

CONFERENCE PRE-PRINT**HELIUM COOLED CERAMIC BREEDER TESTING BLANKET SYSTEM HEAT RELEASE AND TRITIUM RELEASE FOR THE ITER NEW BASELINE DT-1 SCENARIO IN THE PORT CELL**

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Abstract

For China Helium Cooled Ceramic Breeder Testing Blanket System (HCCB TBS) during the ITER DT-1 scenario, heat release and tritium release within Port Cell #18 (PC#18) constitute critical safety parameters, determining compliance with thermal design requirements and the necessity of secondary confinement for the pipeline section. This study employs TriSim – our in-house simulation tool – to calculate these parameters against v2016 baseline values, confirming that under the updated v2024 baseline DT-1 scenario, heat release remains below 31 kW and tritium release maintains <1 DAC, demonstrating full compliance with ITER requirements.

1. INTRODUCTION

ITER has established an updated baseline (v2024) to address emerging technical challenges with 3 operational phases: SRO, DT-1, and DT-2[1]-[3]. Within this framework, the HCCB TBS will operate in ITER from DT-1 [4][5]. During the DT-1 operation, the fusion power will be adjusted to 250 MW with a flat-top duration of 300 s, executing 32 back-to-back pulses totaling 16 hours.

The shared Port Cell 18 including Piping Forest (PF) and Auxiliary Equipment Units (AEU) between Chinese and Japanese systems requires coordinated integration of piping components from both parties. High-temperature pipes in Helium Cooling System (HCS) and Tritium Extraction System (TES) traversing the PF and AEU present 2 challenges:

- Heat dissipation from the pipes potentially exceeding the thermal management capacity of PC#18;
- One fraction of tritium is transported from the breeding zone into the TES via purge gas and permeates through the partition wall into the HCS, while another is implanted from the plasma into the first wall and subsequently enters the HCS. The tritium accumulated in the HCS may then permeate through the high-temperature piping and be released into the environment.

So that it is necessary to analyze heat release and tritium release from CN HCCB TBS pipes to PF and AEU to integrate with Japanese data, and assess compliance with design requirements. In this paper, the heat release and tritium release of PC#18 from HCCB TBS components in DT-1 is simulated by TriSim to support the Port Cell #18 integration design.

2. DESCRIPTION OF THE MODELING**2.1. Modeling for TriSim**

In the previous work[6], to meet the requirements of the dynamic tritium analysis in HCCB TBS and its auxiliary systems, a tritium analysis coupled thermohydraulic tool "TriSim" is developed using a unified object-oriented simulation language Modelica, including zero-dimensional (0-d) control volume and one-dimensional (1-d) solids models. The typical characteristics of dynamic tritium transport for HCCB TBS can be simulated commendably. The tool has passed preliminary verification, and some calculations have been conducted within the framework of the ITER working group.

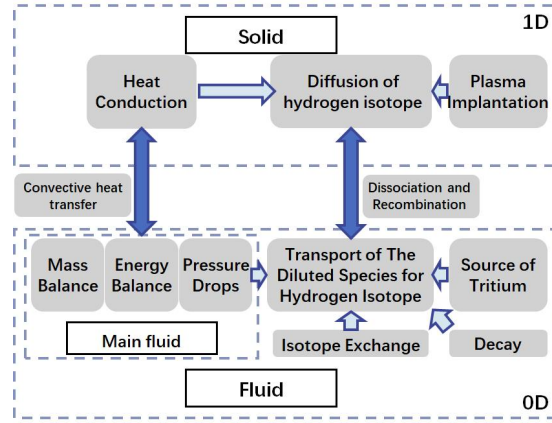


FIG. 1. Structure of TriSim

The TriSim framework is illustrated in Fig. 1. Compared to work[6], the following models remain unmodified:

- 0-d fluid equations in control volume:
 - Main fluid flow models (including mass balance, energy balance, and pressure drop equations);
 - Dilute species transport equations;
 - Tritium source equations.
- 1-d solid equations:
 - Heat conduction equations;
 - hydrogen isotope diffusion equations.

The isotope exchange reactions and decay have been incorporated into the 0-dimensional control volume, enabling more precise control of tritium chemical forms and more accurate calculation of tritium concentration in the fluid.

$$T_2 + H_2 \rightleftharpoons 2HT, \quad k = \frac{(c_{HT})^2}{c_{T_2} \cdot c_{H_2}}$$

$$\frac{d(c_T)}{dt} = -\frac{\ln 2}{T_{1/2}} c_T$$

- k is reaction equilibrium constant.
- c_{QQ} (mol/m³) is the concentration of QQ (Q = H, T) in the main fluid.
- c_T (mol/m³) is the concentration of atom T.
- $T_{1/2}$ (s) is half-life time of tritium.

Convective heat transfer equations have been implemented at the fluid-solid coupling interface to enhance the accuracy of temperature calculations:

$$Qc = A_w h (T_i - T_{wall})$$

- i is CV (Control Volume) i.
- Qc (W/m²/K) is convective heat-transfer coefficient.
- A_w (m²) is area of pipe wall.
- T (K) is temperature.
- h (W/m²/K) is convective heat transfer coefficient.

The dissolution and recombination equations[8] have been substituted for Sievert's law to better accommodate transient calculations of hydrogen isotopes at the fluid-solid interface:

$$J_Q = J_{d,Q} - J_{r,Q} = C_r K_r (2c_Q^2 + 2c_H c_T) - K_d (2P_{i,H_2} + P_{i,HT})$$

- J_Q (mol/s) is the total T flux of Q due to permeation in the solid surface.

- K_r ($\text{mol}^{-1} \cdot \text{m}^4 \cdot \text{s}^{-1}$) is recombination coefficient.
- K_d (J/mol) is dissolution coefficient.
- P_{QQ} (Pa) is the partial pressure of QQ in CV.
- C_r is constant for recombination coefficient to distinguish whether the surface is clean.
- c_Q (mol/m^3) is the concentration of atom Q (Q=H, T).

A thermal resistance formulation has been introduced in the solid domain to characterize heat transfer across solid assemblies more accurately.

$$P = R \times \Delta T \times A_w$$

- P (W) is thermal power.
- R ($\text{W}/\text{m}^2/\text{K}$) is thermal resistance.
- ΔT (K) is temperature difference.

Additionally, plasma-facing materials require consideration of effects from neutral particles originating from the plasma; therefore, a plasma implantation model[9] has been implemented (seen in Fig. 2):

$$J_{0,Q} = D \frac{c_{p,Q} - c_{0,Q}}{R} = D \frac{c_{p,Q} - c_{dx,Q}}{(dx - R)} = J_{dx,Q}$$

- R (m) is the depth of plasma implantation.
- dx (m) is the first mesh size.
- $c_{p,Q}$ (mol/m^3) is the concentration of atom Q in the depth of plasma implantation of solid.
- $c_{0,Q}$ (mol/m^3) is the concentration of atom Q on the solid surface of the plasma-facing side.
- $c_{dx,Q}$ (mol/m^3) is the concentration of atom Q in the depth of the first mesh size.

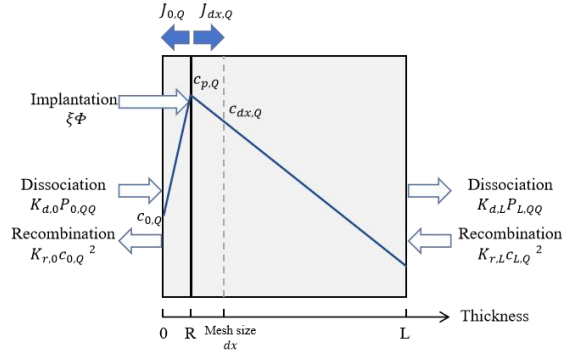


FIG. 2. Plasma implantation and diffusion in FW

2.2. Modeling for ITER HCCB TBS

The pipes and equipment within PC#18, which are included in the simulation, pertain to various subsystems of the HCCB TBS, such as the HCS, Coolant Purification System (CPS) and TES. Due to the small diameter (~ 9 mm) and relatively low temperature ($\sim 100^\circ\text{C}$) of the NAS pipe, its impact on heat release and tritium release is negligible and thus excluded from consideration. The simplified model of HCCB TBS in TriSim is shown in Fig. 3. The main input data are listed in Table 1.

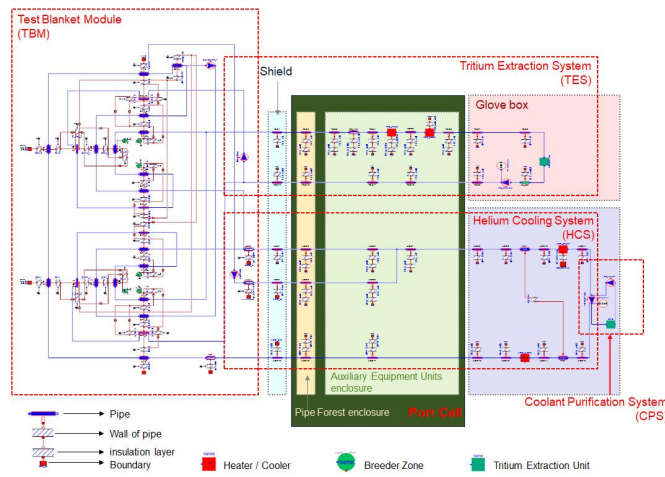


FIG. 3. Simplified HCCB TBS model in TriSim

TABLE 1. MAIN INPUT PARAMETERS FOR THE SYSTEM

Parameter (Units)	Value
The First Wall heat flux from plasma (MW/m ²)	0.26-0.32
TES helium mass flow rate (g/s)	0.3
HCS helium mass flow rate (g/s)	1040
CPS mass flow rate (g/s)	3
TES circulator outlet pressure (MPa)	0.3
HCS circulator outlet pressure (MPa)	8
TES cooler outlet temperature (K)	304.15
HCS heater outlet Temperature (K)	573.15
P _{H2} in TES (Pa)	300
Tritium residence time in ceramic breeder (hour)	$1.28 \times 10^{-5} \exp(9727/T)$
TES tritium removal efficiency	90%
CPS tritium removal efficiency	95%
Thickness of TES pipe wall (mm)	2.9
Thickness of HCS pipe wall (mm)	8.8
Thickness of TES insulation layer (mm)	40
Thickness of HCS insulation layer (mm)	100
Plasma repetition time (s)	1800
Flat top time in v2016 baseline (s)	450
Flat top time in v2024 baseline (s)	300

3. RESULT AND DISCUSSION

3.3. Heat release

Table 2 gives the heat release of HCCB TBS for the ITER v2016 baseline and v2024 baseline DT-1 scenario. The air temperature could be 35°C for reference (to calculate maximum heat release), and then 60, 80 and 100°C for scoping study, the different air temperature is considered. In TOS (tritium outgassing) operation, the inlet and outlet temperature of HCS are 490°C to outgas tritium and the heat release is the maximum conservative value. Safety factor is set as 1.5 to accommodate possible design changes of PC. Baking is one of main operation of ITER condition for tritium removal, the baking of the plasma-facing components may cause an increase in heat release. In baking operation, the inlet and outlet temperature of HCS are 300°C and the air temperature is estimated to be 50°C.

It is shown that in Table 2 the heat release in PC#18 is much lower than the limit value 31kW and it is also lower than the preliminary estimate ~7kW due to the actual design length of the HCS pipe in PC#18 in the latest modeling is much shorter than the estimated value.

TABLE 2. HEAT RELEASE IN PC#18

Cases		Air temperature (°C)	System	PF (W)	AEU (W)	PC (W)	Total (kW)	
Design temperature (v2016 baseline)	35	HCS	842.93	1410.04	2252.97	2.62		
		TES	-199.52	562.16	362.64			
	60	HCS	1165.43	933.98	2099.41	1.92		
		TES	-95.07	-84.78	-179.85			
	80	HCS	1100.12	877.17	1977.29	1.37		
		TES	-275.89	-334.35	-610.23			
	100	HCS	1034.84	820.34	1855.18	0.81		
		TES	-456.67	-583.93	-1040.60			
Fusion power 500MW (v2016 baseline)	Steady operation	35	HCS	1232.72	995.88	2228.60	2.62	
			TES	144.03	242.77	386.80		
		60	HCS	1150.69	924.60	2075.28	2.39	
			TES	134.62	184.67	319.29		
		80	HCS	1006.29	764.12	1770.41	2.04	
			TES	127.19	138.20	265.39		
		100	HCS	1020.06	810.92	1830.98	2.04	
			TES	119.79	91.68	211.47		
	Pulse operation (16h max)	35	HCS	823.72	663.20	1486.92	1.79	
			TES	94.16	205.11	299.27		
	Fusion power 250MW (v2024 baseline)	Steady operation	35	HCS	1107.10	914.28	2021.39	2.37
				TES	121.65	226.15	347.81	
			60	HCS	1024.48	842.62	1867.10	2.15
				TES	112.11	167.96	280.07	
			80	HCS	958.54	785.39	1743.94	1.97
				TES	104.54	121.39	225.93	
100			HCS	892.64	728.16	1620.80	1.79	
			TES	97.01	74.79	171.80		
Pulse operation (16h max)		35	HCS	906.77	776.56	1683.33	1.98	
			TES	93.79	205.74	299.53		
Fusion power 250MW (v2024 baseline)		Steady operation	35	HCS	1127.59	927.80	2055.40	2.41
				TES	124.32	228.14	352.46	
			60	HCS	1045.08	856.21	1901.28	2.19
				TES	114.79	169.96	284.75	
			80	HCS	979.25	799.06	1778.31	2.01
				TES	107.23	123.40	230.64	
	100		HCS	99.72	76.81	176.53	1.83	
			TES	913.46	741.91	1655.36		
	Pulse operation (16h max)	35	HCS	849.80	694.42	1544.22	1.34	
			TES	94.80	205.59	-199.52		
	TOS	35	HCS	1188.40	1477.80	2666.20	3.02	
			TES	131.03	227.22	358.25		
		60	HCS	1128.07	1402.78	2530.85	2.35	
			TES	-95.07	-84.78	-179.85		
		80	HCS	1080.25	1343.31	2423.57	1.81	
			TES	-275.89	-334.35	-610.23		
100		HCS	1032.68	1284.15	2316.83	1.28		
		TES	-456.67	-583.93	-1040.60			
Baking	50	HCS	654.17	813.47	1467.64	1.23		
		TES	-113.12	-127.81	-240.93			
	60	HCS	629.16	782.37	1411.54	0.95		
		TES	-203.77	-252.96	-456.72			
	80	HCS	579.14	720.16	1299.30	0.41		
		TES	-385.08	-503.30	-888.37			
	100	HCS	529.01	657.83	1186.85	-0.13		
		TES	-566.42	-753.74	-1320.16			

For the v2024 baseline DT-1 scenario, approximately 80 kW[5] of electric heating may be added in the breeding zone. Therefore, additional calculations were performed for the electric heating scenario. According to the trend of results in Table 2, since the heat release is highest when the first wall heat flux is 0.32 MW/m² and the air temperature is 35°C, this case was calculated.

TABLE 3. HEAT RELEASE IN PC#18 WITH ELECTRICAL HEATER

Cases	Air temperature (°C)	System	PF (W)	AEU (W)	PC (W)	Total (kW)
Fusion power 250MW (v2024 baseline)	With steady electrical heating	HCS	926.3	785.2	1711.4	2.0
		TES	97.4	208.5	305.9	
Surface heat 0.32MW/m ²	With pulse electrical heating	HCS	957.5	800.1	1757.6	2.1
Pulse operation (16h max)		TES	103.5	213.0	316.5	

3.4. Tritium release

It is evident that under the DT-1 scenario, considering electric heating, the temperature of the breeder zone will be higher. Consequently, the tritium release into the main fluid will increase, and the tritium permeating from the pipe wall into the PF and AEU will also be greater. Therefore, the tritium release for different electrical heater were calculated (steady or pulse heating), and the operating conditions under the v2014 baseline were also calculated for comparison. Due to the lack of tritium data on insulation layers, it is not considered in the tritium release calculation. Safety factor is eliminated in model, considering the accuracy of the tritium model.

The permeation flux of tritium atom into the PC#18 can be seen below in the Fig. 4, and the tritium concentrations (shown in Fig.5) in the PF and AEU were obtained based on the it. The tritium concentration is <1 DAC, which meets the requirements of ITER.

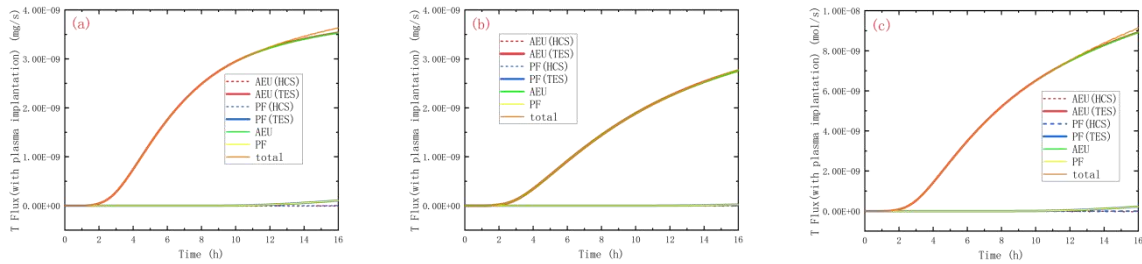


FIG. 4. Tritium release in PC#18 for (a) v2024 baseline DT-1 with steady electrical heating (b) v2024 baseline DT-1 with pulse electrical heating (c) v2016 baseline

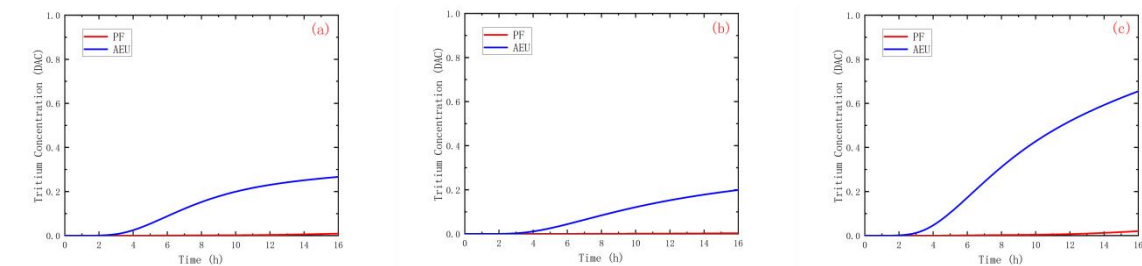


FIG. 5. Tritium concentration in PC#18 for (a) v2024 baseline DT-1 with steady electrical heating (b) v2024 baseline DT-1 with pulse electrical heating (c) v2016 baseline

For the HCS, its tritium comes from two sources: one part is obtained by tritium permeating from the TES into the HCS, and the other part is derived from plasma implantation. Therefore, an exploration was also conducted on whether to consider plasma implantation. During the 16-hour operation of DT-1, whether plasma implantation is considered or not, its impact on tritium release is negligible (Since incorporating plasma implantation yields results consistent with Fig. 4 and Fig. 5, they are not repeated here).

Nevertheless, plasma implantation remains non-negligible for tritium transport in the HCCB TBS. For instance, under steady electrical heating during DT-1 operation, plasma implantation elevates tritium concentration in the HCS by nearly three orders of magnitude (Fig. 6), significantly increasing HT partial pressure. Tritium concentration profiles across the HCS pipe wall at $t=16$ hours (Fig. 7) reveal that implantation prevents monotonic radial decay; instead, a concentration peak emerges at ~ 0.2 mm depth from the inner wall surface. This demonstrates that plasma-implanted tritium release to PC18 requires:

- Time of permeate into the HCS.
- Additional timescales for environmental release

The 16-hour operational period proves insufficient for complete permeation. Validation of this permeation kinetics hypothesis necessitates extended computational duration (exemplified by DT-2 simulations spanning 11 days), which exceeds the scope of this study and will be conducted in the subsequent step targeting in the DT-2 scenario.

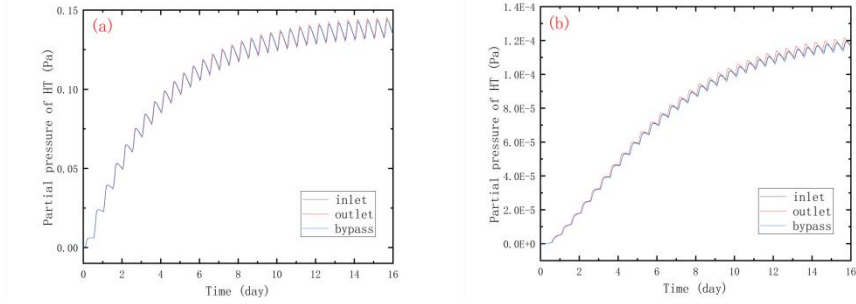


FIG. 6. Partial pressure of HT in HCS for v2024 baseline DT-1 considering steady electrical heating (a) with plasma implantation (b) without plasma implantation

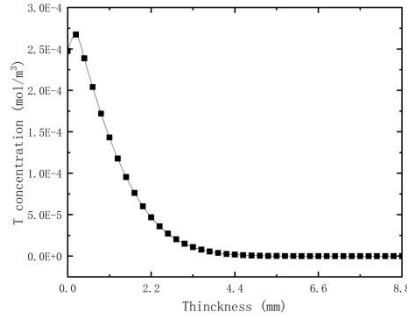


FIG. 7. The tritium concentration distribution in a certain section of the pipe wall in HCS.

4. CONCLUSION

This study quantitatively evaluates variations in heat release resulting from modified ITER input parameters, including power adjustments, flat-top duration, and surface heat flux. Under these conditions, the heat release remains within ITER-specified limits (<31 kW). To refine steady-state tritium partial pressure parameters, supplemental cases incorporating electrical heaters were conducted, consistently maintaining heat release below 31 kW.

Tritium release calculations for the aforementioned scenarios in the PC18 demonstrate:

- Tritium concentration profiles confirm compliance with ITER requirements (<1 DAC) in the DT-1 scenario.

- During 16-hour DT-1 operation, plasma implantation exhibits negligible impact on tritium release, as implantation-induced concentration increases have not yet propagated to the outer surfaces of the HCS.

Under extended operation scenarios, substantial tritium implantation from the plasma side may significantly influence tritium release in PC18, while concurrently elevating release levels in other pipes such as connecting pipes. This will be investigated in future work

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