Oct. 16 (Wed.) 2024
Target Parallel 2
17:05-17:30

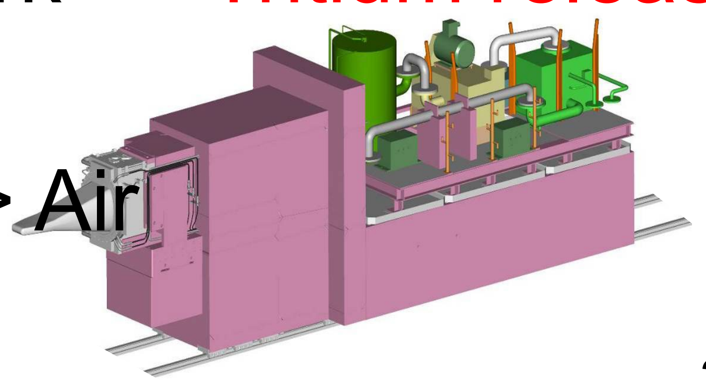
Simplified Model for Simulating Tritium Behavior in the Spallation Neutron Target System

Yoshimi Kasugai

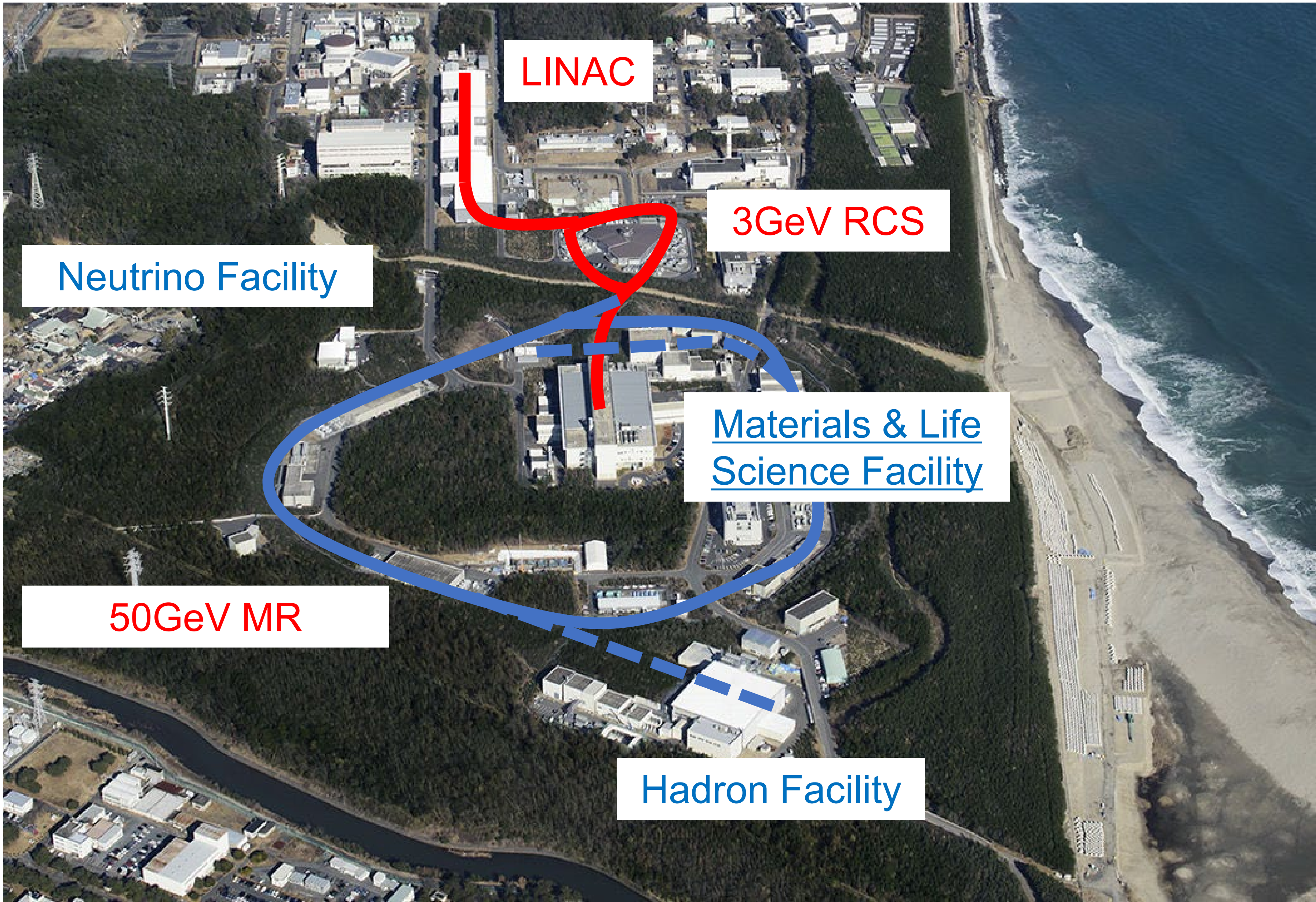
J-PARC（JAEA）

Introduction

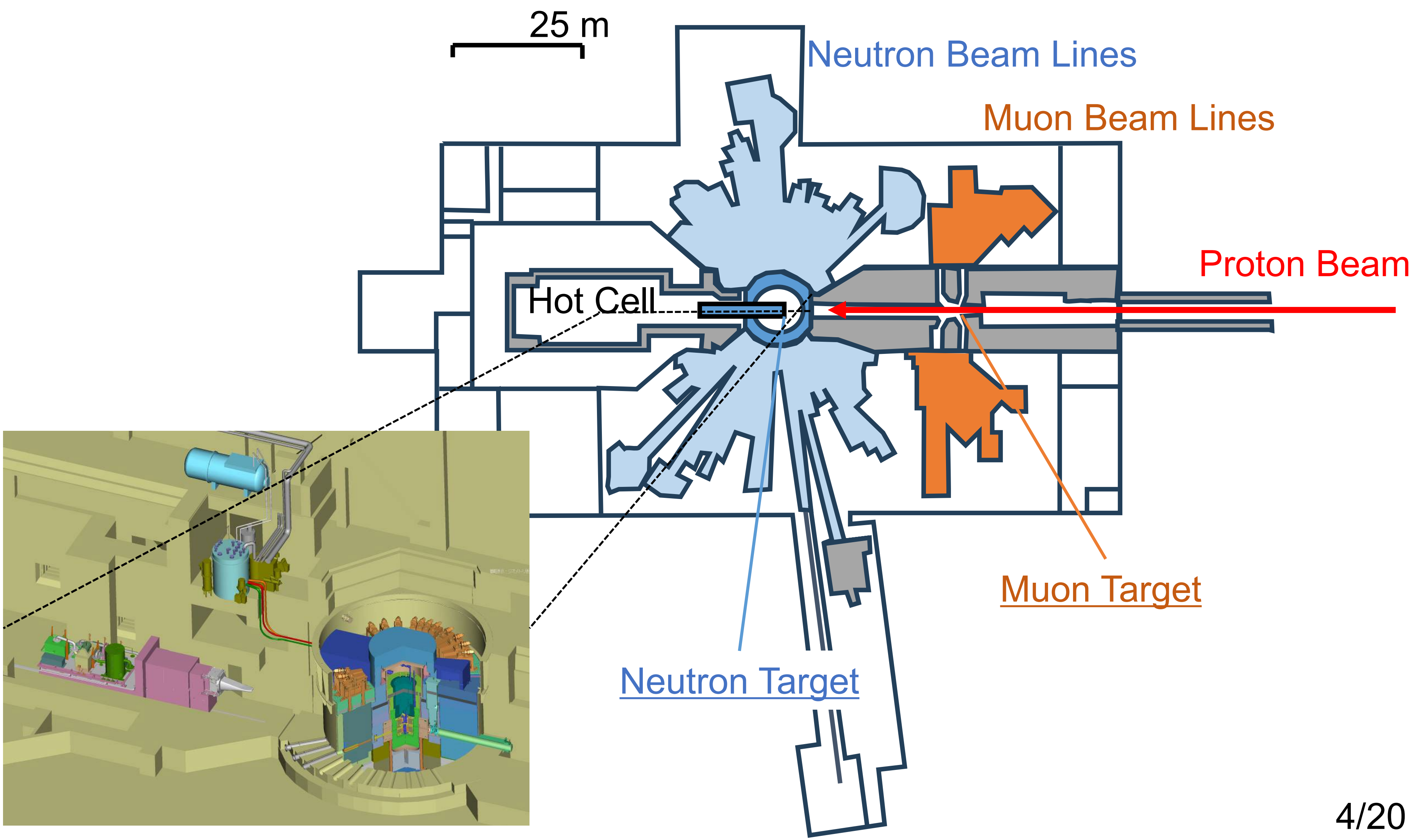
- Spallation Neutron Source using mercury
  - Materials and Life Science Experimental Facility (MLF) of J-PARC
- Mercury Target Vessel
  - Stainless Steel (SS)
  - Radiation and Pitting Damage
  - Periodical exchange work => Tritium release
- Behavior of tritium
  - Mercury => Stainless => Air

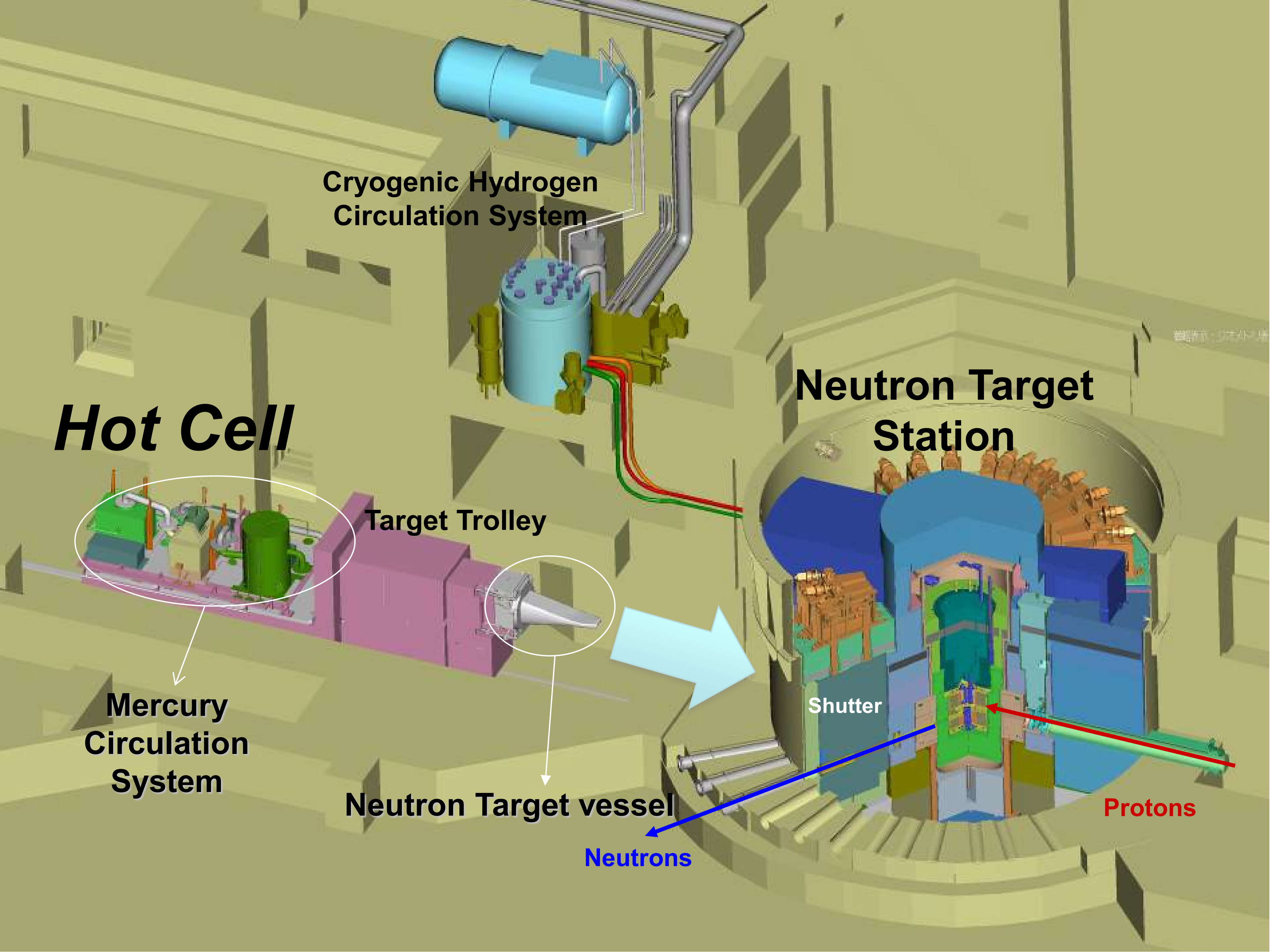


Layout of J-PARC



Materials & Life Science Experimental Facility (MLF)

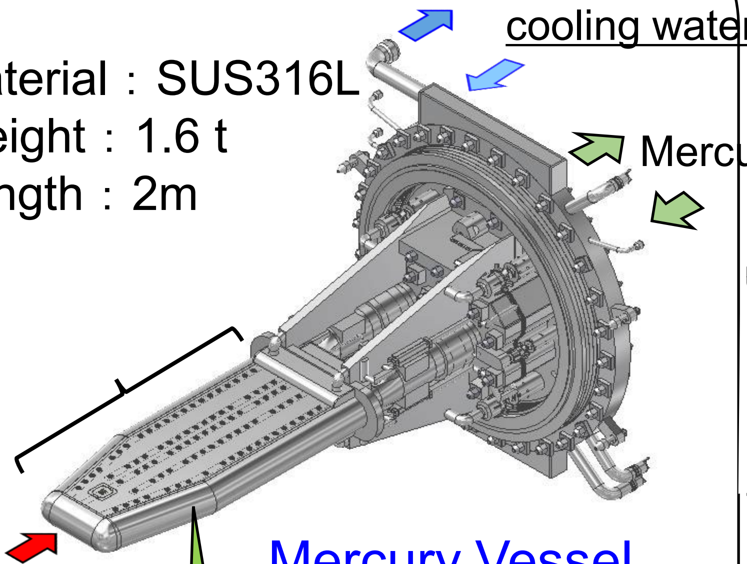



Cryogenic Hydrogen
Circulation System
Neutron Target
Station
Hot Cell
Target Trolley
Mercury
Circulation
System
Shutter
Neutron Target vessel
Protons
Neutrons

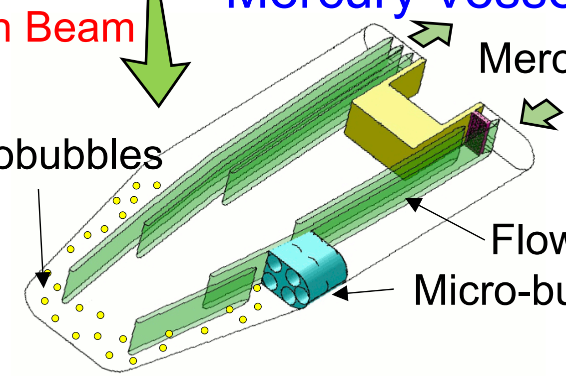
Outline of the Spallation Neutron Target

Neutron Target Vessel

Material : SUS316L
Weight : 1.6 t
Length : 2m



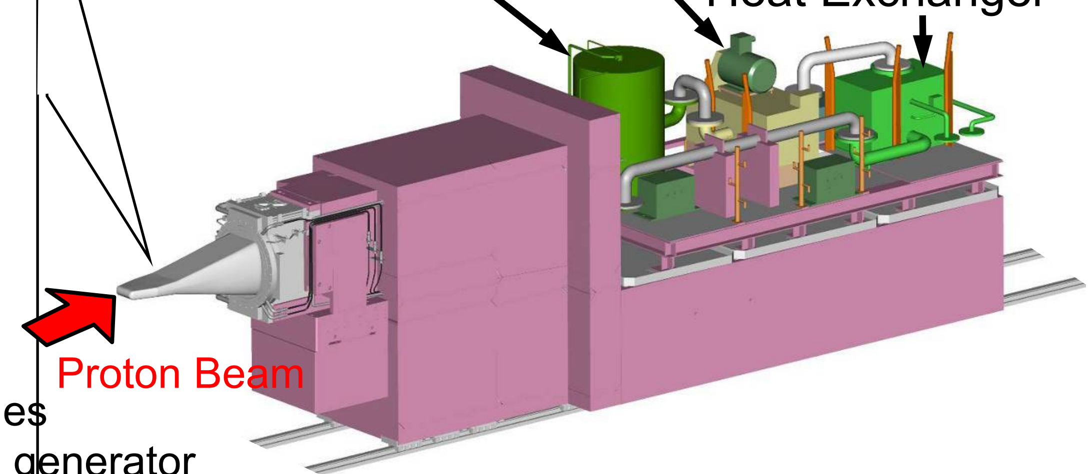
Mercury Vessel



*Mitigation of cavitation damage by microbubbles

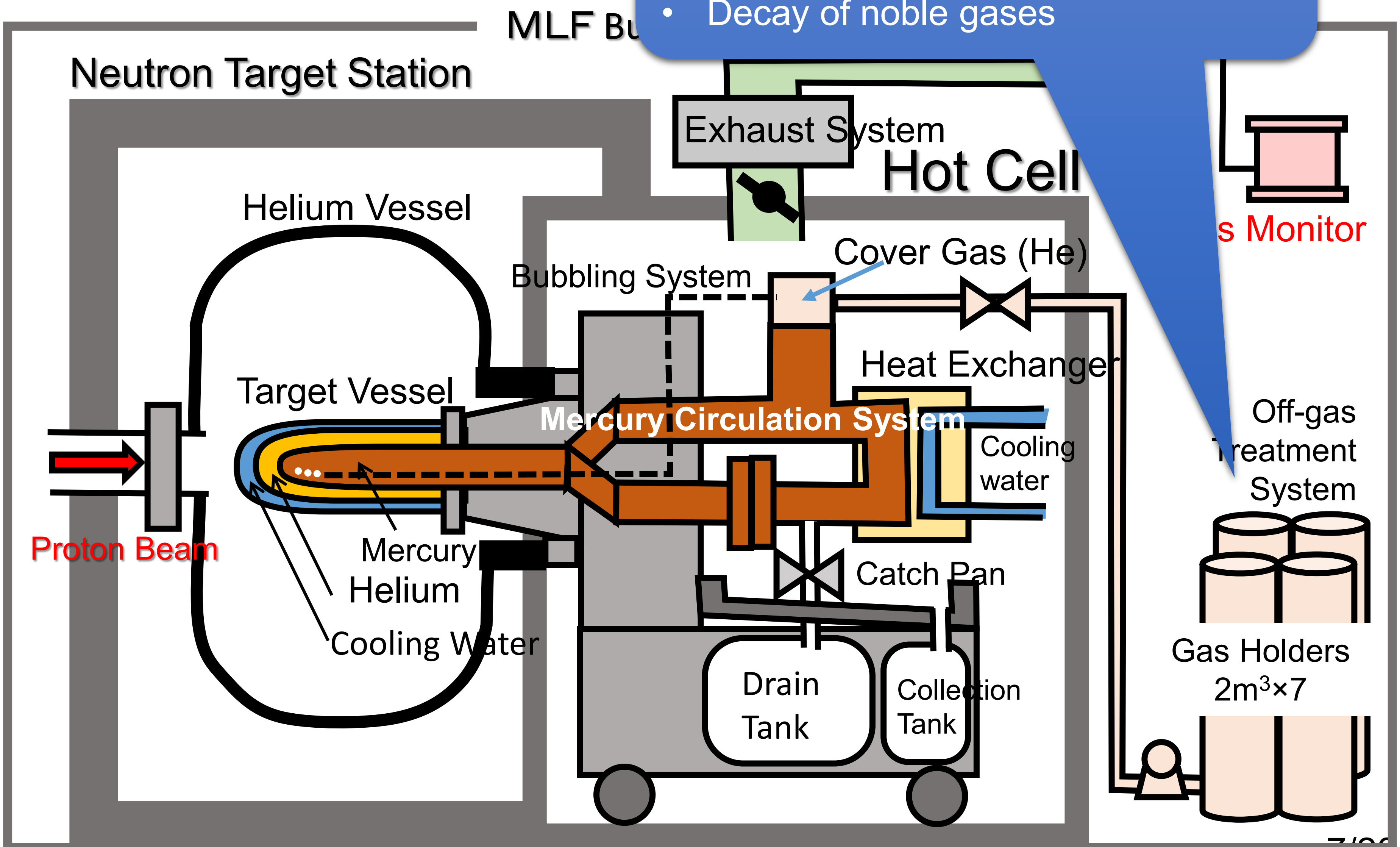
Length :	12 m
Weight :	315 ton
Mercury Volume :	1.5 m^3
Mercury Flow rate :	41m^3/hr

Mercury Circulation System



Concept of the R… Confinement

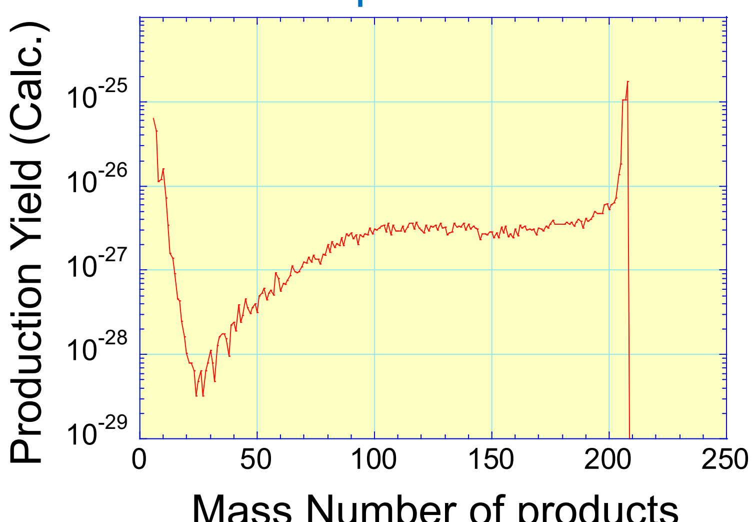
【Off-gas treatment System】
- Removal of mercury
- Removal of tritium
- Decay of noble gases

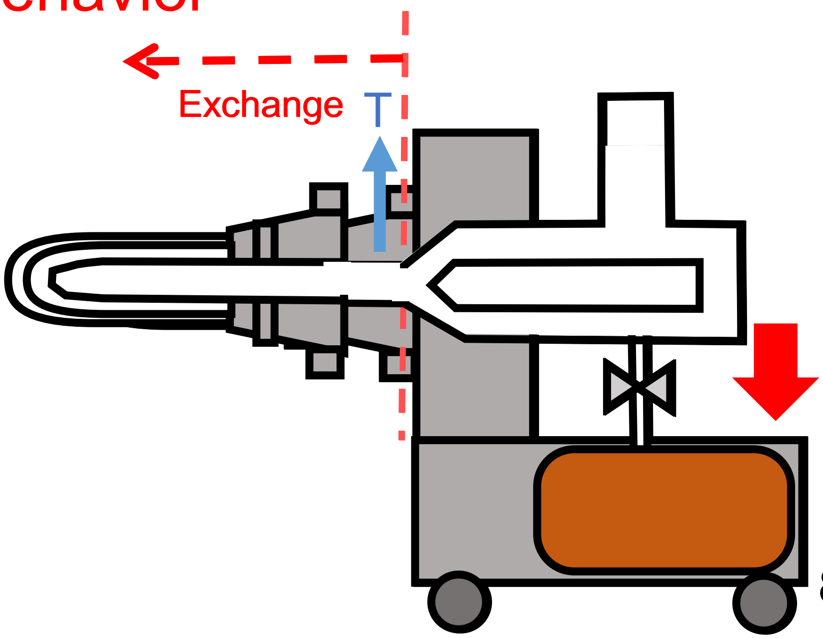


Why We need to Understand the Tritium Behavior?

- Various kinds of radioactive nuclides produced
- Tritium, : T(^{3}H)
  - ~10^{14}Bq for 1MW-1 year operation.
- Suppression of tritium release during the target exchange work
  - Need understanding the T behavior

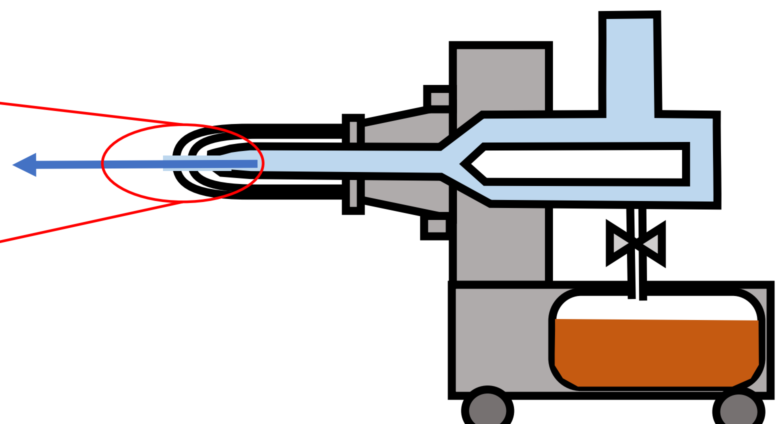
Mass Yield for spallation reactions





First observation of tritium release

- Tritium release from the target vessel was observed on the specimen cut on 2011 for the first time.
  - *Presented on the previous J-PARC Symposium in 2019.*
  - It was shown that the release behavior could be explained as diffusion from the stainless steel.
    - Comparing the observed tritium concentration to the simplified physical model in which an exact solution of a one-dimensional diffusion equation can be applied.
  - The chemical form of the released tritium was HTO
    - Isotope Exchange: $T + H_2O \rightarrow H + HTO$

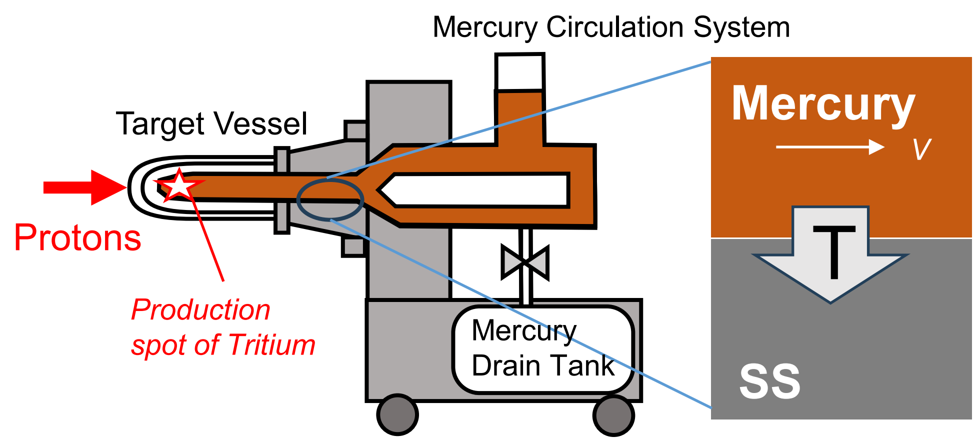


Outline of this work

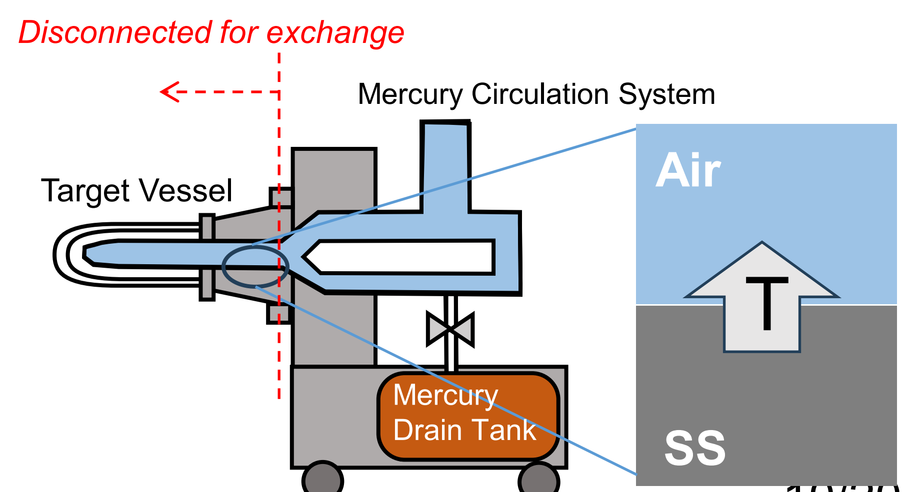
- In this work, a new physical model has been developed to evaluate the averaged behavior of tritium by assuming the whole surface between mercury and the stainless steel as one physical system.
- The evaluations are performed through whole process from (1)Absorption to (2)Release by solving the one-dimensional diffusion equation numerically.

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2}$$

(1) Absorption Process (Beam-Operation Period)



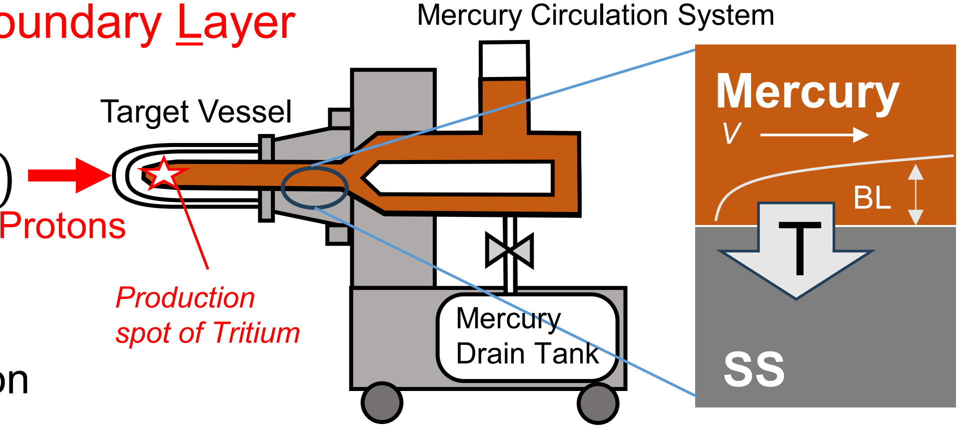
(2) Release Process (Maintenance Period)



(1) Absorption Process

- Tritium concentration in mercury is calculated supposing as
  - Homogeneous distribution in mercury
  - Gradient of the concertation in the Boundary Layer
  - $V \frac{dC_T(t)}{dt} = a_T - \alpha S C_T(t)$

    $\rightarrow \quad C_T(t) = \frac{a_T}{\alpha S}\left(1 - e^{-\frac{\alpha S}{V}t}\right)$
    - $C_T(t)$: Tritium concentration in mercury
    - a_T: Production rate of tritium
    - t: Time from start of the beam operation
    - V: Volume of mercury (=1.5 m^3),
    - S: Effective area of SS (=10 m^2)
    - α : Mass transfer coefficients of tritium from mercury to SS



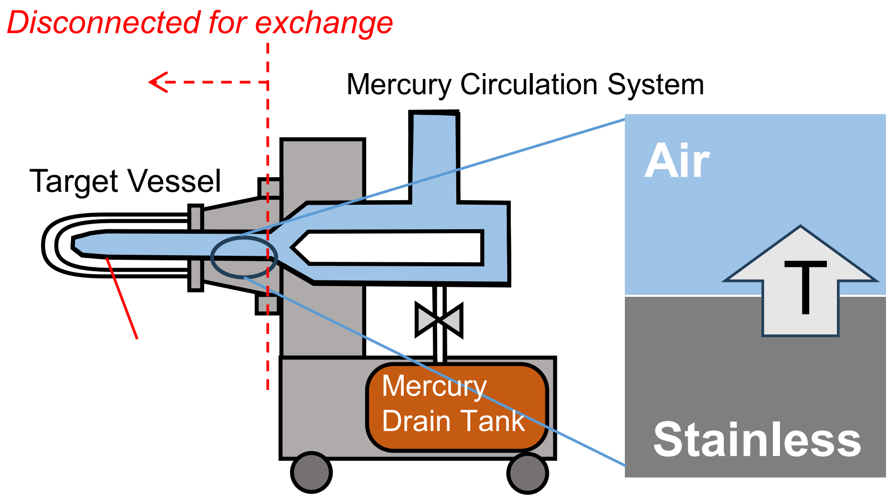
$$\frac{\ln 2}{\left(\frac{\alpha S}{V}\right)} \sim 2{,}000 \text{ sec}$$

- Tritium diffuses into SS in accordance with the diffusion equation
  - Diffusion coefficients: D =1.2 × 10^{-10} cm^2/s (80 ºC)
  - Duration of the beam operation: 5,000 hours(~208 days)

$$\frac{\partial C(x,t)}{\partial t} = D \frac{\partial^2 C(x,t)}{\partial x^2} \Rightarrow \frac{C(x,t+\Delta t) - C(x,t)}{\Delta t} = D \frac{C(x+\Delta x,t) - 2C(x,t) + C(x-\Delta x,t)}{\Delta x^2}$$

(2) Release Process

- Using the depth distribution at the end of the beam operation in SS as initial condition.
- The tritium release rate is calculated by assuming that tritium which reaches at the SS surface is released to air.
- $D = 6.7 \times 10^{-12}$ cm^2/s (30 ºC)



$$\frac{\partial C(x,t)}{\partial t} = D\,\frac{\partial^2 C(x,t)}{\partial x^2} \Rightarrow \frac{C(x,t+\Delta t) - C(x,t)}{\Delta t} = D\,\frac{C(x+\Delta x,t) - 2C(x,t) + C(x-\Delta x,t)}{\Delta x^2}$$

Evaluation of Diffusion Coefficient (Tritium in Stainless Steel)

F. Reiter, K. S. Forcey and G. Gervasini: EUR15217 EN (1993)

$$D\,[\mathrm{m^2/s}] = 5.9 \times 10^{-7}\, e^{-\frac{51.9\times10^{3}}{RT}}$$

T: Temperature[K], *R*: Gas Constant(=8.314 J/K)

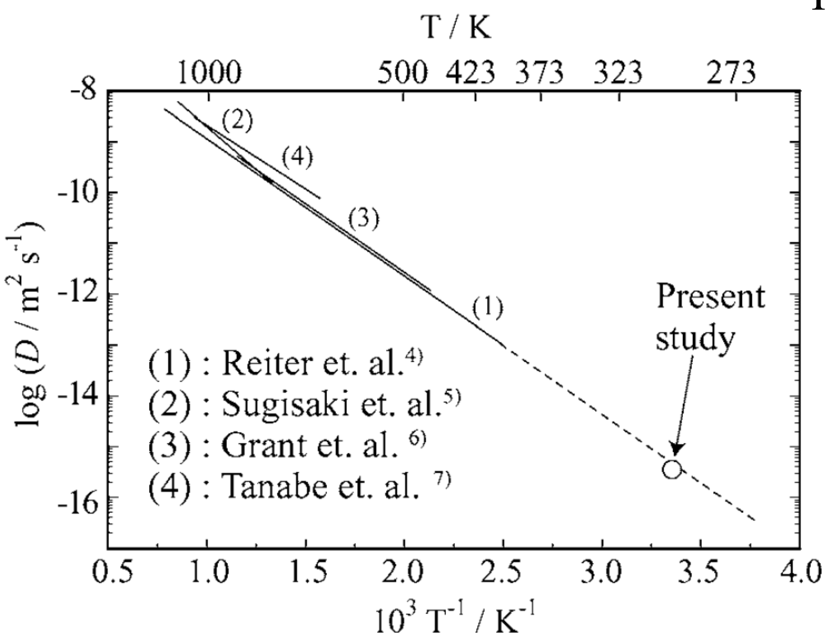


Fig. 5 Comparison of the diffusion coefficients appeared in the literatures with that determined from the chronic tritium release rates at 298 K for series C (○).

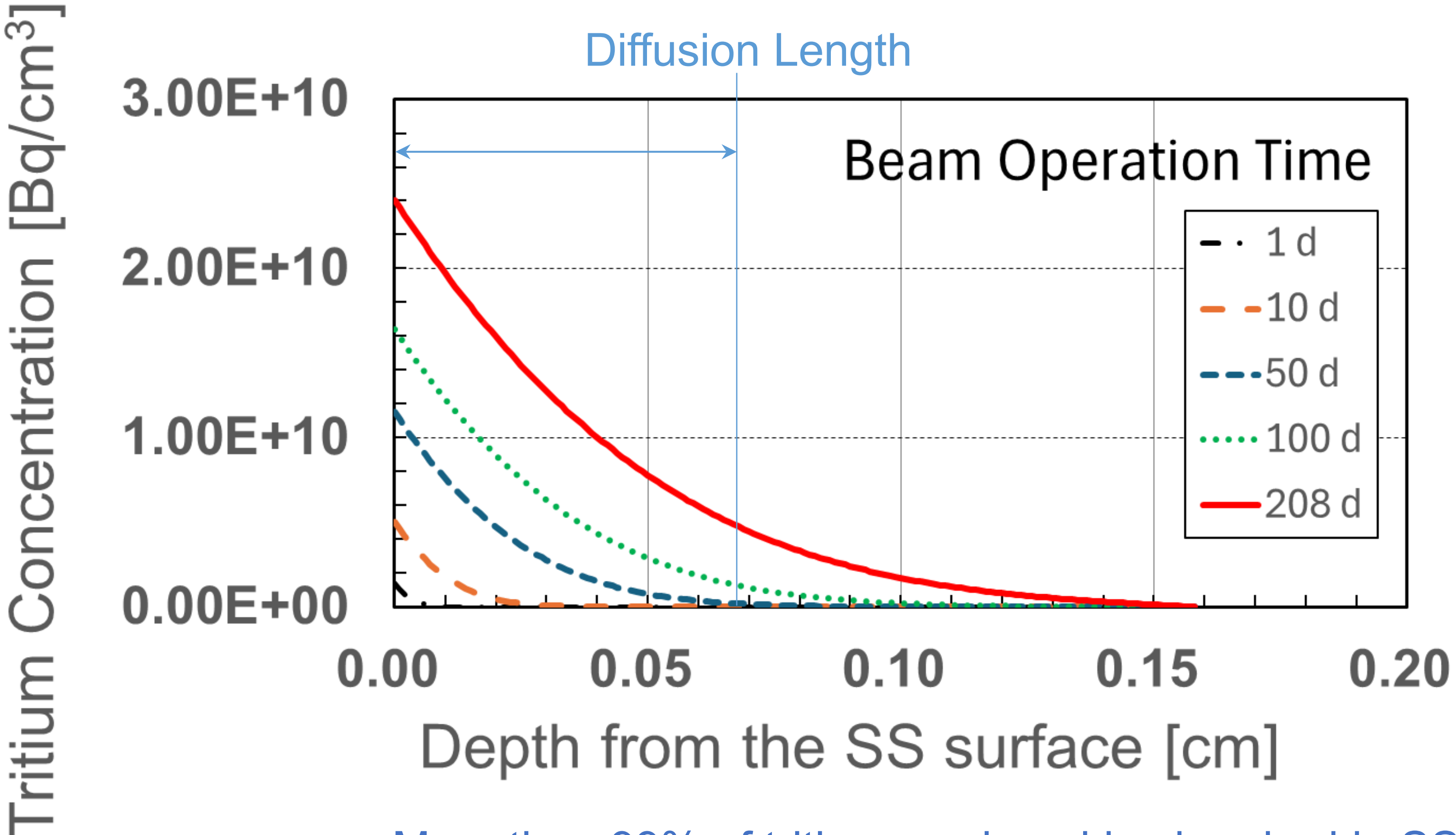
Y. Torikai et al., "Chronic Release of Tritium from Stainless Steel 316", Proceeding of 47th Annual Symposium of the Vacuum Society of Japan (2007)

Period	Temperature	D [cm^2/s]
Beam Operation	80 °C (353 K)	1.2×10^{-10}
Maintenance	30 °C (303 K)	6.7×10^{-12}

Result (1) Absorption Process

Depth distribution of concentration

$$\text{Diffusion Length} = \sqrt{2Dt} = \sqrt{2 \times 1.23 \times 10^{-10}\ \text{cm}^2/\text{s} \times 5000\ \text{h}} = 0.067\ \text{cm}$$

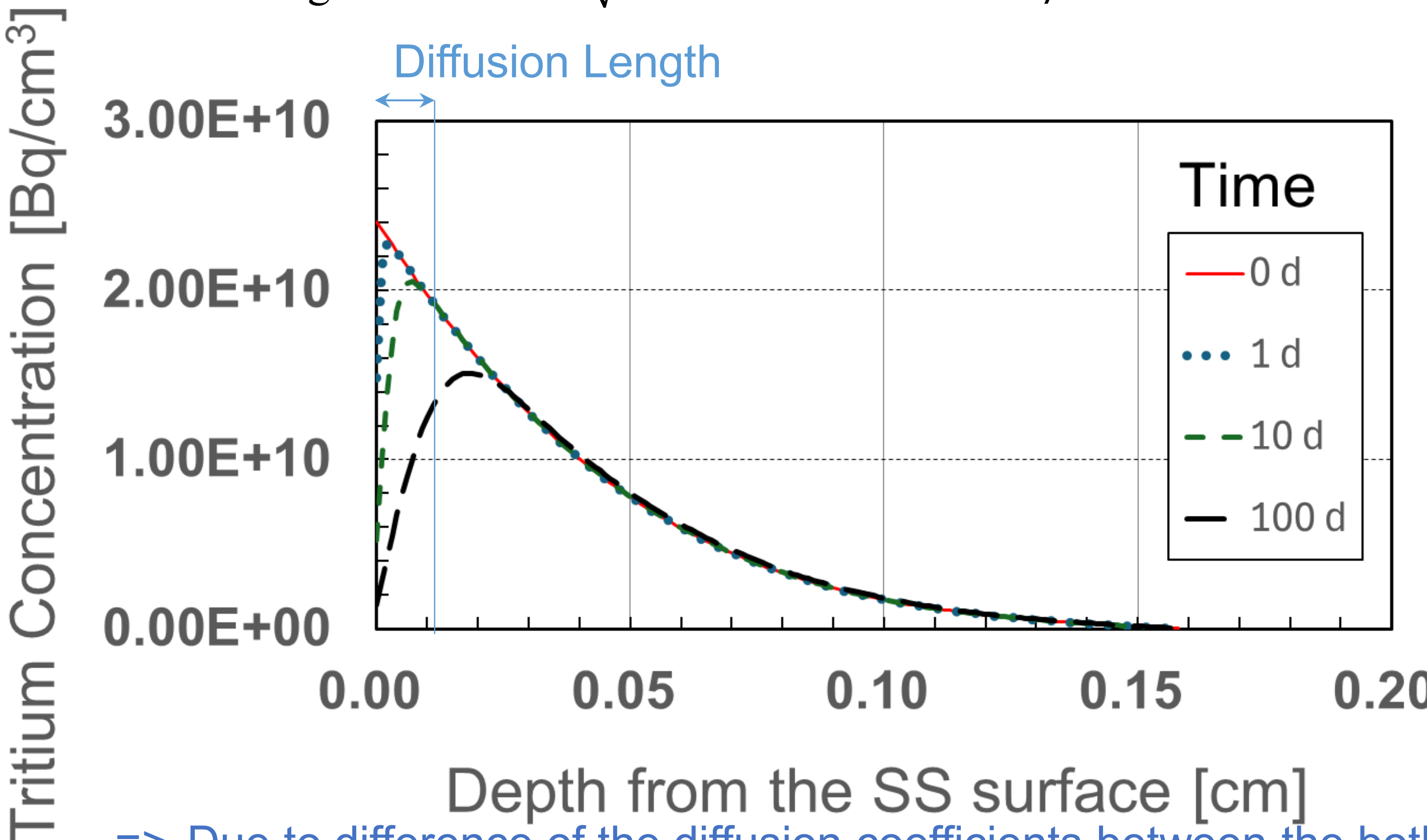


=> More than 99% of tritium produced is absorbed in SS.

Result (2)-1 Release Process

Depth distribution of concentration

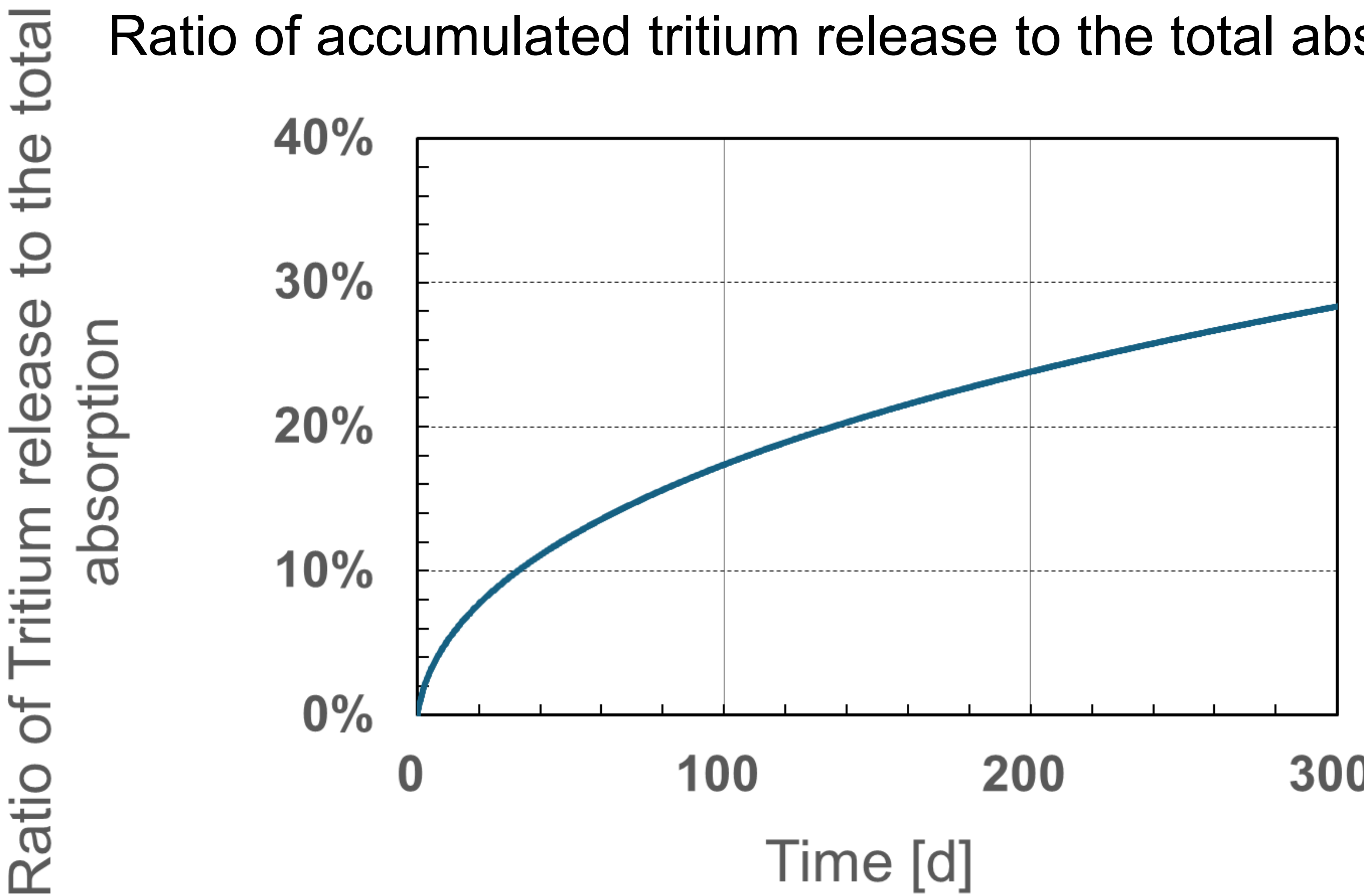
$$\text{Diffusion Length} = \sqrt{2Dt} = \sqrt{2 \times 6.66 \times 10^{-12}\ \text{cm}^2/\text{s} \times 100\ \text{d}} = 0.011\ \text{cm}$$



=> Due to difference of the diffusion coefficients between the both processes, coming from difference of the temperatures, only a part of the whole amounts of absorbed tritium can release.

Result (2)-2 Release Process

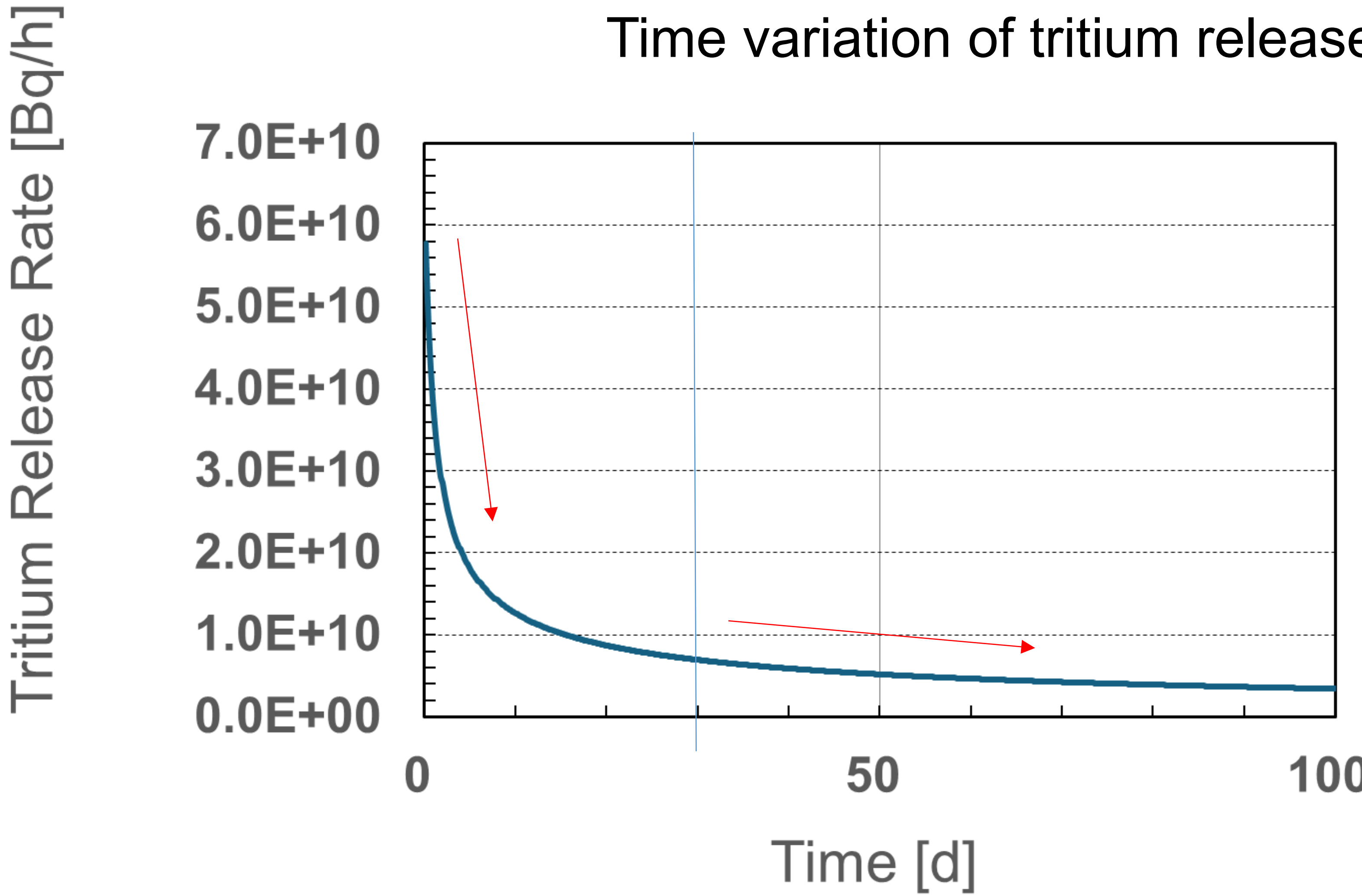
Ratio of accumulated tritium release to the total absorption



=> Only 30% of tritium can be released for about 1 year.

Result (2)-3 Release Process

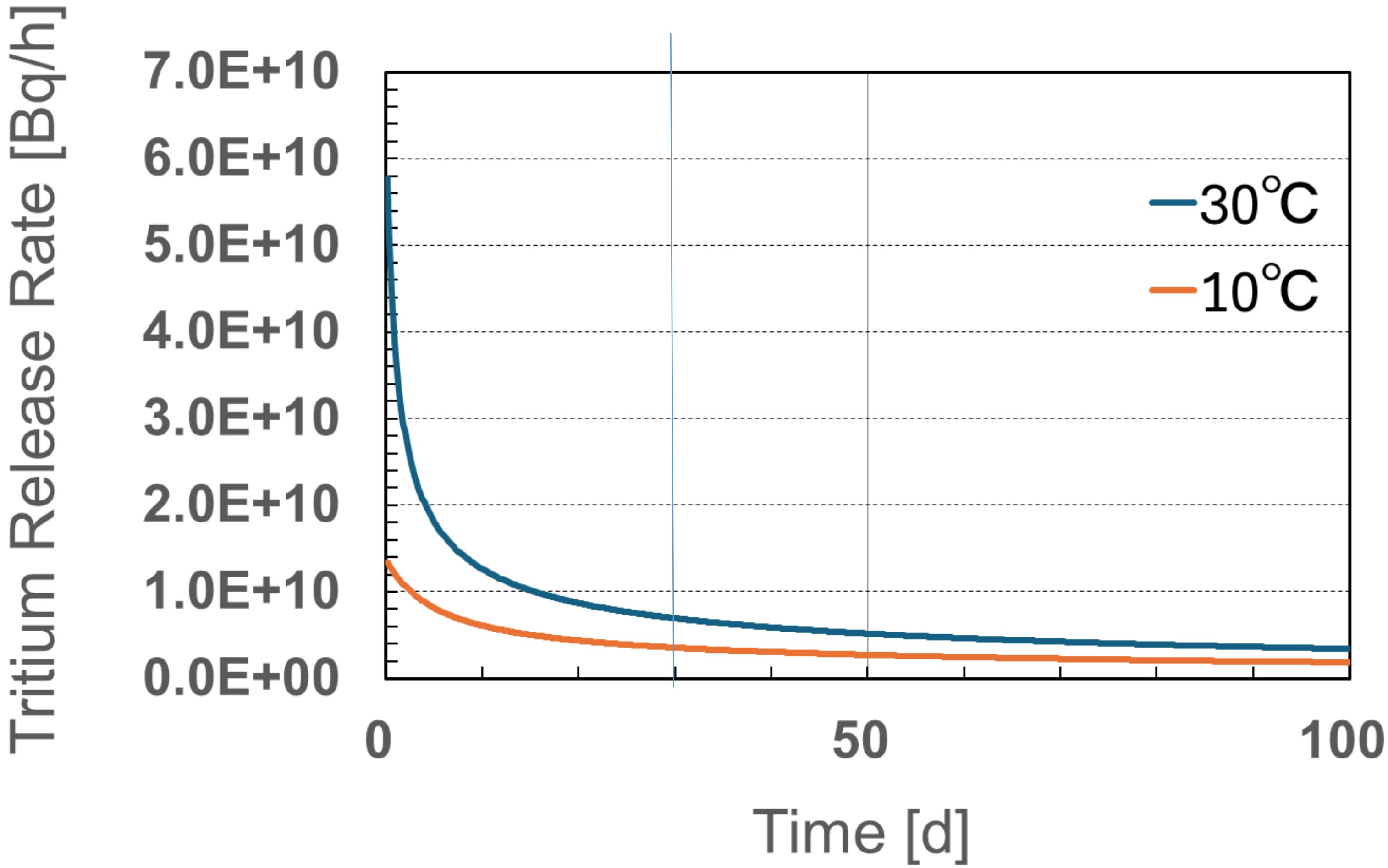
Time variation of tritium release rate



=> Even after 30 days, tritium with rate of 7×10^{9} Bq/h (more than 10^{11} Bq/d) can be continuously released.

Result (2)-4 Release Process

Time variation of tritium release rate



=> If the system temperature can be kept at 10ºC, the release rate after 30 days decrease by 50% in comparison with that at 30ºC.

Future Development

This Work: Evaluated the averaged behavior by assuming the whole surface of the stainless steel as one physical system.

In the Future: Consider tritium movement in mercury using fluid dynamics

=> Evaluate the absorption and release behaviors on stainless steel (SS) in each part separately.

This Work: All tritium that reaches the SS surface by diffusion during the release process is directly released into the air

In the Future: Consider chemical effect of air humidity (water molecules)

[Reference] In the presence of a small amount of oxide layer or in the presence of water vapor of several hundred ppm, almost all of the tritium releases in the form of water (HTO)" ←T. Yamanishi et al., Plasma Fusion Res. Vol.85, No.10 (2009)716-725

In the Future: Comparing the calculation to the actual system

=> Adjust the parameters required for the calculation

=> Precise Evaluation of tritium behavior for more complicated situation.

Summary

- The tritium behavior in the spallation neutron target system with mercury was evaluated using a new physical model.
  - The evaluations are performed through whole process from absorption to release by solving the one-dimensional diffusion equation numerically.
  - The temperature effect for the tritium release rates were shown numerically.
- By developing the model further based on this one, it is expected that tritium behavior can be evaluated more precisely even in a system which is more complicated.