Tritium management in a fusion reactor
- safety, handling and economical issues -

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Abstract. In order to establish a D-T fusion reactor as an energy source, it is not enough to have a DT burning plasma, and economical conversion of fusion energy to electricity and/or heat, a large enough margin of tritium breeding and tritium safety must be simultaneously achieved. In particular, handling of huge amount of tritium needs significant efforts to ensure that the radiation dose of radiological workers and of the public is below the limits specified by the International Commission on Radiological Protection (ICRP). In this paper, after the introduction of tritium as a fuel of DT reactors and as a radioisotope of hydrogen, tritium safety issues in fuel cycle and blanket systems are summarized. In particular, in-vessel tritium inventory, the most important and uncertain tritium safety issue, is discussed in detail.

Keywords: Fusion reactor, Tritium, Fuel, Confinement, Deuterium, Safety, Tritium process
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1. INTRODUCTION

In order to establish a D-T fusion reactor as an economical and safety energy source, it is not enough to have DT burning plasma. We have to achieve efficient conversion of fusion energy to electricity and/or heat, a large enough margin of tritium breeding and safety confinement of tritium, simultaneously. Everyone knows that because of radioactivity, tritium must be physically contained and safely confined. Tritium handling systems, which uses mostly established techniques, can be built for ITER or even a reactor without very high hurdles [1-3]. However, handling of huge amount of tritium would give rise lots of problems to be overcome.

Properties of a mass of tritium is mostly the same as that of hydrogen, and tritium handling system is just like a chemical plant handling hydrogen [1,3]. However its radioactivity adds various problems to handle tritium. The most important point is accountancy. The radioactivity of tritium does not allow any waste or loss of tritium, i.e. even a pico-gram (10^{-9} g) of tritium must be traced on handling of kg order of tritium. Tritium science has been focusing behavior of tritium as a tracer, because of its easy detection of β–electrons emitted and of its importance of biological influence. The detection does mean existence of tritium, but does not indicate its chemical form.

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For tritium safety, the chemical form of tritium does matter, and tritium science and technology for fusion require a little different knowledge obtained from the tracer technique.

For the safety reasons, tritium in a fusion reactor will be limited to only a few kg orders in weight [4] with radioactivity counts up to 10^{17} Bq. While tritium is regulated at a level as tiny as a few Bq/cm^2 to ensure that the radiation dose of radiological workers and of the public is below the limits specified by the International Commission on Radiological Protection (ICRP). Generally quantitative analysis with the accuracy of more than 4 orders of magnitude is hardly possible. This means that the handling of 10^{17} Bq of tritium without missing of 10^{13} Bq or less is impossible. Furthermore limited resource of tritium requires tritium recycling as high as possible or keeps immovable tritium as small as possible. All these must be done under the strict regulation. Thus we are facing to concerns to handle huge amounts of radioactive tritium as a fuel and to be bred in a blanket.

In fusion environment, energy state (temperature) of tritium is so widely spread, from 20 K (Solid or Ice Pellet), through near RT (Gas), to 10^9K (Plasma), that the physics and chemistry of the interactions of tritium with materials of confinement system become very complex. The high level of radioactivity of tritium generates additional problems due to electron emission and/or radiation heat, such as excited state chemistry and non-equilibrium thermodynamics.

In this report, after the introduction of tritium as a fuel of DT reactors and as a radioisotope of hydrogen, tritium safety issues in fuel cycle and breeding systems are summarized. Finally in-vessel tritium inventory, the most important and uncertain tritium safety issue, is discussed in detail.

2. TRITIUM AS THE FUEL OF A DT FUSION REACTOR

2.1. DT fusion

Already 50 years have passed after finding that nuclear reactions give energy, and fission reactors are well established as energy sources, while a fusion reactor seems to need still a few tens years to be realized. Why so much longer time has been required for fusion than fission? Different from any other energy sources, fusion needs significant amount of energy to start burning, i.e. overcome a coulomb potential. The first priority for fusion researches has been plasma confinement to establish DT burning, the easiest fusion reaction, and we will soon attain Q = 10 in ITER. (Q is a ratio of input power to fusion energy output). But this is not enough for a fusion reactor to be an energy source. Lots of scientific and technical issues are remained to be solved. Among them, tritium safety is one of the most important ones.

There are five hydrogen related fusion reactions [5],

$$D + T \rightarrow {}^3He + n + 17.6\ MeV \quad (1)$$

$$D + D \rightarrow T + H + 3.98\ MeV \quad (2)$$

$$D + D \rightarrow {}^3He + n + 3.25\ MeV \quad (2')$$

$$T + T \rightarrow {}^4He + 2n + 11.3\ MeV \quad (3)$$

$D + {}^3He \rightarrow {}^4He + H + 18.3\ MeV$ (4)

$T + {}^3He \rightarrow {}^4He + D + 14.3\ MeV.$ (5)

The energy dependence of their reaction cross-sections are given in Fig.1. Among the five reactions, DT reaction (1) has the highest cross-section at the lowest energy (temperature). D^3He reaction (5) is very much attractive for no neutron production. However the D^3He reaction requires much high energy to ignite. Hence the DT reactor should be the first generation fusion reactor. The DT reactor uses tritium as fuel and requires sophisticated tritium fueling and recycling systems for tritium safety. All other D involved reactions generate tritium, but they do not need tritium fueling or recycling system and tritium safety problems would be much relieved.

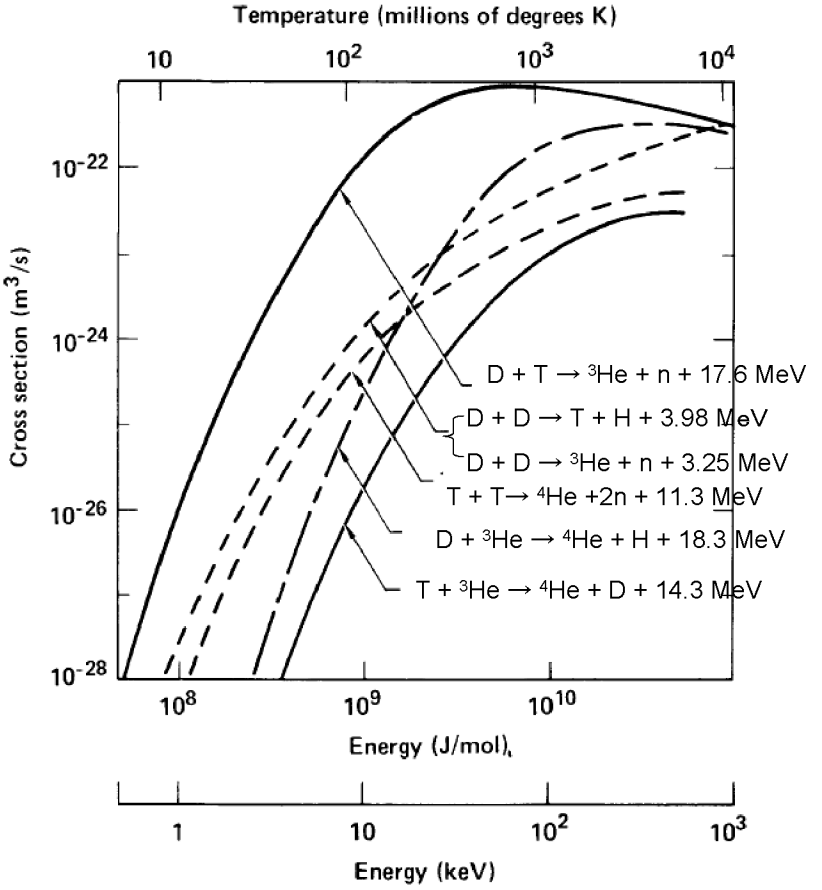

FIGURE 1. Energy dependences of cross sections of hydrogen related fusion reactions [5].

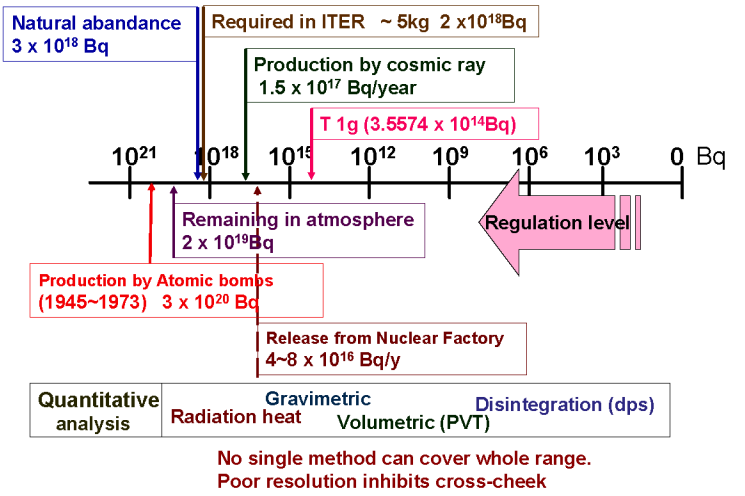

FIGURE 2. Comparison of tritium amounts, resources, abundance and regulation.

2.2. Tritium as fuel of DT reactor

Since natural water contains 0.016% deuterium, we can extract it from the water mostly by means of electrolysis. While the natural abundance of tritium, which is generated by cosmic rays and also by nuclear reactions (atomic bombs and nuclear reactors) after the 2nd word war, is very small as show in Fig. 2. Therefore tritium should be artificially produced.

From simple calculations, 56 kg tritium is required per GW year (thermal) of fusion power for a DT reactor. While about 100 g tritium is produced per year in a standard CANDU fission unit and 20 to 25 kg tritium (mainly in Canada) will be available for operation of ITER. Hence it seems difficult to get sufficient amount of tritium even for a demo reactor. Therefore tritium retained in a fusion reactor should be recovered not only from tritium safety but also tritium economy. Furthermore, tritium must be produced by a nuclear reactor with the reaction (7) using ^{6}Li.

Once sufficient amount of tritium for a DT reactor is available, the DT reactor produces energy and breeds tritium in a blanket system simultaneously [6] as described below. The energy released by DT reactions is distributed to ^{3}He and neutron,

$$D + T \rightarrow {}^{3}He\ (3.5MeV) + n(14.1MeV). \qquad (1')$$

The energy of ^{3}He is to be used for heating plasma for continuing the DT burning and the energy carried by neutron is transformed to heat in a blanket system for electricity or other use, like hydrogen production. At the same time, neutron is used to breed tritium as

$$^{6}Li + n \rightarrow T + {}^{4}He + 4.8MeV, \qquad (6)$$

$$^{7}Li + n \rightarrow T + {}^{4}He + n - 2.5\ MeV. \qquad (7)$$

Although reaction (6) generates both tritium and energy, tritium is not bred (breeding rate is just 1). If a half of neutrons produced by DT reactions are used for the reaction

(6) and the last half for (7), tritium breeding ratio becomes 1.5. However the latter reaction requires energy and reduces the output energy. With using the optimized blanket system, overall tritium breeding ratio in a fusion reactor is expected to be around 1.1 or a little less. In this respect, the tritium inventory increment or retention rate in the reactor ((fueling – (burning + recovering))/fueling) must be below 0.1, otherwise tritium for the 2 nd reactor is not generated. (T burning is only a few % as discussed later). At the moment this seems very hard owing to large in-vessel tritium inventory as described later.

3. TRITIUM SAFETY

3.1. Tritium, a radioactive hydrogen isotope

Tritium is a radioactive hydrogen isotope decaying to ^{3}He emitting a β-electron and an antineutrino (ύ) with a half life of 12.323 year [5],

$$T \rightarrow {}^3He + \beta + \acute{\upsilon}. \qquad (8)$$

Accordingly the decay rate, 1g of tritium is equivalent to 3.5574 x 10^{14} Bq. This means that during storage, about ~ 5.5 % is disappearing in a year. This also requires efficient tritium recovery and breeding. The energy of emitted β-electrons is widely distributed with the maximum of 18.6 keV and average of 5.7 keV. The integrated decay heat is 324 mW/1gT, which is not very large but could result in thermal release of tritium from heavily tritium loaded materials.

Because of its low energy, the effect of β-electrons on living things is also very week. Hence tritium had been used under very mild regulation or sometimes no regulation. And usually no shielding is required to handle tritium, though cross-contamination must be concerned. Tritium is easily detected by β-electron counting with the detection limit and/or accuracy of several Bq/cm^2 on solid surfaces and around 0.1 Bq/cm^3 in water. However, the β-electron counting is limited to below 10^9 Bq or mg order of T. For much larger amount of tritium, mass and/or pressure measurements, the same way to measure other hydrogen isotopes, are employed. The measurement of decay heat allows calorimetry but its accuracy is only 10^{-2} to 10^{-3}. All present tritium measurements except the β-counting give only 3 to 4 digit and any loss of tritium less than 0.1% is hardly possible to detect. Since public exposure to tritium is regulated at a level as tiny as a few Bq/cm^2, tritium must be strictly confined in handling systems. Fortunately, tritium escaping from the handling system by permeation and contamination is easily detected by the β-counting method.

It should be mentioned that, tritium retained in bulk of solid materials can not be detected, because the β-electron can penetrate through materials only a few μm in depth. (Its maximum range in air is 6 mm and less than 1μm in metals.) Therefore movable tritium in the solid, mostly in metals, is problematic for safety.

Tritium can easily replace the ubiquitous lighter hydrogen isotopes like protium (H) / deuterium (D) in water and hydrocarbons in air,

$$HT + H_2 = HTO + H_2 - \Delta G, \qquad (9)$$

$$HT + CH_4 = CH_3T + H_2 - \Delta G. \qquad (10)$$

In particular, any materials surfaces absorb water molecules and enhance isotopical replacement,

$$MOT + H_2O = MOH + HTO - \Delta G, \quad (11)$$

$$MT + H_2O = MH + HTO - \Delta G, \quad (12)$$

producing hazardous tritiated water.

In addition, the β-electrons could cause and/or enhance undesirable chemical reactions (radio-chemical reactions) in living things appearing as radiation hazard.

Fig. 3 is a good example indicating how tritium is transferred by cross-contamination caused by above reactions. Gloves as essential equipment in a tritium handling system are always contaminated and tritium on the glove surface is immediately transferred to non-contaminated materials. However, tritium exposure of skin is not so dangerous owing to thin penetration of the β-electron, while tritium taken into a body usually in the form of HTO or OT is very hazardous. In this respect, gaseous form, HT, is much safer than HTO and OT. It is well known that drinking beer is very effective to remove tritium from the body, and actually beer bottles are prepared at the exit of some tritium laboratories.

It is interesting to note that the β-decay of tritium accompanies the emission of an antineutrino. This means that the precise measurements of edge energy (maximum energy of emitted β electron) would give neutrino mass, which is a positive use of tritium decay [7].

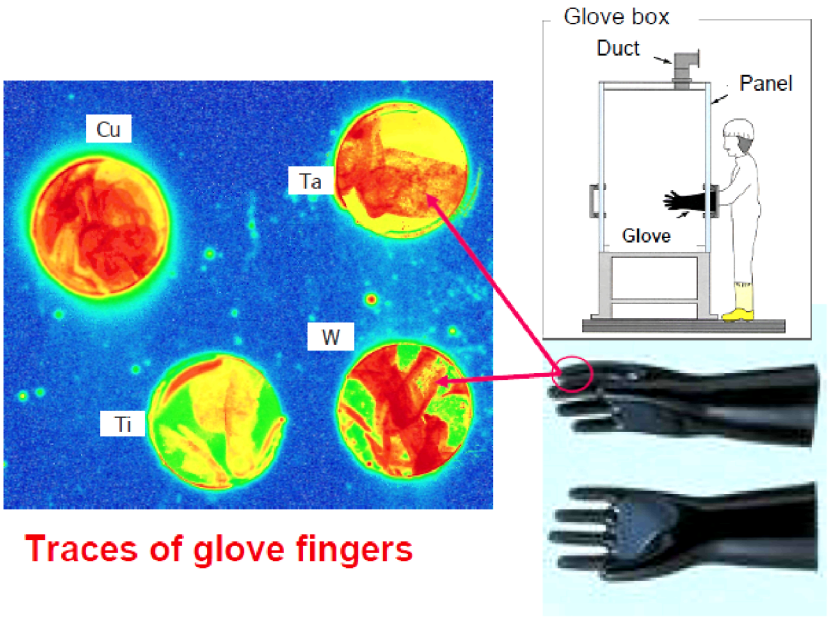

FIGURE 3. Example of cross-contamination of tritium; Tritium surface profiles of metals handled in a tritium handling glove box. The trace of glove fingers appeared very clearly.

3.2. Reactor safety

A fusion reactor is generally much safer than a fission reactor, in other words, the fusion process is inherently safe. Because there is no chain reactions like fission and the reaction is thermally self-limiting with limited burning time, a few seconds without re-fueling. Power/energy densities in the reactor and plasma are low. No radioactive materials are produced by the fusion. However neutrons activate structure materials and the total volume of the activated wastes will be similar or larger than the fission reactor. Currently, materials are not optimized for low-activation under neutron irradiation. In the future, the activated material can be recycled for re-use after 50-100 years and material optimized for low-activation can be readily recycled for use in fusion power-plant reactors. In case of active cooling system failure, decay heat from activated materials is low enough that all in-vessel components can be cooled by natural convection and reactor "melt-down" is physically impossible.

Therefore most of the safety issues are owing to radioactivity of tritium and the activated structure materials. Since the activated materials are not movable, most serious movable hazards involve the tritium fuel itself and activated dusts containing tritium resulting from erosion of plasma facing components. Radiation dose of radiological workers and of the public must be below the limits specified by ICRP. As for ITER, public safety might not be a serious concern.

4. TRITIUM FUEL CYCLE

Figure 4 shows a fusion reactor system with a blanket system generating power and breeding tritium simultaneously, and accompanying problems. In the fusion reactor, the amount of tritium to be handled is ~ 10^{17}Bq under accountancy (or under regulation of) of a few tens Bq. The form of tritium handled includes ice pellets (~ 20 K) and gas at RT (300K) (both for fueling), energetic neutrals and ions (for neutral and ion beam heating) and plasmas, having temperatures ranging from 10^{1} ~ 10^{9} K.

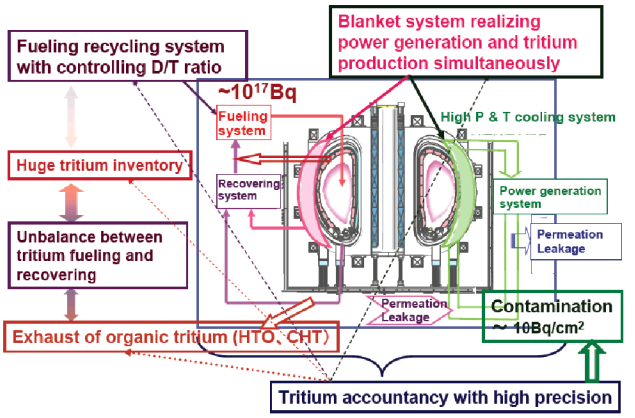

FIGURE 4. Tritium cycling system in a fusion reactor and accompanied problems

Therefore the physics and chemistry of the interactions of tritium with materials used in the reactor or tritium confinement systems are very complex [8]. The high level of radioactivity of tritium generates additional problems due to β-electron emission and/or radiation heat, such as excited state chemistry and non-equilibrium thermodynamics. Furthermore defect formation by electron excitation and He production result in various damages in materials. This, in turn, influences basic process of hydrogen-materials interactions such as adsorption, solution, diffusion and permeation in materials, which are directly related to tritium confinement.

A specialty of the fuel cycle is very poor burning efficiency. i.e. only a few % of input tritium burns and the majority is recovered to be recycled. In addition, several % is likely continuously retained in the reactor vessel to become huge in-vessel tritium inventory which is hard to be recovered. Since the recovered tritium includes H, D, T and He, it should be refined with isotope separation and then recycled.

The reactor is surrounded by blanket systems to realize power generation and tritium production simultaneously. Different from the fission reactor, in which most of the released energy is deposited in a fuel pin with a diameter of only around 10 mm, 14 MeV neutron energy must be transformed to heat for generation of electricity in the large volume of the blanket systems. In addition, tritium produced in the blanket easily permeates into coolant. The permeated tritium readily reacts with surface contaminants to produce hazardous tritiated water and/or hydrocarbons according to the reactions (11) and (12). In particular, ferrite, a low activation structure candidate material, has very high tritium permeability and needs permeation barrier with the permeation reduction of 5-6 orders of magnitude. For a water cooling system, permeated tritium from the plasma facing surface or blanket to the coolant easily produces HTO, resulting diluted tritiated water from which tritium recovery is very cost consuming

Although Lithium (Li) can work as coolant and tritium breeder simultaneously [9], tritium extraction from Li is very difficult. Hence a Lithium Lead (LiPb) eutectic alloy for which T recovery is rather easy, could be promising coolant [10]. Simultaneous generation of electricity and keeping tritium safety still need significant R&D efforts and both must be optimized.

A tritium recycling system, which uses mostly established techniques, can be built for ITER or even for a reactor without very high hurdles and, hence, Tritium Plant is not likely on a critical schedule path towards First Plasma in ITER [1-3]. However, handling of huge amount of tritium in ITER would give problems to be solved. They are mostly relating tritium behavior in plasma, huge inventory in vacuum vessel and its accountancy, controlled fuelling to keep DT burning, possible permeation and leakage leading to contamination of remote handling system, and so on. Most of those tritium problems are directly related to the safety of operators and/or professionals. But public safety does not seem to become significant problems because the emission to outside of the reactor site can be easily kept below the safety limit as already described.

5. TRITIUM INVENTORY

In vessel-tritium inventory is the largest among all tritium handling systems. For the safety, the maximum in-vessel inventory in ITER is limited to be 1 kg (750g including safety margin) [1, 4]. Therefore evaluation of hydrogen retention in present tokamaks is of highest priority to establish a database and a reference for ITER. Although extensive studies have been done to determine or estimate the in-vessel tritium retention, the present estimation includes very large error and uncertainty. In the current tokamaks, a fuel retention rate defined as (deuterium fueling rate – recovering rate)/ fueling rate) has been measured under DD discharges to be 10-50 %, while the retention rate often lower (~10%) is obtained using postmortem analysis of plasma facing tiles and components [11, 12]. A retention rate of 10 % of the tritium injected in ITER would lead to the in-vessel T-limit (1kg) in ~100 pulses as discussed below.

Figure 5 is the latest estimation of tritium inventory in ITER based on the data taken from present large tokamaks [12]. There still remains large uncertainty. It should be noted that the retention rate does not saturate at al. That is mainly because eroded materials at the plasma facing surface are deposited with tritium (codeposition) at plasma shadowed area or remote area and the codeposition simply piles up. Thus it seems hardly possible to attain the fuel retention rate below 20 % in a reactor with carbon as PFM. Carbon has been the most reliable plasma facing material and all present large tokamaks employ carbon as PFM to get good confinement [13]. On the other hand, carbon is well known to retain large amount of tritium. In particular, carbon codeposits with hydrogen at remote area shows hydrogen concentration of 0.4

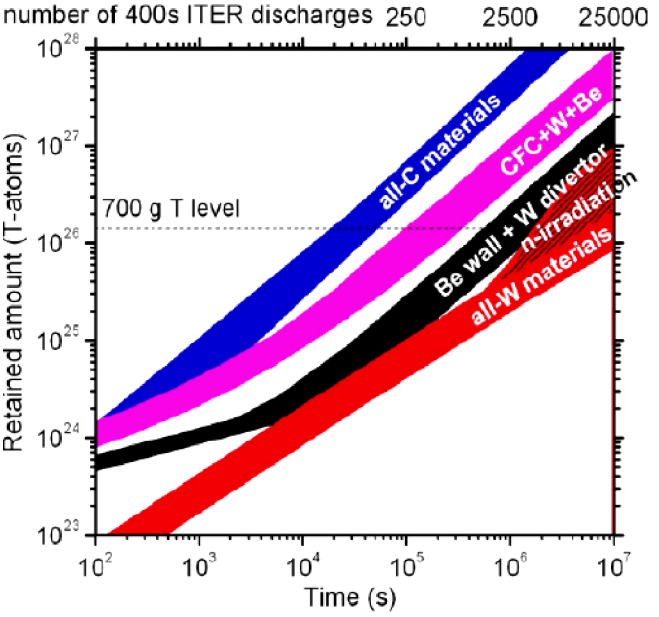

FIGURE 5. Estimation of tritium inventory in ITER plasma-facing materials after Roth et al. [15].

in H/C atomic ratio, although the value decreases with increasing temperature. This is one of the main reasons to avoid carbon materials in ITER and beyond. Although erosion and deposition can not be avoided in any materials, utilization of high Z or heavy metallic materials can minimize erosion, deposition and tritium inventory, which is one of the main reasons to use W in ITER and a DT reactor [14].

Do we need to know tritium inventory in the reactor very precisely? Yes, we do for safety regulation, too. As the balance of fueling and recovering, one may get retained amount in the reactor. Unfortunately, this estimation includes large error. There are two reasons for the uncertainty in the in-vessel fuel retention. One is the accuracy of the recovered amounts (The accuracy of the fueling would not be a problem). Since tritium is recovered by vacuum pumping, a low gas pressure measurement has not enough accuracy and its time integration could result in a huge error. Another difficulty is to measure hydrogen retention in the in-vessel components. Deuterium retention for the in-vessel components has been measured by the out-of-pile measurements for limited numbers of samples. The fuel retention derived by the extrapolation of postmortem analysis of the selected tiles disagrees with that determined by the fuel balance as already mentioned [15].

When the in-vessel tritium inventory would rise up to the limit in a reactor, the reactor must be stopped to reduce the tritium inventory. To do this, one should know where and how much tritium is in the vessel. One may ask whether the radioactivity of tritium can help the tritium measurement. The answer is "No". As already noted that low energy β-electrons allow the detection of tritium only at and in near surface regions and there is no way to measure tritium in bulk except combustion detection and calorimetry measuring the decay heat. Furthermore γ-emission from the neutron activated structure materials and some impurities with large cross-sections for the neutron activation would easily hinder tritium decay. Thus the quantitative measurement of tritium, or tritium accountancy in the reactor, remains as one of the key safety issues. HH phase and DD phase in ITER might be the best test bed for this. At the moment we have to rely on deuterium measurements in current tokamaks.

6. TRITIUM BEHAVIOR IN DD AND DT PLASMA OPERATION IN CURRENT TOKAMAKS

Simulation of tritium behavior in a DT reactor by deuterium behavior in the present D discharge tokamaks is the one of the most important methods to estimate tritium inventory [11-16]. However, the deuterium behavior in DD discharges does not necessarily simulate the tritium behavior in the DT reactor [17].

Most of current deuterium discharge machines have retained tritium produced by the DD reaction in their PFM (plasma facing materials). Even TFTR and JET introduced significant amount of tritium. Therefore, tritium retained in PFM has been detected in most tokamaks. In particular, DTE experiments in JET and Tritium campaign in TFTR have given useful information on the behavior of tritium in tokamaks. Figures 6 and 7 visualize tritium distributions on JET-Mark-IIA divertor tiles [18] and bumper limiter tiles of TFTR [19], respectively. Both cases clearly show tritium distribution coincide with carbon deposition. It should be noted that beneath

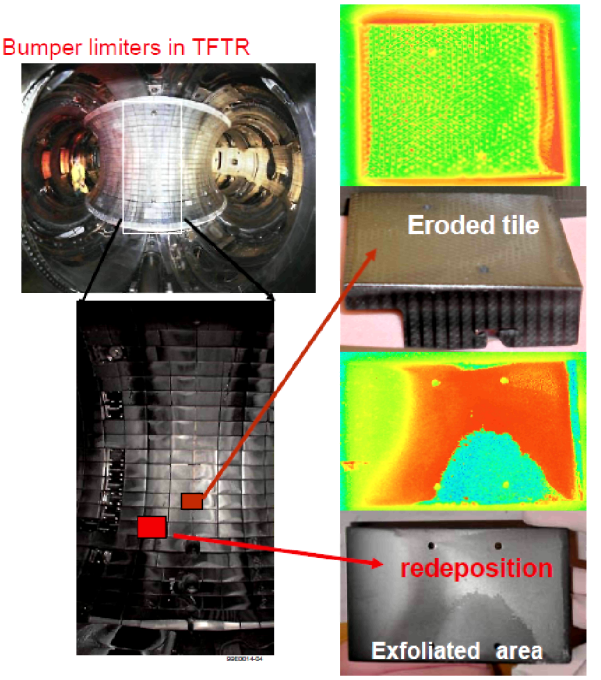

FIGURE6. Tritium distribution on TFTR bumper limiter tiles [18]. Carbon deposition profile is quite the same to tritium profile and no tritium is observed after the exfoliation of the deposited layers. Eroded tile has heavy deposition on tile sides as appeared high tritium level.

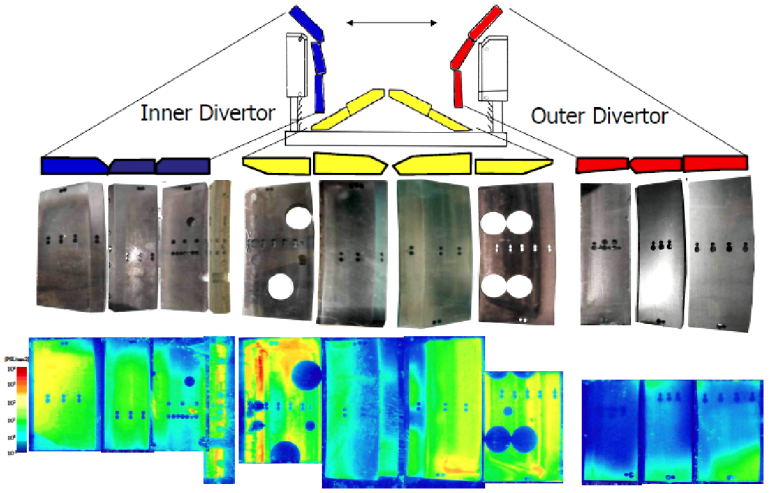

FIGURE 7. Tritium distribution on JET markII-A divertor tiles [19]. Tritium profiles (bottom) are quite the same to carbon deposition seen in photographs (above) and toroidal and poloidal profiles are quite inhomogeneous. (See text)

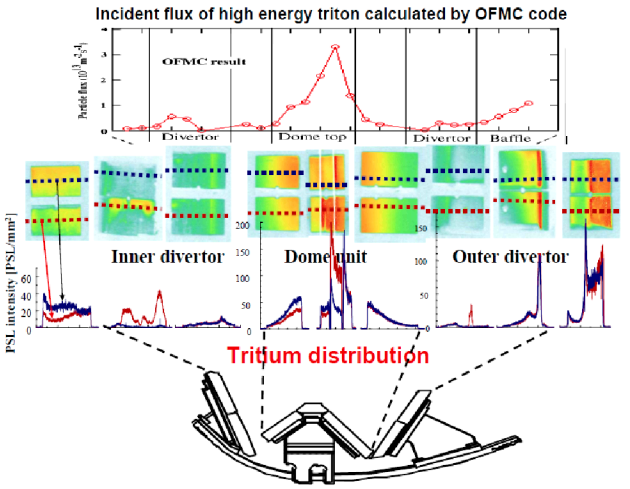

FIGURE 8. Tritium distribution and line profiles on W-shaped divertor tiles in JT-60U [21, 23, 24]. Incident flux of energetic triton calculated by OFMC code is given for comparison [21, 23, and 24]

the deposited layers, or on particular area where the deposited carbon layers were removed, tritium was hardly detected (see Fig. 6). The tritium retention in tile gaps or tile sides was clearly observed as seen in Fig. 6. The appearance of gap deposition differs between the two machines [20]; the gap deposition for the eroded tiles of TFTR (a limiter machine) was more significant than that for JET (a divertor machine). In JET, a wide opening for divertor pumping allows significant amount of carbon transport resulting heavy deposition on louvers for protection of vacuum pumps and tile sides facing to this opening [20]. Such gap retention of tritium is very similar to deuterium in a DD machine.

However, tritium distribution on plasma facing surface in DD machines is quite different. Figure 8 shows tritium distribution on JT-60U divertor tiles in which tritium is located rather deep inside and no tritium was detected near surface layers [21, 22]. There are two reasons. One is isotopic replacement; JT-60U employs HH discharges before ventilation to remove T produced by DD reaction [23]. Hence T is replaced by H during the HH discharges or H_2O by air exposure. Another is direct implantation of high energetic T into plasma facing surfaces. Actually poloidal and toroidal distributions of tritium on the divertor tiles and the fist wall tiles agree well with calculated flux to the wall surfaces of high energy tritium by the OFMC code [24].

Figure 9 schematically shows depth profiles of all hydrogen isotopes in a DD discharge machine [25]. During the DD discharges, deuterium retention dominates within a certain depth which is depending on temperature, e.g. deeper but with lower concentration for higher temperatures. Simultaneously, tritium produced by DD reactions was implanted deep but the concentration was very low. After the DD discharges, HH discharges or air ventilation would isotopicaly replace deuterium retained near surface regions as indicated in the figure. This suggests tritium retained during DT shots could be isotopicaly replaced with D by following DD discharges. For better estimation of T inventory by the postmortem analysis, we have to take H retention into account in addition to deuterium retention. The discrepancy between the

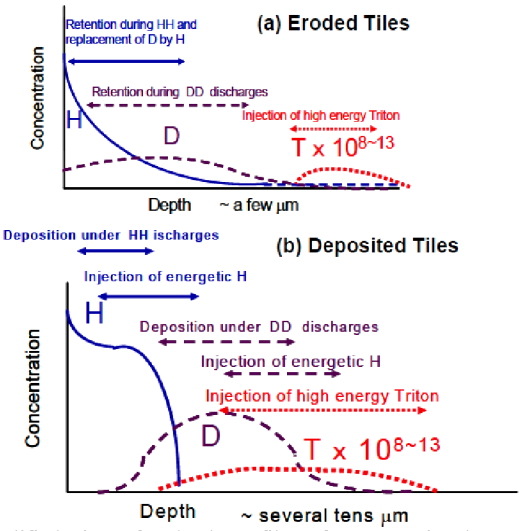

FIGURE 9. Simplified views for depth profiles of H, D, T in plasma facing materials exposed to DD + HH discharges [25]

fuel balance and postmortem analysis could be in neglecting of protium (H) in DD machines. In other words, in a DT reactor, behavior of deuterium and tritium might not be the same depending discharge scenario. Large mass difference between deuterium and tritium leads to different escaping flux from the plasma, even both are in the same temperature.

In this respect, it seems very hard to control D/T ratio constant in burning plasmas. Although the fusion rate can be measured by neutron yield, it would not give the D/T ratio. The concentration ratio of D and T in the plasma facing wall is not likely the same as that in the plasma. The evaluation of the D/T ratio in the plasma is not easy to determine, too. Plasma opacity could disturb optical measurements like Thomson scattering, and fuelling efficiency (penetration depth) into the plasma center might different between D and T. In ITER, study of such isotopic effects must be also an important task, which might not directly related to tritium safety.

7. SUMMARY

Tritium handling systems, which use mostly established techniques, can be built for ITER or even a reactor without very high hurdles. However, handling of huge amount of tritium in ITER would give new problems to be solved, huge in-vessel tritium inventory and its accountancy, controlled fuelling of DT, possible permeation and leakage leading to cross-contamination, contamination of remote handling system and so on.

In vessel-tritium inventory and/or tritium accountability in a reactor is the most serious concern. In the present tokamaks, there is always significant imbalance between input and output of fuels (mostly measured by deuterium), i.e. some of the fuels are continuingly retained and immobilized. Although such in-vessel retention is

very likely caused by incorporation of fuels in redeposited materials at plasma shadowed area, estimation of tritium inventory even in ITER are scattered more than three orders of magnitude depending on models.

Difficulty of quantitative analysis of tritium in the in-vessel components adds additional problems. It is ironical that the accuracy in detecting low levels of tritium (below 10^9 Bq) which utilizes β-electron is better than that in the very high levels which are determined by mass and/or pressure measurements and calorimetry with the accuracy of only 10^{-2} to 10^{-3}. In addition, one can not measure tritium existing in solid deeper than a few μm. The easy isotopic exchange reactions of tritium with hydrogen in water and hydrocarbons result in easy contamination of the surroundings and can significantly affect the analysis.

Most of those tritium problems are directly related to the safety of operators and/or professionals. Public safety does not seem to become significant problems because of so low energy of the β-electrons. We need experiences, as well as knowledge on tritium science and technology for safety confinement of tritium in a fusion reactor. It should be mentioned that we will face to a world wide lack of experts in tritium science and technology in near future. In this respect, ITER will give very good opportunity to make experiments and to get experiences for establishing tritium safety and encouraging experts.

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