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Tritium transport modeling for breeding blanket: State of the art and strategy for future development in the EU fusion program

Italo Ricapito[a,*], P. Calderoni[a], Yves Poitevin[a], Luis Sedano[b]

[a] *Fusion for Energy, Barcelona, Spain*
[b] *CIEMAT, Madrid, Spain*

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ABSTRACT

The design of the Test Blanket Modules for ITER and the breeding blanket for DEMO requires robust and accurate modeling tools. Transport phenomena through the blanket tritium cycle are complex and involve a large number of physical properties and parameters, many of which have not been determined yet with a level of accuracy adequate for design optimization. Similarly, the use of simplified models with experimentally determined lumped coefficients allows satisfactory predictions only in very limited range of operative conditions, strongly reducing their potential to be relevant to the DEMO design.

Within the European Union fusion program a road map to develop such modeling tools has been defined with the purpose of supporting the design of the ITER Tritium Blanket System and to exploit the TBM experimental testing for extrapolation to DEMO. The roadmap includes the development of the simulation tools as well as the supporting validation and verification experiments that must be carried out in parallel. This paper gives an overview of the state of the art of tritium modeling tools for blanket design, proposes a structure of the tritium modeling tools in order to facilitate their development and identifies a realistic work plan to achieve their final delivery.

1. Introduction

Tritium transport modeling tools are essential in the life cycle of the breeding blanket (BB) development, starting from the design and experimental testing in ITER of the Test Blanket Systems (TBSs) up to the complete BB design and assessment of tritium self-sufficiency.

Two are the main requirements that they have to satisfy. First of all, the tritium transport modeling tools have to be capable to “exploit” the TBS experimental campaign in ITER. This means that the physics embedded in the modeling tools has to be sufficiently comprehensive to allow extracting values/correlations for the different physical parameters from TBS experimental campaign. The second requirement is that the modeling tools will have to make possible the extrapolation from TBS to BB for DEMO. In other words they need to be “DEMO relevant”. The DEMO relevancy requires that the physics is sufficiently general to take into account all phenomena that can take place under a wide range of operative conditions. This is the main reason why simplified models, where the true physics of tritium transport is lumped into empirical parameters, although potentially useful in designing TBS experiments, should be disregarded.

Depending on the stage of the project, the tritium transport modeling tools have to be used in correlative or predictive way. During the initial phase of development, the tools will have to be used mainly in correlative way for pre-validation against small scale “cold” experiments. Subsequently, when this pre-validation of the codes will be achieved, the tools will have to predict the performance of the TBS, then giving support to the design of the TBM, the ancillary systems and their main components. Moreover, they will be used to carry out the design of experiments in ITER. During ITER experiments, particularly in the DT phase, again the modeling tools will have to be used in correlative way and adjusted consequently in order to fit (correlate) the experimental outcomes.

2. Structure of the tritium transport modeling tools

Following the ITER nomenclature, used by all Parties involved in the developing breeding blanket concepts for fusion reactors, the Test Blanket System (TBS) consists of the Test Blanket Modules (TBM) and related ancillary circuits. So, from a hierarchical point of view, TBS is the “system” while TBM and ancillary loops are sub-systems (see Fig. 1 for HCLL-TBS), each of them consisting of different components.

* Corresponding author. Tel.: +34 933201848; fax: +34 933201803.
E-mail address: italo.ricapito@f4e.europa.eu (I. Ricapito).

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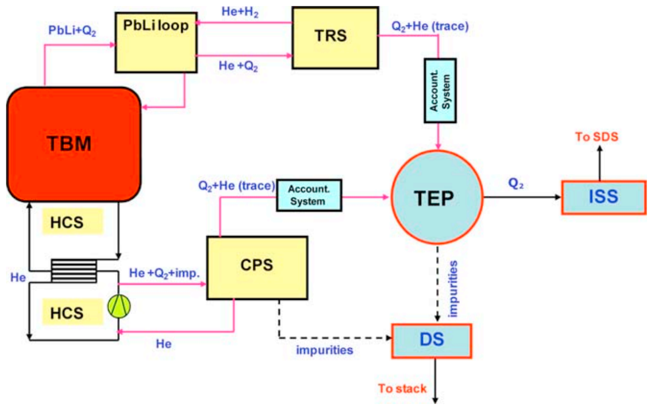

Fig. 1. HCLL Test Blanket System and their interfaces with ITER tritium systems (light blue). HCS: Helium Cooling System; CPS: Coolant Purification System; TRS: Tritium Recovery System; TEP: Tokamak Exhaust Processing System; ISS: Isotope Separation System; DS: Detritiation System. Q = H, D, T. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

This distinction between system, sub-system and components is not just formal. It also provides a natural structure that should be reflected in the tritium transport modeling tools, because of the multi-physics elements that need validation have to be addressed already at level of components. In general, this structure is divided in four layers (Fig. 3).

The lowest level consists of the physics modeling sub-routines, where fundamental equations describing tritium transport through different types of materials and interfaces are numerically solved. For the sub-system TBMs those include:

- tritium mass transport through ceramic pebbles
- tritium mass transport through Be pebbles
- tritium mass transport through quasi-stagnant PbLi
- tritium mass transport through the ferritic–martensitic steel (Eurofer) cooling/stiffening plates
- For the ancillary sub-systems, tritium mass transport through pipes walls, in presence of lead lithium alloy and Helium
- tritium mass transport in the two-phase He/PbLi system
- tritium mass transport through microporous materials

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 component level has the function of connecting the lower level physics solvers in a way peculiar to that particular component.

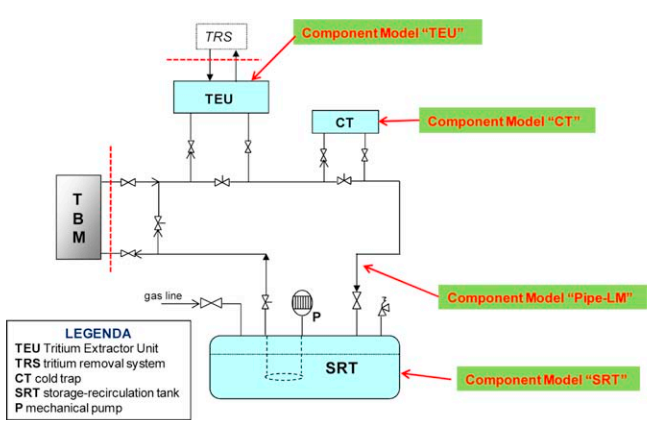

Fig. 2. "PbLi loop" sub-system modeling tool.

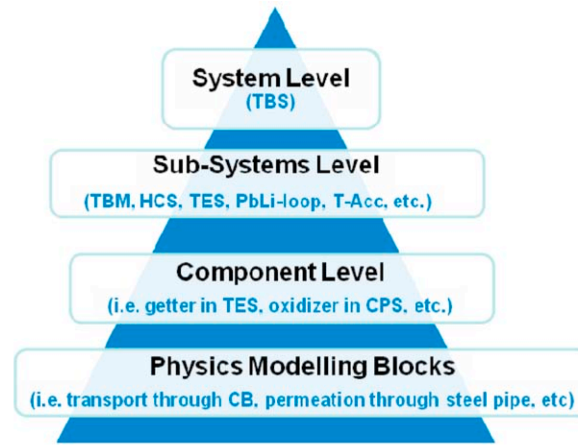

Fig. 3. The four-layer structure of the tritium transport modeling tool in HCLL-TBS and BB.

As an example, the component model for TEU (Tritium Extraction Unit), a packed column that has the function to extract tritium from flowing PbLi in the HCLL-TBM concept, will essentially consist of two subroutines: tritium mass transport in a two-phase He/PbLi system and tritium mass transport through metal pipe walls.

The third level is the one of the sub-systems, i.e. TBM, TES, CPS, HCS, PbLi loop, and accountancy stations. The modeling tool for any sub-system will be made through the integration of the relevant component tools. In Fig. 2 this integration is shown for the sub-system PbLi loop.

The highest level is the one of the TBS as a whole, the system level. In this case the tritium transport system tool will come from the integration of the different sub-systems tools.

3. Issues in the tritium transport physics models

The physics of tritium transport through materials is complex and involves many parameters whose determination is, in some cases, very difficult. In the following, two examples are described.

Let just consider the model of tritium transport through a metallic material. The general tritium mass transport equation for a radioactive species "s" through a material, in both dissolved and trapped states, can be written as:

$$\frac{\partial C_s}{\partial t} + \sum_k \frac{\partial C_{s,t}^k}{\partial t} = -\nabla \cdot J_s + S_s - \lambda_s C_s - \lambda_s \sum_k C_{s,t}^k + \sum_m \left(C_m^s + \sum_k C_{m,t}^{s,k} \right) \quad (1)$$

where C_s is the solubilized concentration of species "s" atoms, J_s the diffusive flux of species "s" atoms, S_s the local source rate of species "s" atoms, $C_{s,t}^k$ the concentration of atoms of species "s" in the kth trap type, C_m^s the concentration of atoms of species "m" that decay into species "s", $C_{m,t}^{s,k}$ the concentration of atoms of species "m" that, decay into species "s" in the kth trap type, λ_s the decay constant of species "s" atoms, λ_m^s the decay constant of species "m" atoms that decay to species "s".

For the trapped states, summation is done over all possible trap states k. The diffusive flux in 1D form has to be written as:

$$\nabla \cdot J_s = \frac{d}{dx} \left[-D \left(\frac{dC_s}{dx} + C_s \frac{Q^*}{kT^2} \frac{dT}{dx} \right) \right] \quad (2)$$

where the first term on the right side is the Fick's diffusive flux while the second term represents the "Soret" effect which takes into account the diffusion in presence of thermal gradient