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

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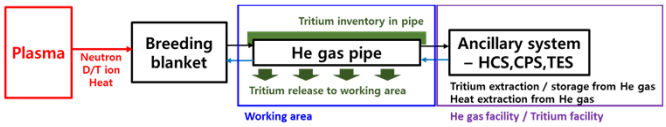
**Accurate prediction and control of tritium behavior within blanket systems is essential to realize the D-T fusion power plant. Tritium inventory, permeation, and transport directly affect operational safety, fuel self-sufficiency, and environmental protection. To address these challenges, the Korea 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.**

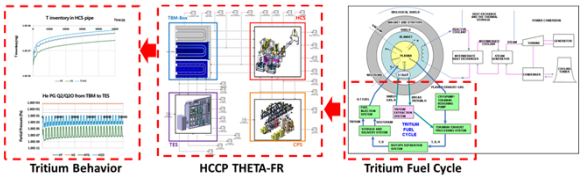
## Why Tritium Transport Analysis shall be develoepd ?




**[Tritium Transport in the HCCP Breeding Blanket]**

- In the He cooled Ceramic Pebble (HCCP) Breeding Blanket system, H isotopes (H/D/T) are accumulated in He coolant / He purge gas due to permeation from the breeding zones.
- Although most of tritium is extracted in the ancillary system, a non-extracted tritium in He gas is accumulated in the pipe and released into working area (buildings).
- Accordingly, a tritium transport analysis has been requested to identify the tritium amount in the working area and to secure the operational safety in the breeding blanket system.
- KFE started to develop a tritium transport analysis platform with UCLA, and the THETA-FR (Tritium/Hydrogen Enhanced dynamic Transport Analysis platform for Fusion Reactor) was developed.

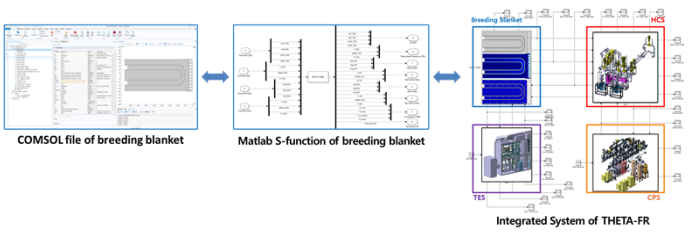
## What's THETA-FR ?




**[Tritium Transport Analysis using HCCP THETA-FR]**

- Integration of 2 commercial software – COMSOL Multiphysics / MATLAB Simulink
- COMSOL : tritium analysis performed under multiphysics, multi-isotope, fusion-like operating conditions in component level
- Matlab : data transfer & integration through S-function in system level
- Multidimensional geometry based design : to capture the detailed spatial effects in the breeding blanket components

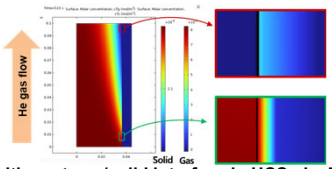
## Integrated System / Components of THETA-FR




**[Overall configuration of HCCP THETA-FR]**

- In HCCP THETA-FR, the tritium analysis of sub-systems (HCS, CPS, TES, FW, BU) are performed in COMSOL, and their resulting outputs are transferred through S-function in the integrated system.


**[He PG flow in BU with pebble bed]**




**[Tritium at gas/solid interface in HCS pipe]**

- In components files, tritium analysis with the 2D based design is performed.
- FW/BU component
  - He PG flow is circulated freely between breeding material
  - Tritium permeation at the gas/solid interface (BU-CP-He coolant, FW-cooling channel) are considered
  - As heat transfer & tritium analysis are simultaneously performed, the temperature-dependent variables can be more accurately applied. (i.e. diffusion related properties)
- Ancillary system (HCS,CPS,TES)
  - For computational purpose, all the pipe model has uniform length in axial direction.
  - Through construction an optimal pipe model design, the efficient sub-system modeling / analysis approach is achieved.

## Analysis Conditions used in HCCP THETA-FR

**[Plasma Operational Scenario]**

| Scenario | Value |
|---|---|
| Fusion power | 500 MW |
| Repetition time | 1800 s |
| Flat top | 450 s |
| Surface heat flux | 0.3 MW/m² |
| Neutron wall load | 0.78 MW/m² |
| Tritium generation | 15 mg/d (2 shift) |
| CXN flux | Not considered |
| Operation | 11 day |
| Maintenance (close) | 3 day |

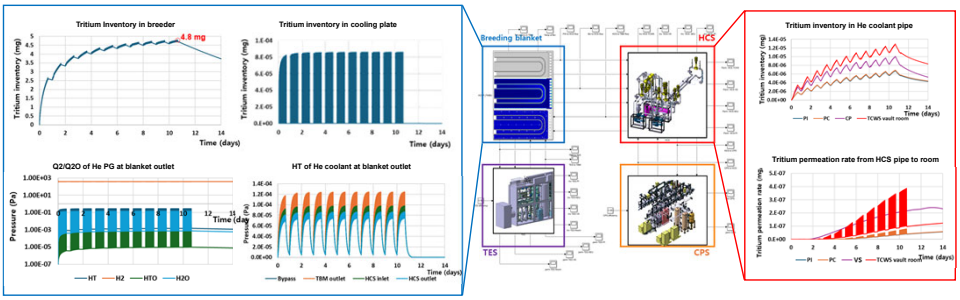
**[HCCP Blanket Materials]**

| 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 |

**[HCCP Blanket Parameters]**

| Parts | 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% |

## Analysis Results from HCCP THETA-FR




## Conclusion

- THETA-FR, developed by KFE–UCLA, integrates COMSOL and MATLAB for simultaneous heat transfer and hydrogen isotope transport analysis at both component and system levels.
- Through THETA-FR analysis, the tritium behavior in overall HCCP breeding blanket (i.e. breeder, cooling plate, pipe) can be predicted.
- It's expected that THETA-FR can sophisticatedly predict tritium transport / behavior in complex system, and THETA-FR will make significant contributions to tritium management and worker safety in future fusion reactor design.

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