Nuclear Materials and Energy 12 (2017) 267–272

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

Efficiency of thermal outgassing for tritium retention measurement and removal in ITER

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ARTICLE INFO

Article history:
Received 14 July 2016
Revised 19 September 2016
Accepted 14 October 2016
Available online 12 November 2016

keywords:
Tritium retention
ITER
Divertor
Outgassing

ABSTRACT

As a licensed nuclear facility, ITER must limit the in-vessel tritium (T) retention to reduce the risks of potential release during accidents, the inventory limit being set at 1 kg. Simulations and extrapolations from existing experiments indicate that T-retention in ITER will mainly be driven by co-deposition with beryllium (Be) eroded from the first wall, with co-deposits forming mainly in the divertor region but also possibly on the first wall itself. A pulsed Laser-Induced Desorption (LID) system, called Tritium Monitor, is being designed to locally measure the T-retention in co-deposits forming on the inner divertor baffle of ITER. Regarding tritium removal, the baseline strategy is to perform baking of the plasma-facing components, at 513 K for the FW and 623 K for the divertor. Both baking and laser desorption rely on the thermal desorption of tritium from the surface, the efficiency of which remains unclear for thick (and possibly impure) co-deposits. This contribution reports on the results of TMAP7 studies of this efficiency for ITER-relevant deposits.

1. Introduction

As a licensed nuclear facility, ITER must limit the in-vessel tritium (T) retention to reduce the risks of potential release during accidents, the inventory limit being set at 1 kg. This limit includes 120 g of T trapped on the divertor cryopumps and 180 g of measurement uncertainty, so that the maximum retention in the in-vessel components is set at 700 g. Simulations and extrapolations from existing experiments indicate that T-retention in ITER will mainly be driven by co-deposition with beryllium (Be) eroded from the first wall [1]. The ITER first wall (FW) is strongly shaped and co-deposition may occur in both magnetically shadowed areas of the wall [2] and in the tungsten (W) divertor (predominantly on the baffle area) [3]. Recent estimates using the WALLDYN code [3] indicate that between 3000 and 20,000 Q = 10 discharges (400 s duration) could be run before the 700 g T-limit is reached. Uncertainties in those estimates mainly lie in the definition of the far Scrape-Off Layer (SOL) plasma parameters.

Global retention measurements will be performed by Pressure–Volume–Temperature-Composition (pVT-c) and calorimetry of T absorbed on uranium beds in the T-Plant [4]. These measurements do not, however, provide information on where the T is locally trapped. The ITER safety strategy foresees that the early years of ITER operations will be used to improve the understanding of T retention and reduce uncertainties. The possibility to perform local measurements of co-deposit thickness and their T retention would allow a direct comparison with modelling results. A diagnostic system, named “Tritium and Deposit monitor” is being designed to measure the T-retention in co-deposits forming on the inner divertor baffle and their thickness [4]. A pulsed laser system is foreseen to locally heat the co-deposits and the desorbed T will be measured from Residual Gas Analysis. The laser system probes the inner baffle region from an equatorial port (Fig. 1) and can cover an area of 50 cm x 10 cm in the poloidal and toroidal directions, respectively. The laser spot size (~3 mm) allows several measurements on a single W monoblock. In parallel, Lock-In Thermography is being considered to measure the co-deposit thickness.

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http://dx.doi.org/10.1016/j.nme.2016.10.016

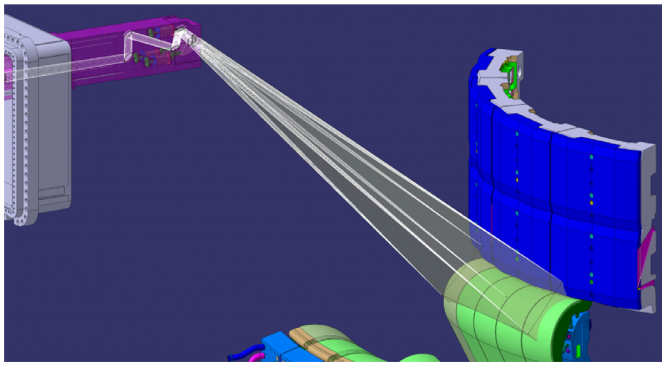

Fig. 1. Isometric representation of the tritium monitor system. The laser beam enters the vacuum vessel from an equatorial port and is scanned over a portion of the inner divertor baffle.

Several studies have investigated the desorption of deuterium from Be following heating by short pulse lasers. Keroack et al [5] used a 25 ns pulse from a Q-switched ruby laser on a bulk Be sample implanted with D_2^+ ions in the energy range 0.5–5 keV. Significant desorption was only observed when the temperature during the laser pulse reached values close to the melting point. A similar conclusion was reached by Yu et al [6] who investigated the effect of 10ms-long laser pulses on the D desorption from Be co-deposits deposited using different methods. Significant desorption could only be obtained when approaching the Be melting temperature. On the other hand, it is well known that full release of deuterium is achieved during thermal desorption spectroscopy (TDS) when samples are heated to temperatures around 1000 K for durations of the order of several minutes. It is therefore interesting to determine what heating duration would be required to ensure complete desorption from co-deposits while preventing melting.

Regarding T removal, the baseline ITER strategy is to perform baking of the plasma-facing components, at 513 K for the FW and 623 K for the divertor. The former will be done by circulating hot water through the cooling circuit of the first wall panels, while the latter will be performed using a hot gas circulated in the cooling circuit of the divertor plasma-facing units which would need to be fully drained and dried beforehand. It is estimated that about 100 hrs are needed to heat up the divertor to 623 K and then cool it down, to which the actual bake duration needs to be added.

Both baking and laser desorption rely on the thermal desorption of T from the surface, the efficiency of which remains unclear for thick (and possibly impure) co-deposits. This contribution reports on the results of TMAP studies of this efficiency for ITER-relevant deposits.

2. TMAP7 simulations of outgassing

In the following, no distinction between D and T will be made in terms of trapping or diffusion. Simulations of T outgassing from Be co-deposits were performed using the TMAP7 code [7] which is a 1D diffusion-trapping code calculating the time-dependent evolution of the concentration of species within structures and flows across the boundaries between the considered structures and the surrounding volume. TMAP7 has been successfully applied to model the thermal release of deuterium from Be co-deposits during TDS experiments [8,9]. Good agreement was obtained between the experiment and the TMAP7 model for a wide range of co-deposit thickness and heating rates during TDS. The trapping of deuterium in co-deposits was described with two trap populations with activation energies for D release of ~0.8 eV and 0.98 eV, and a dynamically computed surface D atomic-to-molecular recombination coefficient [8].

While this model describes well the behaviour of Be co-deposits produced by magnetron sputtering, it is unclear whether co-deposits formed during ITER operations will exhibit the same properties. Recently, Be co-deposits formed in the inner divertor of JET during the first experimental campaign of the JET ITER-like wall, were analysed in terms of their composition and D release properties [10]. Specific TDS experiments were subsequently performed to assess the efficiency of a 623 K annealing for D removal. Different heating rates (1 and 10 K/min) from room temperature to 623 K, and different hold times at 623 K (5 and 15 hours) were used, providing a good dataset to be modelled by TMAP7. After the hold period at 623 K, the samples were heated up to 1273 K to ensure full desorption of retained D. The samples originated from different locations of the so-called Tile 1 from the JET inner divertor which is made of Carbon-Fibre Composite (CFC) coated with tungsten, and where the thickest co-deposits have been found [10].

As a starting point for the TMAP7 model, the diffusion and recombination coefficients from [8] and references therein were used. The film thickness was set to the measured value and the activation energy for D release from a given trap and the trap occupancy were adjusted to match the experimental data. An homogeneous D concentration profile in the co-deposit was assumed. The W substrate is considered in the model but a no-flow condition is assumed at the boundary since diffusion of D across the boundary has not been experimentally observed. A small enhancement of the D concentration is observed in experiment near the plasma-facing surface by Secondary Ion Mass Spectrometry (SIMS), but no quantitative measurements exist and this will be neglected here.

Fig. 2 shows the comparison between the TMAP7 model and the experimental data for the three samples considered here. The first thing to mention is that three traps are needed to properly model the D release, with trap energies of 0.75–0.8, 1.1 and 1.4 eV, respectively. It is interesting to note that the two lowest energy traps correspond very well with those observed in [8]. It is not possible at this stage to ascribe these trap energies to trapping sites in the co-deposit, in particular since the JET co-deposits contain non-negligible fractions of impurities such as carbon and oxygen. It is, however, evident from Fig. 2 that the TMAP7 model reproduces well the experimental TDS measurements from the JET co-deposit, with parameters for the D diffusion and trapping very close to those used for Be co-deposits produced in laboratory conditions. Future studies will aim at understanding better the similarities and differences between those different co-deposits, and will include results from co-deposits formed by different methods. The relative abundance of the different traps varies from sample to sample, even when the two samples come from the same poloidal location but slightly different toroidal locations (within a single tile), which indicates non-homogeneity in the co-deposit properties. The two models described above can now be used to evaluate the D removal during laser heating and divertor baking in ITER.

3. Tritium removal during laser-induced desorption

Simulations for LID are performed for a range of film thickness (up to 10 μm) to investigate the required working parameters for the tritium monitor in ITER. WALLDYN simulations indicate that deposition rates of up to ~200 nm per Q = 10 discharge are possible in the divertor baffle region so that a 10 μm layer could be formed in a couple of days of plasma operations. The kinetics of T release is studied as a function of the pulse number, duration and peak temperature. The temperature evolution during a pulse was described by a fixed heating and cooling time of 1 ms while the temperature was assumed constant for a prescribed duration. Given that the layer thickness remains relatively small in our study, and that the characteristic thermal diffusion distance is of the order of 100 μm for a 1 ms pulse, the temperature is assumed homo-

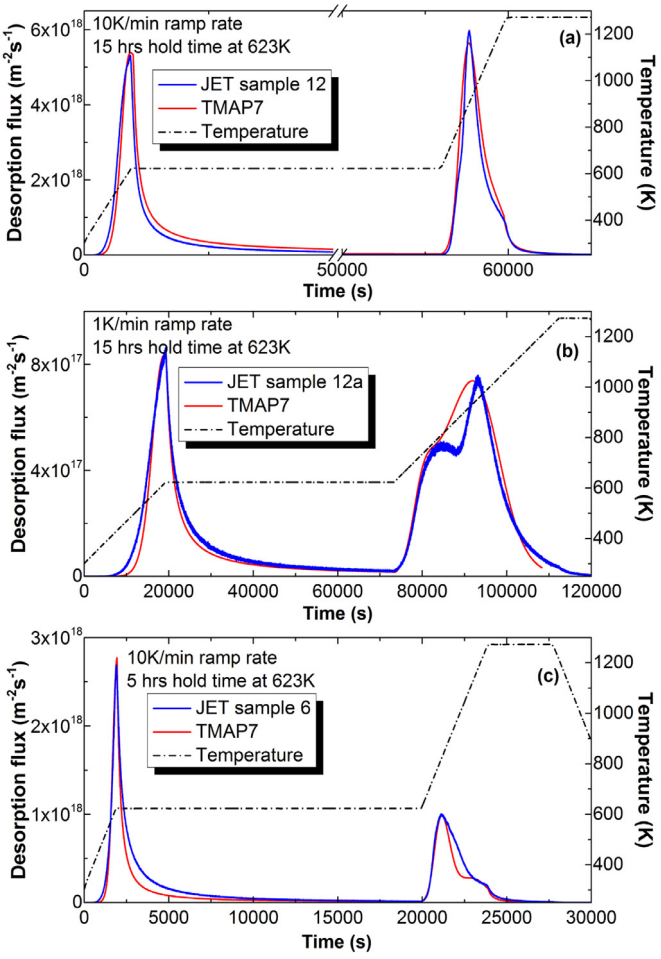

Fig. 2. Comparison between the experimentally obtained thermal desorption spectra from JET Be co-deposits formed on the inner divertor tile 1 and simulations using the TMAP7 code.

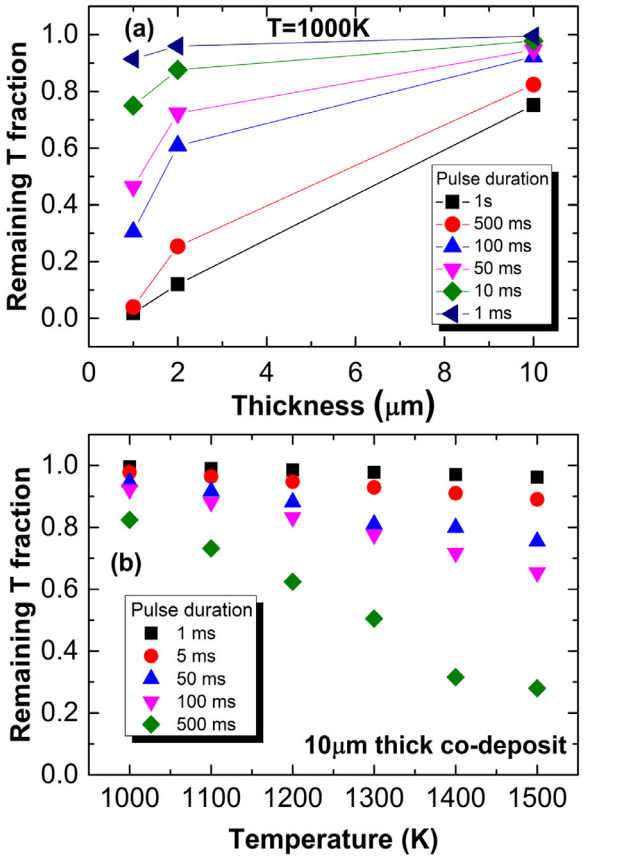

Fig. 3. (a) Simulated evolution of the remaining T fraction in Be co-deposits with varying thickness for different laser heating durations and a peak temperature of 1000 K. (b) Influence of the peak temperature and pulse duration on the remaining T fraction in a 10 μm thick co-deposit.

geneous across the layer during the pulse. The model developed in [8] was used with a (D+T)/Be ratio of 0.08.

Fig. 3a shows the evolution of the remaining trapped tritium fraction in the co-deposit as a function of its thickness and pulse duration for a peak temperature of 1000 K. The mobile inventory is not considered here as it is assumed to diffuse out of the material. As expected, the thicker the layer the more difficult the release: for a 10 μm layer, only 25% of T is released after a 1 s-pulse. The removal efficiency increases with the pulse duration. The peak temperature has a strong influence on the removal efficiency, as illustrated in Fig. 3b for a 10 μm thick co-deposit. About 70% of T can be removed after heating at 1500 K for 0.5 s. The amount of released T scales with the square root of the pulse duration, as expected for a diffusion-limited process.

During laser heating of co-deposits in ITER, it is important not to damage the actively-cooled W monoblocks on which the co-deposits will form. Instead of extending the pulse duration, it is therefore of interest to investigate the effect of multiple laser pulses on the T removal efficiency. To do so, several sequences of pulse numbers were compared with the total heating time being kept constant at 500 ms. The cases of 1 pulse of 500 ms, 10 pulses of 50 ms and 50 pulses of 10 ms were investigated (Fig. 4a) for a 10 μm thick co-deposit and a temperature of 1500 K. For a pulse frequency was fixed at 1 Hz, the x axis in Fig. 4a shows the total simulation time which includes the pulses and the waiting time in between. The three curves have the same final value i.e. the remaining fraction appears to only depend on the total heating time which can be obtained with different combinations of pulse number/duration. When considering a more realistic scenario where the temperature evolution during a laser pulse is computed by solving the heat diffusion equation (not shown here), a longer cooldown phase is typically obtained which leads to a slight increase in the desorbed fraction as the surface remains hotter for longer.

Another apparent feature in Fig. 4a is that the remaining T fraction decreases sharply during the pulse but increases again at the end of the pulse. To better illustrate the reason for this behaviour, Fig. 4b shows the evolution of the trapped T concentration during a 10 ms pulse on a 10 micron thick layer. At the beginning of the pulse a strong detrapping of trap 1 occurs, with partial re-trapping in the higher energy trap, and thus a strong decrease in the total trapped inventory. A progressive decrease of the trapped inventory occurs during the pulse but a sudden increase occurs during the cooldown time caused by re-trapping, as already observed in [6]. This effect is more noticeable for thicker co-deposits as more time is required for T to diffuse and recombine at the surface. From the performed simulations, it is found that a desorption efficiency of ~98% can be reached for a 10 micron thick co-deposit with a total heating time of 2.5 s (Fig. 5). An experimental validation of these multi-pulse simulations would be beneficial, in particular since the current model does not assume the possibility of trap annealing during such high temperatures.

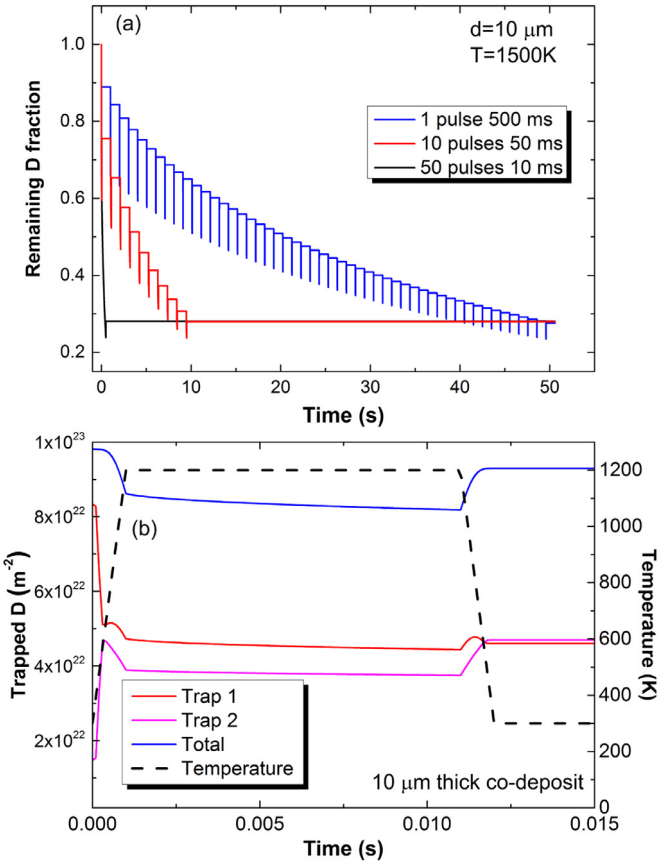

Fig. 4. (a) Comparison of the remaining tritium fraction in a 10 μm thick co-deposit after heating at 1500 K for 0.5 s with different combinations of pulse number and duration. (b) Evolution of the density of trapped T during a 10 ms pulse at 1200 K.

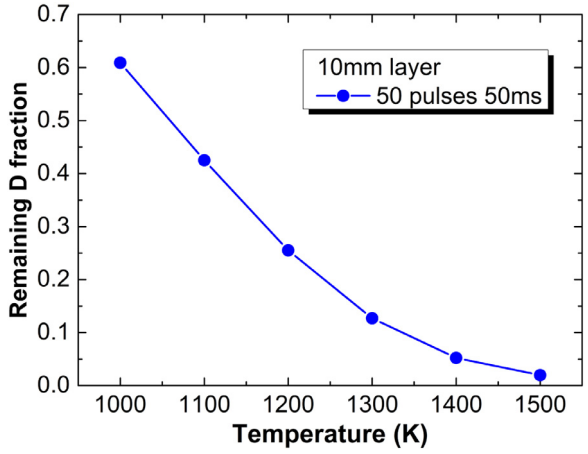

Fig. 5. Evolution of the remaining T fraction in a 10 μm co-deposit after 50 pulses at 50 ms for various temperatures.

4. Efficiency of 623 K divertor bake for T removal

While the retention in Be co-deposits can be derived from the scaling equation derived in [11] as a function of the deposition conditions, it is currently impossible to describe a priori the trapping of hydrogen isotopes in such co-deposits. As seen above from the TMAP7 modelling of JET co-deposits, the relative occupancy of the different traps varies significantly with the local deposition conditions, and co-deposits produced by magnetron sputtering and from JET exhibit differences in terms of trapping, which might be

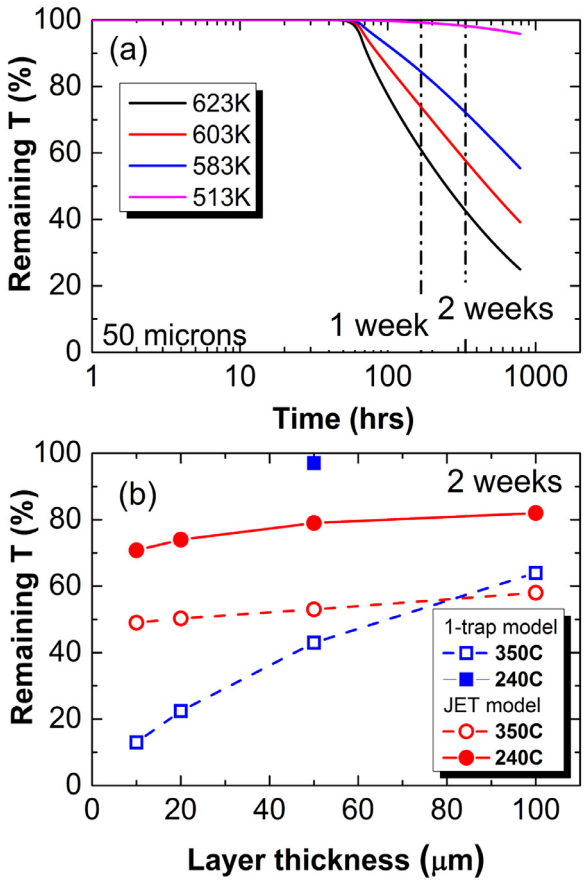

Fig. 6. (a) T removal during an ITER divertor bake as a function of baking time and temperature, for the 1-trap model. (b) Comparison of the outgassing efficiency for the 1-trap and JET models as a function of co-deposit thickness and temperature.

due to the presence of impurities and/or to the differing deposition conditions. The following analysis should therefore be seen as a sensitivity study of the possible efficiency of T removal in ITER rather than an accurate prediction. With that in mind, two models will be used in the following. The 2-trap model from Baldwin et al [8] applies for co-deposits formed at T ~ 50–60 °C. For temperatures higher than 100 K, desorption was mostly due to the high energy trap at 1 eV while the lower energy trap (at ~ 0.8 eV) was virtually absent [12]. The divertor water cooling temperature at the inlet will be 70 °C, and therefore during operations the regions where Be will co-deposit will likely be at temperatures of 373 K or higher (383 K is assumed in [3]). To be conservative, simulations are performed here assuming a single trap at 1 eV Simulations have also been run using the model derived from the JET co-deposits, focusing in particular on the thickest co-deposits which are probably the most ITER-relevant since they have the lowest impurity content [10]. Since Samples 12 and 12a (see [10] for explanations of the nomenclature) had different relative trap populations, an average over the two populations is used here. In the baking simulations, the heating rate is fixed at 5 K/hr and baking durations of up to 1 month have been considered.

Fig. 6a shows the evolution of the remaining fraction of T from a 50 μm co-deposit, assuming here the 1-trap model, as a function of baking time and baking temperature. It is obvious that under these assumptions, a 513 K bake (corresponding to the first wall bake temperature) is inefficient at removing tritium from the co-deposit. Increasing the temperature strongly increases the removal efficiency. It should be mentioned here that going much above 623 K is not possible because of the use of CuCrZr for the diver-

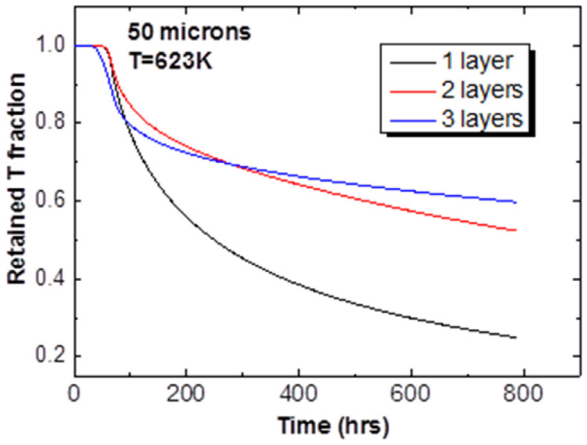

Fig. 7. Effect of partially emptied under-layers on the outgassing efficiency from a 50 μm thick co-deposit.

tor monoblock cooling pipes. Even at 623 K, very long bake durations are required to outgas a significant fraction of the trapped tritium. Only 40% of tritium is removed after 1 week and 75% after 4 weeks.

The co-deposit thickness also has a strong effect on the outgassing efficiency, as illustrated in Fig. 6b, and only ~35% of tritium can be outgassed from a 100 μm thick co-deposit for a 2 week-long bake. In Fig. 6b, the results from the 1-trap model and the JET model are compared. For thin co-deposits (< 50 μm) a lower removal efficiency is observed for the JET-type model. This is because a low-energy trap of ~0.8 eV is present in this model, which can be efficiently de-populated at 623 K, and accounts for about 50% of the trapped tritium. However, the high energy trap at 1.4 eV is not affected at all by the baking. The outgassing efficiency therefore appears to vary less with co-deposit thickness for the JET model than for the 1-trap model. The 1-trap model is mainly diffusion-limited. Both models, however, indicate relatively low outgassing efficiencies for thick co-deposits. This low outgassing efficiency can also be inferred from the graphs in Fig. 2, where a significant amount of deuterium is still present in the co-deposit after 15 hrs at 623 K.

While baking the divertor for durations of the order of months is not practical, a natural alternative would be to bake the divertor more often to prevent the build-up of too thick co-deposits. It has been shown, however, that in the case where a fresh co-deposit is formed on top of a partially depleted layer (from a previous bake), the outgassing of the fresh co-deposit will be affected by the depleted under-layer [12]. To illustrate this effect, TMAP7 simulations were performed with the 1-trap model for a 50 μm co-deposit and a 1-month bake duration. Fig. 7 compares the outgassing kinetics for a single layer, with that of a system with 1 or 2 under-layers which have been partly depleted by a previous bake (25% of the initial inventory is supposed to remain after the bake). A strong decrease of the T-removal efficiency is found as soon as an under-layer is included. While 75% of the initial inventory can be removed for the single-layer case after 1 month, only about 48% and 40% can be removed in the 2 and 3 layer cases, respectively. This is because T can now diffuse both towards the surface but also towards the under-layers, which effectively decreases the speed of release at the surface. In reality, some traps are likely to be annealed out during a bake and the situation might not be as dramatic, but it is clear that cumulative bake sequences have to be considered when discussing the bake frequency in ITER.

From the above discussion, and the fact that the 623 K divertor bake is not very efficient for thick co-deposits, or at least that very long bake durations would be required, one might wonder what impact this may have on the management of T retention in ITER. In response, it should first be recalled that the latest predictions, in line with earlier estimates from Roth et al [13], indicate that between 3000 and 20,000 discharges of flattop duration 400 s could be run before the T inventory limit is reached. In the latter case, this number exceeds the design lifetime of the FW panels [14] and retention is not a real issue. In the former case, alternative tritium removal techniques might be required to complement the divertor bake. Several options are being considered:

- Thermal outgassing: as shown above, short transient heating to temperatures around 1000 K can efficiently remove tritium. Transient local heating to high temperature is already considered for diagnostics. Implementation of a high power laser could be considered on the Multi-Purpose Deployer (a robotic arm planned for insertion into the vacuum vessel during maintenance periods) [15] for example to heat the regions where the thickest co-deposits form. Alternatively, glow discharges could be run during the divertor bake to increase the outgassing rates through isotopic exchange [16].
- Non-T discharges: running pure deuterium discharges could be envisaged to heat and remove co-deposits. This would likely require operations with strike-points located close to where co-deposits accumulate. The feasibility of operating with raised strike-points has been investigated in [17] but even higher strike-point positions might be required. Future studies will investigate the feasibility and stability of such configurations and determine how much input power could be injected in such discharges, which would give an indication of the expected plasma conditions and heat flux to the surfaces to be exposed.

5. Conclusions

Tritium removal by thermal outgassing will be used in ITER both for diagnostics purposes, through laser-induced desorption, and tritium inventory control through the planned 623 K divertor bake. The TMAP7 code was used to evaluate the efficiency of such a process for Be co-deposits with varying thicknesses.

TDS data from JET co-deposits could be successfully modelled using diffusion/trapping parameters similar to those used for Be co-deposits formed by magnetron sputtering, with the difference that a third trap at 1.4 eV is necessary to reproduce the desorption spectrum. The relative occupancy of the different traps in JET co-deposits varies from sample to sample, and a way to relate this to the local deposition conditions is needed to allow for better extrapolations to ITER.

Simulations for LID have been performed for a range of film thickness (up to 20 μm). The removal efficiency is in general limited by the re-trapping during the cool-down phase. When multiple pulses are considered, it is shown that the total heating time defines the final desorbed fraction and can be achieved with different combinations of pulse duration and number.

Finally, the efficiency of the planned 623 K divertor bake on ITER appears limited for thick (> 50 μm) co-deposits, and significant durations (~1 month) might be required to remove significant fractions of retained tritium.

Acknowledgements

ITER is the Nuclear Facility INB no. 174. This paper explores new directions for management of tritium retention that are not yet introduced into the ITER technical baseline. The nuclear operator is not constrained by the results presented here. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization or of the European Commission.

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