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 ~$2x10^{21}$ m^{-2} fluence. The onset of damage occurs when the peak He concentration ~ 2% He/Mo at end of range (~ 1 micron) and the peak dpa ~6 (displacements per atom). Ueda (*J. Nucl. Mater.* ***313-316*** *(2003) 32*) in his review paper lists the critical fluence for blister formation as > $5x10^{21}$ 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 ~$0.5\text{-}1x10^{22}$ 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 ~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, ~5 microns, is ~5x larger, while the depth distribution due to straggling is ~2x larger. While obviously very sparse data, let's take as the simplification that the rate at which the surface will ex-foliate 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 ~50 keV He ion bombardment of tungsten at ~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 previous study [*Bauer, et al Nucl. Fusion* ***19*** *(1979) 93*] examined whether blistering 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 (~5×10^{-6} m) is removed by the He damage after reaching a fluence of $\Phi_{crit}\sim5\times10^{21}$ m^{-2}, or after a time $\tau \sim \Phi_{crit}/\Gamma$ where Γ is the time-averaged flux density of energetic He ions. This garners an effective erosion rate ~ $5\times10^{-6}\ \Gamma / \Phi_{crit} \sim 10^{-27}\ \Gamma$ (m/s), which we assume is roughly correct even if the alphas had been slowed down. A 3 GW (thermal) fusion device produces ~ 10^{21} alpha / second. If a constant percentage, f_{loss} of the alphas are lost (~% for typical stellarator designs, TAE frequency in a tokamak) this gives an erosion rate: $10^{-6}\ f_{loss} / A_{loss}$ (m/s) where A_{loss} is the surface area over which the alphas are lost.

We can estimate if this is ever a concern. Take f_{loss} = 5% as suggested from stellarator studies (ARIES-CS), and that A_{loss} ~ 10-100 m^2. This gives a range of erosion from 0.5-5 nm/s. In a burn-year (~3×10^{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 ~ 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_{loss}~1% Another concern is the volumetric loss of the tungsten. This only depends on f_{loss} which is understood by stating that 5 microns thickness of W is an equivalent areal particle density of $5\text{x}10^{-6} * n_W \sim 5\text{x}10^{23}$ Atoms_W m^{-2} using the solid tungsten density $n_W \sim 10^{29}$ m^{-3}. Therefore one "loses" ~ $5\text{x}10^{23}$ atoms/m^2 / $5\text{x}10^{21}$ alpha/m^2 ~ *100 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_{loss}~5% the rate of losing W atoms from the wall will be ~ $5\text{x}10^{21}$ 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 ~ 1000 kg in ITER. The time-averaged rate of W dust production in our example is ~ $5\text{x}10^{21}$ W atoms/s * $3\text{x}10^{-25}$ kg/W ~ $1.5\text{x}10^{-3}$ kg/s. The 1000 kg limit would then be reached in $0.6\text{x}10^{6}$ 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 ~10^{21} 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 (~10^{23} 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 ~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 ~ mm, so perhaps this criterion is met. However a single blister "flake" would contain only ~ $5\text{x}10^{-6}$ m x $(10^{-3})^2$ m^2 x 10^{29} W/m^3 ~ $5\text{x}10^{17}$ 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 (~10 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.