

Design of a multi-isotopic co- and counter- permeation experiment

S.J. Hendricks^{*,a}, E. Carella^a, D. Jimenez^a, J.M. García^a, J. Molla^a

^a*Ciemat, Av. Complutense, 40, 28040 Madrid, Spain*

Abstract

A safe operation of the HCPB breeding blanket system for nuclear fusion reactors requires tritium permeation from the breeder into the coolant to be kept as low as possible. Numerical simulations of multi-isotopic hydrogen transport scenarios in HCPB related environments could identify an injection of H₂ gas to the coolant as a method to affect the amount of permeating tritium. For the experimental investigation of co- and counter-permeating protium and tritium as a permeation mitigation or enhancement mechanism a new permeation chamber has been designed in which tritium is substituted by deuterium. It consists of two gas chambers separated by a EUROFER sample disk which is heated to temperatures of up to 600 °C. The set-up allows pre-heating and injecting arbitrary partial pressure configurations of H₂ + D₂ gas mixes into each chamber. Via leak valves the permeation cells are connected to a quadrupole mass spectrometer thus enabling measurements of the deuterium permeation flux from a D₂ or H₂ + D₂ filled gas chamber into an evacuated or H₂ filled chamber. Apart from determining general hydrogen transport coefficients of the sample disk material the presented experiment is designed to serve as a validation tool for existing multi-isotopic hydrogen transport models.

Keywords: HCPB, tritium modeling, multi-isotopic transport, co-permeation, counter-permeation, permeation experiment

1. Introduction

Enabling tritium self-sufficiency of future fusion reactors is one of the main purposes of the breeding blanket system (BB). Amongst others, the helium cooled pebble bed (HCPB) is a solid breeding blanket concept currently under development [1, 2]. In this BB design lithium containing ceramic pebbles (Li₄SiO₄, Li₂TiO₃ compositions [3]) are densely packed and stored in compartments surrounding the plasma facing first wall. They are separated by beryllium layers serving as neutron multipliers. Nuclear reactions between high-energy neutrons coming from the fusion plasma and the lithium results in a generation of tritium which diffuses to the ceramic pebble surfaces. The interstitial sites of the pebble bed are rinsed by a He + H₂ purge gas. By adding H₂ to the purge gas recombination and isotope exchange reactions occur at the pebble surfaces causing the release of HT, T₂, H₂O, HTO and T₂O into the gas [4, 5, 6, 7]. The purge gas carries the liberated tritiated molecules to a tritium extraction system [8]. The heat produced by the neutron multiplying and tritium breeding reactions is absorbed by the purge gas and further transferred to EUROFER cooling plates with integrated cooling channels where pressurized helium gas acts as the coolant fluid. Due to the relatively high hydrogen solubility of the cooling plate material a significant fraction of the H₂, T₂, HT, H₂O, HTO and T₂O molecules will dissociate and dissolve into the purge gas channel walls causing a diffusive transport of protium (H)

and tritium (T) through the EUROFER bulk before they recombine and enter the coolant (see figure 1). Although the HCPB concept exhibits the least severe level of coolant contamination among all BB designs, for a safe operation it is essential to minimize the permeation flux of tritium from the purge gas into the coolant as much as possible. For this purpose different methods have been proposed and are currently under intense investigation. One technique focuses on the application of tritium permeation barrier materials coated on the interior wall of the purge gas channels [9]. Another approach consists in a controlled injection of H₂ gas to the coolant which leads to a simultaneous co- and counter-permeation of protium and tritium from both sides through the EUROFER cooling plates. Numerical simulations suggest that in certain H₂ partial pressure regimes this could have a mitigating effect on the net amount of permeating tritium into the coolant [10, 11, 12]. For the experimental investigation of this phenomenon a new multi-isotopic **CO**- and **cO**unter-**PER**meation (COOPER) experiment has been designed within the scope of this work. The experiment enables a quantitative particle flux measurement of D₂ gas permeating from a gas chamber through a thin EUROFER disk into a second gas chamber. Both chambers can be filled with an arbitrary partial pressure distribution of D₂ and H₂ gas, thus creating co- and counter-permeation scenarios under HCPB conditions with the difference of using D₂ gas instead of tritium containing molecules. The aim is to study the effect different H₂ gas partial pressure configuration in the two chambers have on the net flux of permeating deuterium atoms. A further objective of the COOPER experiment is the validation of a developed numerical simulation tool which al-

* Email address: sebastian.hendricks@ciemat.es
URL: <http://dx.doi.org/...>

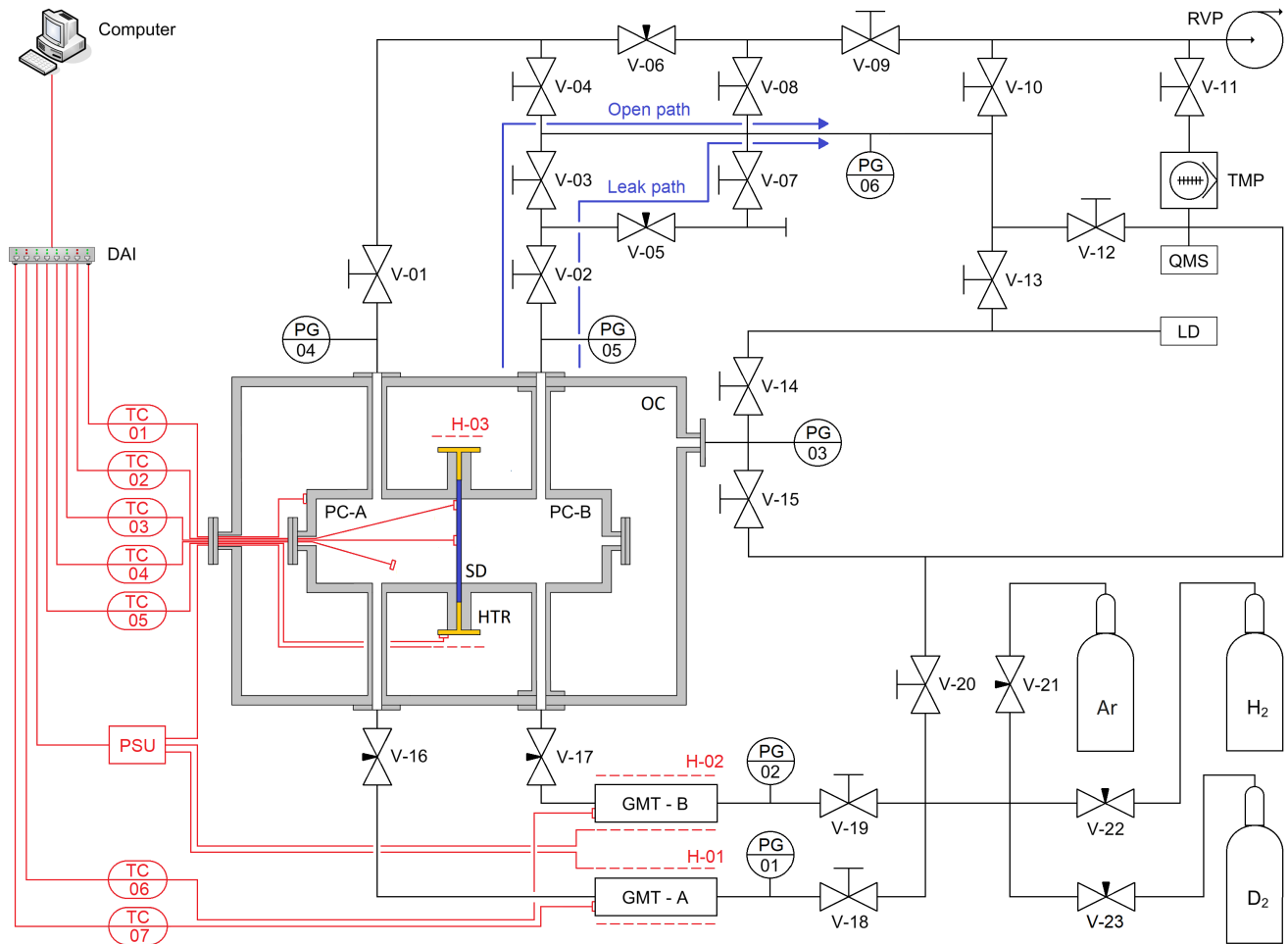


Figure 1: Process flow diagram of the COOPER experimental set-up (DAI: Data acquisition interface, PSU: Power supply unit, TC: Thermocouple, PC: Permeation cell, OC: Outer camera, H: Heater, SD: Sample disk, HTR: Heat transfer ring, V: Valve, PG: Pressure gauge, GMT: Gas mixing tank, LD: Leak detector, QMS: Quadrupole mass spectrometer, TMP: Turbo molecular pump, RVP: Rotary vane pump).

allows calculating multi-isotopic transport in the HCPB breeding blanket system. The design of the COOPER experiment is presented in this article.

2. Experimental design

The process flow diagram (PFD) of the entire experimental set-up can be seen in figure 1. The centerpiece of the COOPER experiment constitutes a cubic shaped vacuum chamber made of stainless steel which is called outer camera (OC). A photo of the fabricated outer camera is shown in figure 2. Its interior dimensions are 200 mm x 315 mm x 210 mm. Both 200 mm x 310 mm planes of the OC are open and form a flange with an embedded Viton® gasket. The two open sides are closed by cuboid shaped cover plates. One cover plate is welded to a DN-16CF half nipple which is connected to electric and thermocouple feedthroughs. At the roof of the OC there is another access to the interior of the OC established by a welded ISO-25 KF flange.

The ISO-25KF flange is linked to a vacuum pumping system. It consists of a rotary vane pump (RVP) and a turbo molecular pump (TMP). Thus, the interior of the OC can be evacuated

while the pressure is controlled with pressure gauge PG-03. A leak detector (LD) allows measuring the particle fluxes of H₂, HD or D₂ gas inside of the OC. The OC houses the permeation cells A and B (PC-A and PC-B), which is where the observed permeation process happens. A photo of the permeation cells mounted inside of the OC is presented in figure 3. It shows PC-B in the front connected to PC-A which is visible in the back of the OC. A section cut of the permeation cell system can be seen in figure 4. The two permeation cells are almost identical square shaped 40 mm wide stainless-steel chambers with a cylindrical inner cavity of 28 mm diameter. This implies a minimum wall thickness of 6 mm. Both PCs have a flat back-wall with a thickness of 5 mm welded to a DN-16CF flange. While the flange of PC-B is closed with a blind flange, the DN-16CF flange of PC-A is connected to a three-pole thermocouple feedthrough which enables inserting three K-type thermocouples TC-02, TC-03 and TC-04 into the interior of the permeation cell without losing leak tightness. On their opposite side the PCs are open and connected to a 80 mm wide round custom-made flange with six M6 screw holes. Gas can enter and exit each PC through a narrow gas inlet pipe and a wider outlet pipe. The gas inlet pipes have a wall thickness of 1 mm

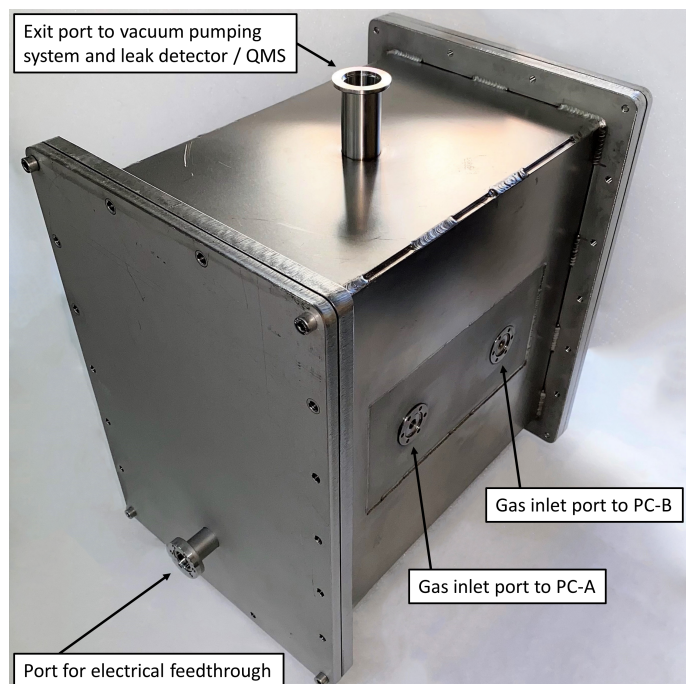


Figure 2: Photo of the fabricated co- and counter-permeation chamber separated from the rest of the experimental system. The picture shows the outer camera which hosts the permeation cells A and B.

and an inner diameter of 6 mm. The outlet pipes exhibit a wall thickness of 1.5 mm and an inner diameter of 17 mm. The gas pipes of both PCs are connected to four exit ports at the inner side of the outer camera, of which two are located at each of the two 315 mm x 310 mm planes respectively (see figure 3). While the inlet and outlet pipes of PC-A are welded from inside to the exit ports of the OC, the pipes of PC-B exhibit a connection via a DN-16CF and a DN-25CF flange. This design enables completely detaching PC-B and remove it from the system while PC-A always remains in its fix position attached to the outer camera. This reduces the possibility of leakages at the flange connections. Outside of the OC the four gas pipe exit ports are each welded to a DN-16CF flange. Placing the copper gaskets and tightening the screws of the CF flanges of PC-B requires some longitudinal and transversal clearance of at least one of the gas pipes. Therefore, the gas outlet pipe of PC-B consists of a flexible bellow tube.

The primary objective of the planned experimental campaign is the measurement of the D_2 and HD permeation flux through a sample disk (SD) while varying the H_2 partial pressures on both sides of the disk. The SD is clamped between the two open flanges of the PCs. It has a diameter of 48 mm and a thickness of 1 mm. Special focus is placed on EUROFER as the disk material. Since the permeation fluxes are usually very small, very good leak tightness between the PCs and the SD is essential for a precise measurement. Due to high disk temperatures of up to 600 °C it is chosen to use custom designed Helicoflex® O-rings for the sealing made of a silver plated Inconel600® jacketed surrounding an internal Nimonic90 spring. The torus shaped gaskets have an inner diameter of 32.3 mm and an outer diameter

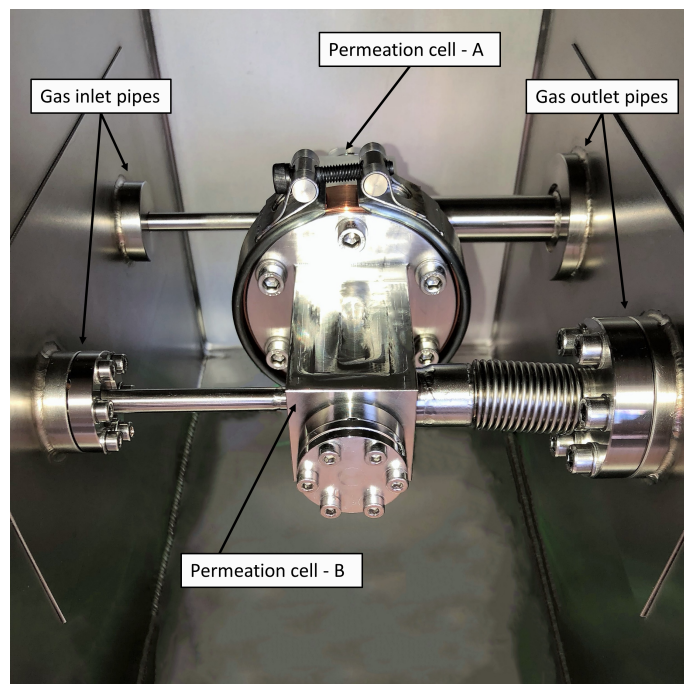


Figure 3: Photo of the permeation cells A and B mounted inside of the outer camera.

of 37.7 mm. They are sitting in a 2.3 mm deep circular groove with a diameter of 38 mm surrounding the cylindrical cavity of each PC (see upper images of figure 5). Consequently, the effective circular disk surface which is in contact with the interior atmosphere of each PC has a diameter of approximately 34 mm. The position of the gasket in contact with the SD is highlighted in the lower right image of figure 5. To heat up the sample disk to the mentioned temperature level a 38 mm long cylindrical band heater (H-03) is used. It is clamped around a copper cylinder which has an outer diameter of 86 mm, an inner diameter of 82 mm and a length of 25 mm. On its inner surface the cylinder is attached to a 1 mm flat copper disk with a circular cut-out in its center. The round cut-out has a diameter of 48 mm. By applying some force the sample disk can be placed inside of the cut-out, thus exhibiting a tight surface to surface connection with the copper ring. The system consisting of the copper disk attached to the copper cylinder will be called heat transfer ring (HTR). It can be seen in the lower left image of figure 5. A 0.5 mm x 1 mm increment located at the inner corner edge between the HTR jacket and the HTR disk enables to well center the HTR between the two permeation cell flanges. When the HTR is positioned between the PCs there is a 1 mm gap between the inner surface of the HTR jacket and the cylindrical outer surface of the flanges. As soon as the band heater is switched on, heat will quickly diffuse into the HTR disk sitting between the PCs before it enters the sample disk. The system consisting of the permeation cells, the heat transfer ring and the sample disk will from now on be called permeation tube (PT). Since the HTR is in tight contact with the permeation cell flanges, they will heat up too. The heat enters the SD through the contact surface between HTR

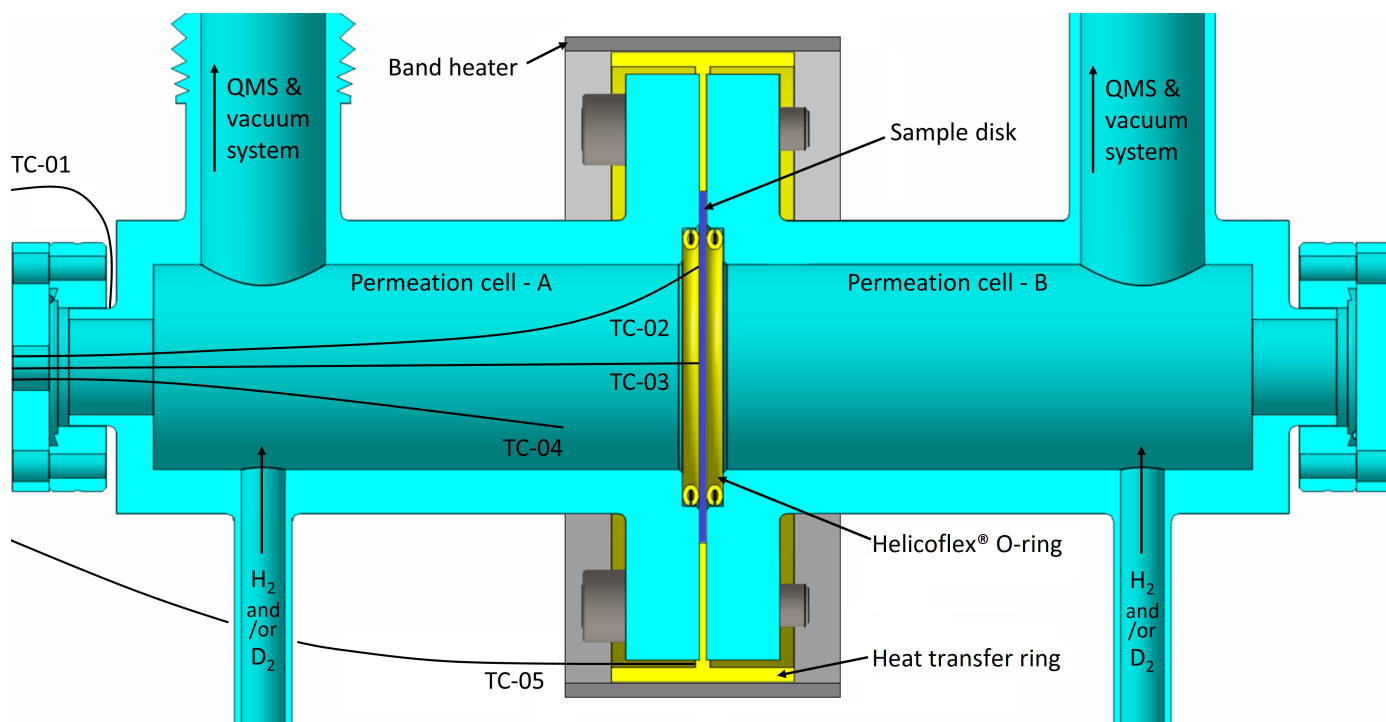


Figure 4: Section cut of the inner permeation cells which are separated by heat transfer copper ring and the sample disk.

and SD as well as through the contact surface between the PC flanges and the SD. To estimate the temperature profile that would establish in thermal equilibrium inside of each component a 3D model of the permeation tube together with the outer camera is imported into the finite element software ANSYS using the steady-state thermal analysis tool. It is assumed that the contact surface of band heater and HTR is maintained at a constant temperature of 650 °C. For the inner walls of the evacuated OD and the surfaces of the permeation tube only heat transfer by thermal radiation and thermal contact conductance are taken into account while outside of the OD also heat transfer through air convection is considered. It is found that in thermal equilibrium the PC walls would be in average 150 °C - 220 °C colder than the HTR. A convection or exchange of gas inside of the PCs would lead to an additional cooling and thus to even lower wall temperatures. Therefore, it is to expect that the temperature dependent permeation flux of hydrogen isotope gas through the walls of the PCs into the OC would have a negligible negative impact on the accuracy of the deuterium permeation flux measurements through the SD. In any case, since the OC is evacuated and connected to a leak detector the hydrogen isotope gas permeation flux through the steel walls of the PCs as well as any possible leakage occurring at the flanges will be detected and quantified. For the future, it is planned to cover the inner surfaces of the permeation cells with a layer of Al_2O_3 [13]. The ceramic material acts as a hydrogen permeation barrier and would therefore prevent an undesirable permeation through the PC walls into the OC. By using the ANSYS tool it is simulated that the temperature of the copper ring would decrease from 650 °C at the HTR jacket to 607 °C at the contact surface of HTR and SD. Thermocouple

TC-02 which is welded to the SD close to the Helicoflex® gasket would indicate a temperature of about 595 °C. Thermocouple TC-03 which sits in the center of the SD would measure a value of approximately 587 °C. The temperature profile in thermal equilibrium which establishes throughout the HTR attached to the SD is presented in figure 6. The simulation shows that the designed heating system would lead to a very small radial temperature gradient in the SD of only about $\Delta T = 10$ °C. Ensuring a flat radial temperature profile of the sample disk is essential for meaningful and precise experimental results. The band heater is fed by a power supply unit (PSU) which is linked to an electrical feedthrough attached to the DN-16CF exit flange at the cover plate of the OC. The temperature measurement data provided by the thermocouples is read out by a computer. The connection is established by a data acquisition interface (DAI). A LabVIEW program uses the temperature data of the thermocouples to control the heating power of the PSU. In this way the SD can be heated with an arbitrary temperature ramp and maintained at the desired temperature. The two DN-16CF entrance flanges of the outer camera that belong to the inlet gas pipes of the PT (see figure 2) are connected to a gas line system which permits inserting an arbitrary amount of Ar, H_2 , D_2 or a mix of these gases into each permeation cell. The gas line configuration of the presented experiment can be seen in the PFD of figure 1. Both gas inlet ports of the OC are connected to ultra-high vacuum all-metal gas dosing valves (V-16 and V-17) which withstand temperatures of up to 300 °C and enable controlling inlet gas flows in a range 1×10^{-10} –500 mbar l s^{-1} . Via flexible 1/4 inch stainless steel tubes both valves are linked to custom-made gas mixing tanks (GMT) with a volume of about 100 ml, each. Both

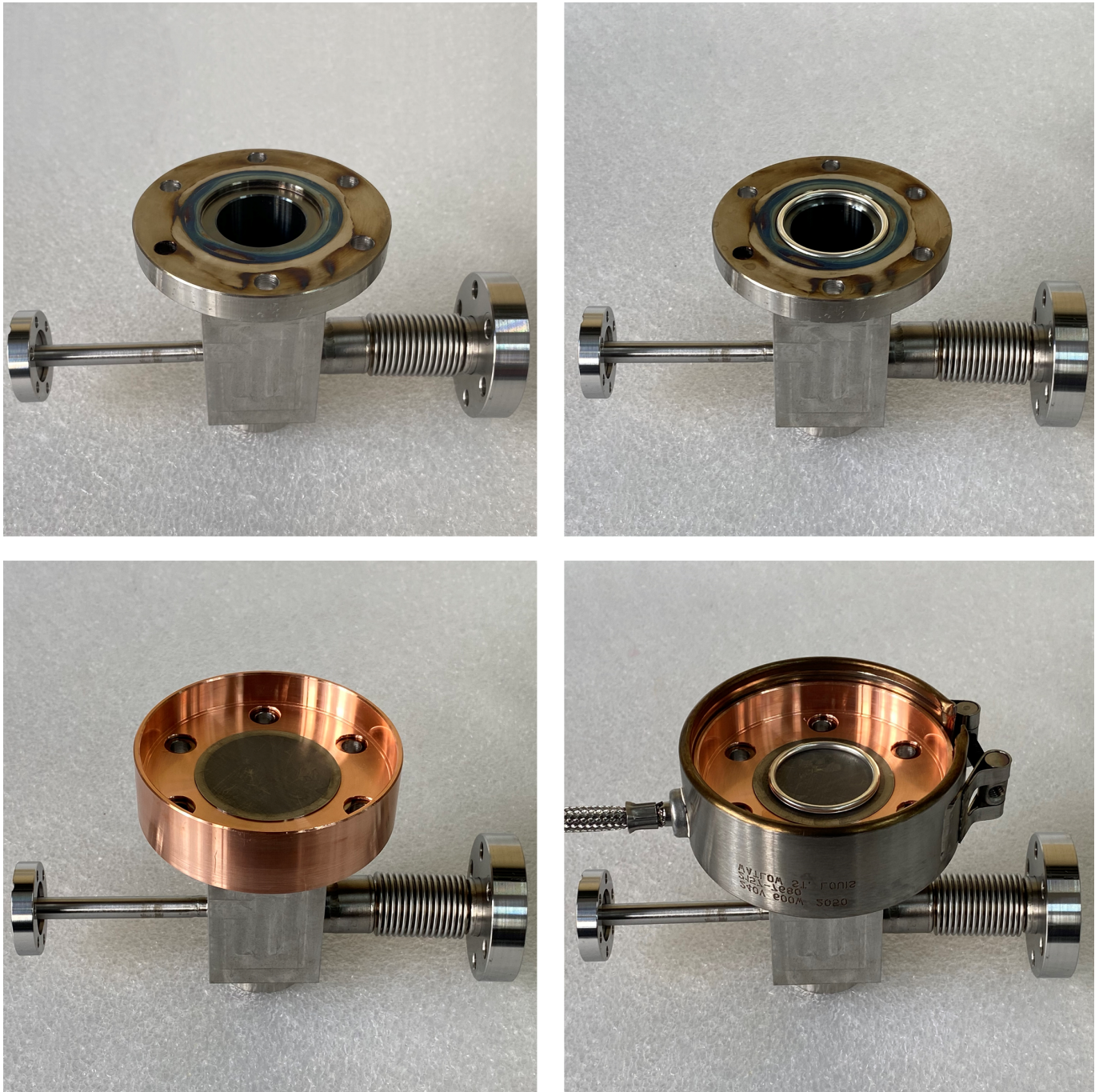


Figure 5: Photos showing the assembling steps of the permeation tube. [**upper left**] Open flange of the detached PC-B. [**upper right**] A Helicoflex® O-ring is placed in the prepared gasket bed of PC-B. [**lower left**] A heat transfer copper ring is centered on top of the open flange. An EUROFER sample disk is pressed in the round cut-out of the copper ring sitting on top of the Helicoflex® O-ring. [**lower right**] A second Helicoflex® gasket is centered on top of the sample disk. To insert heat into the sample disk a band heater is clamped around the cylinder jacket of the heat transfer ring.

GMTs are made of 25 cm long and 1 inch wide stainless steel tubes. A photo of the gas line system detached from the gas bottles is shown in figure 7. The GMTs serve as gas reservoirs where the different gases used in the experiment (H_2 , D_2 and Ar) can be mixed with an arbitrary partial pressure configuration and pre-heated before being injected into the permeation cells. Therefore, both GMTs are wrapped with heating cables (H-01 and H-02) and isolated by thermal insulation superwool

fiber. By pre-heating the gas before it enters the PCs it is intended to avoid an abrupt cooling of the hot sample disk in the moment of the gas injection. Like the band heater the heating cables of the GMTs are controlled by a LabVIEW based control program using temperature measurement data from two installed thermocouples (TC-06 and TC-07) as input parameters. The gas pressure inside of the tanks is controlled by two pressure sensors (PG-01 and PG-02), one connected to each GMT.

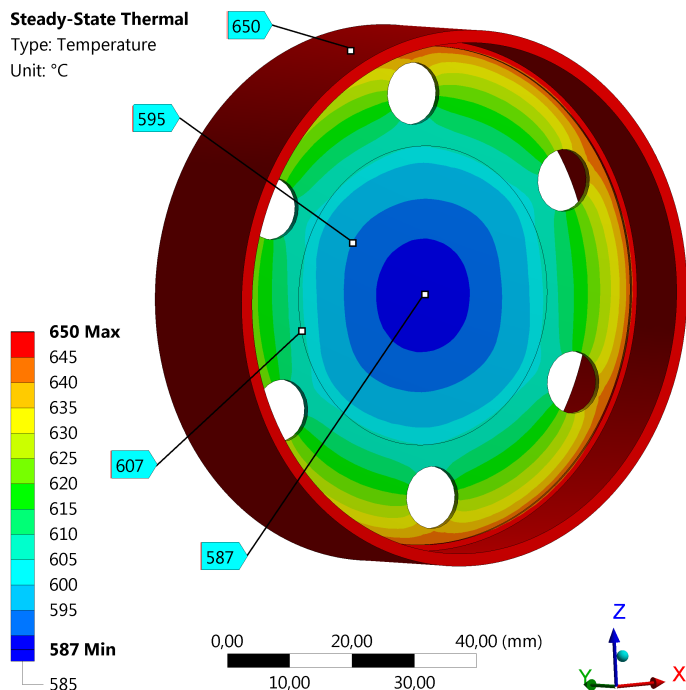


Figure 6: Temperature profile in thermal equilibrium establishing throughout the heat transfer ring attached to an EUROFER sample disk sitting in its center.

Two bellow sealed high temperature valves (V-18 and V-19) are placed right behind the pressure sensors. GMT-A is connected to PC-A and is defined as the volume enclosed between the valves V-16 and V-18. GMT-B is connected to PC-B and is defined as the volume enclosed between the valves V-17 and V-19. Behind the valves V-18 and V-19 the gas lines intersect and split into an Ar gas line, a H₂ gas line and a D₂ gas line. Each gas bottle is equipped with a pressure regulator and an ultra-fine flow needle valve (V-21, V-22 and V-23). The intersection exhibits a further connection to the vacuum pumping system via valve V-20. Following an initial evacuation of the entire gas line system both GMTs can be successively filled with individual gas mixes of arbitrary partial pressure compositions. To insert a gas mix into GMT-A the leak valve belonging to the first gas component is carefully opened until the desired partial pressure fraction of the gas is reached which is controlled by PG-01. Then, the needle valve of the next gas component is slowly opened until the desired partial pressure composition is attained. The partial pressure of the second gas is equal to the momentary pressure subtracted by the final pressure after the previous gas was filled in. If a third gas component shall be added this process is repeated. As soon as GMT-A contains the right gas composition, valve V-18 is closed and the gas line intersection is evacuated. To fill GMT-B valve V-19 is opened and the gas filling procedure is repeated introducing a new arbitrary partial pressure composition. It is important that the total gas pressure which is filled into the GMTs is multiple times higher than the pressure which will later be inserted into the PCs.

Outside of the outer camera, the two DN-16CF flanges of the outlet gas pipes are connected to the pressure gauges PG-04

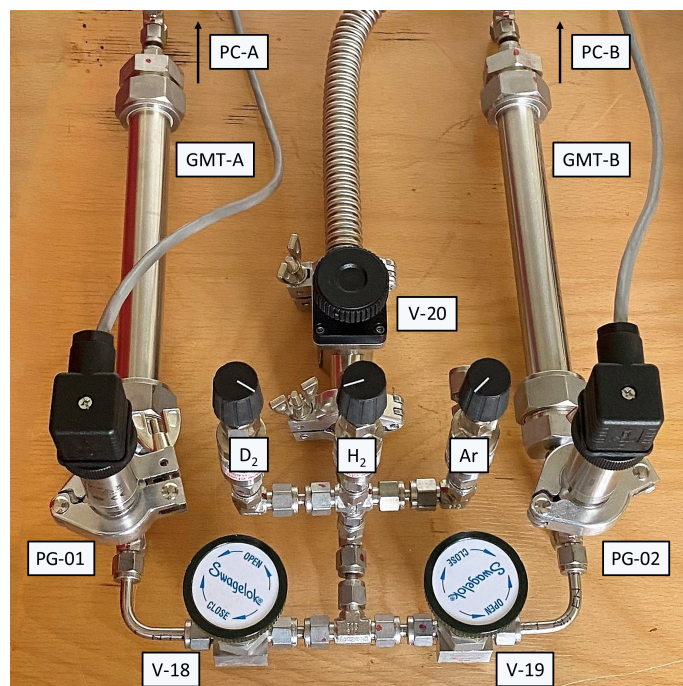


Figure 7: Photo of the gas line system without heating wires and thermal insulation.

and PG-05 as well as to the all-metal bellow sealed valves V-01 and V-02. Both PCs are linked to the vacuum pumping system and a quadrupole mass spectrometer (QMS) with ISO-25KF tube components. During a permeation measurement the tube line of only one of the PCs should be opened to the QMS at a time. This depends on whether the permeation flux from PC-A to PC-B (defined as permeation direction AB) or from PC-B to PC-A (defined as permeation direction BA) will be measured. Both PCs are connected to the QMS via two distinct paths. The open path is defined as a way through the tube system of high throughput via an open-close bellow sealed valve (AB: V-03, BA: V-04). In contrast, the leak path describes a way through the tubes of low throughput since it is interrupted by a gas dosing valve (AB: V-05, BA: V-06) which allows controlling gas flow rates to the QMS in a range 1×10^{-10} –500 mbar l s⁻¹ (see figure 1). Subsequently, the tube lines intersect before they are connected via ISO-25KF bellow tubes to the vacuum system, a QMS and to pressure gauge PG-05 (see figure 1). Valve V-13 provides an additional link to the leak detector. If the permeation flux from a gas filled PC into vacuum is measured the evacuated PC and the QMS/TMP are linked via the open path. Choosing this path allows evacuating the corresponding PC to minimum pressures of 1×10^{-7} mbar. If the permeation flux into a gas filled PC is measured, the valves V-03 and V-04 are kept closed and the leak path over the respective gas dosing valve is chosen. In this way, the pressure in the downstream PC (AB: PC-B, BA: PC-A) can be maintained in the low vacuum regime, while the space surrounding the QMS is evacuated reaching the high vacuum regime where QMS measurements are possible. It is important that the leak valve is adjusted to a very low gas flow rate such that the occurring

pressure decrease in the PC resulting from the intentionally created leakage becomes negligible. The gas flow through the leak valve will have the same relative gas composition as the gas in the PC. By measuring the total pressure in the PC and the partial pressures of the gas compositions entering the QMS the real partial pressure configuration in the downstream PC can be derived. The upstream PC (AB: PC-A, BA: PC-B) which is not connected to the QMS is usually sealed by the valves that are directly attached to the gas inlet and outlet flanges of the OC (AB: V-16 and V-01, BA: V-17 and V-02). However, this implies that permeation and possible leakages will cause a slow decrease of the initial gas pressure in the upstream PC during the measurement. For this reason, the presented experimental design offers the possibility to create a gas flow inside of the upstream PC coming from the upstream GMT (AB: GMT-A, BA: GMT-B). The flow enters through the gas dosing valve (AB: V-16, BA: V-17) at the gas inlet of the PC and exits the outlet pipe of the PC before leaving through the downstream gas dosing valve (AB: V-06, BA: V-05). The downstream gas dosing valve receives an additional connection to the RVP via valve V-09. To create a homogeneous gas flow which causes a stationary gas pressure in the upstream permeation cell both leak valves should be opened by the same level. Since consequently the pressure in the corresponding GMT would slowly decrease the leak valves need to be opened more and more during the time of the measurement in order to keep the pressure in the upstream PC constant.

3. Experimental procedures

The presented design of the COOPER experimental set-up allows executing measurements to study different permeation phenomena and to determine material specific hydrogen transport parameters of the sample disk material.

3.1. Mono-isotopic permeation experiment:

In a mono-isotopic permeation experiment the permeation of a mono-molecular hydrogen gas from a gas filled container through a sample material into vacuum is observed. Such a permeation experiment is usually performed to experimentally obtain the hydrogen permeability or the diffusion coefficient of the sample disk material. Moreover, it allows measuring characteristic surface rate constants that determine the recombination and dissociation velocity of the hydrogen isotopes at the gas-bulk interface. The COOPER experiment is designed to enable permeation measurements in the diffusion-limited and the surface-limited permeation regime. The diffusion-limited regime is present at high driving pressures in which the dissociation rate at the gas-metal interface is fast in comparison with the diffusion flux in the bulk material. Permeation measurements in this regime allow determining the diffusion coefficient of the sample material applying the time-lag method [14]. It was found that in the diffusion limited regime the stationary permeation flux J_{perm} through a sample material of thickness d is approximately proportional to the square root of the gas pressure $J_{\text{perm}} \approx \Phi \cdot \sqrt{P}/d$ with Φ being the temperature dependent hydrogen permeability of the sample material

[15]. By measuring the permeation flux for different temperatures while keeping the pressure constant the temperature relation of the permeability is obtained. The surface-limited permeation regime describes a case in which the driving pressure of the gas is low causing the diffusion flux to be large in comparison with the dissociation rate. In this regime, the permeation flux is approximately proportional to the pressure P and can be expressed by the relation $J_{\text{perm}} \approx \frac{1}{2} \sigma K_d P$ where σ is the surface roughness factor [15]. The temperature dependent dissociation coefficient K_d is measured for different temperature while keeping the pressure constant.

To execute a mono-isotopic permeation measurement with the presented set-up D_2 gas is filled into PC-A and PC-B is evacuated. The deuterium permeation flux through the SD into PC-B is measured using either the QMS or the LD. The permeating particles move towards to QMS or the LD via the open path. For the determination of the diffusion coefficient using the time-lag method pre-heating the gas in the GMTs is essential. For measurements in the surface-limited regime very low D_2 partial pressures are achievable by pre-mixing the D_2 gas with Ar before it is injected into PC-A.

3.2. Multi-isotopic permeation experiment:

The COOPER experiment enables D_2 permeation measurements while H_2 gas is additionally present in one or both permeation cells. The objective of these measurements is the observation of co- and counter permeation as a permeation mitigation or enhancement mechanism. In addition, the experimental data gained from these experiments will be used for the validation of existing numerical multi-isotopic transport models. Therefore, experimental data will be compared with simulation results. With the COOPER experiment special focus is placed on the experimental analysis of the following HCPB relevant co- and counter-permeation scenarios:

3.2.1. Co-permeation experiment:

A $D_2 + H_2$ gas mix is injected into PC-A and PC-B is evacuated. The gases co-permeate side by side from PC-A into PC-B. The permeation flux of H_2 , HD and D_2 molecules is measured using either the QMS or the LD which are connected to PC-B via the open path. The measurements are performed for different initial H_2 partial pressures in PC-A and different sample temperatures.

3.2.2. Counter-permeation experiment:

H_2 gas is filled into PC-A and D_2 gas is injected into PC-B. Both gases counter-permeate in opposite directions into the opposite permeation cell. Since both permeation cells contain gas pressures in the low vacuum regime the permeating particles have to enter the QMS system via the leak path, passing gas dosing valve V-05. The total gas pressure in PC-B as well as the partial pressures of H_2 , HD and D_2 molecules entering the QMS are recorded. The measurement is performed for different sample temperatures and different initial H_2 partial pressures in PC-B.

3.2.3. Co- and counter-permeation experiment:

PC-A is filled with H₂ and D₂ gas is inserted into PC-B. The gases counter-permeate in opposite directions into the opposite permeation cell. The experiment is repeated for different initial H₂ partial pressures in PC-B and different sample temperatures. Special focus is placed on the temperature regime and partial pressure configurations which are relevant for the HCPB breeding blanket system. It will be observed how the deuterium permeation flux into PC-B is affected while varying the H₂ partial pressures in each permeation cell. Again, the leak path is chosen for the connection between PT-B and the QMS.

4. Conclusion

Tritium transport simulations suggest that injecting H₂ gas to the coolant of an HCPB breeding blanket system could, in certain partial pressure regimes, have a mitigating effect on tritium permeation into the coolant. For the experimental observation of this promising method a new multi-isotopic permeation experiment (COOPER experiment) has been designed within the scope of this work. It allows investigating the isotopic effect of co- and counter-permeation of different hydrogen isotopes through an EUROFER disk under HCPB relevant conditions substituting tritium by deuterium. The permeation chamber constitutes two gas cavities which are separated by the sample disk. A band heater is clamped around a custom-designed copper ring which surrounds the sample disk in its center. The heat enters the disk at its circular boundary edge reaching temperatures of up to 600 °C. Finite element thermal calculations anticipate a nearly homogeneous radial temperature profile which would establish inside of the disk in steady state. For reliable measurement results this is an essential requirement. A gas line system consisting of two gas tanks permits to mix, pre-heat and inject arbitrary partial pressure configurations of H₂ and D₂ gas into both permeation cells in a pressure range between 1 Pa and 1.5×10^5 Pa. A leak detection system surrounding the permeation chamber is installed to enhance the accuracy of the permeation flux measurements by detecting and quantifying gas molecules that either permeate through the chamber walls or escape through possible leakages. The experimental design enables measuring H₂, HD or D₂ permeation fluxes into an evacuated or gas filled chamber. Therefore, the downstream cavity and a quadrupole mass spectrometer are either directly connected or linked via a manual leak valve. The COOPER experiment has the purpose to validate numerical simulation results of HCPB permeation scenarios and to measure material specific hydrogen transport parameters. Matching experimental and simulation results would confirm a controlled H₂ injection to the coolant as a promising method to mitigate tritium permeation in HCPB breeding blankets and would allow calculating the simultaneous transport of multiple hydrogen isotopes in HCPB related systems with greater confidence.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

This work has been partially funded by the MINECO Ministry under project ENE2013-43650-R. S. J. Hendricks acknowledges a pre-PhD contract of the Spanish MICINN.

References

- [1] F. A. Hernández, HCPB Design report 2015, Final Report for EUROfusion, EFDA_D_2MNBH9, 2016.
- [2] F. A. Hernández, F. Arbeiter, L. V. Boccaccini, E. Bubelis, V. Chakin, I. Cristescu, B. E. Ghidersa, M. Gonzalez, W. Hering, T. Hernandez, X. Z. Jin, M. Kamlah, B. Kiss, R. Knitter, M. H. H. Kolb, P. Kurinskiy, O. Leys, I. A. Maione, M. Moscardini, G. Nádasi, H. Neuberger, P. Pereslavtsev, S. Pupleschi, R. Rolli, S. Ruck, G. A. Spagnuolo, P. V. Vladimirov, C. Zeile, G. Zhou, Overview of the hcpb research activities in eurofusion, IEEE Transactions on Plasma Science 46 (2018) 2247–2261.
- [3] E. Carella, C. Moreno, F. Urgorri, D. Demange, J. Castellanos, D. Rapisarda, Tritium behavior in HCPB breeder blanket unit: Modeling and experiments, Fusion Science and Technology 71 (2017) 357–362.
- [4] G. Federici, A. R. Raffray, M. A. Abdou, Mistral: A comprehensive model for tritium transport in lithium-base ceramics: Part ii: Comparison of model predictions with experimental results, Journal of Nuclear Materials 173 (2) (1990) 214–228.
- [5] C. Johnson, Tritium behavior in lithium ceramics, Journal of Nuclear Materials 270 (1999) 212–220.
- [6] T. Kinjo, M. Nishikawa, Tritium release behavior from Li₄SiO₄, Fusion Science and Technology 46 (2004) 561–570.
- [7] E. Carella, C. Moreno, F. Urgorri, D. Rapisarda, A. Ibarra, Tritium modeling in HCPB breeder blanket at a system level, Fusion Engineering and Design, 2017.
- [8] F. Cismondi, Lecture notes: Solid and liquid breeder blankets, Politécnico de Turín, Italy, 2011.
- [9] T. Hernández, M. Oron-Carl, Preliminary measurement equipment and design of the experiments and tests, Final Report for EUROfusion, EFDA_D_2MFAB5, 2015.
- [10] K. Kizu, Counter-diffusion and counter-permeation of deuterium and hydrogen through palladium, Journal of Nuclear Materials 258 (1998) 1133–1137.
- [11] K. Kizu, T. Tanabe, Deuterium permeation through metals under hydrogen counter flow, Journal of Nuclear Materials 266 (1999) 561–565.
- [12] T. Takeda, J. Iwatsuki, Counter-permeation of deuterium and hydrogen through inconel 600®, Nuclear Technology 146 (2004) 83–95.
- [13] A. Perujo, K. Forcey, Tritium permeation barriers for fusion technology, Fusion Engineering and Design 28 (1995) 252–257.
- [14] J. Crank, The Mathematics of Diffusion, Oxford University Press, Bristol, England, 1975.
- [15] G. A. Esteban, A. Perujo, L. A. Sedano, B. Mancinelli, The surface rate constants of deuterium in the reduced activating martensitic steel optifer-ivb, Journal of Nuclear Materials 282 (2000) 89–96.