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Section 5.5. Plasma–surface interactions

Effects of plasma impurities on materials erosion and mixing in a steady state magnetic fusion device
A comparison between beryllium and tungsten

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Abstract

Data review and modeling on the effects of plasma impurities on materials erosion and mixing under steady-state plasma bombardment are presented in this paper. Non-condensible plasma impurities such as oxygen will interact with surfaces under recycling conditions to enhance materials erosion. In contrast, condensible impurities such as carbon can either recycle or be redeposited over the host materials surface. Due to the masking effect, redeposited impurity films can reduce or completely eliminate host materials erosion. The critical condition to turnover from recycling to redeposition has been described in terms of impurity-to-fuel plasma flux ratio. Because of their high surface reflectivities, high-Z materials such as tungsten are found to require substantially more impurity contents for redeposition than low-Z materials such as beryllium. Enhanced erosion of tungsten and beryllium due to oxygen and carbon impurities has been compared under recycling conditions. Interestingly, trace amounts of recycling impurities can significantly enhance tungsten erosion whereas this effect on beryllium erosion is barely noticeable.

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1. Introduction

It is widely recognized that materials erosion and resultant impurity generation due to plasma interactions with in-vessel components can affect core plasma cleanliness in magnetic fusion experiments. For future steady-state fusion reactors, materials erosion will even dictate the operation-maintenance scenario. Over the past two decades, the fusion research community has devoted considerable amount of effort to establishing a database on materials sputtering due to energetic particle bombardment with the main emphasis on hydrogenic species. However, it is also true that despite being at low concentration, plasma impurities such as carbon and oxygen can alter the overall erosion behavior of in-vessel components.

It has recently been found that under steady-state deuterium plasma bombardment at elevated surface temperatures around 500°C, beryllium tends to be deposited with carbonaceous films, a phenomenon referred to as “carbon poisoning” [1]. The source of carbon impurities may be vacuum residual gases in the form of CO and/or C_xH_y. Due to the film masking effect, carbon poisoning has been found to reduce beryllium erosion significantly. Interestingly, however, carbon poisoning was not observed if beryllium was kept at room temperature, clearly indicating a surface temperature effect [2]. These erosion yield data on beryllium with and without carbon poisoning are reviewed in Fig. 1.

These findings have led us to a conjecture that if two or more different plasma-facing materials are employed for closely located in-vessel components, these materials can act as the mutual impurity sources, which will then result in materials mixing via impurity redeposition. In fact, the reduced erosion of beryllium components has recently been observed in JET, attributed to carbon poisoning due to carbon components [8].

On the other hand, if plasma impurities are surface interactions interacting with under recycling conditions, plasma-facing materials will be subjected to enhanced

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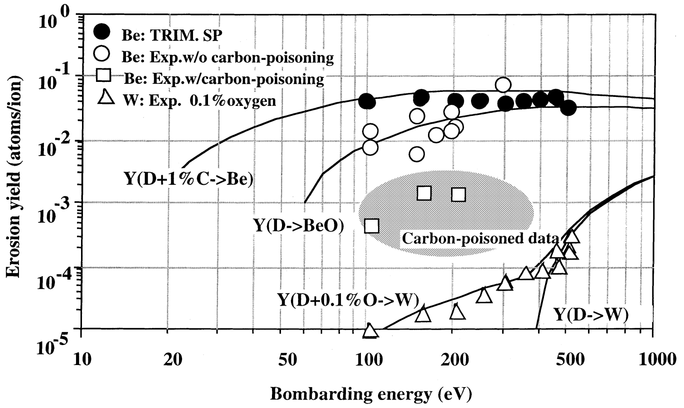

Fig. 1. Review of deuterium plasma erosion yield data taken for beryllium and tungsten under the influence of carbon and oxygen impurities [2–4]. For comparison, calculated sputtering yield data from TRIM.SP [5] for beryllium, those from Yamamura's equation [6] for tungsten and also experimental data for BeO [7] are shown.

erosion. Generally, oxygen impurities such as H_2O or its fragments are not condensible at elevated temperatures. Enhanced erosion by oxygen impurities has been observed for tungsten under deuterium plasma bombardment [4], as shown in Fig. 1. As a result, the effective threshold energy for sputtering is reduced from 341 eV down to 44.5 eV, calculated for deuterium and oxygen [6], respectively.

As demonstrated in these recent experiments, plasma impurities can affect the materials erosion behavior in two completely different manners and can result in materials mixing. These plasma impurity effects have been analyzed in the present work. Using the zero-dimension mass balance model [9], the critical impurity concentration to turnover from a recycling to non-recycling condition will be discussed for selected high-Z and low-Z materials (where Z is the atomic number). Enhanced erosion behavior will be compared between beryllium and tungsten under DT plasma bombardment contaminated with recycling oxygen and carbon impurities.

2. Classification of plasma impurities and their interactions with surfaces

2.1. Recycling and non-recycling conditions

As pointed out in reviewing the data shown in Fig. 1, plasma impurity and surface interaction conditions may be classified into: (1) recycling condition; and (2) partial or non-recycling conditions. To help understand these conditions, a schematic diagram is presented in Fig. 2. For simplicity, plasma impurities to be dealt in the remainder of this paper are assumed to be single-charged unless otherwise specified.

Generally, plasma impurities are originated either from residual gases or from the erosion of in-vessel components due to plasma-surface interactions. In addition to these intrinsic impurities, inert gases such as neon have been puffed into the divertor region for enhanced radiation [10]. These inert gas ions may be trapped by materials until surface saturation, after which a 100% recycling condition is established. Residual gases such as oxygen and nitrogen behave similarly even as they may first form surface oxides or nitrides. As such, non-condensible plasma impurities interact with surfaces essentially under recycling conditions. Consequently, materials erosion will be enhanced by the bombardment of plasma impurities (see Fig. 2(a)).

If the materials surface interacts with condensible impurities such as carbon, both recycling and non-recycling conditions are possible. Most condensible impurities are generated from materials erosion but residual gases such as CO can behave similarly if they are ionized to interact with surfaces. These impurities

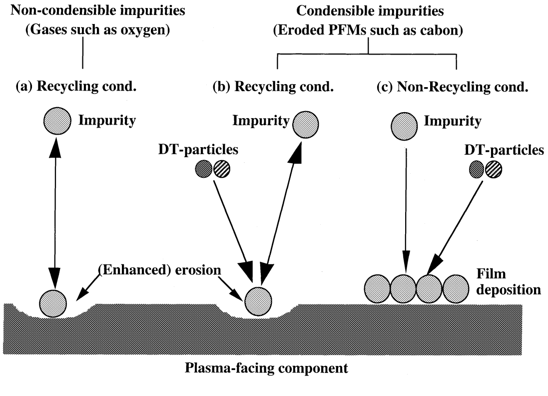

Fig. 2. Schematic illustration of two classes of impurities (condensible and non-condensible) and their interaction behavior with a plasma-facing component.

can enhance materials erosion under recycling conditions whereas film formation occurs under partial and non-recycling conditions (see Fig. 2(b) and (c)). Clearly, film deposition will result in a masking effect and can then completely eliminate host materials erosion, particularly at steady state. Importantly, however, if materials mixing occurs via diffusion, for example, host materials erosion will not be eliminated but will remain at a reduced level (see Section 3).

2.2. Turnover from recycling to non-recycling condition

From the zero-dimension materials balance model [9], the following condition must be satisfied to turnover the surface interaction condition with condensible impurities from recycling to non-recycling under simultaneous DT-fuel particle bombardment:

$$\Sigma\left(\frac{\Gamma_{\mathrm{i}}}{\Gamma_{\mathrm{D,T}}}\right) > \frac{{}_{\mathrm{s}}Y_{\mathrm{D,T}\rightarrow \mathrm{i}}}{(\nu_{\mathrm{i}} - {}_{\mathrm{ss}}Y_{\mathrm{i}\rightarrow \mathrm{i}})}, \qquad (1)$$

where Γ_{i}: impurity particle flux; $\Gamma_{\mathrm{D,T}}$: D,T-fuel particle fluxes; ${}_{\mathrm{s}}Y_{\mathrm{D,T}\rightarrow \mathrm{i}}$: sputtering yield of deposited impurity by D,T-fuel particles; ν_{i}: impurity trapping coefficient by the host material; and ${}_{\mathrm{ss}}Y_{\mathrm{i}\rightarrow \mathrm{i}}$: self-sputtering of impurity element. The right-hand term of Eq. (1) is defined as the 'critical impurity-to-fuel flux ratio', i.e. the minimum impurity content required to achieve a partial or non-recycling condition. Clearly, this flux ratio depends ion bombarding energy, angle and also temperature due to chemical sputtering if the impurity is carbon. In this paper, however, results will be presented only as a function of bombarding energy. For simplicity, the particle bombardment is set at normal incidence. The TRIM. SP code [5] has been used for trapping coefficient and (self) sputtering yield calculations. Results obtained under other conditions such as non-normal incidence have already been reported elsewhere [11].

Shown in Fig. 3 are the critical carbon-to-deuterium flux ratios calculated from Eq. (1) for a variety of host materials, assuming the surface temperature of 500°C. These data are to be interpreted as follows. If the condition falls in the space defined above the curve for the host material of interest, carbon film deposition occurs. Otherwise, carbon impurities will recycle over the surface to enhance host materials erosion. Notice that the critical carbon impurity concentration for beryllium is about 2%. This level of plasma contamination is quite possible for virtually all fusion devices, particularly if carbon is used for in-vessel components. Again, this corroborates the recent observations in JET [8]. In contrast, high-*Z* materials such as tungsten require nearly an order of magnitude higher carbon impurity concentration for film deposition. Therefore, one predicts that high-*Z* in-vessel components will remain without impurity redeposition.

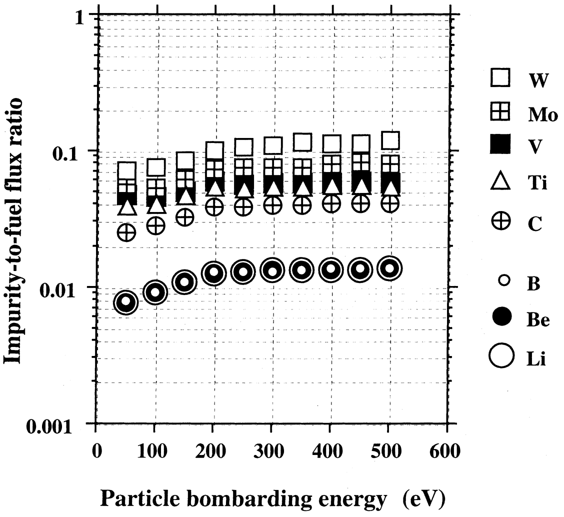

Fig. 3. Critical impurity-to-fuel flux ratio for carbon deposition over a variety of plasma-facing materials.

The effect of materials mixing on carbon deposition is explained briefly here for completeness. Details can be found in Ref. [2]. At elevated temperatures around 500°C, one expects rapid removal of carbon deposits due to chemical sputtering. However, as observed for the Be-C binary system [12,13], materials mixing can occur via thermal diffusion if the host material is a low-*Z* element. This materials mixing results in reduced chemical sputtering due to the well-known metallic impurity catalysis effect [14], which then allows for carbon deposits to survive erosion due to DT-particle bombardment. As to high-*Z* host materials, diffusion-driven mixing with carbon deposits is much less likely. This explains the surface temperature effect on carbon poisoning on beryllium observed in the PISCES experiments [1,2]. The exception to this rule is if carbon is the impurity as well as the host material because clearly, there is no materials mixing (see Fig. 3).

More elaborate time-dependent modeling has been conducted recently to analyze materials erosion under simultaneous impurity and hydrogenic ion bombardment [15]. Unfortunately, this model is not capable of considering the materials mixing effect on chemical sputtering at elevated temperatures but has calculated under a room temperature condition the critical carbon concentration for film deposition on tungsten to be about 4% for the bombarding energies of 40 and 120 eV for D^+ and C^{3+} at, respectively. Assuming only single-charged impurities, the present model has been applied for the bombarding energies of 40 and 120 eV and the critical carbon-to-deuterium flux ratios have been calculated to be about 0.06 and 0.07, i.e., 5.6% and 6.5%, respectively, which is within a reasonable range of agreement, considering the simplicity of analysis.

2.3. Enhanced erosion by recycling impurities

Unless the condition expressed by Eq. (1) is satisfied, both condensible and non-condensible plasma impurities recycle over the surface and enhance materials erosion. From the zero-dimension materials balance model [9], the total erosion rate due to DT-plasmas contaminated with recycling impurities is expressed by the following relation:

$$\Gamma_{\mathrm{host}} = \Sigma\,\Gamma_{\mathrm{D,T}}\left\{Y_{\mathrm{D,T}\to\mathrm{host}} + \Sigma\left(\frac{\Gamma_{\mathrm{i}}}{\Gamma_{\mathrm{D,T}}}\right)Y_{\mathrm{i}\to\mathrm{host}}\right\} \qquad (2)$$

where Γ_{host}: total rate of host materials erosion, $Y_{\mathrm{D,T}\to\mathrm{host}}$: sputtering yield of host materials due to DT particles bombardment; and $Y_{\mathrm{i}\to\mathrm{host}}$: sputtering yield of host materials due to impurity particles bombardment. From Eq. (2) the effective erosion yield under the influence of plasma impurities, Y_{eff}, is defined as follows:

$$Y_{\mathrm{eff}} \equiv Y_{\mathrm{D,T}\to\mathrm{host}} + \Sigma\left(\frac{\Gamma_{\mathrm{i}}}{\Gamma_{\mathrm{D,T}}}\right)Y_{\mathrm{i}\to\mathrm{host}}. \qquad (3)$$

Notice that the impurity-to-fuel flux ratio, $\Sigma\ (\Gamma_{\mathrm{i}}/\Gamma_{\mathrm{D,T}})$, appears both in Eqs. (1) and (3) as the key parameter to describe the impurity-enhanced erosion behavior.

3. Model applications for beryllium and tungsten erosion

Plotted in Fig. 4 as a function of carbon-to-deuterium flux ratio are the effective erosion yield values calculated from Eq. (3) for beryllium and tungsten under carbon-contaminated deuterium plasma bombardment at 150 eV. The surface temperature is fixed at 500°C for convenience. The effective erosion rate increases as carbon concentration increases although this effect on beryllium erosion is barely noticeable. However, at a breaking point the effective erosion yield decreases rapidly to a certain range of values and to zero, respectively, for beryllium and tungsten. This breaking point corresponds to the critical value of $(\Gamma_{\mathrm{C}}/\Gamma_{\mathrm{D}})$ shown in Fig. 3. As mentioned earlier, steady-state carbon deposition will be masking the surface to eliminate host materials erosion completely. This is expected to be the case for tungsten. However, because of the diffusion mixing effect, beryllium erosion will remain at a reduced level, perhaps corresponding to the dynamic surface composition [12,13]. For completeness of the argument, these reduced erosion yield data are imported from Fig. 1 and shown in Fig. 4 as the shaded area. Importantly, under these conditions the effective erosion rate of beryllium is not so different from that of tungsten as one expects from the sputtering yield database.

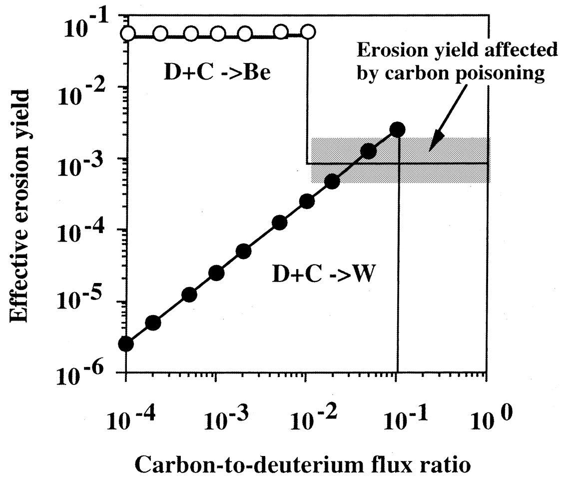

Fig. 4. Effective erosion yields at steady state for beryllium and tungsten at 150 eV and at 500°C as a function of impurity-to-fuel (C/D) flux ratio. The breaking point is at the critical ratio shown in Fig. 3. The Be erosion yield, affected by carbon-poisoned, is imported from Fig. 1.

Enhanced erosion due to DT-plasma bombardment contaminated with recycling carbon and oxygen impurities is compared between tungsten and beryllium as follows. Using Eq. (3), the total erosion rate for tungsten is given by the following equation:

$$\Gamma_{\mathrm{W}} = \Gamma_{\mathrm{D+T}}\left\{\frac{1}{2}(Y_{\mathrm{D}\to\mathrm{W}} + Y_{\mathrm{T}\to\mathrm{W}}) + \frac{\Gamma_{\mathrm{C}}}{\Gamma_{\mathrm{D+T}}}Y_{\mathrm{C}\to\mathrm{W}} + \frac{\Gamma_{\mathrm{O}}}{\Gamma_{\mathrm{D+T}}}Y_{\mathrm{O}\to\mathrm{W}}\right\} \qquad (4)$$

where $\Gamma_{\mathrm{D+T}} \equiv \Gamma_{\mathrm{D}} + \Gamma_{\mathrm{T}}$ and $\Gamma_{\mathrm{D}} = \Gamma_{\mathrm{T}}$. The effective erosion yield is defined as follows:

$$_{\mathrm{W}}Y_{\mathrm{eff}} \equiv \frac{1}{2}(Y_{\mathrm{D}\to\mathrm{W}} + Y_{\mathrm{T}\to\mathrm{W}}) + \frac{\Gamma_{\mathrm{C}}}{\Gamma_{\mathrm{D+T}}}Y_{\mathrm{C}\to\mathrm{W}} + \frac{\Gamma_{\mathrm{O}}}{\Gamma_{\mathrm{D+T}}}Y_{\mathrm{O}\to\mathrm{W}}. \qquad (5)$$

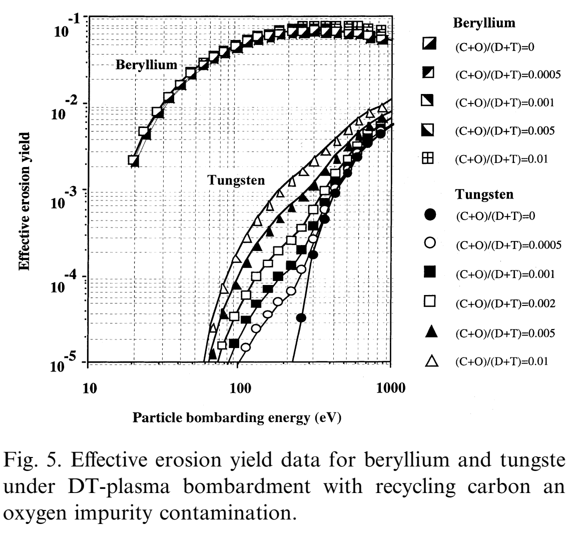

Fig. 5. Effective erosion yield data for beryllium and tungsten under DT-plasma bombardment with recycling carbon and oxygen impurity contamination.

The corresponding relation for beryllium is given by:

$$_{\mathrm{Be}}Y_{\mathrm{eff}} \equiv \frac{1}{2}(Y_{\mathrm{D}\to\mathrm{Be}} + Y_{\mathrm{T}\to\mathrm{Be}}) + \frac{\Gamma_{\mathrm{C}}}{\Gamma_{\mathrm{D+T}}} Y_{\mathrm{C}\to\mathrm{Be}} + \frac{\Gamma_{\mathrm{O}}}{\Gamma_{\mathrm{D+T}}} Y_{\mathrm{O}\to\mathrm{Be}}. \tag{6}$$

Shown in Fig. 5 are the effective erosion yield data for tungsten and beryllium, calculated from Eqs. (5) and (6), respectively. Here, it is assumed for convenience that $\Gamma_{\mathrm{C}} = \Gamma_{\mathrm{O}}$. Corroborating the data shown in Fig. 4, the overall erosion behavior of tungsten is much more sensitive than that of beryllium to the change in impurity-to-fuel flux ratio.

4. Conclusion and implications to future fusion experiments

Effects of plasma impurities on materials erosion and mixing have been analyzed. Under recycling conditions, plasma impurities enhance materials erosion. However, under non-recycling condition, materials erosion can be significantly reduced or completely eliminated by the redeposition of condensible impurities. The turnover condition from recycling to non-recycling has been defined in terms of impurity-to-host plasma flux ratio.

Generally, low-*Z* materials are susceptible to carbon impurity redeposition, particularly at elevated temperatures where diffusion mixing becomes important. The critical carbon-to-deuterium plasma flux ratios for beryllium, boron and lithium is calculated to be around 0.01, which is highly likely in a large fusion device if carbon is used for plasma-facing components. In contrast, high-*Z* materials require substantially higher level of carbon contents for film deposition. Therefore, tungsten plasma-facing components tend to remain without impurity redeposition although impurity-enhanced erosion occurs in exchange for surface cleanliness.

As to enhanced erosion by recycling impurities, beryllium and tungsten have been found to behave rather differently. Because of its high threshold energy for physical sputtering, tungsten is often expected to be sputter-resistant. However, tungsten erosion can be dominated by trace amounts of recycling impurities. In contrast, the plasma impurity effect on beryllium erosion is hardly noticeable because the erosion due to DT-particles is already substantial. Importantly, if carbon-poisoning occurs, the effective erosion of beryllium will be reduced to the level, not so different from that of tungsten.

It is practically impossible to eliminate completely oxygen impurities from a large vacuum vessel, so that plasma-facing components will unavoidably suffer from enhanced erosion. Carbon-containing impurities are equally difficult to eliminate. Therefore, reactor designers must consider the flow of plasma impurities and their effects, as pointed out in this work, in materials selection and positioning of plasma-facing components. One possible idea to reduce carbon impurity contamination is to use a sacrificial low-*Z* gettering surface under non-recycling conditions. This idea has already been practiced in a way, for example, in lithium-pellet wall conditioning in TFTR [16]. However, for future steady-state fusion devices, these gettering surfaces must be continuously refreshed in order that the surface would not be saturated with impurities and fuel particles. To resolve this surface saturation issue, perhaps one should come up with a new concept such as moving-belt plasma-facing components with ex situ processing systems [17].

Acknowledgements

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