# CONFERENCE PRE-PRINT

# DESIGN-BASED MULTIDINENSIONAL TRITIUM TRANSPORT ANALYSIS PLATFORM FOR BLANKET SYSTEM

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**Abstract**

Accurate prediction and control of tritium behavior within blanket systems is essential to realize the D-T fusion power plant. Tritium inventory, permeation, and transport directly affect operational safety, fuel self-sufficiency, and environmental protection. To address these challenges, the Korea Institute of Fusion Energy (KFE), in collaboration with UCLA, has developed the Tritium/Hydrogen Enhanced dynamic Transport Analysis platform for Fusion Reactor (THETA-FR). This integrated analysis platform couples COMSOL Multiphysics and MATLAB Simulink, enabling both component-level and system-level analysis of tritium transport. A distinctive feature of THETA-FR is its multidimensional and multiphysics modeling capability, allowing detailed 2D/3D geometric representations to capture heterogeneous tritium behaviors that arise from complex blanket component structures. The system-level integration is achieved through dynamic coupling via MATLAB S-functions, ensuring synchronized parameter exchange across all modeled components. As an application case, the THETA-FR has been applied to the He-Cooled Ceramic Pebble (HCCP) Test Blanket System (TBS), which includes the First Wall, Breeding Unit, He Cooling System, Coolant Purification System, and Tritium Extraction System. For efficient modeling, the First Wall and Breeding Unit are integrated into a single COMSOL module, while ancillary subsystems such as He piping and purification units are modeled separately. The THETA-FR enables detailed evaluation of tritium generation, permeation, and retention under fusion-like operating conditions. Example analyses demonstrate system responses under ITER-like operational scenarios, including 500 MW fusion power with specified burn and dwell times, heat fluxes, and neutron wall loading. The results illustrate the time-dependent behavior of tritium partial pressures, inventory build-up, and transport within coolant and structural materials. THETA-FR provides a versatile and comprehensive framework for supporting design optimization and safety assessment of tritium management in fusion blanket systems. Its application to HCCP-TBS highlights its capability to bridge component-scale physics with system-level dynamics, contributing to the broader goal of fusion power plant realization.

# 1. INTRODUCTION

Achieving deuterium–tritium (D–T) fusion power generation requires overcoming several critical challenges. Among these, the reliable supply of fusion fuel is one of the most pressing. Deuterium can be readily obtained from sea; however, tritium is almost absent in nature and must be produced artificially. In a fusion reactor, tritium can be bred inside a Li-based blanket installed within the tokamak, via Li–n reactions. The He Cooled Ceramic Pebble (HCCP) breeding blanket, currently under development at the Korea Institute of Fusion Energy (KFE), is one such concept designed to achieve tritium self-sufficiency.

In the HCCP blanket design, tritium generated in the ceramic breeder is extracted by He purge gas flowing through the blanket and subsequently transferred to a tritium extraction system (TES) for processing and storage. While most of the tritium in the He purge gas can be recovered in the TES, complete removal is extremely challenging. As a result, trace amounts of tritium remain in the circulating purge gas, leading to gradual accumulation in piping systems and potential release into the working environment. Furthermore, tritium release is not limited to the TES: it also occurs in the He coolant system (HCS), where tritium bred in the blanket permeates into the cooling plates and enters the coolant loop. These mechanisms highlight the necessity of analyzing tritium transport within the breeding blanket system to assess accumulation and release risks, thereby ensuring safe and reliable operation.

Over the past decades, a number of tritium transport models have been developed to address these challenges. Representative tools include TMAP, which simulates diffusion, permeation, and chemical reactions in materials [1]; ECOSIMPRO, which supports thermo-fluid modeling of tritium cycling [2]; MHIT, which provides multiphysics simulations of hydrogen isotopes [3]; and FESTIM, a Python-based finite element tool for high-resolution tritium transport analysis [4]. These models play an essential role in predicting tritium behavior and guiding tritium management strategies in fusion systems.

This paper introduces a new analysis platform, THETA-FR (Tritium / Hydrogen Enhanced dynamic Transport Analysis platform for Fusion Reactor), developed at KFE in collaboration with UCLA [5, 6]. THETA-FR enables simultaneous simulation of H isotope generation, accumulation, transport, and release processes, while also incorporating dynamic heat transfer analysis at the subsystem level and integrated system level. Unlike 0-1 D models, THETA-FR is based on multi-dimensional geometries, allowing it to capture detailed spatial effects in breeding blanket components.

The THETA-FR integrates COMSOL Multiphysics and MATLAB Simulink into a hybrid modeling environment: COMSOL is used for detailed component-level analyses, while MATLAB Simulink manages system-level integration and dynamic interactions [7, 8]. For the HCCP blanket, the modeled subsystems include the first wall (FW), breeding unit (BU), He cooling system (HCS), coolant purification system (CPS), and tritium extraction system (TES). The combination of these systems within THETA-FR provides a comprehensive framework to investigate tritium inventories, permeation pathways, and release mechanisms [9].

An overview of the THETA-FR as applied to the HCCP breeding blanket system is introduced in this study. The methodology, subsystem modeling approaches, and integrated system simulations are described, with representative results demonstrating the platform's ability to estimate tritium inventories, diffusion, and release across key components. Ultimately, this work provides validated insights for tritium management and contributes to the safe and efficient design of future fusion blanket systems.

# 2. THETA-FR

## 2.1. Integrated system of HCCP breeding blanket in THETA-FR

The THETA-FR for the HCCP breeding blanket consists of multiple sub-systems, including the FW, BU, HCS, TES, and CPS. These sub-systems are integrated within Matlab Simulink, as illustrated in the following figure.

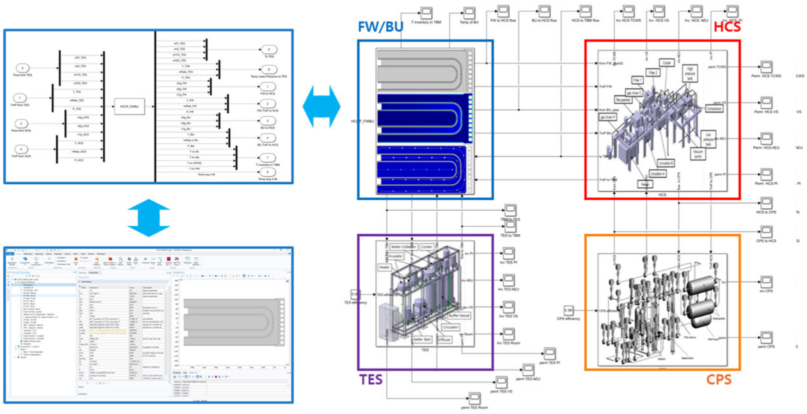


*Fig. 1. Configuration of HCCP Breeding Blanket in THETA-FR*

In the integrated system, each sub-system is linked to the COMSOL file, which directly performs the detailed analysis of its components, through the Matlab S-function. Time-dependent variables are provided via the Matlab S-function, and the resulting outputs are transferred to other sub-systems.

### 2.2. Components of HCCP breeding blanket in THETA-FR

The FW/BU component, as part of the HCCP breeding blanket in THETA-FR, represents a combined model of the first wall, which directly faces the tokamak, and the breeding unit, which is responsible for tritium production.

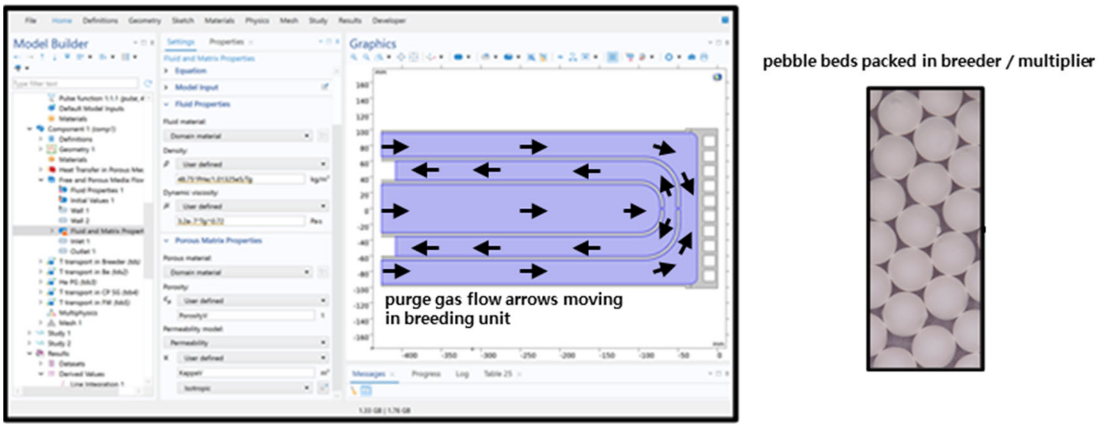


*Fig. 2. He PG flow in the breeding unit with packed pebble beds*

In the HCCP breeding blanket, tritium generated in the breeding material is recovered to He purge gas. To allow the He purge gas to circulate freely between the breeding material and to mitigate the mechanical load induced by thermal expansion, the breeding material is configured in a pebble-bed form. The coupled configuration of the pebble bed and He purge gas is implemented in COMSOL using the 'free and porous media' feature, as shown in Fig. 2.

In addition, the He coolant responsible for transporting the tritium generated in the breeding blanket, and the He coolant for heat absorption and transfer, are directed through dedicated pipes to the Tritium Extraction System (TES), He Cooling System (HCS), and Coolant Purification System (CPS). During transport through these pipes and the blanket, - it picks up the tritium through permeation from the breeding zone, while tritium contained in the He gas may accumulate on the pipe walls or, in part, permeate through the outer surface of the pipe to the surroundings. Therefore, tritium analysis is required for all pipe models within the sub-systems. To enable efficient modeling and analysis, scaling with respect to pipe length was taken into account.

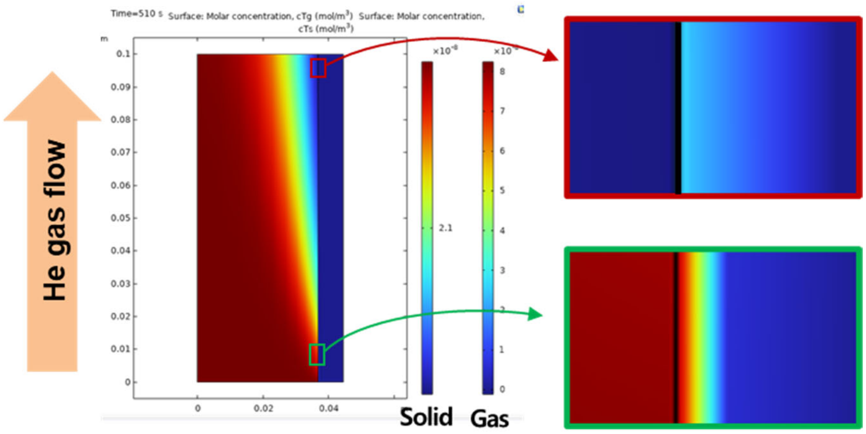


*Fig. 3. Tritium concentration at the gas/solid interface near the pipe inlet / outlet*

In Fig. 3, the pipe model with length 32 m He coolant pipe in axial direction is set to 0.1 m for computational purposes such as meshing. To ensure consistency across all pipe models, the same pipe length was applied, and the parameters and properties of both the pipe wall and He gas in the axial direction were scaled accordingly. By constructing an optimal pipe model and applying it to all pipes, an efficient sub-system modeling and analysis approach is achieved.

## 3. ANALYSIS OF HCCP BREEDING BLANKET IN THETA-FR

### 3.1. Conditions / Parameters applied in the analysis

In this paper, the material used in ITER HCCP TBM and the operation scenario in ITER baseline 2016 is considered, and details are followed.

TABLE 1. MATERIALS CONSIDERED IN HCCP BREEDING BLNAKET [10]

| Parts | Material |
|---|---|
| Breeder | $Li_4SiO_4$ pebble bed |
| Multiplier | Be pebble bed |
| Structural Material | Eurofer97 |
| Coolant | He gas |
| Purge gas | He gas |
| Pipe Wall | Stainless Steel 316L |

TABLE 2. PLASMA OPERATIONAL SCENARIO OF HCCP TBM IN ITER BASELINE 2016 [11]

| Scenario | Value |
|---|---|
| Fusion power | 500 MW |
| Repetition time | 1800 s |
| Flat top | 450 s |
| Surface heat flux | 0.3 $MW/m^2$ |
| Neutron wall load | 0.78 $MW/m^2$ |
| Tritium generation | 15 mg/d (2 shift) |
| CXN flux | Not considered |
| Operation | 11 day |
| Maintenance (close) | 3 day |

TABLE 3. HCCP BREEDING BLANKET PARAMETERS

| Part | Parameters | Value |
|---|---|---|
| He purge gas | Flow rate | 1.96 g/s |
| | Pressure | 0.4 MPa |
| | Inlet Temperature | 300 °C |
| | $H_2$ partial pressure | 400 Pa |
| He coolant | Flow rate | 1.3 kg/s |
| | Pressure | 8 MPa |
| | Inlet Temperature | 300 °C |
| | $H_2$ partial pressure | 300 Pa |
| CPS | Flow rate | 30 g/s |
| | Efficiency | 95% |
| TES | Efficiency | 95% |

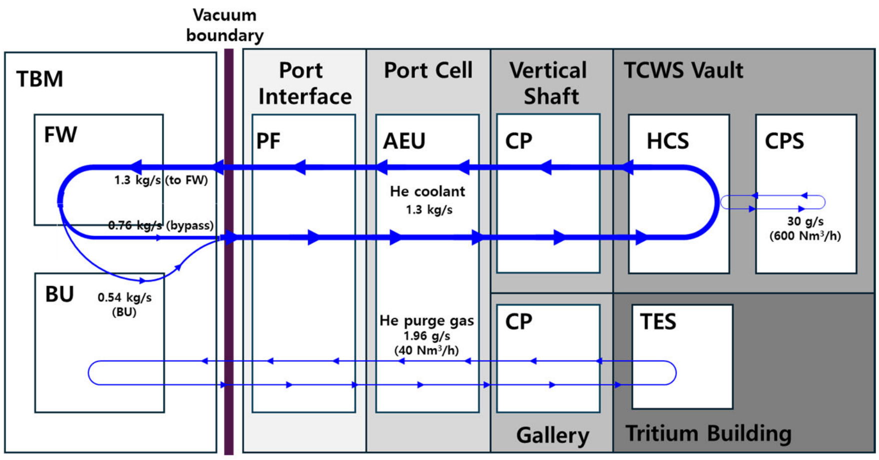


*Fig. 4. Simplified flow diagram for He coolant / He purge gas in HCCP TBM*

### 3.2. Analysis results

Using the conditions / parameters provided in section 3.1, the tritium analysis is performed in THETA-FR, and following results can be obtained. At first, the tritium inventory in the breeding material and cooling plate are provided in following figure.

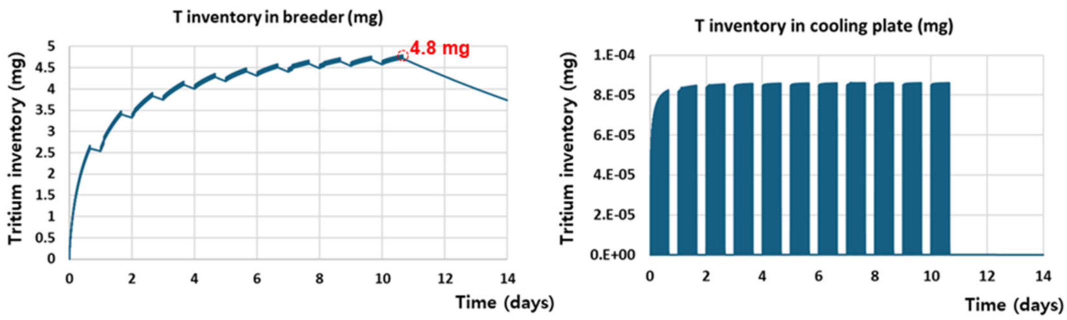


*Fig. 5. Tritium inventory in HCCP breeding blanket a) breeder b) cooling plate*

During tritium generation in the breeding blanket, a portion of the tritium remains in the breeder instead of being carried by the He purge gas. The tritium inventory in the breeder is shown in Fig. 5(a). Meanwhile, the tritium carried by the He purge gas comes into contact with the cooling plate while He PG circulates within the breeding blanket, leading to permeation into the He coolant. However, the amount of tritium accumulated in the cooling plate is negligible compared with tritium inventory in the breeder, and during the dwell time, the tritium inventory releases back to He coolant and approaches nearly zero, as shown in Fig. 5(b).

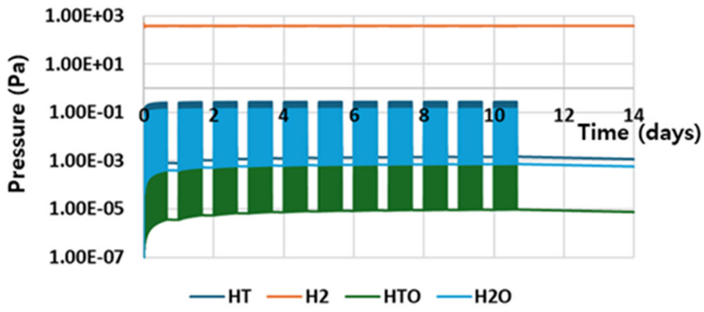


*Fig. 6. Q2/Q2O partial pressure of He purge gas at HCCP breeding blanket outlet*

Tritium generated in the breeder is recovered by the He purge gas in the forms of HT and HTO. During this recovery process, the ratio of HT, $H_2$, HTO, and $H_2O$ are governed by equilibrium reactions, resulting in the $Q_2$/$Q_2O$ partial pressures shown in Fig. 5. To enhance tritium recovery in the TES, 0.1% $H_2$ is included to the He purge gas; accordingly, the partial pressure of $H_2$ remains nearly constant at 400 Pa (due to a much less amount of tritium generation), as illustrated in Fig. 6.

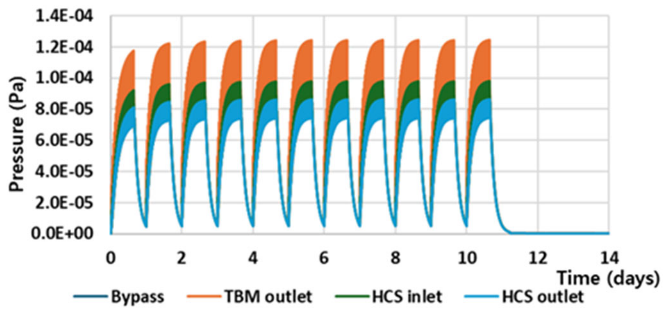


*Fig. 7. HT partial pressure of He coolant at HCCP breeding blanket outlet*

Tritium contained in the He purge gas can permeate into the He coolant through the cooling plate as the He purge gas circulates within the breeding blanket. Since this tritium permeation occurs within the BU, the He coolant bypassing the FW maintains the same tritium partial pressure as the HCS outlet (equivalent to the TBM inlet). In contrast, the TBM outlet shows an increased tritium partial pressure due to permeation through the BU cooling plates. At the HCS inlet, the bypassed He coolant and the TBM outlet coolant are merged, resulting in the tritium partial pressure distribution shown in Fig. 7.

The following graph illustrates the tritium inventory accumulated in the pipes located in each HCS - PI(port interface), PC(port cell), VS(vertical shaft room) / CP (connection pipe), and TCWS vault room - as well as the tritium permeation rates released into these spaces.

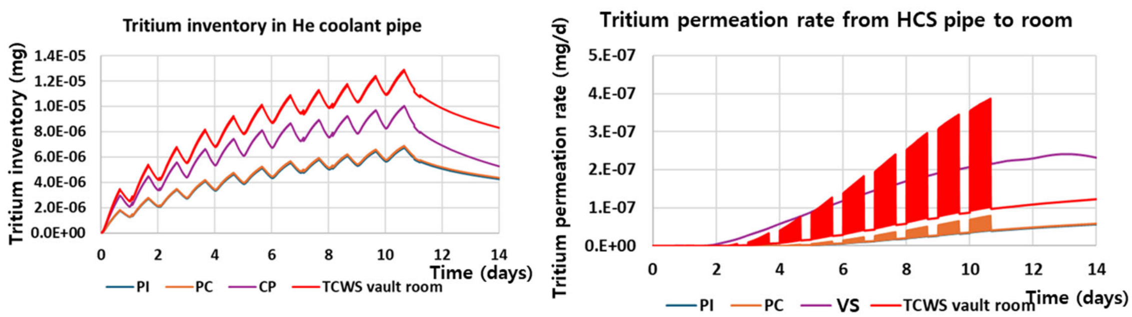


*Fig. 8. Tritium behavior in HCS a) tritium inventory in pipe wall b) tritium permeation rate from pipe to room*

In the pipes located within each HCS area, the tritium inventory increases in response to plasma pulse operation. The tritium permeation rate, however, exhibits a different trend: it remains very low at the beginning and then rises sharply after approximately two days. This behavior arises because the tritium inventory represents the total amount of tritium accumulated throughout the pipe wall, whereas the permeation rate corresponds to the flux of tritium released through the outer surface of the pipe wall. Tritium begins to release once the dissolved tritium in pipe diffuses through the pipe and reaches the outer surface of the pipe. Tritium releases increase after tritium arrives at the outer surface, this time delay depends on the pipe temperature, thus showing the significance of simulating temperature simultaneously in tritium transport analysis.

## 4. CONCLUSION

In this study, the tritium transport and release behavior of the He Cooled Ceramic Pebble (HCCP) breeding blanket was analyzed using THETA-FR, a framework developed by KFE and UCLA. THETA-FR integrates COMSOL Multiphysics and MATLAB Simulink to enable both component-level and system-level analyses, performing heat transfer and hydrogen isotope transport simulations simultaneously. We introduced the key elements of THETA-FR along with the parameters and conditions applied in the analysis. The results include the tritium inventory retained in the breeder and cooling plates of the breeding blanket, the tritium content in helium gases (purge gas and coolant), the tritium inventory in the HCS pipe walls, and the tritium released into each HCS-related buildings. These findings confirm that THETA-FR can sophisticatedly predict tritium transport and behavior in complex systems, and it is expected to make significant contributions to tritium management and worker safety in the design and construction of future fusion reactors.

## ACKNOWLEDGEMENTS

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