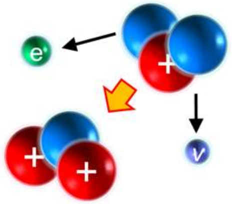
Technical Meeting on Tritium Breeding Blankets and Associated Neutronics

2^{nd} - 5^{th} September, 2025

IAEA Headquarters, Vienna, Austria



Experiments and Modeling on Tritium Mass Transfer in Solid Breeding Blanket

Kazunari KATAYAMA

Kyushu University, Japan

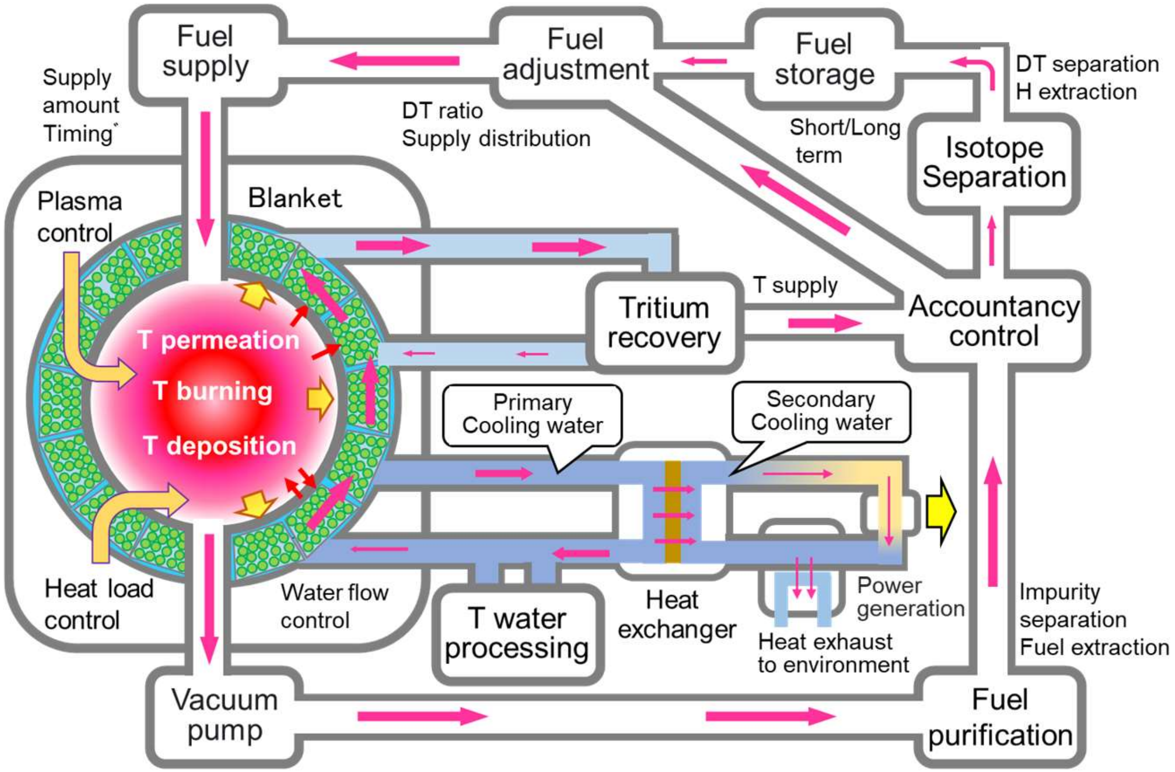
Youji SOMEYA

National Institutes for Quantum Science and Technology (QST), Japan

九州大学
KYUSHU UNIVERSITY

Introduction

From the viewpoint of fuel control and tritium safety in a DT fusion reactor, it is important to correctly understand the tritium mass transfer in the blanket system.



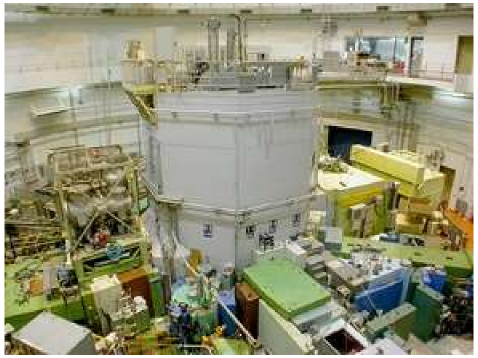
Fuel cycle system with Water Cooled Ceramic Breeding blanket

Contents

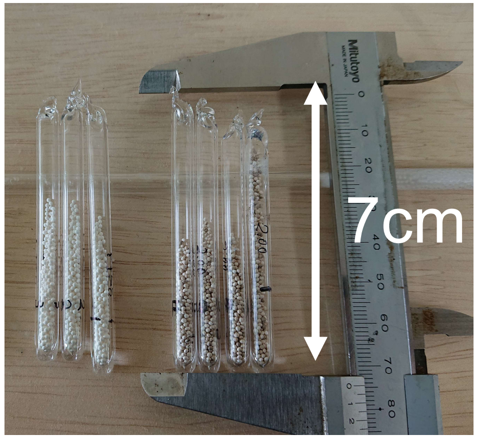
1. T release behavior from Li ceramic breeder
2. T permeation to primary cooling water
3. T permeation from primary to secondary cooling water
4. Evaluation model for T balance in a DEMO reactor

(1) Tritium release from solid breeders

Out-pile experiment



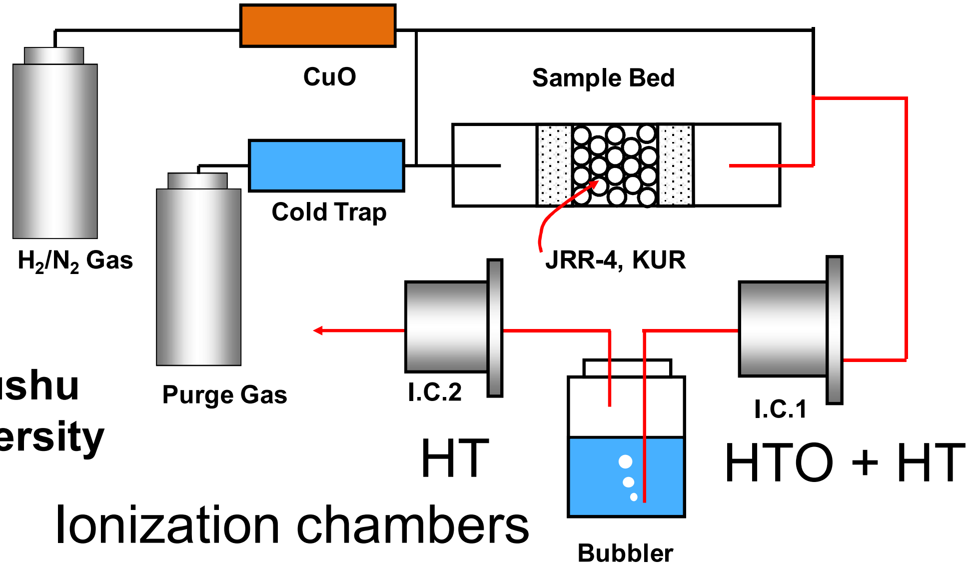
KUR or JRR3



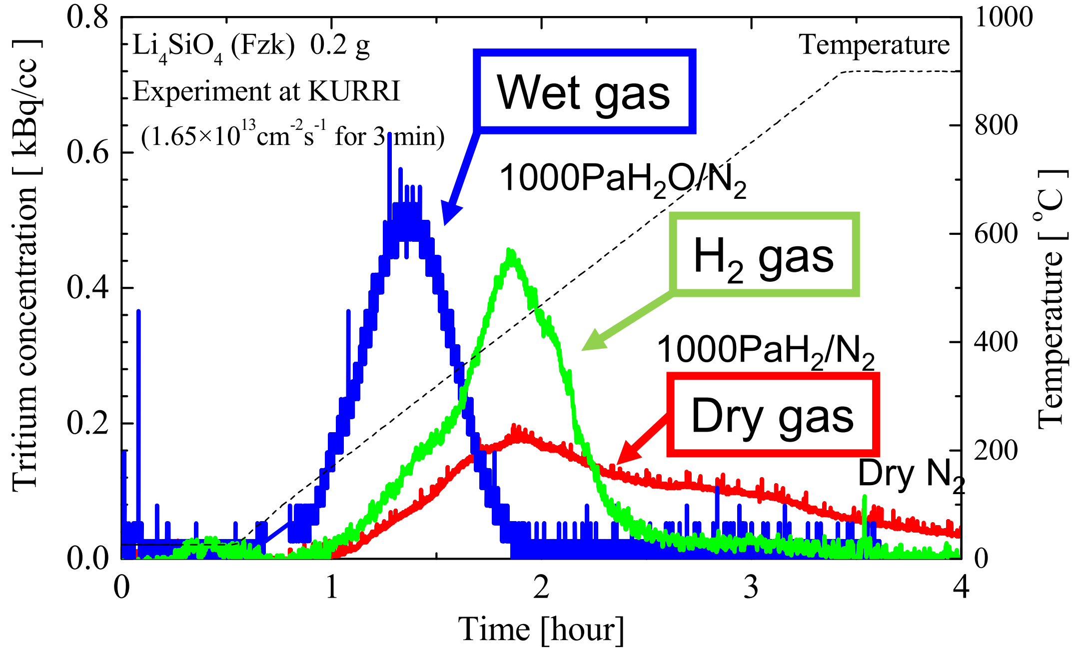
Sample (QST)

(Packed in quartz tube)

Kyushu University



Ionization chambers

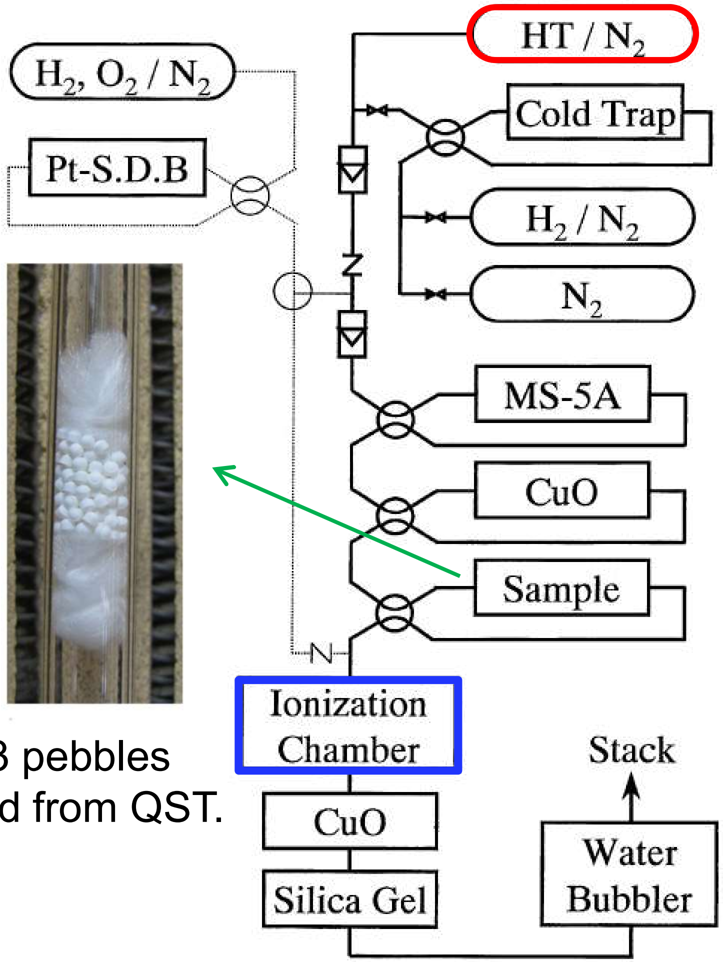


Influence of surface reaction

Surface reaction of tritium on breeder surface

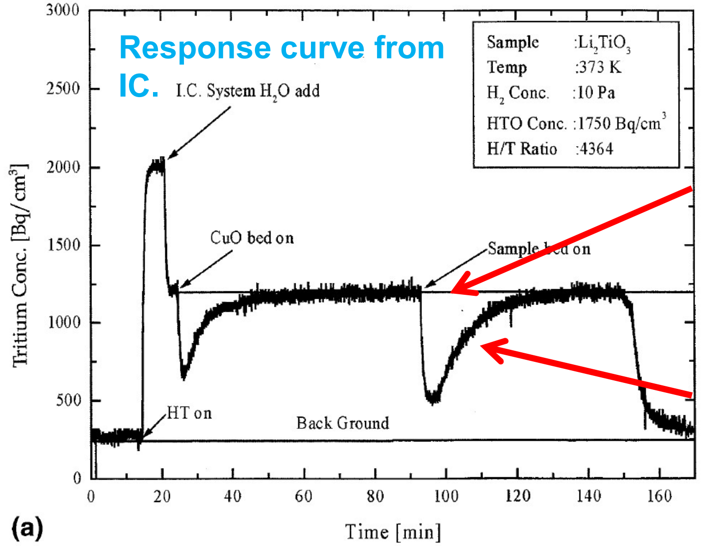
The trapped tritium was released by dry or wet gas purge and monitored by Ionization chamber.

Tritium gas



Li2TiO3 pebbles supplied from QST.

Fig. 1. Schematic diagram of the experimental apparatus.



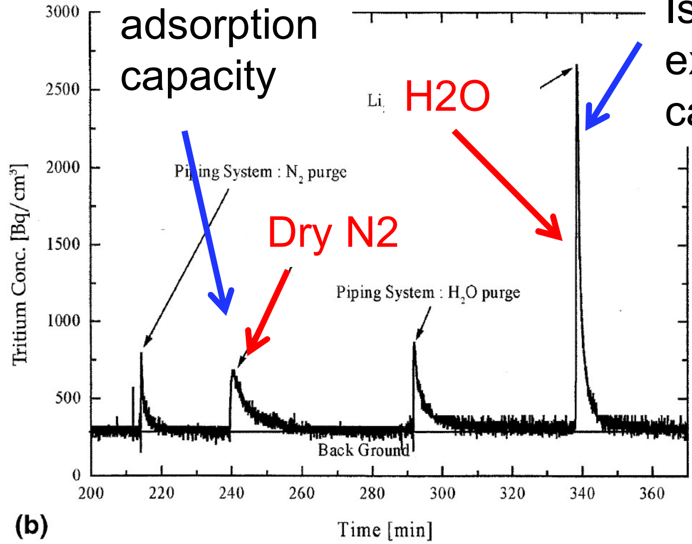
(a)

T trapping capacity

Isotope exchange rate.

Physically adsorption capacity

Isotope exchange capacity.



(b)

T.Kawagoe et al., J.Nucl.Mater.,297(2001)27

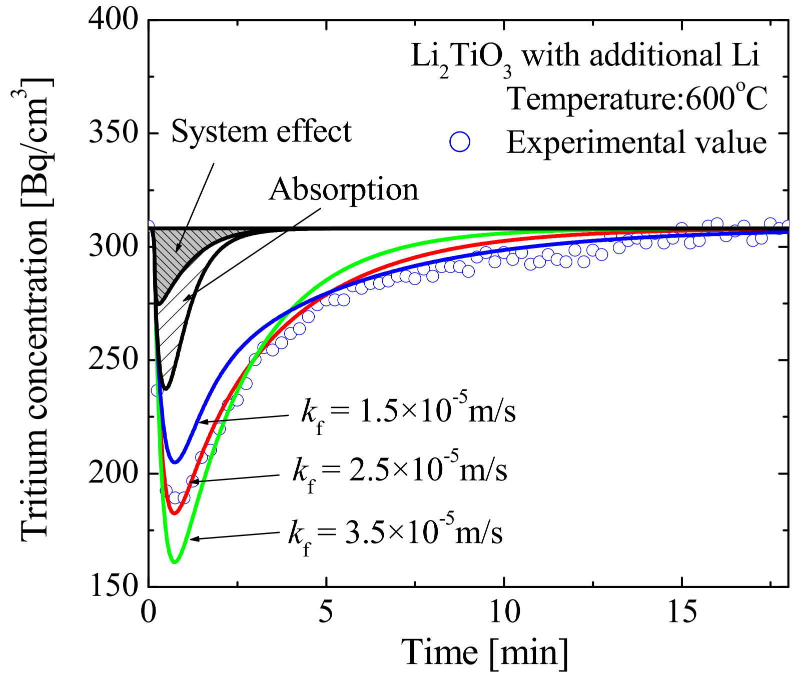
Evaluation of isotope exchange reactionrate

Mass balance equation of tritiated water in the gas stream

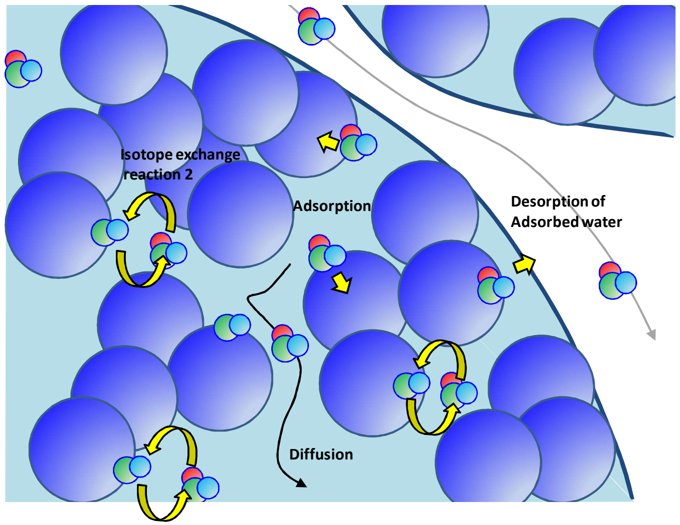
$$u\frac{\partial C_{T_2O}}{\partial z}+\varepsilon\frac{\partial C_{T_2O}}{\partial z}+K_{F,ad}a_v\left(C_{H_2O}+C_{T_2O}-C^*\right)\frac{C_{T_2O}}{C_{H_2O}+C_{T_2O}}+K_{F,ex2}a_v\left(C_{H_2O}+C_{T_2O}\right)\left(\frac{C_{T_2O}}{C_{H_2O}+C_{T_2O}}-\frac{q_{T_2O}}{q_{H_2O}+q_{T_2O}}\right)=0$$

Mass balance equation of tritiated water on the breeder surface

$$a_v\frac{\partial q_{T_2O}}{\partial t}-K_{F,ad}a_v\left(C_{H_2O}+C_{T_2O}-C^*\right)\frac{C_{T_2O}}{C_{H_2O}+C_{T_2O}}-K_{F,ex2}a_v\left(C_{H_2O}+C_{T_2O}\right)\left(\frac{C_{T_2O}}{C_{H_2O}+C_{T_2O}}-\frac{q_{T_2O}}{q_{H_2O}+q_{T_2O}}\right)=0$$

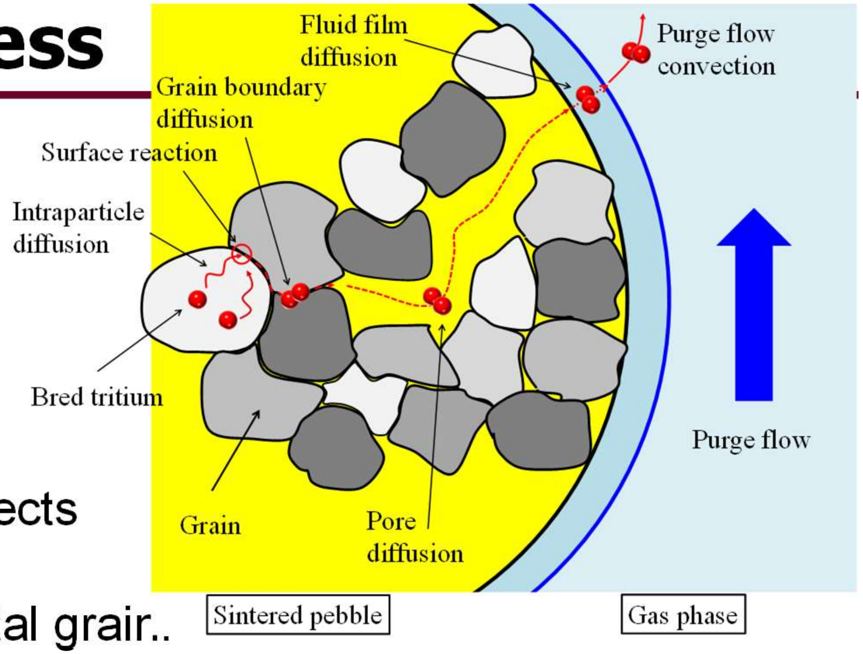


Evaluation of isotope exchange reaction rate



Mass balance equations in the sample bed were numerically calculated and the reaction rate was obtained by the fitting method.

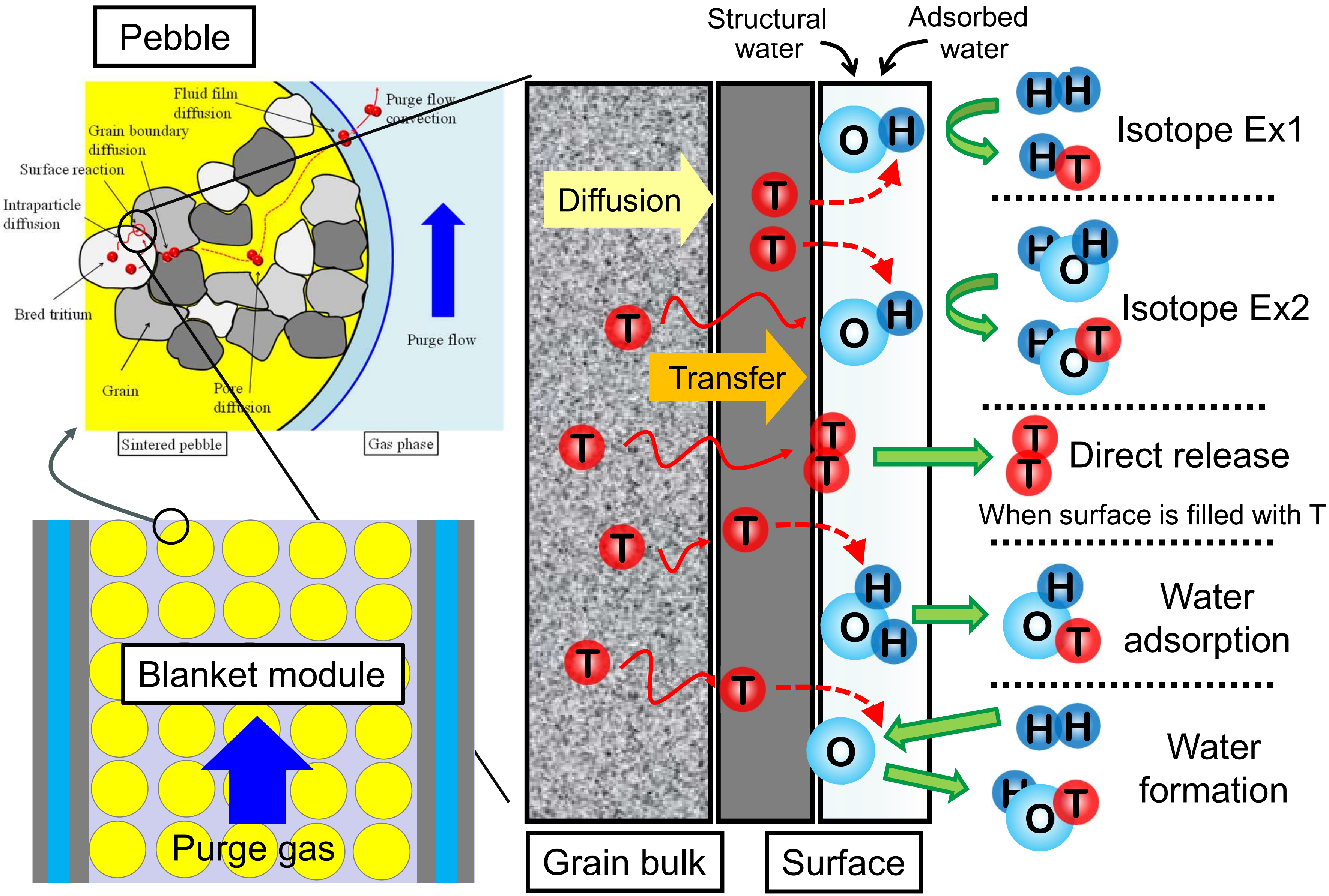
Tritium mass transfer process



T transfer processes and key reactions in overall T release property to a purge gas He containing H_2.

1. T generation in a crystal grain.
2. T diffusion in the crystal grain.
3. Interaction of diffusing T with irradiation defects formed in the crystal grain.
4. T transfer from inside to surface of the crystal grain.
5. Absorption of T into the crystal grain.
6. Adsorption/desorption of HTO and H2O on crystal grain surface.
7. Isotope exchange reaction between H2 in gas phase and T on the crystal grain surface (isotope exchange reaction 1).
8. Isotope exchange reaction between H2O in the gas phase and T on the crystal grain surface (isotope exchange reaction 2).
9. Water formation reaction on the crystal grain surface with H2 in the gas phase.
10. Mass transfer of hydrogen isotopes and water vapor through the interconnected pores to geometrical surfaces of the pebbles.
11. Mass transfer of hydrogen isotopes and water vapor through fluid film formed between geometrical surfaces of the pebbles and the purge gas flow.

Tritium release model in solid breeders



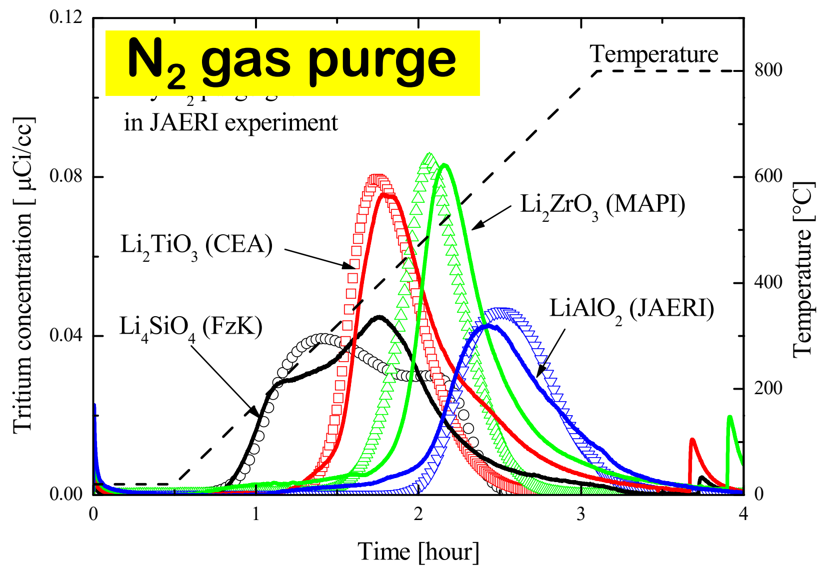
九州大学

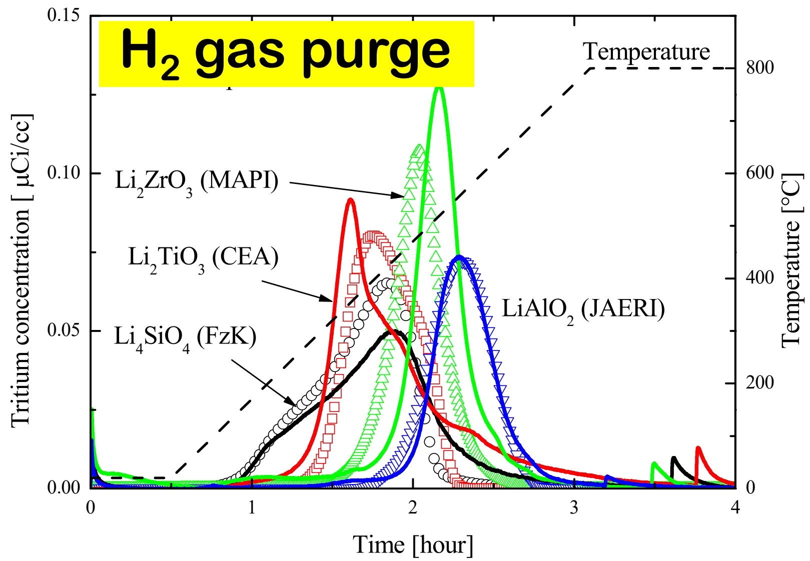
Comparison of calculated with experimental

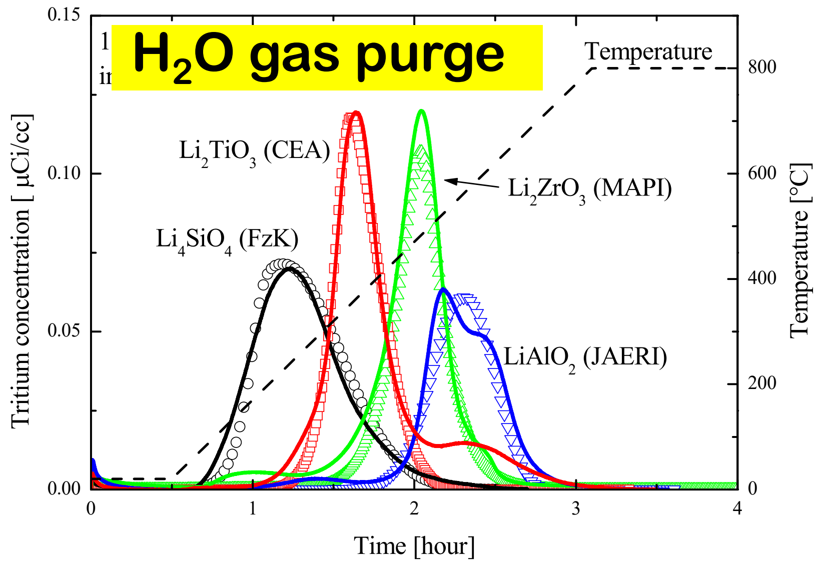
Numerical calculation based on the mass transfer model could reproduce experimental curves well.

Breeders: Li_2TiO_3, Li_4SiO_4, Li_2ZrO_3, $LiAlO_2$

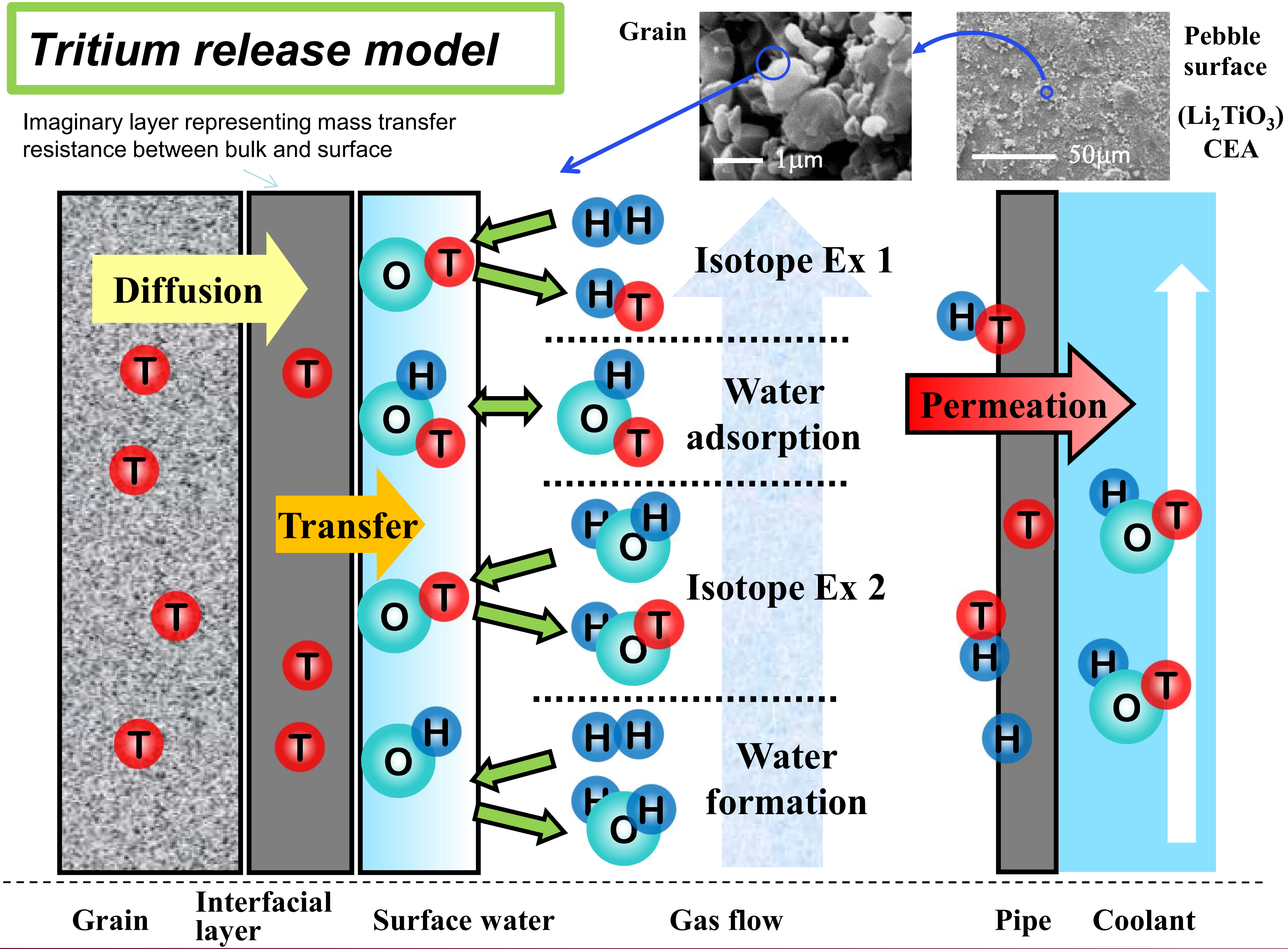
Purge gas: N_2 gas (Dry gas), H_2 gas, H_2O gas



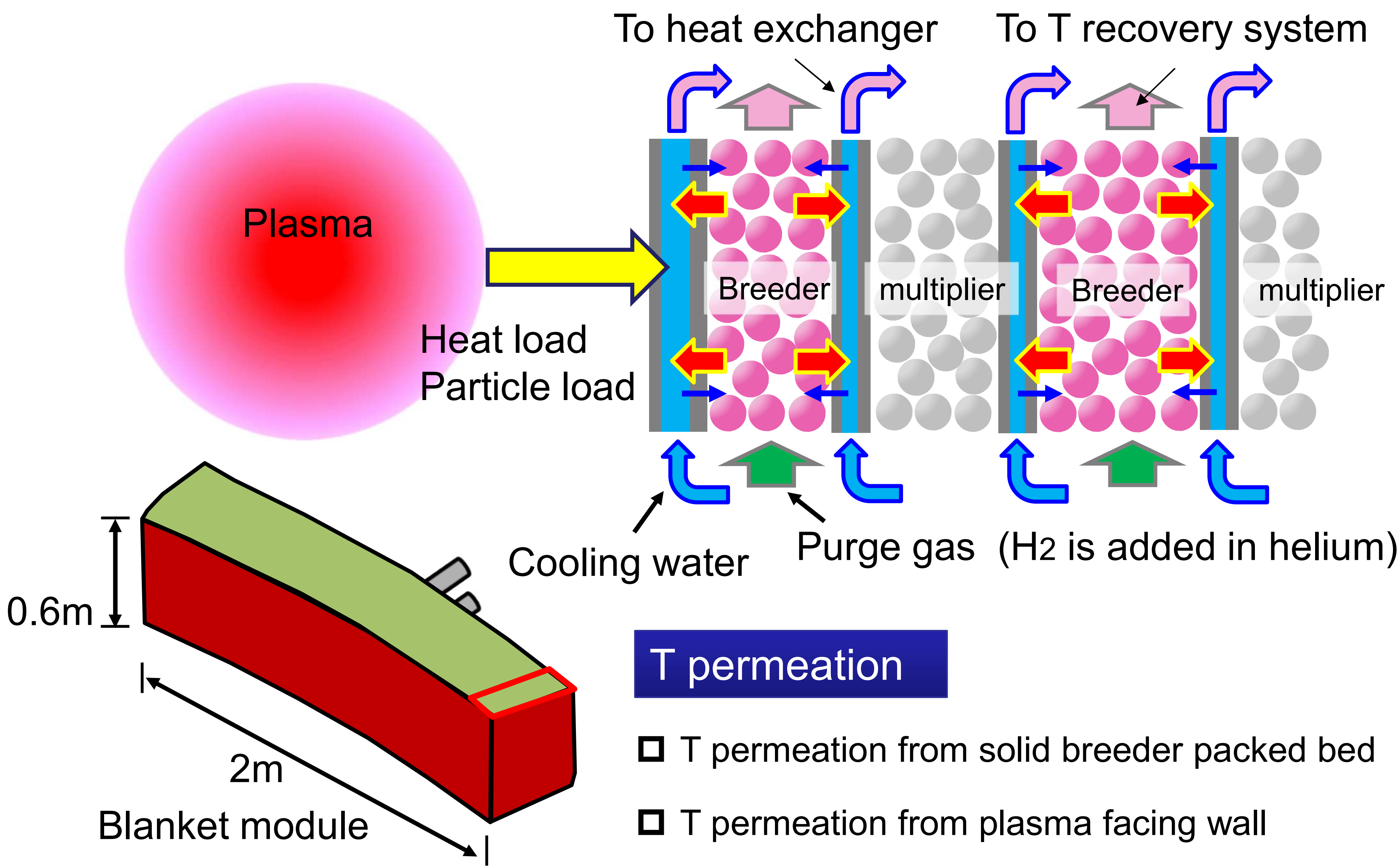




Tritium release model



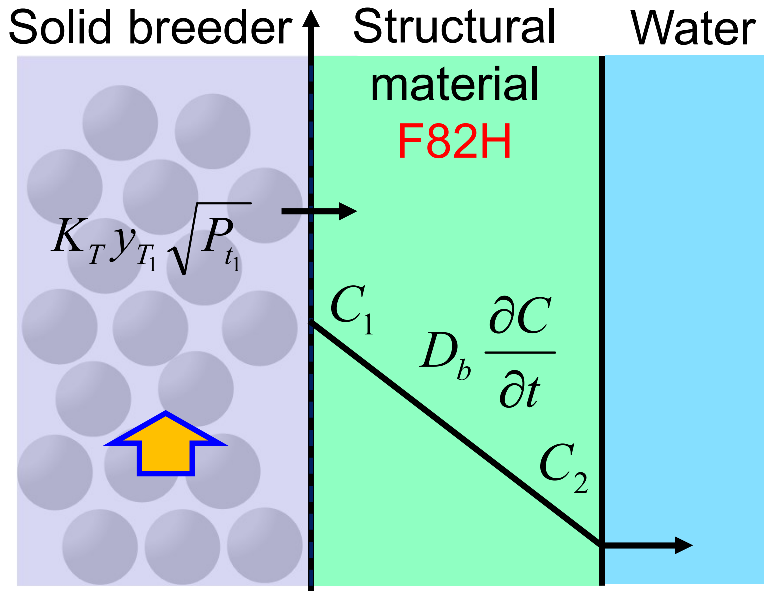
(2) Permeation of tritium to cooling water



T permeation

- T permeation from solid breeder packed bed
- T permeation from plasma facing wall

Bred tritium permeation rate through F82H



*Hickman's law

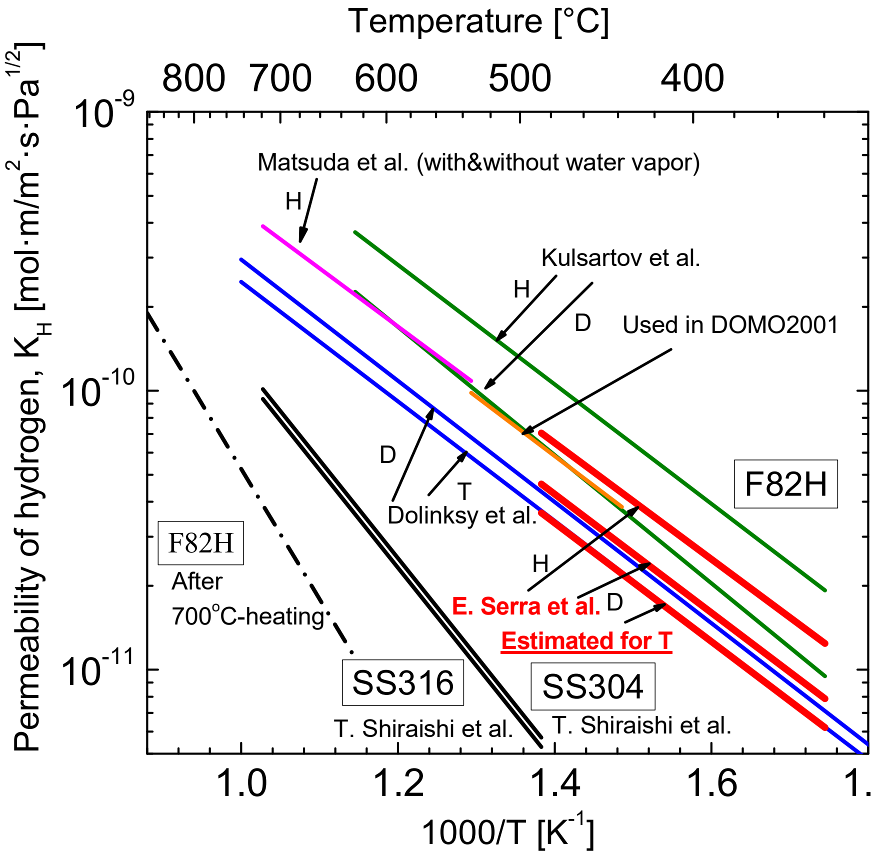
$$J_H = D_H \left(S_H y_{H,1} \sqrt{P_{t,1}} - S_H y_{H,2} \sqrt{P_{t,2}} \right)$$

$$= K_H \left(y_{H,1} \sqrt{P_{t,1}} - y_{H,2} \sqrt{P_{t,2}} \right)$$

$$\frac{T}{H+T}$$

$$J_T = D_T \left(S_T y_{T,1} \sqrt{P_{t,1}} - S_T y_{T,2} \sqrt{P_{t,2}} \right)$$

$$= K_T \left(y_{T,1} \sqrt{P_{t,1}} - y_{T,2} \sqrt{P_{t,2}} \right)$$

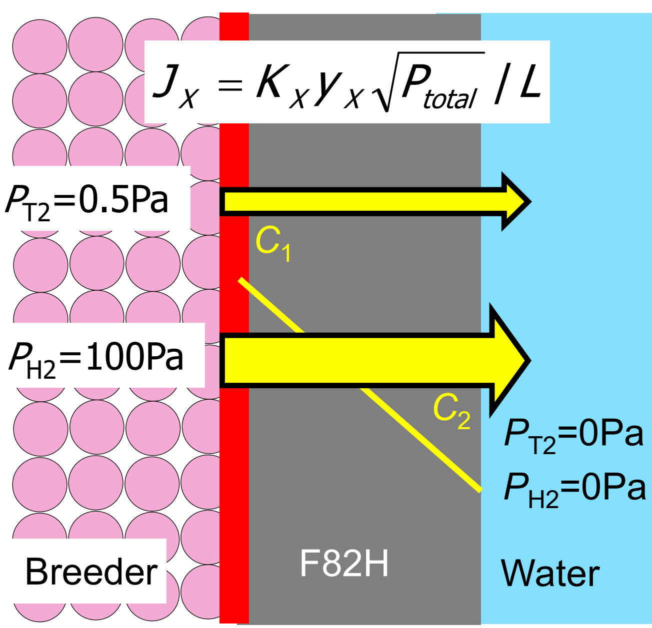


Permeability of Hydrogen isotope in F82H
(Serra's data was used)

J : Permeation rate [mol·m/m^{2}s]
K : Permeability [mol·m/m^{2}s·Pa$^{1/2}$]
D : Diffusivity [m^2/s]
y : mole fraction [mol/mol]
S : Soluvility [mol/m^{3}Pa$^{1/2}$]
P_t : Hydrogen isotope pressure [Pa]

*R.G.Hickman, J.Less-Common Metals, 19 (1969) 369-383.

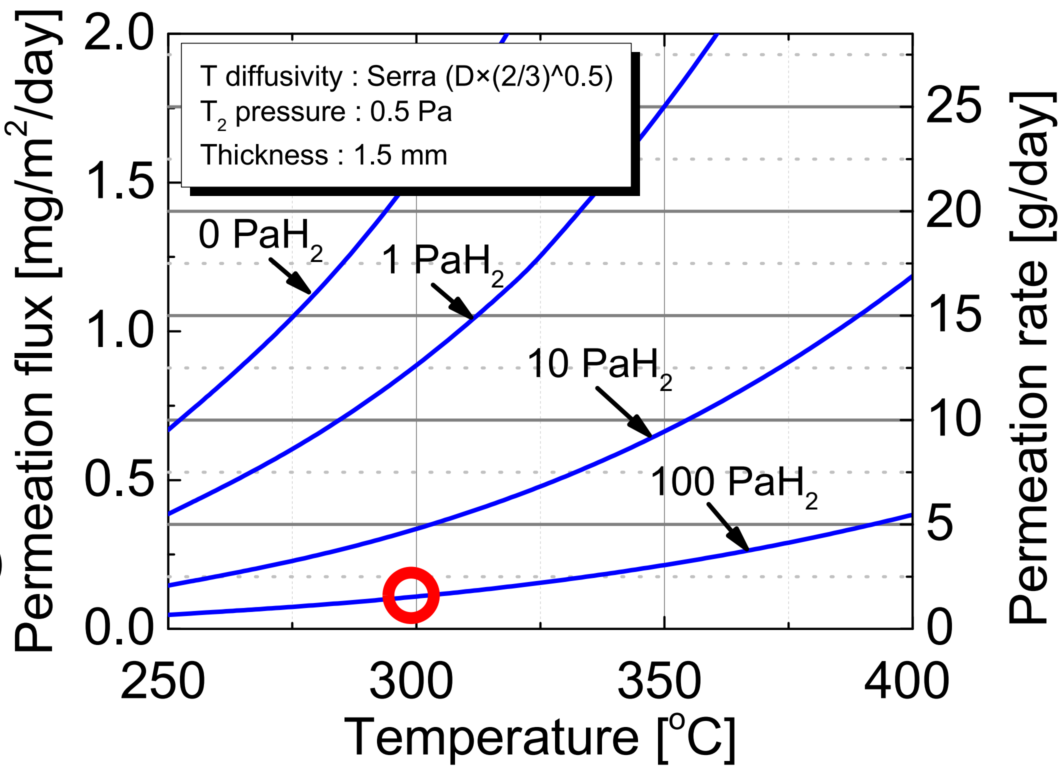
Evaluated tritium permeation to cooling water



J: Permeation flux $\quad y_t$: P_{T2}/P_{total}

K_T: Permeability $\quad P_{total}=P_{H2}+P_{T2}$

Hickman's law was applied.



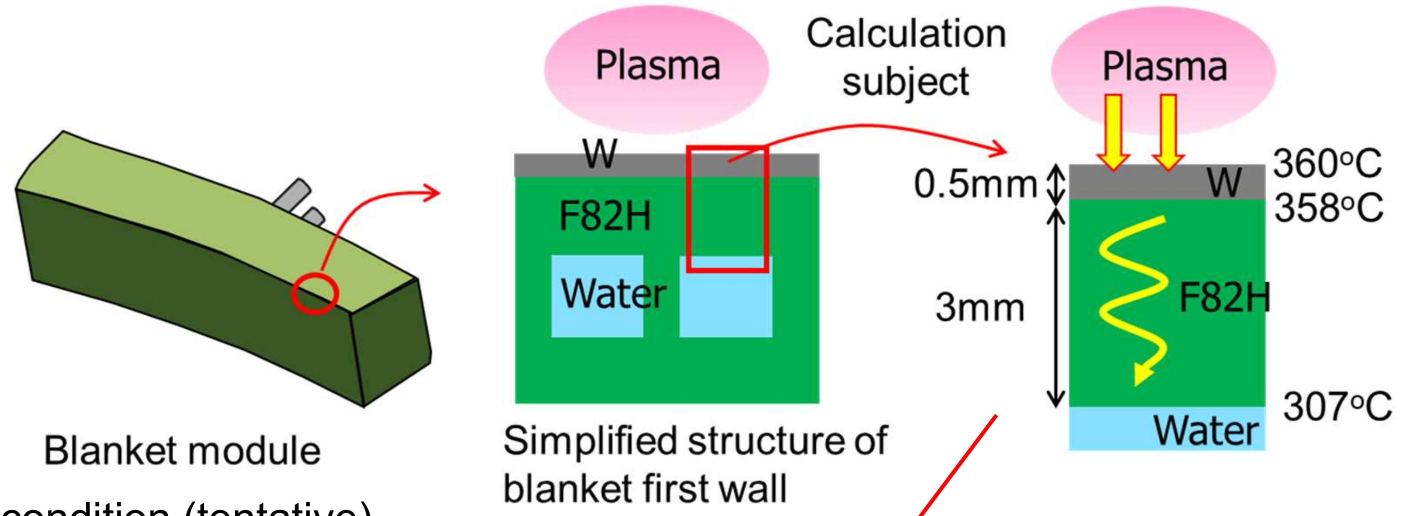
JA-DEMO condition (tentative)

- Material : F82H
- Thickness :1.5 mm
- H2:100Pa , T2:0.5Pa
- Permeation area :14251m^2
- Temperature : 300^{o}C

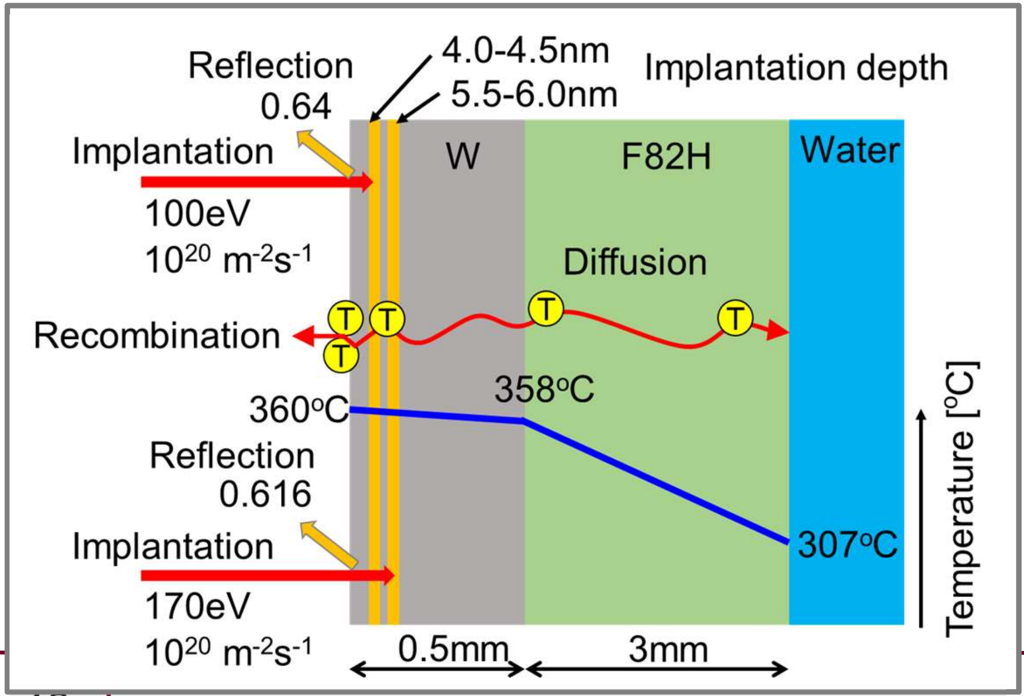
300^{o}C,100 PaH2 => **2.3 g/day**

K. Katayama et al., Fusion Sci. Tech.71 (2017) 261.

Tritium permeation rate through First wall



JA-DEMO condition (tentative)



Tritium behavior was calculated by TMAP code.

Implantation depth was evaluated by SRIM code.

Tritium transport parameters were used from the data by Frauenfelder, Anderl for W, and Serra for F82H.

Evaluated tritium permeation rate in blanket

JA-DEMO condition (tentative)

Region	Surf(m^2)	Surf T(^oC)	Particle ($1/m^2/s$)	Particle E(eV)	Material
First wall	1067	360	Ion : 10^{20}	100	W-F82H
			Neutral : 10^{20}	170	

Evaluated permeation rate in the first wall to cooling water

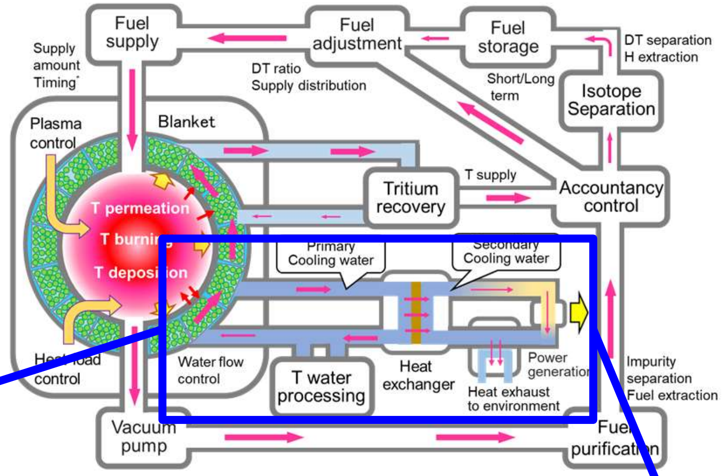
Region	Steady state [hour]	Perm flux ($g/m^2/day$)	Perm rate (g/day)
First wall	2	6.49×10^{-4}	**0.692**

Total permeation rate in the blanket modules

2.3 g/day in breeding zone + 0.692 g/day in first wall
= around 3 g/day K.Katayama et al., Fusion Eng. Des. 169 (2021) 112576.

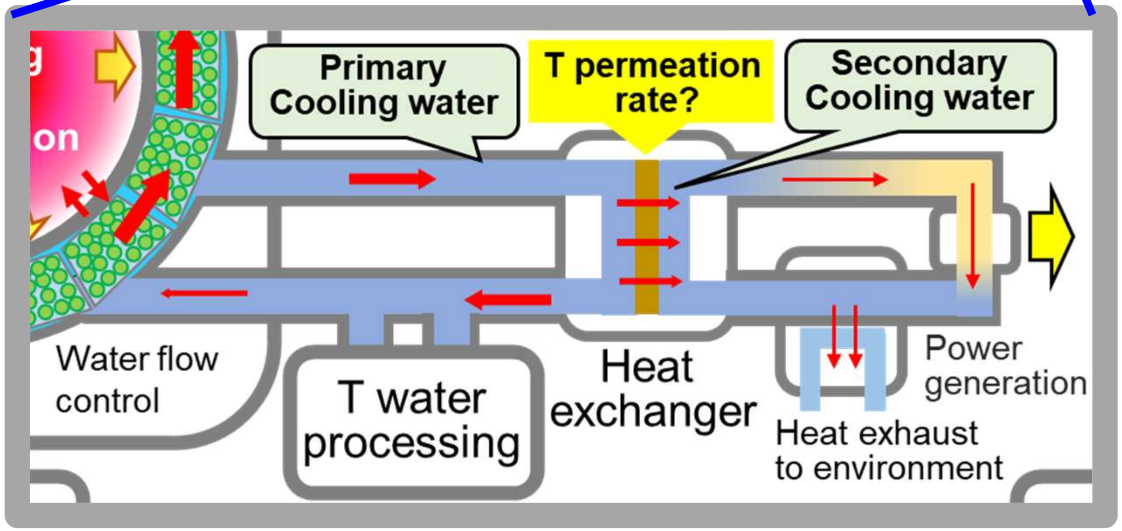
(3) T permeation from Primary to Secondary water

Evaluation of tritium permeation rate through the heat exchanger is very important for safety.



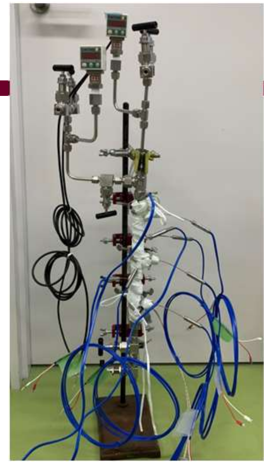
- T inventory in the secondary coolant.
- T contamination level of the turbine system to design the maintenance system.
- T release rate to the environment through the condenser.

The experimental data on tritium permeation from the pressurized water to the pressurized water in a heat exchanger is not sufficient.

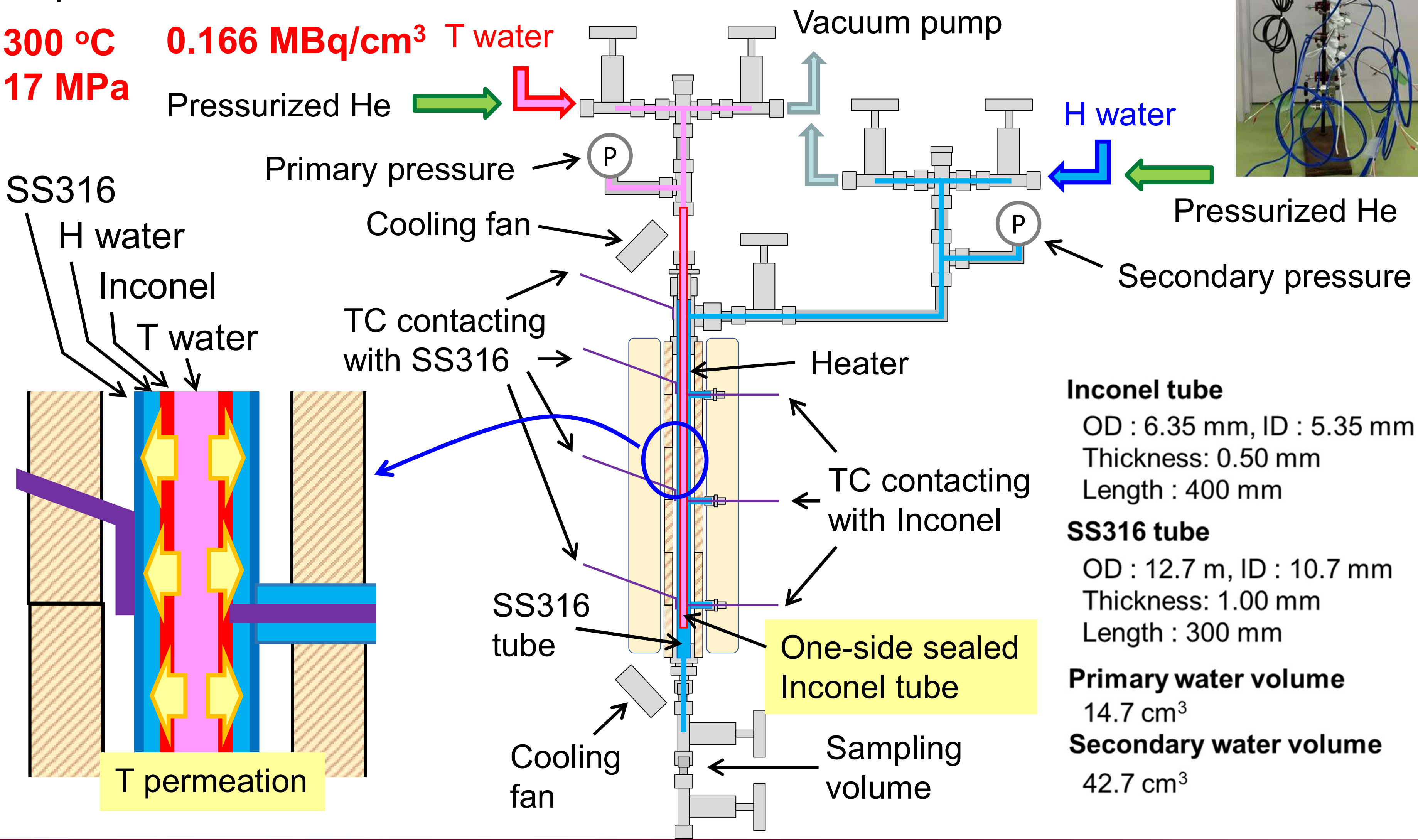


Under KU-QST collaboration, we tried to investigate a T permeation rate from pressurized water to pressurized water through an Inconel tube.

Experimental set up for T permeation test



The permeation device of a static double tube type with Inconel 600 equivalent tube and SS316 tube was assembled.



Inconel tube

OD : 6.35 mm, ID : 5.35 mm
Thickness: 0.50 mm
Length : 400 mm

SS316 tube

OD : 12.7 m, ID : 10.7 mm
Thickness: 1.00 mm
Length : 300 mm

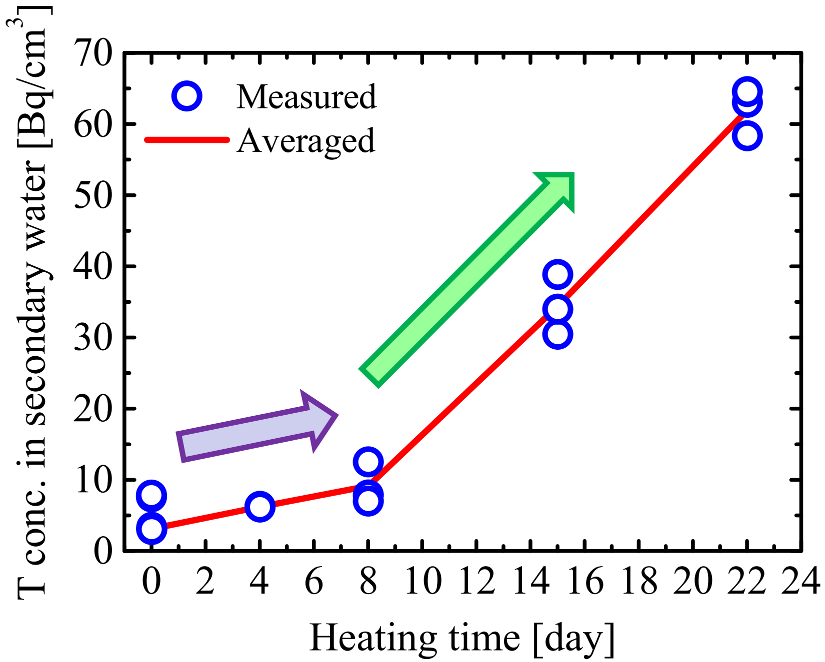
Primary water volume

14.7 cm^3

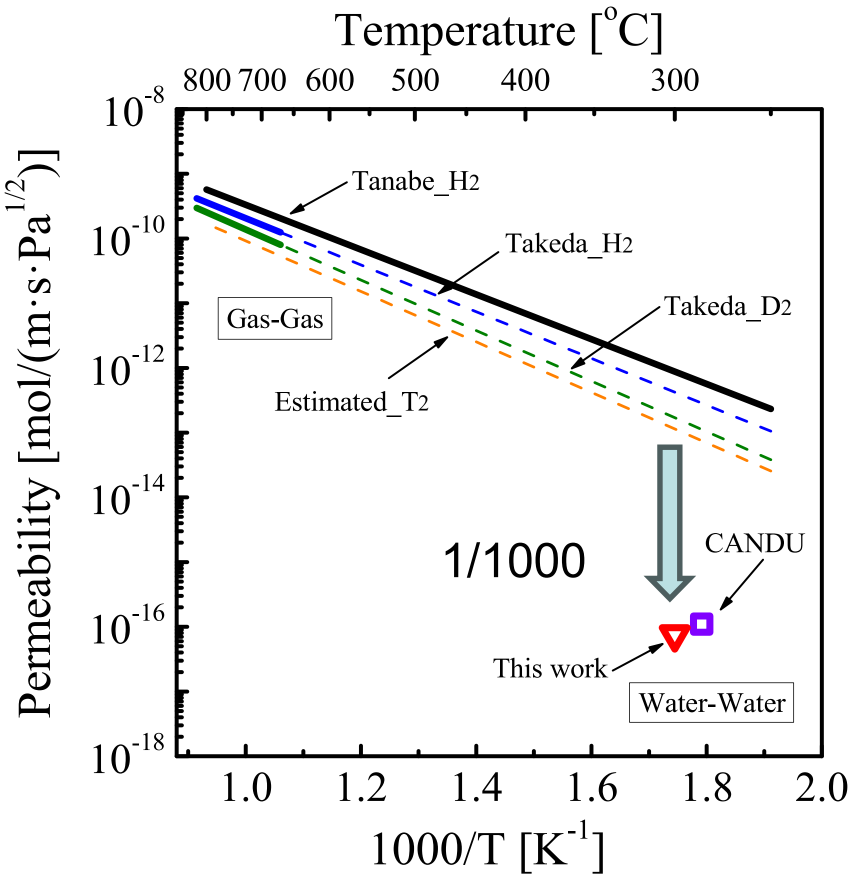
Secondary water volume

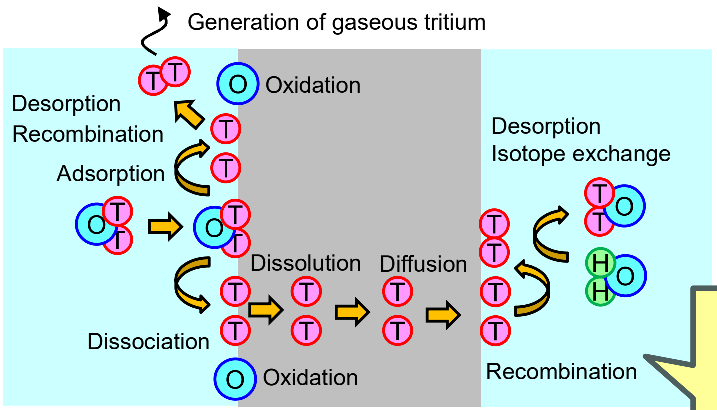
42.7 cm^3

T permeation from water to water



Tritium permeation was observed 17 days after heating started.





Estimated permeability was 1/1000 of gas-gas permeation and is same degree with that estimated from CANDU reactor.

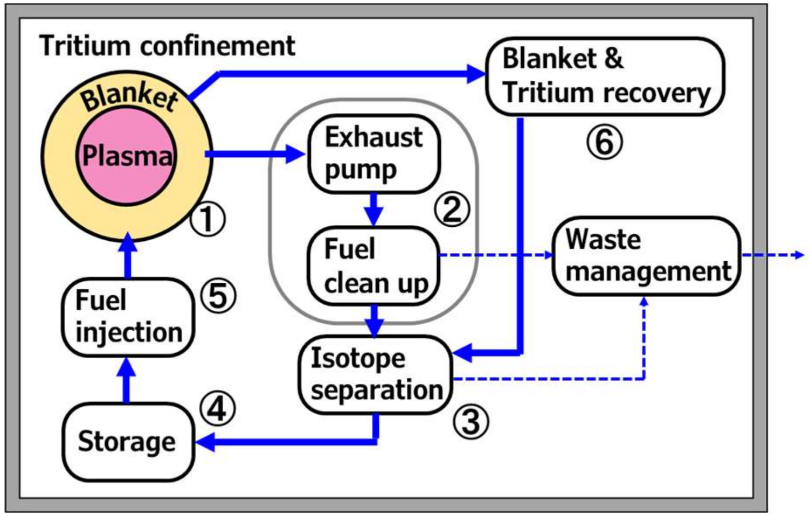
T permeation mechanism is under consideration.
($2T_2O + Ni \Rightarrow T_2 + Ni(OT)_2$)

(4) Evaluation model for T balance in DEMO

Exam.Residence time（Asaoka et al 1996） Y.Asaoka et al, Fusion Technol.(1996)

Mean resident time in each process	
Plasa	1.5 sec
Exhaust pump and clean up	20 min
Isotope separation	60 min
Fuel injection	20 min
T breeding blanket and recovery	5 day *

* Reference: M. Nishikawa, private communication.



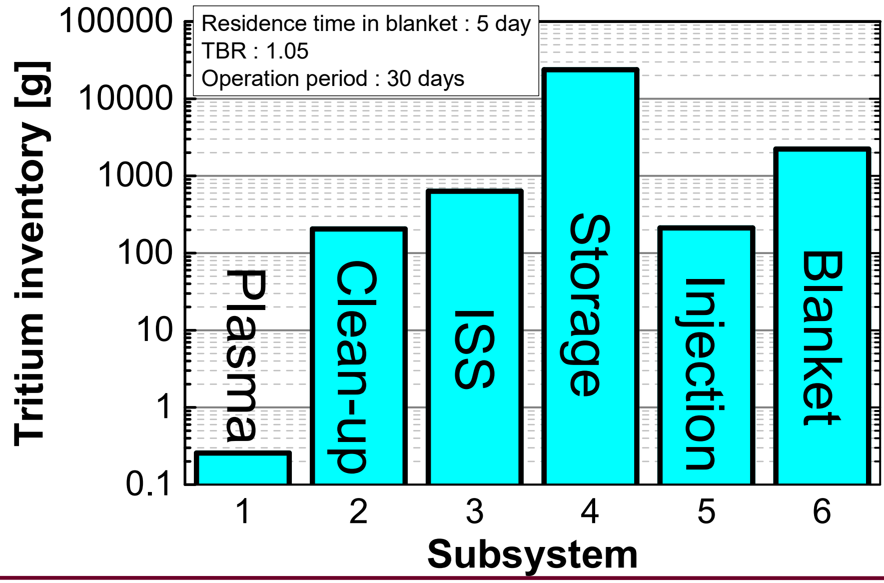
Mean residence time [s]

$$\tau_i = \frac{I_i}{X_i}$$

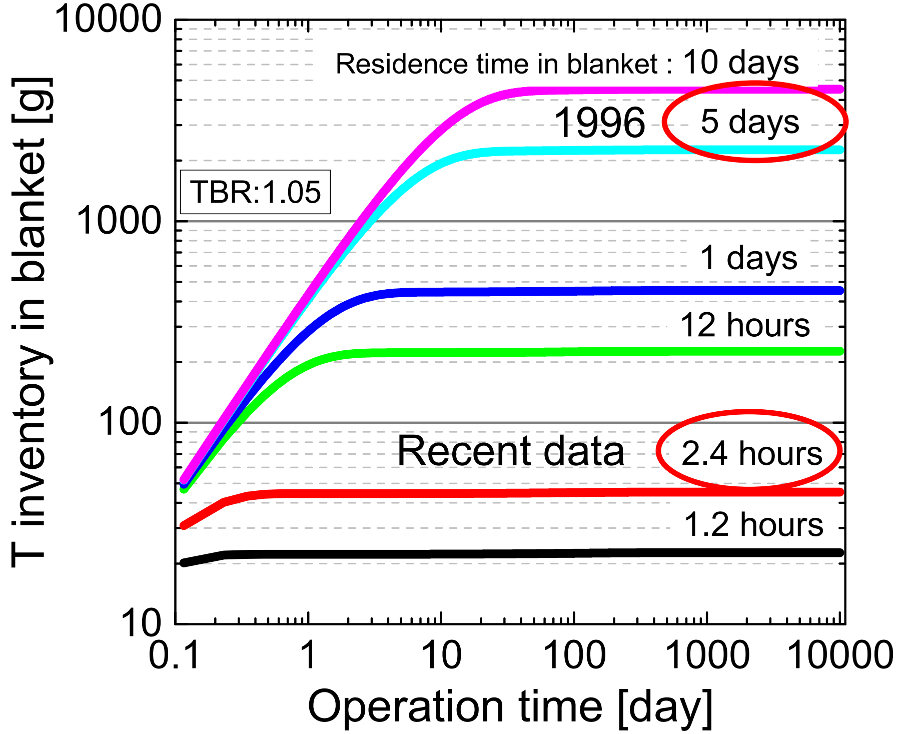
I_i : Inventory [kg]

X_i : Processing rate [kg/s]

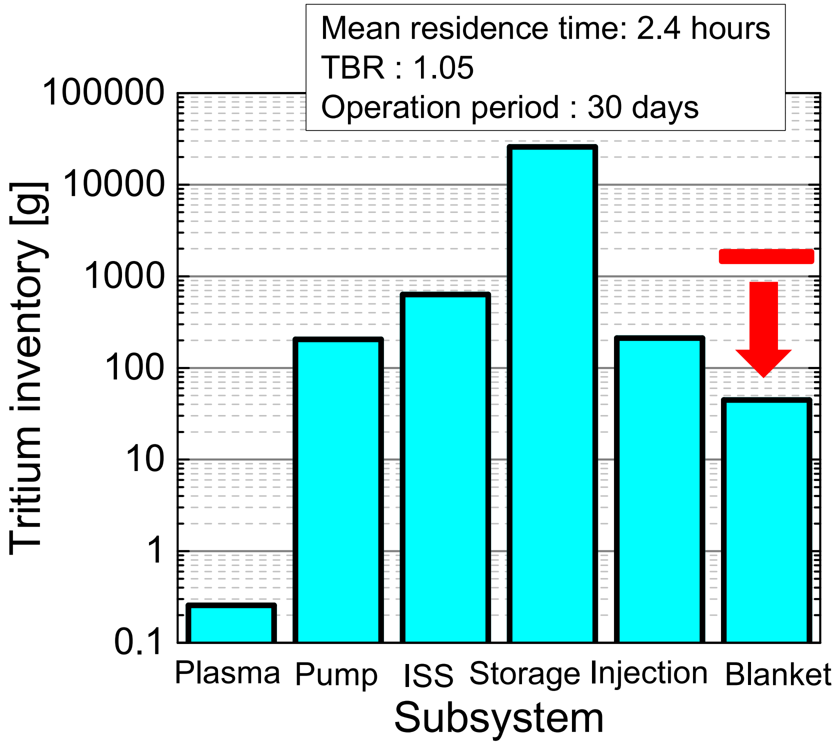
Mass balance equations were proposed and inventory in each sub-system was evaluated.



MRT in Blanket from Recent data



Relationship between MRT and Inventory



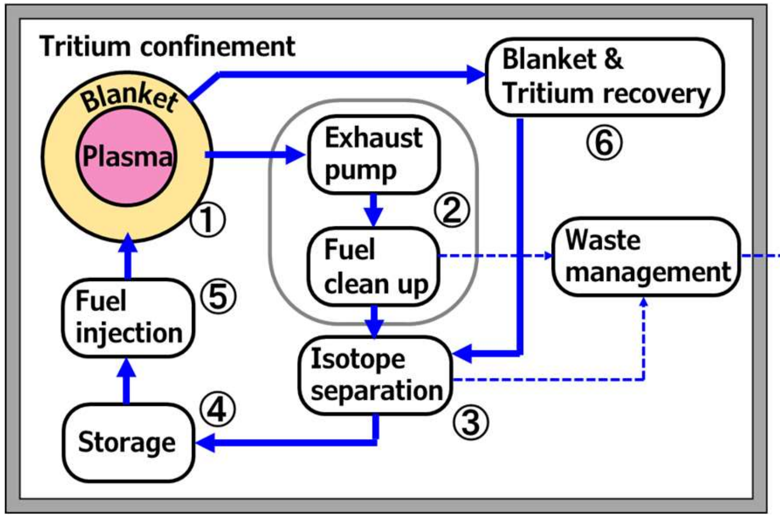
Inventory in each subsystem
（MRT：2.4 hours）

Tritium inventory is strongly dependent on MRT.
MRT = 5 days Inventory = 2000g
MRT = 2.4 hours Inventory = 40 g

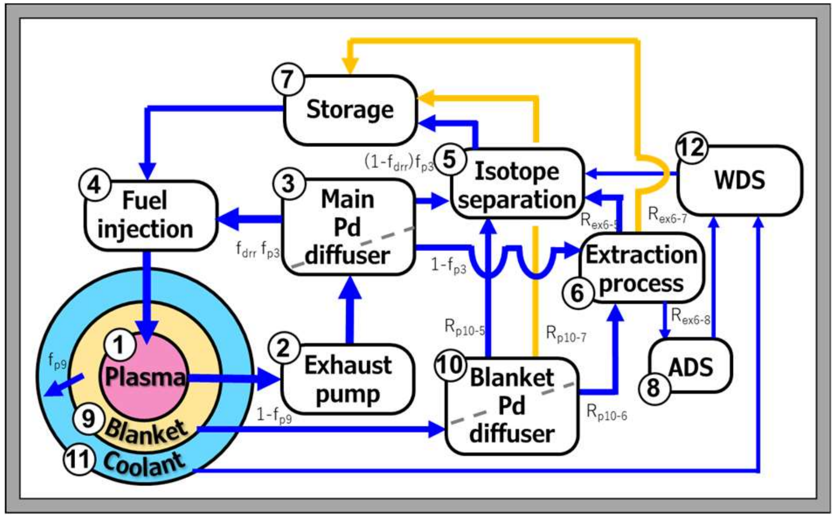
If MRT is 2.4 hours instead of 5 days, the blanket inventory is relatively small.
Isotope separation systems have the largest inventory.

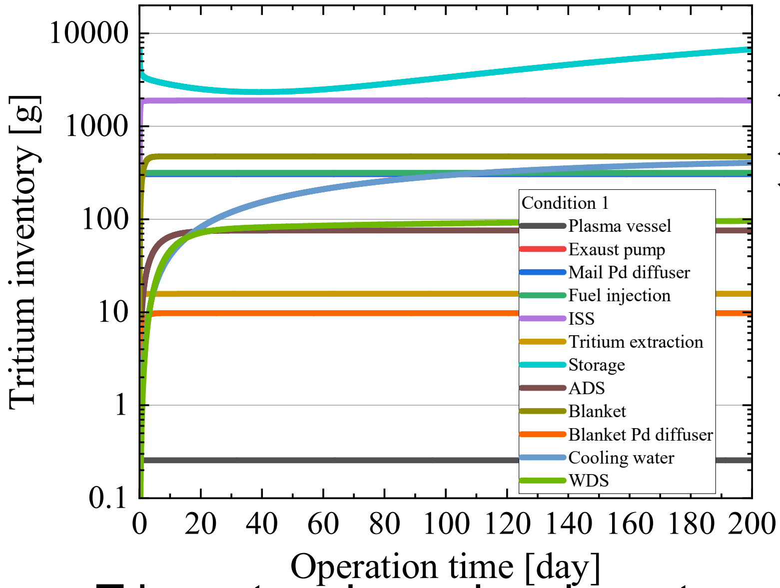
Influence of T permeation to cooling water

Asaoka model (1996)



Model including cooling water





T inventory in each sub-system

Isotope separation system

Breeding zone in blanket

Cooling water

✓ Estimated T inventory :
ISS > Blanket > Cooling water

Tritium inventory in the blanket and cooling water is relatively large following that in ISS.

Summary

1. T release behavior from Li ceramic breeder

From out-pile experiments and fundamental T lab experiments,
T release model including surface reactions are proposed and T release behavior from neutron irradiated Li ceramic breeders can be predicted approximately.

2. T permeation to primary cooling water

In JA DEMO conditions, it was estimated that T permeation is 2.3 g/day in breeding zone and 0.692 g/day in first wall, totally 3 g/day.

3. T permeation from primary to secondary cooling water

We successfully observed tritium permeation from tritiated water to light water through Inconel under conditions of 300℃ and 17MPa.

4. T balance in a DEMO reactor

In T balance evaluation using the MRT method, T inventory in the cooling water and blanket seems to be the second largest following the ISS.