TRITIUM MANAGEMENT IN THE EUROPEAN TEST BLANKET SYSTEMS AND EXTRAPOLATION TO DEMO

I. Ricapito 1)*, L.V. Boccaccini 2), P. Calderoni 1), A. Ciampichetti 3), D. Demange 2),
Y. Poitevin 1)

1) Fusion for Energy, Barcelona, Spain
2) KIT, Karlsruhe, Germany
3) ENEA-Brasimone, Bologna, Italy
* e-mail address: italo.ricapito@f4e.europa.eu

ABSTRACT

One of the main objectives of the experimental campaign of the TBS (Test Blanket Systems) in ITER is the efficient management and accurate accountancy of tritium from its source, the Test Blanket Module (TBM), up to its final routing to the ITER inner fuel cycle system. Indeed, the data collected by the tritium accountancy system, interpreted through comprehensive modelling tools, will be one of the most relevant outcomes in support of the blanket design for DEMO and beyond.

This paper describes various aspects of HCLL (Helium Cooled Lithium Lead) and HCPB (Helium Cooled Pebble Bed)-TBS activities that have a direct impact on tritium management systems and then discusses their potential extrapolation in support of DEMO design. It includes:
i) the design baseline of TBS sub-systems, also in light of new interface requirements coming from ITER Organization, relevant to the tritium management, focusing on the components potentially DEMO relevant;
ii) the preliminary design of Tritium Accountancy Stations (TAS) to be used in HCLL and HCPB-TBS;
iii) an overview on the activities related to the tritium transport modelling tools that will be validated through the TBM project and used for DEMO design.

1. Introduction on HCLL and HCPB Breeding Blanket Concepts

Thanks to the European TBM Programme a strong acceleration is expected in the development of design, technologies, materials and processes potentially relevant for a first series of breeding blankets (BB) for DEMO and power plants. A testing strategy has been developed in the past years based on the construction of different TBM modules designed to perform specific experiments in the fields of neutronics, tritium extraction and recovery, thermo-mechanics and thermo-hydraulics, in order to maximize the scientific outcomes with respect to the ITER operational plan.

In the European HCLL BB system for DEMO the liquid metal alloy Pb–16Li acts as tritium breeder, neutron multiplier and tritium carrier, with Li enriched at 90% in $^6\text{Li}$ to optimize the tritium breeding ratio. The reduced activation ferritic/martensitic steel EUROFER is the selected structural material for the breeding blanket box modules and internals. The cooling function is accomplished by He at 8 MPa pressure and inlet/outlet temperatures of 300 °C/500 °C flowing through radial-toroidal cooling plates [1]. The plant efficiency of a fusion reactor with this BB concept is between 30 and 36% [1, 2], depending on the adopted divertor technology and heating and current drive systems efficiency. The European HCPB-BB for DEMO uses either $\text{Li}_4\text{SiO}_4$ or $\text{Li}_2\text{TiO}_3$ pebbles as tritium breeder, beryllium pebbles as neutron multiplier and, again, EUROFER steel [2] as structural material. Lithium is enriched 30% in $^6\text{Li}$ in case of use of $\text{Li}_4\text{SiO}_4$ as breeding material and 60% in case of $\text{Li}_2\text{TiO}_3$. Maximum temperatures are 920 °C in ceramic Li, 650 °C in Be and 550 °C in steel. As for HCLL concept, it is cooled by helium at the same temperature and pressure. The plant efficiency is in the same range as for HCLL-BB.
The corresponding HCLL and HCPB-TBM [3] consist of a EUROFER-97 steel box cooled by vertical multi-passes rectangular cross section channels and closed by side cooled covers and in the rear part by steel plates (Fig. 1). Poloidal-radial and toroidal-radial He-cooled plates stiffen the TBM box in order to withstand the accidental internal pressurization at the coolant pressure. The stiffening grid forms several radial cells where, in case of HCLL-TBM, Pb–16Li circulates at a speed of few mm/s. In the HCPB-TBM the cells are filled with the ceramic breeder and beryllium in form of a pebble bed, purged by helium at low pressure (around 0.4 MPa).

The block diagram of HCLL-TBS ancillary sub-systems is shown in fig. 1: i) Pb-16Li loop, for recirculation of Pb-16Li alloy externally to the HCLL-TBM ii) HCS (Helium Cooling System), the primary cooling circuit for the extraction of thermal power from the TBM first wall, box and breeding region; iii) CPS (Coolant Purification System), which has to extract tritium permeated into the primary cooling circuit and to control the TBM coolant chemistry; iv) TES (Tritium Extraction System), whose function is to extract tritium generated in Pb-16Li, making it available for accountancy and further processing operations in ITER Tritium Plant.

A similar scheme applies to HCPB-TBS. However, in this case TES is directly connected to the HCPB-TBM for the extraction of tritium with a helium purge stream.

2. Design Baseline of EU TBS with focus on the tritium management sub-systems

While the design of the TBMs, including the steel box and functional materials, must be driven by DEMO relevancy, the priority in designing the ancillary and tritium management systems is to be compliant with the ITER reliability and safety requirements. With this preamble, the design of the Pb-16Li loop is of interest. Its current conceptual, whose process flow diagram is shown in fig.2, consists of the following main equipments:

- a recirculation/storage vessel, hosting the mechanical recirculation pump that assures a liquid metal flow-rate in the range of 0.1÷1 kg/s;
- a detritiation unit to extract tritium from the liquid metal into a gas phase;
- a cold trap to control the level of impurities and corrosion products in the liquid metal;
- heating wires for piping heating along all the loop to avoid plugs along the circuit;
- a γ-shield surrounding the loop to allow hands-on maintenance operations in Port Cell that require, due to limits imposed by ITER Organization, contact dose rate less than 10 µSv/h.
The need to keep low the corrosion rate is a good argument to use ferritic and/or ferritic/martensitic steels, like EUROFER 97 or P/T91, instead of austenitic steel for the loop. Use of austenitic steel could be acceptable only if coupled with corrosion barriers. Because of the lower tritium permeability, this option could become important if the estimated tritium permeated through the Pb-16Li loop piping in ferritic or ferritic/martensitic steel is not compatible with the TBM experimental programme and ITER requirements.

The performance of tritium extractor in Pb-16Li will be of basic importance in a DEMO or power reactor. As a matter of fact, the higher its tritium extraction efficiency, the lower is the average tritium concentration in the Pb-16Li loop which leads to less tritium permeation into the cooling circuit and ultimately into the environment. Although different methods for tritium extraction from Pb-16Li were explored in the past, the two main candidate technologies are currently packed columns, belonging to the family of gas liquid contactors (GLC), and permeators against vacuum (PAV). The main advantage of GLC-packed columns is the low sensitivity to the gas-bubble coalescence because the interfacial exchange area is provided directly by the packing structure. In addition, this is a mature technology used in many industrial sectors and with some encouraging preliminary experimental results (Melodie campaign, CEA, [4]) with Pb-16Li. On the other side, when extrapolated for use in DEMO (required large flow-rate to be processed and high tritium extraction efficiency), packed columns become large systems. Moreover, energy consumption in compressing the stripping gas to win the liquid metal hydrostatic pressure and the pressure drop in the column is considerably high. Last, use of GLC technology requires a downstream process for tritium concentration in He stripping gas before its delivery to TEP. PAV is more compact, requires less electrical power and doesn’t need a downstream process for tritium concentration before delivery to Tritium Exhaust Processing System (TEP). However, the reliability of this technology is unproven, particularly the stability of the status of pipe materials on the vacuum side and then of the tritium extraction efficiency. In conclusion, to comply with the ITER requirements, a packed column has been selected for use in HCLL-TBS.
The process flow diagram of HCPB-TES for tritium extraction from He purge gas and subsequent concentration is shown in fig. 3. It consists of a two step process: molecular sieve beds for tritiated water adsorption and regenerable getters for pure hydrogen isotope ($Q_2$) extraction from the He stream and concentration afterwards. Use of molecular sieves can be of interest for DEMO, as demonstrated in many large scale industrial applications, although issues could rise for the possible presence of a tritium memory effect between the adsorption and regeneration cycles [5].

Interesting to be tested in TBS, also in perspectives of a possible use in DEMO, will be PERMCAT, a catalytic reactor-permeator developed by KIT (Germany) to convert $Q_2O$ and other tritiated impurities in $Q_2$. PERMCAT is foreseen in the current design baseline of HCPB-TES and HCLL/HCPB-CPS regeneration loops of the molecular sieve beds.

3. Preliminary design of EU TBS Tritium Accountancy Station (TAS)

TAS (Tritium Accountancy Station) accomplishes two functions: i) it accounts for the amount of tritium that in a given period of time enters the ITER inner fuel after being generated in the TBM and transported along the TBS sub-systems. In this sense it provides an administrative service of basic importance for the nuclear operator; ii) through the measurement of the tritium amount collected at the end of the TBS chain it provides data for scientific elaboration and, particularly, modelling tools validation. In the present design HCLL and HCPB-TBS TASs are independent and physically located in the Tritium Plant Building, as shown in fig. 1.

Tritium is typically present in traces (vppm levels, or even below) as HT in the gas streams from the regeneration loops of TES and CPS for both HCLL and HCPB-TBS. They are [6]:

- n. 3 He streams containing water detritiated through PERMCAT from the regeneration loop of HCPB-TES-AC (adsorption columns), HCLL-CPS-AC, and HCPB-CPS-AC, with a relatively large flows rate (around 100 mol/h). Provided a nominal PERMCAT
operation occurs, the tritium concentration in these streams is around $10^8$ Bq/m$^3$. Therefore, they could be discharged without any dedicated accountancy.

- n. 3 pure Q$_2$ streams from the PERMCAT (PC): the ones from HCPB-TES-PC, HCPB-CPS-PC, and HCLL-CPS-PC consist in moderate flow rates (around 9 mol/h in TES and 17 mol/h in CPS) containing pure Q$_2$. Provided a nominal PERMCAT operation, the tritium concentration is around $10^{11}$ Bq/m$^3$. The total amount of tritium is estimated around 20 Ci per day, which is about 5% of the total tritium bred (HCPB+HCLL). Tritium accountancy is mandatory and will allow estimating the tritium permeation into the coolant and tritium released in the form of water in the purge gas of HCPB.

- n. 2 streams of He containing Q$_2$ from getter beds (GB): these streams contain the main amount of bred tritium. Then, high accuracy is requested.

In fig. 4 the summary of the gas streams entering the Tritium Accountancy Station is reported, with indication of the sub-systems from which they come from.

![FIG. 4. Block diagram of the tritiated streams from TBS, necessary accountancy steps and preliminary indication of the interfaces with Tritium Plant][6]

The configuration and preliminary design of the tritium accountancy station for TBS has been driven by the need to satisfy three main requirements: good accuracy in order to meet the scientific objectives, high operation flexibility due to the experimental needs, strong space constraints. In the light of these requirements, the configuration selected for TAS is as follows:

- for the n.3 pure Q$_2$ streams from PERMCAT, dynamic accountancy was selected. It is based on the use of thermal mass flow rate measurement at the PERMCAT inlet (3% accuracy) and real-time tritium measurement by on-line ionization chambers calibrated with tritiated certificated gases (4% accuracy). The overall expected accuracy should be \[ [(3)^2 + (4)^2)]^{1/2} = 5\% \]

- for the stream from HCPB-TES-GB, dynamic accountancy could be performed. It relies on Coriolis mass flow meters (3% accuracy on average) and real-time tritium measurement with on-line ionization chambers calibrated by tritiated certificated gases (4% accuracy). Then, the overall expected accuracy is 5%.

- for the stream from HCLL-TRS-GB, considering the low mass flow-rate and the Q$_2$ content in He that is expected to vary significantly (between traces of pure tritium up to 20% Q$_2$), the dynamic approach is not recommended due to potential high uncertainty on the mass flow-rate measurement. Therefore, static accountancy appears as the most suitable option. Static accountancy could be performed using two collecting vessels...
working in sequence for pVT measurement (1% accuracy) and tritium measurement with GC (5% accuracy, including calibration), then with an overall accuracy of around 5.1%.

A schematics of the dynamic accountancy is shown in fig. 5.

![Configuration of dynamic tritium accountancy](image)

*FIG. 5. Configuration of dynamic tritium accountancy*

When considering the extrapolation to DEMO, it appears evident the need to improve the accuracy because of its impact on the tritium breeding ratio uncertainty.

4. Tritium Transport Modelling tools: present situation

Two are the main requirements that the tritium modelling tools, simulating the tritium transport in the breeding blanket and ancillary systems, have to satisfy. The first one is that the tritium transport modelling tools have to be capable to "exploit" the TBS experimental campaign in ITER. This means that the embedded physics has to be comprehensive enough to allow extracting values/correlations for the different physical parameters from TBS experimental campaign. The second requirement is that the modelling tools will have to make possible the extrapolation from TBS to BB for DEMO in order to provide support to the design of the main BB components. In other words, they need to be “DEMO relevant”. The DEMO relevancy requires that the physics modelling is sufficiently general to take into account all phenomena that may take place in DEMO-like operative conditions. As discussed in a previous paper [7], the structure of the tritium modelling tool should consist of four layers, as in fig. 6.

![Structure of the tritium transport modelling tool](image)

*FIG. 6. Structure of the tritium transport modelling tool [7]*
The lowest level refers to the physics modelling sub-routines, where basic equations describing tritium transport through materials and interfaces are numerically solved. The second level from the bottom consists of the component models. They have to be able to determine the tritium concentration in all points of a component. Tritium permeation from the component will be also provided by the tool. The third level is related to the sub-systems, i.e. TBM, TES, CPS, HCS, Pb-16Li loop, tritium accountancy stations. The modelling tool for any sub-system will be set through the integration of the relevant component tools. The TBS level, so the systems level, is the highest one. In this case the tritium transport system tool will come from the integration of the different sub-systems tools.

Also in view of the possible use of relevant results in the TBS preliminary safety report, a first tritium transport tool for TBS with simplifying assumptions is presently under development through a collaboration between Fusion for Energy and TBM-CA (TBM Consortium of Associates) with CIEMAT as leading Association. The goal of this collaboration is to prepare a tool able to determine quickly but in reliable way the amount of tritium permeated from the breeding region into the main coolant, the amount of tritium solubilized in the functional and structural materials of the TBM, the tritium permeation rate through the pipe wall of the ancillary systems into the Port Cell and Port Interspace and, finally, the percentage of tritium reaching the tritium accountancy station over the tritium generated in the TBM per unit time. The results are being calculated for the various ITER reference operating scenarios. A run output run is reported in fig. 7 for an irradiation scenario consisting of 48 consecutive inductive plasma pulses. The graph reports the cumulative tritium permeation into the helium coolant, the tritium specific flow-rate at the HCLL-TBM outlet and tritium generation rate.

FIG. 7. Cumulative tritium permeated into HCS, extraction and generation rate in HCLL- TBM for 48 daily inductive plasma pulses. Tritium concentration at TBM inlet is equal to zero

5. Conclusions

An effective tritium management in HCLL and HCPB-TBS is of basic importance to validate tritium fuel cycle modeling, relevant for DEMO development and particularly tritium self sufficiency demonstration, as well as for their safe operation. The design and technology choices to be implemented in the Test Blanket Systems have been driven more by compliancy with the safety and reliability ITER requirements more than by DEMO relevancy aspects. This is evident, for example, in the design of the tritium extraction system from Pb-16Li where a packed column
has been selected as reference technology instead of a permeator against vacuum. However, testing some particular technologies like cold traps for Pb-16Li purification, molecular sieve beds and, likely, tritium permeation barriers, is a first validation step towards possible applications to a DEMO breeding blanket.

A preliminary design of HCLL and HCPB-TBS tritium accountancy station has been carried recently. In this case, the main requirements were an acceptable accuracy and flexibility in measuring all tritium coming from the different regeneration streams of the ancillary TBS loops and to design a system as compact as possible. For the majority of the tritiated gas streams, a dynamic accountancy configuration was selected, based on the use of mass flow-meters coupled with ionization chambers. In a specific case, a static configuration has been foreseen (pVT method) with tritium concentration measured by gas-chromatography. In general, for all streams accuracy in tritium measurement of 5% is expected. The tritium accountancy dynamic configuration is promising with respect to the possible use in a DEMO breeding blanket provided that a significant effort is made in enhancing accuracy, necessary to reduce the uncertainty in measured the tritium breeding ratio.

The development of tritium transport modelling tools able to predict tritium transfer from its generation up to its delivery to the inner fuel cycle is probably the most crucial activity related to tritium within the blanket development programme. The strategy for achieving the final goal, a qualified tool for tritium breeding ratio and inventory prediction in the different points of the fuel cycle, was briefly recalled in this paper. Ongoing activities, aimed at the development of an initial, simplified tool, were also described.

REFERENCES


