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Tritium Extraction Technologies and DEMO Requirements

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The conceptual design of the tritium extraction system (TES) for the European DEMO reactor is worked out in parallel for four different breeding blankets (BB) retained by EUROfusion. The TES design has to be tackled in an integrated manner optimizing the synergy with the directly interfacing inner fuel cycle, while minimizing the tritium permeation into the coolant. Considering DEMO requirements, it is most likely that only advanced t technologies will be suitable for the tritium extraction systems of the BB. This paper overviews the European work programme for R&D on tritium technology for the DEMO BB, summaries the general first outcomes, and details the specific and comprehensive R&D program to study experimentally immature but promising technologies such as vacuum sieve tray or permeator against vacuum for tritium extraction from PbLi, and advanced inorganic membranes and catalytic membrane reactor for tritium extraction from He. These techniques are simple, fully continuous, likely compact with contained energy consumption. Several European Laboratories are joining their efforts to deploy several new experimental setups to accommodate the tests campaigns that will cover small scale experiments with tritium and inactive medium scale tests so as to improve the technology readiness level of these advanced processes.

Keywords: Breeding Blanket, Tritium Technology, Outer Fuel Cycle, Demo, D-T Fusion

1. Introduction

The conceptual design of the tritium extraction system (TES) for the European DEMO reactor is worked out in parallel for four different breeding blanket (BB) options covering one solid and three liquid BB concepts [1]. The TES has to be tackled in an integrated manner optimizing the synergy with the directly interfacing inner fuel cycle, and minimizing the tritium permeation into the coolant. As a preamble, previous numerical studies [2] suggested specific anti-permeation strategies for different BB, but acknowledged that both TES throughput and efficiency are of almost priority [3]. Very powerful TES is required, but large R&D efforts are crucial since the technologies currently retained for the ITER test blanket modules are likely inadequate due to insufficient performances or scaling up difficulties.

This paper covers the comprehensive R&D program that has been launched along the new established EUROfusion program to study experimentally immature but promising technologies such as vacuum sieve tray or permeator against vacuum for tritium extraction from PbLi, and advanced inorganic membranes and catalytic membrane reactor for tritium extraction from He. These techniques have numbers of basic advantages: they are simple (improving reliability), fully continuous (reducing tritium inventory), likely compact (easing integration) with contained energy consumption (not impacting overall reactor efficiency). Laboratory scale tests with tritium for process proof of principle and medium scale tests for component demonstration are being started to improve the technology readiness level of these advanced processes so that they could be chosen at the Horizon 2020 as baseline for the TES of the European DEMO.

2. Overview of the European work programme for R&D on tritium technology for the DEMO breeding blanket and summary of first outcomes

Along the new established EUROfusion framework and DEMO design related activities, the R&D activities for the Tritium Technology is articulated into 4 strongly interconnected main areas of work: (1) Tritium System Design, (2) Tritium Transport Modelling, (3) Tritium Extraction Processes, and (4) Tritium Control.

2.1 TES conceptual design

The design at the conceptual level of the Tritium Extraction Systems (TES) of the 4 breeding blankets is organized in 3 consecutive phases. During the first preliminary phase, the different techniques for tritium extraction are being reviewed and assessed to identify the baseline process and the back-up solution(s), and first pipe and flow diagram and pipe and instrumentation diagram will be produced. A consolidation phase shall follow, extending the analysis towards safety and integration issues. The last phase will also consider the control systems and the detailed interface managements so that the final conceptual design of DEMO TES for the

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four breeding blanket is expected by end of 2018. The design work is a central activity that is strongly connected to the others. At the moment different tritium extraction technologies have been assessed: cryogenic trapping and permeator against vacuum have been preselected as baseline methods for solid and liquid blankets respectively, whereas membranes / membranes reactors and vacuum sieved trays have been kept as back-up solution for further considerations. This choice was largely motivated by the technology readiness level of the different processes that might evolve along the R&D phase.

2.2 Tritium transport modelling

Modelling of Tritium Transport is considered at both systems and Breeder Zone levels. A clear and precise understanding of tritium transport and migration inside the breeder unit and its management along the TES is a key aspect that defines directly the required performances for TES but also the ones for the coolant purification system and the permeation reduction factor (if any) to be used as anti-permeation strategy. Along the work programme, the four breeding blankets will be first analysed at the macroscopic system level in order to fix tentatively the necessary flow rates and efficiency of both the TES and CPS; additional specific analyses at the microscopic level (including MHD effect, other boundary layers like oxide layers or coatings) will be progressively integrated to refine the estimations of the amount of tritium permeating the coolant. At the breeder unit level for HCLL and WCLL, ENEA produced results on T inventories, permeation, and losses based on a numerical approach close to the FUS-TPC code developed by KIT in the previous EFDA studies and updated input data when relevant new information was available from the design of the Breeding Blankets and PbLi systems [4].

2.3 Tritium Extraction Technologies development

Experimental work dedicated to characterising advanced tritium extraction techniques (from He and PbLi) is a key part of the R&D programme. In this area, the huge gap between ITER TBM and DEMO in term process capacity (size, efficiency) has motivated the comprehensive R&D on advanced and promising techniques not studied so far for the ITER TBM tritium extraction system. Processes based on membranes and catalytic membranes reactors for the tritium extraction from the solid BB, and also the vacuum sieve tray and the permeator against vacuum for the tritium extraction from the liquid BBs will be meticulously tested. Several facilities shall be deployed in different laboratories (CIEMAT, ENEA, KIT) to implement the experimental programme covering i) the proof of principle of the process based on laboratory scale experiments with tritium, and ii) the validation at component level throughout experiments with hydrogen or deuterium at medium scale. For demonstrating advanced tritium extraction technologies, several new setups for testing TES process candidates have been conceptually formulated enabling several experimental campaigns on all relevant and promising techniques (PAV, VST, membranes and catalytic membrane reactors) retained as baseline or as back-up solutions to be executed in the near future and in parallel.

2.4 Tritium control

Mostly experimental activities are dedicated to the crucial topic of tritium control and anti-permeation technology. Permeation tests allowing the measurements of Permeation Reduction Factor (PRF) of anti-corrosion barriers shall be performed in several laboratories (CCFE, CIEMAT) with deuterium or tritium on virgin specimens as well as on samples after neutron irradiation or during electron bombardment. Beyond coatings also acting as anti-corrosion barriers for liquid blankets, the in-situ and on-line investigation of oxide layers promoted by He chemistry control (H_2 / H_2O addition) will be investigated. Such experimental campaigns shall produce many key data of importance to be reintroduced in the tritium transfer simulation tools so as to refine the different strategies proposed for the different blankets to mitigate the tritium migration issue. New experimental setups to study anti permeation barriers under electron irradiation or after ageing in contact of PbLi or in presence of neutrons were designed at the conceptual level.

3. R&D on Tritium extraction techniques from liquid breeding blankets

3.1 Vacuum Sieve Tray

The tritium extraction from liquid breeding blankets using Vacuum Sieve Tray (VST) has been first disregarded and considered not to be efficient enough [5]. Actually the extraction efficiency was calculated considering the diffusivity of hydrogen isotopes in liquid PbLi. It has been shown recently that falling droplets of PbLi in vacuum are animated by a high frequency oscillation movements that seem to enhance the mass transport in the droplets and hence the extraction efficiency [6,7]. This method simply consists in letting droplets fall from an upper tank to a lower tank under vacuum through nozzles. The efficiency of the extraction is governed by the falling time and so the velocity of the droplets. It also depends on the VST engineering design details like the number of nozzles, their length and diameter. Deuterium extraction experiments using a single nozzle have been performed and the extraction efficiency measured for different nozzle diameters. The mass transport coefficient has derived as the quasi-dispersion coefficient for deuterium from falling PbLi droplets in vacuum with a value of 3.40×10^{-7} $m^2.s^{-1}$. The mathematical approach used to describe deuterium extraction considers that the extraction efficiency can be expressed as follows:

$$\eta = \frac{M_{(t)}}{M_\infty} = 1 - \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-Dn^2\pi^2 t}{r_0{}^2}\right)$$

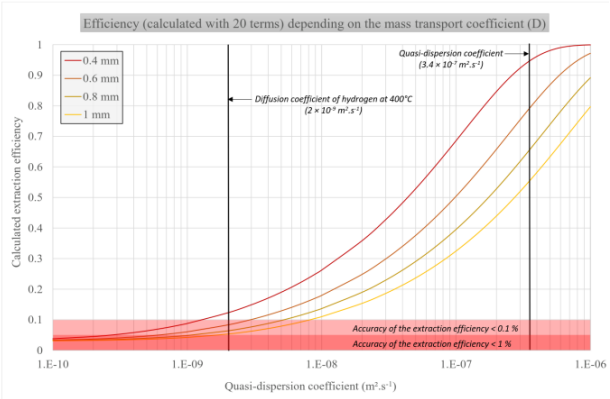

Fig 1: calculated extraction efficiency of a VST as a function of the value of the diffusion-dispersion coefficient

with:

$\frac{M_{(t)}}{M_\infty}$: the ratio between the extracted amount at time t, and the one after infinite time

D: the quasi dispersion coefficient ($m^2.s^{-1}$)

t: the falling time (s)

r_0: the radius of the droplets (m)

The falling time depends on the height and on the velocity of the droplets:

$$t = \frac{-v_0 + \sqrt{v_0 + 2gh}}{g} \quad (2)$$

with:

g: the gravitation acceleration (9.8 $m.s^{-2}$)

v_0: the initial velocity of falling droplets ($m.s^{-1}$)

h: the falling height (m)

Figure 1 shows the computed values of the extraction efficiency as a function of the quasi-dispersion coefficient for different nozzle diameters between 0.4 and 1 mm. Considering a falling time of 0.1 s and a nozzle diameter of 0.4 mm, the extraction efficiency is calculated to be 12% when using the diffusion coefficient or 95 using the quasi-dispersion coefficient measured experimentally.

A new experimental setup is being designed to test the VST principle at small scale but with tritium at TLK. It consists of 4 tanks: (1) an upper tank where PbLi is loaded with T_2, (2) a lower tank where droplets are falling, (3) a T_2 gas supply chamber with pressure control system, and (4) a PbLi draining tank. The shape and dimensions of upper tank, tubes and valves, nozzles (VST) and lower chamber, are currently optimized by simulation to develop next an extraction unit designed to be operated with tritium. Figure 2 shows the very large operating range and possible design values for the height of the lower chamber (lower than 1.2 m) for which the expected efficiency will be better than 0.9.

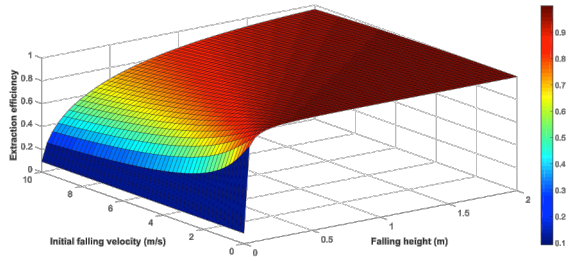

Fig 2: Computed extraction efficiency of a VST as a function of falling height and initial falling velocity for a 0.5 mm nozzle diameter and considering the quasi-dispersion coefficient.

3.2 Permeator against vacuum

Permeation against vacuum has been recognized as the most adequate technique to recover tritium from eutectic lithium-lead in fusion power plants based on Dual Coolant Lithium-Lead (DCLL) breeding blankets. The main advantages of this technique, in which tritium diffuses through a permeable membrane in contact with the liquid metal and is then extracted by a vacuum pump, are the achievable efficiency and the minimization of the residence time in the Tritium Extraction System (TES), which involves the minimization of the tritium starting inventory in the reactor. The construction of a loop to test the PAV technique at high velocity PbLi flows was started at CIEMAT. The main objectives of the loop are to evaluate H/D permeation in flowing PbLi in a range of DEMO relevant conditions and to characterize different permeator design concepts, configurations and materials for efficiency and reliability assessments. The CIEMAT loop showed on Figure 3 is designed to operate under forced circulation at a maximum temperature of 500ºC and a maximum PbLi velocity of 1 $m.s^{-1}$. The design is modular and the final layout comprises two zones (cold and hot legs). This allows lower operational requirements in terms of temperature for some important loop components (piping, melting tank, flow meter…) and limits the corrosion issue. The flow is driven by a permanent magnets electromagnetic pump. More details can be found in [8].

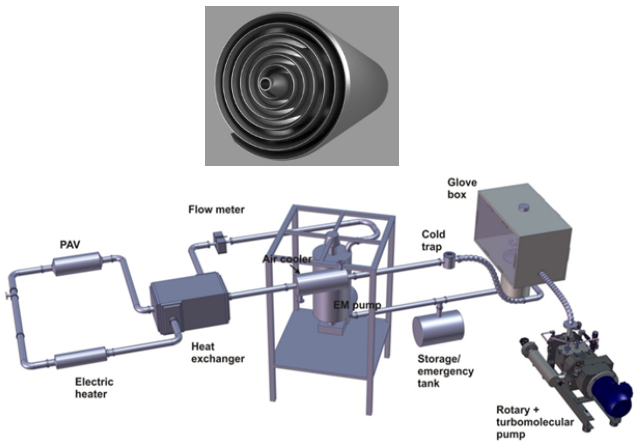

Fig 3: Spiral shape permeator against vacuum and drawing of the new PbLi loop for testing PAV (CIEMAT)

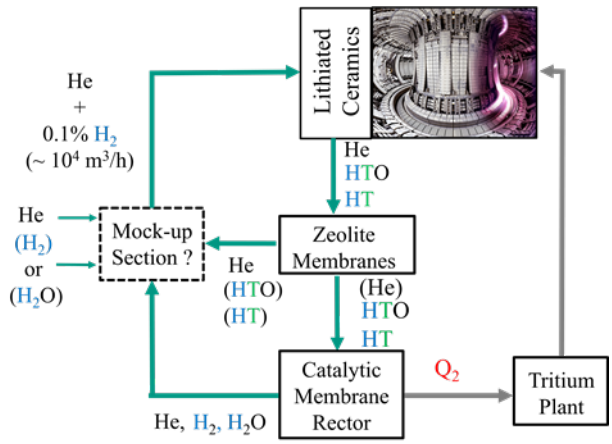

Fig 4: Schematic diagram of the advanced TES concept of the solid Breeding Blanket of DEMO. The curly brackets () evidence the species depleted in the corresponding streams.

4. R&D on Tritium extraction techniques from solid breeding blankets

4.1 Advanced HCPB TES

The tritium extraction from solid breeding blankets (BB) is expected to be achieved by purging it with large flows of He (~ 10^4 Nm^3/h) doped with 0.1% H_2. Thus, the emerging gas stream to be processed contains ppm amounts tritium distributed in Q_2 and Q_2O (Q means H, D, T mixture) and other impurities. The tritium recovery takes place removing the tritium from the tritiated species at the Tritium Extraction System. The TLK recently proposed an advanced concept [9,10] that relies on continuous process based on a catalytic membrane reactor (CMR) based on the PERMCAT process routing finally a pure Q_2 stream towards the Tritium Plant as depicted in Figure 4. A pre-concentration stage is necessary to maintain reasonable the size of the CMR tritium recovery stage. Zeolite (inorganic thus tritium compatible) membranes were identified as the most promising material to pre-concentrate simultaneously the Q_2 and Q_2O species. Such advanced process based on membrane technology is fully continuous thus improving the overall tritium management since it ensures short process time and hence minimum tritium inventory.

4.2 Zeolite Membranes characterisation

Zeolite membranes are unfortunately at relatively low maturity level and experimental data on separation performances of Q_2 or Q_2O from He are rather scarce. A dedicated experimental programme has been launched to explore the potential of these membranes for the DEMO TES. Several experiments with He, H_2, and H_2O, feeding different zeolite membranes prototypes as single gases or as mixtures have been performed (Figure 5) [10-12]. Similar separation performances for H_2/He mixtures of different MFI-ZSM5 membranes have been observed. The results evidenced relatively high single gas permeances (~ $7x10^{-7}$ mol m^{-2} s^{-1} Pa^{-1} for H_2 at 25 °C) but limited separation factors (around 1.7 towards H_2 at 25 °C), regardless of the feed composition (in the range 0.1% - 10% H_2/He). More interestingly, considerably higher separation performances for H_2O/He experiments

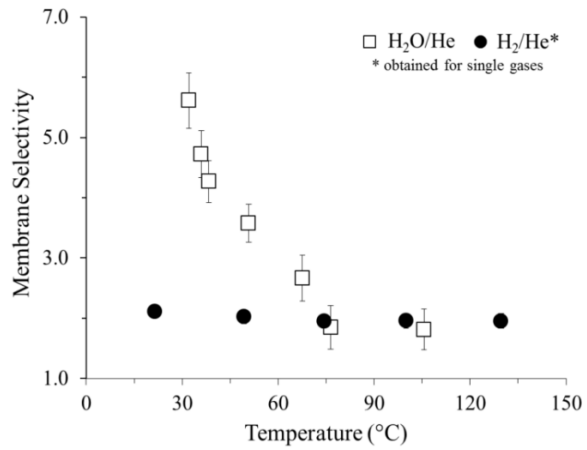

Fig 5: Comparison of the membrane MFI selectivity as a function of the temperature for 1% H2O/He binary mixture (empty squares). The H2/He selectivity values (filled circles) were obtained from the single gas permeances.

for MFI-ZSM5 and NaA zeolite membranes were obtained. The separation factor greatly increases with the decrease of the membrane temperature (Figure 5) for the MFI-ZSM5 at 1% H_2O/He. The higher separation factors towards H_2O (among other reasons given in [10]) suggest that the purge gas could be doped with this species instead of H_2. Recently, a more complete set of results at different H_2O/He concentrations with different membranes have been obtained and will matter of a dedicated paper. Finally, four different membrane material candidates (Figure 6) were tested and results shown on Figure 7 highlight that MFI and NaA membranes are good candidate for further investigation.

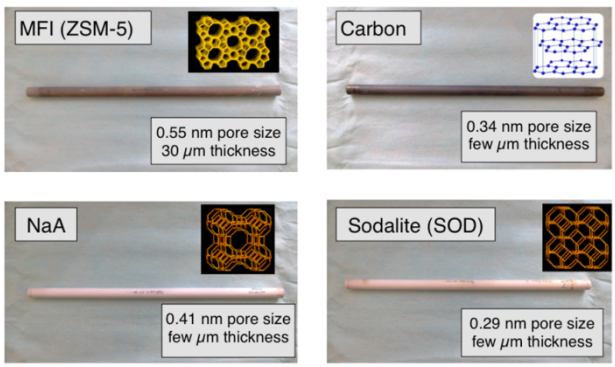

Fig 6: Tubular membranes used in the experiments (active layer synthesized on the inner surface of the tubes).

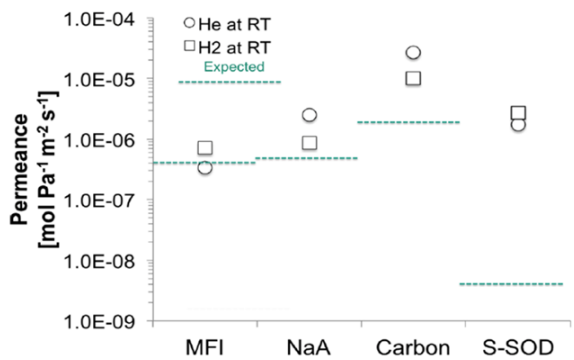

Fig 7: Comparison of the performances of the four membranes measured with single gas experiments at RT.

4.3 Catalytic Membrane Reactors characterisation

Pd-based catalytic membrane reactors are under investigation because of their large hydrogen selectivity, continuous operation capability, reliability and compactness. The construction and operation of a medium scale CMR device at ENEA Frascati is included in the work plan. Up to now only preliminary experiments on a small scale reactor were performed to identify most suitable operative conditions and catalyst materials.

An experimental campaign was carried out on a Pd-based membrane aimed at measuring the capability of this device in separating hydrogen from the helium. Many operative conditions have been investigated by considering different He/H_2 feed ratios several lumen pressures and reactor temperatures. The performances of a CMR (composed of a Pd-Ag tube having a wall thickness of about 100 μm, length 500 mm and diameter 10 mm) in processing the water contained in the purge gas were measured by using commercial (Ni-based) catalyst. Two different reactions were investigated: i) isotopic swamping and ii) water gas shift. The presence of methane between the products of the water gas shift reaction indicates that a catalyst with higher selectivity is required. Details on this study can be found in [13].

7. Summary and outlook

Along the EUROfusion R&D work programme for the tritium technology of the breeding blanket, major resources are devoted to the validation and demonstration of advanced and efficient technologies for extracting tritium from He and PbLi. Since all of the following processes are fully continuous, simple, can potentially provide high efficiency, likely saving space and energy (compared to conventional processes foreseen for the TBM ancillary systems), the zeolite membranes, the Pd-based catalytic membrane reactors, the vacuum sieve tray and the permeator against vacuum are considered as the only ones that could fulfil DEMO requirements, thus being meticulously studied. KIT Tritium Laboratory, ENEA Frascati, ENEA Brasimone and CIEMAT are joining their efforts to deploy several new experimental setups to accommodate the tests campaigns that will cover small scale experiments with tritium and inactive medium scale tests.

Acknowledgments

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References

[1] L.V. Boccaccini, G. Aiello, C. Bachmann, T. Barrett, A. Del Nevo, D. Demange, et al. “Objectives and status of EUROfusion DEMO blanket studies”, this conference

[2] F. Franza, L.V. Boccaccini, A. Ciampichetti, M. Zucchetti. “Tritium transport analysis in HCPB DEMO blanket with the FUS-TPC code” Fusion Eng. Des. 88 (2013) 2444

[3] D. Demange, L.V. Boccaccini, F. Franza, A. Santucci, S. Tosti, R. Wagner “Tritium management and anti-permeation strategies for three different breeding blanket options foreseen for the European Power Plant Physics and Technology Demonstration reactor study” Fusion Eng. Des. 89 (2014) 1219.

[4] L. Candido, M. Utili, I. Nicolotti, M. Zucchetti “Tritium Transport in HCLL and WCLL DEMO Blankets”, this conference

[5] H. Moriyama, S. Tanaka., D. Sze, J. Reimann, A. Terlain “Tritium recovery from liquid metals” Fusion Eng. Des. 28 (1995) 226.

[6] F. Okino, K. Noborio, R. Kasada, S. Konishi “Enhanced Mass Transfer of Deuterium Extracted from Falling Liquid Pb-17Li Droplets” Fusion Sci. Technol. 64 (2013) 543

[7] F. Okino, P. Calderoni, R. Kasada, S. Konishi “Feasibility Analysis of Vacuum Sieve Tray for Tritium Extraction in the HCLL Test Blanket System”, this conference

[8] I. Fernandez, D. Rapisarda, B. Garcinuno, A. García, C. Moreno, A. Ibarra “Conceptual Design of a Lithium-Lead Loop for Testing the Permeator Against Vacuum Technique at High Velocity Flows”, this conference

[9] D. Demange, S. Stämmler, M. Kind “A new combination of membranes and membrane reactors for improved tritium management in breeder blanket of fusion machines” Fusion Eng. Des. 86 (2011) 2312

[10] D. Demange, O. Borisevich, N. Gramlich, R. Wagner, S. Welte “Zeolite membranes and palladium membrane reactor for tritium extraction from the breeder blankets ITER and DEMO” Fusion Eng. Des. 88 (2013) 2396.

[11] M. Simplício, M.D. Afonso, O. Borisevich, X. Lefebvre, D. Demange “Permeation of single gases and binary mixtures of hydrogen and helium through a MFI zeolite hollow fibres membrane for application in nuclear fusion” Sep. Purif. Technol. 122 (2014) 199.

[12] O. Borisevich, R. Antunes, D. Demange “Experimental study of permeation and selectivity of zeolite membranes for tritium process” Fusion Eng. Des. xx (2014) xx (in press; doi:10.1016/j.fusengdes.2015.04.015).

[13] A. Santucci, M. Incelli, M. Sansovini, S. Tosti “Catalytic Membrane Reactor for Tritium Extraction System from He Purge: Catalyst Optimization”, this conference