Tritium permeation with different boundary conditions on the exit side

WP PWIE 2022 review meeting

F. Montupet-Leblond, E. Bernard, E. Hodille, M. Payet, S. Vartanian, R. Delaporte-Mathurin, J. Mougenot, Y. Charles, C. Grisolia

Outline

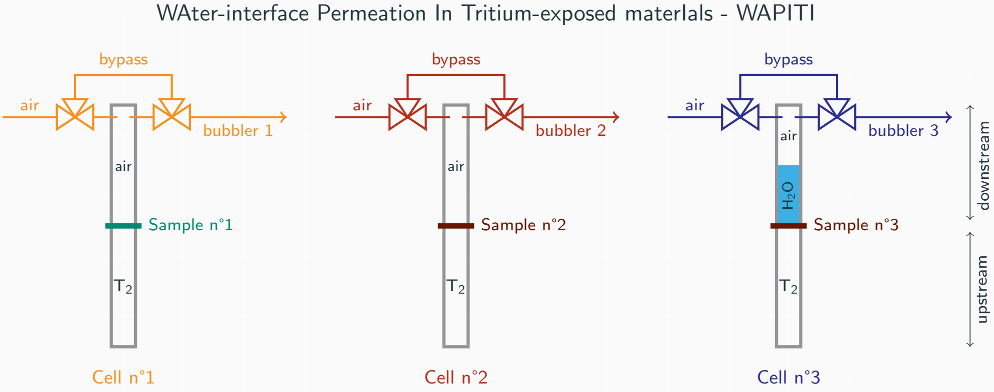
1. Presentation of the Wapiti experiment
2. Preliminary measurements with H and D
3. Tritium permeation simulations
4. Adapting this method to 316L steel

Presentation of the Wapiti tritium experiment

Goals & setup of the Wapiti experiments

- Goal 1: Confronting our model to tritium experimental results
- Goal 2: Extending our experimental range: low temperatures, permeation into water

- Goal 1: Confronting our model to tritium experimental results
- Goal 2: Extending our experimental range: low temperatures, permeation into water



Pictures of the Wapiti experiments

Close-up of the three permeation cells:

Close-up of the three permeation cells:

View of the glovebox and bubblers:

Pros and cons of tritium experiments

Pros	Cons
Access to new conditions	Simplified devices
High sensitivity	Costly measurements
Relevance for safety	Complex to operate

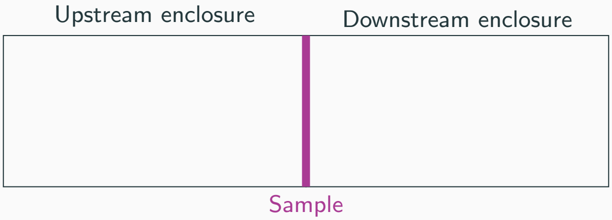
Pros	Cons
Access to new conditions	Simplified devices
High sensitivity	Costly measurements
Relevance for safety	Complex to operate

$\Rightarrow$ H/D experiments are performed first:
tritium experiments require to know the permeation behaviour of the investigated material!

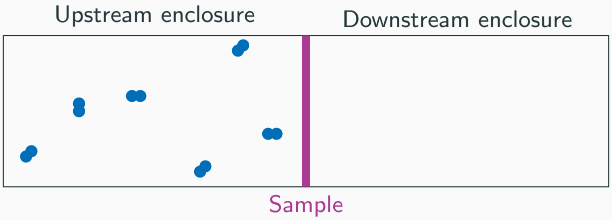
Preliminary measurements with H and D

Diffusivity D, permeability Φ and solubility K
can be determined with gas-driven permeation experiments

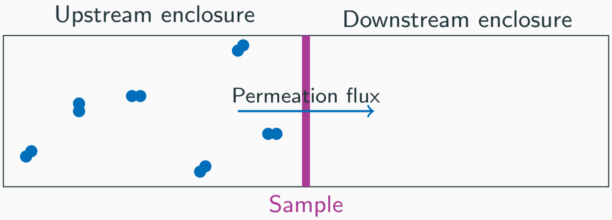
Diffusivity D, permeability Φ and solubility K
can be determined with gas-driven permeation experiments



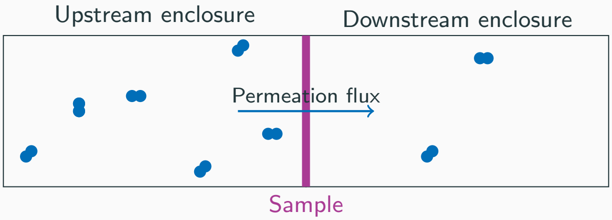
Diffusivity D, permeability Φ and solubility K
can be determined with gas-driven permeation experiments



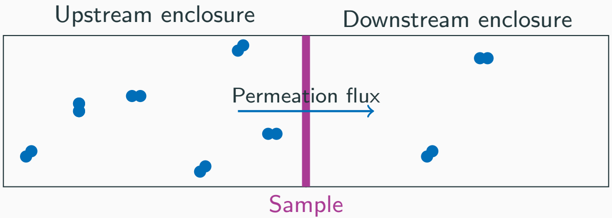
Diffusivity D, permeability Φ and solubility K
can be determined with gas-driven permeation experiments



Diffusivity D, permeability Φ and solubility K
can be determined with gas-driven permeation experiments



Diffusivity D, permeability Φ and solubility K
can be determined with gas-driven permeation experiments



If permeation is diffusion-limited, the permeation flux contains D and Φ

Objectives:

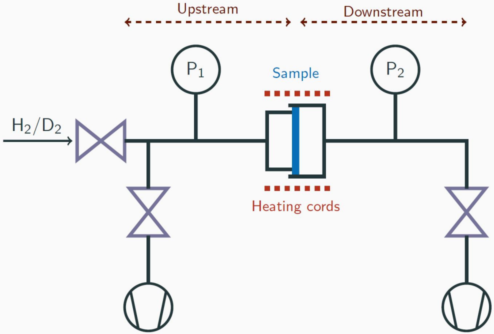
- Measuring transport parameters with H or D

Objectives:

- Measuring transport parameters with H or D
- Paving the way for a tritium experiment

Objectives:

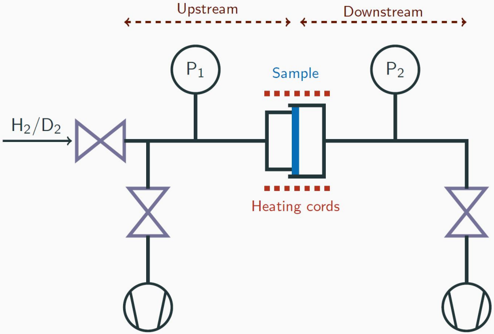
- Measuring transport parameters with H or D
- Paving the way for a tritium experiment

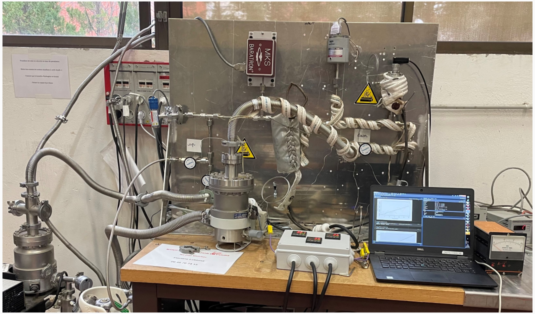


HYdrogen PERmeation in TOkamak-relevant MATErials - Hypertomate

Objectives:

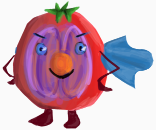
- Measuring transport parameters with H or D
- Paving the way for a tritium experiment

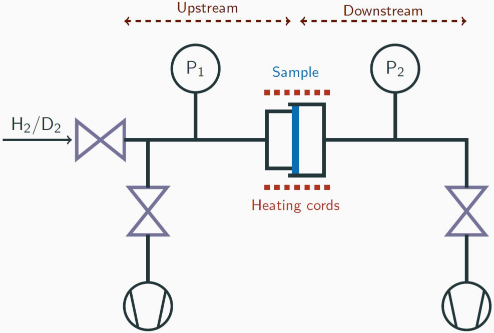


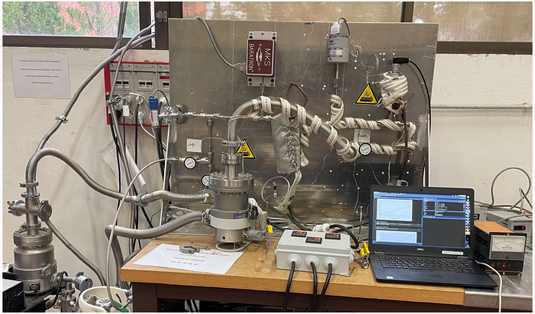


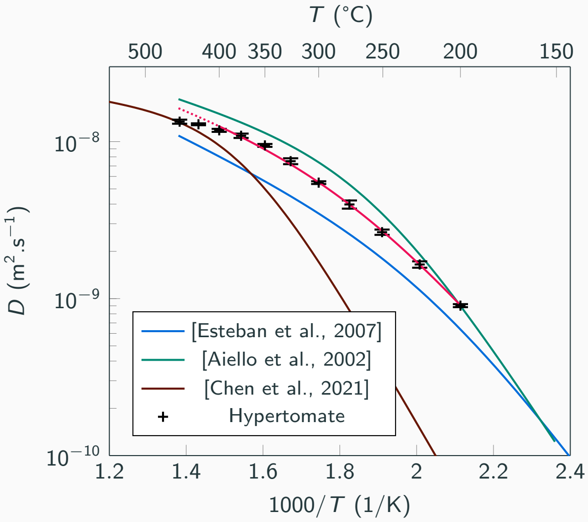
Objectives:

- Measuring transport parameters with H or D
- Paving the way for a tritium experiment









Trapping has an influence on the diffusivity of this material: further investigation of trapping is required

Experimental procedure:

1. Gas loading: 6 hours at 673 K under D_2

Experimental procedure:

1. Gas loading: 6 hours at 673 K under D_2
2. Thermal quenching: cool-down to 300 K

Experimental procedure:

1. Gas loading: 6 hours at 673 K under D_2
2. Thermal quenching: cool-down to 300 K
3. Resting and pumping down

Experimental procedure:

1. Gas loading: 6 hours at 673 K under D_2
2. Thermal quenching: cool-down to 300 K
3. Resting and pumping down
4. TDS itself: 1 $K.s^{-1}$ ramp up to 873 K (maximum temperature chosen to remain within Eurofer97 specifications)

Eurofer97 TDS up to 873 K

Experimental procedure:

1. Gas loading: 6 hours at 673 K under D_2
2. Thermal quenching: cool-down to 300 K
3. Resting and pumping down
4. TDS itself: 1 $K.s^{-1}$ ramp up to 873 K (maximum temperature chosen to remain within Eurofer97 specifications)

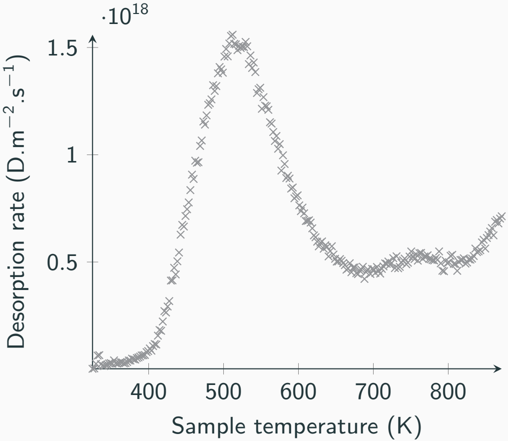
The sample is unannealed

Eurofer97 TDS up to 873 K

Experimental procedure:

1. Gas loading: 6 hours at 673 K under D_2
2. Thermal quenching: cool-down to 300 K
3. Resting and pumping down
4. TDS itself: 1 $K.s^{-1}$ ramp up to 873 K (maximum temperature chosen to remain within Eurofer97 specifications)

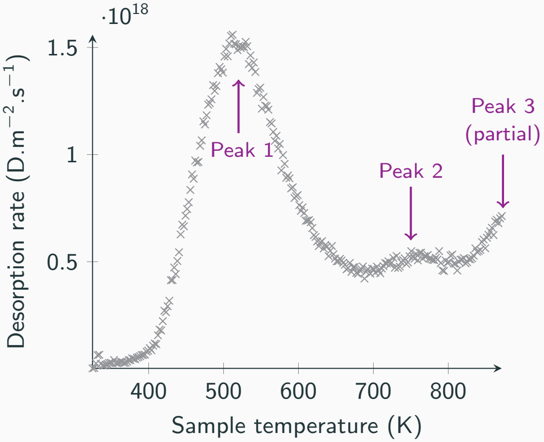
The sample is unannealed

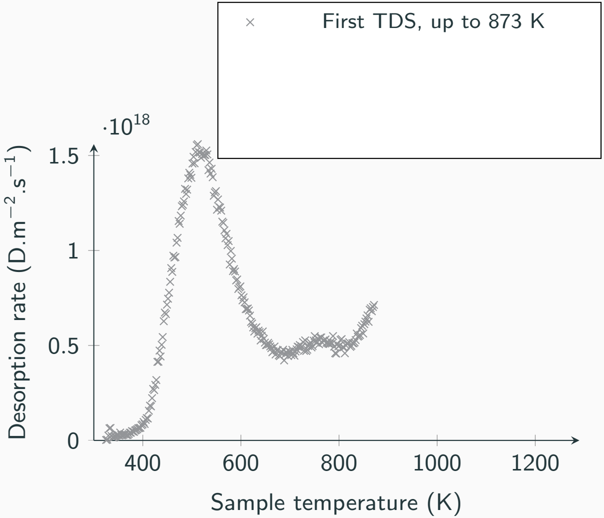


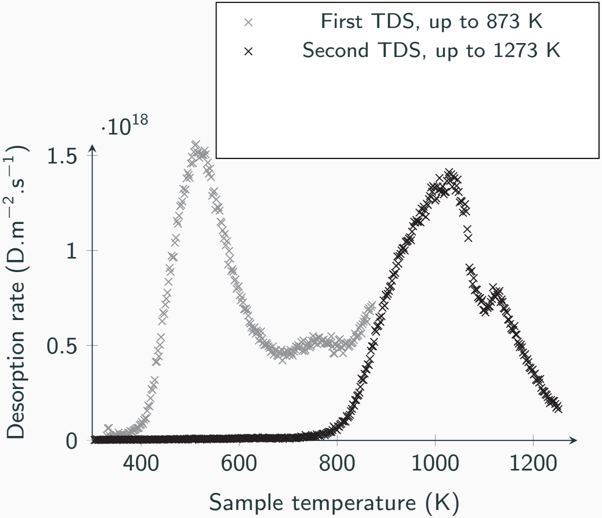
Experimental procedure:

1. Gas loading: 6 hours at 673 K under D_2
2. Thermal quenching: cool-down to 300 K
3. Resting and pumping down
4. TDS itself: 1 $K.s^{-1}$ ramp up to 873 K (maximum temperature chosen to remain within Eurofer97 specifications)

The sample is unannealed

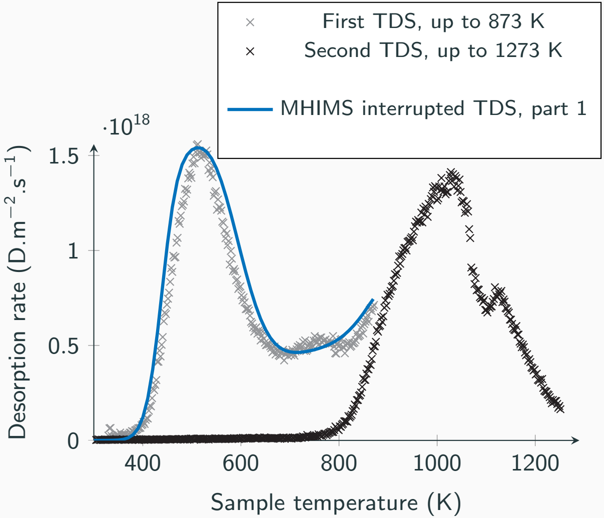



First TDS, up to 873 K
·10^18
1.5
1
0.5
0
400
600
800
1000
1200
Desorption rate (D.m−2.s−1)
Sample temperature (K)

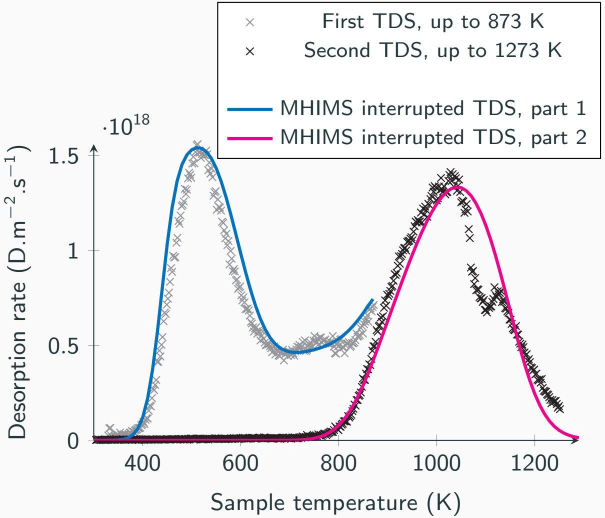


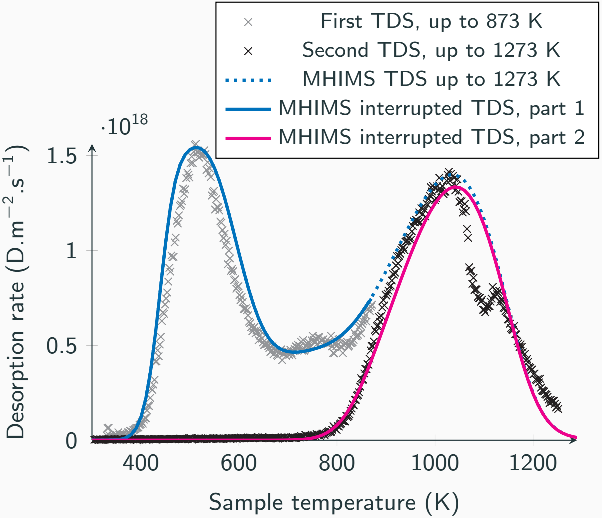
First TDS, up to 873 K
Second TDS, up to 1273 K
$\cdot 10^{18}$
1.5
1
0.5
0
400
600
800
1000
1200
Desorption rate ($D.m^{-2}.s^{-1}$)
Sample temperature (K)

Eurofer97 TDS and MHIMS TDS

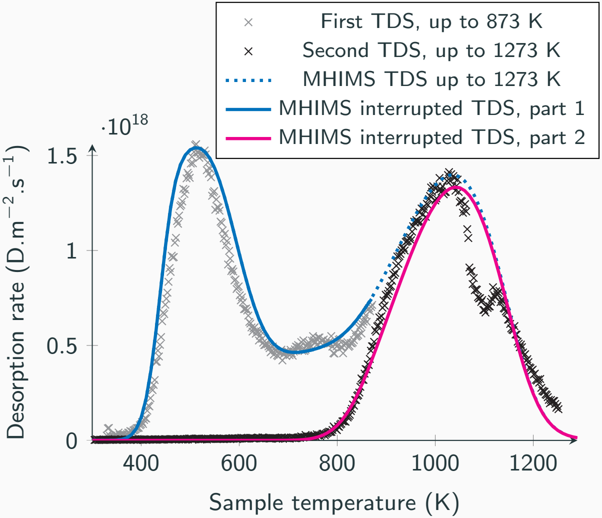


Eurofer97 TDS and MHIMS TDS





- Satisfactory simulation of the two experiments



- Satisfactory simulation of the two experiments
- Three trapping sites are required to model trapping in this material

	Site 1	Site 2	Site 3
Energy (eV)	0.51	1.27	1.65
Density (m^{-3})	$6.01 \cdot 10^{25}$	$6.44 \cdot 10^{22}$	$3.88 \cdot 10^{23}$

We now have transport and trapping parameters for this material:

we can use MHIMS[1] to predict the outcome of tritium permeation experiments

[1] our reaction-diffusion code, see [Hodille, Bonnin, et al., 2015]

Tritium permeation simulations

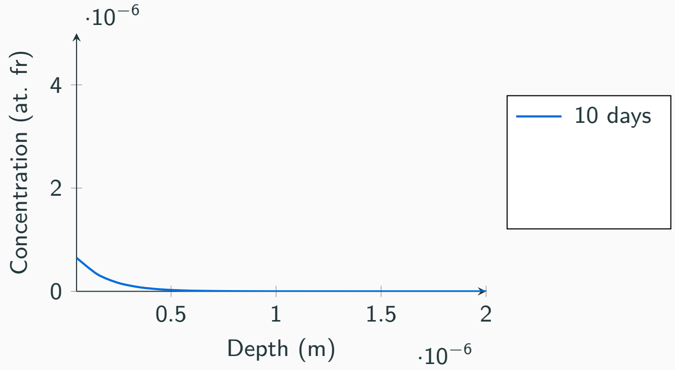
Wapiti experiments take place at room temperature

$\Rightarrow$ MHIMS predictions (taken with a grain of salt) are required

MHIMS predictions of Wapiti experiments

Wapiti experiments take place at room temperature

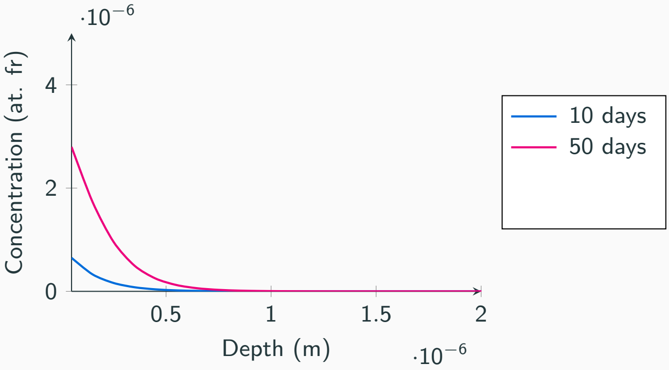
$\Rightarrow$ MHIMS predictions (taken with a grain of salt) are required



MHIMS predictions of Wapiti experiments

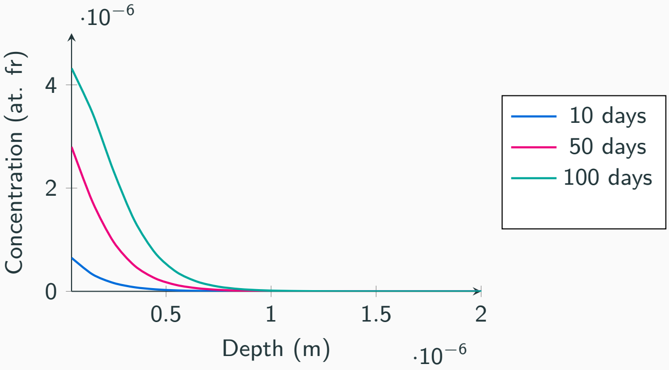
Wapiti experiments take place at room temperature

$\Rightarrow$ MHIMS predictions (taken with a grain of salt) are required



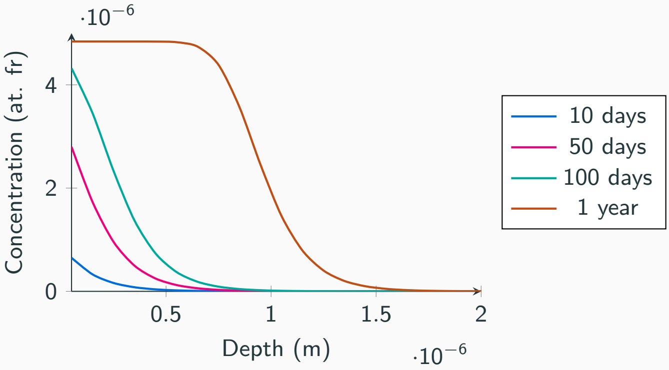
Wapiti experiments take place at room temperature

$\Rightarrow$ MHIMS predictions (taken with a grain of salt) are required



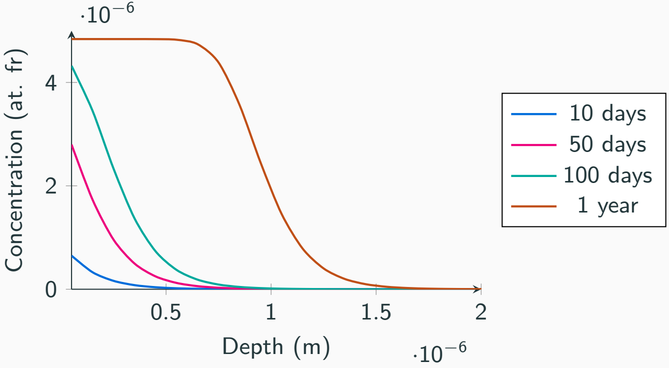
Wapiti experiments take place at room temperature

$\Rightarrow$ MHIMS predictions (taken with a grain of salt) are required



MHIMS predictions of Wapiti experiments

Wapiti experiments take place at room temperature
$\Rightarrow$ MHIMS predictions (taken with a grain of salt) are required

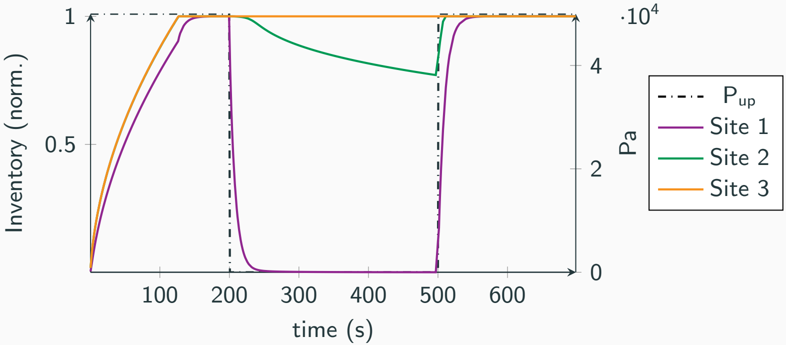


Low-temperature permeation experiments cannot be performed directly on Eurofer97 samples...

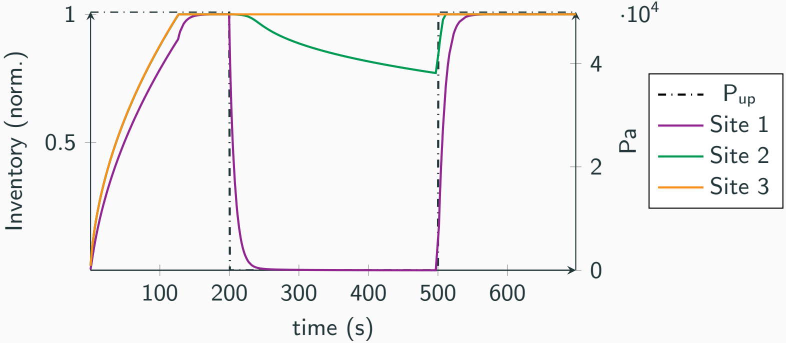
How does each trapping site contribute to permeation?

We have witnessed experimentally that the first timelag behaves differently from the following ones.

We have witnessed experimentally that the first timelag behaves differently from the following ones. This can be explained by looking at the inventories during two permeation cycles:

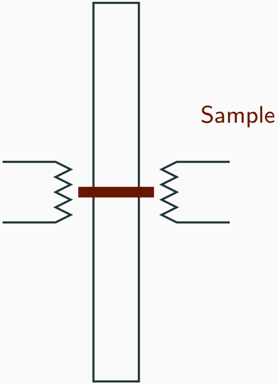


We have witnessed experimentally that the first timelag behaves differently from the following ones. This can be explained by looking at the inventories during two permeation cycles:



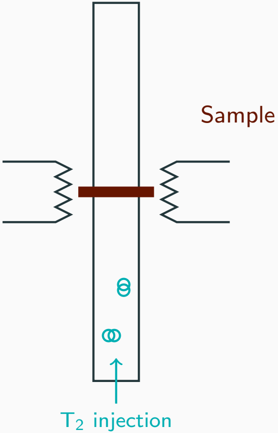
The extra time is required to fill the third trapping site, which is irreversible at this temperature

Loading procedure:



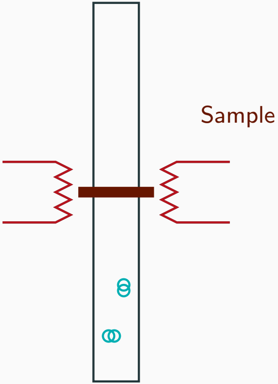
Loading procedure:

- Injection of tritium upstream, at the pressure required for the experiment



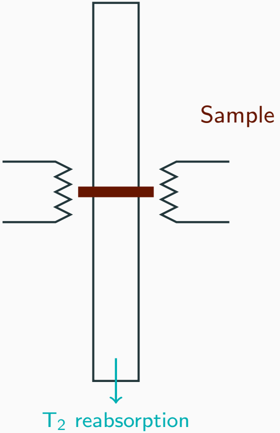
Loading procedure:

- Injection of tritium upstream, at the pressure required for the experiment
- Heating up: 150°C during 45 minutes



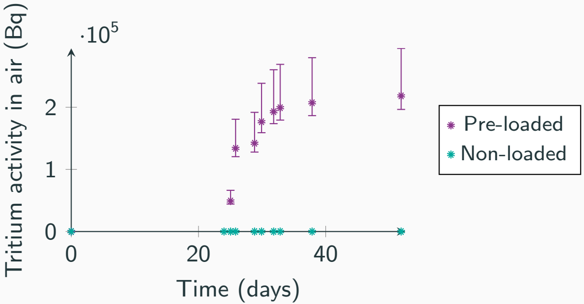
Loading procedure:

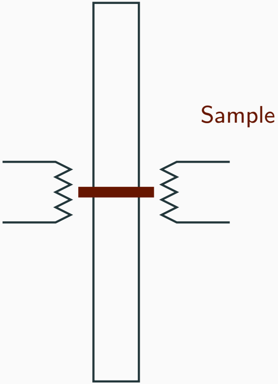
- Injection of tritium upstream, at the pressure required for the experiment
- Heating up: 150°C during 45 minutes
- Reabsorption: tritium is removed from the upstream part



Loading procedure:

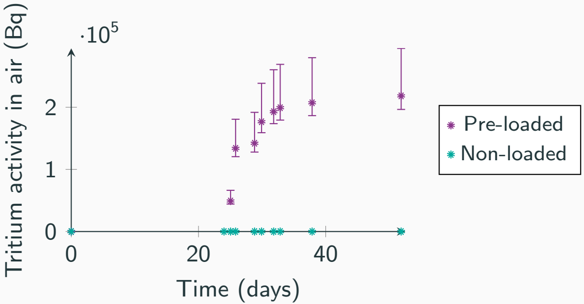
- Injection of tritium upstream, at the pressure required for the experiment
- Heating up: 150°C during 45 minutes
- Reabsorption: tritium is removed from the upstream part

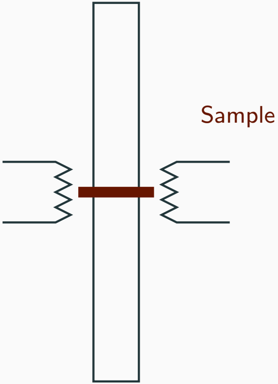




Loading procedure:

- Injection of tritium upstream, at the pressure required for the experiment
- Heating up: 150°C during 45 minutes
- Reabsorption: tritium is removed from the upstream part





The loading procedure is necessary to measure RT permeation in Eurofer97

Adapting this method to 316L steel

No satisfying result obtained: the permeation regime is not diffusion-limited, repeatability is not within the usual range

No satisfying result obtained: the permeation regime is not diffusion-limited, repeatability is not within the usual range

This is actually caused by the native Cr_2O_3 formed even at low temperatures if the H_2O concentration is higher than 10 ppm

No satisfying result obtained: the permeation regime is not diffusion-limited, repeatability is not within the usual range

This is actually caused by the native Cr_2O_3 formed even at low temperatures if the H_2O concentration is higher than 10 ppm

Workaround to this issue: coating the 316L samples with a Pd layer

No satisfying result obtained: the permeation regime is not diffusion-limited, repeatability is not within the usual range

This is actually caused by the native Cr_2O_3 formed even at low temperatures if the H_2O concentration is higher than 10 ppm

Workaround to this issue: coating the 316L samples with a Pd layer

Next steps: H permeation tests (november) and tritium tests (december)

References

References i

Pearson, Richard J et al. (2018). "Tritium supply and use: a key issue for the development of nuclear fusion energy". In: *Fusion Engineering and Design* 136, pp. 1140–1148.

Tanabe, T (2013). "Tritium fuel cycle in ITER and DEMO: Issues in handling large amount of fuel". In: *Journal of Nuclear Materials* 438, S19–S26.

Perrault, Didier (2017). *Nuclear Fusion Reactors - Safety and radiation protection considerations for demonstration reactors that follow the ITER facility*. Institut de Radioprotection et de Sûreté Nucléaire.

De Temmerman, G. et al. (2017). "Efficiency of thermal outgassing for tritium retention measurement and removal in ITER". In: *Nuclear Materials and Energy* 12. Proceedings of the 22nd International Conference on Plasma Surface Interactions 2016, 22nd PSI, pp. 267–272. ISSN: 2352-1791.

McNabb, A. and P. K. Foster (1963). "A new analysis of the diffusion of hydrogen in iron and ferritic steels". In: *Transactions of the Metallurgical Society of AIME* 27, pp. 227–618.

Hodille, Etienne, A Založnik, et al. (2017). "Simulations of atomic deuterium exposure in self-damaged tungsten". In: *Nuclear Fusion* 57.5, p. 056002.

Hodille, Etienne, Xavier Bonnin, et al. (2015). "Macroscopic rate equation modeling of trapping/detrapping of hydrogen isotopes in tungsten materials". In: *Journal of Nuclear Materials* 467, pp. 424–431.

Esteban, G.A. et al. (2007). "Hydrogen transport and trapping in Eurofer97". In: *Journal of Nuclear Materials* 367-370, pp. 473–477.

Aiello, A. et al. (2002). "Hydrogen isotopes permeability in Eurofer97 martensitic steel". In: *Fusion Science and Technology* 41, pp. 872–876.

Chen, Ze et al. (2021). "Deuterium transport and retention properties of representative fusion blanket structural materials". In: *Journal of Nuclear Materials* 549, p. 152904.

Martynova, Y et al. (2017). "Deuterium retention in RAFM steels after high fluence plasma exposure". In: *Nuclear Materials and Energy* 12, pp. 648–654.

Oriani, R.A. (1970). "The diffusion and trapping of hydrogen in steel". In: *Acta Metallurgica* 18 (1), pp. 147–157.

Benannoune, S et al. (2019). "Numerical simulation by finite element modelling of diffusion and transient hydrogen trapping processes in plasma facing components". In: *Nuclear Materials and Energy* 19, pp. 42–46.

Fernández-Sousa, Rebeca, Covadonga Betegón, and Emilio Martinez-Pañeda (2020). "Analysis of the influence of microstructural traps on hydrogen assisted fatigue". In: *Acta Materialia* 199, pp. 253–263.

Ryabtsev, SA et al. (2017). "Deuterium thermal desorption and re-emission from RAFM steels". In: *Physica Scripta* 2017.T170, p. 014016.

Qiao, L et al. (2017). "Erosion and deuterium retention of CLF-1 steel exposed to deuterium plasma". In: *Physica Scripta* 2017.T170, p. 014025.

Hu, Xunxiang et al. (2019). "Deuterium retention in advanced steels for fusion reactor structural application". In: *Journal of Nuclear Materials* 516, pp. 144–151.

Michler, Thorsten and Michael P Balogh (2010). "Hydrogen environment embrittlement of an ODS RAF steel–Role of irreversible hydrogen trap sites". In: *International Journal of Hydrogen Energy* 35.18, pp. 9746–9754.

Oliveira, VB, KD Zilnyk, and HRZ Sandim (2017). "Thermodynamic simulation of reduced activation ferritic-martensitic Eurofer97 steel". In: *Journal of Phase Equilibria and Diffusion* 38, pp. 208–216.