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Tritium management and anti-permeation strategies for three different breeding blanket options foreseen for the European Power Plant Physics and Technology Demonstration reactor study

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ABSTRACT

In DT fusion reactors like DEMO, the commonly accepted tritium (T) losses through the steam generator (SG) shall not exceed about 2 mg/d that are more than 5 orders of magnitude lower than the T production rate of about 360 g/d in the breeding blanket (BB). A very effective mitigation strategy is required balancing the size and efficiency of the processes in the breeding and cooling loops, and the availability and efficiency of anti-permeation barriers. A numerical study is presented using the T permeation code FUS-TPC that computes all T flows and inventories considering the design and operation of the BB, the SG, and the T systems. Many scenarios are numerically analyzed for three breeding blankets concepts – helium cooled pebbles bed (HCPB), helium cooled lithium lead (HCLL), and water cooled lithium lead (WCLL) – varying the T processes throughput and efficiency, and the permeation regimes through the BB and SG to be either surface-limited or diffusion-limited with possible permeation reduction factor. For each BB concept, we discuss workable operation scenarios and suggest specific anti-permeation strategies.

1. Introduction

Any DT nuclear fusion reactor beyond ITER will have to produce its own tritium (T) at unprecedented throughputs. Many different T breeding blankets (BB) concepts have been proposed over the last decades. The European Power Plant Physics & Technology Demonstration reactor (PPP&T DEMO) study is focusing on the most four practicable ones [1]. The T management in the BB is in principle clear and simple: recover as much as possible T as close as possible to its production. T can then be immediately routed to the inner fuel cycle to sustain the fusion reaction, and the T losses towards the coolant and later into the environment through the steam generator (SG) can be minimized. However, it is very challenging in practice given the huge constrain from the maximal allowed T losses into the environment that should not exceed a target value commonly set between 0.6 and 1 g/y. In comparison, the amount of T necessary to power a fusion reactor at 1 GWe output is a bit more than 100 kg/y, i.e. more than 5 orders of magnitude higher. To meet such high confinement requirements, and given operation at high temperatures that increase T losses via permeation, very large and efficient T recovery systems will have to be implemented for both the breeding and coolant loops – the T extraction (TES) and coolant purification (CPS) systems – as shown in Fig. 1. Both the TES and CPS shall be scaled-up according to T extraction performances (flow rates × efficiencies) requirements; but their physical size will have to be kept as low as possible for economic reasons. The use of anti-permeation barriers (APB) made of coatings or chemically sustained is the only other countermeasure to reduce T permeation and losses. Finally, effective permeation mitigation consists in defining the optimized T management in BB, as a trade-off between the size/efficiency of the T processes and the feasibility/efficiency of the APB.

The T permeation issue has been addressed at the early beginning of the nuclear fusion technology development [2]. Many independent studies have covered the water cooled lithium lead (WCLL) [3], the helium cooled lithium lead (HCLL) [4–7], and the helium cooled pebbles bed (HCPB) [8,9] BB concepts. HCLL seems to be among the different BB candidates the most critical one in term of T permeation where very efficient APB should counteract as final but critical mitigation. Although correct and exhaustive,

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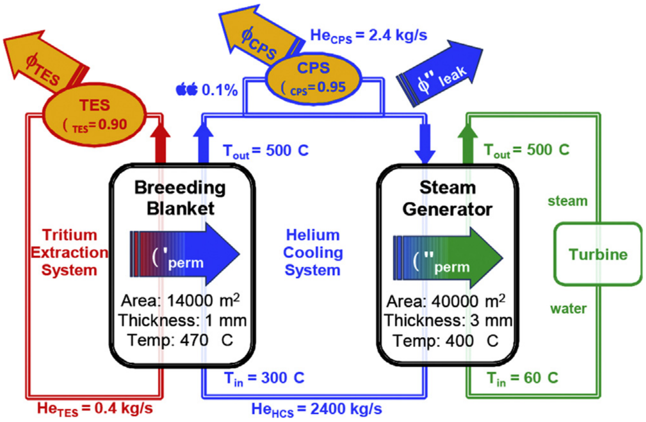

Fig. 1. Simplified view of tritium migration path from the breeding zone to the environment (numbers here are indicative and mostly refer to the HCPB DEMO reactor design).

Source: Taken from Ref. [10].

all these studies were considering different assumptions, scenarios, and material data making a clear comparison among different BB options very difficult. We report in this paper on a unified BB T transport simulation tool that can handle simplified BB characteristics but comprises all relevant and significant phenomena participating to T flows and inventories from the breeding region up to the environmental releases point. The most recent engineering data under consolidation under the PPP&T DEMO study were used to compare on the same complexity level 3 different BB candidates. The numerical outcomes for tritium releases are discussed with regard to technological readiness of the different T processes to better assess the amount and direction of the future R&D.

2. Simulation tool for tritium migration study

This numerical study has been performed using the FUS-TPC tritium permeation code developed under MATLAB environment. This code considers mass balance equations for T in various chemical forms coupled with a variety of T sources, sinks, with several permeation models [9,11,12]. It computes with time dependency all T flows and inventories considering the design and operation of the BB, the SG, and the T processing systems. Slightly different FUS-TPC variants have been developed to reflect the specificities of the three different BB candidates studied herein. The same material database, models and assumptions are used; solely the specific geometry and operation of BB and SG are tuned to reflect the specificities of HCPB, HCLL and WCLL BB. This ensures high consistency and enables fair comparison for T migration issues among the different BB concepts. For all the BB blankets concepts numerically studied, the following simplifications and assumptions are made:

- All processes (T generation, permeation. . .) in steady-state;
- 1D geometry without radial distribution of T generation (homogeneous production in "black box");
- Lumped parameters for T and temperatures in BB and SG (arithmetic mean);
- T processes as black box (no physics behind).

3. Input parameters for different BB

The material database for Eurofer, Incoloy and PbLi was taken from latest relevant literature. BB and SG design and operation data were taken from the latest available PPP&T DEMO studies. All three BB concepts have been equally scaled for a DEMO fusion power of 2119 MW and tritium breeding ratio (TBR) of 1.1. This corresponds to a tritium production rate of 356 g/d at full power day operation. The cooling loop and the SG are common for both HCLL and HCPB. The main data used in our work are given in Table 1.

4. Numerical analysis for different BB

Many scenarios were computed varying the T systems throughput and efficiency, and also studying the influence of the permeation regimes through the BB and SG assumed being either diffusion-limited with varying the permeation reduction factors (PRF) or surface-limited. For all blankets, a huge influence of the permeation regime used was observed. T losses, if calculated with diffusion limited regime, are definitively too high and significant PRF values are required to maintain T losses to be kept below the 2 mg/d target. In contrast, when assuming surface limited regime the losses through the SG are decreased by several orders of magnitude especially for oxidized surface. Under this condition, T losses can be kept below the 2 mg/d target even keeping the T processes requirements reasonable.

The different BB concepts were compared first according to a "starting scenario" considering reasonable values for the T systems and conservative computation with diffusion-limited regime and modest PRF. At first, no anti-permeation barriers are considered, but PRF-BB of 10 for WCLL is assumed with double-wall tubes (Table 2). For numerical consistency more than related to engineering facts, the same values for extraction efficiencies in TES and CPS were used for the three blankets. We compute very large differences for T permeation and releases between the different BB concepts. Tritium losses are predicted between 1 mg/d for WCLL and 320 mg/d for HCLL, with HCPB releases around 110 mg/d. Beyond these "starting scenarios", all the key parameters

Table 1
Design and operation of BB and SG for input data in simulation (n.a., not applicable; CP, cooling plates; SP, stiffening plates; FW, first wall; BZ, breeding zone; SG, steam generator).

	HCPB	HCLL	WCLL
Breeding zone (design and operation)			
T production [g/d]	356	356	356
He purge inventory [kg]	15	n.a.	n.a.
He purge mass flow rate [kg/s]	0.4	n.a.	n.a.
PbLi inventory [m^3]	n.a.	583	360
PbLi mass flow rate [kg/s]	n.a.	810	560
BB wall area [m^2]	13,370 (CP) 0 (SP)	17,924 (CP) 8214 (SP)	1760 (FW) 13,532 (BZ)
BB wall thickness [mm]	1	1	2
Cooling zone (design and operation)			
Coolant mass flow rate [kg/s]	2400	2400	4800 (FW) 4800 (BZ)
Coolant inventory [kg]	10,700	10,700	1156 (FW) 14,160 (BZ)
Coolant leakage [% inv/y]	4.4	4.4	n.a.
SG wall area [m^2]	40,000	40,000	6272 (FW) 12,302 (BZ)
SG wall thickness [mm]	2	2	2