Status and Issues of Plasma Facing Materials for Fusion Reactors

Yoshio Ueda

Graduate School of Engineering, Osaka University, Osaka, Japan

Abstract: Development of plasma facing materials is one of the key issues for realization of fusion reactors. In this overview, explanation on the research status and issues of wall materials in terms of (1) compatibility with fusion plasma, (2) lifetime, (3) safety, (4) compatibility with in-vessel components will be shown. Important issues toward fusion power reactors under steady-state plasma and neutron irradiation are also explained.

Keywords: Plasma Facing Materials, Fusion Reactor, High Heat Flux, Helium, Tritium

1. INTRODUCTION
Development of fusion reactors are entering new stages to demonstrate fusion power production safely with a newly constructing device, ITER. Seven countries and areas are collaborating to build ITER in France. Achieving a fusion energy gain factor Q of more than 10 is a main target of ITER with the pulse length of 400 sec[1]. Several important issues, however, still remain to operate ITER machine steadily and safely. These include appropriate choice of plasma facing materials and optimization of plasma operation.

Plasma facing materials in divertors in fusion reactors are subject to high heat load up to ~ 10 MW/m². To withstand this heat flux, only materials with high thermal conductivity and high melting (sublimation) points can be used. Tungsten and CFC (Carbon Fiber Composite) graphite are the sole candidates. Both materials, however, have concerns such as enhanced erosion of graphite by chemical sputtering and cooling of fusion plasma by tungsten accumulation in the core plasma.

In this paper, I will briefly summarize necessity conditions for plasma facing materials and issues of tungsten and graphite for ITER and future power reactors.

2. NECESSITY CONDITIONS FOR WALL MATERIALS
There are four important viewpoints to select wall materials and optimize plasma operation; (1) compatibility with high performance core plasma, (2) sufficient lifetime of wall materials, (3) safety, (4) compatibility with in-vessel components such as blankets. In this chapter, I will discuss these subjects in detail.

2.1. Compatibility with fusion plasma
There are critical limits of atomic concentration of wall materials in the core plasma to obtain enough fusion reactions. In general, low Z materials such as carbon have high critical concentration (order of 10⁻⁷). On the other hand, high Z materials such as tungsten have very low critical concentration (order of 10⁻⁵). These concentration limits are determined by dilution of fuel ions for low Z impurities and by radiative cooling of core plasmas for high Z ions. Therefore, special cares must be needed to avoid core accumulation in the case of tungsten wall.

2.2. Lifetime of wall materials
Lifetime of wall materials are determined mainly by erosion processes such as physical sputtering, chemical sputtering, sublimation, melt layer loss, and exfoliation of surface layers and grain ejection. The physical sputtering yield depends on the mass ratio between the impinging ions and target atoms, and surface binding energy. Graphite and tungsten have relatively high surface binding energies (7.41 eV for Graphite and 8.68 eV for tungsten), which tends to reduce the yield and the threshold energy. The threshold energies for D bombardment is 35eV for graphite and 220eV for tungsten. Since the ion impinging energy at divertors plates is less than 100 eV, physical sputtering of tungsten by hydrogen isotopes is negligible.

Graphite has unique erosion processes such as chemical sputtering by hydrogen isotope bombardment and radiation enhanced sublimation. Chemical sputtering yield of graphite is by an order of magnitude higher than physical sputtering around 800 K. In addition, since there is no clear threshold energy for chemical sputtering, its yield is not negligible for low impinging energy (divertor conditions). Therefore, erosion of graphite plasma facing walls is a serious concerns for fusion reactors. Radiation enhanced sublimation (RES) is a sublimation enhanced by ion irradiation. RES reduces onset temperature of sublimation, which could decrease the upper limit of graphite operation temperature. However, RES could be suppressed under high flux conditions.

In order to reduce heat flux to divertors, inert (Ne or Ar) gas puffing to edge plasmas is planned. Inert gas in the edge plasmas reduces electron temperature by radiation cooling, leading to reduction in heat flux to divertors. Inert gas ions, however, have higher sputtering yield for tungsten due to its higher mass and higher impinging energy (higher charge state) than hydrogen isotopes. Evaluation of the effects of inert gas puffing on the erosion of divertor materials is necessary.

Recently, helium effects have attracted increasing attention in terms of material degradation, leading to exfoliation and grain ejection (dust formation). Helium atoms have high trapping energy with point defects (4.0 eV – 4.4 eV), while hydrogen atoms have much lower binding energy with point defects (~1.4 eV). Therefore, He atoms are hardly detrapped from these defects even at...
elevated temperatures. In addition, when tungsten temperature exceeds recrystallization temperature (1500–1600 K), helium and defect complexes becomes mobile and tend to agglomerate to form, so-called, helium bubbles. It is important to study formation conditions, effects to core plasma, and suppression technique (if necessary) for He bubbles in fusion reactor environments.

For more than 20 years, many good confinement modes of core plasmas have been found and are the keys to achieve economical fusion reactors. One of them is H-mode, which has transport barriers near the edge plasma. This mode, however, is known to be accompanied by repeated pulsed plasma energy ejection, ELM (Edge Localized Mode). For ITER, a pulse length and a heat load of Type I ELMs were predicted to be ~0.2 ms and 0.5–1.2 MJ/cm², respectively[8]. This Type I ELM pulse can raise the surface temperature of tungsten above the melting point (3422°C). Once tungsten melts, grain growth and significant reduction of yield strength will occur, leading to crack formation and dust generation. Therefore, it is believed that the mitigation of ELM pulse energy is of great importance for fusion reactors.

Recently it has been pointed out that even under non-melting conditions the repeated ELM pulse effects could be serious[9]. Repeated heat pulse cause surface expansion and contraction alternately, which would cause metal fatigue and cracking. Particle induced processes, mainly due to helium ions, could enhance this effects. More studies will be needed to comprehensively understand this effect and to avoid serious effect in fusion reactors for tungsten walls.

2.3. Safety Issues

Safety issues in fusion reactors have many aspects, but mainly relate to radioactive materials, tritium and activation materials due to neutron irradiation. Among these, safe handling of tritium is the most important issue. Tritium is radioactive with the half life of 12.3 years by beta decay. For the safety regulation, total tritium amount in fusion reactors will be limited to an order of kg. Since most of solid materials can generally keep tritium as solution or trapped atoms in defects, it is of great importance to know tritium retention in wall materials and to control its amount well less than the safety limit.

Tritium retention in materials have been extensively studied by ion beam implantation and plasma exposure[10]. In the very early stage of implantation, most of ions except reflected ions are retained in the materials. Then the tritium retention near the surface layers (within ion ranges) saturates and most of implanted ions are desorbed from the surface. At elevated temperatures, implanted ions also diffuse into bulk to be trapped at defects, or to permeate through the wall materials to cooling channels or to inside structure of blankets.

Generally tritium retention in metallic materials are low due to low trapping energy and low trapping site density. On the other hand, tritium retention in graphite is relatively high. At the room temperature, tritium concentration of as high as 0.4 in graphite could be reached by ion implantation. In this case, most of hydrogen atoms are trapped by forming covalent bond to carbon atoms. For this reason, high temperature (more than 1000K) annealing is needed to desorb hydrogen. Therefore, tritium retention in graphite walls at the temperature less than 1000 K is a matter of concern.

As was pointed out, graphite has high erosion rate mainly due to chemical sputtering by hydrogen isotopes. Eroded carbon atoms from the wall will migrate in plasmas, eventually reach some other surfaces of walls to form redeposition layers, which contain tritium. The amount of tritium is a function of wall temperature and depends on characteristics of carbon films. Hydrogen isotope concentration in codeposited layers tends to be higher than that by hydrogen isotope implantation. In some cases, it exceeds over 1.0. It is believed that these films are formed by the accumulation of hydro-carbon radicals.

Removal of tritium in wall materials is also of great importance. For plasma facing surfaces, technique using plasma exposure (glow discharge, Taylor discharge cleaning, soft disruption cleaning, etc.) would be useful. The removal rate can be improved by using oxygen plasma. The removal of remaining oxygen, however, could be the issue.

Codeposition layers have been also found in plasma-shadowed area such as rear side of divertor plates. These layers could be formed by migration of neutral hydrido-carbon radicals. Sticking coefficient of these radicals can be significantly low at elevated temperatures. These radicals travels far from the plasma facing surface through the shadowed region. In general, it is not easy to remove tritium in the codeposition layers formed in the remote area. In addition, codeposition in gaps of wall tiles also becomes a matter of concern.

2.4. Compatibility with in-vessel components

Wall materials sometimes affects function of in-vessel components. For example, surface coating materials can change tritium breeding ratio (TBR) in blankets[11]. When tungsten is used as a first wall material, TBR tends to decrease due to the capture of low energy neutron by tungsten. On the other hand, Be first wall tends to increase TBR due to neutron multiplication reactions. Therefore, in order to meet every needs in terms of wall materials and blankets, close cooperation between research groups of wall materials and blankets is necessary.

3. ISSUES FOR REACTOR ENVIRONMENTS

3.1. Steady state operation

Plasma duration in present magnetic confinement devices are limited to a few hours. Especially for high performance plasmas with the fusion energy gain factor around 1, the duration is limited to an order of seconds. On the other hand, the discharge duration of commercial fusion reactors must be an order of several months. There still remains quite a significant gap between the present experiments and future operations.

There are several time constants in terms of plasma wall interaction. Wall saturation with fuel atoms (hydrogen isotopes) is one of the important lifetimes. This could be an order of minutes. In JT-60U, plasma performance under these wall-saturated conditions have been investigated[12]. In these studies, however, wall conditions are very limited such as graphite walls and the relatively low
first wall temperature (less than 300 °C). We need more database for the other conditions in order to extrapolate present results to fusion reactor conditions.

As was described, tritium retention in codeposited layers is a matter of concern. Since erosion of wall materials do not have a clear limit, formation of codeposition layers would continue during plasma operation. Therefore, estimation of tritium retention in codeposition layers and development of effective removal methods are important issues.

Degradation of wall materials under high fluence plasma exposure also needs to be studied. There have been quite a few studies for the effects of plasma exposure to wall materials. Ion fluence of these studies, however, are limited up to $10^{28} \text{m}^{-2}$, while ion fluence to divertor plates in fusion reactors will reach $10^{31} \text{m}^{-2}$ in a year. At present, no plasma device can simulate wall materials under this condition, or there are no plans for it. We need to make a strategy for the development of reliable wall materials under very high fluence conditions.

### 3.2. Neutron effects

One of the most significant differences between ITER and fusion reactor environments is neutron fluence. ITER will handle fusion plasmas, which produce 14 MeV fusion neutrons. Its fluence is much lower in ITER than fusion reactors due to low duty in ITER. ITER will be able to provide the average neutron fluence of 0.3 MWm$^{-2}$. On the other hand, neutron fluence to wall materials of fusion reactors would reach about 10 MWm$^{-2}$ per year[11].

Fusion neutrons (14 MeV) will have several effects on wall materials. Radiation damages produced by elastic collision between fast neutrons and lattice atoms. These damages will results in hardening, swelling and some other material degradation. In addition, transmutation of materials needs to be taken care of. For example, tungsten is transmuted to Re, then Os[13]. Thermal conductivity of tungsten contained with Re was measured. This study showed that thermal conductivity decreases with Re concentration. Tungsten with 10at% Re has lower thermal conductivity than pure tungsten by about 30% at 1000 K[14]. In fusion reactors, this composition would reach in about 2 years of operation. The other transmutation effects other than reduction of thermal conductivity have not known well.

Transmutation reaction between wall materials and fast neutrons generally produce light elements such as hydrogen and helium. As already mentioned, helium would cause deteriorating effects on metals due to the formation of He bubbles.

### 4. CONCLUSION

Development of nuclear fusion reactors are getting into a new phase by building ITER. However, to see fusion power reactors following ITER there still remain quite a few issues in the field of plasma wall interaction (or development of plasma facing material). Steady-state plasma exposure and high dose of neutron irradiation are of great importance for material research. Synergistic effects of these must be clarified before the construction of commercial reactors. However, there are no plans to study these phenomena at present. We have to construct strategies for the development of plasma facing materials toward realization of fusion reactors.

### REFERENCES