Effect of Purge-Gas Conditions and Flow Direction on Tritium Release and Inventory in a Solid Breeder Blanket Module for a DEMO Reactor under an Axial Temperature Gradient

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Abstract

This paper reports a simulation study of tritium transport in a solid breeder rib of a DEMO reactor blanket module. A representative rib was selected from the sixteen identical ribs in the breeder submodule, based on the detailed design information available for JA-DEMO. Two purge-gas flow directions were compared under an axial temperature gradient: from the plasma-side hemispherical tip to the rear side, and in the opposite direction. For comparison, tritium inventory values reported for the EU-DEMO in publicly available literature were also used as reference data. The results suggest that the purge-gas flow direction modifies the local gas-composition history, the balance of surface reactions, and water-mediated trapping behavior, thereby affecting both the tritium release rate and the inventory in the packed bed. The present findings can be used in future evaluations of tritium-processing cost and safety from the viewpoint of the entire fusion reactor system.

1 Introduction

The authors previously proposed a tritium-transport model for solid breeder materials, performed fitting to out-of-pile experimental data, and discussed the tritium release rate, the release chemistry (HT/HTO ratio), and tritium inventory [1]. The EXOTIC experimental results were also analyzed using the same modeling framework [2].

Quantitative understanding of tritium transport in solid breeder materials is useful from the following viewpoints:

1. evaluation of tritium inventory in blanket modules for safety assessment,
2. estimation of the tritium amount required during reactor start-up scenarios before reaching the steady state, and
3. evaluation of the chemical form of released tritium, because the HT/HTO ratio affects the load and design of the downstream tritium extraction system (TES).

In this paper, simulation results for tritium transport from Li_2TiO_3 in the gear-type breeder concept reported for JA DEMO are presented. Particular attention is paid to start-up transients and to the influence of water-generation reactions caused by interactions between the solid breeder and hydrogen in the purge gas. Their effects on tritium inventory, release chemistry, and tritium release rate are discussed.

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2 Calculation Conditions

The dimensions and temperature distribution of the gear-type breeder concept proposed for JA DEMO were taken from the paper reported by Someya Youji *et al.* [3]. Although sixteen breeder ribs are arranged in JA DEMO, tritium release from one representative rib was calculated in the present work. Strictly speaking, the rib cross section is trapezoidal; however, for simplicity it was approximated here by an equivalent cylindrical cross section with the same sectional area. The rib volume is shown in Fig. 1 and the adopted axial temperature distribution is shown in Fig. 2.

Several axial cells were introduced along the rib, and the temperature distribution was assigned to these cells. The tritium generation rate was assumed to be proportional to the temperature distribution. The tritium generation rate in the hottest cell was set to 1.7×10^{-5} mol m^{-3} s^{-1}. This value corresponds to the tritium generation rate in the first layer shown in Fig. 1 of Ref. [4].

The purge-gas flow rate was set to 5.34×10^{-6} m^3 s^{-1}, corresponding to a linear velocity of 5.06×10^{-2} m s^{-1}. This velocity is comparable to that estimated from the purge-gas flow rates used in previous out-of-pile experiments by the authors, and it is also not far from the value used in Ref. [4]. The hydrogen concentration added to the purge gas was set to 1000 ppm.

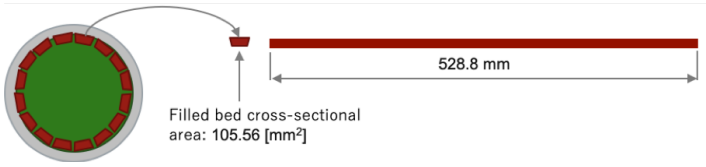

Figure 1: Volume of the packed-bed rib used in the present calculation.

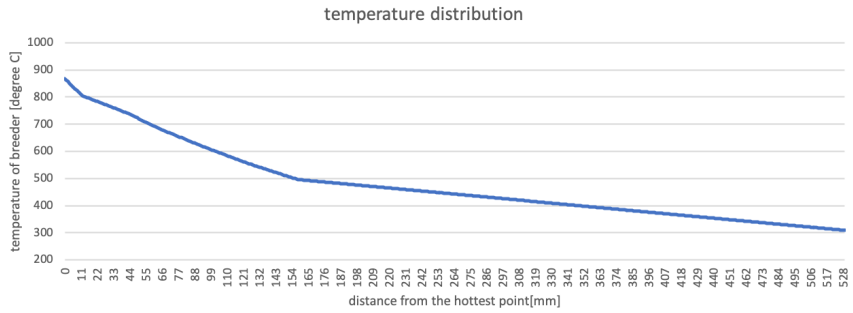

Figure 2: Axial temperature distribution assigned to the representative rib.

3 Case A: Purge Gas Introduced from the High-Temperature Side

Figure 3 shows the calculated tritium release behavior. In this figure, “T from grain bulk to interfacial layer” and “T from interfacial layer to surface water” are expressed as equivalent concentrations in the purge gas.

Tritium reaches the interfacial region and the surface water rapidly. However, approximately 30000 s are required before tritium is released into the purge gas as HT or HTO. This indicates that tritium transfer at the solid breeder surface is rate-controlling in the present model. In this model, tritium that has reached the surface water is released into the purge gas through one of the following pathways:

- desorption as HTO,

- isotope exchange with H_2 in the purge gas, and
- isotope exchange with H_2O in the purge gas.

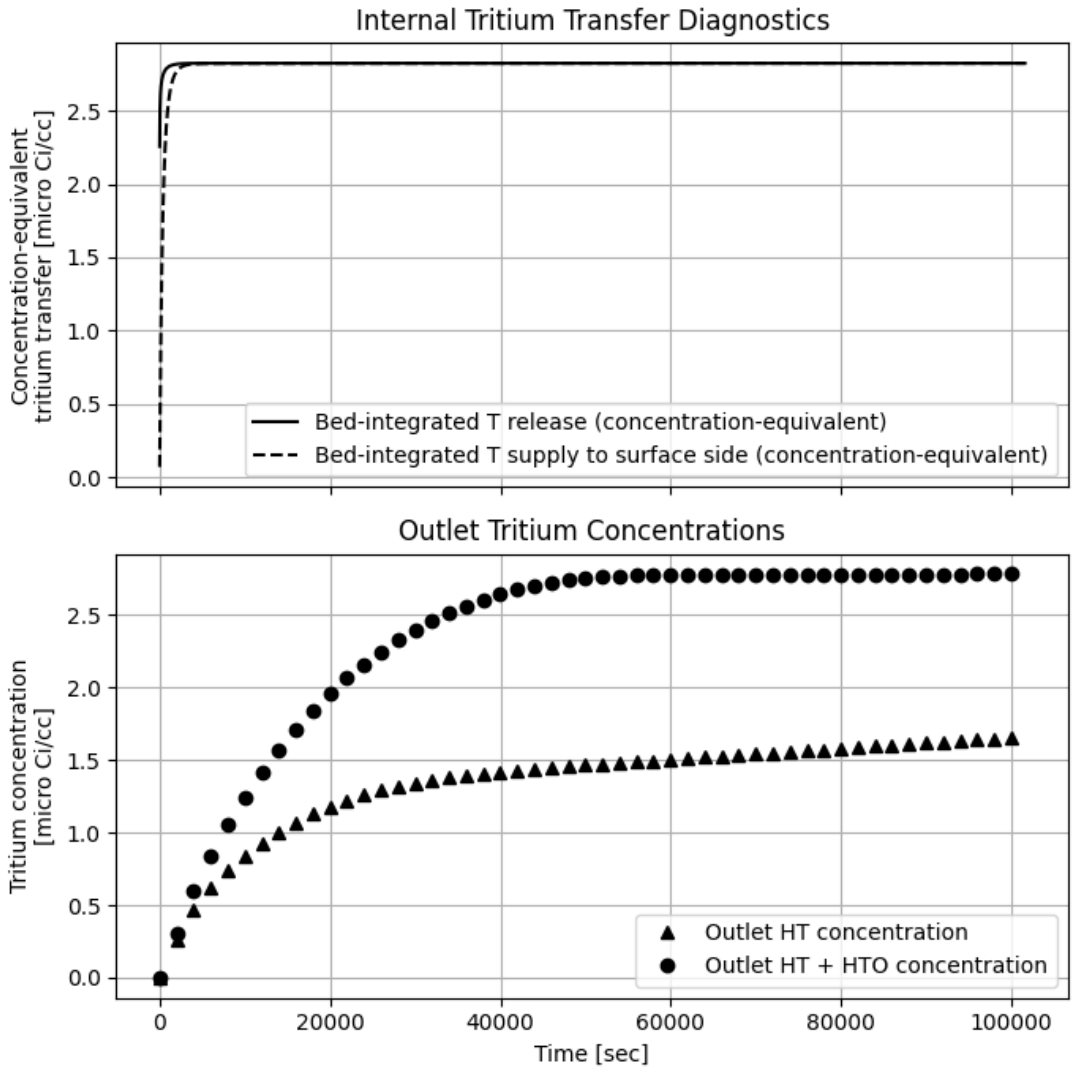

Figure 3: Calculated tritium concentrations in the purge gas when the purge gas is introduced from the high-temperature side (Case A).

In this case, the purge-gas inlet is located at the hottest side of the rib. Water is produced by the water-generation reaction. Such water is known to be produced when hydrogen is introduced to a sample bed containing solid breeder candidates above approximately 400 °C. Among major breeder candidates, the water-generation capacity of Li_2TiO_3 is reported to be the largest, while that of $LiAlO_2$ is the smallest [5, 6].

Due to the water-generation reaction, the H_2O concentration in the purge gas is about 30 ppm at the beginning of reactor start-up. As the water-generation capacity is gradually consumed, the H_2O concentration decreases to about 10 ppm after 24 h of operation, as shown in Fig. 4. Based on the amount of water-generation capacity consumed during 24 h, proportional estimation suggests that water generation would continue for about 2.5 days near the high-temperature side and about 19 days near the low-temperature side, as shown in Fig. 5.

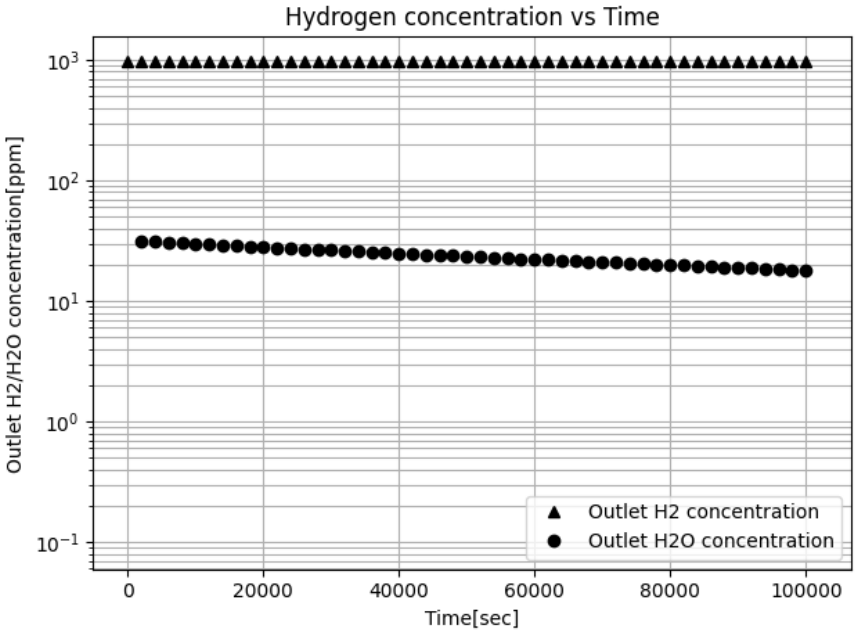

Figure 4: Hydrogen-related concentrations in the purge gas for Case A.

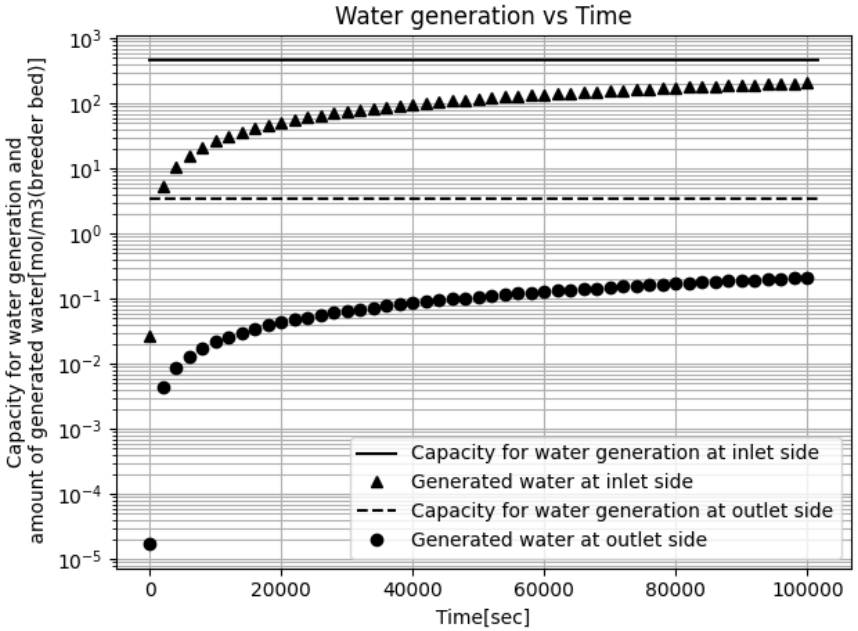

Figure 5: Water-generation behavior for Case A.

Because of the elevated H_2O concentration caused by the water-generation reaction, approximately 40% of the released tritium appears as HTO after 24 h of operation. As water generation decreases, the HT fraction increases. Nevertheless, a substantial amount of HTO released during the early stage of reactor start-up would have to be treated by the downstream TES.

H_2O generated in the upstream side of the rib and HTO released there are adsorbed again on the solid breeder surface in the downstream side. After repeated adsorption and desorption, they are finally released from the downstream end of the blanket module. In the low-temperature region, the isotope-exchange rate between tritium and H_2 in the purge gas is slower than that between tritium and H_2O. Therefore, a larger fraction of tritium is released as HTO in the

downstream part of the rib. Moreover, H_2O generated upstream promotes isotope exchange in the downstream region. An increase in H_2O concentration in the purge gas enhances the tritium release rate and contributes to a reduction in tritium inventory at the solid breeder surface. The tritium inventory after 24 h of operation is about 1.0×10^{-5} mol, as shown in Fig. 6.

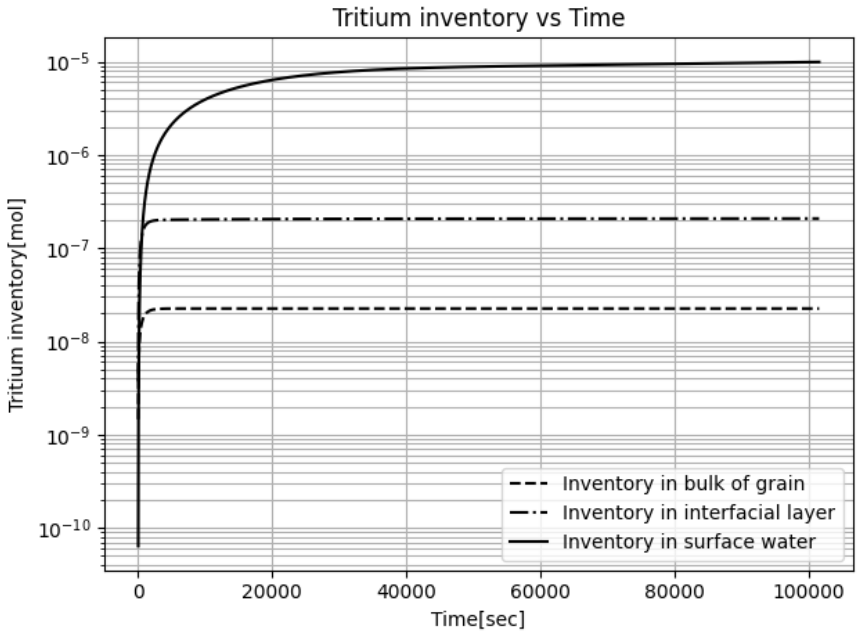

Figure 6: Calculated tritium inventories when the purge gas is introduced from the high-temperature side (Case A).

The calculated JA DEMO tritium inventory is compared with a reported value for the European HCPB DEMO in Table 1. The values for the European HCPB DEMO were taken from a KIT report [7].

Table 1: Comparison of tritium inventory with a reported value for the European HCPB DEMO.

	Europe HCPB DEMO	JA DEMO, one rib
Packed-bed volume [m^3]	4.92×10^{1}	5.58×10^{-5}
Inventory per breeder volume [$\mathrm{mol\,m^{-3}}$]	6.69×10^{-1}	1.79×10^{-1}
Tritium generation rate [$\mathrm{mol\,m^{-3}\,s^{-1}}$]	3.41×10^{-5}	1.70×10^{-5}

4 Case B: Purge Gas Introduced from the High-Temperature Side without Water-Generation Reaction

This case assumes that the increase in H_2O concentration due to the water-generation reaction does not occur. It corresponds to a condition where Li_2TiO_3 has already been exposed to a hydrogen-containing atmosphere above 400 °C and the water-generation reaction has been exhausted. Even in this condition, the H_2O concentration in the purge gas is assumed to be 5 ppm, because an H_2O concentration arbitrarily close to zero is difficult to assume from a practical cost viewpoint.

After approximately 42 h of operation, about 16% of the released tritium appears as HTO. Because the purge-gas H_2O concentration is not elevated by the water-generation reaction, isotope exchange between H_2O in the purge gas and tritium incorporated into the breeder surface water is not strongly promoted. The temperature at the center of the packed bed is about

450 °C, and tritium transfer in the downstream region occurs at relatively low temperature. In this temperature range, isotope exchange between tritium and H_2 in the purge gas is slower than that with H_2O. Therefore, the tritium release rate from the solid breeder becomes slower than in the case with an increased H_2O concentration due to the water-generation reaction, as shown in Fig. 7.

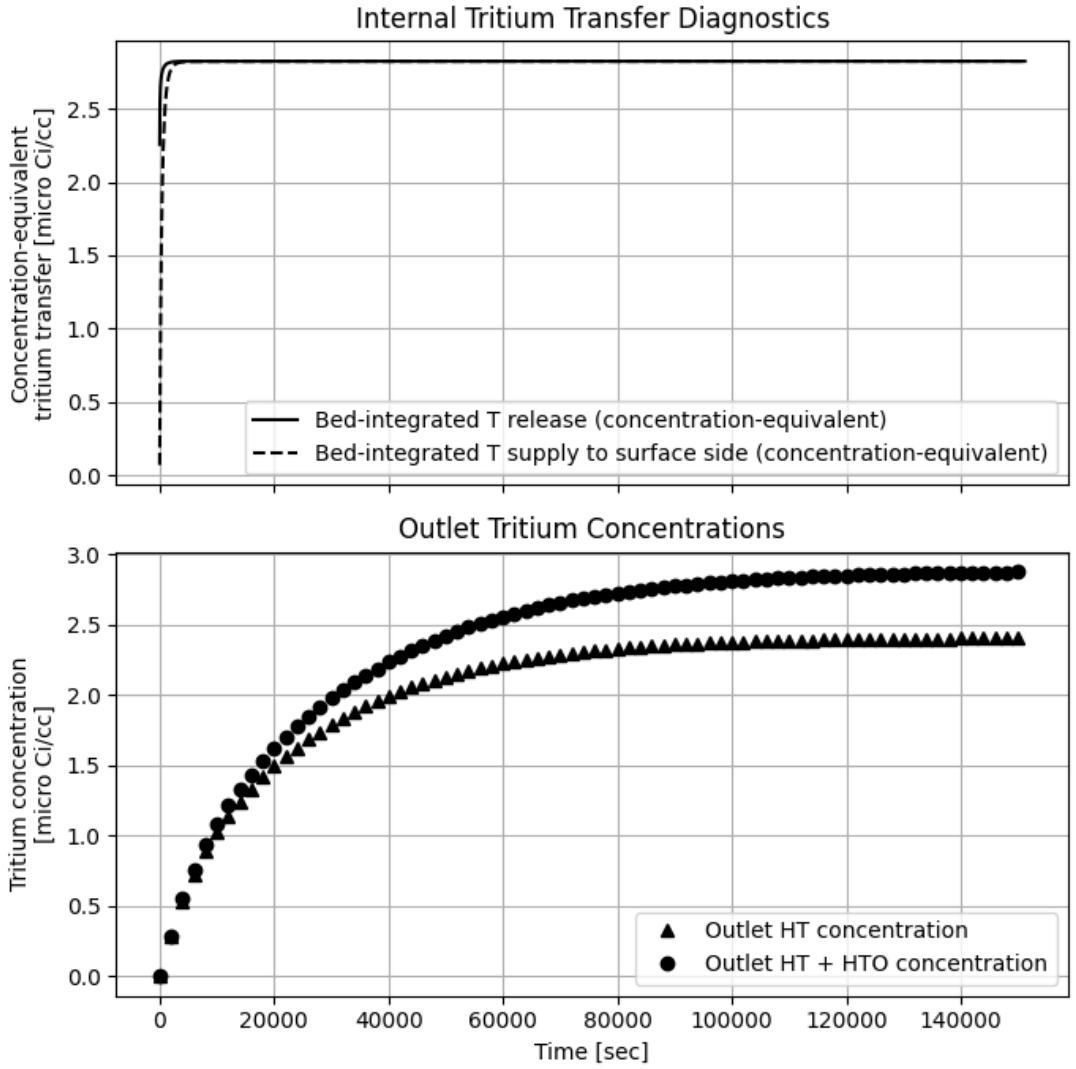

Figure 7: Calculated tritium concentrations in the purge gas for Case B, where the purge gas is introduced from the high-temperature side and the water-generation reaction is absent.

The tritium inventory in the solid breeder was also examined. When the purge-gas H_2O concentration is not increased by water generation, the tritium release rate becomes slower, as discussed above. The tritium inventory in the surface water of the solid breeder is about 1.4×10^{-5} mol, approximately 40% larger than that in Case A, as shown in Fig. 8.

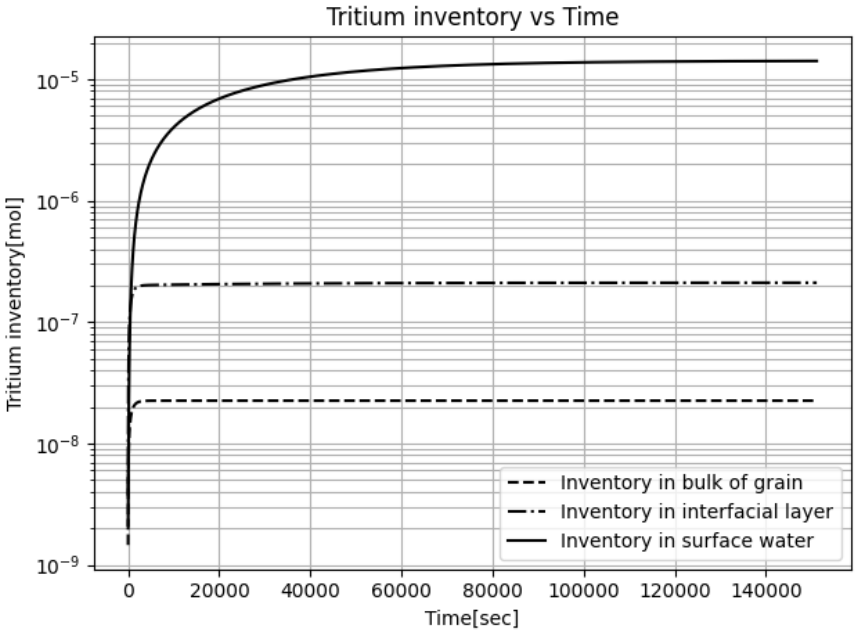

Figure 8: Calculated tritium inventories for Case B.

5 Case C: Purge Gas Introduced from the Low-Temperature Side

When the purge gas is introduced from the high-temperature side of the solid breeder, H_2O is released into the purge gas in the upstream side, and isotope exchange between H_2O in the purge gas and tritium incorporated into the surface water of the solid breeder is promoted in the downstream side. When the purge-gas flow direction is reversed and the gas is introduced from the low-temperature side toward the high-temperature side, the upstream side is exposed to relatively dry He+H_2 purge gas, while only the downstream high-temperature region is exposed to H_2O-rich gas.

The tritium release behavior from Li_2TiO_3 in this case is shown in Fig. 9, and the tritium inventory is shown in Fig. 10.

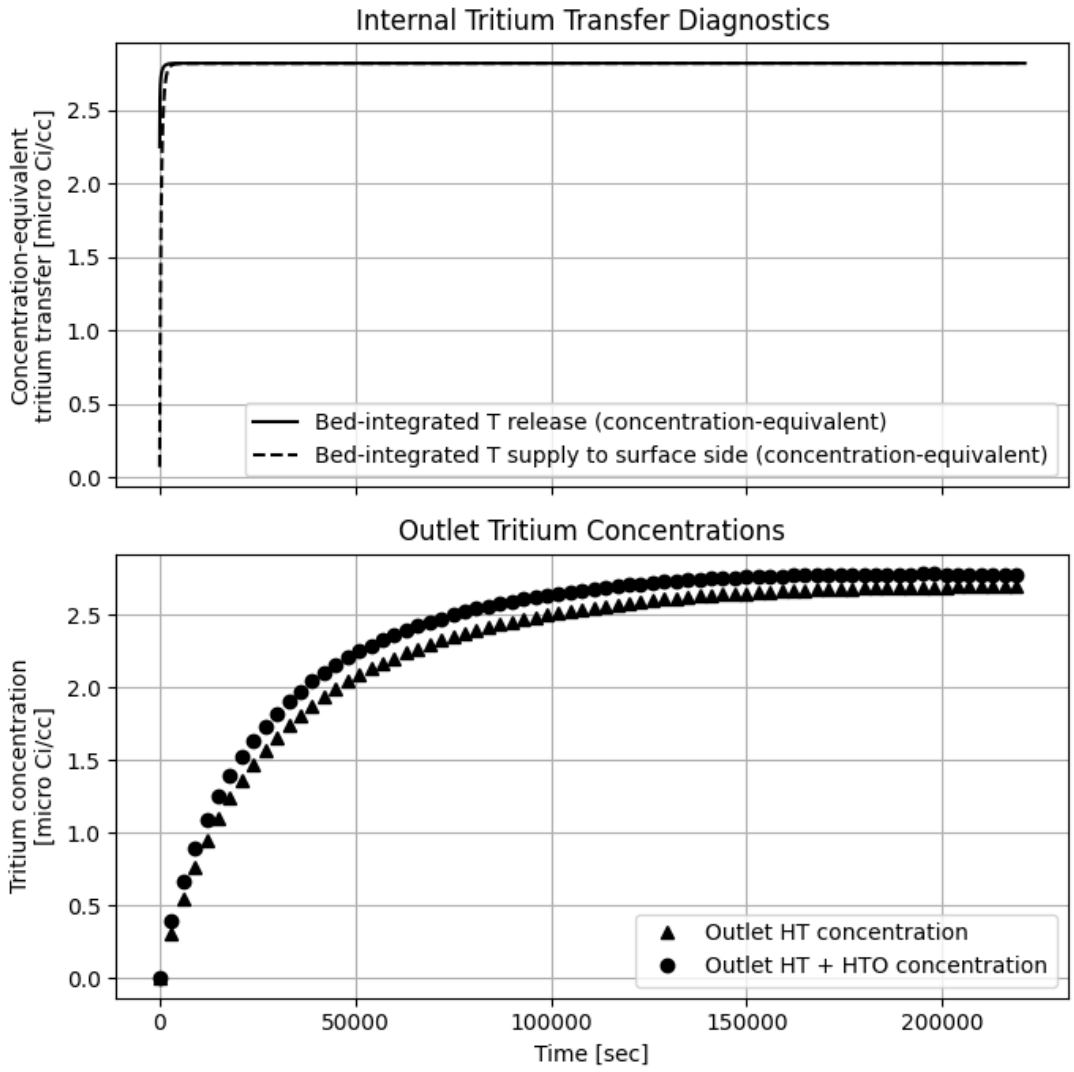

Figure 9: Calculated tritium concentrations in the purge gas when the purge gas is introduced from the low-temperature side (Case C).

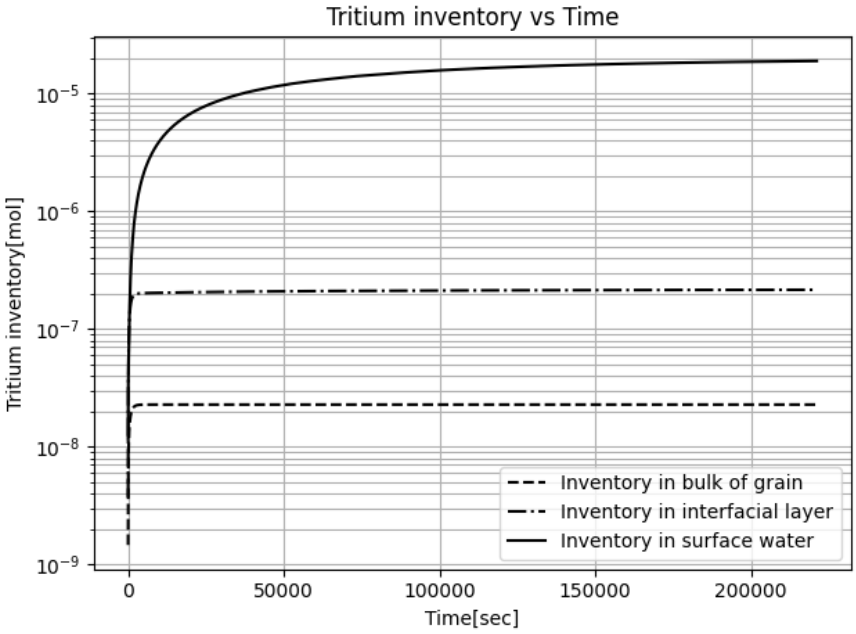

Figure 10: Calculated tritium inventories when the purge gas is introduced from the low-temperature side (Case C).

After about 61 h of operation, about 3% of the released tritium appears as HTO, and the tritium inventory in the surface water of the solid breeder is about 1.9×10^{-5} mol.

6 Summary of the Calculated Results

Table 2 summarizes the calculated results from the viewpoints of tritium inventory, HT/HTO ratio, and tritium release rate.

Table 2: Summary of the calculated cases.

Case	Flow direction	Drying	$I_{\max}$ [mol]	$invS_{\max}$ [mol]	HT/(HT+HTO) [-]	t_{90} [s]
A	Hot → Cold	No	1.01×10^{-5}	9.90×10^{-6}	0.60	33,621
B	Hot → Cold	Yes	1.44×10^{-5}	1.41×10^{-5}	0.84	62,266
C	Cold → Hot	No	1.92×10^{-5}	1.90×10^{-5}	0.97	74,910

Case A gives the smallest tritium inventory because the purge gas is introduced from the high-temperature side and the H_2O concentration in the purge gas is increased by the water-generation reaction. As a result, the HT/(HT+HTO) ratio also becomes the smallest.

In Case B, the breeder is pretreated so that the water-generation reaction does not occur, while the purge gas is still introduced from the high-temperature side. The tritium inventory becomes 1.4 times larger than in Case A. Because the H_2O concentration in the purge gas is suppressed, the HT/(HT+HTO) ratio becomes larger than in Case A.

In Case C, the purge gas is introduced from the low-temperature side toward the high-temperature side without pretreatment to suppress the water-generation reaction. This case gives the largest tritium inventory and the largest HT/(HT+HTO) ratio.

The present calculation suggests that both the tritium inventory and the HT/HTO ratio can be controlled by changing the H_2O concentration in the purge gas and the purge-gas flow direction. From the viewpoint of the solid breeder in the blanket, Case A may be preferable because it minimizes the inventory. However, in the downstream TES, the amount of HTO

to be treated increases in this case. The present findings are expected to be useful for future evaluation of tritium-processing cost and safety from the viewpoint of the entire fusion reactor system.

7 Conclusions

A simplified one-rib simulation was carried out for the gear-type JA DEMO breeder concept. The calculations indicate that purge-gas flow direction and purge-gas water conditions strongly affect the tritium release rate, the tritium inventory in the surface region, and the HT/HTO ratio of released tritium. Introducing the purge gas from the high-temperature side reduces tritium inventory, especially when water generation increases the local H_2O concentration. In contrast, suppressing the water-generation reaction or reversing the purge-gas flow direction increases the retained tritium inventory while shifting the release chemistry toward HT. These results highlight a trade-off between minimizing breeder-side tritium inventory and reducing the HTO load to the downstream tritium extraction system.

References

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