QUANTIFICATION OF DOMINATING FACTORS IN TRITIUM PERMEATION IN PbLi BLANKETS

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In this paper the problem of tritium transport in PbLi (Lead-Lithium) blankets has been studied and analyzed by means of our recently developed computational models. Several simulations are performed by incorporating the geometric configurations of the PbLi blankets including both DCLL (Dual Coolant Lead Lithium) and HCLL (Helium Cooled Lead Lithium) blankets. Tritium permeation loss percentage from the HCLL concept is about one order of magnitude higher than from the DCLL concept (~ 17%. vs. 1.2%). Sensitivity study also shows that the most relevant factors on tritium permeation are: 1) the level of tritium solubility in PbLi, 2) the gap velocity of the liquid metal in a DCLL blanket, 3) Hartmann number, and 4) the FCI (Flow Channel Insert) electrical conductivity.

I. INTRODUCTION

Tritium is generated inside the breeder and moves via several mechanisms. It could potentially reach the environment, giving a potential radiological hazard. Thus, it is critical to be able to predict tritium transport in lead-lithium liquid metal (LM) blankets with great accuracy to provide information for fusion reactor safety and economic analyses. The purpose of this study is to analyze tritium transport in a prototypical PbLi tritium breeding blanket by means of our recently developed computational model,[1] taking into account effects of tritium generation profiles and magnetohydrodynamic (MHD) velocity profiles and to model the phenomena directly using geometric features of the design. Specifically, we compare the tritium transport behavior between HCLL (Helium-Cooled Lead Lithium) and DCLL (Dual Coolant Lead Lithium) blankets. In particular, to address how a much lower velocity as seen in HCLL increases tritium permeation. Parametric studies are also performed to quantify the key factors that govern tritium transport and permeation in the aforementioned PbLi blankets, such as the MHD impacted velocity profile, the uncertainties of transport properties, etc.

II. FORMULATION OF THE PROBLEM

A general, passive, scalar transport equation for the concentration c_s of a species *s*, can be expressed as:[2]

$$\frac{\partial c_s(\mathbf{x},t)}{\partial t} = -\nabla\cdot\mathbf{J}_s(\mathbf{x},t) + \dot{S}_s(\mathbf{x},t) - \sum_k\left(\frac{\partial c_s^{t_k}}{\partial t} + \nu_s c_s^{t_k}\right) - \nu_s c_s + \sum_m \nu_m^s (c_m + \sum_k c_m^{t_k}) \quad (1)$$

where c_s is the concentration of species "s" atoms (mol/m^3), $\dot{S}_s$ is the local source rate per unit volume ($mol/m^3 s$), ν_s is the radioactive decay frequency of species "s" atoms, ν_m^s is the radioactive decay frequency of species "m" atoms that decay to species "s", and $\mathbf{J}_s$ is the flux of dissolved atoms "s", which is given by

$$\mathbf{J}_s = -D(T)\nabla c_s - \frac{D(T)Q_s^* c_s}{kT^2}\nabla T + c_s\mathbf{u} \quad (2)$$

where *D(T)* is the diffusivity, *Q** is the heat of transport or Soret coefficient, and *T* is the local temperature.

For tritium transport in the liquid PbLi blankets, since generated tritium atoms are transferred to the extraction system, they stay in the blanket only for a short time (up to 2 hours for a HCLL blanket with 12 recirculation per day) comparing to half-life of tritium (12.3 years). Thus, there is negligible radioactive decay of tritium in PbLi. The flux associated with temperature gradients is assumed to be much smaller compared to that due to concentration gradients and is therefore omitted. Traps due to irregularities in structure and traps due to He bubbles in PbLi will affect tritium transport, but lots of uncertainties still exist and could be included in future study.

Tritium transport in PbLi blankets involves multiple tritium transport processes in multiple regions, such as tritium diffusion and convection in the liquid metal (LM), transfer across the LM/wall interface, and diffusion through the wall. An adequate set of boundary conditions at material interfaces are applied to couple the individual transfer mechanisms. At LM/ferritic steel (FS) and LM/flow channel insert (FCI) interfaces, we apply continuity of species flux and chemical potential balance at interfaces. To ensure continuity of fluxes, we write:

$$(-D_{LM}\nabla c_{T\_LM})\cdot\mathbf{n} = (-D_{FS}\nabla c_{T\_FS})\cdot\mathbf{n} \quad (3)$$

$$(-D_{LM}\nabla c_{T\_LM})\cdot\mathbf{n} = (-D_{FCI}\nabla c_{T\_FCI})\cdot\mathbf{n} \quad (4)$$

Where c_{T_LM}, c_{T_FS}, and c_{T_FCI} are the tritium concentrations (mol/m^3) in the LM, FS structure and FCI. D_{LM}, D_{FS}, and D_{FCI} are the diffusion coefficients (m^2/s) in the respective regions, $\mathbf{u}_{LM}$ is the velocity (m/s) in the LM.

In addition, we consider diffusion-limited permeation and apply Sievert's law and impose continuity of partial pressure, this leads to the concentration discontinuities at interfaces:

$$\frac{c_{T\_FS}}{c_{T\_LM}} = \frac{K_{s\_FS}}{K_{s\_LM}} \qquad \frac{c_{T\_FCI}}{c_{T\_LM}} = \frac{K_{s\_FCI}}{K_{s\_LM}} \quad (5)$$

Where K_{S_LM}, K_{S_FS} and K_{S_FCI} are the solubility of tritium in LM, FS, and FCI.

Since there is not yet a single code to solve both MHD flow and tritium transport equations simultaneously, the flow field and tritium concentration fields are obtained by means of our recently developed computational framework,[1] which integrates a MHD/CFD solver and a mass transfer solver with a data mapping utility developed for passing data from MHD solver to mass transfer solver.

III. CASES STUDIED AND RESULTS

Ideally, tritium analysis should be integrated with heat transfer analysis where material temperatures are analyzed and used to determine tritium transport properties. This temperature effect will be performed in our next step. In the present analysis, the average operating temperature of 773K is used. Main tritium transport properties in relative materials are given in TABLE I (Ref. 3, 4).

TABLE I. Tritium Transport Properties in Case Studies

Property	Expression
Liquid metal Pb-17Li	
Diffusivity	4.03e-8×(-19500/RT) m^2/s
Solubility	1.31e-3×(-1350/RT) mol m^{-3} Pa$^{-0.5}$
Ferritic steel	
Solubility	0.1×(-23810/RT) mol m^{-3} Pa$^{-0.5}$
Diffusivity	1.22e-7×(-14470/RT) m^2/s

III.A. Tritium Transport and Permeation in PbLi Based Blankets

The analyzed DCLL U-shaped channel with FCI and FS walls connected through the inlet/outlet with manifolds is shown in Figure 1. A detailed description of DCLL blanket design specifications is reported in reference.[5] The outer wall of the channel is constructed from reduced activation ferritic steel with 4mm thickness and just inside there is a flow channel insert of silicon carbide composite with a 2-mm gap in between. As a comparison, a HCLL two-breeder unit (Fig 1) is also analyzed. This blanket concept is characterized by a low velocity (8e-4m/s) of the liquid metal breeder, which is much lower than in the DCLL concepts (0.05~0.1m/s) since the PbLi is only used for tritium extraction, not for heat extraction. The geometry under study consists of two breeder units (BU) with PbLi and cooling plates separated by stiffening plates. The permeation wall thickness in cooling plates is about 1.5mm. The HCLL blanket design specifications are reported in.[6] Note that, permeation reduction due to tritium permeation barriers is not considered.

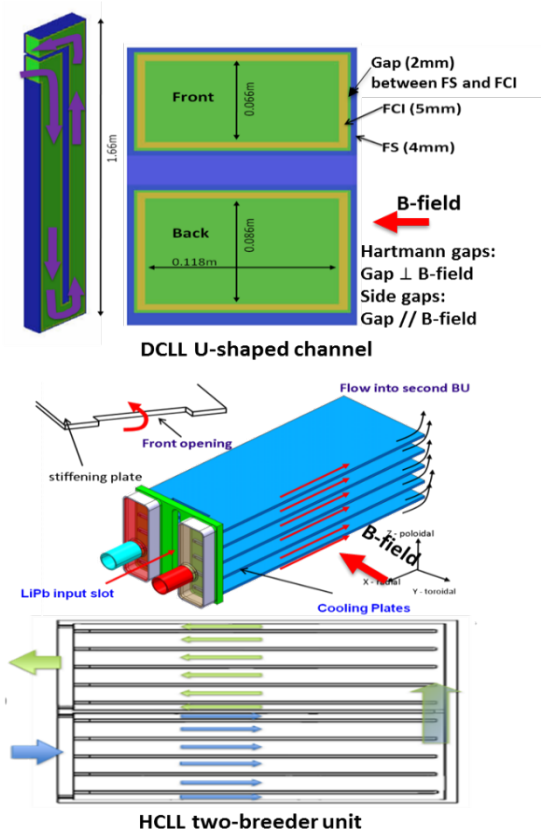

Fig 1. The analyzed DCLL central U-shaped channel and the HCLL two-breeder unit

Tritium transport calculation was performed by solving 3-D mass transfer equations with aforementioned boundary conditions. In addition, zero concentration is given at the inlet and a convective flux is given at the outlet. In real situation, the inlet LM contains already tritium concentrations due to the efficiency of tritium extraction system and will have impacts on the permeation results. In future study, once the blanket design is more defined, the effect of TES efficiency on the permeation can be included. The tritium generation rate under the ITER neutron load is applied into the calculation.[5, 6] The radial distributions of the tritium production rates for the DCLL

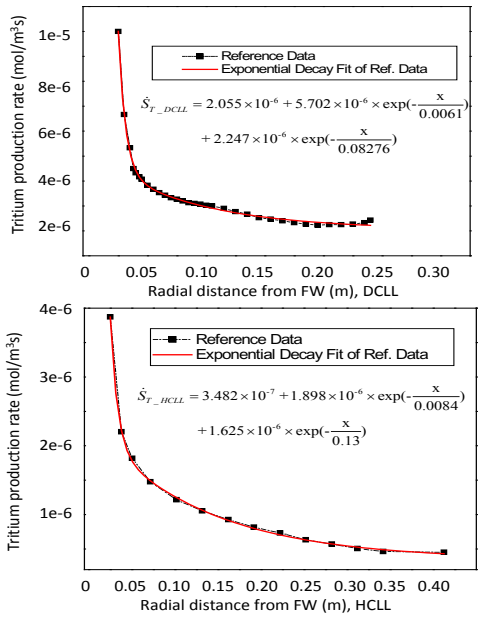

Fig 2. Radial distributions of the tritium production rates for the DCLL and HCLL blankets

and HCLL blankets are fitted by exponential decay (Fig 2).

Fig 3 shows tritium concentration profiles in the DCLL U-shaped duct, including the enlarged view of tritium concentration profiles for the central cross-sections of the duct. The high tritium generation rate in the side layer next to the First Wall (FW) does not lead to a high tritium concentration. There is a high tritium concentration in the Hartmann gap because of the low velocities, and low tritium concentration in the side gaps because of relatively high velocities there. Tritium concentration decreasing in the radial direction of the gaps reflects the decreased tritium generation rate away from the front wall. There are also high tritium concentration peaks near the four corners of the gap because of low velocities there.

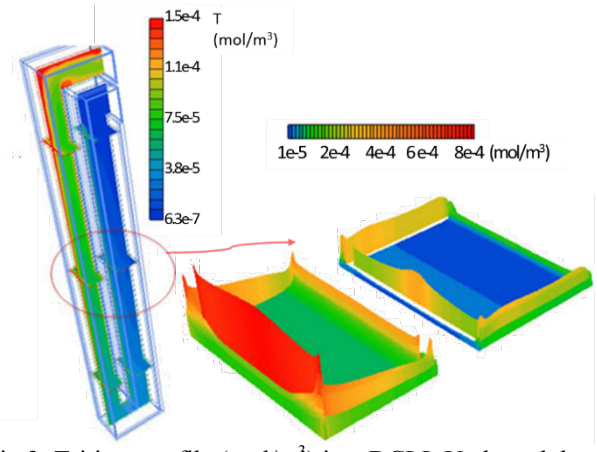

Fig 3. Tritium profile (mol/m^3) in a DCLL U-shaped duct.

Under the analyzed conditions, the simulation shows 1.2% of generated tritium in PbLi permeated through the ferritic steel structure wall to the helium coolant, which confirms earlier results (less than 2%) for a DCLL duct flow.[7] Tritium permeation flux is higher through the Hartmann walls due to higher tritium concentration in the Hartmann gaps. Tritium permeation through the front wall is higher than the back wall because of the high tritium generation rate in the front gap.

How the gap velocity affects tritium transport is more interesting. The gap velocity magnitude and profile highly depend on the manifold design. Since the details of such a design are not yet available, it is assumed that the gaps will receive the same inlet velocity as the PbLi core in one extreme case, and, at the other extreme, assumed that the inlet velocity to the gaps is only 10% of the core bulk inlet velocity. Note that the velocity in the gap or the core will evolve to the respective MHD velocity profile as the PbLi proceeds downstream. This results in an approximately 3-times increase in tritium permeation from 1.16e-9 mol/s to 2.81e-9 mol/s when the gap velocity is decreased by about 10-times as shown in TABLE II. This is because a lower mass flow rate in the gap provides a higher tritium concentration in the gap and thus increases the tritium permeation rate. This also shows the importance of being able to predict the gap velocity, in particular velocity at the gap next to the FW where tritium generation is the highest.

TABLE II. Effect of Gap Velocity on Tritium Transport

A: Gap inlet velocity=Core inlet velocity; B: Gap inlet velocity=10% of core inlet velocity		
	A	B
T generation rate (mol/s)	9.72e-8	9.72e-8
T inventory (mol)	2.64e-6	3.57e-6
T exit rate from outlet (mol/s)	9.60e-8	9.44e-8
T permeation rate (mol/s)	1.16e-9	2.81e-9
Losses (%)	1.2%	2.9%

Fig 4 shows the distribution of the tritium concentration in the analyzed HCLL two-breeder unit. Tritium accumulates along the PbLi pathway with lower values in the first breeder unit and higher values in the second breeder unit. Along the poloidal direction the tritium concentration increases as the channel aspect ratio increases. The second channel of the top breeder unit has highest tritium concentration. The top channel of the first breeder unit has the lowest tritium concentration due to the relatively high velocity there.

For the analyzed HCLL two-breeder unit, PbLi flows at a much lower velocity (~ 8e-4m/s) compared to that of a DCLL concept (average ~ 0.07m/s). This low velocity results in a higher tritium concentration and a tritium partial pressure, which leads to a higher tritium permeation. Tritium permeation loss is about 17% of the tritium produced in the analyzed HCLL two-breeder unit,.

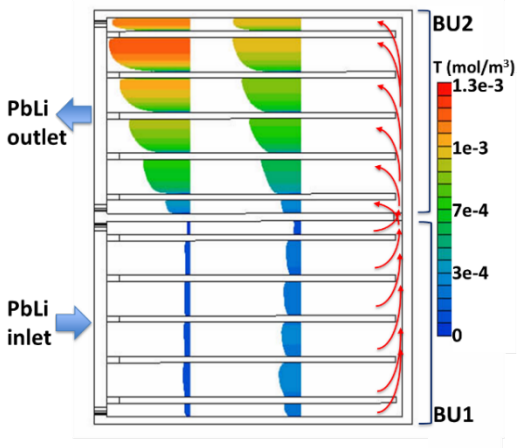

Fig 4. Tritium concentration (mol/m^3) in the HCLL 2-breeder unit shows concentration increases as the channel aspect ratio increases along the poloidal direction.

which is more than 10 times higher than that in a DCLL U-shaped channel (1.2% of tritium losses) as shown in TABLE III. To control these permeation losses, efficient tritium permeation barriers as well as efficient tritium extraction systems are necessary for the HCLL blanket concept.

III.B. Parametric Studies

The tritium transport and permeation are affected by blanket designs, material properties, operating parameters, etc. In order to show the importance and the impacts of these factors, we will report tritium losses, while considering the following factors:

- The MHD effect;
- The effect of uncertainties of tritium solubility;
- The effect of uncertainties of tritium diffusivity;
- The PES (pressure equalization slot) effect;
- Effect of the FCI electric conductivity.

TABLE III. Comparisons between the HCLL 2-Breeder Units and a DCLL U-shaped Channel

	HCLL BU(2)	DCLL U-Channel
PbLi average velocities	~8e-4 m/s	~0.07 m/s
Volume (m^3)	0.026	0.0324
Permeation area (m^2)	1.99	1.45
T generation rate (mol/s)	2.49e-8	9.72e-8
T inventory (mol/m^3)	4.38e-4	8.15e-5
T exit rate from outlet (mol/s)	2.06e-8	9.60e-8
T permeation rate (mol/s)	4.31e-9	1.16e-9
T permeation flux (mol/m^{2}s)	2.16e-9	8.00e-10
Losses (%)	17%	1.2%

In the parametric studies, the cases are mostly based on simplified DCLL-type duct flows. They are not as same as the aforementioned DCLL U-channel in III.A.The main purpose of this section is to discovery some important factors on tritium transport and permeation and to provide some guidance on the lead-lithium liquid metal blanket designs to comply tritium control requirements with regard to the reduction in tritium permeation.

III.B.1. The MHD Effect

Flows of electrically conducting liquid metal will experience complicated MHD effects in the magnetic fusion environment. MHD effects can have dramatic impacts on the flow distribution and thus affect the tritium transport and permeation rate. Tritium permeation is controlled by the near wall velocities. The Hartmann number is the main parameter that affects the side layer and Hartmann layer velocities. A sensitivity analysis was carried out for the PbLi flow in a duct with 1-m length, 60-mmx60-mm cross-section, and 2-mm conducting walls. The following Hartmann numbers were selected for the analysis: Ha=0, 100, 1000, 1440, and 3175, together with an inlet velocity of 0.0675m/s. However, in the ITER reactor, Ha number will be much higher, in this analysis since we just want to see how the MHD would affect tritium permeation and also due to computing limitations, we didn't do the calculations on the higher Ha numbers.

Fig 5 shows that the total permeation rate decreases as the Hartmann number increases. Higher Hartmann number provides a higher convective effect due to its higher velocity near the wall especially the side walls and consequently brings certain benefits in terms of reducing tritium permeation. By changing the Hartmann number from 0 to 1000, the permeation rate dropped from 2.98e-10 mol/s by 60% to 1.25e-10 mol/s. However, the decrease rate due to the increase of Ha number becomes slower as the Ha number increases. For example, permeation rate dropped by only about 10% from 1.25e-10 mol/s to 1.1e-10 mol/s as the Ha number increased from 1000 to 3175.

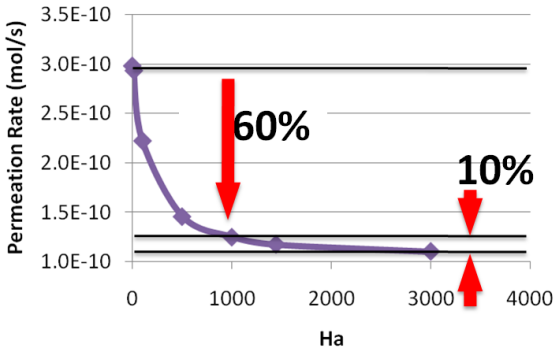

Fig 5. Tritium permeation rate decreases as Hartmann number increases, but it becomes slower at high Ha.

III.B.2. Effect of the Tritium Solubility.

Tritium solubility in PbLi is one of the critical data because of its strong impact on tritium permeation rate. Available databases on tritium solubility show considerable data scattering and discrepancies.[8] Therefore, a sensitivity analysis is done in the same duct flow as the previous case to evaluate the impact of the solubility on the tritium permeation and to evaluate the urgency of further experiments to find reliable data. Fig 6 shows the steady state tritium permeation rate obtained by varying the tritium solubility over a range of reference values from 5e-4 to 1e-2 $mol \cdot m^{-3} \cdot Pa^{-1/2}$ obtained by different authors.[8] As shown in the results, higher tritium solubility provides a smaller tritium permeation rate. This is mostly due to the tritium partial pressure decreasing at a high tritium solubility. Over the range of reference tritium solubility, the tritium permeation rate decreases from 1.5e-10 mol/s by about 80% to 2.4e-11 mol/s. The effect of the uncertainty of tritium solubility on tritium permeation is quite marked, especially for the reference range (as marked by a rectangle in Fig 6), in which the tritium permeation rate is most sensitive to the values of tritium solubility.

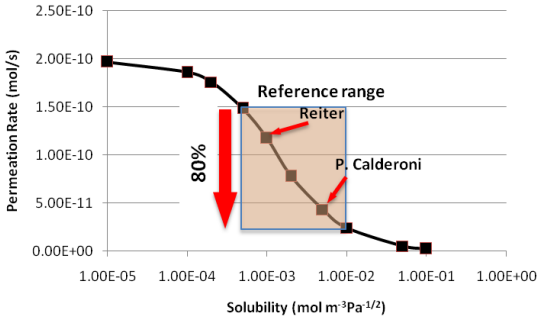

Fig 6. Effect of tritium solubility on permeation rate

III.B.3. Effect of the Tritium Diffusivity.

Tritium diffusivity is another basic property that plays a major role in tritium transport in the liquid metal breeder blanket concept. Available data on tritium diffusivity in PbLi are spread over about one order of magnitude.[8] Therefore, a sensitivity analysis is also carried out to evaluate the effect of the tritium diffusivity.

Fig 7 shows the effect of the tritium diffusivity in PbLi on the tritium permeation rate. Four cases were investigated in the range of reference values of tritium diffusivity from 1e-9 m^2/s to 1e-8 m^2/s: (1) 1e-9 m^2/s, (2) 3e-9 m^2/s, (3) 6e-9 m^2/s, and (4) 1e-8 m^2/s. As shown, the diffusion coefficient clearly affects the tritium permeation rate by controlling the amount of tritium diffusing from the PbLi to the PbLi/FS interface. Higher tritium diffusivity provides a higher tritium permeation rate. Over

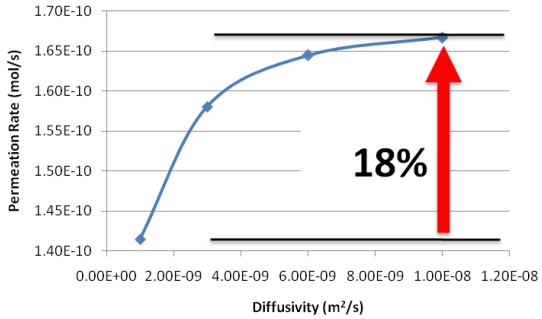

Fig 7. Effect of tritium diffusivity on permeation rate

the range of reference tritium diffusivity, tritium permeation rate increase from 1.41e-10 mol/s by 18% to 1.67e-10 mol/s.

III.B.4. The PES Effect.

The PES effect on tritium transport and permeation has been reported in our previous paper.[9] The analysis considered three types of poloidal DCLL ducts: one without the PES in the FCI, one with the PES perpendicular to the magnetic field and one with the PES parallel to the magnetic field. The main observations can be summarized as: (1) If there is no PES, we see low tritium concentrations in the front and back gaps because of high velocities there and high tritium concentration in Hartmann gaps due to very low velocities there. (2) If a PES is introduced on the back wall of a FCI, we see a high tritium concentration in the bulk area near the PES because of a strong reversed flow at the location of the PES.

Fig 8 shows tritium permeation rates decrease as Hartmann number increases for three different cases. If a PES is introduced on the wall opposite the First Wall, the tritium loss rate increases by about 15% because the velocity is reduced near the front wall.

III.B.5. Effect of the FCI Electric Conductivity

Tritium transport is not directly dependent on the electrical conductivity of the FCI, the flow field depends strongly on this property and so will influence the tritium

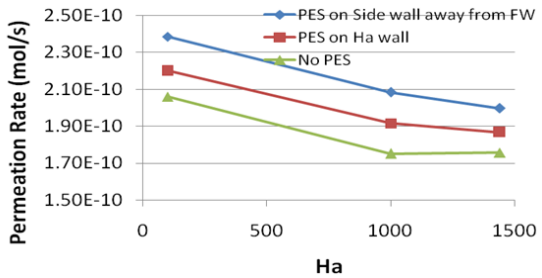

Fig 8. The PES effect on permeation rate at different Ha numbers

transport. As the electric conductivity of the silicon carbide composite decreases, the effect of electromagnetic coupling between the flow in the gap and the bulk flow reduces; thus the velocity in the gap drops.[7]

Fig 9 shows the effect of a change in the FCI electric conductivity on the tritium permeation rate for the case of the PES opened on a side wall away from the FW. Five cases were investigated in the range of reference values of FCI electric conductivity from 5 to 500 $\Omega^{-1}m^{-1}$. As shown, the FCI electric conductivity clearly affects the tritium permeation rate by changing the gap velocities. A higher electric conductivity provides a higher velocity in the gap and thus a lower tritium permeation rate. Over the range of reference electric conductivity from 5 to 500 $\Omega^{-1}m^{-1}$, tritium permeation rate decreased by about 46%.

Fig 10 summarized the key factors that affect tritium permeation in the DCLL PbLi blanket. It shows that the most relevant factors on tritium permeation are: 1) the level of tritium solubility in PbLi, 2) the gap velocity of the liquid metal in a DCLL blanket, 3) Hartmann number, and 4) the FCI electrical conductivity.

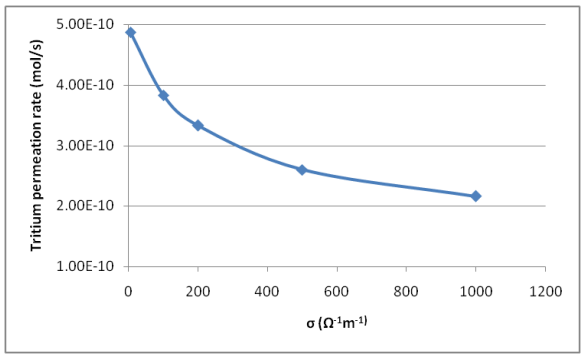

Fig 9. Tritium loss rate as a function of FCI conductivity

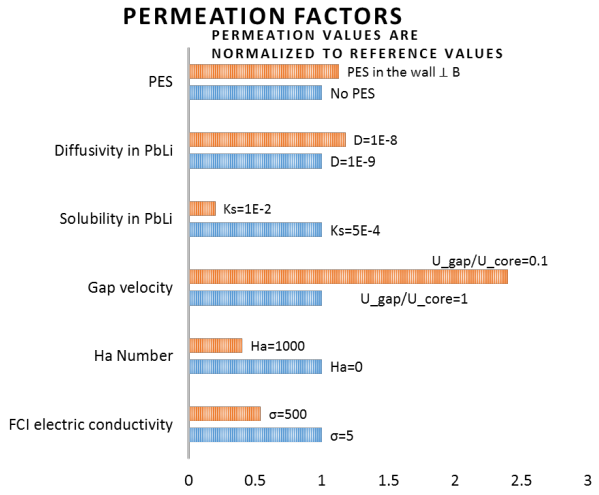

Fig 10. Effect of tritium solubility on permeation rate

IV. CONCLUSIONS

In this paper, we quantified the difference in tritium permeation rates between DCLL and HCLL blanket concepts. For the HCLL two-breeder unit and a DCLL U-shaped channel analyzed, the percentage of the tritium permeation loss from the HCLL concept (without accounting reduction due to tritium permeation barriers) is about one order of magnitude higher than from the DCLL concept (~ 17%. vs. 1.2%). Parametric studies are also performed to quantify the key factors that govern tritium transport and permeation in the DCLL PbLi blanket. The effect of tritium solubility is significant because it directly affects tritium partial pressure. Over the range of reference tritium solubility from 5e-4 to 0.01 $mol \cdot m^{-3} \cdot Pa^{-1/2}$, the tritium permeation rate decreases from 1.5e-10 mol/s by about 80% to 2.4e-11 mol/s. The values of Hartmann number and FCI electrical conductivity also have strong impacts on tritium permeation because these parameters change the velocities in the gap. A higher Hartmann number or a higher FCI electrical conductivity increases the gap velocities, thus reducing the tritium concentrations in the gap and the tritium permeation rate.

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