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# Tritium transport in HCLL and WCLL DEMO blankets

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## HIGHLIGHTS

- Tritium inventories and tritium losses are the main output of the presented model for HCLL and WCLL.
- A parametric study has been performed, to show the behavior of the two systems when certain parameters are changed, in order to minimize inventories and/or losses.
- An improved design is needed, in order to reduce the radiological hazard related to tritium activity. According to test number 7, HCLL-BB could be able to have a tritium inventory of 33.05 g and losses of 19.55 Ci/d.
- WCLL-BB shows a very low radiological risk, much lower than that suggested (inventory: 17.48 g, losses: 3.2 Ci/d). An ptimization study has been performed aiming to minimize the water flow rate for an upgraded design.
- Both for HCLL and WCLL, the most critical parameters able to produce relevant variations in inventories and losses are the helium/water fraction, the CPS/WDS and the permeation reduction factors.

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## ABSTRACT

The Helium-Cooled Lithium Lead (HCLL) and Water-Cooled Lithium Lead (WCLL) Breeding Blankets are two of the four blanket designs proposed for DEMO reactor. The study of tritium transport inside the blankets is fundamental to assess their preliminary design and safety features. A mathematical model has been derived, in a new form making makes easier to determine the most critical components as far as tritium losses and tritium inventories are concerned, and to model the tritium performance of the whole system. Two cases have been studied, the former with tritium generation rate constant in time and the latter considering a typical pulsed operation for a time span of 100 h. Tritium inventories and tritium losses are the main output of the model. Tritium concentrations, inventories and losses are initially calculated and compared for the two blankets, in a reference case without permeation barriers or cold traps. A parametric study to show the behavior of the two systems when certain parameters are changed, in order to minimize inventories and/or losses, has been carried out.



## 1. Introduction

The Helium-Cooled Lithium Lead (HCLL) and Water-Cooled Lithium Lead (WCLL) Breeding Blankets are two of the four blanket designs proposed for DEMO reactor [1–6].

The activities referred to as *TBM (Test Blanket Model) Program* in ITER [6,7] foresee that six mock-ups of six whole DEMO-BB systems will be tested in ITER; this means that the TBMs are connected with several ancillary systems, such as cooling systems, tritium extraction systems, coolant purification systems, and instrumentation and control systems. TBMs and associated systems are called Test Blanket Systems (TBSs).

The HCLL Breeding Blanket configuration [3,4,6] is a specific DEMO version called HCLL-DEMO-2007, whose preliminary project was carried out in 2007 by CEA [8]. In 2012, the EFDA agency issued new specifications for DEMO: we will refer to this blanket configuration simply by HCLL-BB. The Water-Cooled Lithium Lead Breeding Blanket (WCLL-BB) [1,5,6], according to PPCS model A from which it derives, it is based on near-future technology requiring small extrapolation from present-day knowledge both on physical and technological aspect [5–8].

The study of tritium transport inside the blankets is fundamental to assess their preliminary design and safety features. For this purpose, a mathematical model has been derived, in a new form. making easier to determine the most critical components as far as

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tritium losses and tritium inventories are concerned, and to model the tritium performance of the whole system. Tritium generation rate has been considered either constant or pulsed. Tritium inventories and tritium losses are the main output of the model. Tritium is mostly produced in breeding reactions and inventories are inside the breeder, steels, water loop (for WCLL) or He loop (for HCLL). Tritium losses are due to the tritium permeation flux through the walls and joints. For both the HCLL and WCLL case, we give a representation of the physical processes linked to the tritium permeation inside the breeding blanket.

Tritium concentrations, inventories and losses are initially calculated and compared for the two blankets, in a reference case without permeation barriers or cold traps. A parametric study follows, to show the behavior of the two systems when certain parameters are changed, in order to minimize inventories and/or losses.

## 2. Models and methods

A tritium transport model for HCLL and WCLL breeding blanket configurations for DEMO has been built: it takes into account both the breeding blanket and all the auxiliary systems, in order to develop a tritium balance for the whole DEMO reactor. This model is based on the 1-D approximation, therefore Fick's law and Richardson's law are deduced for a slab configuration. On the other hand, all the concentrations have been considered uniform in space but time-varying. With these hypotheses, it has been possible to evaluate tritium concentrations, inventories, losses and partial pressures, with the purpose of comparing these two breeding blanket configurations. Moreover, a parametric analysis has been performed, characterizing the system dynamics and the most critical components.

From a mathematical point of view, an analytical model suitable to describe the average tritium concentrations, inventories, losses and partial pressure needs two phases. The first one is aimed to formulate a generic model for what regards the tritium balance inside the HCLL and WCLL breeding blankets: in this section, two suitable mass balance equations will be deduced, both for the breeder/multiplier loop and for the coolant loop(s). Within the second phase, the tritium fluxes which appear in the general balance equations in terms of the average concentrations of all the tritium forms (HT, HTO), are expressed. The first pahse is common to both configurations, since the balance is carried out for the same subsystems.

The HCLL and WCLL breeding blankets are supposed to be self-sustaining in terms of tritium production and consumption. To achieve this purpose, several ancillary devices have to be present, both for the breeder and for the coolant loops. Tritium self-sufficiency depends on plasma burn-up, the blanket Tritium Breeding Ratio (TBR), and the residence time in the Tritium Extraction System (TES). The TES is made by the Tritium Extraction Unit (TEU) and by the Tritium Removal System (TRS) [1–6,9,10].

The considered steels for the different BB sub-systems are: for HCLL, EUROFER for FW, CP, SP; INCOLOY for SG tubes. For WCLL: EUROFER for FW, BZ; INCOLOY for SG tubes. Concerning the system Pb-16Li/tritium, it was used the Sievert constant evaluated by Reiter [11] in order to evaluate the permeated fluxes through FW, CP, SP or FW, BZ.

Tritium leakages are mostly due to Q2 species (where Q indicates H, T, or D) permeation through high-temperature pipes and joints in the primary coolant circuit. The leakage rate, F [mol/s], in literature is taken from Gas Cooled Reactors field [15]. Estimates of the rate of replenishment necessary to evaluate He leakage vary between 0.1% of total He inventory per day2. (0.1% inv./d). Concerning HCLL, the equation for the tritium flux is expressed as a sum of two contributions: 1) the tritium flux from He loop 2) the tritium permeation through the steam generator tubes into the steam line. Concerning WCLL, they are due to the tritium permeation flux through the SG walls and joints.

**Table 1**
HCLL Tritium Inventory.

| | Constant Op. [g] | Pulsed op. [g] | | |
|---|---|---|---|---|
| | | Max | Min | Aver. |
| T inventory in Pb–Li | 8.29 | 8.29 | 1.13 | 4.71 |
| T inventory in steels | 6.5 | 6.5 | 0.89 | 3.695 |
| T inventory in He loop | 0.29 | 0.29 | 0.04 | 0.165 |
| Total | 15.08 | 15.08 | 2.06 | 8.57 |

**Table 2**
HCLL Tritium losses.

| | Constant Op. [Ci/d] | Pulsed op. [Ci/d] | | |
|---|---|---|---|---|
| | | Max | Min | Aver. |
| T leakages from He loop | 0.8 | 0.8 | 0.1 | 0.5 |
| T leakages from SG tubes | 686.0 | 686.0 | 242.4 | 464.2 |
| Total leakages | 686.8 | 686.8 | 242.5 | 464.7 |

The calculation for 1) has been divided into two steps. First, for both HT and HTO species, the tritium leakages flux have been evaluated using the leakage rate, thus it has been easy to estimate the total lost flux equation from helium loop just as sum of the two contributions. Secondly, the other source of losses is the tritium permeation through the steam generator tubes: on SG tubes walls, an oxidation layer for corrosion control has been considered, reducing the tritium permeation of a factor equal to their PRF (equal to 100). The calculation for 2) was carried out by writing down the expressions of the permeation fluxes through the tubes of the steam generators both for the FW/SB water coolant loop and for the BZ water coolant loop.

The methodology we have used to determine the tritium leakage from He in the loop and through the SG tubes is the following: for HCLL, the tritium leakage from He in the loop and through the SG tubes has been conducted by expressing the density leakage flux [mol/m2/s], according to Richardson's law, and assuming He as an ideal gas. For WCLL, the permeation flux is here calculated considering fugacity and Henry's constants evaluated at the average water temperatures in the FW/SB and BZ.

### 2.1. HCLL blanket

A study was performed aiming to investigate tritium balance in HCLL-BB. This study gives a representation of the physical process linked to the tritium permeation inside the blanket. Three subsystems can be distinguished (see Fig. 1): the Pb-16Li loop, the He Coolant System, HCS, and the steam/water loop

Two cases of generation rate have been studied:

1. The generation rate is constant: G = 385 [g/d];
2. The generation rate is variable and follows a typical DEMO pulse: ramp up = 2 h, flat top = 2 h, ramp down = 1 h, dwell = 0.5 h (see Fig. 2).

For HCLL, Pb-16Li flow-rate is 810 kg/s, TES efficiency is 0.8, PRF_HCLL is 5 and PRF_SG is 100. For WCLL, Pb-16Li flow-rate is 560 kg/s, TES efficiency is 0.8, PRF_WCLL is 5, PRF_SG is 100, $\alpha_{CPS}$ is 0.01, and $\eta_{CPS}$ is 0.6.

Results are available in Figs. 3 and 4 and in Table 1. Tritium inventory is 15 g as a maximum and 8.57 g as an average in the pulsed generation rate case. Tritium losses are due to the tritium permeation flux through the SG walls and to the helium leak-