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The coolant purification system in DEMO: candidate technologies, requirements and interfaces

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The coolant purification system in DEMO: interfaces and requirements

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The blanket concepts investigated under the EUROfusion program rely on water or helium as primary coolant medium; main duty of the coolant is to recover the thermal power from the first wall and the blanket units and drive it into the Primary Heat Transfer System (PHTS). The coolant path goes through three different systems: the breeder, the tritium plant and the PHTS. In the breeder region, part of the produced tritium can permeate into the coolant loop, from the coolant into the steam generator and thus reach the environment. The Coolant Purification System (CPS), located inside the tritium plant, is responsible to recover tritium from the coolant and to control the coolant chemistry.

The paper provides the status of the CPS design: the technology review was completed last year, while now the CPS interfaces and requirements are defined. Main issues arise from the definition of the amount of coolant to be routed inside the CPS due to the large uncertainties related to the amount of tritium permeation rate from blanket into coolant and to the presence and effectiveness of anti-permeation barriers.

Keywords: coolant purification system, tritium technology, DEMO.

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1. Introduction

The blanket concepts developed within the EUROfusion program mainly rely on helium or water as primary coolant mediums [1]. As illustrated in Fig.1, the coolant loop passes through the breeder blanket where tritium is expected to permeate from the breeder zone into the cooling system [2]. Tritium, in fact, has the ability to permeate across metallic walls and, in the blanket region, there are all the favorable conditions to encourage the permeation phenomena, such as: high temperature, reduced wall thickness and high tritium concentration in the blanket side. Once tritium has reached the coolant loop, it must be removed. The need to remove the tritium present in the coolant comes from the requirement to keep low the tritium partial pressure inside the coolant itself, in order to: 1) avoid the tritium release via permeation and/or coolant leakage into the working environment and 2) minimize the risk of further permeation into the secondary coolant loop and from there into environment. Moreover the need to remove and account for the tritium permeated from the blanket is mandatory for monitoring the tritium balance and blanket performances [3]. Main function of the Coolant Purification System (CPS) is to recover the tritium permeated into the coolant. Considering the large coolant flow rate of the DEMO blanket concepts, it is reasonable to assume that the CPS can treat only a small fraction (about 1%) of the total coolant amount. This means that the control of the tritium permeation can be achieved only by combining a well-adjusted coolant loop and CPS with effective anti-permeation barriers [4]. Particularly, the research about anti-permeation barriers still require qualification tests to verify the stability of the coating in a corrosive environment and under irradiation.

This work, carried out within the frame of the WPTFV (Tritium Fuelling and Vacuum), presents the recent achievements of the activity, the final scope of which is the design of the CPS for DEMO, both in case of helium and water coolant.

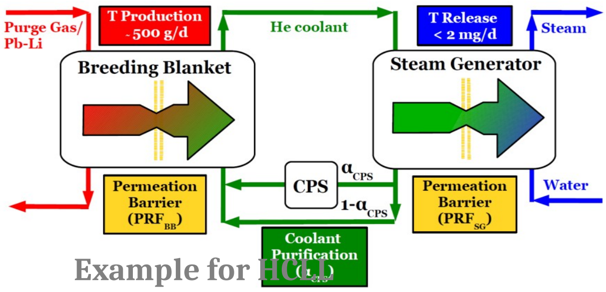

Fig.1 Schematic view of the coolant path in HCLL blanket concept (numbers are only indicative).

Starting from a literature review, a first phase was aimed at classifying possible candidate technologies, as described in [2]. While, in this second phase, there is the need to identify main CPS interfaces and requirements. With the definition of the CPS requirements, it will be possible to start the design phase that is the third step of the task. In this work only the HCPB and WCLL blanket concepts are considered since these two concepts are representative for the two coolant mediums: helium and water. In the HCPB, the breeder material is solid (different types of lithiated ceramics are under investigation), while the coolant is helium at 8 MPa. Conversely in the WCLL blanket, the breeder material is the alloy $Li_{17}Pb$ at liquid phase (Pb with 17% Li, melting point 235 °C) and the coolant is water at 15.5 MPa.

2. Assessment of the tritium permeation issue and of the CPS interfaces

The CPS has many interfaces with other systems that are currently under development in several projects. This because, as better described later, one of the most important parameter for CPS design and operation is the tritium permeation rate from the blanket into coolant loop. Such parameter can be defined only considering an integrated approach in which many systems are involved. Particularly, Fig. 2 represents an attempt of the authors to illustrate all the relevant information required to correctly assess the tritium permeation rate from one system to another. The different colors indicate the projects (in EUROfusion) responsible for the definition of each information and thus provide also the CPS interfaces.

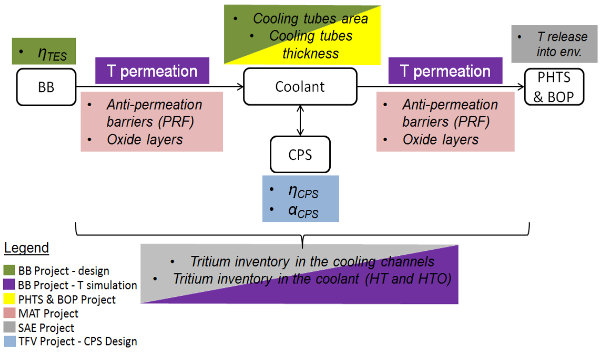

Fig. 2 Assessment of the tritium permeation issue: integrated approach.

The breeder blanket (BB) project should define many fundamental aspects that can be divided in two main areas: a) the blanket design, which defines the type of coolant (helium or water), the design of the coolant loop (total surface, thickness and materials of the tubes and plates), the coolant flow rate and inventory, the coolant operating conditions (temperature and pressure), the tritium solubility value (in case of liquid blanket), the tritium extraction system and its efficiency (η_{TES}) etc., and b) the blanket modelling at system level, in which all the information coming from the blanket designer should be collected and used to assess the tritium permeation from blanket into coolant and the tritium inventory via modelling simulation. The Primary Heat Transfer System (PHTS) & Balance of Plant (BOP) project, together with the BB project, should define the geometry of the coolant loop; moreover, it should be also interested in receiving information from the CPS project since it directly affects the tritium partial pressure in the coolant loop and thus the tritium permeation from the primary into the secondary coolant (steam generator). The Environmental and Safety Project are responsible for the definition of two important parameters, which are: the maximum tritium concentration in coolant (both for HT and HTO) and the maximum tritium release into rooms (due to permeation and leakage) and into environment (T release from secondary coolant). The Material (MAT) Project also has very important role since it is responsible for the development of anti-permeation barriers, which Permeation Reduction Factor (PRF) has to be guaranteed also under neutron irradiation and in a corrosive environment. Finally the Tritium Fuelling and Vacuum (TFV) project, being responsible of the CPS design, has to provide two important parameters: the efficiency of CPS (η_{CPS}) and the amount of coolant to be treated inside the CPS (α_{CPS}).

At this stage, most of the above listed information is not available since still under investigation among the different projects. Therefore the estimation of the tritium permeation rate according with the illustrated integrated approach is now not possible (but has to be considered for the future). However, in order to proceed with the activity, the tritium permeation rate has been assessed according with a “stand-alone” approach that considers only part of the systems illustrated in Fig. 2.

3. CPS requirements

In order to design the CPS, few inputs have to be defined, they are:

- tritium permeation rate from the blanket;
- CPS efficiency (η_{CPS});
- amount of coolant to be treated inside the CPS (α_{CPS});
- chemistry of the coolant.

Once the tritium permeation rate from the blanket ($F_{T,p}$), the CPS efficiency (η_{CPS}) and the allowable tritium specific activity (c_0) in the coolant at the blanket outlet are defined, then it is possible to calculate the amount of coolant to be treated inside the CPS according to the scheme reported in Fig. 3 and the mass balance equations illustrated below.

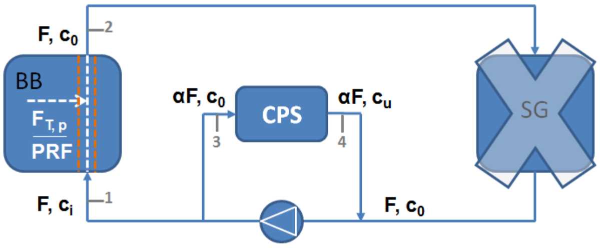

Fig. 3 Scheme of the coolant loop used to perform the mass balance of the CPS (the contribution of steam generation, SG, is neglected).

Regarding the coolant chemistry, some H_2 and H_2O are usually added to the coolant (in case of water coolant only H_2) to adjust its oxidation-reduction potential and to control the isotopic exchange of tritium from the liquid to the gas phase and vice versa; in addition also few chemical impurities can arise inside the coolant. At this preliminary stage this issue is less demanding compared to the tritium permeation and, therefore, it is not taken into account. However it is very important to consider such aspect during the design phase, since the size and the effectiveness of some technologies are strongly affected by the coolant chemistry (i.e. getter bed).

According with Fig. 3, the tritium mass balance can be assessed according with the following equations:

$$F c_0 = F c_i + \frac{F_{T,p}}{PRF_{BB}} \tag{1}$$

$$\eta_{CPS} = \frac{c_0 - c_i}{c_0} \tag{2}$$

$$F c_i = (F - \alpha F) c_0 + \alpha F c_u \tag{3}$$

Where c_u and c_i (mol mol^{-1}) are the tritium concentration at the CPS outlet and at the blanket inlet, respectively. By combining the above equations, it is possible to express the coolant fraction to be routed inside the CPS as follow.

$$\alpha_{CPS} = \frac{\dfrac{F_{T,p}}{PRF_{BB}}}{F c_0 \eta_{CPS}} \tag{4}$$

Therefore, for a fixed value of CPS efficiency (η_{CPS}), the coolant fraction to be processed inside the CPS (α_{CPS}) depends on the total coolant flow rate (F, kg s^{-1}), the tritium permeation rate from the blanket to the coolant loop ($F_{T,p}$, kg s^{-1}), the value of the permeation reduction factor on the blanket side (PRF_{BB}, dimensionless) and the allowable tritium concentration at the blanket outlet (c_0, mol mol^{-1}). As previously described, at this early stage of DEMO design, the most difficult data to obtain is the tritium permeation rate from blanket into coolant. In the past such value was assessed with a dedicated code (called FUS-TPC in Matlab [6]) based on the integrated approach illustrated in Fig. 2. The results provided by that code, see [4] and [7], where obtained using a 2005 DEMO design that now is out of date. For this reason, in the frame of the BB project, a novel simulation tool (with Ecosim Pro) at system level is under development considering the most recent DEMO design [8]. Currently the model with Ecosim Pro is able to provide the tritium permeation rate without taking into account the presence of CPS, SG and permeation barriers, which will be integrated in the near future. In view of a possible comparison between the results obtained with the two simulation tools, the amount of coolant to be treated inside the CPS is calculated below considering two different cases; in both of them the allowable tritium concentration at the blanket outlet (c_0) is assumed to be equal to 5 ppb (very conservative value). In the first case, the tritium permeation rate is assessed according with the most recent data available from the tritium modelling a system level (Ecosim Pro) while, in the second case, the tritium permeation rate is considered equal to 5% of the total tritium production rate; previous results with the FUS-TPC code had demonstrated that, in most of the performed parametric analysis, the tritium permeation rate from blanket into coolant was between 1 and 10%.

To help the reader in visualizing the amount of the coolant flow rate in the DEMO CPS, it is useful to report some numbers from ITER in which the CPS of the HCPB-TBM will treat about 0.00372 kg s^{-1}, while the entire Water Detritiation System (WDS) should process 0.00023 kg s^{-1} of water.

3.1 CPS coolant flow rate: case #1

In this case, the amount of coolant to be treated in CPS has been calculated according with the most recent data coming from the Ecosim Pro simulation. Unfortunately, such data are not published yet and are available only on the EUROfusion IDM [8-9]. For this some relevant parameter used for the simulation are reported in Table 1 while Table 2 provides one of the output of the model, that is the tritium permeation rate for the HCPB and WCLL blanket concepts.

Table 1. Main data used in the Ecosim Pro simulation.

Blanket concept	T generation rate*, g d^{-1}	Coolant pressure, MPa	Coolant flow rate, kg s^{-1}
HCPB	189	8	2400
WCLL	270	15.5	4800

* pulse operation regime.

Table 2. T permeation rate obtained with Ecosim Pro simulation.

Blanket concept	T permeation rate, g s^{-1}	% of the total T production rate
HCPB	9×10^{-6}	0.4 %
WCLL	1.7×10^{-4}	5.4 %

By using the output of the Ecosim Pro simulation (Table 2) and the equation (4), it is possible to estimate the amount of coolant to be treated inside the CPS. Table 3 and 4 illustrates these results for HCPB and WCLL blankets. In both cases a parametric analysis has been done in order to identify the most important parameters that affect the amount of coolant inside the CPS.

Table 3. Amount of coolant to be treated inside CPS for different CPS efficiencies and PRF values: HCPB concept, case #1.

η_{CPS}	PRF_{BB}	α_{CPS}	$\alpha_{CPS} \times F$, kg s^{-1}
0.9	1	0.00083333	2.000
	10	0.00008333	0.200
	100	0.00000833	0.020
0.95	1	0.00078947	1.894737
	10	0.00007895	0.189474
	100	0.00000789	0.018947

Table 4. Amount of coolant to be treated inside CPS for different CPS efficiencies and PRF values: WCLL concept, case #1.

η_{CPS}	PRF_{BB}	α_{CPS}	$\alpha_{CPS} \times F$, kg s^{-1}
0.9	1	0.00787037	37.77777
	10	0.00078704	3.777778
	100	0.00007870	0.377778
0.95	1	0.00745614	35.78947
	10	0.00074561	3.578947
	100	0.00007456	0.357895

From the results, it is evident that by increasing the CPS efficiency only a small reduction in terms of coolant flow rate to be routed inside the CPS is achieved, while a very significant reduction is attained by increasing the value of the permeation reduction factor (e.g. by increasing the efficiencies of the anti-permeation barriers).

3.2 CPS coolant flow rate: case #2

In this case, the coolant fraction inside the CPS is assessed by considering a tritium permeation rate from blanket into coolant equal to the 5% of the total tritium generation rate. As already mentioned such value represents an average of the results obtained with previous simulation performed with the FUS-TPC code. Therefore, by considering the same data reported in Table 1, Table 5 gives the tritium permeation rate from blanket into coolant.

Table 5. T permeation rate considering a T permeation equal to 5% of the total T generation rate.

Blanket concept	T permeation rate, g s^{-1}	% of the total T production rate
HCPB	1.094×10^{-4}	5 %
WCLL	1.562×10^{-4}	5 %

By using the data in Table 5 in equation (4), it is possible to assess the CPS coolant flow rate, as illustrated in Table 6 and 7 for HCPB and WCLL, respectively. Also in this case, results obtained by considering different CPS efficiencies and PRF values are reported.

Table 6. Amount of coolant to be treated inside CPS for different CPS efficiencies and PRF values: HCPB concept, case #2.

η_{CPS}	PRF_{BB}	α_{CPS}	$\alpha_{CPS} \times F$, kg s^{-1}
0.9	1	0.01012963	24.31111
	10	0.00101296	2.431111
	100	0.00010130	0.243111
0.95	1	0.00959649	23.03157
	10	0.00095965	2.303158
	100	0.00009596	0.230316

Table 7. Amount of coolant to be treated inside CPS for different CPS efficiencies and PRF values: WCLL concept, case #2.

η_{CPS}	PRF_{BB}	α_{CPS}	$\alpha_{CPS} \times F$, kg s^{-1}
0.9	1	0.00723148	34.71111
	10	0.00072315	3.471111
	100	0.00007231	0.347111
0.95	1	0.00685088	32.88421
	10	0.00068509	3.288421
	100	0.00006851	0.328842

As in the previous case, the most significant reduction of the coolant amount inside CPS is possible by increasing the PRF.

3. Conclusion

The work illustrates the status of the CPS design activity. From the definition of the CPS interfaces it is possible to recognize the strong interaction between the CPS and at least other five projects. This suggests a more general consideration about the tritium permeation issue that it has to be treated by considering an integrated approach since it is a cross-project matter.

Concerning the CPS requirements, it is possible to fix the η_{CPS} equal to 0.9 since higher values do not provide significant advantages. Conversely for the amount of coolant to be treated inside the CPS, this analysis define a range of values based on the available input data. In case of HCPB (η_{CPS} = 0.9), the amount of coolant flow rate in CPS goes from 0.02 kg s^{-1} to 24.3 kg s^{-1}. This large uncertainty is due to two main factors: 1) very different estimation of the tritium permeation rate from blanket into coolant according with the two simulation tools (Ecosim Pro vs. FUS-TPC) and 2) presence and effectiveness of anti-permeation barriers. In WCLL, the range of the amount of coolant flow rate inside CPS is a bit more restricted compared to the HCPB and goes from 0.34 to 34.7 kg s^{-1}. In this case, the outcome of the two simulation tools is rather similar and the large range is only due to the presence and effectiveness of anti-permeation barriers, which surely have the greatest impact on the tritium permeation phenomena.

In order to reduce the large uncertainty about the coolant flow rate inside CPS, in the near future two aspects have to be better defined: the tritium permeation rate and the PRF value.

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References

[1] L. V. Boccaccini et al., Fus. Eng. and Des., 2016. 109–111, Part B: p. 1199-1206.

[2] B. Bornschein et al., Fus. Eng. and Des., 2013. 88(6–8): p. 466-471.

[3] A. Ciampichetti et al., Fus. Eng. and Des., 2010. 85(10–12): p. 2033-2039.

[4] D. Demange et al., Fus. Eng. and Des., 2014. 89(7–8): p. 1219-1222.

[5] C. Day et al., Fus. Eng. and Des., 2016. 109–111, Part A: p. 299-308.

[6] F. Franza et al., Fus. Eng. and Des., 2012. 87(4): p. 299-302.

[7] A. Santucci et al., Plasma Science, IEEE Transactions on, 2014. 42(4): p. 1053-1057.

[8] E. Carella, Preliminary system modeling for HCPB, IDM Ref. No.: 2N2BKU, 2016.

[9] C. Moreno, Preliminary system modeling for WCLL, Ref. No.: 2MKYST, 2015.