Studies on bi-directional hydrogen isotopes permeation through the first wall of a magnetic fusion power reactor

IAEA-CRP
Plasma-Wall Interaction with Reduced Activation Steel Surfaces in Fusion Devices
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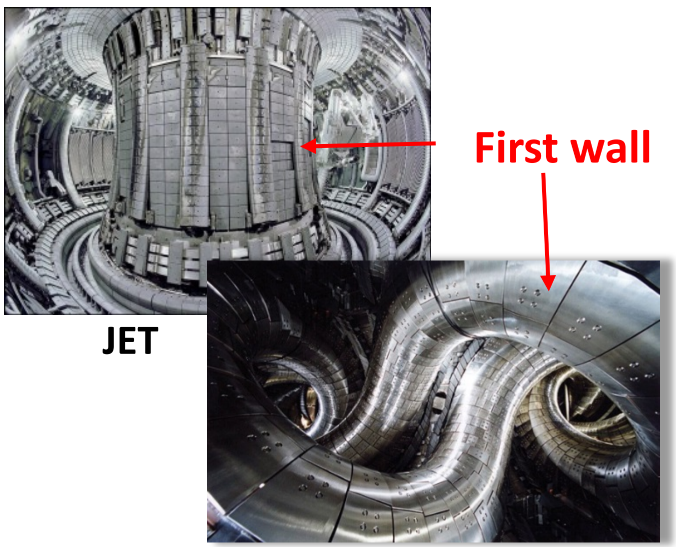
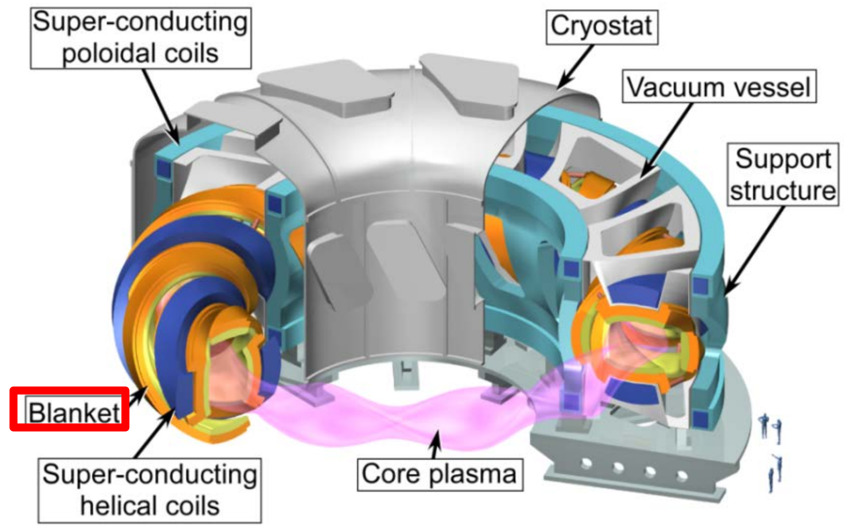
Background (1)

- **Definition of the first wall:**
  - ✓ **All the fusion experimental devices up to ITER: the first wall is a vacuum chamber wall to separate plasma from the environment.**
  - ✓ **Power reactors: the first wall is the plasma-facing surfaces of breeding blanket units.**



The first walls of existing fusion devices.



FFHR reactor

A. Sagara et al,. research report, NIFS-MEMO-64 (2013).

Background (2)

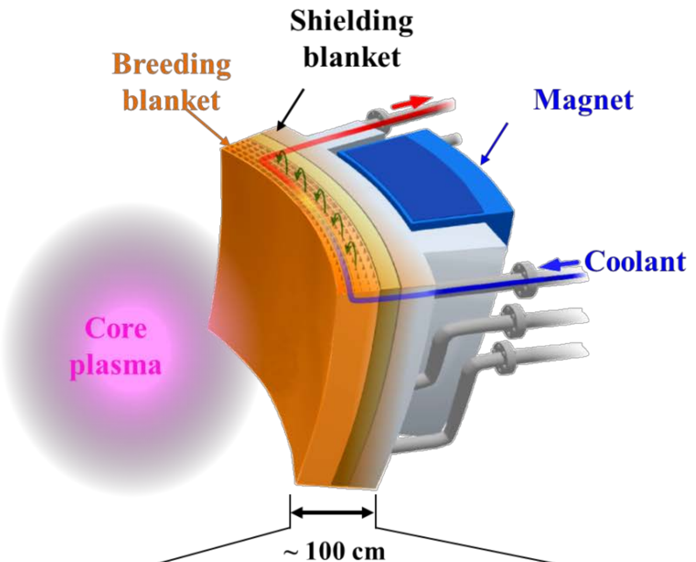
- **Blanket concepts include:**

  water-cooled solid breeder (e.g. Li_2TiO_3),

  He-cooled solid breeder (e.g. Li_4SiO_4),

  self-cooled liquid breeder (e.g. FLiBe),

  water-cooled liquid breeder (e.g. Li-Pb)…



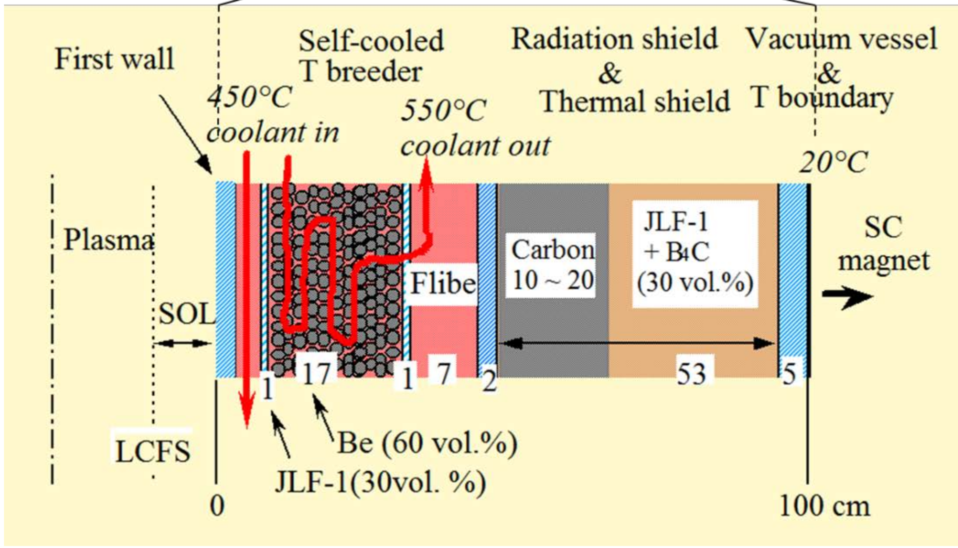
- **Typical of the first wall of a fusion power reactor are:**

I. Large surface area: ~10^3 m^2;

II. Made of reduced activation materials;

III. High temperature operation, e.g. ~500°C for ferritic steel alloys;

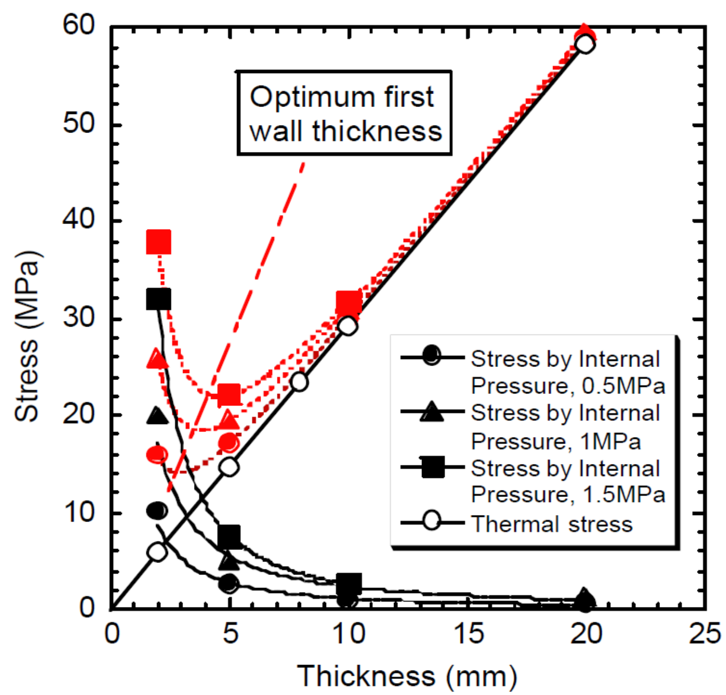
IV. Thin wall design to reduce thermo-mechanical stress.



A. Sagara et al., J. Nucl. Mater. 258-263 (1998) 2079-2082.

Background (3)

In most of the recent reactor studies, the first wall is designed to be 5 mm or even less, although these concepts employ various first wall materials.

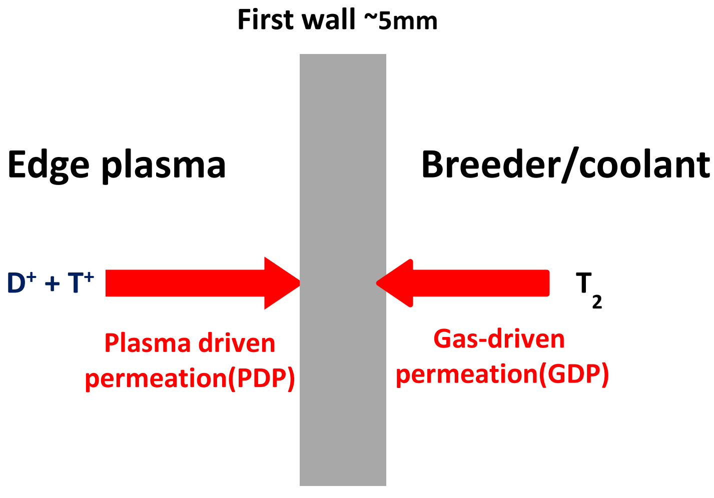


Thickness optimization [2]

[2] A. Sagara et al., Fusion Technol. 39(2001)753-757.

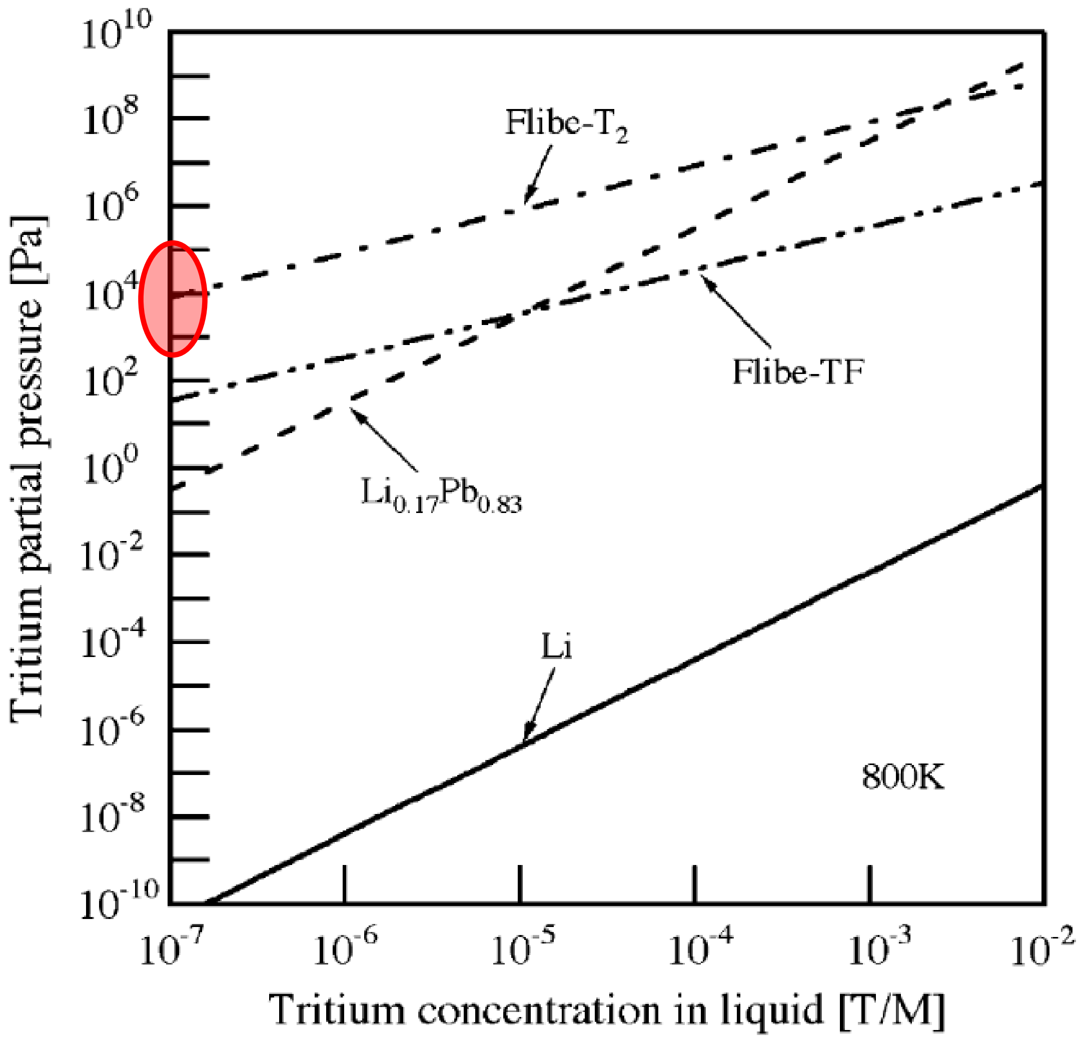
Y. Ueda et al. J. Nucl. Mater. 313-316(2003)32-41.

Potential Issues with the “thin” wall design



Potential issues, but not quite well addressed, with the “thin” wall design are:

Tritium equilibrium pressures in breeders



Solubility of gases in metals (Sieverts' law):

$$C_{\mathrm{T\ in\ wall}} = S(T) \cdot \sqrt{p_{\mathrm{T}_2}}$$

Assuming 0.1 ppm, the total tritium inventory is of the order of 10 g in the FLiBe blanket.

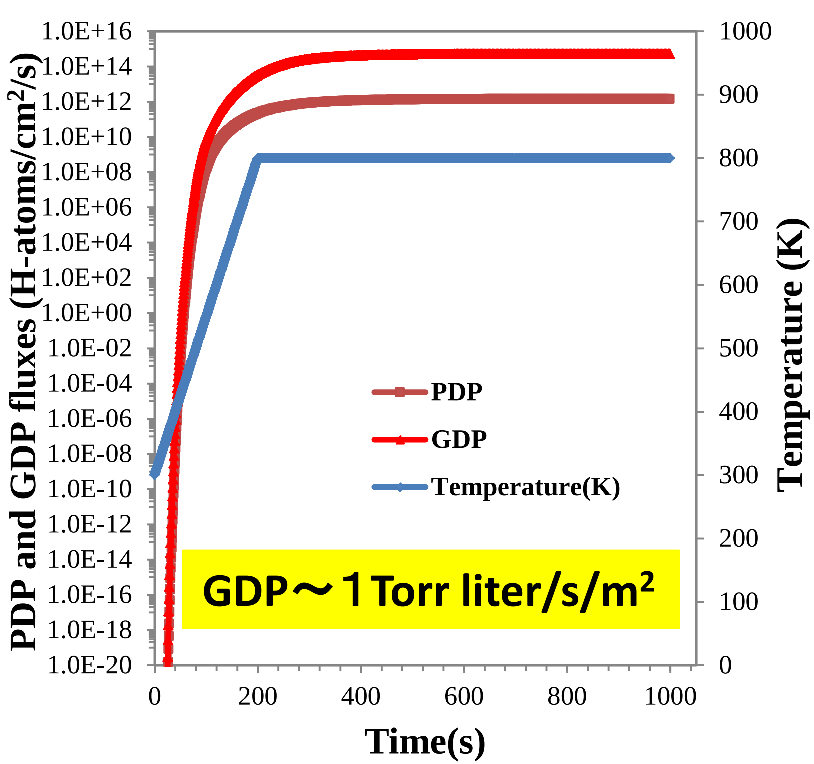
For blanket employing FLiBe, the tritium thermodynamic equilibrium pressure is ~10^4 Pa at 527 °C at a tritium concentration of ~0.1 ppm.

S. Fukada, Y. Edao, Y. Maeda and T. Norimatsu, Fusion Eng. Des. 83, 747 (2008).

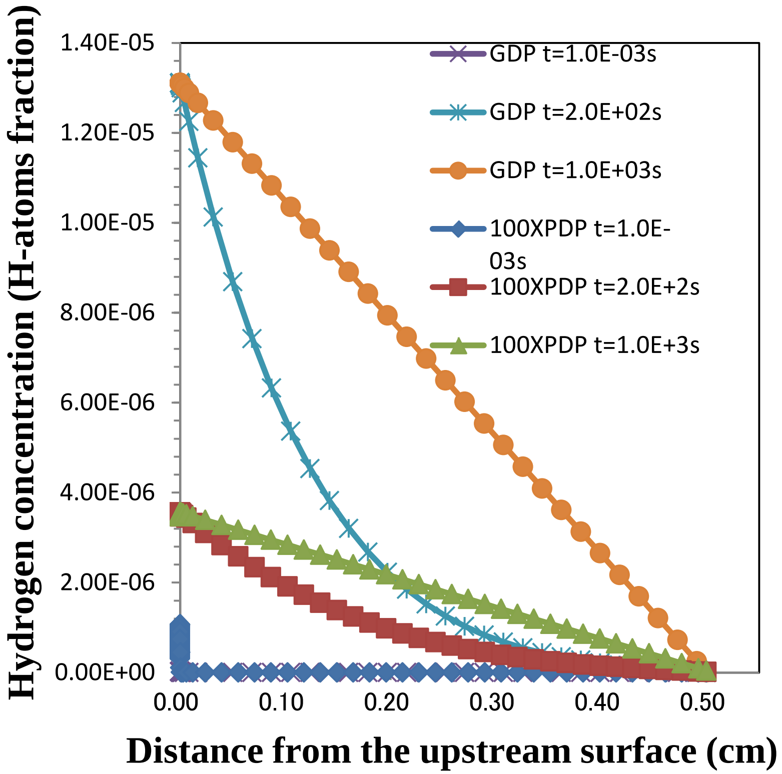
DIFFUSE-code predictions on FLiBe-blankets

(PDP: 100eV, e16 H^+/cm^2→5㎜α-Fe, GDP: 10^4Pa H_2→5㎜α-Fe at 300→800K)

Permeation fluxes

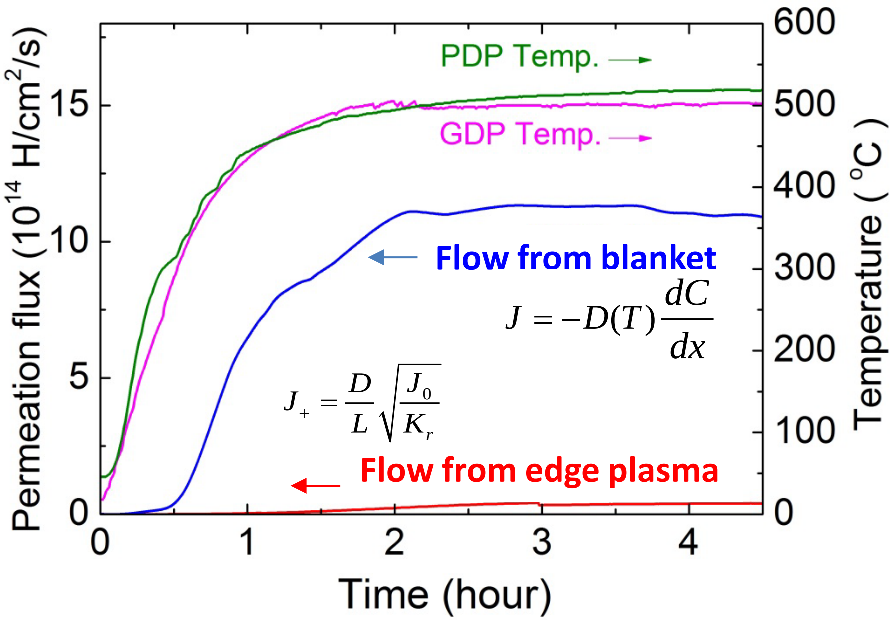


Concentration profiles



F82H: Hydrogen PDP and GDP fluxes

Hydrogen PDP and GDP fluxes measured in VEHICLE-1 for a **5 mm** thick F82H membrane (under the FLiBe-blanket conditions)



Membrane temperature	~500 °C
Net Implantation flux for PDP	2.0×10^{16} $H\cdot cm^{-2}\cdot s^{-1}$ (-100 V bias)
H_2 driving pressure for GDP	~10^4 Pa(Fukada) (Thermodynamic equilibrium data)

- Hydrogen transport in the first wall is dominated by the flow from the blanket.
- Using the experimental data, the hydrogen recycling rate has been estimated to be R= 1.025.

Evaluation of bi-directional permeation

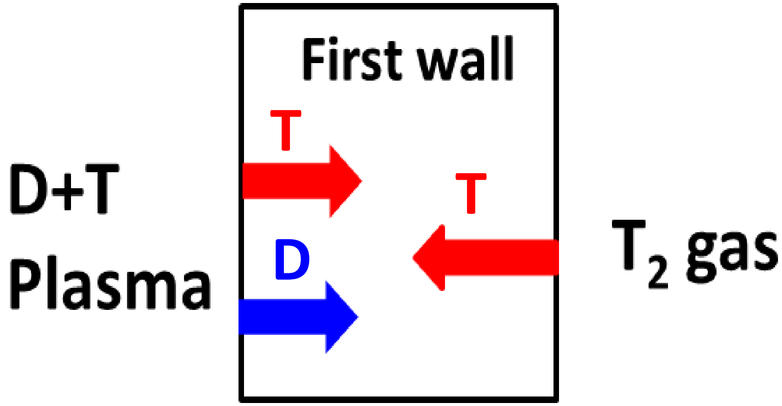
Conditions for DIFFUSE calculation:

- T_2 pressure: 1 ×10^4 Pa (Fukada)
- Implantation flux assumptions:

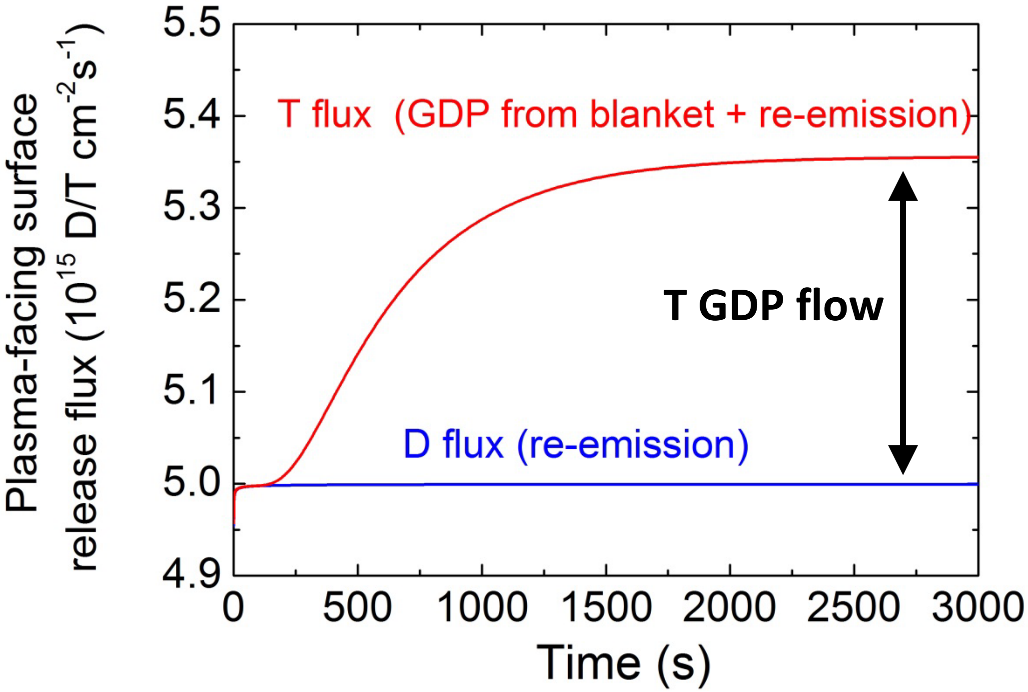
  $\Gamma_D = 5\times10^{15}$ D·cm^{-2}·s^{-1}

  $\Gamma_T = 5\times10^{15}$ T·cm^{-2}·s^{-1}

- Membrane: 5 mm thick α-Fe
- Temperature: 550°C



D/T release fluxes at the plasma-facing surface



The tritium release flux at the plasma-facing surface is a total flux from GDP and re-emission.

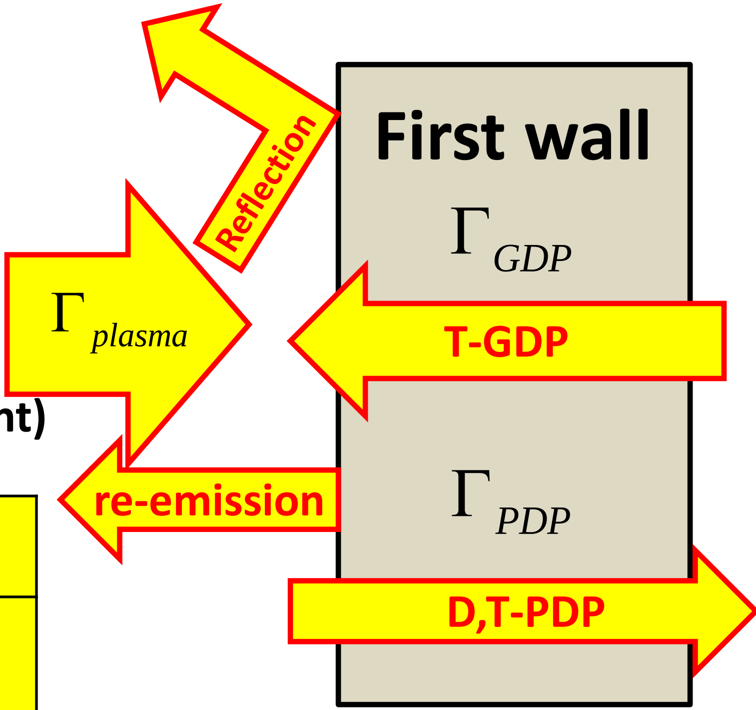
PDP and GDP under reactor-relevant conditions

PDP and GDP through a **5 mm** thick F82H membrane (FLiBe-blanket conditions)

Hydrogen recycling coefficient:

$$R = \frac{\Gamma_{reflection} + \Gamma_{re-emission} + \Gamma_{T-GDP}}{\Gamma_{plasma}}$$

$\Gamma_{\mathrm{reflection}} = \gamma\, \Gamma_{\mathrm{plasma}}$ (γ is the particle reflection coefficient)



Membrane temperature	550 °C
Net Implantation total flux for PDP	1×10^{16} (2×10^{16}) $DT\cdot cm^{-2}\cdot s^{-1}$
T_2 driving pressure for GDP	10^4 Pa (Fukada) (Thermodynamic equilibrium data)

Assuming a particle reflection coefficient of 0.5, the total incident flux is 2×10^{16} $D\&T\cdot cm^{-2}\cdot s^{-1}$ and the first wall recycling rate has been estimated to be **R= 1.018**.

Motivation

Potential issues associated with bi-directional DT permeation:

- **PDP–D lowers the recovery efficiency of T from the breeder.**
- **Gas-T permeation increases recycling on the first wall side.**

What is necessary to address the bi-directional hydrogen permeation and its associated reactor operation issues?

- **Understandings of hydrogen PDP and GDP individually in detail;**
- **Evaluation of the tritium equilibrium pressure in the fuel recovery loop system;**
- **Determination of missing hydrogen isotopes transport parameters (solubility, diffusivity and surface recombination coefficient).**

  No literature data available for the surface recombination coefficient (for F82H), which is important for recycling and retention.

Objectives

I. To understand the mechanisms driving hydrogen isotopes transport processes.

II. To demonstrate experimentally hydrogen transport phenomena that are predicted for the first wall of a fusion power reactor.

III. To establish a database on hydrogen transport parameters for designing fusion power reactors.

2. Experimental facility and setup

Experimental facility

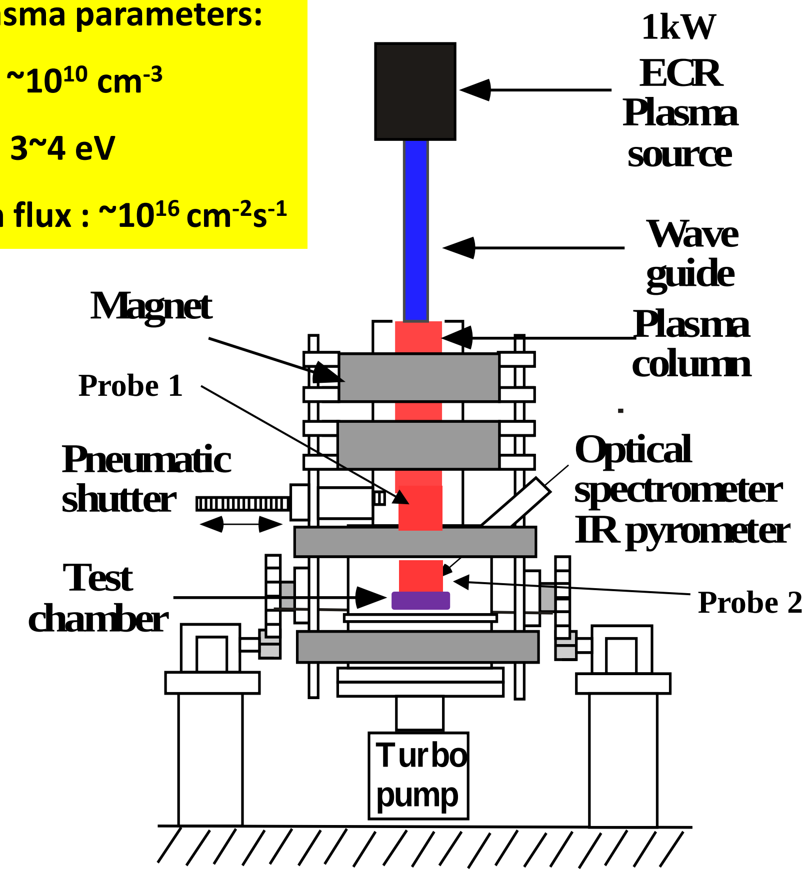
VEHICLE-1

Plasma parameters:

n_e: ~10^{10} cm^{-3}

T_e: 3~4 eV

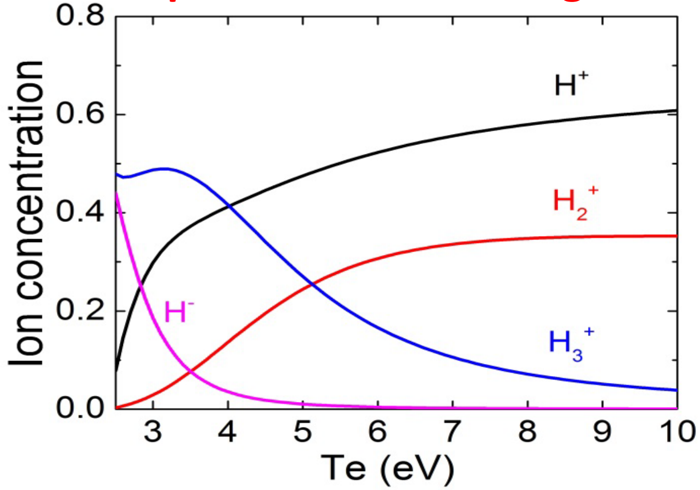
Ion flux : ~10^{16} $cm^{-2}s^{-1}$

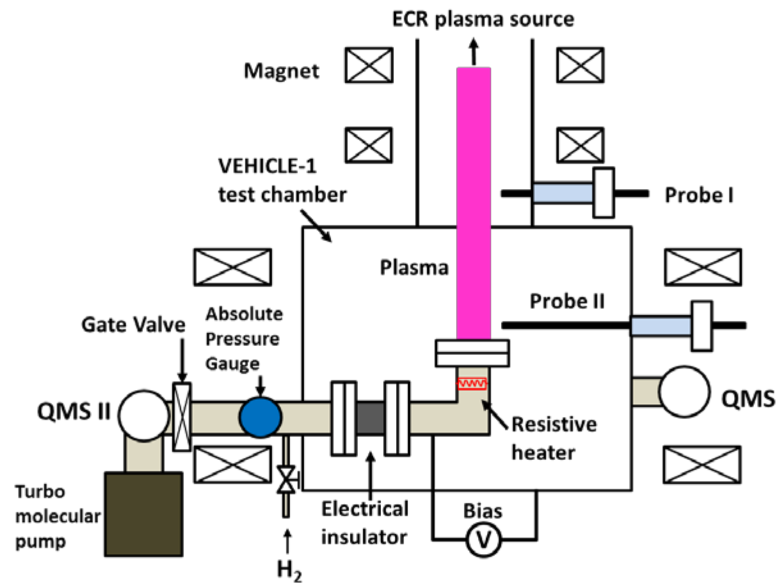


Y. Hirooka et al., J. Nucl. Mater. 337-339(2005)585-589.

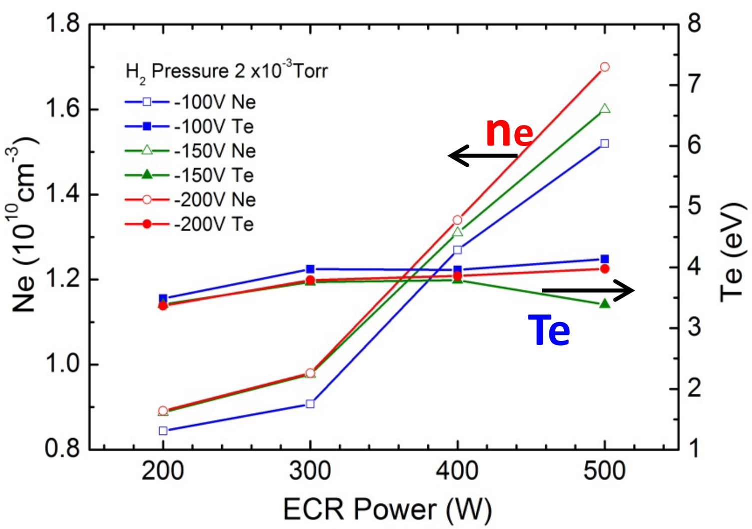
Plasma characteristics in VEHICLE-1

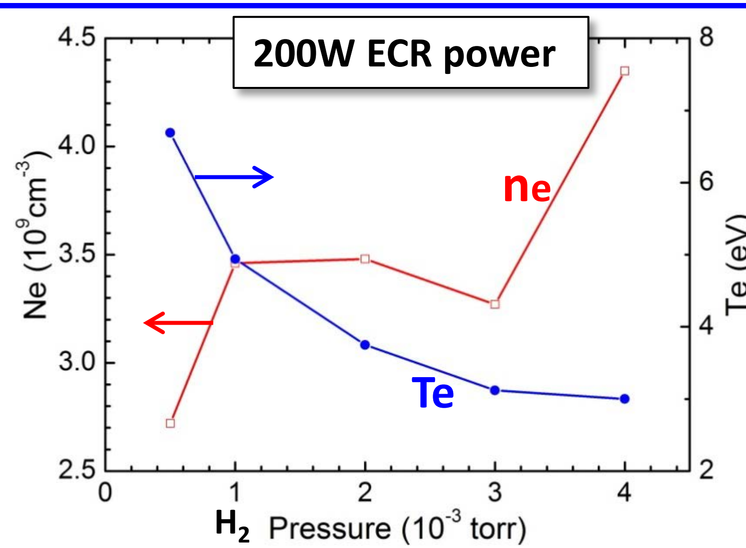
Species mix modelling





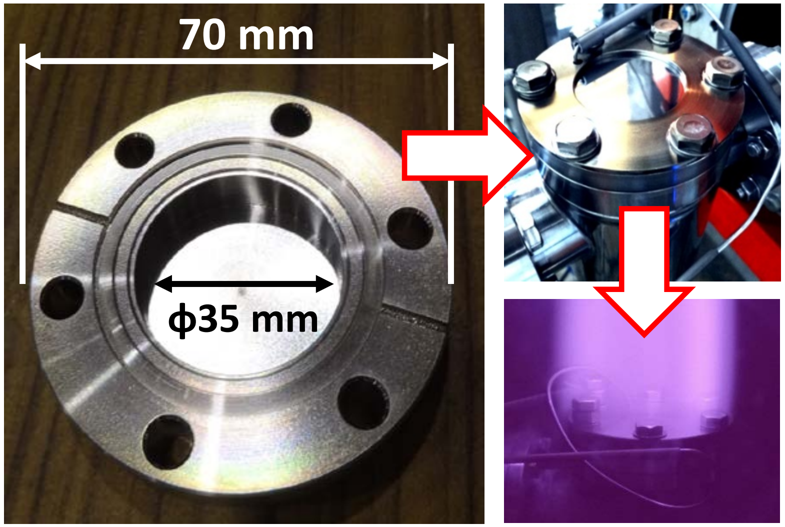
Langmuir Probe data





Experimental setup

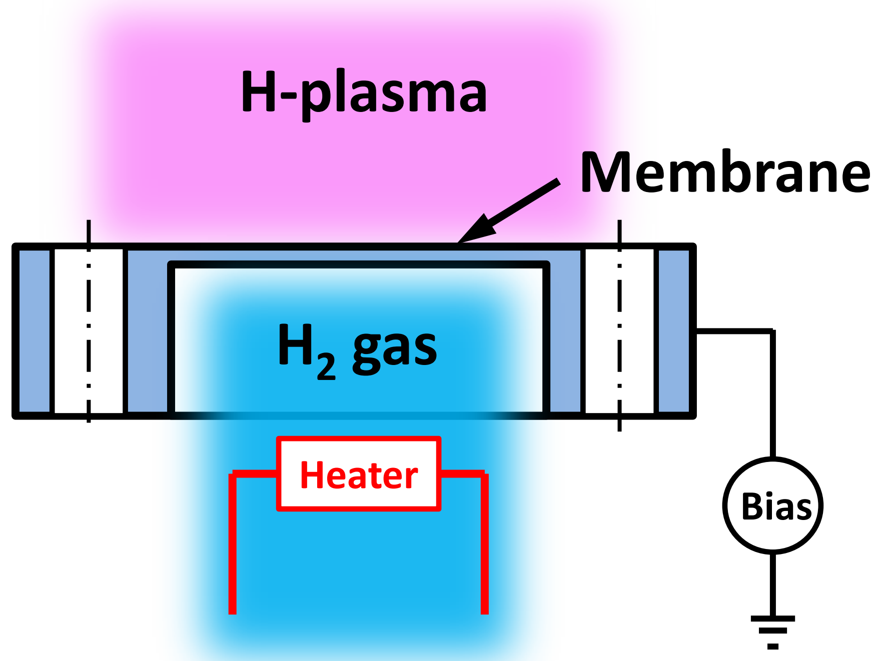
Permeation membrane sample



Thickness: 0.5-5.0 mm
Diameter: 35 mm

Materials:

- F82H (Fe-8Cr-2W)
- SUS304 (Fe-19Cr-11Ni)

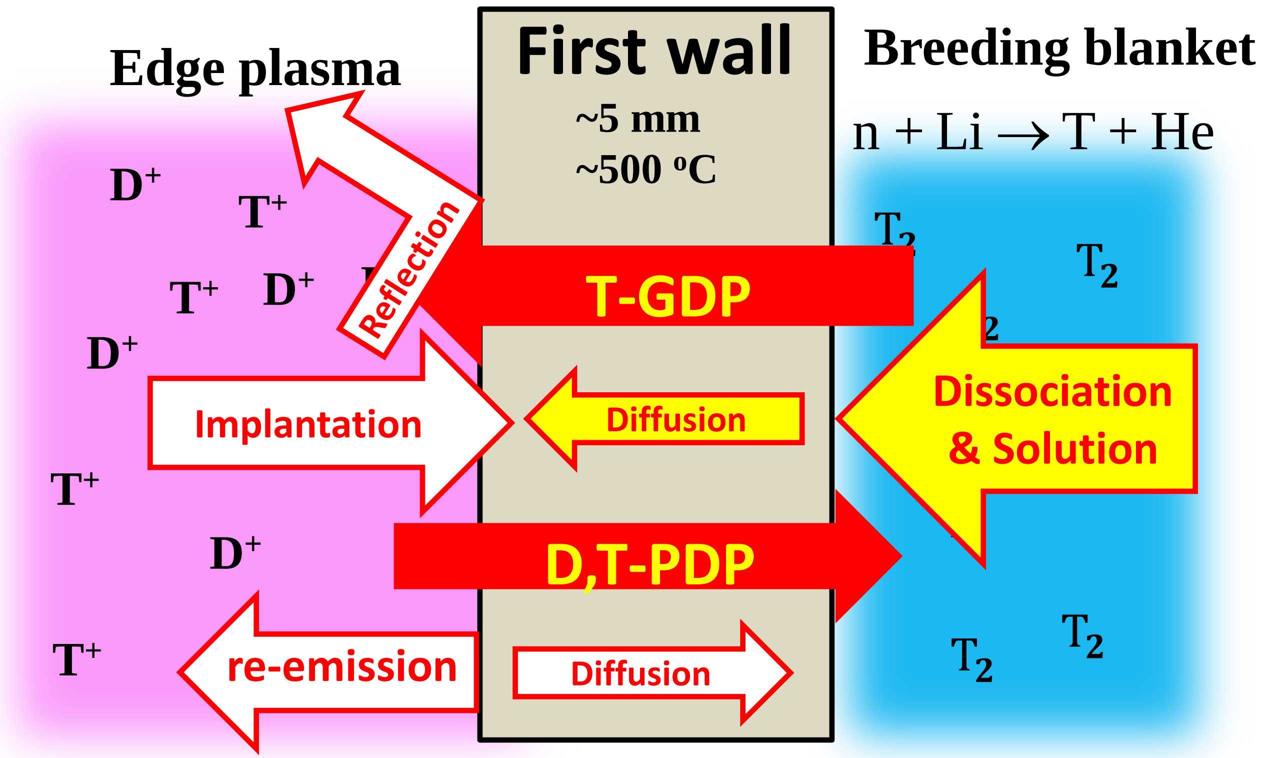


- The plasma- and gas-driven permeation fluxes are measured by two H_2 partial pressure gauges, respectively.
- Ion bombardment energy is provided by a negative bias (-100 V or -50 V).
- Temperature: ~200 - 520 °C

3. Bi-directional hydrogen permeation experiments and modelling

Bi-directional permeation

- For the self-cooled breeder blankets, hydrogen isotopes will penetrate through the first wall by **plasma-driven permeation (PDP)** in one direction and **gas-driven permeation (GDP)** in the opposite direction.



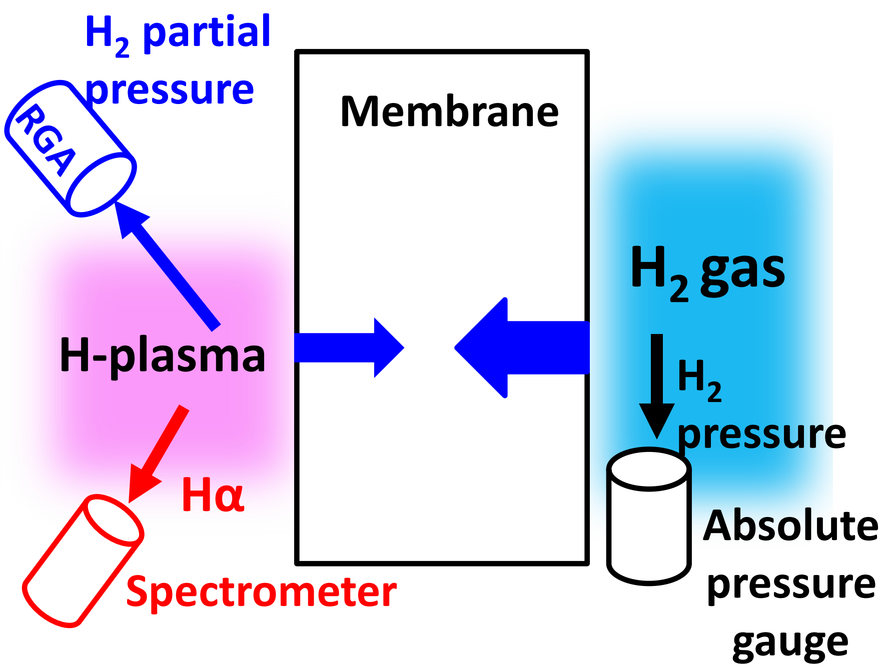
Important parameters

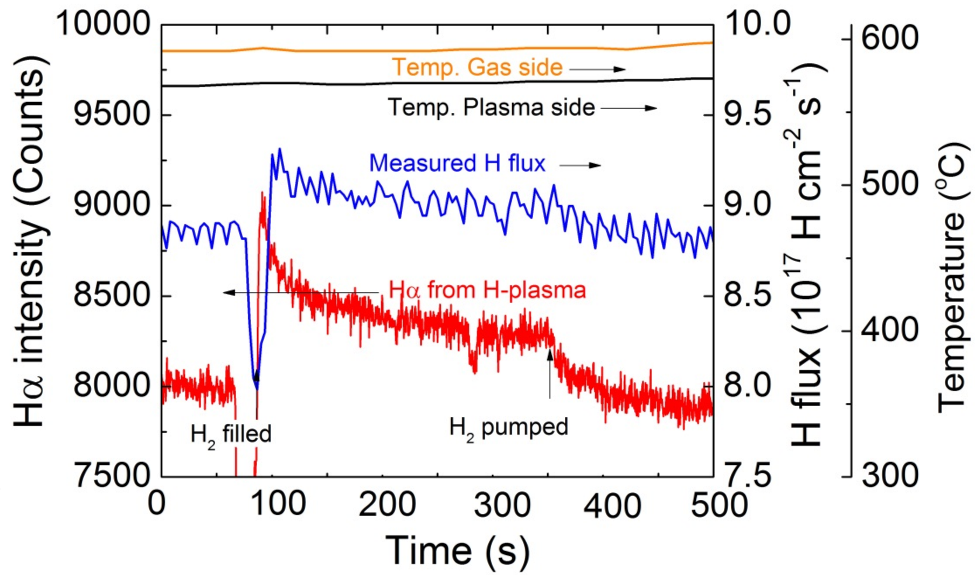
GDP:
- Solubility
- Diffusivity
- External pressure

PDP:
- Surface recombination coefficient
- Diffusivity
- Implantation flux
- Reflection coef.

PDP ⟷ GDP: Bi-directional permeation

Hydrogen bi-directional permeation experiment





H plasma: Te: ~10 eV
Ne: ~1.0×10^{10} cm^{-3}
Bias: -50V

H_2 pressure: ~7×10^{4} Pa

Membrane: 0.6 mm thick F82H

- H GDP flows in the counter direction to H PDP flow and affects the upstream plasma.
- The GDP flux has been measured to be 9.9×10^{15} $H/cm^2/s$.

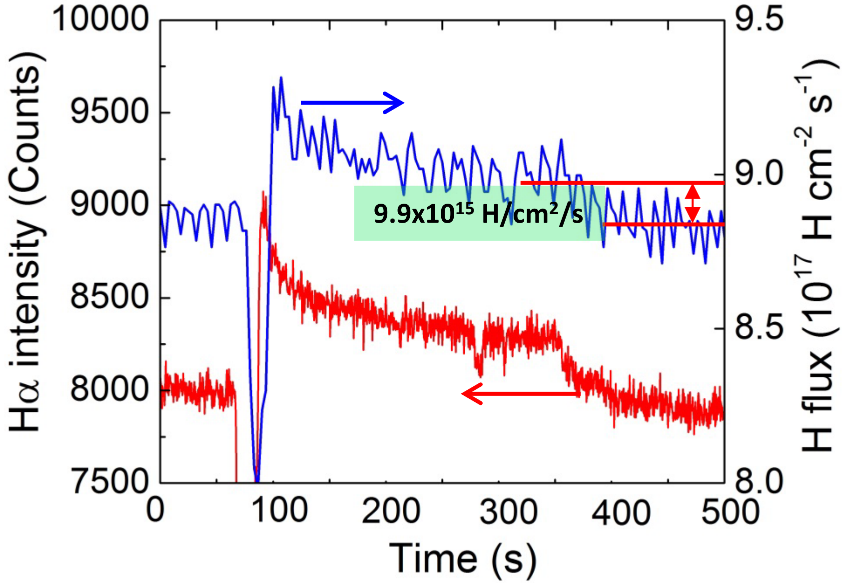
Hydrogen bi-directional permeation modelling

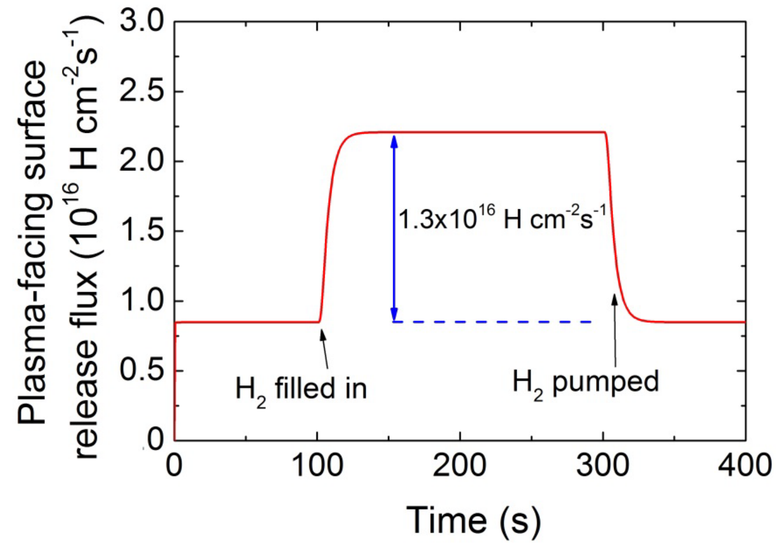
- **GDP-T_2 pressure:**
  ~7x10^4 Pa
- **Ion flux:**
  ~8.5×10^{15} H·cm^{-2}·s^{-1}

- **Membrane:**
  0.6 mm thick α-Fe
- **Temperature:**
  Gas-facing side: ~580 °C
  Plasma-facing side: and ~550 °C

- **Boundary conditions:**
  Gas side: Sieverts' law
  Plasma side: recombination

- **Intrinsic trap density: 1%**
- **Trapping energy: 0.62 eV**

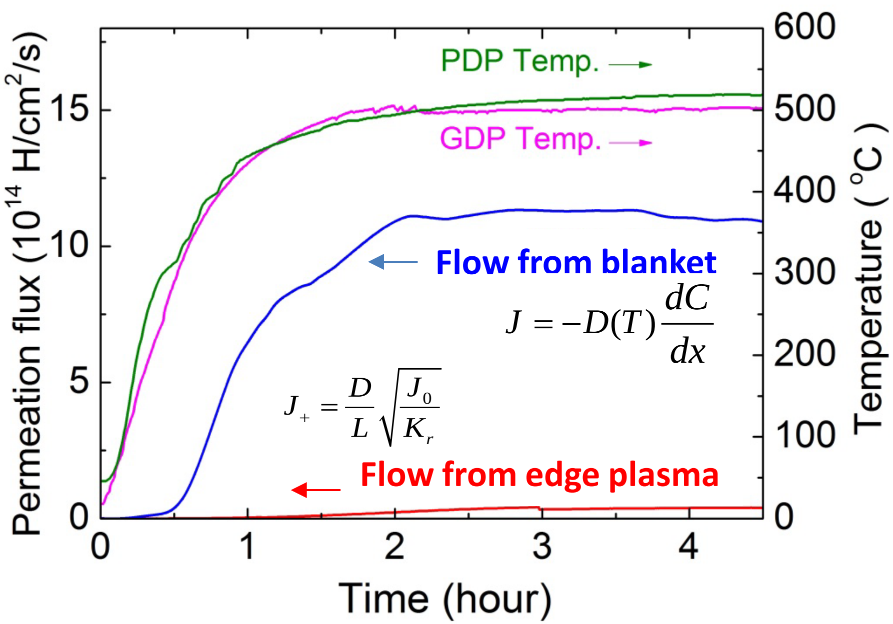




The experimental result is in relatively good agreement with the prediction by modelling.

F82H: Hydrogen PDP and GDP fluxes

Hydrogen PDP and GDP fluxes measured in VEHICLE-1 for a 5 mm thick F82H membrane (under the FLiBe-blanket conditions)



Membrane temperature	**~500 °C**
Net Implantation flux for PDP	**2.0×10^{16} H·cm^{-2}·s^{-1} (-100 V bias)**
H_2 driving pressure for GDP	**~10^4 Pa(Fukada) (Thermodynamic equilibrium data)**

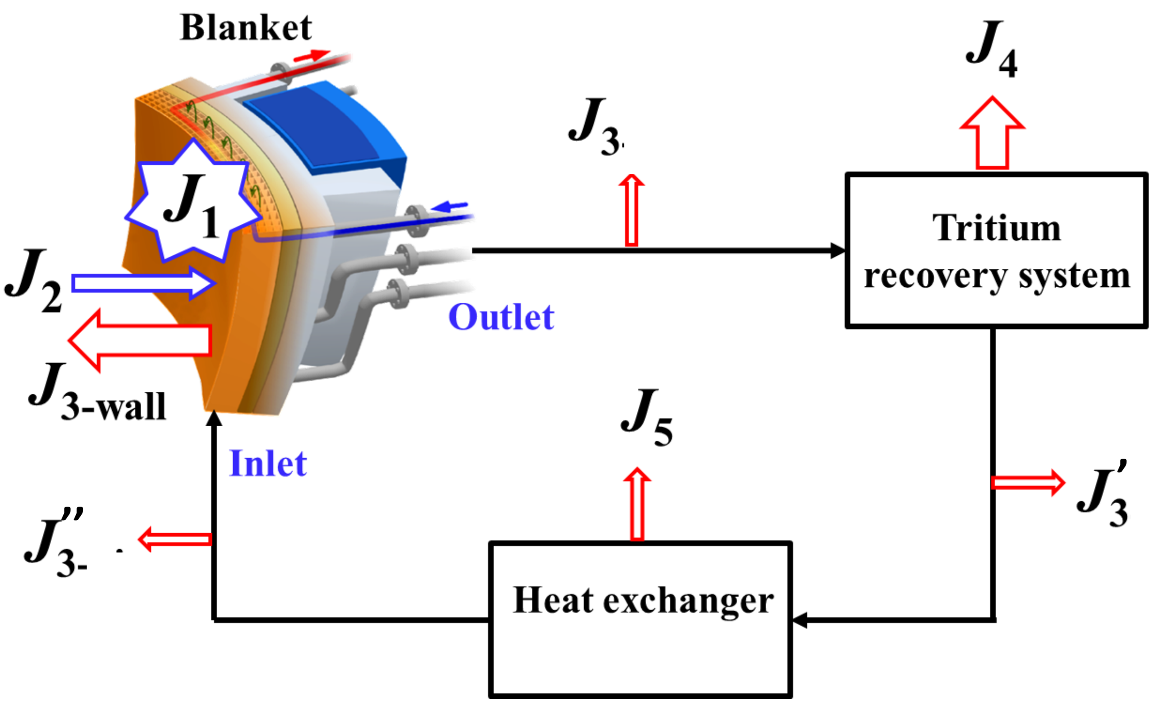
- **Hydrogen transport in the first wall is dominated by the flow from the blanket.**
- **Using the experimental data, the hydrogen recycling rate has been estimated to be R= 1.025.**

4. Modelling on the reactor fuel loop operation with hydrogen isotopes bi-directional permeation through the first wall

4-1. Re-evaluation of hydrogen bi-directional permeation fluxes through the first wall for FLiBe blankets

Re-evaluation of the tritium pressure for FLiBe blankets

Re-evaluation of the tritium flows in a FLiBe loop has been performed, taking into account tritium leakage from the first wall.



M_T: tritium inventory in the loop;

J_1: tritium production rate;

J_2: tritium PDP flow into blanket;

J_3: tritium GDP flow from blanket and GDP leak from pipes;

J_4 : recovered tritium;

J_5: tritium GDP leak from heat exchanger

Overall tritium inventory: $$\frac{dM_T}{dt} = J_1 + J_2 - \sum J_3 - J_4 - J_5$$

Re-evaluation of the tritium pressure for FLiBe blankets

Conditions for analysis:

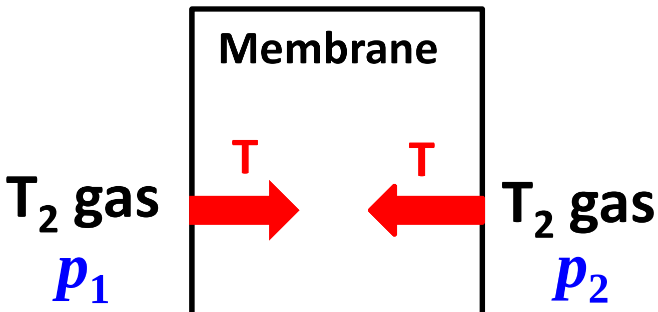
*Song et al., Plasma Fusion Res. 7 (2012) 2405016.

	This work	*Song et al.
Fusion power	3 GW (Sagara)	1 GW
Tritium breeding ratio	1.3 (Sagara)	1.25
Blanket surface area	3000 m^2 (Tanaka)	489 m^2
FLiBe flow rate	2.2 m^3/s	2.2 m^3/s
Tritium recovery rate	0.99 (Sagara)	0.98
First wall	5 mm thick F82H	10 mm thick F82H with coatings
Plasma flux	5×10^{15} D cm^2/s 5×10^{15} T cm^2/s	No PDP assumed
Calculated tritium pressure	1.1×10^3 Pa	4.3×10^3 Pa

4-2. Isotopes effects on hydrogen permeation

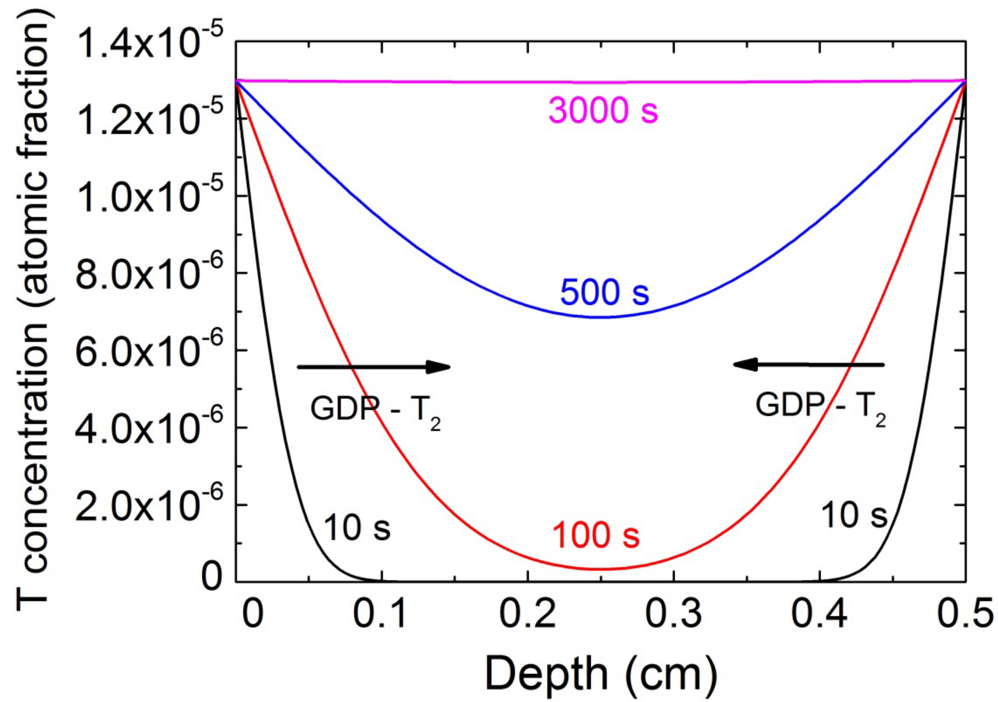
Modelling of bi-directional permeation involving multiple hydrogen isotopes

Bi-directional GDP of the same hydrogen isotope



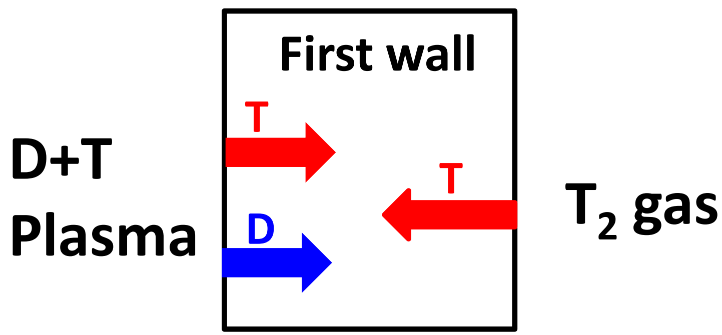
Equal pressure: $p_1 = p_2$

- **GDP-T_2 pressure: ~10^4 Pa (Fukada)**
- **Membrane: 5 mm thick α-Fe**
- **Temperature: 527 °C**
- **Boundary condition:**
  Sieverts' law
- **Intrinsic trap density: 1%**
- **Trapping energy: 0.62 eV**

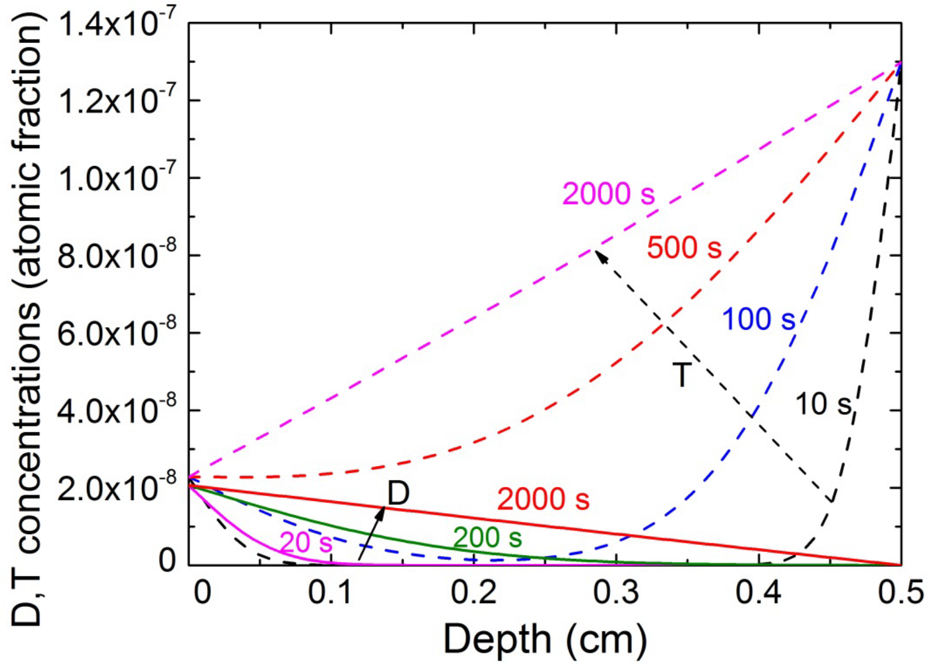


The tritium concentration profiles interact with each other in the two counter flows, finally reaching a flat profile with no net directional flow (quasi-thermodynamic equilibrium).

Bi-directional PDP-D/T and GDP-T_2 flows.



- T_2 pressure: ~1 Pa
- Implantation flux:
  5×10^{15} $D\cdot cm^{-2}\cdot s^{-1}$ 5×10^{15} $T\cdot cm^{-2}\cdot s^{-1}$
- Membrane: 5 mm thick α-Fe
- Temperature: 527°C
- Boundary conditions:
  Gas side: Sieverts' law
  Plasma side: recombination
- Intrinsic trap density: 1%
- Trapping energy: 0.62 eV



- The tritium concentration profiles interact with each other in the two counter flows.
- Deuterium flow appears to be independent of these tritium flows, driven by its own concentration gradient.

4-3. Re-evaluation of hydrogen bi-directional permeation fluxes through the first wall for FLiBe blankets

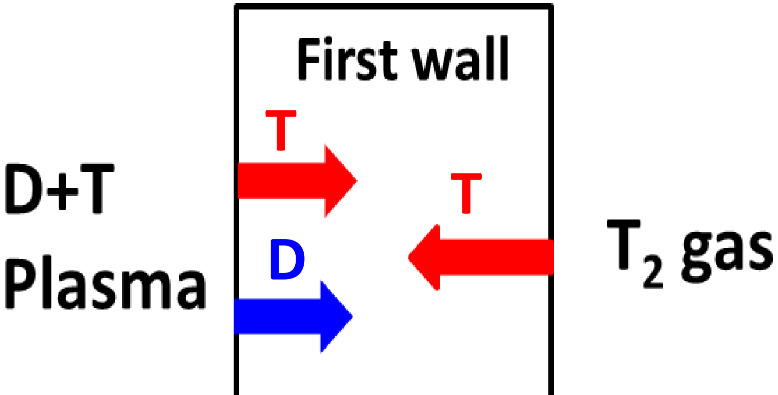
Re-evaluation of the bi-directional permeation process

Conditions for DIFFUSE calculation:

- **T_2 pressure: 1.1×10^3 Pa**
- **Implantation flux assumptions:**

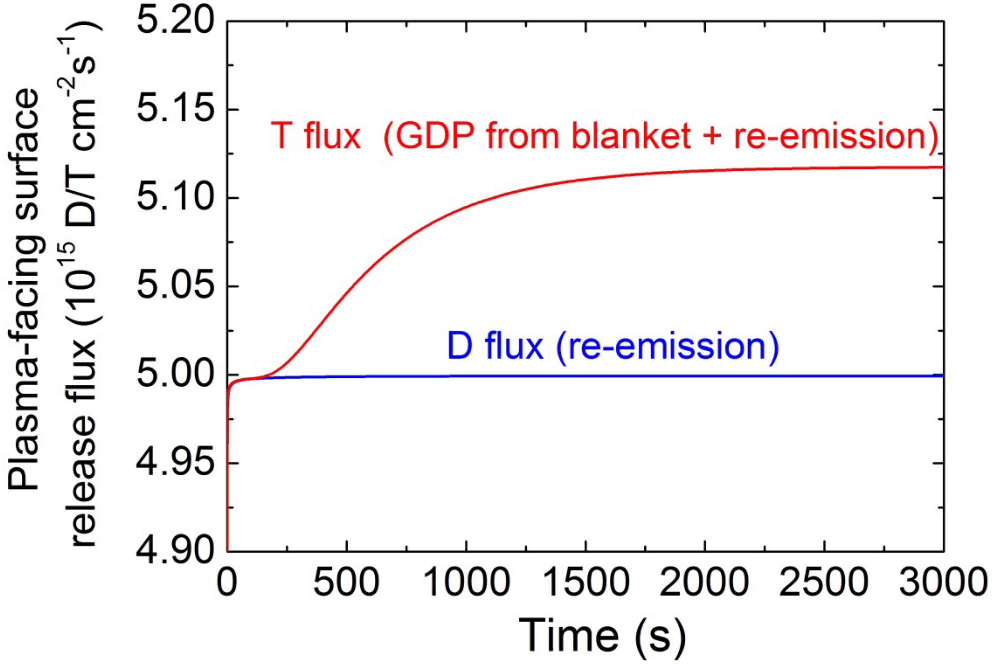
  $\Gamma_D = 5\times10^{15}$ D·cm^{-2}·s^{-1}

  $\Gamma_T = 5\times10^{15}$ T·cm^{-2}·s^{-1}
- **Membrane: 5 mm thick α-Fe**



- **Intrinsic trap density: 1%**
- **Trapping energy: 0.62 eV**

D/T release fluxes at the plasma-facing surface



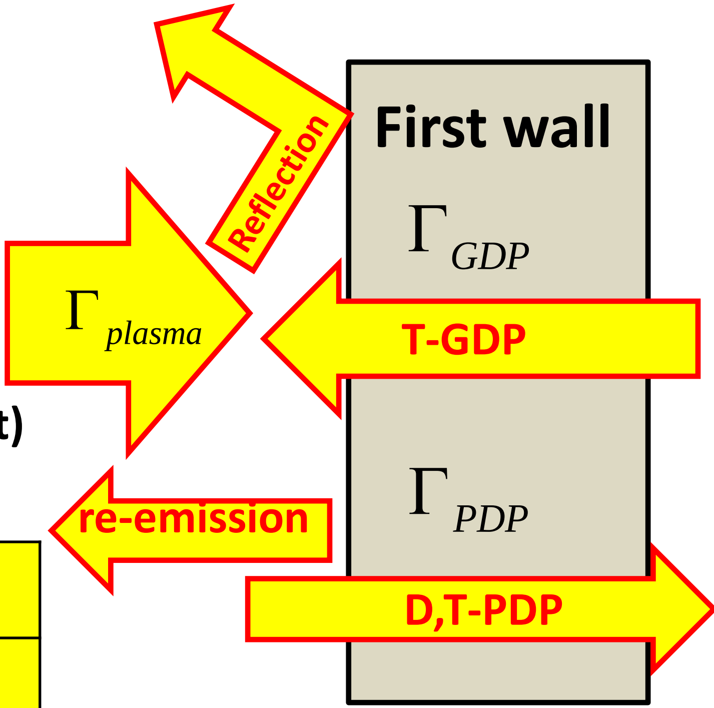
The tritium release flux at the plasma-facing surface is a total flux from GDP and re-emission.

PDP and GDP under reactor-relevant conditions

PDP and GDP through a 5 mm thick F82H membrane (FLiBe-blanket conditions)

Hydrogen recycling coefficient:

$$R \equiv \frac{\Gamma_{reflection} + \Gamma_{re-emission} + \Gamma_{T-GDP}}{\Gamma_{plasma}}$$



$\Gamma_{\mathrm{reflection}} = \gamma\, \Gamma_{\mathrm{plasma}}$ **(γ is the particle reflection coefficient)**

Membrane temperature	550 °C
Net Implantation flux for PDP	1×10^{16} (2×10^{16}) $DT\cdot cm^{-2}\cdot s^{-1}$
T_2 driving pressure for GDP	1.1×10^{3} Pa (This work)

Assuming a particle reflection coefficient of 0.5, the total incident flux is 2×10^{16} $D\&T\cdot cm^{-2}\cdot s^{-1}$ and the first wall recycling rate has been estimated to be R= 1.006.

5. Experimental work on hydrogen isotopes transport parameter

5-1. Gas-driven permeation (GDP) experiments for the evaluation of solubility and diffusivity

Gas-driven permeation

Solubility of gases in metals (Sieverts' law):

$$C = S(T)\cdot\sqrt{p_{\mathrm{H}_2}}$$

***S*(*T*): Sieverts' constant as a function of temperature**

P_{H_2}: hydrogen pressure

Diffusion limited gas-driven permeation flux:

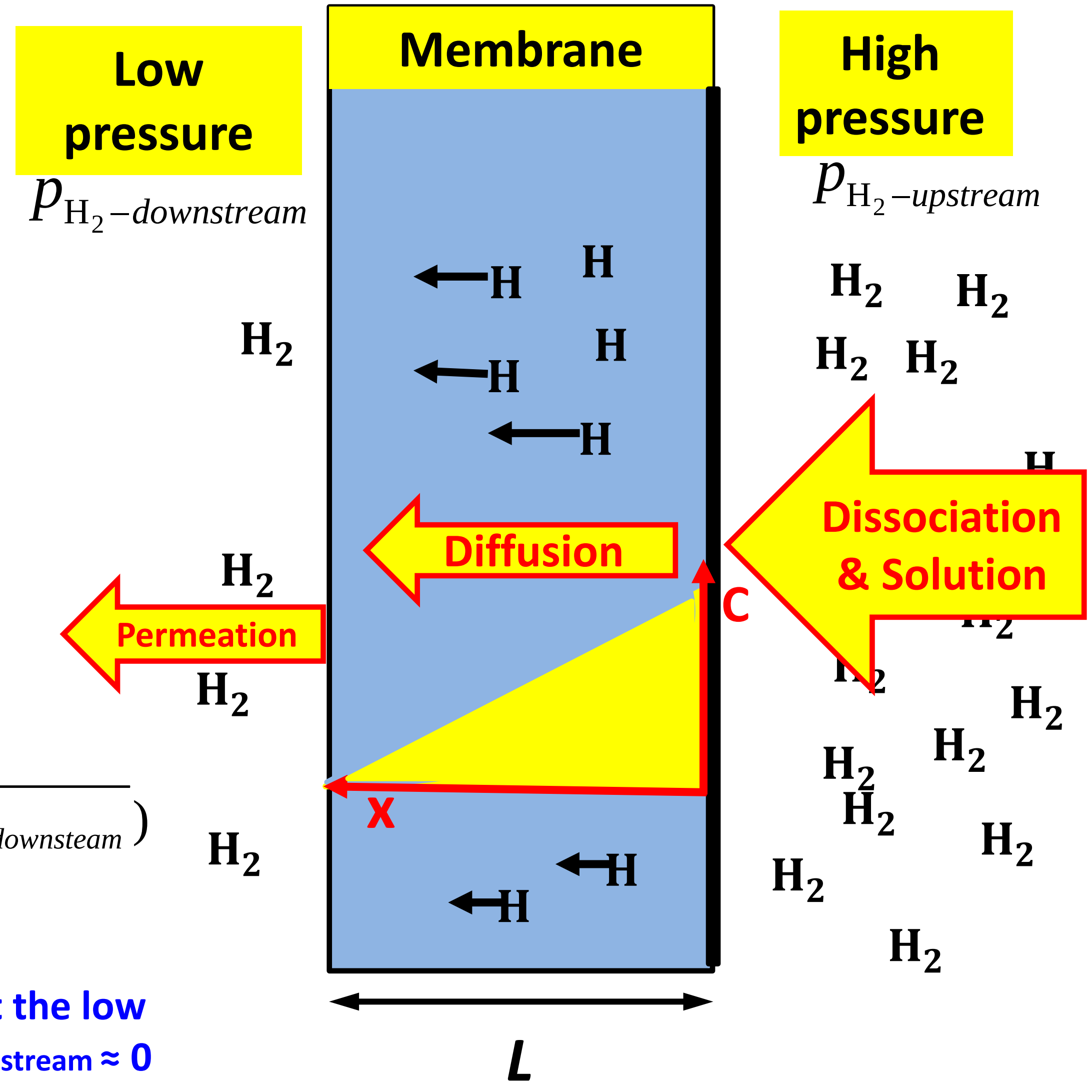
$$J = -D(T)\frac{dC}{dx}$$

$$= \frac{D(T)S(T)}{L}\left(\sqrt{p_{\mathrm{H}_2-upsteam}} - \sqrt{p_{\mathrm{H}_2-downsteam}}\right)$$

***L*: membrane thickness**

***D(T)*: diffusion coefficient**

P_{H_2}-downstream: hydrogen pressure at the low pressure side, usually P_{H_2}-downstream ≈ 0



Permeability for GDP: $P(T) \equiv D(T)S(T)$

Diffusion coefficient from GDP

3 methods to evaluate the diffusion coefficient, D:

1. Transient curve fitting method[1]

Solving the diffusion equation:

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

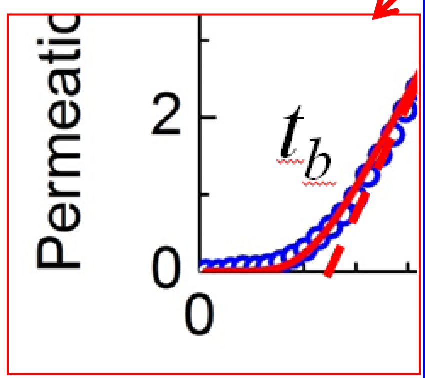
$$J(t) = \frac{D(T)S(T)\sqrt{p_{H_2}}}{L} \times [1 + 2\sum_{n=1}^{\infty}(-1)^n \exp(-D(T)\frac{n^2\pi^2}{d^2}t)]$$

2. Time lag method[2]:

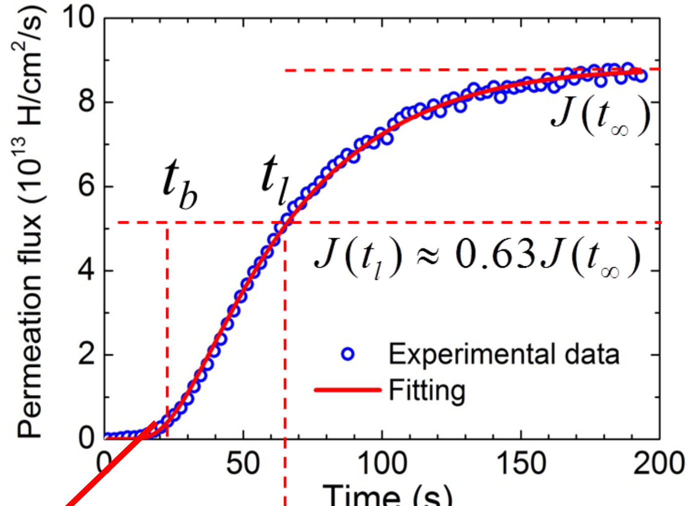
$$t_l = L^2 / 6D \qquad J(t_l) \approx 0.63 J(t_\infty)$$

3. Breakthrough time method[2]:

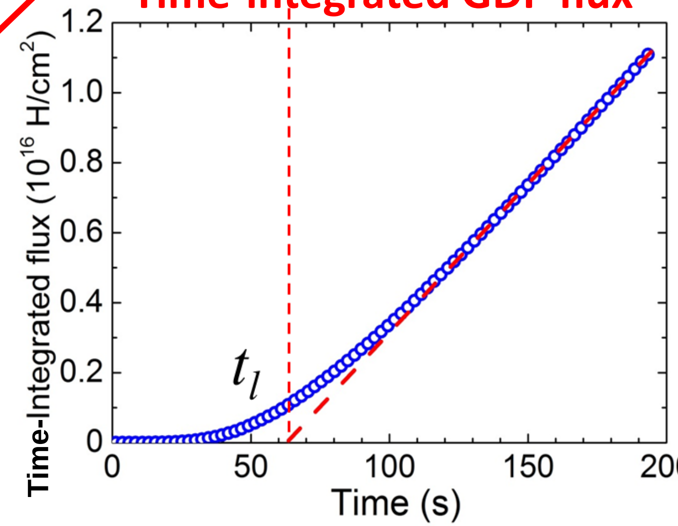
$$t_b = \frac{L^2}{D}(\frac{1}{6} - \frac{1}{\pi^2}) \approx \frac{L^2}{15.3D}$$



Transient GDP flux curve



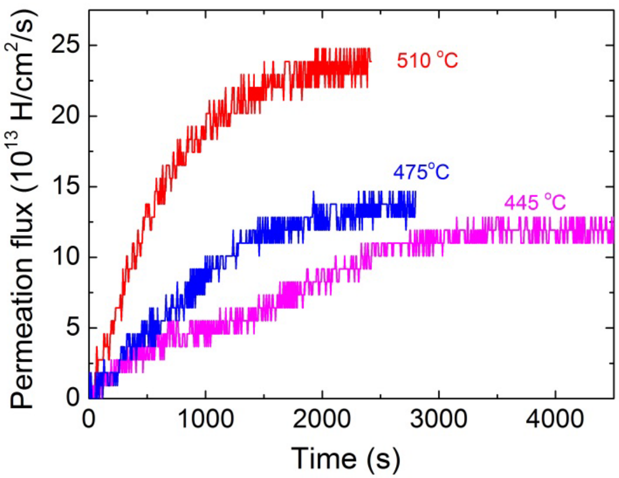
Time-integrated GDP flux



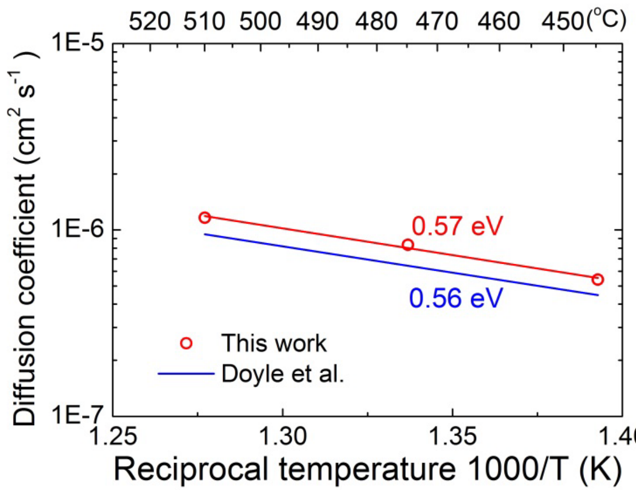
[1] E. Serra *et al.*, J. Nucl. Mater. 245 (1997) 108-114.
[2] MAV Devanathan *et al.*, Proc. R. Soc. Lond. A270 (1962) 90-102.

SUS304: Validation of the experimental setup and data analysis

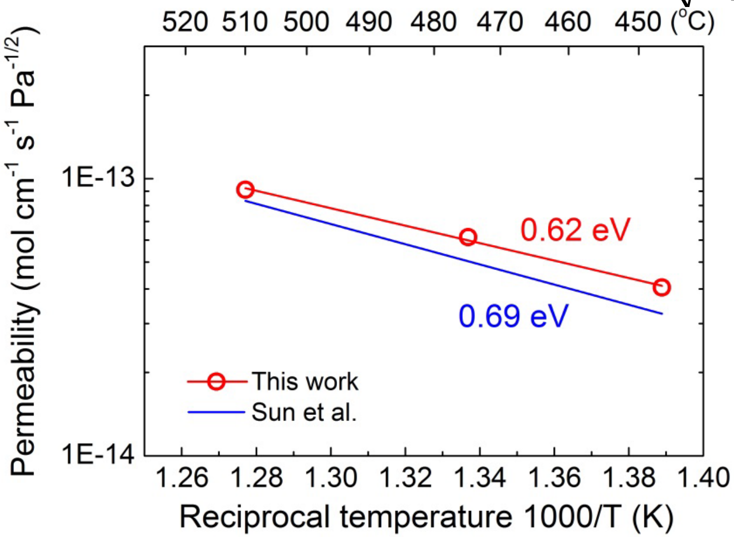
GDP through 0.65 mm thick SUS304



Diffusion coefficient



Permeability $P(T) \equiv D(T)S(T) = \dfrac{J_{\mathrm{GDP}}L}{\sqrt{p_{\mathrm{H_2}}}}$



Diffusivity:

$$D = 5.5\times10^{-3}\exp\left(\frac{-0.57\ [\mathrm{eV}]}{kT}\right) \quad [\mathrm{cm^2\cdot s^{-1}}]$$

Permeability:

$$P = 9.6\times10^{-10}\ \exp\left(\frac{-0.62\ [\mathrm{eV}]}{kT}\right) \quad [\mathrm{mol\cdot cm^{-1}\cdot s^{-1}\cdot Pa^{-1/2}}]$$

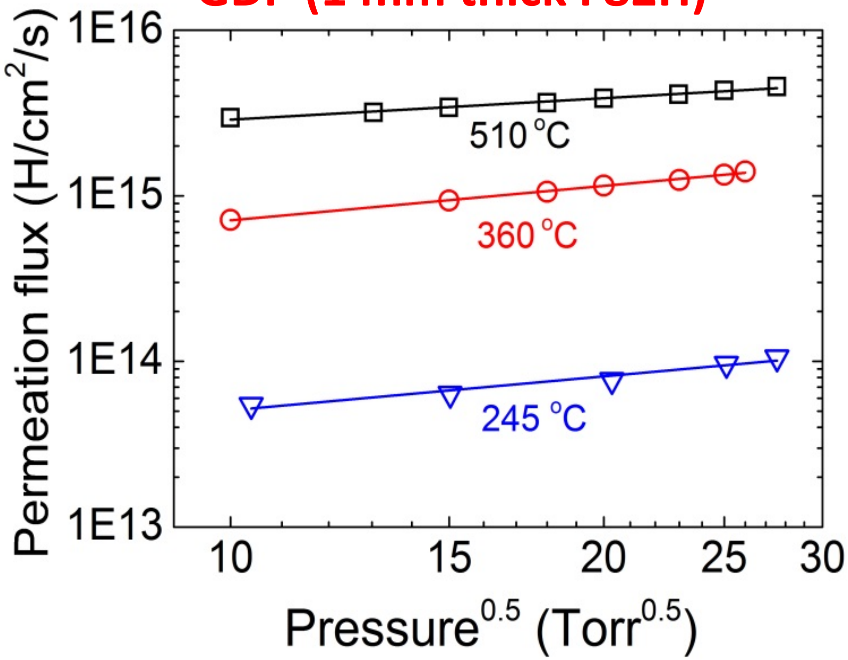
Solubility:

$$S = 1.8\times10^{-7}\ \exp\left(\frac{-0.05\ [\mathrm{eV}]}{kT}\right) \quad [\mathrm{mol\cdot cm^{-3}\cdot Pa^{-1/2}}]$$

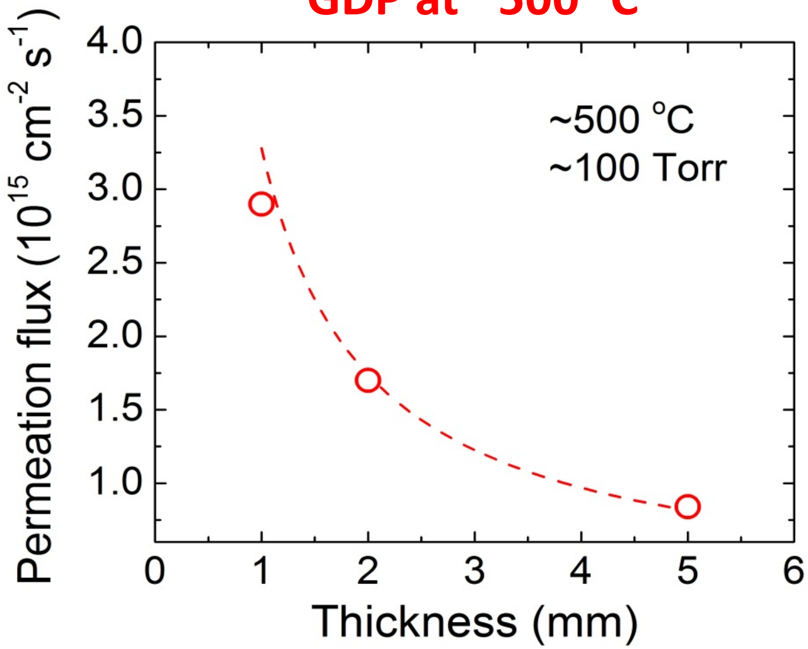
Sun et al., Materials Science and Engineering, Al14 (1989) 179-187.
B. L. Doyle and D. K. Brice, J. Nucl. Mater. 122 & 123 (1984) 1523-1530.

F82H: pressure and thickness dependence of GDP flux

GDP (1 mm thick F82H)



GDP at ~500 °C



- **A linear relation between GDP flux and the square-root of upstream pressure has been found at all the temperatures examined in this work.**

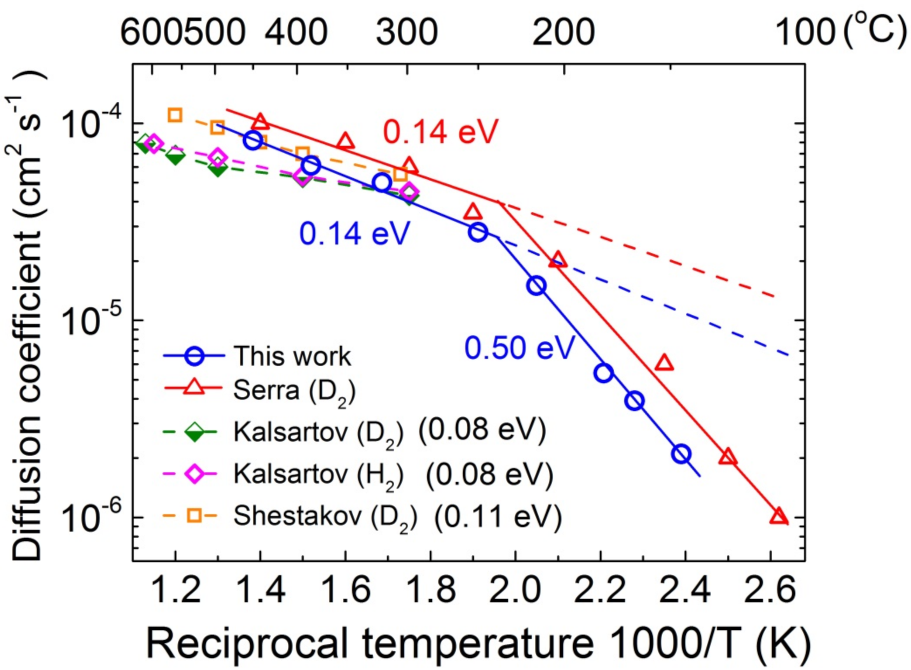
GDP is diffusion-limited model:

$$J_{\mathrm{GDP}} = -D(T)\frac{dC}{dx} = \frac{D(T)S(T)}{L}\sqrt{p_{\mathrm{H}_2}}$$

- **Even for a 5 mm thick membrane, reactor-relevant, hydrogen GDP has been found to be diffusion limited.**

F82H: hydrogen diffusion coefficient evaluation

The diffusion coefficient of H through F82H has been evaluated from the transient permeation behavior.



A breaking point has been found for the diffusion coefficient data, which we attribute to the trapping effect.

In the presence of traps:

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

$$\boxed{= D_a(T)} \frac{\partial^2 C(x,t)}{\partial x^2}$$

$\Rightarrow$ $D(T) \geq D_a(T)$ **(with traps)**

Measured diffusion coefficient:

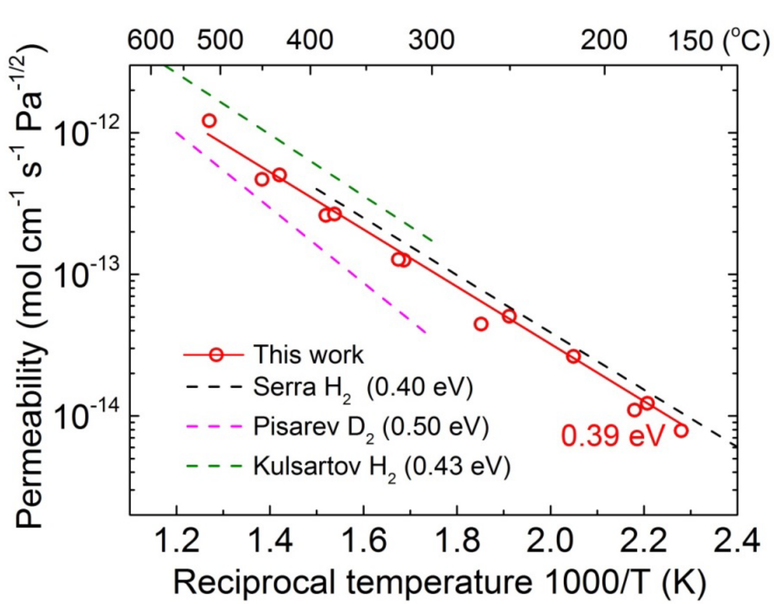
>~250 ℃ $D = 7.5\times 10^{-4} \exp\left(\dfrac{-0.14\ [\mathrm{eV}]}{kT}\right)$ [cm^2·s^{-1}]

< ~250 ºC $D = 1.9 \exp\left(\dfrac{-0.50\ [\mathrm{eV}]}{kT}\right)$ [cm^2·s^{-1}]

E. Serra et al., J. Nucl. Mater. 245 (1997) 108.
V. Shestakov et al., J. Nucl. Mater. 307-311 (2002) 1494.
T.V. Kulsartov et al., Fusion Eng. Des. 81 (2006) 701.

F82H: hydrogen permeability and solubility

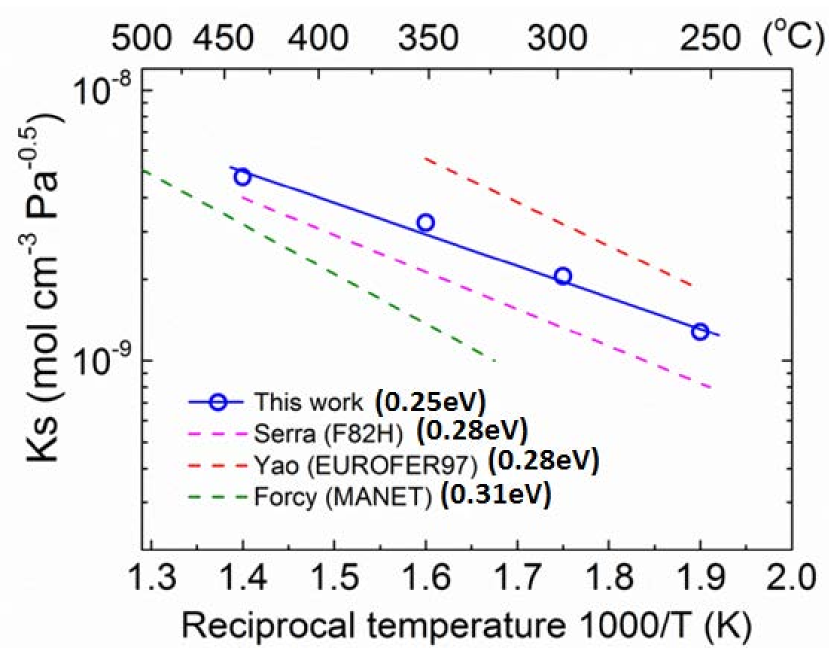
The permeability and solubility of H in F82H have been evaluated from the steady state temperature dependent GDP data.



$$P = 2.3\times10^{-10}\ \exp\left(\frac{-0.39\ [\mathrm{eV}]}{kT}\right)$$

$[\mathrm{mol\cdot cm^{-1}\cdot s^{-1}\cdot Pa^{-1/2}}]$

E. Serra et al., J. Nucl. Mater. 245 (1997) 108.
A. Pisarev et al., Phys. Scr. T94 (2001) 121.
T.V. Kulsartov et al., Fusion Eng. Des. 81 (2006) 701.



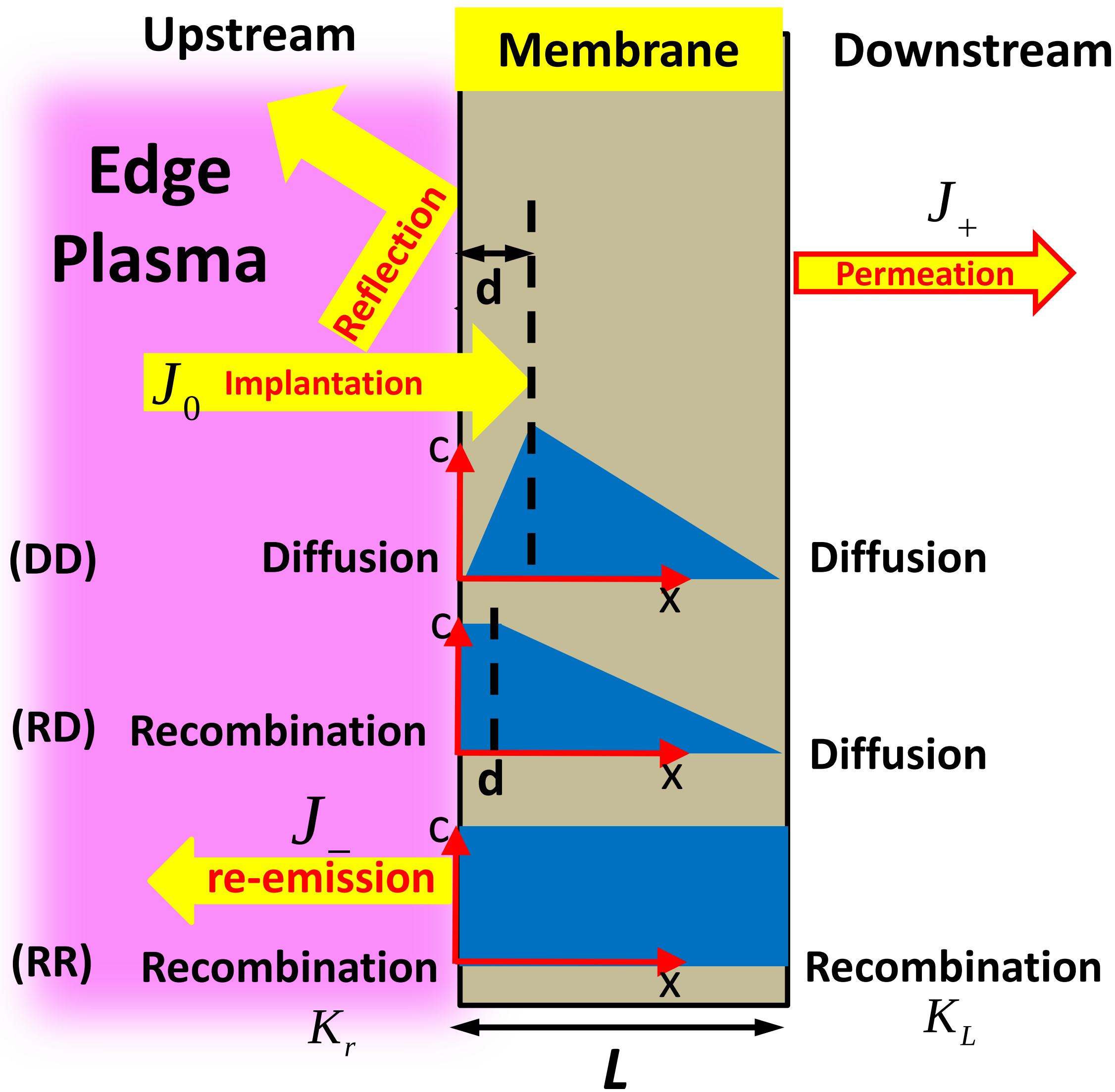
$$S = 3.1\times10^{-7}\ \exp\left(\frac{-0.25\ [\mathrm{eV}]}{kT}\right)$$

$[\mathrm{mol\cdot cm^{-3}\cdot Pa^{-1/2}}]$

E. Serra et al., J. Nucl. Mater. 245 (1997) 108.
Z. Yao et al., Fusion Sci. Tech. 48 (2005) 1285.
K. Forcy et al., J. Nucl. Mater. 160 (1988) 117.

5-2. Plasma-driven permeation (PDP) experiments for the evaluation of surface recombination coefficients

Steady state plasma-driven permeation models



- **Flux conservation:**

$$J_0 = J_- + J_+$$

$$(J_- >> J_+)$$

(DD): $\Rightarrow J_+ = \frac{d}{L} J_0$

(RD): $\Rightarrow J_+ = \frac{D}{L}\sqrt{\frac{J_0}{K_r}}$

(RR): $\Rightarrow J_+ = \frac{K_L}{K_r + K_L} J_0$

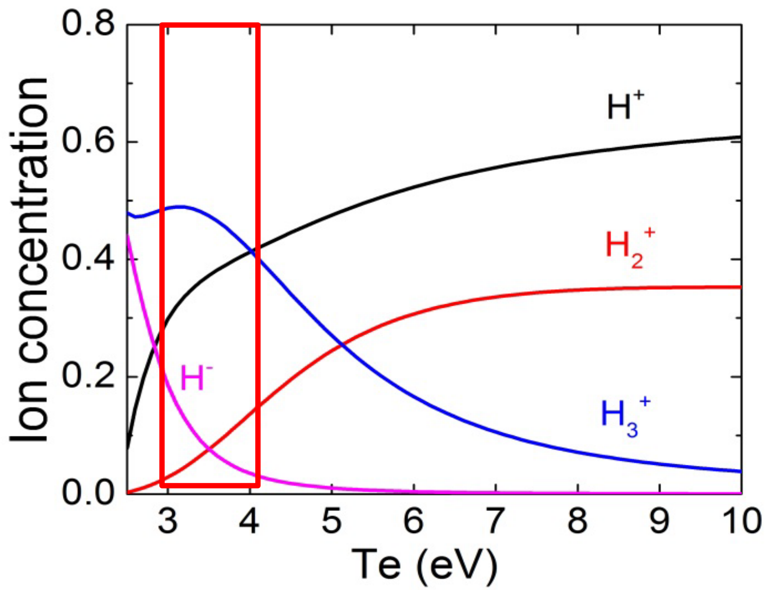
Recombinative desorption flux: $J_- = K_r \cdot C_{\mathrm{H}}^2$

(C_H is hydrogen atomic concentration at the upstream surface)

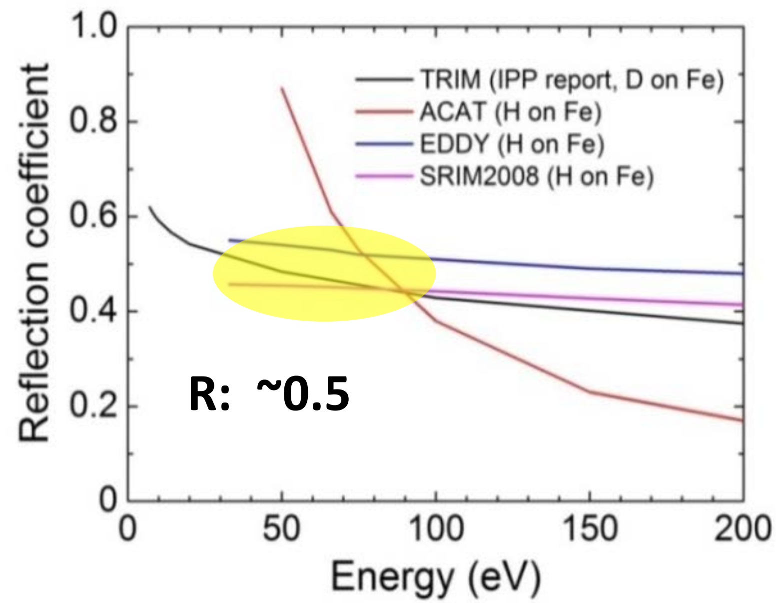
B.L. Doyle, J. Nucl. Mater. 111 & 112 (1982) 628-635.

Estimation of the net implantation flux for PDP experiments

The ion species mix has been estimated by modelling.



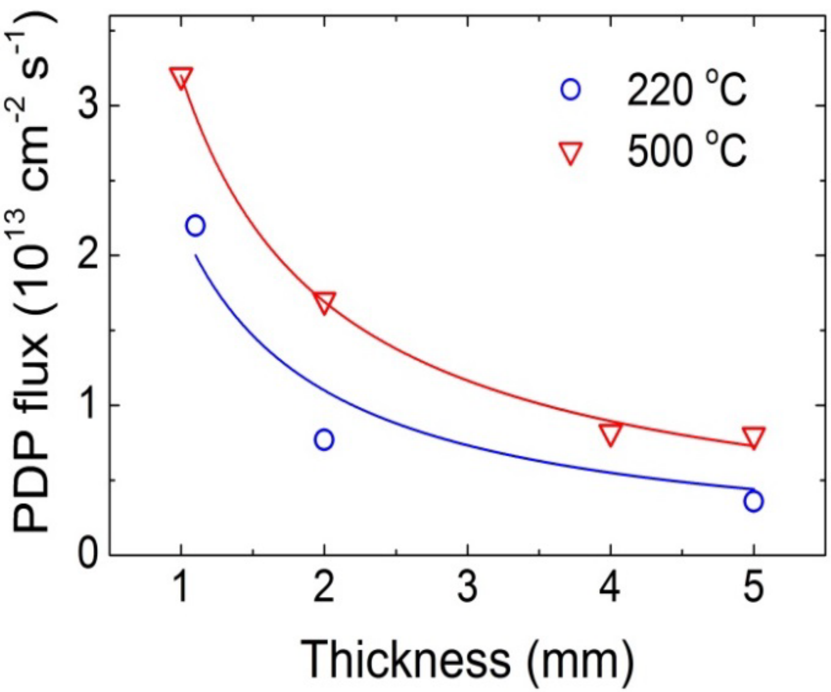
Particle reflection coefficient



- H_3^+ is the dominant ion species in the electron temperature range of the experiments.
- The concentration of H^+ increases as the increase of electron temperature and becomes the dominant species when the electron temperature is higher than 4 eV.

F82H: membrane thickness effects on steady state PDP

Steady state PDP data for F82H membranes at ~220 °C and ~500 °C (-100 V bias)



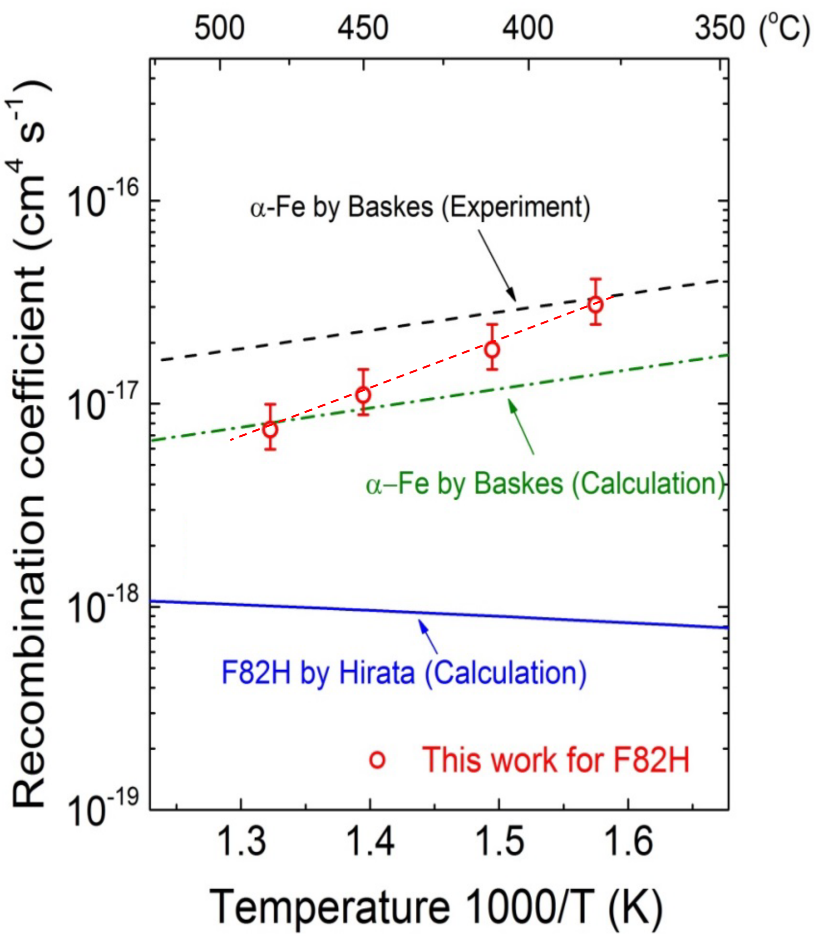
Te	~3 eV
ne	~1x10^{10} cm^{-3}
Net Implantation flux	~5x10^{15} cm^{-2}s^{-1}
Permeation flux	~10^{13} cm^{-2}s^{-1}
PDP flux ratio	~10^{-3}

RD limited flux: $$J_+ = \frac{D}{L}\sqrt{\frac{J_0}{K_r}}$$

- **The steady state permeation flux is inversely proportional to the membrane thickness, meaning that the hydrogen transport process is in the recombination-diffusion limited regime.**

F82H: surface recombination coefficient measurements

The surface recombination coefficient of H on F82H has been measured from the steady state temperature dependent PDP data.



The surface recombination coefficient:

$$K_r = 4.8\times10^{-21}\exp\left(\frac{0.48\ [\mathrm{eV}]}{kT}\right)$$

$[\mathrm{cm}^4\cdot\mathrm{s}^{-1}]$

- **The recombination coefficient for F82H has been estimated for the first time from the experimental data.**

M.I. Baskes, J. Nucl. Mater. 92 (1980) 318.
S. Hirata et al., JAEA report, JAERI-M-91-081, pp. 276.

5-3. Surface condition effects on PDP

Earlier studies related to surface condition effects

Surface condition effects interpretations in earlier studies:

(1) changes in surface recombination coefficient due to sputtering or deposition of contaminations (Causey et al.);

(2) changes in surface recombination coefficient and diffusivity due to ion-induced surface defects (Winter et al.).

This work will:

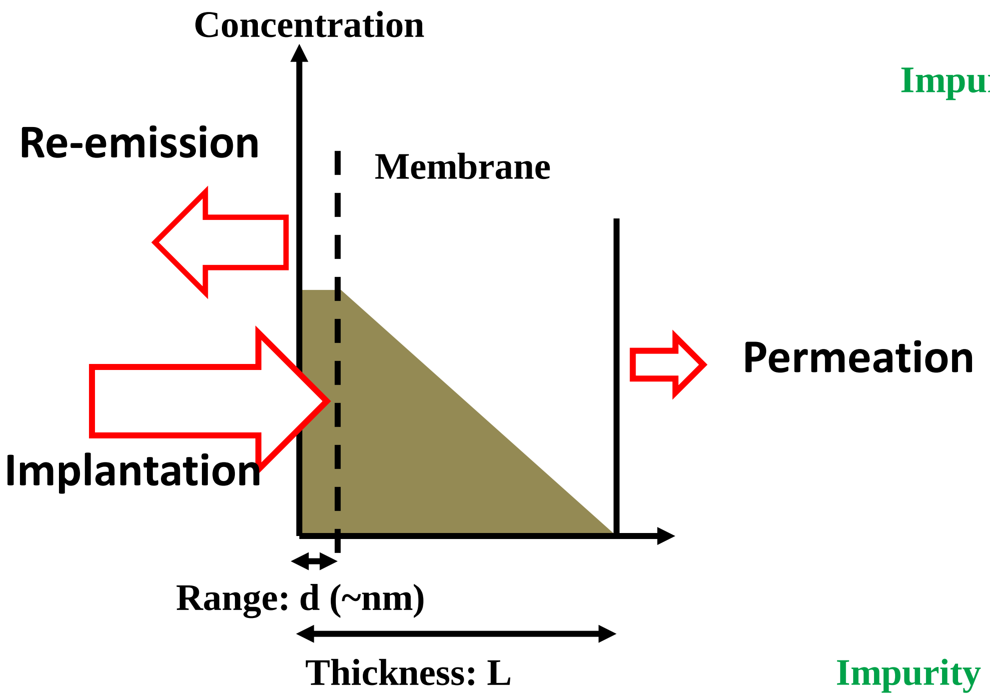
(1) propose a new hypothesis to interpret the surface contamination effects and;

(2) propose a new model to describe the surface area/roughness effects.

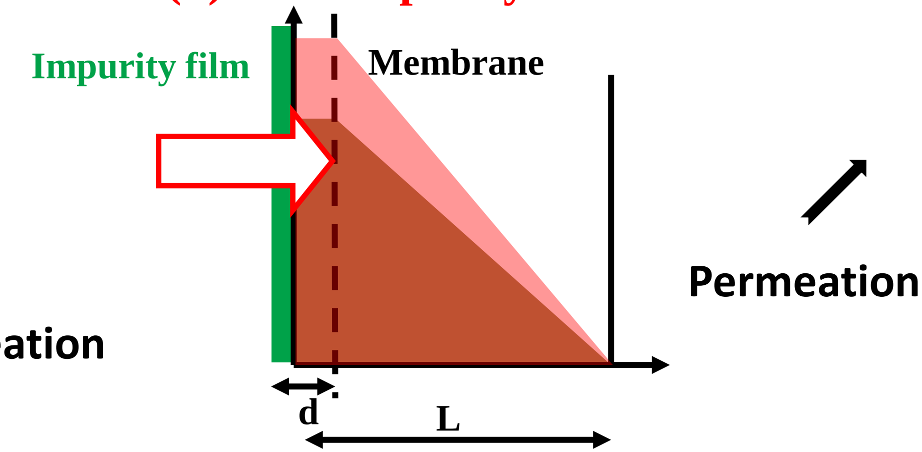
Surface contamination effects on PDP (1)

(1) Surface contamination effects

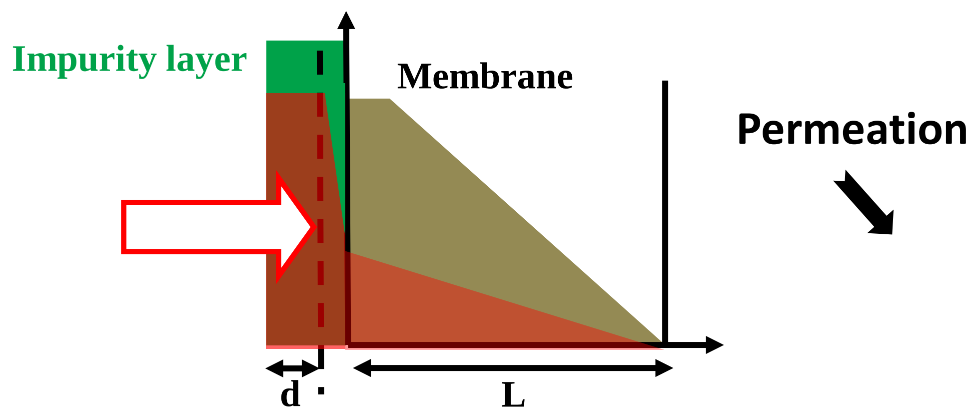
(a) Clean surface (RD-regime)



(b) Thin impurity film



(c) Thick impurity film

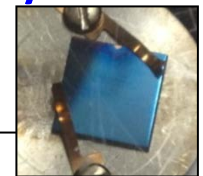


A new hypothesis:

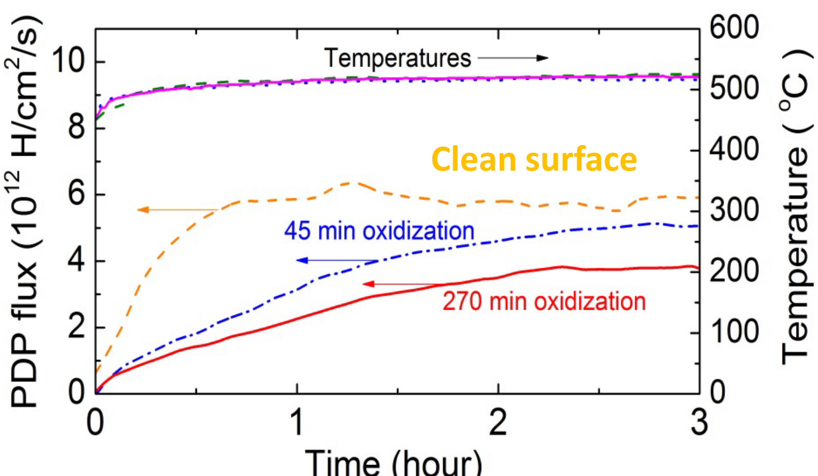
Comparing the implantation range and the thickness of the impurity layer.

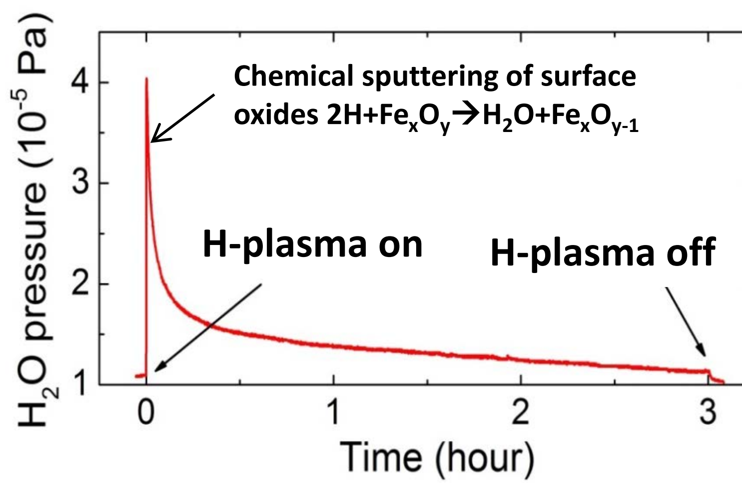
Surface contamination effects on PDP (2)

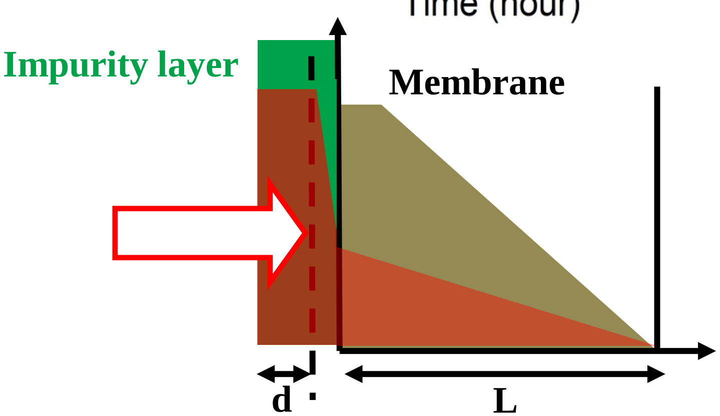
The contamination effects have been investigated by the surface oxidization method.



PDP with clean surface → (O_2 gas $1\text{x}10^{-2}$ Pa at 450-500 °C) → **Surface oxidization** → **PDP with oxidized surface**





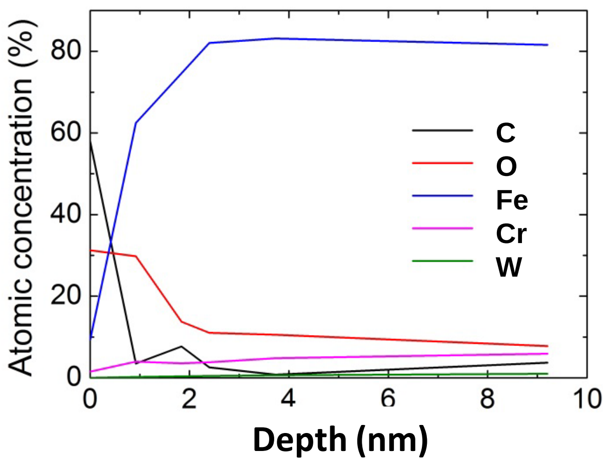


- **After oxidization, it takes longer time for the permeation flux to reach steady state, suggesting a lower effective diffusion coefficient for the oxidized samples.**

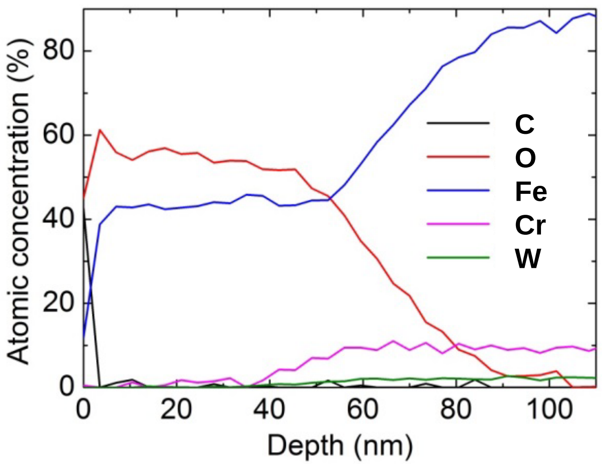
Surface contamination effects on PDP (2)

Surface composition of the samples are examined by X-ray photoelectron spectroscopy (XPS).

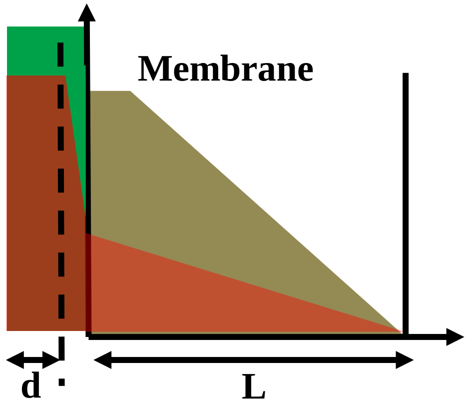
Polished surface



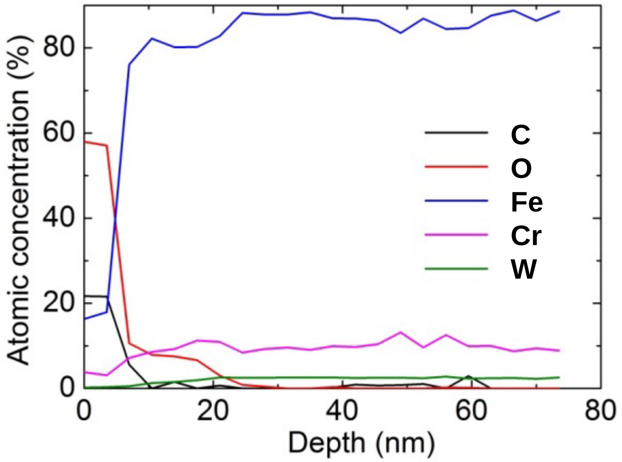
After 45 min oxidization



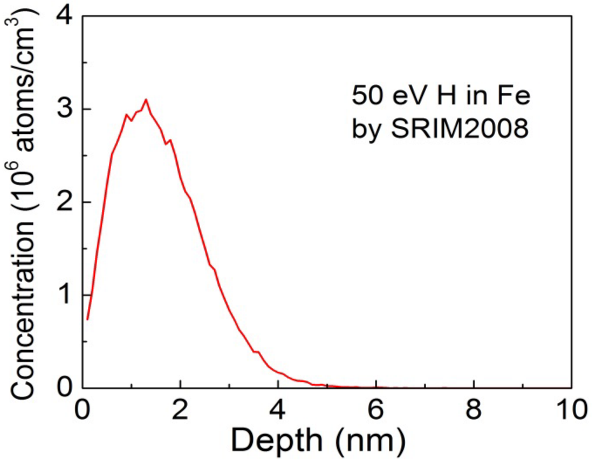
Impurity layer



After 45 min oxidization and PDP



Hydrogen implantation profile

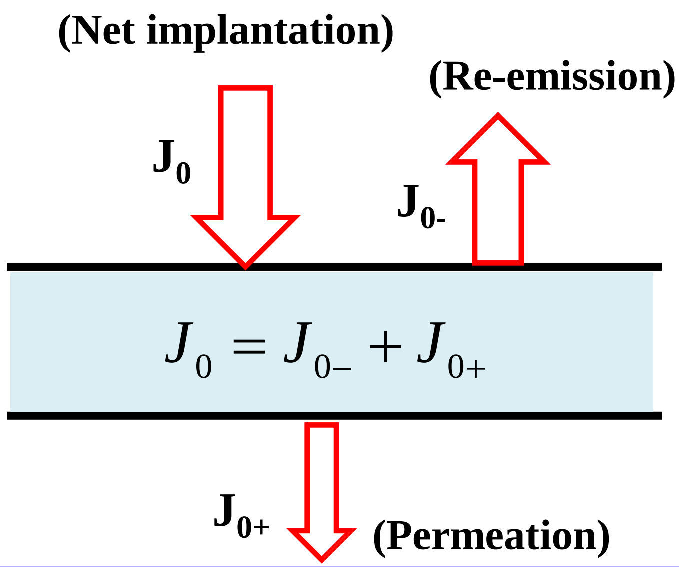


The thickness of the impurity layer is larger than the implantation range.

Surface area effect on PDP behavior

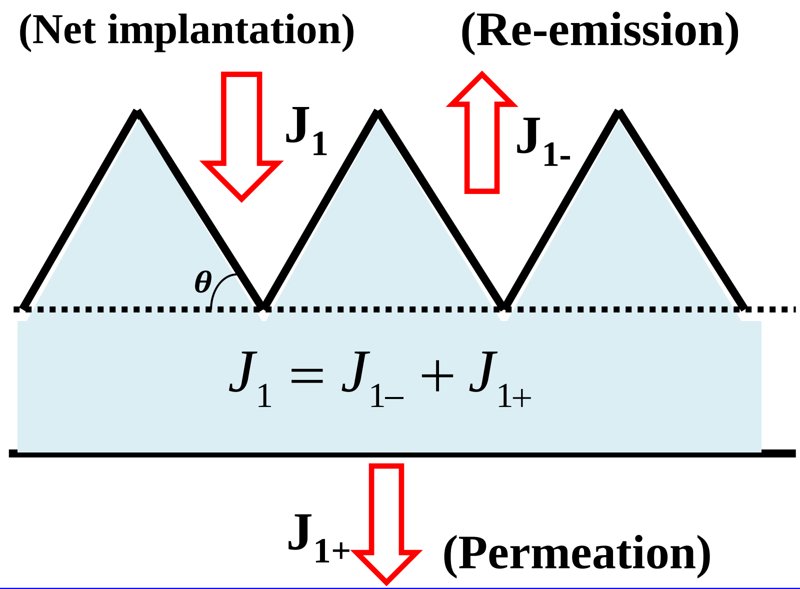
(a) PDP through a flat surface

Surface area A_0



(b) PDP through a modified surface

Surface area A_1



Surface flux ratio: $J_1/J_0 = A_0/A_1$

Surface concentration ratio:

$$\left.\begin{aligned} J_0 &\approx J_{0-} = K_r C_0^2 \\ J_1 &\approx J_{1-} = K_r C_1^2 \end{aligned}\right\} \Rightarrow C_1 / C_0 = \sqrt{J_1 / J_0}$$

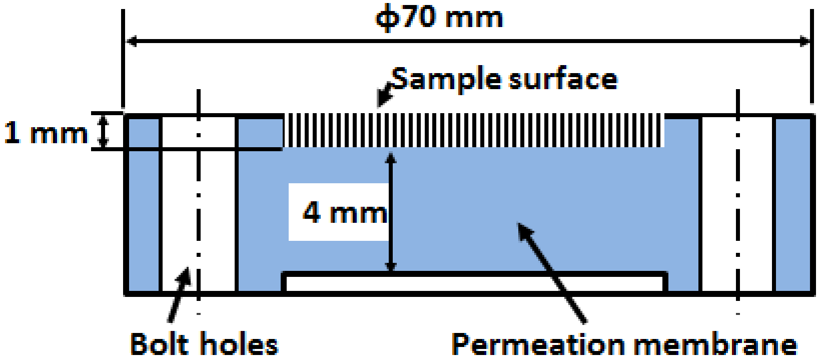
$$J_+ = -D(T)\frac{dC}{dx} \quad \Longrightarrow$$

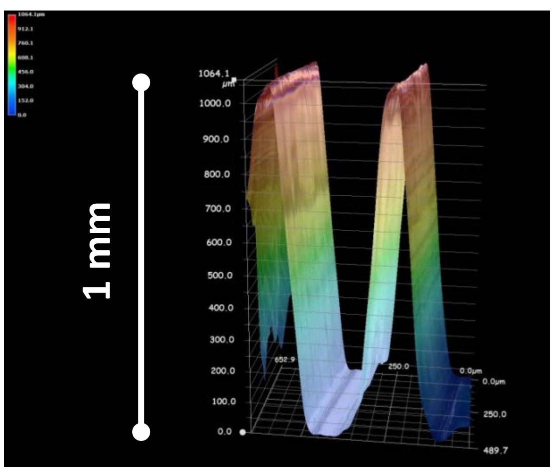
The permeation flux ratio: $J_{1+} / J_{0+} \propto \dfrac{1}{\sqrt{A_1 / A_0}}$

Surface area effects on PDP (1)

To verify surface area effect, PDP experiments have been performed using samples with well controlled surface morphology.

Modified surface-1





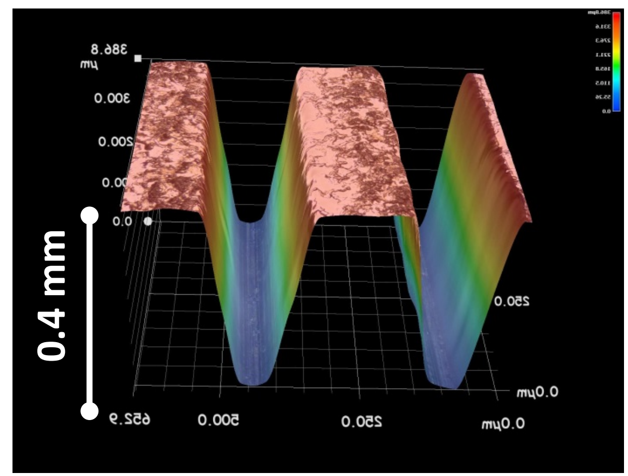
Surface area ratio: A_1/A_0=6.4
Effective thickness:

4 mm< L_{eff} < 5 mm

Three samples:

- **Flat surface**
- **Modified surface-1**
- **Modified surface-2**

Modified surface-2

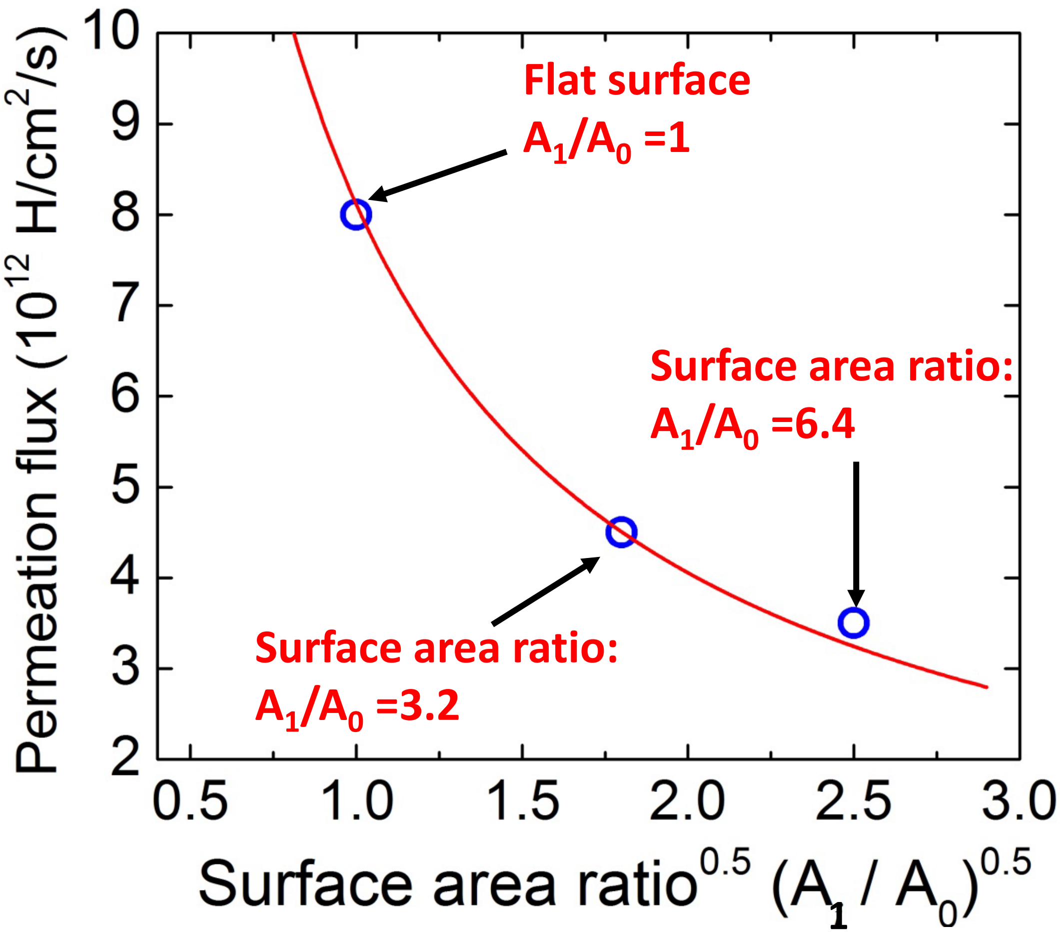


Surface area ratio: A_1/A_0=3.2
Effective thickness:

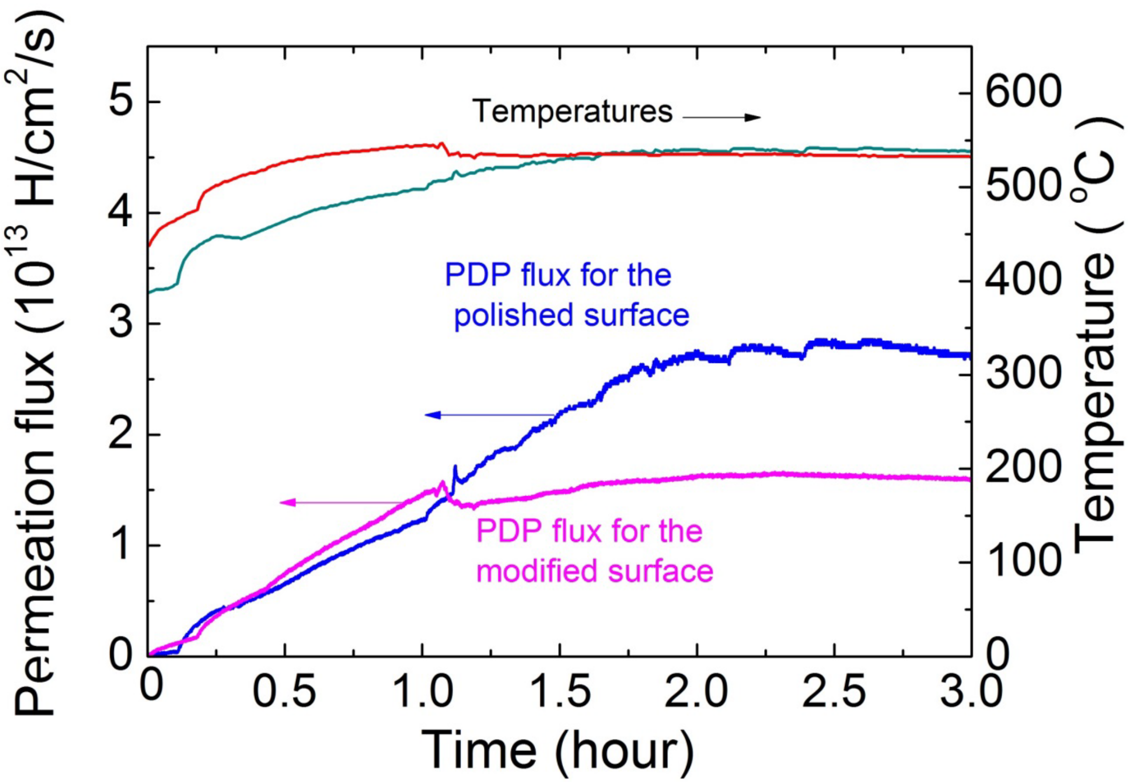
4 mm< L_{eff} < 5 mm

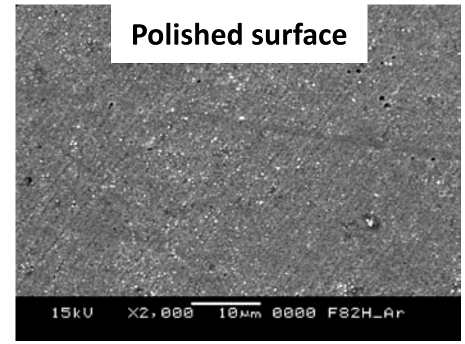
Surface area effects on PDP (2)

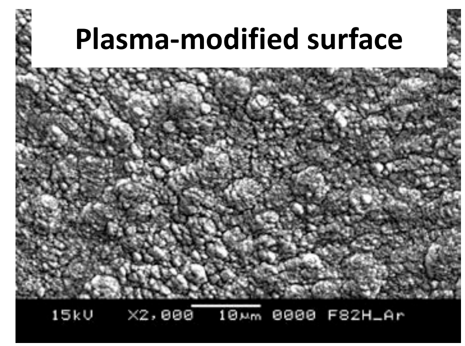
The measured steady state permeation flux has been found to be inversely proportional to the square root of surface area, which is in good agreement with the model prediction.



Surface area effects on PDP (3)

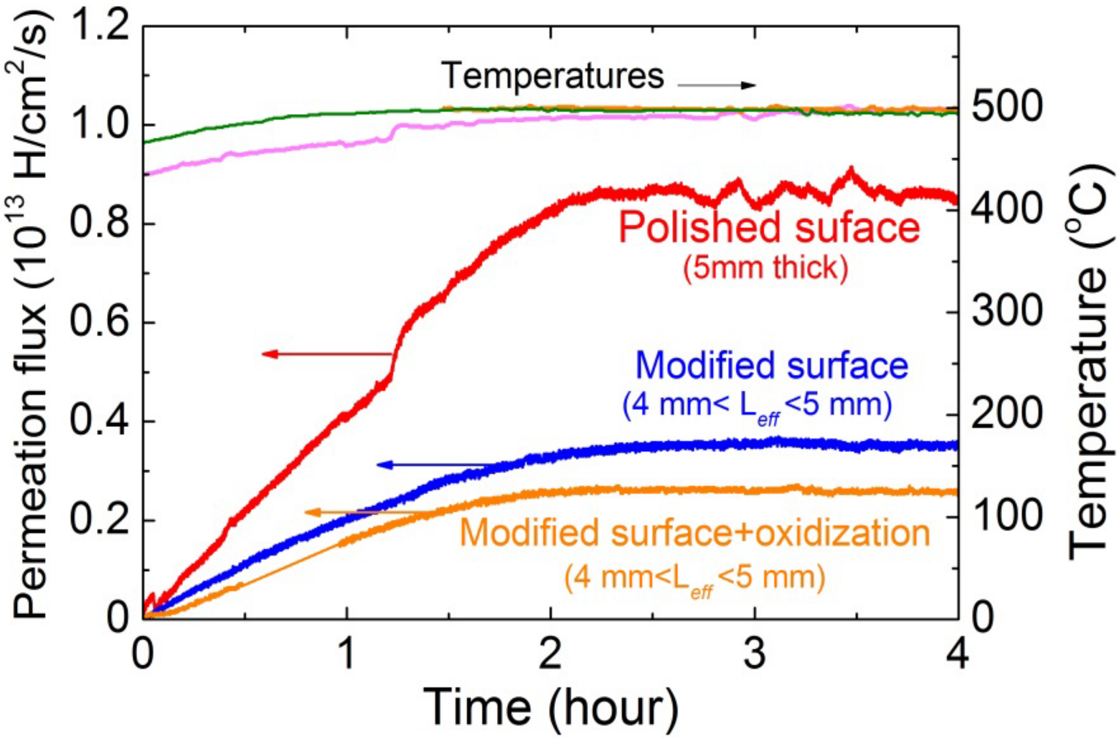




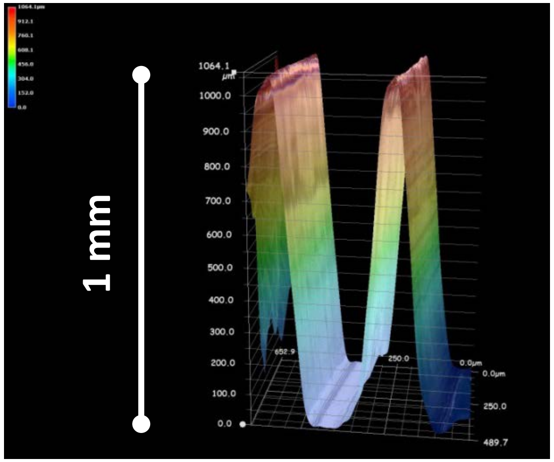


- **Compared with the polished surface, the steady state PDP flux for the plasma modified surface has been found to decrease by a factor of ~1.7, indicating a surface area ratio of A_1/A_0=~2.8.**
- **The surface area is increased due to the surface modification.**

Combined two surface condition effects



The modified surface



- A combined effect has been observed as follows:

Combined surface effect ≈ oxidization effect × surface area effect

~3.2 ~ 1.4 ~2.5

Summary and future plans

I. **Bi-directional hydrogen permeation has been demonstrated for the first time in a laboratory-scale steady state plasma facility.**

II. **Revaluation of the dynamic tritium pressure in a fuel recovery loop has been performed.**

III. **Hydrogen PDP and GDP through F82H have been investigated under some of the reactor-relevant conditions.**

IV. **Hydrogen transport parameters have been evaluated for F82H, including the recombination coefficient.**

V. **Surface condition effects on hydrogen permeation have been examined and a new model has been proposed to interpret the data.**

VI. **Future plans include: deuterium PDP and GDP experiments to evaluate the isotope effects and also surface coatings effects (i.e. W-coatings).**