 25 shows the neutron energy spectra in the W armor of the different PPCS models. The spectra are dominated by the 14.1 MeV source neutrons coming directly from D-T reactions within the plasma. A broad spectrum of reduced energy neutrons is backscattered from materials behind the W armor. The neutron spectrum in front of Model-AB, C, and D blankets are the hardest, followed by the spectrum for Model-B, then Model-A. The softest spectrum in Model-A is mainly due to the use of water as a coolant for the FW/blanket. The water moderates neutrons through scattering reactions with the hydrogen atoms. The softer spectrum in Model-B is mainly due to the use of beryllium as a neutron multiplier.

Table 24. PPCS blankets concepts.

Blanket:	A	AB	B	C	D
Stuctural material	Eurofer	Eurofer	Eurofer	SiC, CC	SiC, CC
Breeder / Neutron multiplier	LiPb	LiPb	Li_4SiO_4/Be	LiPb	LiPb
Coolant	H_2O	He	He	He	He

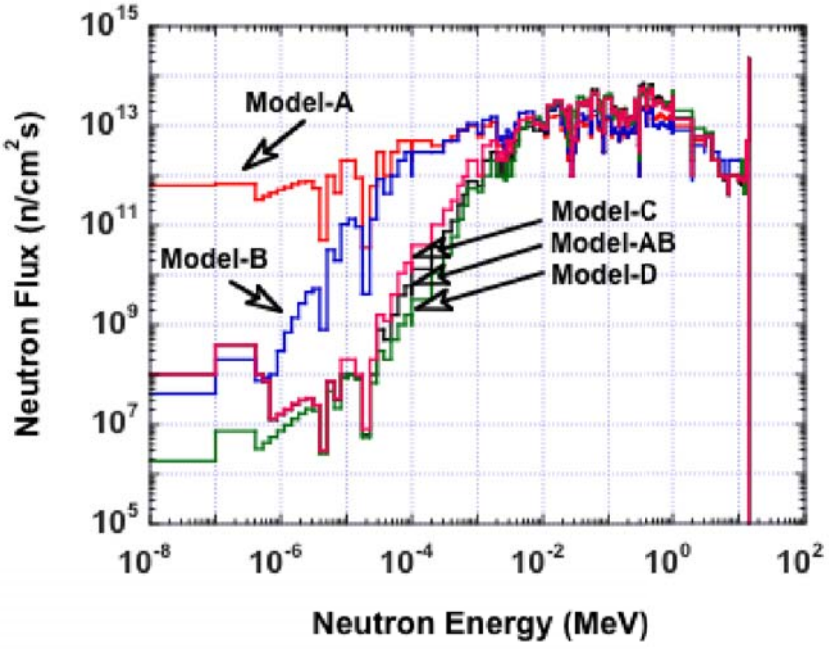


Figure 25. Neutron energy spectra in the W armor of PPCS models normalized to 3 MW/m² NWL.

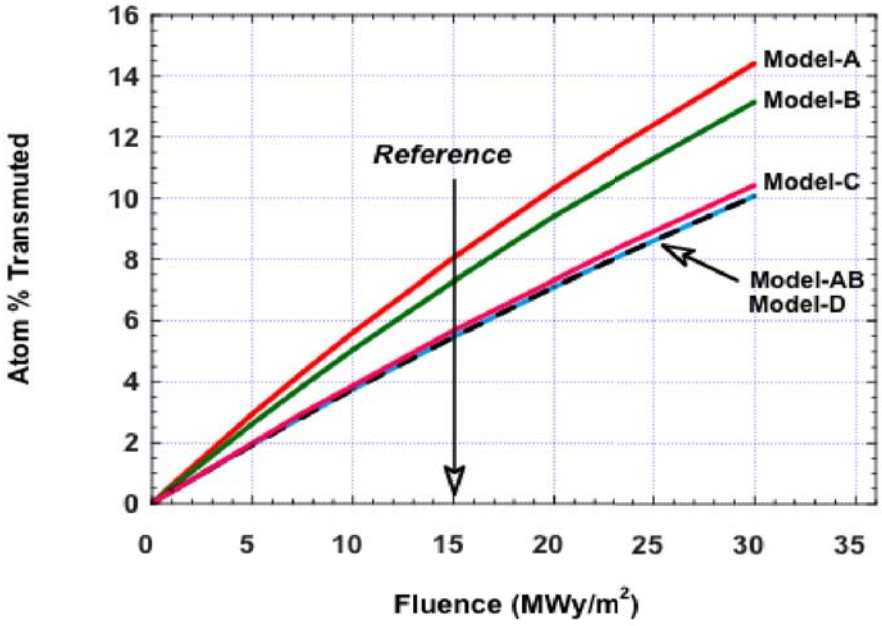


Figure 26. Percentage of W transmuted in the first pure W protective armor of different PPCS models versus fluence.

4.4. Degree of transmutation in W armor

Figure 26 indicates that the neutron spectra and the fluence have a significant impact on W transmutation, especially at higher fluences. The softer spectrum (of Model-A with water coolant and Model-B with Be multiplier) results in higher W transmutation. After 5 FPY of irradiation (the reference component lifetime), the percentage of W transmuted in Model-A is 8.05%, 5.5% in Model-AB, 7.3% in Model-B, 5.7% in Model-C, and 5.5% in model D (see Table 25). Our results are consistent with previous findings [4,5,23]. The possibility of extending the W-armor/FW/blanket lifetime up to 30 MWy/m² has been considered to represent a case with more radiation resistant FW/blanket structure. The transmutation products in W are mainly Re, Ta and Os as shown in Table 26. This means after an extended irradiation period under a typical D-T neutron spectrum, pure W will turn into W-ReOsTa alloy exhibiting different materials properties which could be detrimental in the protective role of the W armor.

Table 25. Percentage of transmutation in pure W armor in PPCS models at various fluences.

Fluence (MWy/m²)	A	AB	B	C	D
0	0	0	0	0	0
7.5	4.30	2.85	3.85	2.97	2.85
15	8.05	5.47	7.29	5.67	5.46
22.5	11.39	7.87	10.37	8.15	7.86
30	14.42	10.08	13.16	10.43	10.07

Table 26. Transmutation products in W armor for the five PPCS models (contributors < 0.1 % are not included).

PPCS-A		PPCS-AB		PPCS-B		PPCS-C		PPCS-D	
Number Density (atoms /m^3)	2.46E+27	Number Density (atoms /m^3)	1.67E+27	Number Density (atoms /m^3)	2.23E+27	Number Density (atoms /m^3)	1.74E+27	Number Density (atoms /m^3)	1.67E+27
radioisotope	% Contribution to Number Density	radioisotope	% Contribution to Number Density	radioisotope	% Contribution to Number Density	radioisotope	% Contribution to Number Density	radioisotope	% Contribution to Number Density
re-185	25.96	re-185	44.83	re-185	40.33	re-185	44.82	re-185	44.95
re-187	25.16	ta-181	28.66	ta-181	19.25	ta-181	27.28	ta-181	29.15
os-186	16.22	re-187	13.18	re-187	19.12	re-187	13.92	re-187	12.73
ta-181	15.23	os-186	3.83	os-186	8.50	os-186	4.34	os-186	3.69
os-188	8.07	w-181	3.23	os-188	4.32	w-181	3.10	w-181	3.28
w-185	2.82	w-185	3.06	w-185	3.12	w-185	3.09	w-185	3.06
w-181	2.00	os-188	1.02	w-181	2.35	os-188	1.26	os-188	0.94
os-187	1.76	hf-180	0.75	os-187	0.68	hf-180	0.72	hf-180	0.78
os-189	0.74	ta-182	0.29	ta-182	0.54	ta-182	0.33	ta-182	0.29
ta-182	0.50	h-1	0.21	hf-180	0.54	ta-180m	0.20	h-1	0.21
hf-180	0.44	ta-180m	0.21	os-189	0.30	h-1	0.20	ta-180m	0.22
os-190	0.24	re-186m	0.13	re-186m	0.15	re-186m	0.13	re-186m	0.13
re-186m	0.16	hf-179	0.11	ta-180m	0.15	os-187	0.13	hf-179	0.12
h-1	0.14	re-184	0.10	h-1	0.15	hf-179	0.11	re-184	0.10
ta-180m	0.12	os-187	0.10			re-184	0.10		
re-186	0.10								

4.5. Conclusions

The transmutation in a W protective armor is an important phenomenon to take into consideration by the materials community as it could directly affect the bulk properties of W and impact their performance in a fusion device. As shown in the analysis, materials behind the W armor with a high potential for neutron moderation, such as water and beryllium, can have a significant impact on the W transmutation in comparison with other materials (about 30% difference between water-cooled and a helium cooled system). In summary:

- W transmutation is sensitive to neutron spectrum and fluence.
- Blanket with softest spectra (Model-A and Model-B) results in highest W being transmuted
    - Softer spectrum in Model-A mainly due to use of water as coolant.
    - Softer spectrum in Model-B mainly due to use of beryllium multiplier.
- Percentage of W transmuted in W armor after 5 FPY of irradiation (maximum component lifetime) are:
    - Model-A: 8.1%
    - Model-AB: 5.5%
    - Model-B: 7.3%
    - Model-C: 5.7%
    - Model-D: 5.5%.

5. General observations and main conclusions

The past decade has witnessed more challenging operating conditions for the FW and divertor due to the significantly higher heat flux than previously anticipated, coupled with notable surface erosion/blistering and absorption of tritium. At present, ITER will utilize W armor for the divertor dome. Power plant designs, such as ARIES and PPCS, will likely require the full application of W to all plasma facing components to withstand the high heat flux conditions and cope with the tritium retention limitations.

Several puzzling W-related issues remained widely recognized within the fusion community: what is the best W alloy for fusion applications, how does it transmute under neutron irradiation, and any adverse environmental impact for the candidate alloy(s)? This study addressed a few W-related issues, identifying a list of the most recent W alloys for fusion applications, a scheme to handle the continuous stream of radioactive W generated during ITER, ARIES, and PPCS operations, and the sensitivity of transmutation in a W armor to the neutron flux at the surface of various PPCS blanket concepts.

One of the main goals of fusion is to evolve toward a radwaste-free nuclear system. This will greatly depend on the development of a new strategy that recycles all materials, avoids the geological disposal, and minimizes the volume of radwaste by clever designs. Our analysis indicates that the classification of radwaste as LLW or HLW (according to US regulations) or as MA-VL (according to French regulations) is very dependent on the choice of materials, alloying elements (such as Re, Mo, Ni, and Cu), and impurities (especially Nb, Ag, and Mo). In fact, in most cases, geological disposal could be avoided, but clearance is not feasible particularly for plasma-facing components (FW/blanket and divertor) even after an extended storage period of 100 years. Nevertheless, all components could be handled shortly after shutdown and eventually recycled with advanced remote handling equipment.

For the ITER divertor, the dome classifies as MA-VL (intermediate-level long lived waste) due to the high level of T, Ni-63, or Nb-94. In France, there is no possibility for recycling MA-VL radioactive waste. This means ITER waste will be disposed of in geological repositories.

For ARIES and PPCS divertors, the most attractive alloys appear to be W-TiC, W-1%Ta, W-K and W-La_2O_3 because their specific activity and recycling dose closely match that of W with nominal impurities. At the end of the divertor service lifetime and according to US regulations ARIES divertor classifies as LLW for all W alloys, except W-Re while the PPCS divertor classifies as LLW for any W alloy. According to French regulations, both the ARIES divertor (utilizing W-La_2O_3) and PPCS divertor (utilizing W-La_2O_3, W-K, and W-Ta) classify as MA-VL (intermediate-level long lived waste).

The transmutation in W strongly depends on the neutron spectrum and fluence. The five PPCS blanket concepts offer a wide variety of neutron spectra at the FW where the W armor is attached. Generally speaking, W transmutes at a higher rate in the presence of a soft spectra caused by water coolant and/or beryllium multiplier. Our analysis demonstrated the notable impact of neutron energy spectrum on W armor transmutation (up to 50% increase). The percentage of W transmuted in W armor at the surface of the PPCS FW/blanket after 5 FPY of irradiation (maximum component lifetime) reached 8%. This feature is important to take into consideration by the materials community, especially when W is used as a structural material. Transmutations into Re, Os, and Ta could affect the bulk properties of W structure as such byproducts, as well as the He and H gases, could migrate to the grain boundary and make the W more brittle. Fortunately, our analysis shows that, for both ARIES and the PPCS divertors, the degree to which the W transmutes is low. Less than 1 at.% of the W transmutes at the end of the divertor lifetime. Such a low transmutation level is not expected to impair the physical properties of the structural W alloys employed for the ARIES and PPCS divertors.

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References

1. The ITER project: http://www.iter.org/.
2. Maisonnier, D., Cook, I., Sardain, P., Andreani, R., Di Pace, L., Forrest, R. et al., "A Conceptual Study of Fusion Power Plants," European Fusion Development Agreement Final Report EFDA-RP-RE-5.0 (2005). Available at: http://www.efda.org/eu_fusion_programme/scientific_and_technical_publications.htm.
3. The ARIES project: http://aries.ucsd.edu/ARIES/.
4. L. El-Guebaly, R. Kurtz, M. Reith, H. Kurishita, A. Robinson, "W-Based Alloys for Advanced Divertor Designs: Options and Environmental Impact of State-of-the-Art Alloys," Fusion Science and Technology 60, Number 1 (July 2011) 185-189.
5. A. Robinson, L. El-Guebaly, D. Henderson, "Activation and Radiation Damage Characteristics of W-Based Divertor of ARIES Power Plants," Fusion Science and Technology 60, Number 2 (July 2011) 715-719.
6. R. Alcouffe et al., "DANTSYS: A Diffusion Accelerated Neutral Particle Transport Code System," Los Alamos National Laboratory Report, LA-12969-M (1995).
7. A. Pashchenko, H. Wienke, J. Kopecky, J. Sublet and R. Forrest, "FENDL/A-2.0, Nuclear Activation Cross Section Data Library for Fusion Applications," International Atomic Agency Report IAEA-NDS-173 (1998).
8. D. Henderson, University of Wisconsin-Madison, private communications (April 2012).
9. P. Wilson and D. Henderson, "ALARA: Analytic and Laplacian Adaptive Radioactivity Analysis: A Complete Package for Analysis of Induced Activation - Volume I," University of Wisconsin Fusion Technology Institute, UWFDM-1070 (1998). Available at: http://fti.neep.wisc.edu/pdf/fdm1070.pdf .
10. P. Wilson and D. Henderson, "ALARA: Analytic and Laplacian Adaptive Radioactivity Analysis: A Complete Package for Analysis of Induced Activation - Volume II," University of Wisconsin Fusion Technology Institute, UWFDM-1071 (1998). Available at: http://fti.neep.wisc.edu/pdf/fdm1071.pdf .
11. D.L Aldama, A. Trkov, "FENDL-2.1 Update of an Evaluated Nuclear Data Library for Fusion Applications," International Atomic Agency Report INDC(NDC)-467(2004).
12. International Atomic Energy Agency, Application of the concepts of exclusion, exemption and clearance, IAEA Safety Standards Series, No. RS-G-1.7 (2004). Available at: http://www-pub.iaea.org/MTCD/publications/PDF/Pub1202_web.pdf .
13. L. El-Guebaly, P. Wilson, and D. Paige, "Evolution of Clearance Standards and Implications for Radwaste Management of Fusion Power Plants," Fusion Science and Technology, 49, 62-73 (2006).
14. L. El-Guebaly, V. Massaut, K. Tobita, and L. Cadwallader, "Goals, Challenges, and Successes of Managing Fusion Active Materials," Fusion Engineering and Design 83, Issues 7-9 (2008) 928-935.
15. S. Fetter, E. T. Cheng, and F. M. Mann, "Long Term Radioactive Waste from Fusion Reactors: Part II," Fusion Engineering and Design, 13 (1990) 239.
16. Nuclear Regulatory Commission, 10CFR61, "Licensing Requirements for Land Disposal of Radioactive Waste," Federal Register FR47 (1982) 57446.
17. ITER report, Recommendation on plasma scenarios (2V3V8G), 10 Dec 2009/v1.2/Approved.
18. X.R. Wang, S. Malang and M.S. Tillack, "High Performance Target Concept for a Power Plant: a Combination of Plate and Finger Concepts," Fusion Science and Technology 60, Number 1 (July 2011) 218-222.
19. P. Norajitra, M. Richou, L. Spatafora, "Technological Study on Manufacturing of Multifinger Module of He-cooled Demo Divertor and Investigation of NDE Method," To be published in Fusion Science and Technology (July/August 2012).
20. A. Jaber, University of Wisconsin-Madison, private communications (April 2012).
21. A. Robinson, L. El-Guebaly and D. Henderson, "W Based Alloys for Advanced Divertor Designs: Detailed Activation and Radiation Damage Analysis," University of Wisconsin Fusion Technology Institute Report UWFDM-1378 (2010). Available at: http://fti.neep.wisc.edu/pdf/fdm1378.pdf.
22. R. Pampin, "Tungsten transmutation and resonance self-shielding in PPCS models for the study of sigma-phase formation," EURATOM/UKAEA Fusion, UKAEA FUS 525 (October 2005).
23. M.R. Gilbert and J.-Ch. Sublet, Neutron-induced transmutation effects in W andW-alloys in a fusion environment, Nucl. Fusion 51 (2011) 043005 (13pp).
24. R. Pampin, P. Karditsas and N. Taylor, "Neutron Transport and Material Activation in a Power Plant Based on the HCLL Blanket Concept," IAEA Technical Meeting on First Generation of Fusion Power Plants, Vienna (July 2005).
25. Y. Chen, U. Fischer, P. Pereslavtsev and F. Wasastjerna, "The EU Power Plant Conceptual Study – Neutronic Design Analyses for Near Term and Advanced Reactor Models," Institut für Reaktorsicheiheit, Programm Kernfusion, FZKA 6763 (2003).