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Progresses in the development of the tritium extraction and removal system for the water-cooled lithium-lead breeding blanket in EUROfusion

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In the EU DEMO reactor, the Water-Cooled Lithium-Lead Tritium Extraction and Removal system (WCLL TER) is dedicated to transporting tritium-rich PbLi from the Breeding Blanket to the Tritium Extraction Unit and then back to it, after tritium is extracted and routed to the fuel cycle. In addition to circulating PbLi and extracting tritium, the TER system maintains constant PbLi temperature of 330 °C, provides safe storage of PbLi during reactor shutdowns as well as PbLi purification from by-products and contaminants linked both to structural materials corrosion processes and neutronic reactions of Pb, Li and other dissolved species. This contribution presents the latest developments in the design of the WCLL TER and in some of the related key areas of research. Among the most significant outcomes, the Permeator Against Vacuum was selected as a reference tritium extraction technology, preferred over the Gas-Liquid Contactor and the Liquid Vacuum Contactor, and its design was updated based on recent experimental evidence. All components of the TER such as tanks, pipelines, valves and other equipment were integrated into the tokamak building, ensuring compliance with fundamental operating principles.

1. Introduction

EUROfusion is currently working on the design of the EU DEMO reactor [1], whose Breeding Blanket candidates are the Water Cooled Lithium-Lead Breeding Blanket (WCLL BB [2]), the Helium Cooled Pebble Bed Breeding Blanket (HCPB BB [3]) and the Water-cooled liquid Lead Ceramic Breeder Breeding Blanket (WLCB BB [4]).

The WCLL BB relies on the eutectic alloy PbLi to fulfil the blanket goals of tritium breeding, shielding and heat generation. In addition, PbLi is used to improve neutron economy by the (n,2n) reaction and to transport tritium from the BB towards an extraction system, which in turn delivers the tritium to the tokamak fuel cycle [5]. The system that performs this task is called WCLL Tritium Extraction and Removal (TER) and, by means of auxiliary components, it also serves the purposes of circulating PbLi through the blanket and controlling PbLi chemistry and temperature.

The goal of this paper is to describe the latest achievements in the design and R&D of the WCLL TER as a whole and of its subsystems, such as the Tritium Extraction Unit, the Safety Tank and the purification systems.

The previous most recent published work on WCLL TER design can be found in [6], while previous steps in the integration in the Tokamak Building are described in [7].

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2. TER layout and design parameters

Considering the current design of the WCLL BB with 16 sectors, six PbLi loops are foreseen to feed the Outboard (OB) and Inboard (IB) segments:

- 4 loops for the OB segments, so that one loop is connected to 4 OB sectors.
- 2 loops for the IB segments, so that one loop is connected to 8 IB sectors.

The IB and OB loops are connected to nine Storage Tanks, used to store all the PbLi during long-term maintenance and located in the lowest floors of the Tokamak Building and Tritium Building, and to a shared Safety Tank, aimed at mitigating the impact of an In-box LOCA (Loss Of Coolant Accident). The Safety Tank is kept isolated from the main loops by rupture discs that will only open in case of over-pressurization of the system.

Besides the pumping system that ensures the PbLi circulation, each of the six loops has auxiliary systems devoted to extract tritium (Tritium Extraction Unit or TEU), keep the PbLi temperature at the nominal value of 330 °C (heating cables and heat exchanger) and remove corrosion products (Purification System), activated products (Activated Products Removal System or APRS) and helium, generated by lithium transmutation in the blanket. Relying on the very low helium solubility in PbLi [8] [9], the latter function is accomplished by the tank that also includes the main pumping system and serves as expansion tank. Fig. 1 shows the simplified layout of a single loop with the connections to the shared Storage Tanks and Safety Tank.

Instrumentation, not shown in the layout of Fig. 1, will include sensors to monitor tritium concentration at the exit from the BB and downstream of the TEU, PbLi mass flow rate, differential pressure across the pump and the systems more prone to be clogged (e.g. the Purification System), and temperature. R&D efforts are ongoing on commercial and custom-built instruments to characterize their performances in stagnant and flowing PbLi [10] [11,12],.

Table 1 shows the main parameters of the current WCLL TER, including the total PbLi inventory, PbLi mass flow rates and expected tritium partial pressure in PbLi. Adding together the volumes of the Breeding Blanket, of the piping and of the ancillary systems, the total inventory of PbLi amounts to 1478 m^3, with the BB being the main contributor by far (about 840 m^3).

With reference to the recent publication [6], the PbLi flow rates have been recalculated assuming 10 full replacements per day of the PbLi inventory in the BB OB and IB segments. The obtained flow rates, together with the design driving constraint of 80% tritium extraction efficiency for the TEU, are enough to supply the fuel cycle with the required 0.32 kg per day of tritium [13], which fulfils the main goal of the PbLi as tritium carrier.

The value of the tritium partial pressure in PbLi is calculated from the predicted tritium concentration at the BB outlet (about $1.4{\bullet}10^{-2}$ mol/m^3) and using Sieverts' constant values recently measured in EUROfusion [14] (which are close to the ones measured in the past by Aiello [15], Katsuta [16] and Wu [17]).

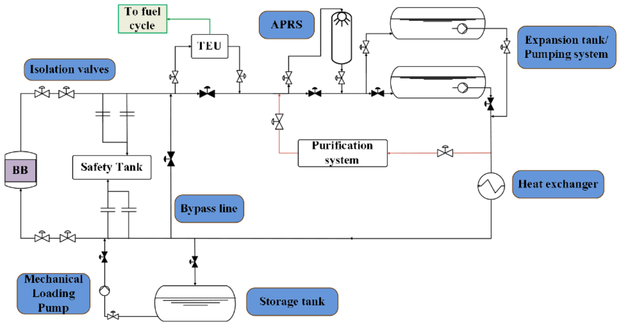

Fig. 1. Layout of the WCLL TER system.

Table 1
WCLL TER main parameters.

Parameters	Value
Total PbLi inventory [m^3]	1478
PbLi inventory in BB [m^3]	840
PbLi volume in components [m^3]	348
PbLi volume in the loops [m^3]	290
Number of circulations per day	10
PbLi flow rates [kg/s]	169 (OB) 139 (IB)
PbLi loop main pipe diameter [m]	0.26
Average PbLi velocity in a loop [m/s]	0.33 (OB) 0.27 (IB)
T partial pressure in PbLi [Pa]	~0.5
PbLi temperature In/Out [°C]	330

Fig. 2 shows the whole WCLL TER arranged in the allocated rooms of the Tokamak Building, with the majority of the auxiliary components of the six loops located in a dedicated room at level 3 and the nine Storage Tanks divided between the basements of the Tokamak Building and Tritium Building (the Tokamak Building is composed of several levels above and below the ground level, which is defined by the presence of the Heating Neutral Beam cell, with level 3 being the highest one [18]).

3. Tritium extraction unit – permeator against vacuum

3.1. TEU technology selection

In 2020 a process to select the TEU (Tritium Extraction Unit) reference technology was started, aiming at providing a sound basis for the choice by the end of 2023. Three candidate technologies were considered for extracting tritium from PbLi, namely the Gas-Liquid Contactor (GLC), the Permeator Against Vacuum (PAV) and the Liquid Vacuum Contactor (LVC) (in a Free Surface configuration).

The approach of weighted votes was chosen for the selection, with the final ranking being the sum of the weighted votes. Five categories have been identified, each of them composed of different items associated to a weight coefficient, from 0 to 1. The weight coefficient represents the importance on the success of the TEU technology in the WCLL TER of that specific item. The sum of all weight coefficients is equal to 1. Then, a value ranging from one to four is used to evaluate how the technology satisfies the sub-items. Finally, the total score is the product of the weight coefficient times the value for each technology. The five

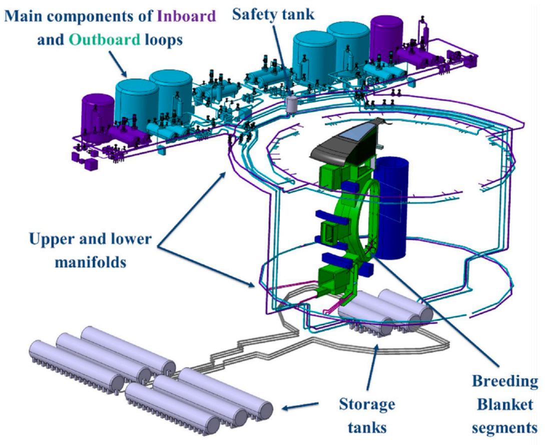

Fig. 2. 3D drawing of the WCLL TER (the OB loops are colored in teal, the IB in purple, shared components in grey).

categories are:

SAFETY-WASTE: the tritium solubilized into the TEU has to be minimized in order to reduce the contaminated waste generated and to route the tritium to the Tritium Fuel System. Moreover, tritium leakage and permeation towards the environment have to be considered. Amount of generated tritiated wastes also has an impact on the choice of the TEU technology.

DESIGN-INTEGRATION: Reduced physical size of the component allows better integration in the Tokamak Building and remote handling operation. Good performances of the tritium extraction unit mean low tritium concentration into PbLi TER loop components and less contaminated waste and tritium permeation. The complexity in the operation of the equipment, the auxiliary systems and the remote handling of the auxiliary systems are also considered in this category. Integration with the fuel cycle in terms of required purification or separation steps after extraction is also evaluated.

TECHNOLOGY: evaluation of availability of sound manufacturing techniques, use of common materials and maturity of the technology (via the TRL: Technology Readiness Level) is carried out in this category.

OPERATION: the reliability and availability during operation in DEMO are very important: the failure of an extractor device and/or required unanticipated maintenance would have a strong impact on the overall operation of the machine. Good maintainability and inspectability will allow for quick and effective maintenance operations. Flexibility describes the prompt ability of TEU to “follow” the possible variation of operative conditions driven by changes in the BB conditions. For example, TEU will have good flexibility if it is able to work changing the tritium partial pressure without requiring external operations.

ECONOMICS: the capital cost of the equipment and auxiliary circuits and the operational costs (gas, electricity and maintenance) have to be taken into account in the design of the equipment.

Table 2 shows the complete list of evaluation items, divided by category, together with their weight coefficients and the scores assigned to each of them. At the end of the scoring process, the Permeator Against Vacuum had the highest score with a significant margin over the other two options (GLC and LVC) and was therefore selected as the reference technology for the Tritium Extraction Unit of the WCLL TER.

This result was helped by the higher maturity reached by the PAV in recent years, with activities devoted to the manufacturing of prototypical mock-ups [19] [20], experimental campaigns [21] [22], design activities (see the next two sections) and simulations [23] [24],. Compatibility of membrane materials with flowing high temperature PbLi was also recently addressed, showing generally good resistance to the corrosive attack [25].

The selection process was based on the data available at the time. Therefore, some R&D activities are still ongoing also on the GLC and LVC to confirm the present evaluation and to have back-up technologies in case unexpected showstoppers on the PAV would be highlighted by further activities. Moreover, further experimental activities on the PAV to acquire more data and to find strategies to optimize the extraction process are ongoing in TRIEX-II [26] (ENEA Brasimone) and CLIPPER [27] (CIEMAT) facilities.

Table 2
Results of the scoring process divided into the five categories for the three tritium extraction technologies.

Item	Weight	Value			Score		
		GLC	PAV	LVC	GLC	PAV	LVC
SAFETY-WASTE	**0.1**						
Tritium inventory	0.05	2	3	3	0.1	0.15	0.15
Generated contaminated waste	0.05	2	3	4	0.1	0.15	0.2
DESIGN-INTEGRATION	**0.45**						
Physical size	0.1	3	2	1	0.3	0.2	0.1
Complexity	0.1	2	4	3	0.2	0.4	0.3
Required auxiliary systems	0.05	2	2	1	0.1	0.1	0.05
Performances	0.1	3	3	1	0.3	0.3	0.1
Integration with the fuel cycle	0.1	2	4	2	0.2	0.4	0.2
TECHNOLOGY	**0.15**						
Manufacturing and materials	0.05	4	1	3	0.2	0.05	0.15
TRL	0.1	2	3	1	0.2	0.3	0.1
OPERATION	**0.2**						
Reliability and Availability	0.1	2	2	3	0.2	0.2	0.3
Maintainability and Inspectability	0.05	2	3	4	0.1	0.15	0.2
Flexibility	0.05	2	1	1	0.1	0.05	0.05
ECONOMICS	**0.1**						
Cost (capital)	0.05	3	2	3	0.15	0.1	0.15
Cost (operation)	0.05	2	3	2	0.1	0.15	0.1
Total					**2.35**	**2.7**	**2.15**

3.2. *Reference design for EU DEMO*

This section addresses the dimensioning of the Tritium Extraction Unit (TEU) based on the Permeator Against Vacuum (PAV) technology. The reference design is based on a bundle of niobium U-tubes, divided into two groups. The tritium rich PbLi enters the first group of tubes and then, after mixing in a collector, continues to the second group, effectively performing two passages in the PAV [6]. Fig. 3 shows a sketch of the PAV and of the PbLi path inside it.

The primary goal of this design activity is to ensure that the system achieves a tritium extraction efficiency of at least 80% while adhering to constraints on size, pressure drop, and operational efficiency.

Experimental data obtained from the campaign performed at ENEA Brasimone in the TRIEX-II facility [26] were compared to a GETTHEM model of the PAV. The GETTHEM model was adapted to mimic the TRIEX-II PAV mock-up geometry and it was simulated under the same operating conditions of the experiments, as a first step towards the model validation [23].

Then, the GETTHEM code was used for simulating the performances of a DEMO-scale PAV, varying PbLi flow velocities and permeator lengths to identify the optimal design that satisfies efficiency and operational constraints.

The input parameters for the simulations were:

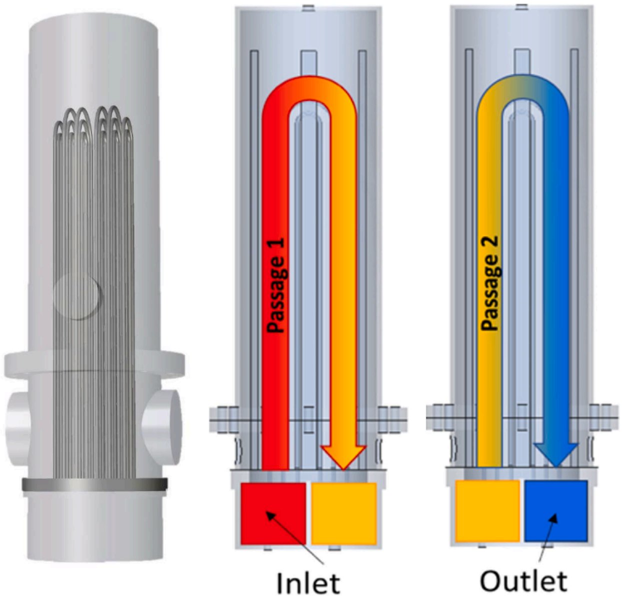

Fig. 3. Sketch of the PAV: on the left, simplified 3D drawing; in the middle and on the right, PbLi path in the U-tubes (figures taken from [35]).

- PbLi mass flow rates: 169 kg/s for the outboard (OB) loop and 139 kg/s for the inboard (IB) loop.
- Operating temperature: 330 °C.
- Target extraction efficiency η ≥80% ($\eta = \frac{c_{in}-c_{out}}{c_{in}}$). This value of extraction efficiency, combined with the PbLi mass flow rates, is enough to supply the fuel cycle with the required amount of tritium and to significantly reduce tritium concentration downstream of the TEU, thus minimizing total permeation towards the environment.
- Constraints: Vessel diameter ≤7 m, height ≤10 m (translating to a maximum permeator length of 40 m per unit), and pressure drop ≤2 bar. Of these constraints, the geometrical ones depend on integration activities in the room where the PAV will be hosted in the tokamak building, with in particular the PAV height being limited by the ceiling. The value of the maximum allowable pressure drops is more arbitrary, but conceived to not overcome about 10% of the total pressure drops in a loop (which have been calculated to about 23 and 26 bar for OB and IB loops in [2]).
- PAV niobium tubes with inner diameter of 9.2 mm and wall thickness of 0.4 mm (same values as TRIEX-II mock-up).
- PbLi thermophysical properties were taken from [28], the PbLi Sieverts' constant from [29], the niobium Sieverts' constant and diffusivity from [30] and [31], the recombination constant for niobium from [32], the mass transfer coefficient from a correlation for the Sherwood number taken from [33] ($Sh = 0.096Re^{0.913}Sc^{0.346}$, *Re* and *Sc* being the Reynolds and Schmidt numbers) and the PbLi diffusivity from [34].

Note that the constraint on the PAV vessel height (10 m) translates into a maximum permeator length of ~40 m, given the PbLi flow pattern inside the extractor through 2 U-pipe passages.

Results are shown in Fig. 4 and Fig. 5. The performance of the extractor, shown in terms of extraction efficiency, improves for smaller velocities of PbLi in the channels, other than for larger permeator lengths. This may be explained by the fact that, for smaller values of the velocity, the residence time of the liquid metal in the permeator increases, requiring shorter pipes to reach a given extraction efficiency. As it seems by these results, the effect of the velocity on the residence time prevails over the effect on the mass transport from the bulk towards the membrane inner wall, which is enhanced for larger values of the velocity, as it results in a higher level of turbulence.

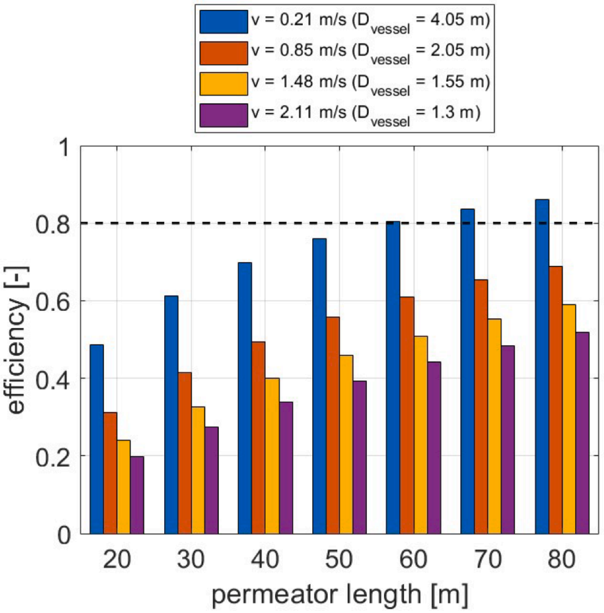

Fig. 4. Niobium-U-tube-PAV efficiency for the WCLL OB loop, varying total permeator length and PbLi velocity.

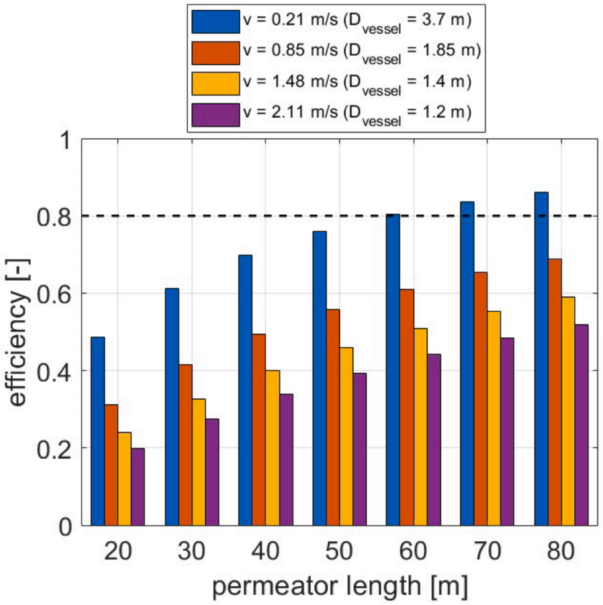

Fig. 5. Niobium-U-tube-PAV efficiency for the WCLL IB loop, varying total permeator length and PbLi velocity.

The optimal case at PbLi temperature of 330 °C is that featuring the lowest flow velocity of 0.21 m/s and a permeator length of 60 m (hence requiring 2 PAV units in series), being the case adopting the shortest permeator length that allows meeting the requirement on the target extraction efficiency (to be at least equal to 80%). Due to the low PbLi velocity (corresponding to a mass flow rate of 0.14 kg/s in each channel), the total pressure drop, equal to ~ 0.6 bar, is well below the maximum allowable value of 2 bar, while still satisfying the constraints on the vessel diameter: a diameter of 4.05 m for the OB loop and 3.7 m for the IB loop are sufficient to process the entire mass flow rate. In the optimal case, the number of U-tubes in the PAV is 2456 for the extractor of the OB loop and 2020 for that of the IB loop.

An increase of the PAV operating temperature to 450 °C would of course allow to reduce the total permeator length. In particular, for a PbLi velocity of 0.15 m/s, an extraction efficiency slightly above 80% is achieved with a permeator length of only 20 m, with a very low total pressure drop of ~ 0.1 bar and a vessel diameter of 4.9 m for the OB loop PAV and 4.45 m for the IB loop one (3608 and 2968 U-tubes for the OB and IB loops, respectively).

Finally, a first model of a vacuum pump is being developed and integrated in the GETTHEM PAV model, aiming at realistic boundary conditions for the PAV simulations. The model computes the pumping speed of the pump required to maintain the desired vacuum in the PAV shell side, with the pumping speed depending on the permeated hydrogen flux and the vacuum chamber temperature.

3.3. *Alternative PAV design based on vanadium channels*

Another possible configuration for a PAV under study consists of rectangular channels made of thin membranes of a permeable material, such as vanadium. The design is based on stackable modules alternating vacuum and PbLi channels [36]. The upper and lower walls of the channel are made of vanadium, while the side walls are made of steel as a supporting structure.

Applying the model developed in [36] a rectangular-vanadium-based PAV is defined. Considering that the channels are significantly wider than they are high, the tritium mass transport will be preferably upwards and downwards, so tritium will diffuse towards the vacuum channels and will permeate through the membranes.

A unique design is made considering the WCLL OB PbLi mass flow rate of 169 kg/s. The aim is to reach 80% efficiency and keep a pressure drop below 2 bar.

By applying the last published results on the H-isotopes solubility in PbLi [37] and vanadium permeability [38] an evaluation of the efficiency achievable is plotted in Fig. 6. There are some fixed parameters, such as the channel width (1.4 m), height (5 mm) and membrane thickness (1 mm), following previous studies [6] [39],. It is possible to infer that 80% efficiency is obtained for lengths above 40 m and for velocities below 2 cm/s (achieved with 200 PbLi channels).

Pumping speed requirements for the vacuum system have been evaluated in a range of tritium concentrations around the value of $1{\cdot}10^{-2}$ mol/m^3 exiting the BB (Fig. 7) [39]. By fixing the geometrical parameters of length equal to 50 m and number of PbLi channels equal to 200, values up to 130 m^3/s are required if the solubility constant measured by Peñalva et al. is employed [37]. As comparison, results when considering values below 1 m^3/s are needed if Reiter's correlation for the Sieverts' constant is applied [40]. These values are less dramatic than in previous studies due to the low velocity of PbLi.

The preferred configuration of the rectangular PAV using vanadium membranes is presented in the Table 2.

Table 3

The low velocity scale depicted in Table 2 corresponds to a laminar regime. This allows for high extraction efficiency at the cost of having a relatively large number of channels. Alternatively, if the velocity was increased by a factor of 4 or 5, operation would be in the so-called transition to turbulence regime, where the qualitative behavior of the extraction efficiency in terms of velocity shown in Fig. 6 varies. In such a regime, a local efficiency maximum is expected. This offers a design window where the number of channels can be reduced in the same way as the velocity is increased and the channel length can also be reduced while keeping the efficiency goal of 80 %.

This idea has been explored with computational simulations for velocities in the transition regime ($Re \sim 2500$) and a Schmidt number of 100 [24]. Significant boosts of up to 15 % in extraction efficiency were observed when the transition to turbulence is triggered with turbulators. Fig. 8 shows the obtained Sherwood number for a simulation in the laminar regime compared to three different turbulator configurations. These turbulators consist of one or two flow obstacles, mono or double in the legend. The actual efficiency boost depends on the chosen turbulator configuration. Therefore, a compromise between efficiency, channel length and pressure drop needs to be analyzed and found.

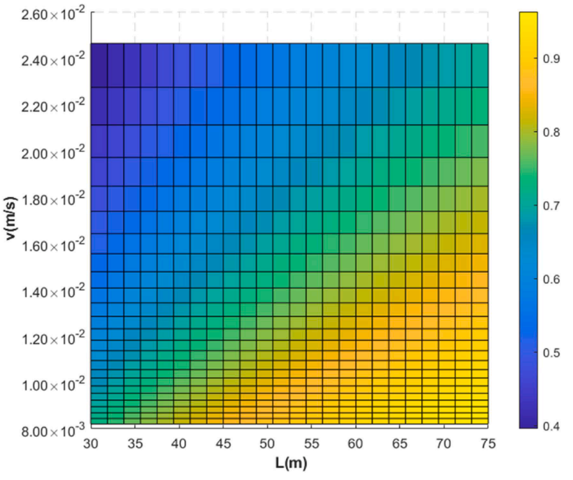

Fig. 6. Vanadium-plate-PAV efficiency as a function of PbLi velocity and membrane length. [width = 1.4 m; channel height $5{\cdot}10^{-3}$ m; membrane thickness = $1{\cdot}10^{-3}$ m; 200 PbLi channels].

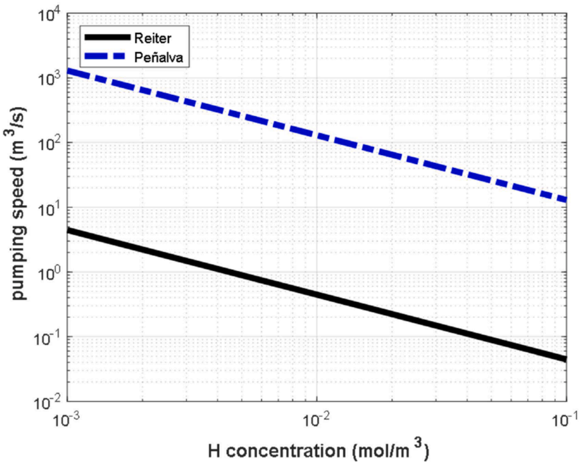

Fig. 7. Vacuum pumping requirements as function of tritium concentration in PbLi. [width = 1.4 m; channel height $5{\cdot}10^{-3}$ m; membrane thickness = $1{\cdot}10^{-3}$ m; length = 50 m; 200 PbLi channels].

Table 3

Vanadium-plate-PAV main parameters.

Parameter	OB-PAV
Width	1.40 m
Channel height	$5{\cdot}10^{-3}$ m
Membrane thickness	$1{\cdot}10^{-3}$m
Number of PbLi channels	200
PbLi velocity	$1.2{\cdot}10^{-2}$ m/s
Total membrane area in contact with PbLi	28,000 m^2
Volume of PbLi	70 m^3

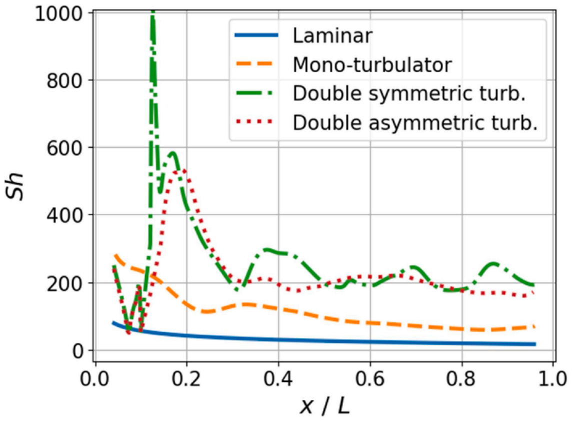

Fig. 8. Sherwood number along the normalized axial coordinate (x/L) obtained for a laminar simulation and three different turbulator configurations (see details in [24]).

3.4. PAV auxiliary systems

Fig. 9 shows the PFD (Process Flow Diagram) of the PAV auxiliary system.

The auxiliary system here presented is based on the reference design of the PAV described in Section 3.2 and is a direct update of the system presented in [41]. Nevertheless, it can also be applied, with small changes, to the alternative concept based on vanadium channels. It can be divided into four subsystems: the PbLi piping, the Vacuum system, the Gas system and the Tritium Getters system.

The piping system feeds the inlet of the PAV with tritium rich PbLi coming from the BB and sends it back to the TER. The vacuum system

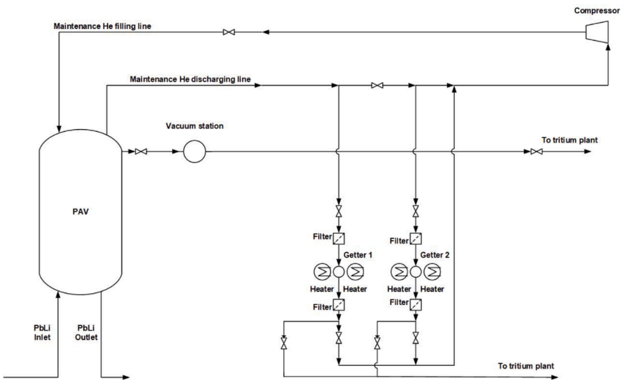

Fig. 9. PFD of the PAV auxiliary system.

consists of the vacuum chamber surrounding the permeable pipes and the vacuum pumping system. The pumping system is installed near the chamber and a gate valve is positioned between the vacuum station and the chamber to allow its isolation. The vacuum chamber has connections with the Gas system lines: these lines allow to fill the chamber with inert gas (helium) during the start-up phase, emergency situations or maintenance. The line should be equipped with a compressor to circulate helium and gas cylinders to store the gas when not in use. From the Gas system lines, branches lead the tritium towards the Tritium Getter system [42] where helium is purified from tritium carried away from the PAV [43] [44],. The Getter system is also connected to the Vacuum System: if there is an emergency shutdown of the tritium plant, the vacuum line directs the collected tritium to the getter systems, where it is stored until the tritium plant is put into operation again [13]. This system is redundant for safety reasons and to allow the maintenance of a line of components. The two lines are equipped with two valves which allow to isolate each branch. Filters are installed at the inlet and the outlet of each getter. Moreover, each getter is equipped with a heating system that will allow the release of the absorbed tritium from the getters. Helium is used as stripping gas of the getters when they reach their maximum tritium storage capacity.

The instrumentation that will be integrated in the system is composed of tritium sensors in PbLi [12], tritium sensors in Gas system lines, gas flow meters, vacuum pressure transducers, thermocouples and valves.

The Vacuum System of PAVs has so far received limited attention, despite being the driver of tritium extraction. Vacuum pumps in PAVs have two key requirements, namely, 1) to achieve a very low pressure on the vacuum side which provides the driving force for the extraction; and 2) to achieve a high tritium throughput to ensure tritium self-sufficiency. Additionally, pumps must operate continuously, reliably (including during transient scenarios), with very high availability, in fusion environments, utilize tritium compatible materials, and satisfy safety and regulatory requirements.

Currently available vacuum pumps satisfy some but not all these requirements. For example, turbomolecular pumps have been used continuously and reliably in fusion environments (for example, in JET campaigns) but there is a gap in throughput between the largest available turbomolecular pump and the tritium throughput in the TEU of one EU-DEMO PbLi circuit, which become of about two orders of magnitude if high values of the Sieverts' constant, such as those recently found by Peñalva et al. [37], are used in the calculations. On the other hand, metal foil pumps and vapour diffusion pumps may provide the demanding throughputs but are much less technologically mature than turbomolecular pumps [45] [46],; other types of pumps (e.g. roots style pumps, liquid ring pumps) present their own limitations [45–48].

As such, two possible ways forward would be to: 1) increase the throughput of turbomolecular pumps; or 2) increase the technological maturity of promising novel alternatives that do not have a throughput limitation. Both of these paths are actively being explored. Recent and ongoing R&D activities within the Work Package Breeding Blanket programme address the many engineering trade-offs in the vacuum side of PAVs. These include quantifying the effect of residual pressure (in contrast with assuming a perfect vacuum) on the extraction efficiency and tritium inventories with modelling, gathering operational expertise in vacuum engineering within fusion, and developing roadmaps for pump technologies specifically for PAVs. To satisfy the developmental needs of vacuum pumps in either of the ways forward, further efforts in PAV-specific modelling, experimentation, operational experience, and development of vacuum solutions will be needed.

4. PbLi purification systems

Three main types of impurities must be controlled during operation of the WCLL TER: corrosion products, Pb activation products and helium.

During WCLL BB operation, PbLi dissolves some of the alloying elements of structural material of BB and PbLi loop, such as Fe, Ni, Mn, Cr and Mo. Moreover, via interaction with neutrons from the tokamak, these elements can be transformed into activated corrosion products (ACP) which will thus occur in the PbLi system. Subsequent deposition and accumulation of these corrosion products and ACPs in colder parts of the system would lead to operational and safety issues. To ensure long-term and reliable operation of the BB and its sub-systems, it is necessary to remove these products in dedicated systems providing purification of PbLi either in continuous or periodic mode.

Based on the operational experience in liquid metal experimental loops (especially with sodium [49] and NaK [50], although cold traps have been operated [51] and designed also for PbLi facilities [52] [53],), a cold trap is considered as the current baseline purification system for PbLi of the WCLL TER, as well as for the WCLL TBS (Test Blanket System) of ITER [54]. As a complementary solution is considered the use of filters filled with wire mesh (as in [51] and [55]) or ceramic foam (similar to those applied in the aluminium foundry industry [56], but using ceramics which are chemically compatible with PbLi). To reach sufficient performance in terms of efficiency, the purification system of the WCLL TER will likely combine both technologies, cold traps and filters. Nevertheless, during the ongoing R&D phase it is necessary to experimentally investigate the efficiency in PbLi of cold traps and ceramic foam filters, as well as to carry out design optimisation of these technologies. The EUROfusion project includes experimental assessment of cold traps of different designs, filters, and combination of both technologies at an experimental facility at CV Řež. Such testing will lead to recommendations of suitable purification technologies and their parameters for designers of the PbLi purification system of the WCLL loop. A scale-up of these devices is the next logical step towards the reliable PbLi purification system of the EU DEMO WCLL breeding blanket.

However, a good knowledge of solubility of RAFM (Reduced Activation Ferritic Martensitic) steel alloying elements, such as Fe, Cr and Mo, in PbLi is essential for designing the purification system. For this purpose, a series of solubility measurements have been carried out within the project in recent years [57].

Another important ongoing activity is the estimation of mass transfer (dissolution and redeposition of elements) for the WCLL BB, piping and all the PbLi loop subsystems using computer simulations. It requires as inputs exact material composition of structural materials of BB and PbLi loops (including piping and all the major components in contact with PbLi), information on the inner surface of BB, length of pipes as well as both PbLi temperature and PbLi velocity maps of the entire system. To this end, a model is currently under development within the GETTHEM code to study generation, deposition and removal of corrosion products (using cold trap efficiency as an input) [58].

Apart from corrosion products, PbLi exits the Breeding Blanket containing also two undesired byproducts of the interaction with neutrons: activation products of lead, mainly thallium, polonium and mercury, and helium.

Some of the activation products are radioactive, which leads to secondary products that must be considered when calculating expected concentrations in the PbLi. On the other hand, most activation products are volatile, a characteristic that can be used in the removal system. Indeed, the current reference separation process is based on evaporation from the free surface of PbLi into a gas phase, in a similar fashion to what happens in the Vacuum Sieve Tray tritium extraction technology (see e.g. [59]), but with the difference that an inert gas continuously flows through the column. The mass transfer rate in a sieve tray column depends on the interfacial area (the total surface of the liquid in the form of droplets) and the resistance of the liquid interface to element diffusion to the liquid surface. This resistance is expected to be significantly lower for activation products compared to that for tritium or other species present as diatomic molecules in the gas phase.

A mock-up of this technology is being characterized with the VOSA facility at CV Řež, using a non-radioactive tracer (e.g. zinc) as a substitute to the above-mentioned activation products. The testing campaign foresees to characterize different PbLi distributors, droplets behaviour during the free fall phase and finally the attainable mass transfer coefficients, varying the falling height, the gas and PbLi velocities and the operating pressure.

Finally, helium removal is based on its very low solubility in PbLi [8]. This will cause helium to be released from PbLi in the Activation Products Removal System and in the Expansion Tank, the component that accommodates PbLi thermal expansion and hosts the pumping system. In particular, the latter can be designed to increase the PbLi residence time, favouring helium removal. Although small, literature values of calculated helium solubility in lead [60], lithium [61] [62], and PbLi [9] are scattered over several orders of magnitude. For this reason, it was decided to directly measure helium solubility in PbLi within EUROfusion. This task is currently ongoing at CV Řež with the HeLeLiA apparatus, which uses the absorption-desorption method, similarly to the activity performed for liquid sodium by Thormeier [63] and for liquid sodium and potassium by Slotnik [64]. These measurements will contribute to a more accurate sizing of the Expansion Tank and complement simulations on helium bubble nucleation and growth at WCLL BB conditions [65] [9],.

5. Preliminary sizing of the safety tank

The Safety Tank has been conceived as a component to allow discharge of the PbLi displaced from the Breeding Blanket after the occurrence of an In-box LOCA (Loss Of Coolant Accident), widely considered one of the most severe accidental transient for the WCLL BB [66]. In normal operation, the tank is empty and isolated from the TER system by rupture discs. It is shared by all the six loops and connected to the outlet and inlet legs of each loop (i.e. in the upper part and lower part of the tokamak building), as, after the In-box LOCA, the displaced PbLi will move equally towards the top of the BB, i.e. the outlet leg, and the bottom, i.e. the inlet leg. It should be located as close as possible to the BB, but downstream of the Isolation Valves. The mitigation strategy conceives the Isolation Valves as a way to stop the PbLi-water mixture from exiting the Breeding Blanket, while the Safety Tank should allow the expansion of PbLi and partially dampen the pressure wave that propagates beyond the Isolation Valves before their closure.

Proper sizing would require simulating the entire transient and to this aim a code is being developed and validated in the framework of WCLL BB R&D activities [67]. However, conservative assumptions can be adopted to have an approximate maximum size, which is useful at this stage to perform a more precise integration of the whole WCLL TER system in the tokamak building.

In case an In-box LOCA will occur in one of the Central Outboard Segments (COB), which contain the most PbLi among all the segments, the worst possible occurrence is that all the PbLi is displaced and must be discharged in the Safety Tank (i.e. the Isolation Valves do not stop any of the PbLi to come out from the BB). That means that the upper bound for the tank's volume is about 13 m^3, approximately the PbLi volume of a COB segment. For a better integration work, it is possible to assume that the Safety Tank is cylindrical with 2.5 m of inner diameter and 3 m of height.

6. TER integration in the tokamak building

The PbLi loops with updated dimensions were integrated into the Tokamak Building as shown in Fig. 10 and Fig. 11, considering the following technical issues:

- The total PbLi flow rate must pass through the Expansion Tank to ensure the discharge of the helium bubbles.
- The TEU must be placed as close as possible to the outlet from the BB to reduce the tritium inventory into the loop and, therefore, the tritium leakage into the environment.
- To ensure the gravitational draining of the BB and TER, all the pipework must be tilted at least 3°, taking care to avoid stagnation points, and the Storage Tanks must be located at the lowest level in the building.
- The purification systems should be placed in the upper part of the system.
- It is necessary to duplicate some PbLi components (pumping system, isolation valves, rupture disks).
- Both the outlet and the inlet legs are joined to the ring manifolds, placed respectively at the level of the Upper Port Annex and of the Lower Port. The Upper Port Annex is placed at floor Level 3, while the Lower Port is at floor Basement 3.

The total length of the piping system has been estimated at about 4.17 km, slightly more than previously assessed in [7].

7. Tritium release mitigation strategies

Tritium release in the Tokamak Building is a key issue that must be faced to ensure a sustainable and safe development of the EU DEMO reactor. The extensive surface of the TER PbLi pipeline constitutes a relevant release source and requires putting in place some mitigation measures. The two main measures under consideration are the deposition of anti-permeation coatings on the internal surface of the piping and the use of guard pipes installed outside of the piping.

The use of anti-permeation coatings will also help mitigating the corrosive action of PbLi on the piping structural steel. Alumina coatings deposited by Pulsed Laser Deposition (PLD) [68], Atomic Layer Deposition (ALD) and Electrochemical Deposition (ECX) [69], have been widely studied within the EUROfusion community, proving to have high Permeation Reduction Factors (PRF, ratio of the permeated fluxes through the bare material and through the coated one), a protective action against corrosion and a good resistance to many damaging loads [70]. Moreover, the recently discovered lithium diffusion into the alumina layer, whose effects on coating performances and lifetime are

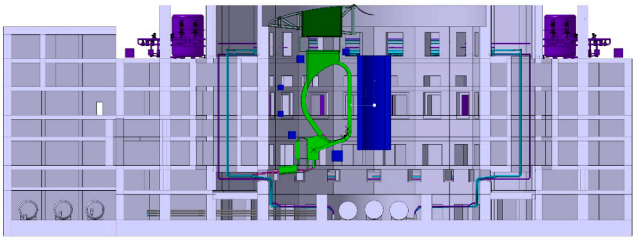

Fig. 10. Cross section of the Tokamak and Tritium Building with the routing of the piping from the Storage Tanks in the basements to the Breeding Blanket and finally to the auxiliary components at level 3.

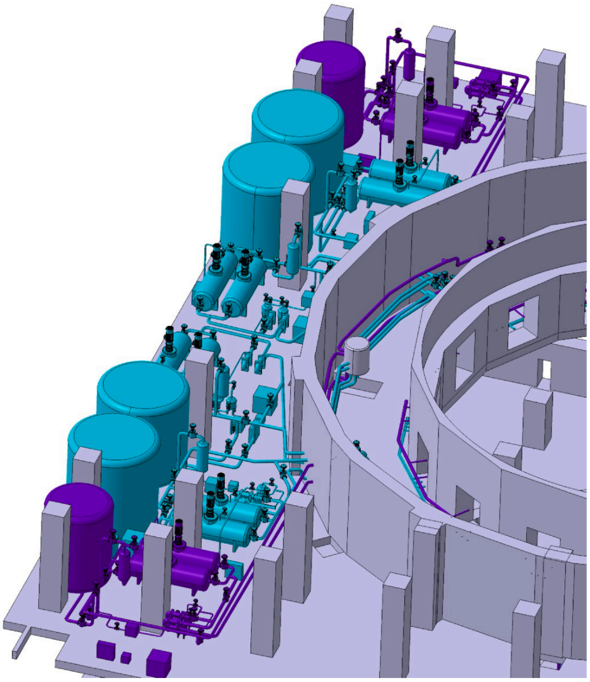

Fig. 11. Auxiliary components of the six WCLL TER loops integrated in the allocated room at level 3 of the Tokamak Building.

currently being investigated for the in-blanket service [71], would probably have a minimum impact on the coating performances outside the Vacuum Vessel (i.e., far from intense neutron and gamma-ray fluxes). While PLD coatings cannot be deposited on internal surfaces, ALD and ECX techniques are more promising for this purpose and have proved sufficient performances for the needs of the WCLL TER (a PRF of 100 is currently considered the required value for this application).

On the other hand, the use of a guard pipe can serve also as a system to eliminate the concern of PbLi leakages (and, possibly, to easily locate them with properly positioned leak detectors) and, if designed correctly, can also contribute to shield the gamma radiation coming from the activated products contained in PbLi.

With a TEU efficiency of 80%, the tritium partial pressure in PbLi downstream of the TEU drops from about 0.5 to 0.02 Pa, resulting in more than 90% of the total release happening through the piping upstream of the TEU, i.e., those at high partial pressure. For this reason, both mitigation measures can likely be only applied to this part of the piping, greatly reducing the total area to coat or the length of the double piping.

8. Conclusions and future perspectives

This paper describes the current status of the WCLL TER design, related R&D and integration in the Tokamak Building.

Manufacturing and testing of a Permeator Against Vacuum mock-up allowed this technology to reach a level of maturity on par with the Gas-Liquid Contactor, cancelling out the only major edge of the GLC and thus justifying the selection of the PAV as reference tritium extraction technology for the WCLL TER. Moreover, experimental results were used to achieve more mature designs of the Tritium Extraction Unit for Outboard and Inboard PbLi loops that meet the operational requirements and the space constraints. An alternative PAV design has also been developed based on vanadium plates, instead of niobium tubes. Indeed, manufacturing and testing activities continue on mock-ups based on both membrane materials to enhance the manufacturing techniques, improve the current database and optimize the extraction efficiency.

Progresses also involved the three purification technologies to remove helium, corrosion products and volatile activation products from PbLi, with an accurate measurement of the solubility of iron, chromium and manganese and the preparation of experimental campaign to measure helium solubility and to characterize the operation of cold traps, filters (with wire mesh or ceramic foam) and sieve trays.

CRediT authorship contribution statement

Alessandro Venturini: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Data curation, Conceptualization. **Francesca Papa:** Visualization, Methodology, Conceptualization. **Ciro Alberghi:** Writing – original draft, Visualization, Validation, Conceptualization. **Daniele Martelli:** Resources. **Roberto Bonifetto:** Resources, Funding acquisition, Conceptualization. **Antonio Froio:** Software, Formal analysis, Conceptualization. **Fabrizio Lisanti:** Writing – original draft, Investigation, Conceptualization. **Belit Garcinuño:** Formal analysis, Data curation, Conceptualization. **Fernando R. Urgorri:** Software, Methodology, Investigation. **Iván Fernández-Berceruelo:** Software, Investigation, Formal analysis. **Guillermo G. Fonfría:** Investigation, Formal analysis, Data curation. **Michal Kordac:** Data curation, Conceptualization. **Ladislav Vála:** Writing – original draft, Funding acquisition, Formal analysis. **Adéla Gottfriedová:** Methodology, Investigation, Formal analysis. **Rocco Mozzillo:** Methodology, Funding acquisition, Formal analysis. **Vincenzo Claps:** Software, Investigation, Data curation. **Eduardo Garcia-diego-Ortega:** Methodology, Investigation, Formal analysis, Data curation. **Hannah Askill:** Software, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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