The Tritium Extraction and Removal System for the DCLL-DEMO fusion reactor

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During the pre-conceptual design phase of DEMO different alternatives have been explored to be implemented as Tritium Extraction and Removal System (TERS) for the blanket concepts considered in EUROfusion. The TERS is conceived to extract tritium from the breeder and to route it to the Tritium Plant for final processing. A careful review showed that those blankets operated with PbLi should use the Permeation Against Vacuum (PAV) technique as primary option which is based on a one-step, fully continuous procedure. In this paper a conceptual design of the TERS for the Dual Coolant Lithium Lead (DCLL) breeding blanket is presented, based on the European DEMO2015 layout (18 sectors, 2037 MW fusion power). The P&ID of the proposed TERS, integrated in the DCLL-PbLi loop, includes valves and instrumentation, as well as a revised design of the DCLL-PAV. The dimensioning of the permeator considered a tritium extraction efficiency of 80%. An exhaustive investigation on the vacuum system needed for the PAV is also presented. The choice of the most promising vacuum systems took into account the reliability and tritium compatibility of both high and rough pumps. Their pumping requirements, which are dependent on the PAV efficiency, tritium solubility and tritium partial pressure in the loop, are also discussed in this work.

Keywords: Tritium Extraction and Removal System, DCLL, DEMO, Permeation Against Vacuum

1. Introduction

Within the EUROfusion DEMO program several blanket concepts are being developed [1]. Among them, the Dual Coolant Lithium Lead (DCLL) uses liquid PbLi as primary coolant, tritium breeder and neutron multiplier. Additionally, helium is also used as coolant of the first wall and supporting structures [2]. An intrinsic characteristic of this blanket, when compared with the other liquid metal concepts, is the high velocity of the liquid metal. In order to extract most of the reactor power, this blanket has to manage a huge amount of PbLi which leads to this high velocity (~ 2 cm/s in the blanket [2]). An immediate consequence is that the tritium concentration in the liquid is rather low, meaning that the tritium partial pressure in DCLL is about two orders of magnitude lower than the expected one in other blanket concepts [3], [4]. From the point of view of safety, it can be an advantage since the permeation of tritium to the secondary coolant is reduced. However, the low tritium content complicates the recovery process needed to reach the self-sufficiency of the reactor, which gives special importance to the Tritium Extraction and Removal System (TERS). Its main requirements rely on the tritium extraction from the liquid metal to be pumped to the tritium plant where it is stored or processed to be re-injected into the torus. The TERS should be compact to facilitate its integration in the reactor, it should reduce the number of steps, and ideally, it should work under a continuous operation mode in order to simplify and diminish the processing time. The integration in the reactor is made through the PbLi loop that connects the breeding blanket to a heat exchanger for power extraction, a purification system and the TERS.

During the last years the extraction of tritium from the carrier has been extensively studied in the framework of the ITER Test Blanket Modules (TBMs) [5]. In the case of the Helium Cooled Lithium Lead (HCLL) the carrier is the breeder itself (PbLi), while for the Helium Cooled Pebble Bed (HCPB) a purge gas (He) is used to carry the tritium from the breeder to the extraction system.

The main functions of the Tritium Extraction System (TES) for HCPB-TBM are to remove the tritium from the breeder by gas purging, to extract it from the purge gas and to route it to the Tritium Accountancy System (TAS). First, helium purge gas doped with a small percentage of hydrogen flows at low pressure to extract tritium from the lithiated ceramic pebble bed. Then, tritium compounds are removed from the purge gas by using an adsorption column, for aqueous based compounds and a getter bed of zirconium/cobalt to retain tritium. The use of a catalytic membrane of palladium/silver alloy, PERMCAT, allows the recovery of tritium from tritiated water prior to sending the tritium to the TAS [6].

In the case of the HCLL-TBM, the tritium extraction has been designed as a two-step process in which, firstly, tritium is extracted from the liquid metal and, secondly, it is concentrated in a stripping gas (He). Therefore, two systems are required for this purpose: a tritium extraction unit (TEU) in charge of the first step; and the tritium removal system (TRS) in charge of the second step [7]. Tritium is extracted thanks to a gas-liquid contactor, in which a flow of He stripping gas with a small percentage of hydrogen passes through the liquid metal in a packed column dragging the tritium. In the TRS, tritium is retained in a getter bed and separated from the purge gas [7].

The common assumption in the DCLL blanket and the HCLL-TBM is the liquid metal connection with the other systems via a PbLi loop [8]. However, in the case of a DCLL-DEMO the tritium extraction has to be a one-step procedure being directly pumped to the tritium plant when it is extracted from the PbLi, since a batch process increases the steady tritium inventory and also the start-up inventory. For ITER this issue can be dealt with, since the generation of tritium is around 0.11 mg/day (HCLL) and 0.17 mg/day (HCPB) [9]. Meanwhile, the generation in a DCLL-DEMO is 3 orders of magnitude higher, around 400 g/day [10], and, therefore, tritium processing in ITER is too far to be considered as a reliable baseline for the DEMO outer fuel cycle [11]. Another technological step is the PbLi mass flow to be processed in the loops, between 0.1 and 1 kg/s in the HCLL-TBM and above 2000 kg/s in DCLL DEMO. These aspects go on the side of the requirements with regard to the self-sufficiency of DEMO. As shown, a scale-up of TBM components to DEMO throughput it is not straightforward due to the huge difference on the tritium and PbLi inventories to manage [12]. The extrapolation of the outcomes from ITER to DEMO tritium extraction could not be easy since the requirements are quite different, compromising the feasibility of the system. The present work constitutes the next step towards a comprehensive design of the TERS for DEMO, based on a DCLL blanket.

Thus, the use of the permeation against vacuum technique as primary option for the DCLL TERS is the result of an exhaustive review of the available technologies in terms of safety, tritium inventory, design integration, size, complexity, etc. [13]. Vacuum Sieve Tray (VST) [14] was selected as backup solution always looking for future developments.

The Permeator Against Vacuum (PAV) concept is based on tritium diffusion through a permeable membrane thanks to a pressure gradient established between the two membrane surfaces. A conceptual design for a PAV unit to work at DCLL conditions was produced in [15]. An expression for the permeator efficiency, defined as the ratio between the difference of the inlet and outlet tritium concentrations and the tritium concentration at the inlet was obtained by analyzing the transport processes occurring during tritium extraction under a diffusive limited regime. This relation, which depends on the different parameters involved in the PAV geometry and the permeation process, is the basis for the design and optimization of the PAV.

The scope of this paper is to present a consolidated conceptual design of the DEMO TERS in the case of a DCLL breeding blanket, according to input data from the blanket and PbLi loops, including its flow diagram and operational points. An exhaustive study on the vacuum auxiliary system and issues related with the tritium solubility in PbLi is presented. Finally, a preliminary design of the TERS, integrated in the DCLL PbLi loop, is depicted. It should be noted that the main values for the DCLL (coolants temperatures, mass flow rates, tritium breeding ratio (TBR)…) are evolving with its engineering design. Therefore, in this paper, the most updated parameters, corresponding to the DEMO2015 reactor, are taken. Nevertheless, the order of magnitude of those parameters is maintained from one design to another, allowing extrapolations for future DCLL designs.

2. DCLL-DEMO input data

a) DCLL main parameters

For a good performance of DEMO fusion reactor, the breeding blanket must comply with some requirements. The main functional requirements for the DCLL are shared with the other blanket concepts: tritium breeding; power extraction and amplification; and shielding performance [1]. Together with the blanket system, some key systems are needed for achieving the main blanket requirements: the PbLi Systems (PbLi loop and Tritium Extraction System), the Helium Cooling System, the Coolant Purification System…

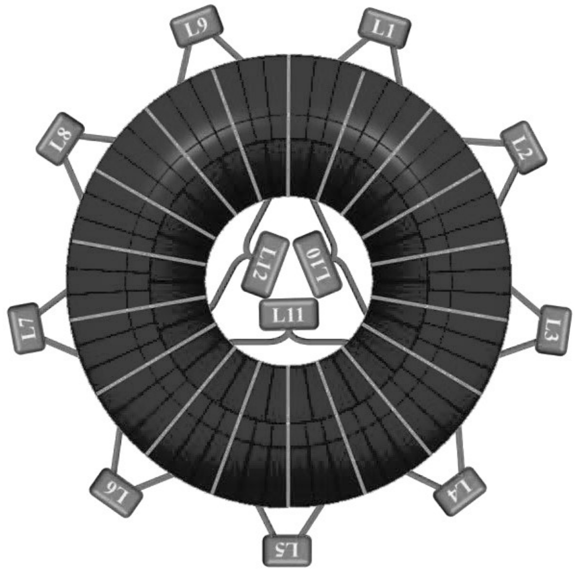

Figure 1. Toroidal section view of the DEMO TOKAMAK showing the 18 sectors (outboard: L1-L9, inboard: L10-L12) with the corresponding 12 PbLi loops for the DCLL breeding blanket concept

The DEMO2015 layout consists of 18 sectors distributed every 20º and composed of 2 inboard (IB) and 3 outboard (OB) blanket segments each [10], as shown in Figure 1. Each segment (both OB and IB) is based on a multi module approach, consisting on a number of breeding modules attached to a common Back Supporting Structure. In order to maximize the power extracted by the PbLi, its route inside the blanket has been optimized following the premise of having an outlet temperature as high as possible. Due to restrictions imposed by the structural material (Eurofer), the maximum PbLi temperature is limited to 550 ºC [1]. The DCLL breeding zone is composed of several PbLi circuits (from 5 to 7, depending on the segment and module) with an optimized route which facilitates gravity drainage, see Figure 2. These circuits are delimited by radial stiffeners and one toroidal plate, which separate each individual circuit into two poloidal channels. Most of the power is deposited in the channel closest to the first wall, with a gain of approximately 200 ºC. Figure 2 shows a cut view of one OB module in the central segment situated at the equatorial level of the reactor. The radial length of the breeding zone is 630 mm, while the supporting structure has 637 mm. As it can be seen, the latter has specific channels to feed (‘cold’ channels) and collect (‘hot’ channels) the coolants from the different DCLL modules. The dimensions of these channels have been adjusted to minimize the coolant velocity, and thus ensuring low pressure drops and corrosion. This dimensioning also takes into account a compromise existing with the space required in the breeding zone to maintain an adequate tritium breeding ratio.

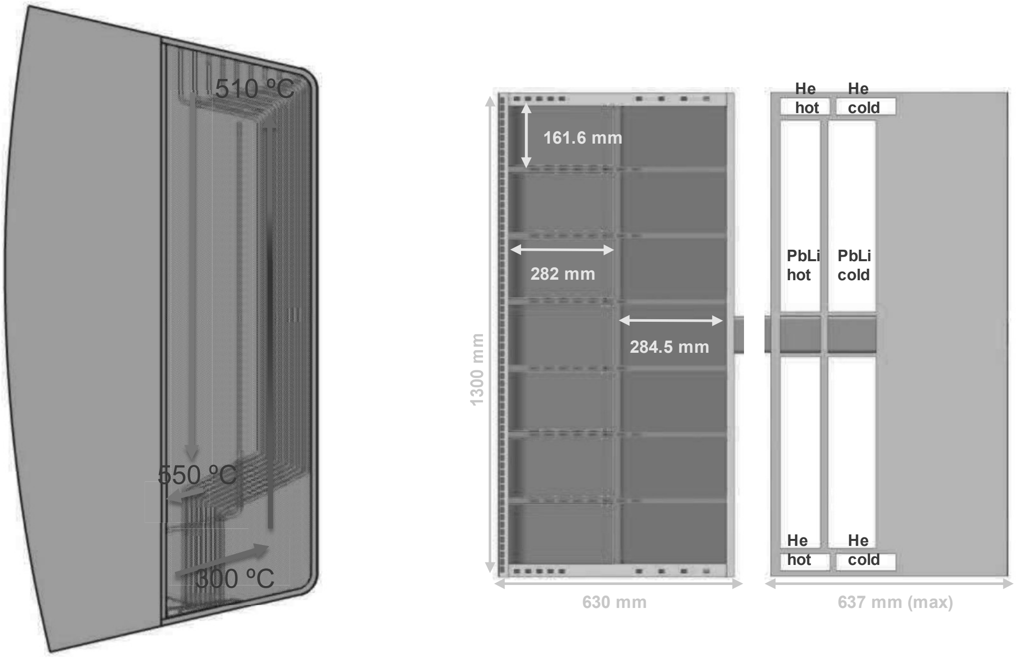

Figure 2. (Left) lateral view of the equatorial module showing the PbLi routing in the breeding zone; (right) distribution of the PbLi channels in the OB equatorial module and main dimensions. The breeding zone is depicted together with the supporting structure

In order to comply with the power balance of the reactor, the total PbLi mass flow rate has been adjusted to 26466.8 kg/s and the helium mass flow rate to 1542 kg/s [16]. In this configuration, helium carries away 44% of the power extracted while the PbLi carries away 56%. The input parameters for the TERS design are imposed by the liquid metal mass-flow and temperature values. Thus, the PbLi total mass flow is spread between the IB and the OB blankets as follows: 7865 kg/s for the whole IB (36 segments) and 18601 kg/s for the OB (54 segments). The values for the DCLL DEMO2015 regarding to the PbLi mass flow rate are shown in Table 1 together with the inlet and outlet temperatures.

The function of the TERS is the extraction of tritium generated in the PbLi and its routing to the tritium plant. Tritium generated in the DCLL blanket is $5.55 \cdot 10^{-4}$ mol/m^3, considering $7.323 \cdot 10^{20}$ neutrons per second and a TBR of 1.266 [10]. The importance of the concentration is directly connected with the extraction process since the driving force is given by the difference between the tritium partial pressures in the liquid metal and in the vacuum sides. Furthermore, as will be discussed in the following sections, the vacuum system is highly dependent on the amount of tritium to be pumped and its partial pressure.

Table 1. PbLi parameters for a DCLL reactor [16]

PbLi parameters	Outboard	Inboard
Segment mass flow	344.5 kg/s	218.5 kg/s
Sector mass flow	1033.4 kg/s	437.0 kg/s
PbLi loop mass flow	2066.8 kg/s	2622.0 kg/s
Total mass flow	18601.1 kg/s	7865.7 kg/s
Breeding Blanket Inlet temperature	300 ºC	300 ºC
Breeding Blanket Outlet temperature	534 ºC	535 ºC

b) PbLi loops

The extraction of tritium generated in the blanket is ensured by a PbLi loop connected to it. Besides, in the case of the DCLL, the loop is also in charge of the heat transfer to the heat exchanger [1]. The DCLL PbLi system is divided into 3 PbLi closed loops dedicated to the inboard blanket segments (L10 to L12 in Figure 1) and 9 closed PbLi loops dedicated to the outboard ones (L1 to L9 in Figure 1). This subdivision tries to manage the huge PbLi mass flow rate which is necessary in a DCLL blanket by minimizing the number of loops as much as possible. A larger number of loops would imply a duplication of most of the systems with the consequent increase in the cost and reliability of the reactor. In addition, it would be difficult to integrate the loops in the reactor due to the limited available space.

Figure 3 shows the Process and Instrumentation Diagram (P&ID) of the DCLL PbLi loop for the DCLL blanket [1]. The main components of the loop are the tanks devoted to the load and storage of the liquid metal, the buffer and relief tanks, the pumping system, the Tritium Extraction and Removal system, the heat exchanger and the purification system. During normal operation, in a first stage the PbLi comes from the breeding blanket and enters into the corresponding TERS (one per loop), which is placed in the hot part of the loop in order to minimize tritium losses to the rest of the components. As a preliminary assumption, the design considers that all the PbLi flow will move through the TERS in order to maximize the tritium extracted. However, regulation valves allow the adjustment of PbLi flow to be sent to the TERS through the by-pass line or its complete by-pass (if necessary).

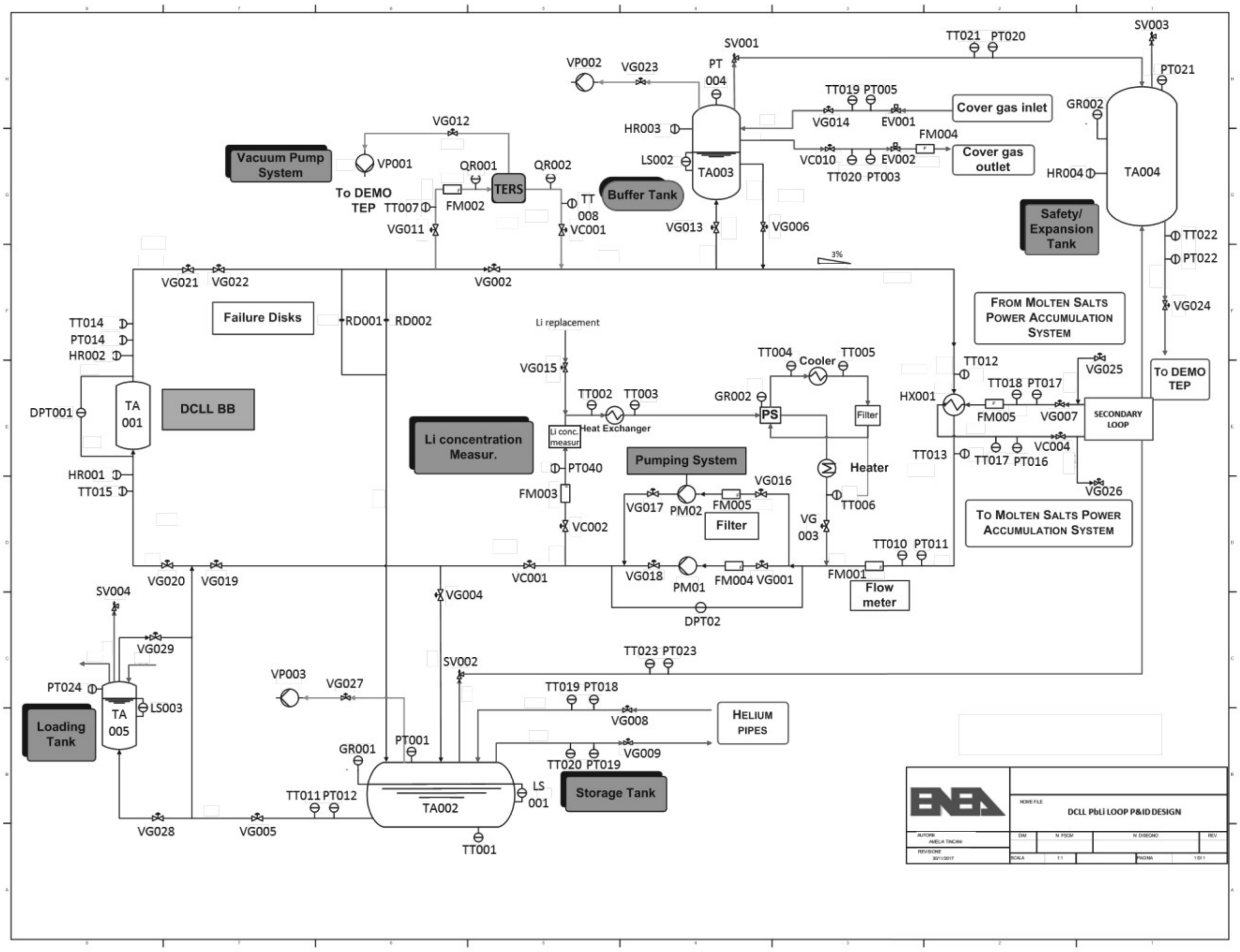

Figure 3. Process and Instrumentation Diagram of the DCLL PbLi loop. DPT: differential pressure transmitter; FM: flow meter; GR: gamma activity monitoring; HR: hydrogen sensor; LS: PbLi level sensor; PT: pressure transmitter; QR: Q_2 sensor; RD: failure disk; SV: relief valve; TT: temperature transmitter; VC: control pneumatic valve; VG: pneumatic valve; VP: vacuum pump.

The expansion tank is located just after the TERS to compensate the thermal expansion of PbLi and to allow the release of helium which could be generated inside the modules due to the neutron capture reaction in ^{6}Li [17]. The rest of the components are placed after the heat exchanger, where the temperature is decreased down to 300 ºC, to minimize the damage caused by corrosion [18]. Thus, the TERS operational temperature and the blanket outlet temperature are the same (assuming no heat losses through the pipes). The pumping system is based on a mechanical pump, which has been selected because it covers two basic requirements: no cavitation of the pump throughout the broad operational range and minimum continuous flow maintained during operation. Part of the flow is then sent to the Coolant Purification System (CPS) and the other part is directly sent back to the blanket segments. The requirements of the CPS are to remove the solubilized impurities and solid particles from PbLi and to remove lithium oxides that may appear during operation.

The basic parameters of the DCLL PbLi loop which are important for the TERS definition (mass flow rate, temperature, velocity and efficiency) are summarized in Table 2. The tritium partial pressure is determined by the tritium concentration via the Sievert's law. It is important to note that the dispersion in the measured hydrogen solubility in PbLi leads to a considerable discrepancy in the tritium partial pressures. Depending on the methodology followed for the measurement of the Sieverts' constant and the eutectic grade of the alloy, a variation up to two orders of magnitude is found in the literature [19]. For this reason, the solubilities of Reiter [20] and Aiello [21] have been considered as the upper and lower values in order to establish the operational limits of the TERS.

Table 2. Table of input parameters defining the TERS characteristics [16]

Parameter	Value
PbLi temperature	535 ºC
Total OB Mass flow rate	18601.1 kg/s
Total IB Mass flow rate	7865.7 kg/s
Total mass flow rate	26466.8 kg/s
PbLi relative pressure	2-3 bar
Tritium concentration	$5.55\cdot10^{-4}$ mol/m^3
Tritium partial pressure [20]	288 mPa
Tritium partial pressure [21]	0.251 mPa

3. DCLL TERS design

As previously mentioned, the function of the TERS is to extract the tritium from the PbLi and send it to the processing system in the tritium plant to have tritium available for the reactor. Different techniques can be applied for this purpose [22] among which the permeation against vacuum shows better performances and can comply with the management of bigger mass flow rates of PbLi, as in the case of a DCLL blanket [13]. The main advantages of this technology are the reduced residence time of tritium in the TERS and its low operational cost. Furthermore, regarding the flexibility and complexity, the permeation against vacuum can provide higher extraction efficiency with lower size and less requirements in terms of maintainability than the other techniques. The continuous operation mode and the high extraction efficiency situate the PAV as a baseline in the EUROfusion R&D Program on Tritium Extraction Techniques from PbLi [13]. Currently there is no efficiency target defined for any of the blanket concepts considered for DEMO, although some works have proposed a range between 70% and 90% for the DCLL or the HCLL [23], [24]. However, and for economic reasons, the tritium recovery efficiency shall be as high as reasonably achievable [25]. Therefore, due to the high requirements with regard to the self-sufficiency of the reactor and in order to reduce the tritium inventory in the PbLi loop to avoid the release to the second confinement due to the safety issues related with the management of tritium, in this work a minimum efficiency of 80% has been stablished to deal with these recovery requirements. As previously mentioned, the VST has been proposed as back-up solution since it is still in a recent stage of study. There are other available technologies such as the use of gas-liquid contactors or Getter Systems. The former is the most mature technique and can operate in continuous mode. The characterization of gas-liquid contactors was performed in flowing PbLi using a structured packing with a specific surface of 750 m^2/m^3 [26]. Following those results, the behavior of the system was later analyzed with a packing of 350m^2/m^3 by varying the liquid metal/gas flow rate ratio showing an efficiency in the range of 25-30% [27]. Due to the complexity of the system and to the maximum efficiency achieved for one stage (30% [27]), in order to obtain an efficiency of 80-90%, [23], [24], required by DEMO, it is necessary to use four or five stages with relevant complexity of the system. Nevertheless, further modeling activities showed that the efficiency could be improved by adding hydrogen or deuterium to the stripping gas or by optimizing the geometry of the column. In the other side, even though the getter bed can provide a high extraction efficiency in a compact system, the operation mode has been rejected since it needs a regeneration step which implies the use of two systems working alternatively. Furthermore, several experiments were carried out to demonstrate the stability of gettering materials against corrosion caused by PbLi. It was found that, for most of them, corrosion rates are too high and a strong embrittlement caused by lead dissolved in the metal may limit the operation reducing the tritium uptake rate [28].

a) TERS Process and Instrumentation Diagram

The Process and Instrumentation Diagram (P&ID) of the proposed TERS for the DCLL, including valves and instrumentation, is shown in Figure 4. Coming from the PbLi loop, the liquid metal passes through the PAV, where tritium is extracted, in one-single pass and continues along the PbLi loop. The efficiency of this system relies, among other aspects, on the pressure gradient established through the membrane of the permeator [15]. Therefore, the vacuum level achieved in one side of the membrane is critical and has to be carefully studied, selecting an adequate vacuum system not only for a high tritium extraction but to properly route it to the tritium plant. As seen in Figure 4, this system consists of a two-pumps train, a rough vacuum pump (RVP) and a high vacuum pump (HVP), connected in series with the PAV vacuum side. A bypass line is used to connect the PAV to both pumps due to the working range of each one: while a RVP can work in a range of 10^{3}-10^{-3} mbar, the range for a HVP is 10^{-3}-10^{-7} mbar. Thus, in order to proceed with the vacuum generation, the first stage is to initialize the RVP since HVP are not allowed to work at atmospheric pressure. When a medium vacuum level is achieved, the HVP is switched on and the bypass is closed. Then, the RVP is kept working to help the HVP.

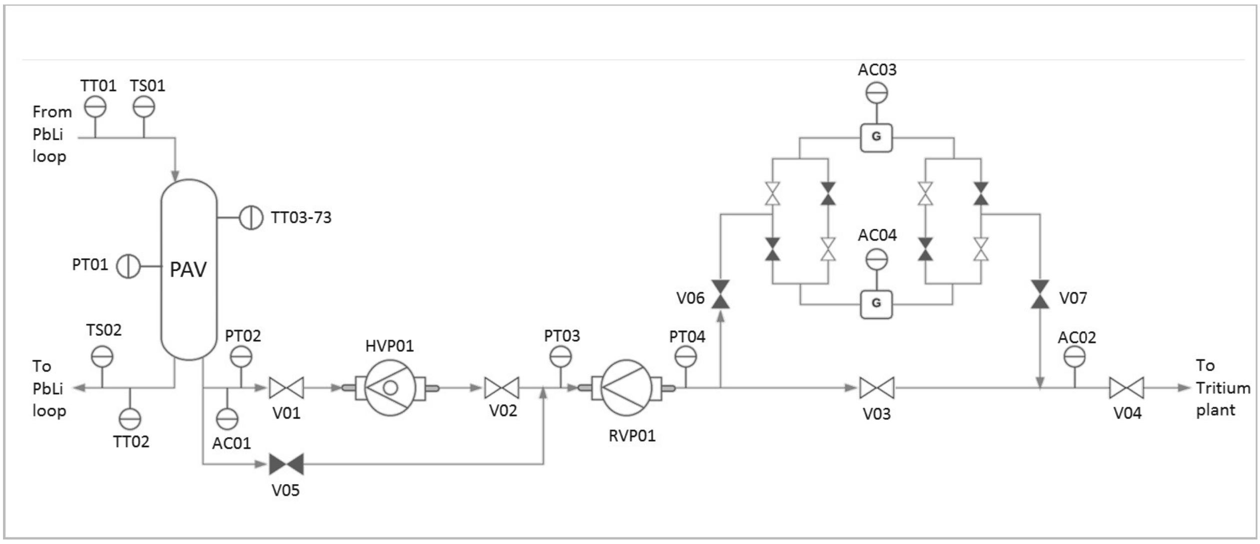

Figure 4. TERS P&ID. PAV: Permeator Against Vacuum; G: Getter System; HVP: high vacuum pump; RVP: rough vacuum pump; TT: temperature sensor; PT: pressure transducer; TS: tritium sensor in PbLi; AC: tritium sensor in gas phase; V: valve.

As it has been stressed, a Getter System in contact with the liquid metal is not the most proper technique for this application; however, getter beds for extracting hydrogen/tritium from a carrier gas have been proved in the past demonstrating high extraction capabilities [29]. In fact, it is the current technology proposed for the ITER tritium removal from a carrier gas of the HCPB-TBM [30]. Since there are some important uncertainties in the calculation of the tritium production, and consequently its concentration in PbLi (the TBR is based on neutronics calculations, cross sections, the concentration depends on the tritium-PbLi solubility value which has a large dispersion [19]), a Getter System could be useful as a supporting component in the TERS. This system could deal with an excess of tritium if it is produced during the first operational phases of the reactor. Moreover, if any problem occurs in the Tritium Plant and the PAV is still working, the Getter System will store the extracted tritium until the closing of the PbLi loop. During normal operation, the extracted tritium will go directly from the PAV's vacuum side to the Tritium Plant. Nevertheless, in case of necessity, a by-pass is available to allow tritium to be stored in the Getter System. As can be seen in Figure 4, the getters are duplicated in order to have the Getter System available even when a full getter is under regeneration.

The TERS (Figure 4) works in different operational modes which determine the state of the different components and valves:

- Mode 1: start-up. Shut-off valves V01 and V05 isolate the PAV from the vacuum circuit. Valves V02 and V05 work as a bypass of the RVP connection to the PAV. At the beginning of the operation, V05 will be opened (while V01 and V02 will be closed) and the RVP starts to work. In the meantime, the system is heated up and the components outgassed. When a proper vacuum level is achieved, V01 and V02 are opened followed by the switching on of the HVP and the closing of V05. From this moment, V05 will be continuously closed. Then, HVP and RVP work together in series to achieve the required vacuum level to extract the tritium in the PAV and to produce enough pumping speed to route the tritium to the Tritium Plant or the Getter System.

- Mode 2: normal operation. Valves V01 and V02 are open and V05 is closed. Both pumps, RVP and HVP are working. V03 works as a by-pass of the Getter System and V04 isolates the complete TERS from the Tritium Plant. During this phase of operation, these two valves will be continuously opened to allow the pumping system to move the tritium.
- Mode 3: emergency operation. When the tritium cannot be routed to the Tritium Plant for maintenance reasons (e.g., due to malfunction or during commissioning periods), valves V03 and V04 are closed followed by the opening of V06 to store the tritium in the Getter System. In this phase, HVP and RVP are running, V01 and V02 opened and V05 closed. Since getters are duplicated, firstly the tritium will be stored in one of them and then, when it reaches its total storage capacity, valves are switched to route it to the other getter.

b) Tritium extraction: PAV

A PAV design was previously proposed for the conceptual DCLL design developed in the framework of the EUROfusion Breeding Blankets Project [1], [15]. This DEMO configuration consisted of 16 sectors with equal mass flow distribution between 16 PbLi loops (1 per sector). Each loop had one PAV unit, which was designed considering its efficiency, i.e. the ratio between the tritium extracted and the tritium concentration at the inlet, as driving parameter for its optimization. The equation relating tritium transport, extraction efficiency and physical and geometrical parameters involved in the process was applied considering different materials to be used as membrane. As result of this work, it was concluded that vanadium, niobium and tantalum would be the optimum materials to manufacture the PAV. These elements present good capacities to be implemented as membrane for permeation due to their high permeability to hydrogen in the range of temperatures of interest [31]. With regard to the compatibility against the liquid metal PbLi, it has been experimentally demonstrated the stability of these three compounds when immersed in the liquid in static conditions up to 600ºC [28]. The dissolution rates are around 0.01 g/m^2 for V and below 0.004 g/m^2 for Nb and Ta. However, at these high PbLi velocities a larger rate of corrosion is expected due to the inherent increase on the impact of this phenomenon with the velocity of the fluid. Nevertheless, currently there is no material fully compatible with this alloy that presents the same high capacities as membrane of permeation. For that reason this group of materials remains as the best option. Dedicated corrosion experiments should be conducted to corroborate this point.

In the new DEMO scheme, the reactor is divided into 18 sectors and, according to Section 2, the number of PbLi loops has changed, together with the mass flow rate circulating through each loop (one TERS per loop). Therefore, an update of the PAV design is required, and it has been produced by maintaining the same configuration of rectangular PbLi flowing channels alternated with vacuum channels, as shown in Figure 5. Although the mass flow rate in the IB and OB loops is different (2066.8 kg/s OB, 2622.0 kg/s IB, see Section 2), as a first approach the same design is proposed for both PbLi loops (IB and OB) but considering the requirements for the IB PAV, since it is more demanding in terms of mass flow.

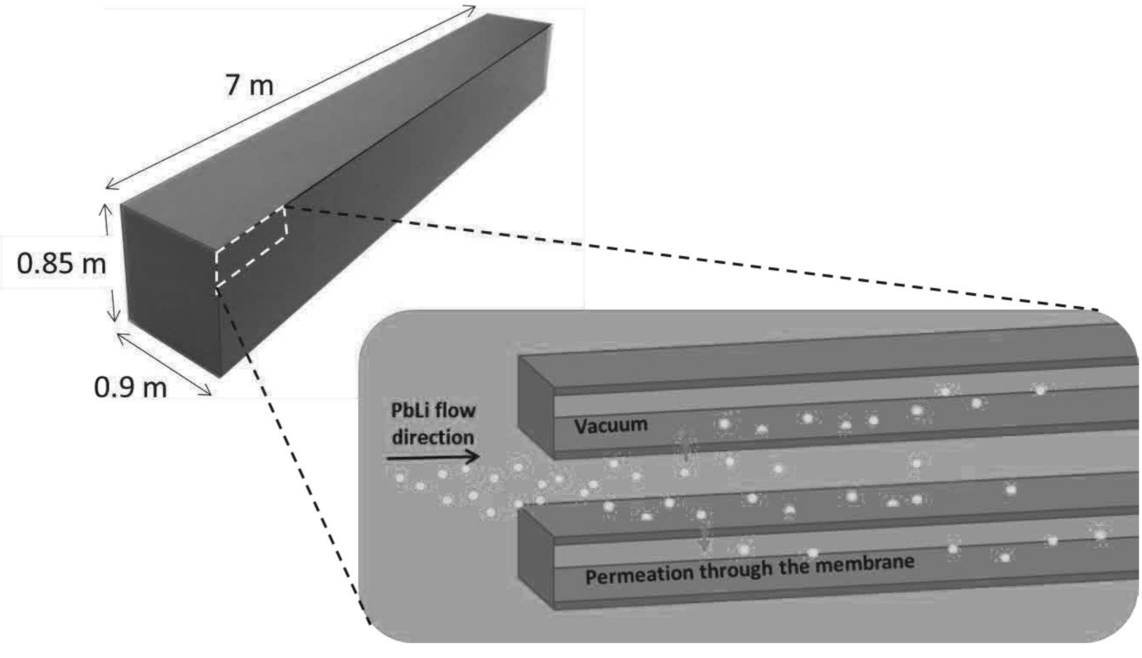

Figure 5. Left) Overall design of the PAV showing length, width and total height. Right) Detailed view of the extraction process: tritium flowing within the PbLi is extracted into vacuum channels

By applying the same procedure followed in [15], a parametrical analysis of the PAV efficiency leads to a design, Figure 5, whose geometrical characteristics are shown in Table 3. They have been fixed aiming at the need of maximizing the contact area between the liquid metal and the membrane in order to assure the minimum efficiency of 80% already mentioned at the beginning of this section, and keeping the PbLi velocity within a reasonable value lower than 1 m/s in the channels.

Table 3. PAV geometric characteristics

Parameter	DEMO 2015
Width	0.900 m
Channel height	0.005 m
Length	7.000 m
Membrane thickness	0.001 m
Number of PbLi channels	70
Total number of channels	141
Total height	0.850 m
PbLi velocity OB-PAV	0.68 m/s
PbLi velocity IB-PAV	0.87 m/s
Total membrane area in contact with PbLi	882 m^2
Structural material volume	0.923 m^3
Volume of PbLi	2.20 m^3
Vacuum volume	2.24 m^3

For the design parameters referred in Table 3, the relation between the efficiency and the tritium permeability for the chosen materials (Ta, V, Nb) [31] is presented in Figure 6. As mentioned before, the upper and lower values of tritium solubility in PbLi are considered in order to establish the ranges in between the results are. For tritium extraction, a lower value of solubility is desired (Reiter [20]), since it implies a higher partial pressure and, therefore, the extraction is enhanced. On the contrary, a high value (Aiello [21]) is considered as the pessimistic case because it means a stronger tendency of tritium to remain solved inside the liquid metal. In this sense, the optimization of the design has been made in order to achieve a minimum 80% efficiency in the worst scenario, which is considering Tantalum as membrane material, Aiello's solubility and a PAV working in an IB loop.

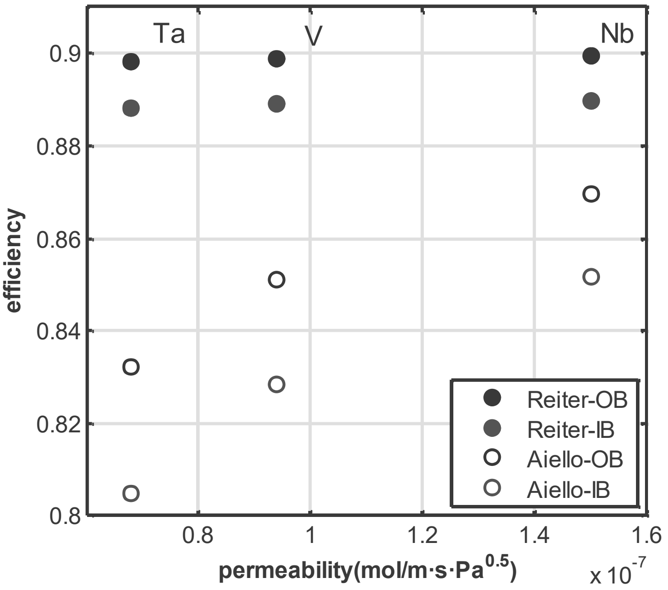

Figure 6. Relation between tritium permeability and efficiency of the PAV for the two limiting cases, Reiter's (filled circles) and Aiello's (open circles) solubility constant. Blue: inner board, black: outer board.

As expected, the higher solubility of tritium in PbLi given by Aiello disfavors the extraction process and, therefore, the efficiency is lower. In this permeability range, the permeation process is driven by mass transport (i.e. tritium transport in the PbLi) and the high solubility of tritium in PbLi has a negative impact on the tritium transport to the membrane, which, as seen in Figure 6, is more accentuated at lower values of permeability. Hence, the presented design of the PAV provides an efficiency between 80.5% and 89% for the IB-TERS, and from 83% to 90% for the OB-TERS, depending on the material used as membrane and the solubility constant (Figure 6).

Other important aspect in the PAV design is the integration in the PbLi loop and the impact on the loop performances. Some calculations of the pressure drop that the PAV causes in both the IB and OB loops have been made. Pressure drop and friction factor in an individual PbLi channel can be obtained through Darcy and Haaland equations [32], respectively. The parameters of the designed PAV (Table 3) have been considered for this calculation.

$$\Delta p = f \cdot \frac{L}{D_H} \cdot \rho_{PbLi} \cdot \frac{v^2}{2} \tag{1}$$

Eq. 1 shows Darcy equation for pressure drop, where D_H is the hydraulic diameter of the channel, L, the length and v and ρ_{PbLi}, the velocity and the density of the liquid metal, respectively. The friction factor, f, is defined as a non-dimensional number dependent on the surface roughness (ε) and Reynolds number (Re) according to eq. 2.

$$\frac{1}{\sqrt{f}} = -1.8 \log\left[\left(\frac{\varepsilon/D_H}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right] \tag{2}$$

The calculated pressure drop over one individual channel, considering an absolute roughness of 0.2 μm as the typical value for polished metal surfaces [33], is 0.31 bar in the OB-PAV and 0.47 bar in the IB-PAV.

For the permeator arrangement to the PbLi flowing circuit, a gradual enlargement consisting on a round to squared connection has been considered. In this way the PbLi can be equally distributed among the flowing channels. The relation between the pressure drop and the connection dimensions is defined in [34]. The final length of this connection between the PAV and the PbLi circuit is 0.3 m, which provides a pressure drop of 0.14 bar and 0.05 bar for the OB in the entrance and the outlet connection, respectively. In the case of the IB, 0.22 bar for the entrance, whereas the pressure loss is 0.08 bar for exit. Finally, the total pressure drop caused by the OB-PAV is 0.50 bar, while the pressure drop for the IB-PAV is 0.77 bar.

c) Auxiliary system/vacuum system

In order to calculate the vacuum pressure necessary into the PAV vacuum ducts some calculations must be done attending to the tritium flux, the partial pressure of tritium transported with the PbLi stream, the pressure on the vacuum side, the Sieverts' constant and the permeator efficiency.

The basic equation defining a vacuum system is as follows (eq. 3):

$$Q = P \times S \tag{3}$$

Where Q represents the gas throughput and it is given by the product between the pressure of equilibrium (P) and the effective pumping speed (S). In the case of this study, Q is given by the tritium which is permeating from the PbLi to the vacuum side (eq. 4) and P is the equilibrium pressure needed in the vacuum side. Two orders of magnitude have been considered as a minimum value for the ratio between the tritium partial pressure at both sides of the membrane. This value was chosen to account for the tritium depletion along the permeator, and thus to ensure sufficient driving force for the tritium permeation through the membrane.

$$Q = \frac{C_{PbLi} \cdot \dot{m} \cdot \eta_{extractor} \cdot R \cdot T \cdot V_{PbLi}}{2 \cdot A \cdot L \cdot N \cdot \rho_{PbLi}}$$

(4)

As shown in eq. 4, the total amount of permeating tritium is obtained through the tritium concentration in the PbLi (C_{PbLi}) taking into account its mass flow ($\dot{m}$), the efficiency of the PAV ($\eta_{extractor}$), as well as its physical parameters (channel cross section area, A; length, L; number of PbLi flowing channels, N), the PbLi density (ρ_{PbLi}), the total PbLi volume inside the PAV (V_{PbLi}) and the temperature (T). R represents the ideal gases constant.

Pumping speed values depend on the tritium concentration in the PbLi and on the vacuum pressure necessary to keep continuous extraction (through the relation between equations 3 and 4). Therefore, the Sieverts' constant (Ks) plays an important role in the pumping speed due to the pressure required in the vacuum side. In fact, the scattering on this constant leads to difficulties in defining the precise pumping speed requirements as it is shown in Figure 7. In this figure it is represented the efficiency achieved for a given pumping speed. As can be seen the required pumping speed increases with the efficiency of the system, i.e. with the gas load. It is also observed that, for a higher solubility of tritium in PbLi, therefore lower partial pressure, which is the case of Aiello's constant, a higher pumping speed is needed. This is due to the fixed premise of keeping a minimum ratio between the tritium partial pressure in the PbLi and in the vacuum side.

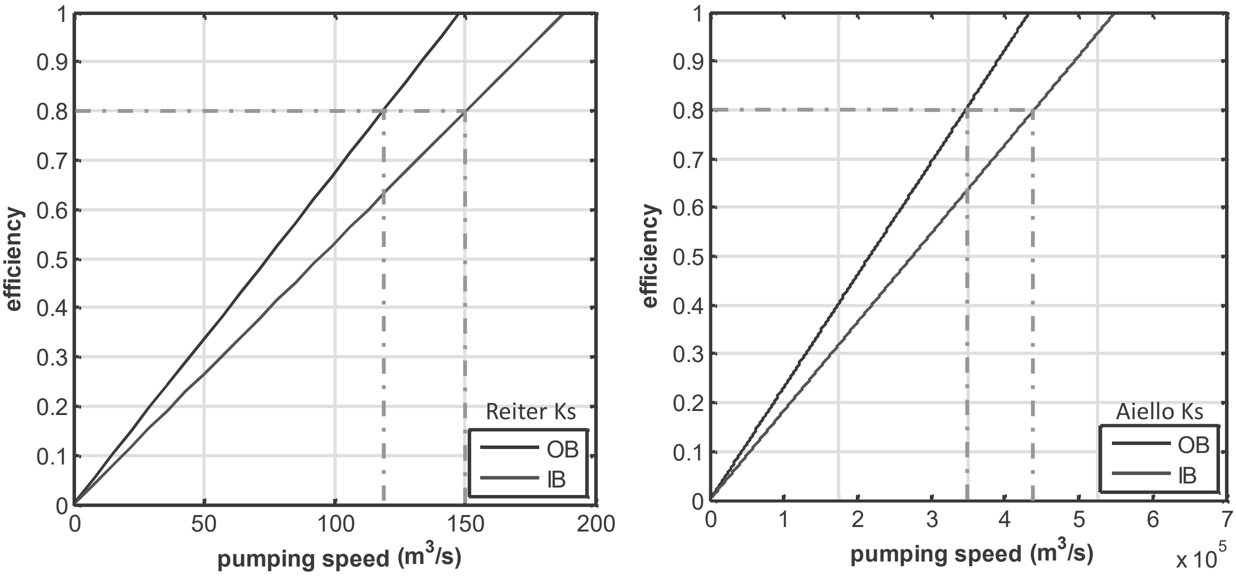

Figure 7. Tritium extraction efficiency as a function of the pumping speed considering Reiter's (left) and Aiello's (right) Sieverts constants for a fixed tritium concentration in PbLi of $5.55 \cdot 10^{-4}$ mol/m^3

In Figure 7 the tritium concentration is fixed to $5.55 \cdot 10^{-4}$ mol/m^3 (Table 2) and it can be observed that for an 80% efficiency, it is needed a pumping speed of 113-148 m^3/s considering Reiter's Ks for the OB-IB, respectively. In contrast, a much higher pumping speed is required (>$4 \cdot 10^5$ m^3/s) when considering Aiello's Ks. If Aiello's is confirmed as the correct value of solubility, the Permeation Against Vacuum technique could not be feasible to work at 80% of efficiency, and even at much lower values where the required pumping speed would be in the order of 10^4-10^5 m^3/s. The need of setting the appropriate value of Ks is once again highlighted.

An evaluation of the dependence of the pumping speed with the tritium concentration in the PbLi, Figure 8, shows that as the amount of tritium increases, pump requirements are relaxed. This fact is a consequence of the ratio between the tritium partial pressure in the PbLi and the vacuum pressure. When the tritium partial pressure increases, the ultimate vacuum pressure is less demanding. Note that the efficiency of an Nb-based PAV has been considered for being more demanding in terms of pumping speed required, i.e. as the efficiency increases, the gas load to be pumped is higher, as seen in Figure 7.

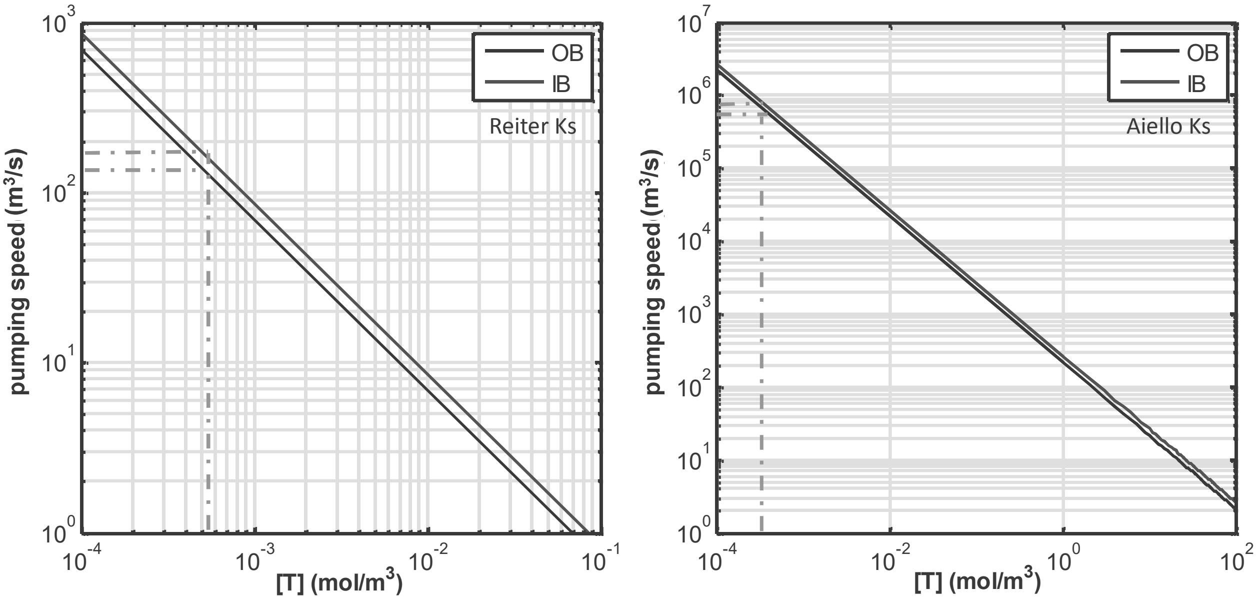

Figure 8. Pumping speed as a function of the tritium concentration at the PAV entrance. Efficiency of Nb-based PAV for Reiter's and Aiello's Ks

It can be concluded that the pumping speed required for HV pumping systems is highly demanding. Based on the work published in [35], an exhaustive literature research has been made among all the vacuum pumps available or under development following some requirements such as: large pumping speed, good pumping for light gases, low gases retention, full compatibility with tritium and possibility to scale up for DEMO applications. Within the range of HVP, turbomolecular and diffusion pumps present good performances for the application: simple design, compactness and compatibility with tritium. Nevertheless, there are some disadvantages on the use of these pumps; turbomolecular pumps present difficulties to be scaled-up and with maintenance requirements. However, recent R&D on pumping concepts for the European DEMO torus vacuum vessel has shown that diffusion pump could be also useful for PAV purposes due to the absence of moving parts, compatibility with tritium and good pumping speed for light molecules [35], [36]. Its main disadvantages are the use of mercury as working fluid and the maximum pumping speed achievable of ~20 m^3/s for a size of 1.6 m x 2 m x 0.4 m (length x height x width) [35]. However, it is estimated that the pump length is directly related to the pumping speed as about 20 m^3/s per meter of pump length. This means that a 6 x 2 x 1 m, approximately, pump could comply with the requirements established if Reiter's constant is considered and for that reason it is selected as primary option for the TERS [36].

Cryopumps are being taken as backup solution since they are well developed for the ITER torus [37]. However, their working principle is based in two steps: gases go into the condensed phase below their saturation temperature (hence, the particles leave the gas volume and the gas pressure drops). Then, the pumps need to be regenerated when their capacity limit or the regulatory limit for maximum allowed tritium/hydrogen inventory is reached. One regeneration cycle at ITER takes approximately 600 s [37].

Within the range of RV pumps available, liquid-ring pumps may be applicable. The LVPM 600 by Hermetic and KIT pump has been proposed as suitable for DEMO requirements but with some modifications such as the replacement of all polymer seals and flanges modifications, among others. Its dimensions are 2.5 m long, 2 m height, 1 m width and it provides a pumping speed near to 160 m^3/s [35]. However, screw pumps and scroll pumps are the two options considered as back-up for the TERS.

d) Instrumentation

A preliminary definition of the instrumentation necessary for the TERS includes the following components:

Temperature sensors (TT): They are placed close to the PAV, in the PbLi Loop, in order to measure the temperature of the PbLi upstream and downstream of the PAV. The measurement is made through the use of thermocouples installed inside a stainless steel tube which is in direct contact with the liquid metal. The tube thickness together with the diameter of the sensor determines the time resolution of the measurement. Since no abrupt changes in the bulk temperature are expected, this point should not be a showstopper. A thermocouple type-k (NiAl-NiCr) with a diameter between 0.5 and 1.5 mm could be appropriate for this application. Additionally, type N- Nicrobell D sheath thermocouples are installed into vacuum channels to measure the internal temperature of the permeator along its length.

Tritium concentration in PbLi (TS): placed before and after the PAV in order to know the tritium concentration in PbLi and therefore the PAV efficiency. Sensors for measuring the permeation of hydrogen isotopes have been demonstrated to be a suitable technique for this purpose [38], [39]. The sensor consists in a hollow capsule with a membrane permeable to hydrogen. The whole capsule is immersed in the PbLi stream and it is connected to an external vacuum pumping system. The measurement of the hydrogen partial pressure in the capsule can be correlated with the hydrogen concentration in the liquid metal.

Accountancy Systems (AC): The design includes a*ccountancy systems*, for the monitoring of the tritium extracted by the PAV in gas phase, located in different points in the vacuum system and right after each getter bed to know whether it is full. Taking advantage of the tritium specific activity, ionization chambers can be used for an indirect/real-time measurement of the tritium flow. The measurement is performed thanks to beta emission produced by tritium atoms, which interacts with the gas of the chamber producing its ionization. If a correct voltage is applied between two electrodes of the chamber the current produced is directly proportional to the amount of radiation [40].

Pressure transducers (PT): located at the exit of the PAV and between the vacuum pumps to control the vacuum level. Piezoresistive and capacitive sensors are the reference technologies for the measurement of the pressure. Pirani/cold cathode full range gauge are used to control the vacuum level. The sensor placed on the PAV is disposed in the opposite face of the pump connection.

4. CAD-TERS integration

Following the P&ID proposed in Section 3(a), Figure 3, a CAD model of the TERS has been produced for its integration in the PbLi loop design. PAV dimensions (Table 3) and pumping sizing explained in Section 3 (6 x 2 x 1 m for the HVP and 2.5 x 2 x 1 m for the RVP) have been considered, and the result is presented in Figure 9. The final TERS design possesses an envelope volume of 15 m x 10 m x 9 m. In this preliminary design, the main components of the TERS are plotted as follows: Tritium Extraction Unit: permeator against vacuum; High Vacuum Pump: linear diffusion pump; Rough Vacuum Pump: liquid ring pump; piping for vacuum system and valves for vacuum system.

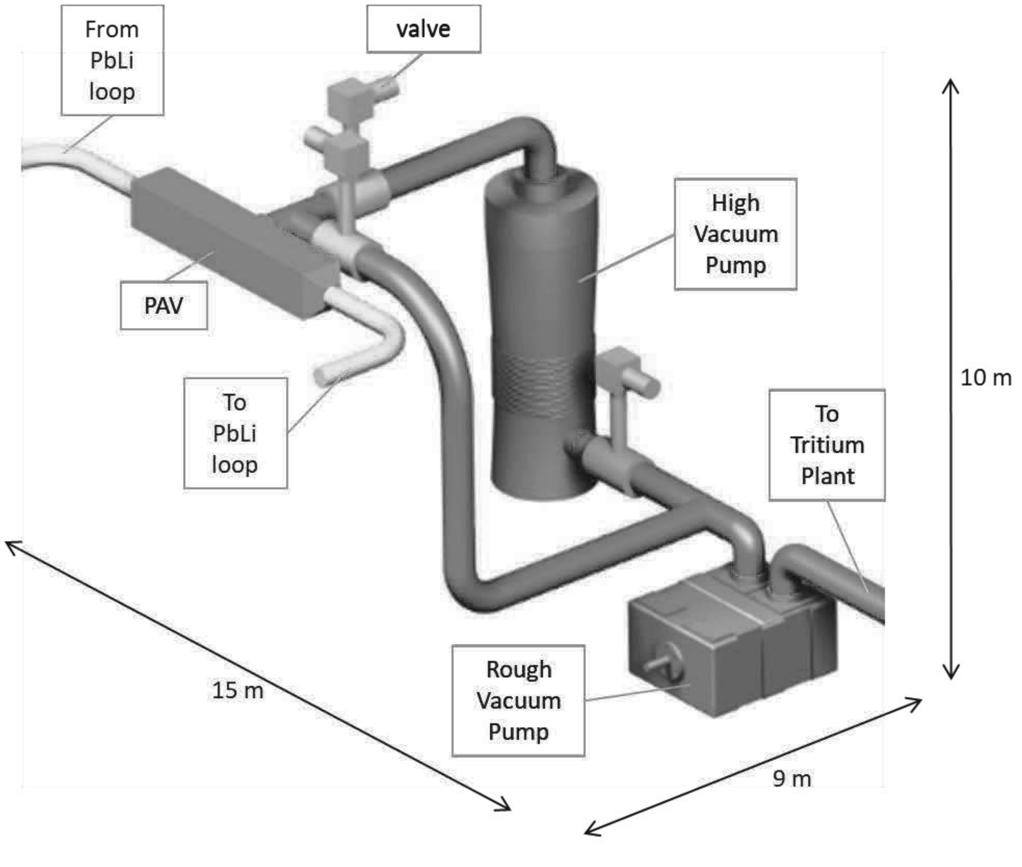

Figure 9. TERS CAD model overview

Taking as basis the CAD modeling of DCLL PbLi loop [1], the integration of the TERS is presented in Figure 10. It includes the heat exchanger, the storage and expansion tanks, flowmeters, the pump for circulating the PbLi, the purification system and the PbLi piping system and valves.

The integration of the PbLi loop in the DEMO tokamak building accomplishes the following requirements [1]:

1. The components should be placed as close as possible to the tokamak (and the breeding blanket) to reduce tritium and heat losses
2. There should be the possibility to drain by gravity both the PbLi loops and the breeding blanket
3. The pipes should be inclined a minimum angle of 3° in order to allow correct draining by gravity
4. Pressure drops should be as low as possible
5. The pipe route should compensate thermal expansion
6. The loop components should be grouped in the minimum number of floors to make easier the maintenance and to avoid interaction with other systems

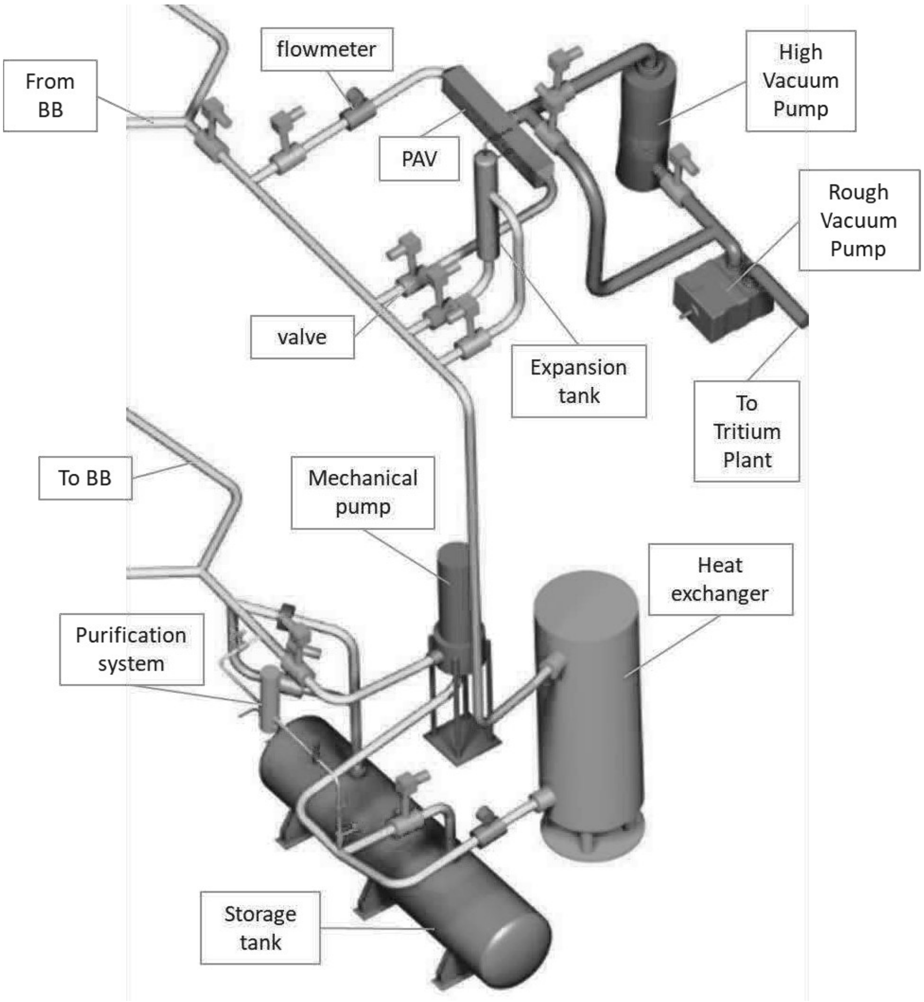

Figure 10. View of the OB PbLi loop model [1] with the integration of the TERS

5. Summary

In this paper, the conceptual design of the Tritium Extraction and Removal System for the European DCLL-DEMO is presented and discussed. For this aim, the functionalities of the DCLL blanket and the main components, such as the PbLi loop, are identified. In the DEMO2015 layout, the torus is divided into 18 sectors, composed of 3 outboard and 2 inboard blanket segments each, and the total PbLi mass flow rate is spread into 9 outboard and 3 inboard PbLi loops. Each loop owes one TERS, among other components, which is in charge of the tritium extraction for its transport to the tritium plant.

Within the available technologies for tritium recovery from liquid metals, the permeation against vacuum has been chosen due to its expected high capabilities in terms of extraction efficiency, low operational requirements, simplicity and its continuous operation mode. The process and instrumentation diagram of the proposed PAV-based TERS including valves, instrumentation, vacuum and auxiliary storage systems are presented, together with the operation scenarios. Furthermore, the design of the PAV which is able of managing the PbLi flow rate, with a minimum efficiency of 80%, is optimized in terms of geometry and extraction capability. Three different membrane materials (V, Nb, Ta) are proposed considering the high tritium permeability and compatibility with PbLi. Due to the discrepancy among Sieverts' constants for the dissolution of hydrogen isotopes in PbLi, two extreme values are used. The same design is proposed for both OB and IB loops with a slight difference in the efficiency due to the different mass flow they process. Hence, considering the different scenarios presented, the tritium extraction efficiency of the system is between 80.5% and 90%. A suitable vacuum system has been selected, taking into account the tritium compatibility and technological maturity. Diffusion pumps for the high-vacuum and liquid-ring pumps for the rough-vacuum, already under development for the pumping of the European DEMO vacuum vessel, have been chosen. The dimensioning of these vacuum systems is also presented, taking into account several factors, such as the tritium partial pressure in the PbLi at the inlet of the permeator. For this evaluation, the tritium partial pressure plays an important role since it is the input parameter to fix the vacuum level required to keep an adequate difference of pressure in both sides of the membrane. It is worth noting that the value of the Sievert's constant plays a decisive role in the pumping speed requirements of the permeator. If Aiello's is confirmed as the value of solubility, the technique could not be feasible.

Finally, the CAD model of the TERS has been produced following the sizing of the equipment described in each section. It includes the PAV, the pumping system and its processing components integrated into the PbLi loop. Additionally, a heat exchanger, storage and expansion tanks, a mechanical pump for circulating the PbLi and a purification system are also shown.

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