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Preliminary system modeling for the EUROfusion Water Cooled Lithium Lead blanket

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Title: Preliminary system modeling for the EUROfusion Water Cooled Lithium Lead blanket

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Abstract

The Water Cooled Lithium Lead (WCLL) blanket is one of the four breeder blanket technologies under consideration within the framework of EUROfusion Consortium activities. The aim of this work is to develop a preliminary model that can track the tritium concentration and fluxes along each part of the WCLL blanket and their ancillary systems at any time.

Because of tritiums nature, the phenomena of diffusion, dissociation, recombination and solubilisation have been taken into account when describing the tritium behavior inside the lead-lithium channels, the structural materials and the water coolant circuits. The simulations have been performed using the object oriented modeling software EcosimPro.

Results have been obtained for a pulsed generation scenario for DEMO. The tritium inventory in every part of the blanket has been computed. Permeation rates have been calculated as well allowing to know how much tritium ends up in the coolant system and how much remains in the liquid metal. The amount of tritium extracted from the lead-lithium loop has been also obtained. All this information allows having a global perspective of tritium behavior all over the blanket at any time.

The model provides valuable information for the design of the WCLL blanket. More complex upgrades are planned to be implemented based on this model in future stages of the EUROfusion Project

1 WCLL Blanket Description

The WCLL blanket is based on the liquid lead-lithium as neutron multiplayer and tritium breeder. One of its characteristic features is the presence of coolant water pipes embedded in the liquid metal. The design of the EUROfusion WCLL is on progress, the assessments here presented are based on WCLL 2014 [1].

The 2014 WCLL blanket is divided in sixteen sectors and 608 breeding modules. In each sector there are fourteen inboard breeder modules and twenty four outboard breeder modules. The modules essentially consist in some liquid metal channels with water pipes embedded on it to cool them. The geometry of an outboard equatorial module is shown in figure 1.

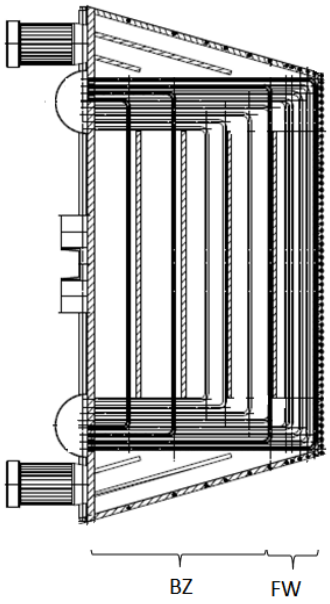

Figure 1: Poloidal-radial section of an WCLL outboard equatorial module. The first wall (FW) and the breeder zone (BZ) are remarked

The objective of this work is to perform a preliminary mathematical model that allows simulating the tritium behavior in the blanket and ancillary systems associated to it. The aim of the model is not obtaining a detailed 3D model that includes all the relevant physical phenomena that affects the tritium concentration (thermohydraulics effects, magnetohydrodynamics effects, diffusion, surface effects, etc). The perspective of this model is global, in other words, the

results has to compute variables related with the whole blanket not with a specific part of it. For developing the model the object oriented modeling software EcosimPro [2] has been used.

2 Tritium Model Description

A system level model requires some assumptions and simplifications. The first and probably one of the strongest one is considering all the WCLL blanket modules equal. Under this assumption it is only necessary to implement a model of the most representative module, the outboard equatorial module, and then multiply the results by the total number of modules.

Figure 2 depicts the process flow diagram used for modeling of a complete lead-lithium loop. As shown in figure 1, the geometry of the WCLL outboard equatorial module is rather complex but it can be roughly divide into two zones: the first wall (FW) and the breeder zone (BZ). The lead-lithium enters firstly in the BZ which is connected in series with the FW. When leaving the FW channel, the flow is multiply by the number of breeder modules that are fed by one lead-lithium loop (an average of 76 modules per loop). Immediately after, the PbLi flow goes through the Tritium extraction system (TES) where part of the tritium is extracted while the rest reenters the blanket closing the loop. When going through the BZ and FW channel tritium can permeate through the Eurofer walls reaching the water. In contrast to the lead-lithium channels, the water pipes of the BZ and the FW run in parallel.

Each box of the diagram has associated a series of spatially discretized equations that the model have to solve. The lead-lithium and water flows have been discretized only in the direction of their flows. In contrast, the Eurofer material has been discretized also in the direction of the tritium diffusion flow. However, it is assumed that the equations in both dimensions are decoupled from each other.

Regarding the lead-lithium flow, the 1D equation that governs the tritium concentration behavior in the model is equation (1). This equation takes into account the phenomena of

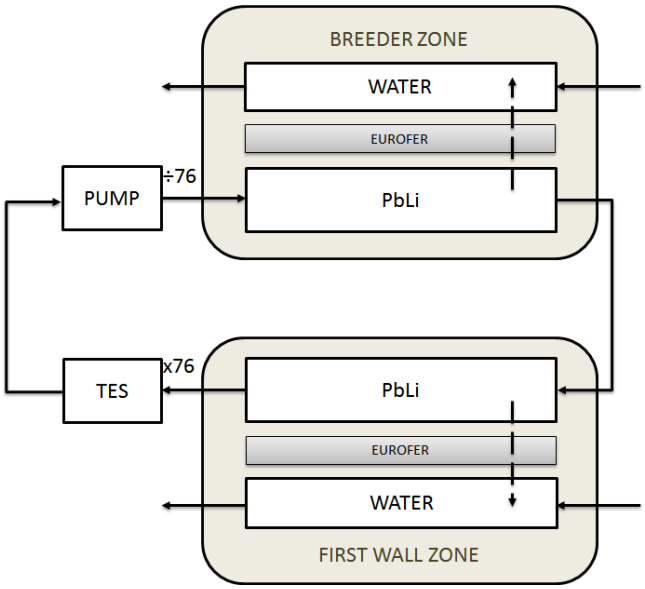

Figure 2: WCLL lead-lithium loop process flow diagram. In dotted line the tritium permeation path, in full lines the PbLi water flows

advection, diffusion, generation and permeation.

$$\partial_t c(t, x_i) = -\frac{u(x_{i+1})c(t, x_{i+1}) - u(x_i)c(t, x_i)}{\Delta x} + G(t, x_i) - \frac{J(t, x_i)}{\Delta x} \qquad i = 1, ..., M \tag{1}$$

Where M is the number of nodes in the axial direction, Δx is the discretization length, x_i is the position of the i-th node and $J(t, x_i)$ is the flux of tritium through the Eurofer walls in this node.

The function G represents the generation of tritium inside the iquid metal. It has been decomposed into a temporal component and a spatial component. The temporal component is given by the DEMO reactor pulses [3] while the spatial component follows an exponential profile along the radial direction and an approximately constant profile along the poloidal and toroidal directions as shown in equation (2).

$$G(t, r) = G_t(t)\ p \exp(-b(r - \omega)) \tag{2}$$

The parameters p, b and ω has been chosen accordingly with the neutronic [4] studies of the WCLL blanket.

The walls of the water pipes are made of Eurofer. Inside this steel, tritium diffusion follows the Fick's law (equation (3)) along the radial coordinate of the pipe.

$$J(t, x_i, r_i) = -D\frac{c(t, x_i, r_{j+1}) - c(t, x_i, r_j)}{\Delta r} \tag{3}$$

Inside the lead-lithium and the Eurofer the tritium is present in its atomic form. As a consequence there is no recombination nor dissociation process at this interface. The systems tends to balance the partial pressures at both sides of the interface which according with Henry's law implies the boundary condition over the concentration described in equation (4)

$$\frac{c_{PbLi}}{Ks_{PbLi}} = \frac{c_{EU}}{Ks_{EU}} \tag{4}$$

Where Ks is the solubility constant of tritium in Eurofer or in lead-lithium. The properties of the hydrogen isotopes in the Eurofer [5] and in the lead-lithium [6] have been measured experimentally. The value of those macroscopic constants have an important impact over the permeation to the coolant, the results obtained differs significantly when using different measures of the solubility.

Inside the water, tritium is no longer present in its atomic form but in any of its molecular forms: T_2, HT, HTO and T_2O [7]. The concentration of any of those chemical species follows an equation very similar to (1) but in this case the source term can comes from the permeation through the Eurofer-water interface or from the chemical reactions that have to be included in the concentration evolution.

The molecular fluxes that enter or leave the water flow can be written in terms of the

constants of recombination (K_r) and dissociation (K_d) at the interface between the Eurofer and the coolant as shown in equation (5)

$$\begin{aligned} J_m(H_2) &= K_d\, p(H_2) - K_r\, c(H)^2 \\ J_m(T_2) &= K_d\, p(T_2) - K_r\, c(T)^2 \\ J_m(HT) &= K_d\, p(HT) - K_r\, c(T)c(H) \end{aligned} \tag{5}$$

Where p(Q_2) is the partial pressure of the gas dissolved inside the water and c(Q) is the atomic concentration of tritium or hydrogen in the Eurofer. With this description it is not assumed neither a diffusion limited process nor a surface limited process, the regime depends on the specific values of the constants and the concentrations.

It is patent in equation (5) that the formation of HTO at the surface has not been considered in this model. However, this does not mean that the model does not consider other tritium molecules inside the water. The HTO is rapidly formed via the isotopic exchange between H_2O and HT. Acording with [7], the the formation of HTO at the interfaces via the recombination of HO^- ions and T atoms has been observed experimentally, however this preliminary model does not take this surface effect into account. The formation of T_2O and HT via isotopic exchange has not been taken into account either due to the low value of the kinetic constants in comparison with the reaction of HTO formation.

Finally, in order to fully describe a complete lead-lithium loop it is necessary to take into account the effect of the tritium extraction system (TES). This system is placed outside of the blanket and it has been considered, as a first approximation, a black box that extracts the tritium with certain efficiency η according with equation (6).

$$c(t)_{out} = (1 - \eta)c(t)_{in} \tag{6}$$

After the extraction the lead-lithium with the leftover tritium reenters the blanket as shown in figure 2. The remaining component of the diagram is just a pumping system that imposes a constant mass flow rate of lead-lithium.

3 Reference Case Results

The input data of this model has been mainly obtained from [1] and from direct communication with the designers of the blanket. Those data has been adapted to the model input requirements. As mentioned before, the macroscopical constant that characterise the materials have a deep impact over the tritium behaviour. For the reference case, the solubility constant used was obtained from [6] while the recombination and dissociation constants comes from [8]. This choice has been motivated to obtain the worst case scenario in terms of permeation as shown in previous works [9].

Several results have been obtained for the DEMO pulse generation scenario [3]. In figures 3-5 some of them are exposed. Even though the simulations have been launched for only one of the eight loops, it has been assumed that the loops are approximately equal thus, the present results correspond to the complete blanket.

Figure 3 depicts the total amount of tritium generated, the total amount of tritium extracted, the inventory of tritium in the whole system and the total amount of tritium permeated to the coolant. The generation curve has a step like shape due to the generation pulses. The ideal extraction system described in (6) makes that the majority of the tritium generated in the blanket ends up extracted (around the 92%). After a brief transient period, the inventory remains constant but some oscillations due to the pulses, this means that the equilibrium be-

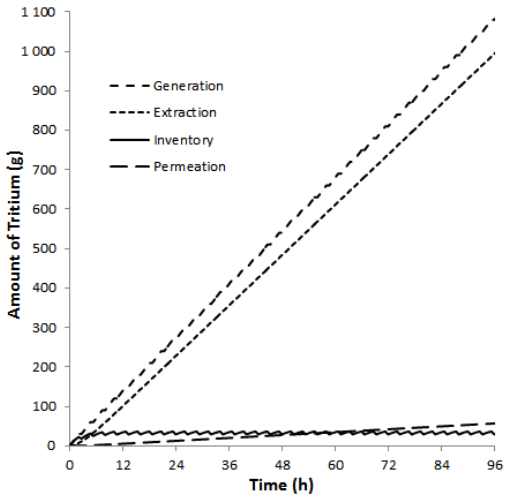

Figure 3: Total generation, total extraction, total inventory and total permeation in the WCLL blanket system

tween the generation, the extraction and the permeation is reached. After the sufficient amount of time approximately the 8% of the tritium generated ends up in the coolant loop.

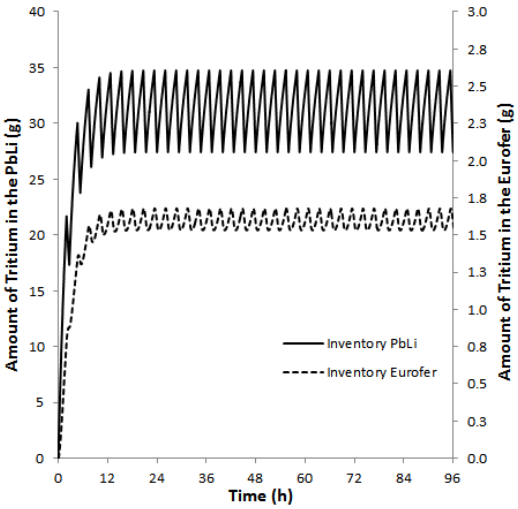

Figure 4: Inventories of tritium inside the PbLi channels (full line) and inside the pipe walls (dashed line)

Figure 4 shows the distribution of the inventory along the different parts of the blanket. Naturally, the majority of tritium inventory resides in the lead-lithium where is generated. However, there is a certain amount of tritium, an average of 1.6 grams, that is present in the Eurofer walls of the water pipes.

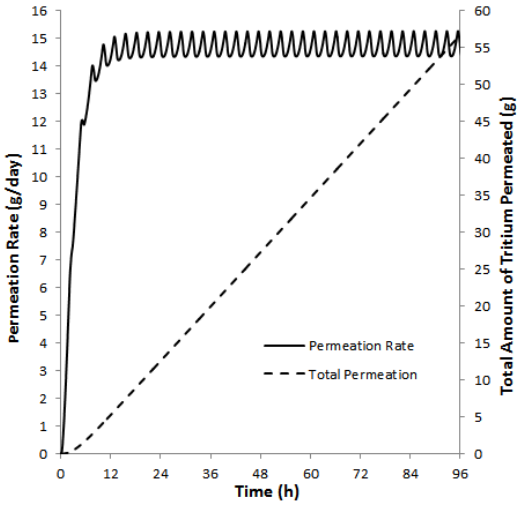

Figure 5: Permeation rate in the interface Eurofer-water (straight line) and total amount of tritium permeated (dashed line)

Figure 5 display the permeation rate throug the interface Eurofer-water. The hydrogen presence in the water favors the permeation via the formation of HT at this interface which is responsible of the relatively high permeation value. The tritium permeates to the coolant at an average rate of 14.9 grams per day. Once in the coolant the vast majority of the tritium adapts the form of HTO with only very small traces of HT and T_2 molecules. Eventhough this value is significantly high, it is comparable with previous studies like [10] where a permeation of 51 grams per day was obtained.

4 Conclusions

This preliminary model has been developed with the objective of provide handful information to the WCLL blanket designers. It has been implemented with a system level approach, favoring the computing of global variables in detriment of an accurate local description.

Results of section 3 shows a relatively high permeation of tritium from the lead-lithium to the water pipes and a relatively low inventory in the structural material of the pipes. Both effects are caused by a significant fast tritium flow inside the steel due presence of H_2 in the

water. Nevertheless, the high extraction efficiency considered for the reference case in the TES makes that the majority of tritium generated, around the 92% ends up extracted while only around 8% ends up in the coolant circuit.

Acknowledgments

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