White paper on alpha losses and high-Z metal PFC surface damage
Off-normal panel ReNeW; D. Whyte, March 9, 2009

High-energy alphas (~MeV) incident on metals are known to cause surface blistering. In a fusion device, we may be concerned with the degradation of the surface properties and its consequences such as erosion or material removal. The purpose of this white paper is to provide rough semi-quantitative estimates of such effects to see if they could be a concern.

Threshold for surface damage and defoliation Takagi et al [Fusion Sci. Tech. 41 (2002) 897] bombarded 470 K Mo (very similar damage response as W) with 0.8 MeV He ions. They found surface damage and blistering after \( \sim 2 \times 10^{21} \) m\(^{-2}\) fluence. The onset of damage occurs when the peak He concentration \( \sim 2\% \) He/Mo at end of range (\(~1\) micron) and the peak dpa \( \sim 6 \) (displacements per atom). Ueda (J. Nucl. Mater. 313-316 (2003) 32) in his review paper lists the critical fluence for blister formation as \( > 5 \times 10^{21} \) m\(^{-2}\). Based on the cited paper Constantinescu & Sarbu (Fusion Eng. Design 49-50 (2000) 171) using 3 MeV alphas bombarding a variety of PFC materials at room temperature, showed Mo blistering \( \sim 0.5-1 \times 10^{22} \) m\(^{-2}\) or roughly 2-4x larger than required at 0.8 MeV. Das and Kaminsky [J. Appl. Phys. 44 (1973) 25] found blistering at \( \sim 10^{22} \) He m\(^{-2}\) for niobium (close to Mo) but did not establish a minimum fluence limit. They also found complex behavior changes due to annealing and high temperature, which sometimes produced very large blisters. Interestingly the range of 3.5 MeV alphas, \( \sim 5 \) microns, is \( \sim 5x \) larger, while the depth distribution due to straggling is \( \sim 2x \) larger. While obviously very sparse data, let’s take as the simplification that the rate at which the surface will exfoliate is roughly independent of energy for these non-thermalized alphas, i.e. if the energy is lower, the concentration is higher at the end of range due to lower straggling which triggers the defoliation, but of a thinner layer. The effect of incidence angle can also be treated similarly: grazing incidence reduces the penetration/damage depth but also increases end of range concentration. This crude assumption is somewhat verified by the work of Radel & Kulzinski [J. Nucl. Mater. 367-370 (2007) 434] reported severe surface damage from \( \sim 50 \) keV He ion bombardment of tungsten at \( \sim 1000 \) C.
So to first order the rate of surface removal is independent of energy and angle, and only
depends on flux density and energy distribution; also we assume that once a layer is
removed the process repeats itself on the underlying virgin surface layer. On reviewing
the literature, the main topic of concern has been the onset of the surface damage. Here
we attempt to examine the possible consequences of continuous damage in a Demo-class
fusion device. Thus we attempt to estimate effects of total erosion and dust production. A
would be expected from alpha losses at some point during operations. Their conclusion
was that blistering would be more important for high-Z materials due to their low erosion
rates from plasma (thermal) sputtering. We consider high-Z tungsten only.

Rate of surface loss Take the case of ~3 MeV alphas: assume that the material above the
implantation depth (~5x10^-6 m) is removed by the He damage after reaching a fluence of
\( \Phi_{\text{crit}} \sim 5x10^{21} \text{ m}^{-2} \), or after a time \( \tau \sim \Phi_{\text{crit}} / \Gamma \) where \( \Gamma \) is the time-averaged flux density of
energetic He ions. This garners an effective erosion rate \( \sim 5x10^6 \text{ m}^{-2} \) \( \Phi_{\text{crit}} \sim 10^{-27} \Gamma \) (m/s),
which we assume is roughly correct even if the alphas had been slowed down. A 3 GW
(thermal) fusion device produces \( \sim 10^{31} \) alpha / second. If a constant percentage, \( f_{\text{loss}} \)
of the alphas are lost (~% for typical stellarator designs, TAE frequency in a tokamak) this
gives an erosion rate: \( 10^{-6} f_{\text{loss}} / A_{\text{loss}} \) (m/s) where \( A_{\text{loss}} \) is the surface area over which the
alphas are lost.

We can estimate if this is ever a concern. Take \( f_{\text{loss}} = 5\% \) as suggested from stellarator
studies (ARIES-CS), and that \( A_{\text{loss}} \sim 10-100 \text{ m}^2 \). This gives a range of erosion from 0.5-5
nm/s. In a burn-year (~3x10^7 s) this translates to ~15-300 mm of erosion. In comparison
net erosion rates in the divertor for high-Z metals like Mo / W are \( \sim 10^{-10} \) m/s. So it
would be likely that this scenario would produce erosion much faster than found from
sputtering, and given that typical PFC thickness is ~5-10 mm, would suggest this is a
serious impediment to long PFC lifetime. This was the tentative conclusion of Bauer et
al.

We must note that this erosion rate model is quite crude. For example, the details of
energy distribution for the alphas, the bombardment temperature and the defoliation of
the blisters have all been ignore. However since the erosion rate appears sufficiently high, it would seem to warrant more investigation.

Other implications to wall lifetime with $f_{\text{loss}} \sim 1\%$ Another concern is the volumetric loss of the tungsten. This only depends on $f_{\text{loss}}$ which is understood by stating that 5 microns thickness of W is an equivalent areal particle density of $5 \times 10^{-6} \text{ m}^2 * n_w \sim 5 \times 10^{23} \text{ Atoms}_{\text{W}} \text{ m}^{-2}$ using the solid tungsten density $n_w \sim 10^{29} \text{ m}^{-3}$. Therefore one “loses” $\sim 5 \times 10^{23} \text{ atoms/m}^{2} / 5 \times 10^{21} \alpha_{\text{m}^{2}} \sim 100 \text{ tungsten atoms for each impinging high-energy alpha}$. While this may seem unphysical, note that the 3 MeV alphas produce $>300$ displacements in the W per alpha ion. These are highly perturbing to the W lattice over the implantation range! Again to our example, with $f_{\text{loss}} \sim 5\%$ the rate of losing W atoms from the wall will be $\sim 5 \times 10^{21} \text{ W atoms/s}$. This raises two concerns.

The first concern is the production of dust/particulates from the defoliation; the activated dust is mobile in accident scenarios and is limited $\sim 1000 \text{ kg}$ in ITER. The time-averaged rate of W dust production in our example is $\sim 5 \times 10^{21} \text{ W atoms/s} * 3 \times 10^{-25} \text{ kg/W} \sim 1.5 \times 10^{-3} \text{ kg/s}$. The 1000 kg limit would then be reached in $0.6 \times 10^{6} \text{ s}$ or less than 10 days of operation.

The second concern is the perturbative nature of the W flakes entering the plasma. For ITER/Demo class device, the presence of $\sim 10^{21} \text{ W atoms}$ in the core plasma will certainly disrupt the plasma through radiative collapse, since this amount of W ($A=74$) has as many electrons as the entire core plasma ($\sim 10^{23} \text{ m}^{-3}$). At first glance this would suggest that the core plasma would disrupt in 1 second since $W/s > 10^{21}$ but this is not the case. The important criterion here is that the W find its way to the core. For example the level of W sputtered from the wall and divertor will also be $\sim 10^{21} / s$, however these have very low probability of accessing the core plasma because their ionization MFP is too small. Rather we’re concerned with “chunks” of W large enough that they are not really affected directly by ionization, but rather stopped through ablation (rough equivalent to difference between gas fuel neutrals vs. fuel pellets). Ablation is very weak in the SOL for particulates which are on the mm size. According to Constantinescu & Sarbu the characteristic blister size was $\sim \text{ mm}$, so perhaps this criterion is met. However a single blister “flake” would contain only $\sim 5 \times 10^{-6} \text{ m} \times (10^{-3})^{2} \text{ m}^{2} \times 10^{29} \text{ W/m}^{3} \sim 5 \times 10^{17} \text{ W}$. 
atoms. Therefore it appears a single flake would not be a concern for a disruption. Rather it would require something more akin to a simultaneous “burst” of many defoliating blisters from say a single tile (\(\sim 10 \text{ cm}^2\)) would meet the criterion for instigating a radiative collapse. Since we know so little of the response of the W surface with the alpha damage + large incident heat loads, etc. it is difficult to judge if this is realistic or not.

**Summary** Prompt alpha losses to the wall at a time-averaged level of 5% would be of serious concern to the high-metal (tungsten) PFC lifetimes due to

1) Large local effective net erosion at the regions of alpha loss
2) Dust production
3) Possible radiative plasma collapse (more speculative)

While numerical estimates are crude, this suggests several research thrusts.

a) Significant investigation of alpha-induced damage on W at high fluence, over a range of bombarding temperatures and incident alpha energies.

b) Simultaneous with the alphas, bombard the surface with plasma ions (D and He) to try and uncover the effects (positive or negative) of simultaneously placing the near-surface under intense plasma damage. This would better simulate conditions expected in the confinement device.

c) Characterize the size and defoliation properties of the damage to better understand threats to plasma operations through disruptions and dust production.