W-Based Alloys for Advanced Divertor Designs: Detailed Activation and Radiation Damage Analyses

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FUSION TECHNOLOGY INSTITUTE

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Abstract

Currently, there is an ongoing international effort to develop and characterize W alloys that are suitable for fusion applications. In this report, five key W alloys were examined for the advanced divertor design of ARIES-DB – the latest ARIES tokamak design. The most promising alloys appear to be W-1.1TiC and W-La_2O_3. At the end of the divertor lifetime (~ 4 years), the specific activity and maintenance dose of these alloys very closely match those of W with nominal impurities. Unfortunately, not even pure W meets the IAEA clearance index after 100 years, which indicates that the divertor must be recycled or disposed of in a geological repository.

The radiation damage and transmutation are expected to degrade the physical properties of any material. Fortunately, the radiation damage level in W is low compared to ferritic steel – a remarkable feature for tungsten. For the hard neutron spectrum at the front of the ARIES-DB divertor, the transmutation of W does not appear to present a significant issue. However, the transmutation of Re in the commercially available W-26Re alloy is significant. Moreover, under ARIES operating conditions, the W-26R alloy generates high-level waste, which is undesirable. For these reasons, the use of W-26Re alloy should be avoided.

1. Introduction

Analyses done in recent years have shown that previous divertor designs were inefficient in dealing with the thermal heat loads from the plasma. In order to withstand heat fluxes of 10 MW/m^2 or more and to operate at high temperatures of 800-1200^{o}C, the Europeans and American fusion experts have redesigned their power plant divertors over the past 10 years [1], switching from water coolant to He coolant to be able to operate at elevated temperatures, increase the thermal conversion efficiency above 40%, and enhance the economics of the overall design.

A helium-cooled divertor with W alloy structure is judged as an innovative and credible concept for dealing with these conditions. In addition, the use of a W armor, which will face the largest surface effects of the plasma, has been deemed mandatory in these divertor designs to protect the divertor surface during operation. Figure 1 shows the newly developed ARIES divertor design complete with dimensions [2].

Currently, there is an ongoing effort to develop and characterize W alloys that are suitable for such a fusion environment [3]. In this report, the detailed activation and radiation damage characteristics of several W alloys that have been developed for use in advanced divertor designs will be analyzed. To conduct these analyses, the newest ARIES design,

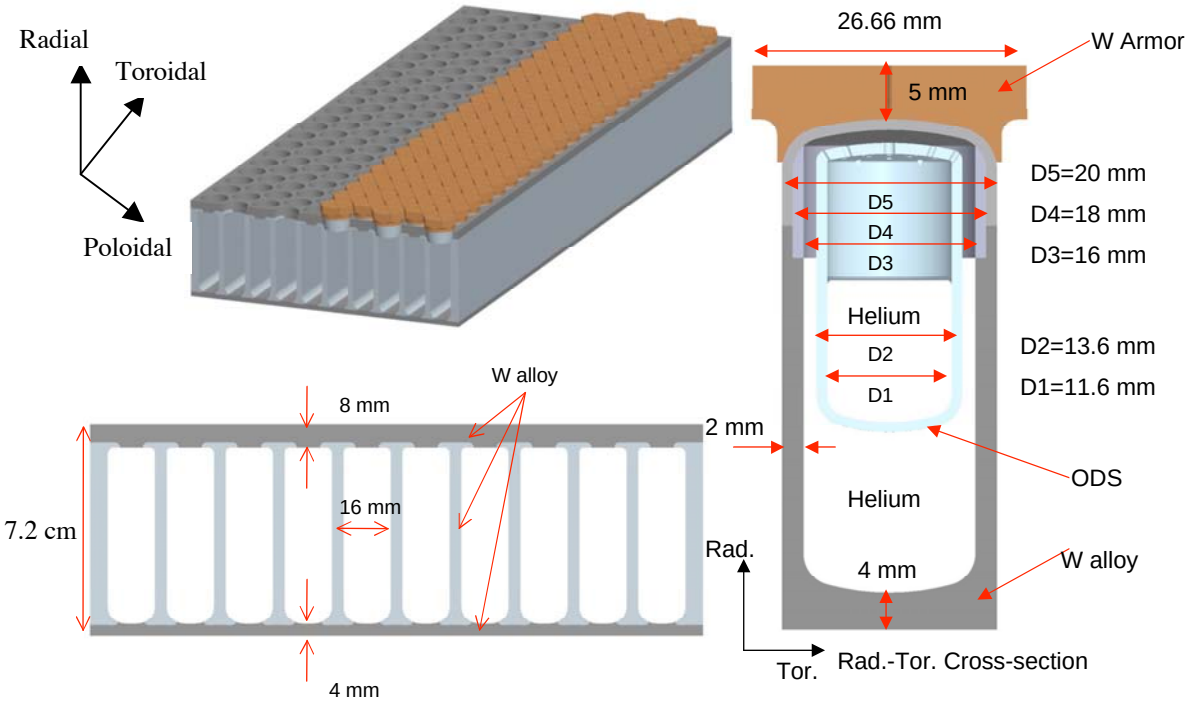

Figure 1. Several views of the ARIES advanced divertor design with dimensions. The top left diagram shows an isometric view of the divertor. The brown colored top material is the 0.5 cm thick W armor. The bottom left diagram shows a poloidal-radial cross section of the cooling channels without the W armor. The right diagram shows the radial-toroidal cross section of a unit cell. Courtesy of X. Wang (UCSD).

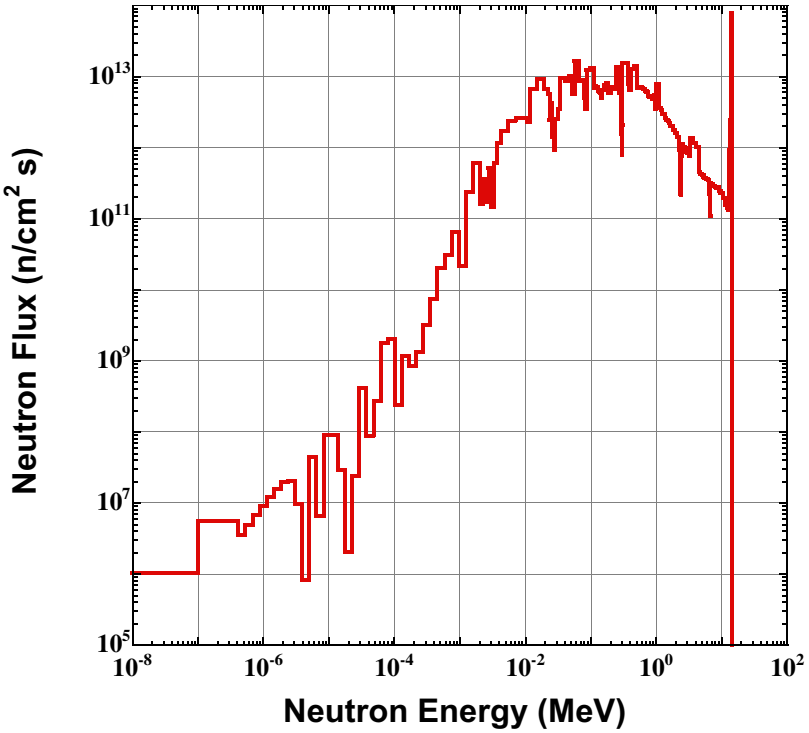

Figure 2. The neutron energy spectrum at the surface of the divertor for ARIES-DB. In this hard neutron spectrum, 13% of the neutrons carry 14.1 MeV.

ARIES-DB, which is still under development, was used. However, the results of the analyses apply to any divertor design that has a neutron spectrum similar to the ARIES-DB's shown in Fig. 2. Near the end of this report, the effects of other softer neutron spectra on the characteristics of W will be discussed.

The environmental impact of the W alloys has been also analyzed. There is a growing international effort to avoid the geological disposal of radioactive materials. Instead, recycling (reuse within the nuclear industry) and clearance (release to the commercial market if materials contain traces of radioactivity) offer an alternate, more environmentally attractive means for dealing with the radwaste stream [4]. We applied all three scenarios (disposal, recycling, and clearance) to the ARIES W-based divertor to identify the technical issues for each approach. The neutron wall loading (NWL) averages 1 MW/m^2 over the divertor surface. The design calls for replacing the divertor with the blanket on the same time basis every 3.4 full power years (FPY), assigning a lifetime of 3.4 MWy/m^2 to the divertor. Extended lifetimes (up to 20 MWy/m^2) have also been examined to represent a situation where the divertor can be reused for 20 FPY without a mechanical failure. The details of the divertor radial dimensions, compositions, alloying elements, and impurities are all given in Table 1.

Table 1. ARIES-DB divertor composition and list of W impurities.

Divertor composition (by volume):		
W armor		88% W
		12% void
Cooling channel		30% W alloy structure
		3% W
		12% FS
		56% He coolant
W alloy composition (by weight):		
W-26Re		74% W, 26% Re
W-La_2O_3		99% W, 1% La_2O_3
W-1.1TiC		98.9% W, 1.1% TiC
W-Ni-Cu		90% W, 6% Ni, 4% Cu
W-Ni-Fe		90% W, 7% Ni, 3% Fe
W impurities (in wppm):		
C 10	Ba < 2	Na < 2
H 2	Ca < 2	Nb < 5
N < 2	Cd < 2	Mo 20
O 5	Co < 2	Ni < 2
P < 10	Cr < 5	Pb < 2
S < 2	Cu < 5	Ta < 10
Si 5	Fe 10	Ti < 2
Ag < 5	K 5	Zn < 2
Al 5	Mg < 2	Zr < 2
As < 2	Mn < 2	

2. Methodology and Codes

Before conducting our analyses a radial build of the ARIES-DB near the divertor region was developed. The two main regions of interest in this analysis are the 0.5 cm thick W armor and the 7.2 cm thick cooling channel, which make up the complete divertor (refer to Fig. 1). The W armor region consists of W. Depending on the analysis, the W was assumed to be either pure or contain impurities given in Table 1. The cooling channel, which is a homogenized region in our model, consists of 29.6% W alloy, 2.6% W, 11.6% ODS-MF82H, and 56.2% He coolant, by volume.

Two codes were used to conduct the activation and radiation damage analyses for the divertor. The first code was the DANTSYS discrete ordinate, neutral particle transport code [5]. The code was run in the $S_{12}P_5$ approximation using one-dimensional cylindrical equivalent geometry model. The cross section data library used was the coupled neutron and dose using the rigorous biological dose method developed by the UW-Madison Fusion Technology Institute [7]. In addition, the DANTSYS code was used to calculate the atomic displacement and helium production rates in the W and ferritic steel components. The second code was the ALARA activation code [8,9]. Input data to this code is the IAEA FENDL-2 activation library [10]. The operational schedule reflects the 85% availability of ARIES-DB and the ALARA code accurately models all operation and downtimes.

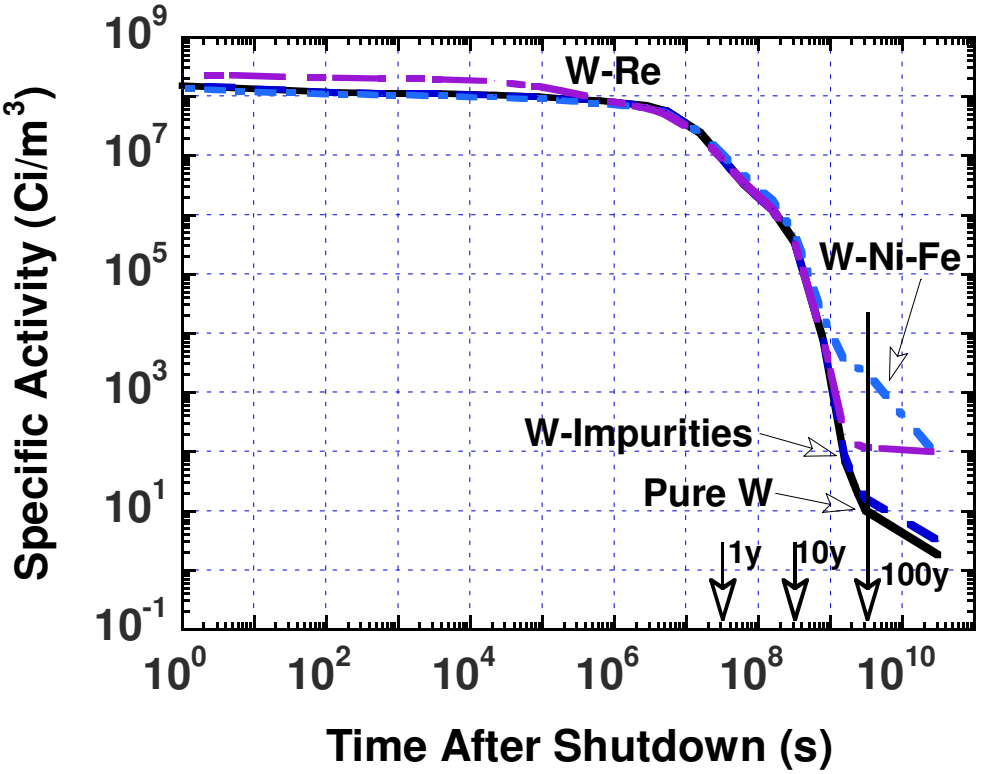

Figure 3. Specific activity of the W alloys in the divertor cooling channel versus time after shutdown. The activities of W-1.1TiC and W-La_2O_3 (not shown in the figure) very closely match the activity of W with impurities at all times after shutdown.

3. Results

Within the cooling channel of the divertor, five W alloys were examined in the activation analysis. These five alloys are W-Re, W-Ni-Cu, W-Ni-Fe, W-La_2O_3 and W-1.1TiC. Pure W and W with nominal impurities were also examined to determine the lower bounds for the analyzed parameters.

3.1 Specific Activity of the W Alloys

The first parameter analyzed was the specific activity of the W alloy in the cooling channel. This is shown in Fig. 3 for all W alloys after 3.4 FPY. The W-Re gets highly activated after 3.4 FPY of irradiation. However, after several years following shutdown, the W-Ni-Cu and W-Ni-Fe alloys become the most activated alloys. W-Li_2O_3 and W-1.1TiC look very promising because they very closely match the specific activity of W with impurities at all times after shutdown. This indicates that these alloys are essentially optimized in terms of reducing their activation potential.

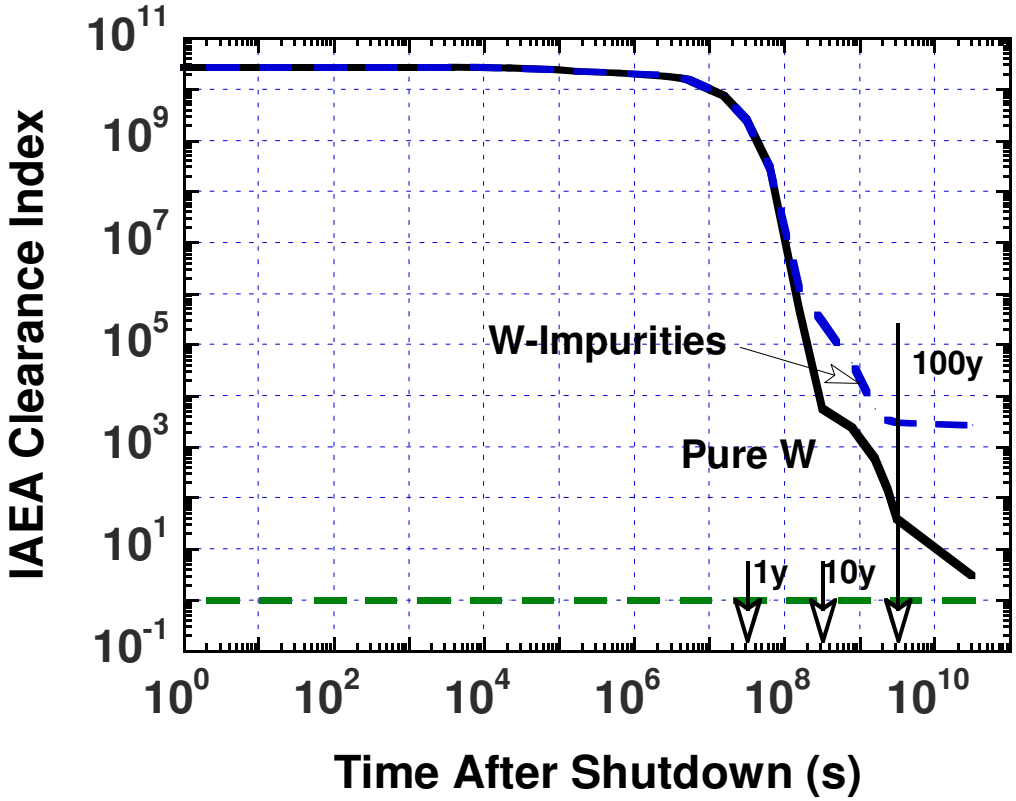

Figure 4. IAEA clearance index for pure W and W with impurities after being exposed to a fluence of 3.4 MWy/m^2. This figure indicates that the divertor will have to be recycled because even pure W does not fall below the limit after 100 years of cooling.

3.2 Divertor Clearance, Recycling, and Multiple Reuse

Designing fusion materials that could be clearable or recyclable would make any fusion device look much more attractive than disposing of the radwaste in geological repositories. The US Nuclear Regulatory Commission (NRC) did not develop clearance guidelines for W [11]. Therefore, the clearance index of the divertor was evaluated using the IAEA standards [12]. Because of the highly energetic neutrons that are produced in the fusion process, clearance is a difficult goal to achieve not only for the divertor, but for all plasma facing components [13]. To evaluate the lower bound of the clearance index, only pure W and W with nominal impurities were looked at, which is shown in Fig. 4. It is apparent that even pure W is not clearable after a 100 year cooling period given that the W is exposed to a fluence of 3.4 MWy/m^2. Fortunately, another option exists that can still reduce the volume of radioactive material that must be placed in a permanent repository, which is known as recycling.

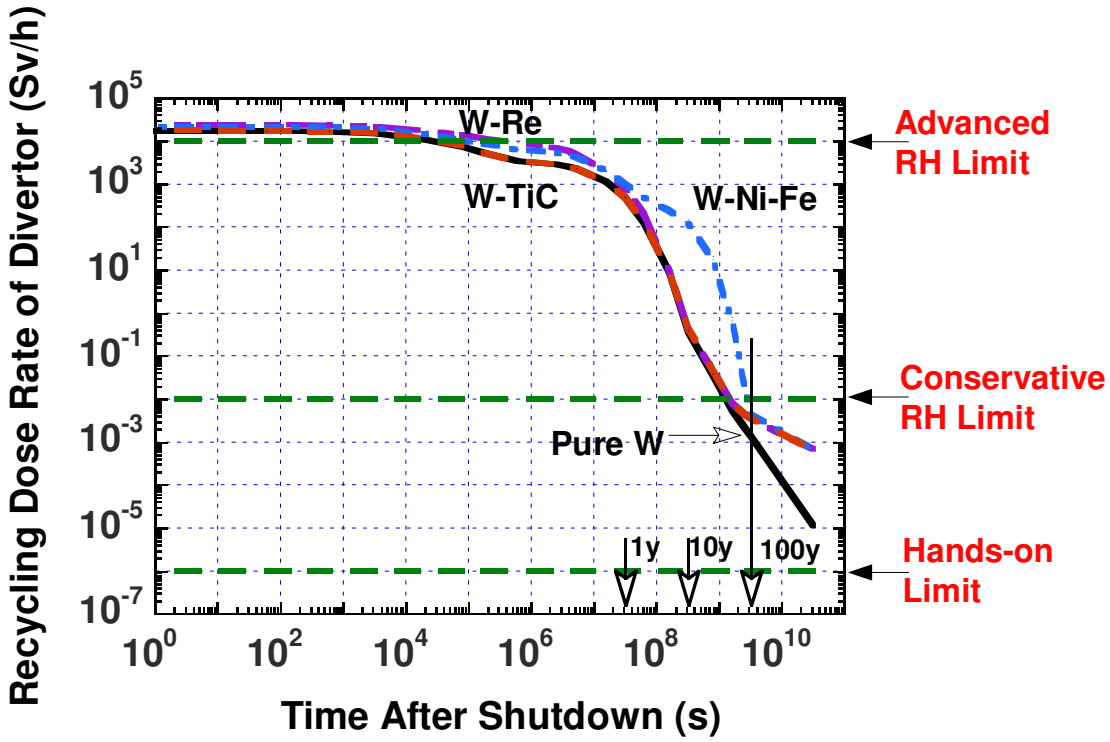

Figure 5. The recycling dose to the divertor after one irradiation cycle (3.4 MWy/m^2). It should be noted that the biological dose is being used to approximate the dose that remote handling equipment would receive. This figure shows that direct handling of the divertor is not possible even after 100 years. In addition, advanced remote handling equipment could be used after less than one day for the W-1.1TiC and W-La_2O_3 alloys.

The ability to recycle a radioactive material is chiefly driven by the availability of advanced equipment to handle the highly irradiated components. Currently, the type of handling processes falls into three categories. The first is hands-on – a direct handling by a person. It could only be done if the biological dose to the person is below 1 μSv/h (ten-fold lower than the absolute limit) in order to comply with the ALARA (as low as reasonably achievable) principle. The second category is conventional remote handling. This method should only be done if the dose to conventional remote handling equipment is below 10 mSv/h. The final category is advanced remote handling. This method should only be done if the dose to the advanced equipment is below 10,000 Sv/h. Admittedly, categories two and three are more expensive and require significantly more time to accomplish the same tasks than category one. However, the advantage of using the third category is that the cooling time of radioactive materials can be much shorter before the materials are worked on. To determine the kind of equipment that would be required to refabricate the recycled divertor, a rigorous method was used to determine the dose that a person (or equipment) would receive if directly standing in front of the divertor. Figure 5 shows the results of this calculation. The three limits that are shown in Fig. 5 indicate the limits for the three handling categories. Ideally, the challenging tasks of recycling and refabricating the divertor would preferably be done through hands-on processes. However, Fig. 5 indicates that even after 100 years of cooling, this approach would not be possible. Note that the doses for W-La_2O_3 and W-Ni-Cu

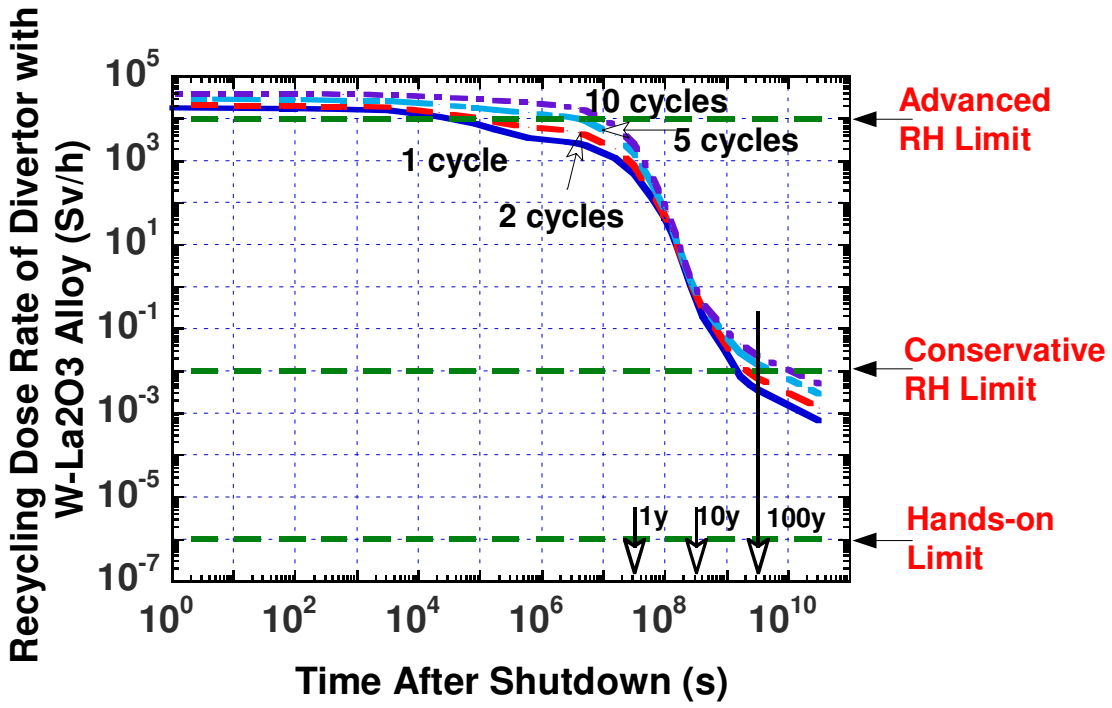

Figure 6. Recycling dose rate of the divertor with W-La_2O_3 after 1, 2, 5 and 10 cycles. This figure indicates that the divertor must cool for a longer period before it can be handled as the number of cycles that it is used increases.

alloys (not shown in Fig. 5) are almost identical to that of W-TiC and W-Ni-Fe, respectively. If a divertor, containing any of the W alloys was allowed to cool for around 100 years, then conventional remote handling equipment could be used. Since advanced remote handling equipment is currently available within the nuclear industry [4], less than one day of cooling would be needed in order to refabricate a divertor containing either the W-1.1TiC alloy or the W-La_2O_3 alloy. Roughly 10 days of cooling would be required before a divertor containing the W-Re alloy could be re-fabricated. One of the characteristic features of W is that it generates relatively high decay heat compared to ferritic steel [14]. This mandates active cooling during storage and recycling. It should also be noted that Fig. 5 assumes that the initial divertor is new, i.e. it has not undergone more than one cycle in ARIES-DB. The radiological effects of using the recycled divertors for many cycles will be discussed next.

Because divertors with W-1.1TiC and W-La_2O_3 alloys give the lowest dose to equipment after shutdown, these two divertors were chosen to analyze the effects of reusing the same divertor for several cycles, covering the entire lifetime of the plant. Figure 6 shows the dose to equipment from the divertor with W-La_2O_3 after 1, 2, 5 and 10 cycles in ARIES-DB assuming no removal of radioactive byproducts during reprocessing. A divertor cycle in ARIES-DB is 3.4 FPY followed by 3 years of cooling, refabrication, and inspection. It is clear that after 2 cycles, the divertor cannot be handled until roughly 2 days of cooling have

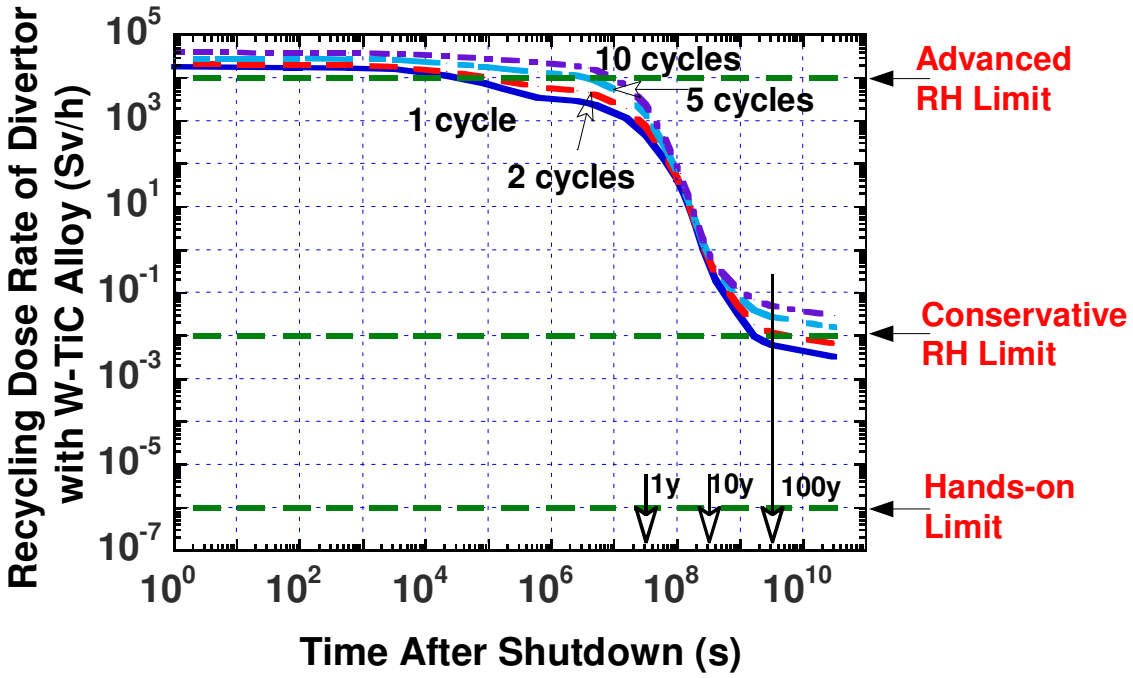

Figure 7. Recycling dose rate of the divertor with W-1.1TiC after 1, 2, 5 and 10 cycles. This figure indicates that the divertor must cool for a longer period before it can be handled as the number of cycles that it is used increases. The main difference between this figure and Fig. 6 is the dose at time > 100 years. This divertor deposits roughly twice the dose that the divertor with W-La_2O_3 deposits at 100 y.

passed. After 10 cycles, several months must pass before the divertor can be handled. The effect of using a divertor for more cycles is also apparent at times greater than 10 years after shutdown. The increase in the dose to equipment from cycle to cycle at these longer times is from the buildup of long-lived radionuclides, mainly from impurities. Overall, both alloys do not have to cool down very long before being refabricated.

Figure 7 shows the dose to equipment from the divertor with W-1.1TiC after 1, 2, 5 and 10 cycles in ARIES-DB. This figure is very similar to Fig. 6 in the length of time that the divertor must cool after a given number of cycles before it can be handled. The main difference between Fig. 6 and Fig. 7 is in the dose at times > 100 years. The dose deposited by the divertor with W-1.1TiC is about a factor of two greater at 100 y than the divertor with W-La_2O_3.

3.3 Divertor Disposal

The geological disposal is the least preferred option for fusion components. Before a radioactive material can be disposed of, though, the level of its radioactivity must be classified. The two classifications described by the NRC are high-level waste (HLW) and low-level waste (LLW) [15]. One of the goals of fusion power plant designers is to produce

no HLW in order to avoid deep geological burial. Table 2 shows the main contributors to the waste disposal ratings (WDR) of the cooling channel of the divertor containing FS structure with different W alloys. Table 3 and Fig. 8 summarize the WDR of the fully compacted divertor (100% dense armor and cooling channel). This data was acquired by using Fetter's limits [16] after 3.4 MWy/m^2 of exposure to the divertors and at the end of the 100 year NRC monitoring period. From Table 3, a divertor with any of the W alloys, except the W-Re alloy, could marginally be classified as LLW. Because a divertor with W-Re generates HLW, the use of the W-Re alloy should be avoided. All alloys contain 5 wppm Nb impurity. From Table 3, Nb activation appears to be one of the main contributors to the waste disposal rating. Therefore, by working to remove the Nb impurity in W, the WDR margin could be increased (e.g. WDR is roughly 0.6 for 1 wppm Nb).

If the divertor is used for a cycle longer than 3.4 FPY, the WDR of the divertor will change. Figure 9 shows a plot of the waste disposal rating of a divertor with W-Re, a divertor with W-La_2O_3 and a divertor with W-1.1TiC versus fluence. From Fig. 9 it is clear that even a divertor with W-La_2O_3 or W-1.1TiC cannot be exposed to a fluence much greater than 3.4 MWy/m^2 without becoming high-level waste, violating the ARIES top-level requirement of generating only LLW. This will pose a problem for divertors with W-La_2O_3 or W-1.1TiC exposed to fluences > 3.5 MWy/m^2 unless the Nb impurity is controlled below 1 wppm. Recycling represents the only viable option for such divertors operating at higher fluences.

Table 2. Main contributors to the WDR (evaluated at 100 y) of the divertor cooling channel containing FS with various W alloys.

Pure W Case		W - Impurities Case		W - Re Case		W - Ni - Fe Case	
8.3566E-02		9.1221E-01		3.3360E+00		8.9825E-01	
isotope	%	isotope	%	isotope	%	isotope	%
Nb-94	51.70	Nb-94	53.86	Re-186m	72.69	Nb-94	49.13
Tc-99	21.00	Ag-108m	28.42	Nb-94	14.95	Ag-108m	25.65
Re-186m	17.64	Tc-99	14.58	Ag-108m	7.90	Tc-99	13.37
Al-26	2.86	Re-186m	1.62	Tc-99	4.04	Ni-59	8.72
Ho-166m	2.16	-	-	-	-	Re-186m	1.33

W - Ni - Cu Case		W - La_2O_3 Case		W-TiC	
8.9281E-01		9.1140E-01		8.6583E-01	
isotope	%	isotope	%	isotope	%
Nb-94	49.43	Nb-94	53.79	Nb-94	53.67
Ag-108m	25.81	Ag-108m	28.38	Ag-108m	28.19
Tc-99	13.45	Tc-99	14.56	Tc-99	14.57
Ni-59	7.52	Re-186m	1.60	Re-186m	1.59
Re-186m	1.33	-	-	-	-

Table 3. Waste disposal ratings of a compacted divertor after 3.4 MWy/m^2 of exposure and 100 years of cooling. This table shows that a divertor with any W alloy of interest except for W-Re would classify as low level waste. A divertor made with W-TiC would have the highest waste disposal rating margin. Because all of the alloys contain 5 wppm Nb, which becomes one of the main contributors to the waste disposal rating when activated, removing some of the Nb impurity could increase the waste disposal rating margin.

	WDR	Classification
Pure W	**.08** (49% from ^{94}Nb)	**Class C LLW**
W + Impurities	**0.98** (52% from ^{94}Nb)	**Class C LLW**
W-La_2O_3	**0.98** (54% from ^{94}Nb)	**Class C LLW**
W-Ni-Cu	**0.96** (48% from ^{94}Nb)	**Class C LLW**
W-Ni-Fe	**0.96** (48% from ^{94}Nb)	**Class C LLW**
W-TiC	**0.94** (52% from ^{94}Nb)	**Class C LLW**
W-Re	**3.1** (73% from ^{186m}Re)	**HLW**

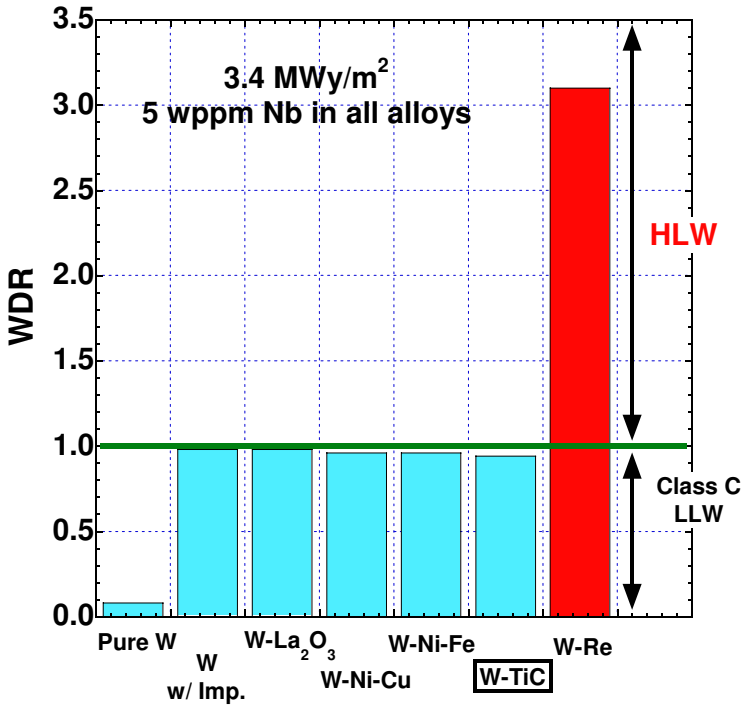

Figure 8. Waste disposal ratings of a compacted divertor after 3.4 MWy/m^2 of exposure and 100 years of NRC control.

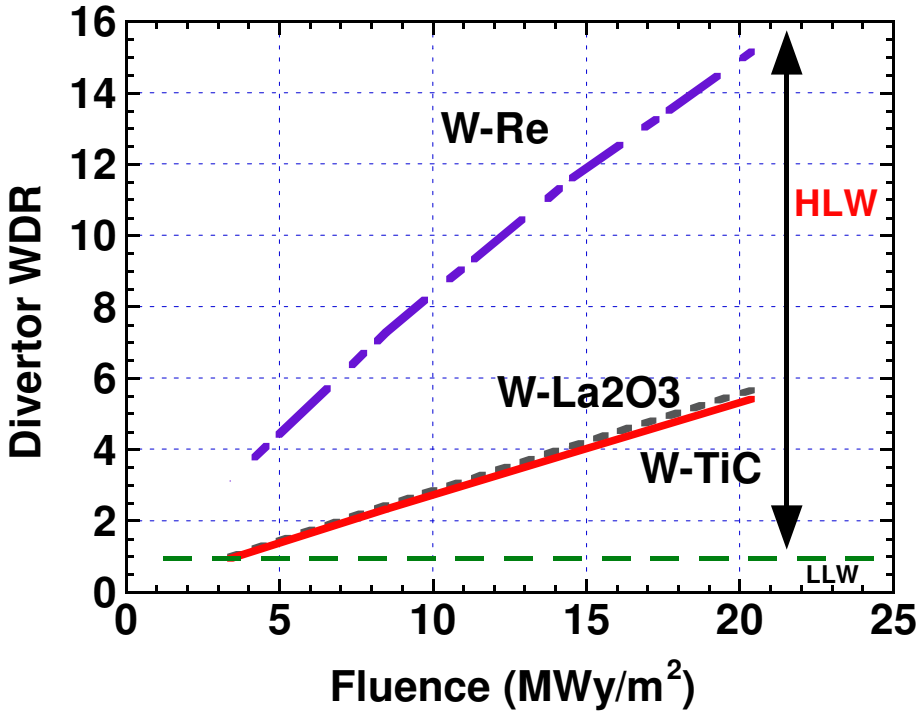

Figure 9. Waste disposal rating of a divertor with W-Re, a divertor with W-La_2O_3, and a divertor with W-1.1TiC versus fluence. This figure indicates that even divertors made with the two most promising W alloys (W-La_2O_3 and W-1.1TiC) cannot be exposed to a fluence much greater than 3.4 MWy/m^2 without being classified as high-level waste.

3.4 W Transmutation

The transmutation of the W and its alloying materials in the divertor is expected to adversely affect the material properties of the divertor [17]. Therefore, it is necessary to evaluate the degree to which the W and alloying materials will transmute when employed inside ARIES-DB. Although several studies [18,19] have been made recently to assess the degree to which tungsten and other elements transmute in a fusion environment, transmutation results are quite sensitive to the neutron energy spectrum and the end-of-life fluence. This is why a separate analysis for ARIES-DB has been performed. For the neutron energy spectrum of ARIES-DB at the divertor (refer to Fig. 2), Fig. 10 displays the buildup of W transmuted in the W armor of the divertor with fluence. After being exposed to a fluence of 3.4 MWy/m^2, only 1.2% of the W in the W armor transmutes. After being exposed to a fluence of 20.4 MWy/m^2, 7% of the W in the W armor transmutes. Figures 11 and 12 show the transmutation products in the W armor of the divertor.

Figure 13 shows the percentage of W and Re transmuted in the cooling channel of a divertor made with the W-Re alloy. From this figure it is clear that Re transmutes at a much faster rate than W. After being exposed to 20.4 MWy/m^2 of fluence, 21% of the Re will transmute and will certainly degrade the bulk properties of the W-Re alloy. Besides generating the undesirable high-level waste, this is another strong reason why the use of W-Re alloy should be avoided for fusion applications

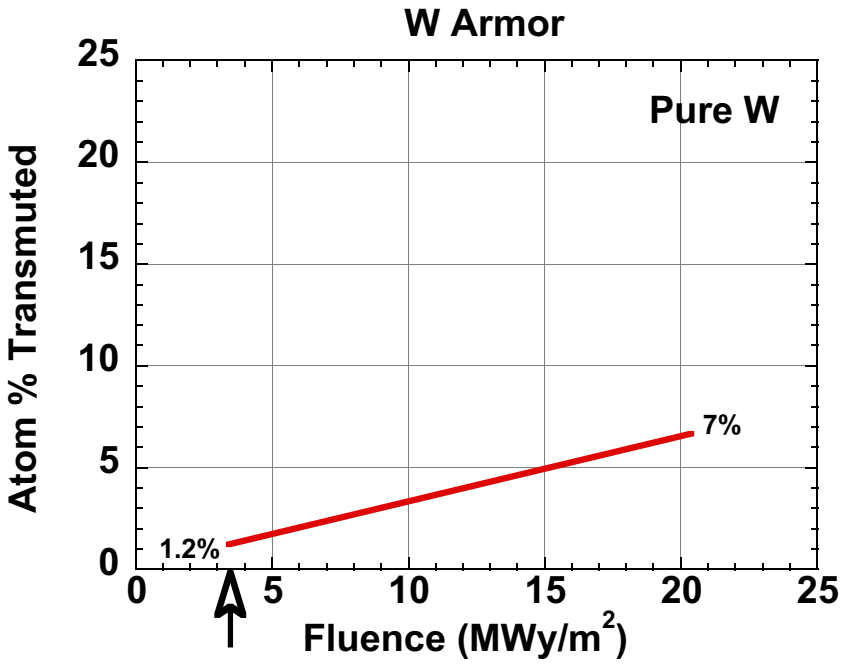

Figure 10. Percentage of W transmuted in the W armor of a divertor versus fluence. Even after being exposed to a fluence of 20.4 MWy/m^2, only 7% of the W in the W armor transmutes.

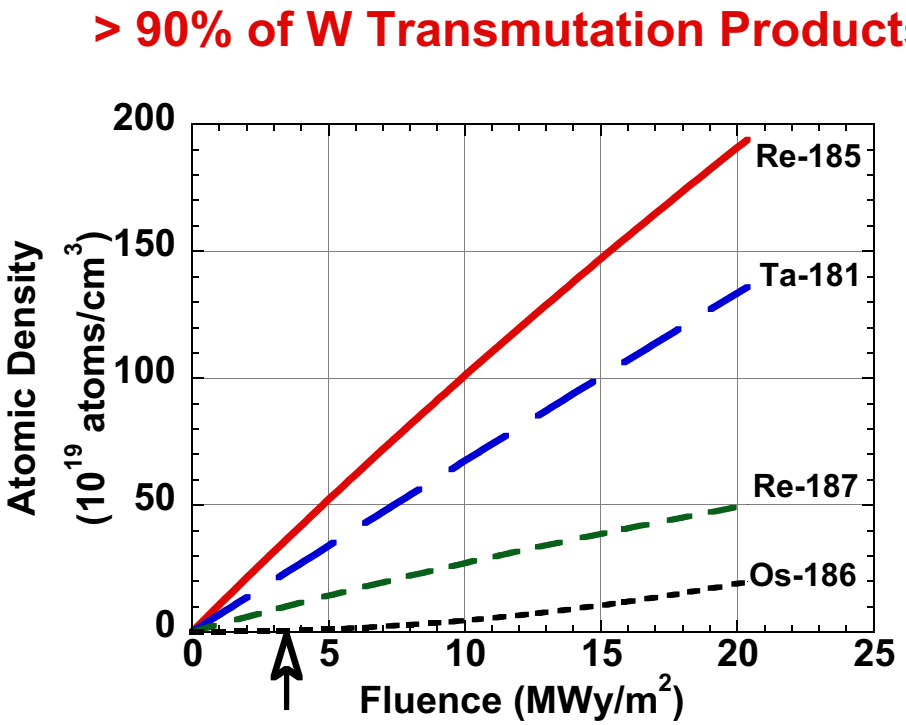

Figure 11. Atomic density of the transmutation products making up over 90% of all transmutation products in W armor.

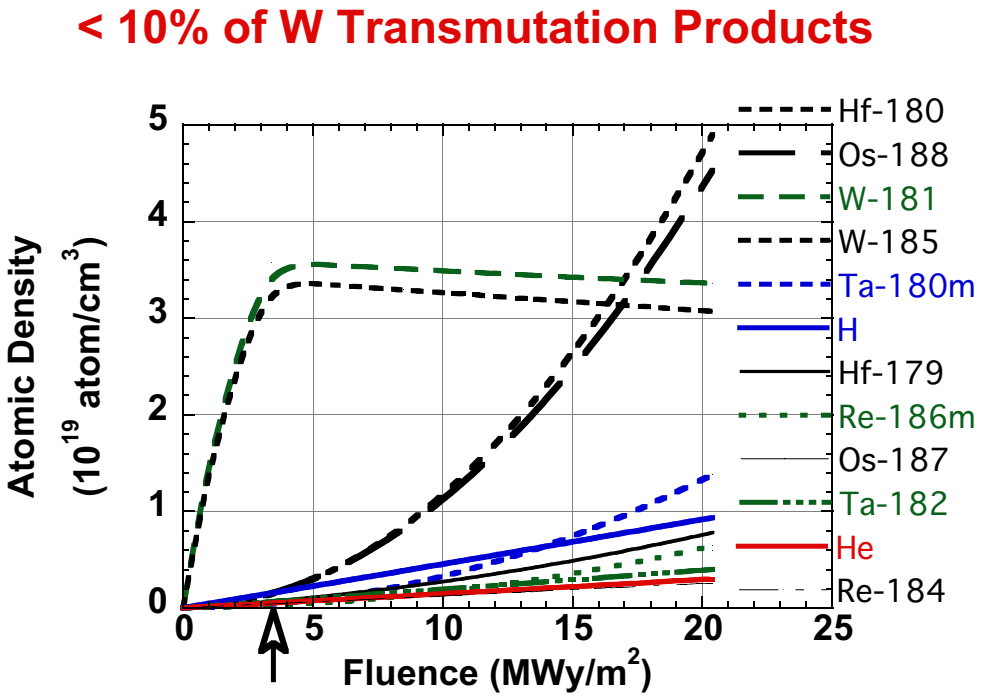

Figure 12. Atomic density of the transmutation products making up less than 10% of all transmutation products in W armor.

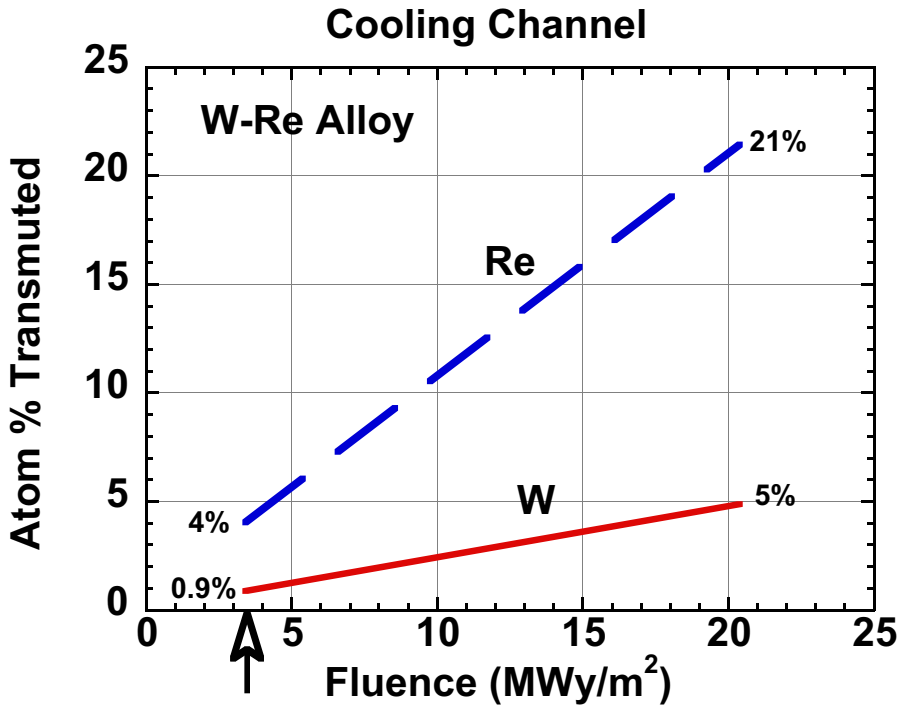

Figure 13. Percentage of W and Re transmuted in the cooling channel of ARIES-DB divertor versus fluence.

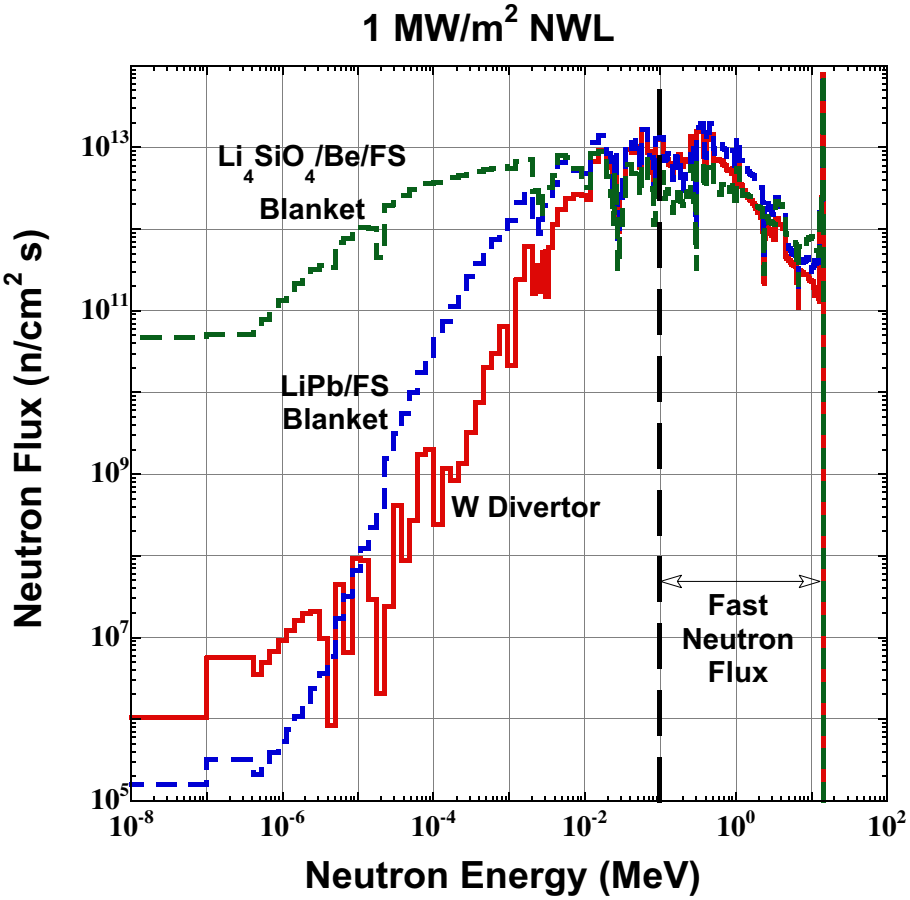

Figure 14. Neutron spectrum in front of the divertor of ARIES-DB, the LiPb/FS blanket and the Li_4SiO_4/Be/FS blanket normalized to 1 MW/m^2 NWL. The spectrum in front of the divertor is the hardest, followed by the spectrum in front of the LiPb/FS blanket, then the Li_4SiO_4/ FS blanket with beryllium multiplier.

3.5 Effect of Spectrum on W Transmutation

As stated earlier, the analyses so far have been carried out for the hard neutron spectrum at the divertor of ARIES-DB (see Fig. 2). The spectrum at different parts of the ARIES-DB design, e.g., at the first wall (FW) of the blanket, will be softer. This is plotted in Fig. 14 for two blanket concepts (with liquid and ceramic breeders) and summarized in Table 4. The spectrum at the FW of the LiPb/FS blanket is slightly softer than the spectrum at the divertor. If a ceramic Li_4SiO_4/Be/FS blanket were used instead of the liquid LiPb/FS blanket, the spectrum at the FW of the blanket would be much softer, mainly due to the use of beryllium multiplier. Figure 15 shows the effects that these different neutron spectra would have on the percentage of W transmuted in a 0.5 cm thick W armor attached to the FW of the various blankets. The softer spectrum results in more W being transmuted. The figure also illustrates that 50-75% of the transmuted atoms is produced by the 14.1 MeV source neutrons. As expected, the source neutron contribution dominates as the spectrum becomes harder at the divertor surface.

Table 4. Summary of the neutron spectra in front of the divertor of ARIES-DB, the LiPb/FS blanket, and the Li_4SiO_4/Be/FS blanket normalized to 1 MW/m^2 NWL.

Neutron Flux @ Surface	**Total**	**E_n < 0.1 MeV**
Divertor	6e14	25%
LiPb/FS Blanket	7.5e14	29%
Li_4SiO_4/Be/FS Blanket	5e14	43%

This analysis confirms that the transmutation results are very sensitive to the neutron spectrum and fluence. Several recent studies [17,18] assessed the degree to which W transmutes in fusion designs and showed that ceramic breeder blankets with beryllium multiplier result in high transmutation level (25% for W and 78% for Re) [17].

3.6 Radiation Damage to W Armor

Because of the high neutron energies to which the W armor will be exposed, the atomic displacement and gas production need to be analyzed to determine how long the W armor can survive the intense fusion environment based on radiation damage. Table 5 shows the displacement per atom (dpa), He production, and H production in the W armor of the divertor and in 0.5 cm thick W armor attached to the LiPb/FS blanket or Li_4SiO_4/Be/FS blanket. Figure 16 shows where the W armor would be placed relative to the LiPb/FS blanket. These results are normalized to a NWL of 1 MW/m^2. Interestingly, for the same fluence, the materials behind the W armor change the damage to the W by only 10-30%. In advanced tokamaks, the distribution of the NWL varies poloidally, peaking at the divertor at ~2 MW/m^2 and at the outboard midplane at ~4 MW/m^2. The second part of Table 5 lists the peak damage to the W armor at the end of the 3.4 FPY service lifetime, indicating that the radiation damage to the W in front of the outboard LiPb/FS blanket could reach 53 dpa, 30 He appm, and 110 H appm at the end-of-life. Note that the He to dpa ration is quite low for W compared to FS (~11) [3]. The dpa level is an important parameter for all structural components as it helps determine their service lifetime. At present, the dpa limit for the structural use of W alloys is unknown. Worldwide effort is underway to determine the failure mechanism for the most promising W alloys under a fusion environment.

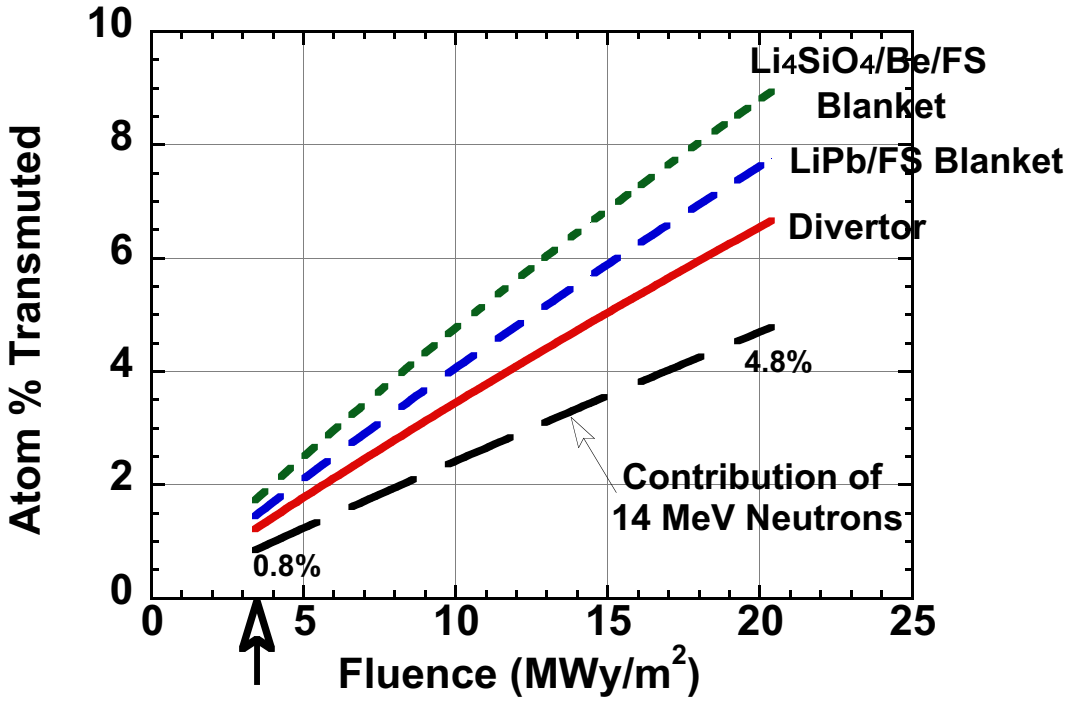

Figure 15. Percentage of W transmuted in the W armor versus fluence for different neutron spectra. The percentage of W transmuted increases at higher fluences and as the neutron energy spectrum becomes softer.

Table 5. dpa, He production and H production in W armor in front of divertor and blanket. The W armor in front of the LiPb/FS blanket displays the highest atomic displacement.

Damage/FPY @ 1 MW/m²	**dpa** (dpa/FPY)	**He*** (appm/FPY)	**H*** (appm/FPY)
Divertor	3	1.9	7.1
LiPb/FS Blanket	3.9	2.2	8.1
Li_4SiO_4/Be/FS Blanket	3.1	2.16	8
Realistic Designs **Peak Damage @ 3.4 FPY**			
Divertor @ 2 MW/m²	20	13	49
OB LiPb/FS Blanket @ 4 MW/m²	53	30	110
OB Li_4SiO_4/Be/FS Blanket @ 4 MW/m²	42	29	109

*1-D He/H results increased by 20% to account for additional He/H production from multiple reactions and radioactive decay.

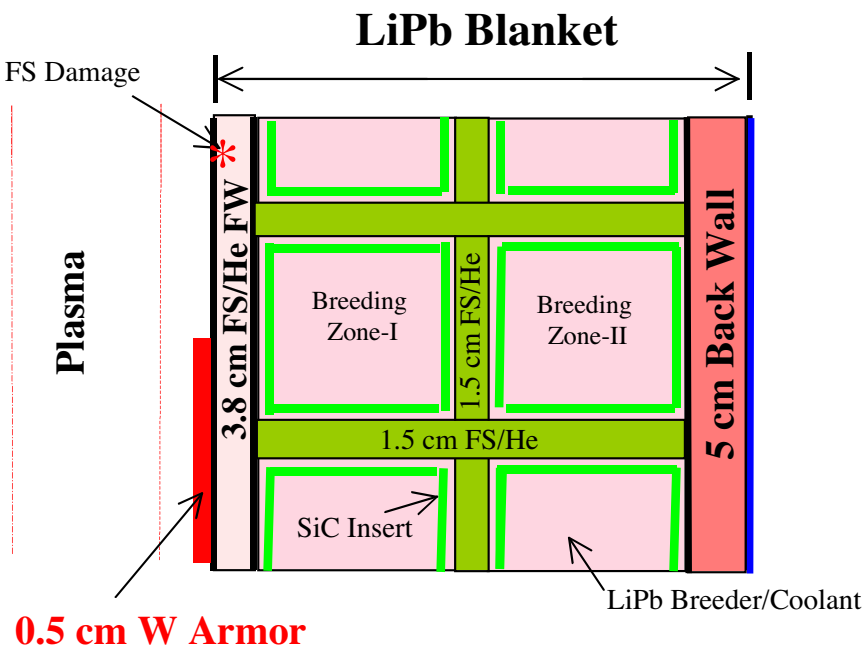

Figure 16. Location of W armor if attached to first wall of LiPb/FS blanket.

4. Conclusions

In this report, five key W alloys for use in advanced divertor designs have been analyzed. The most promising alloys appear to be W-1.1TiC and W-La_2O_3. After 3.4 FPY, the specific activity and recycling dose of these alloys very closely match that of W with impurities. Unfortunately, not even pure W meets the IAEA clearance index after 100 years of storage, which indicates that the divertor must be either recycled or disposed of in a geological repository. If the preferred recycling option is chosen, both the W-1.1TiC alloy and the W-3 alloys again look very promising. This is because they could be refabricated with advanced remote handling equipment after less than a day following shutdown (assuming that the divertor had just undergone its first cycle). As these divertors approach 10 cycles, they must cool off for several months before they could be handled with advanced remote handling equipment. This is still well within the 3 year cooling time planned for recycling the divertor. If the disposal option is chosen, a divertor with any of the alloys would classify as low-level waste after 100 years of NRC control, except for a divertor with the W-Re alloy. For this reason, the use of the W-26Re alloy in divertors should be avoided. The lowest waste disposal rating of 0.94 is for a divertor containing W-1.1TiC. In order to increase the waste disposal rating margin of all W-based divertors, reducing the 5 wppm Nb impurity in W would be necessary.

For the same neutron environment, the radiation damage level in W is low compared to ferritic steel – a remarkable feature for tungsten. More importantly, the He to dpa ratio is only 0.6 in W vs. 11 in ferritic steel. For the hard neutron spectrum at the front of the divertor of ARIES-DB, the transmutation of W does not appear to be a significant concern. Even after being exposed to a fluence of 20 MWy/m^2, only 7% of the W in the W armor transmutes. For the W-26Re alloy in the cooling channel of the divertor, 21% of the Re transmutes after 20 MWy/m^2. The Re transmutation is expected to adversely affect the bulk material properties, which is another reason why the use of W-26Re alloy should be avoided in fusion applications. For softer neutron spectrum (such as at the blanket surface), the transmutation of W in a W armor attached to the first wall is larger than that at the divertor. Ceramic breeder blankets with beryllium multiplier result in the highest transmutation level in the W armor.

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