ID: 3204

Helium Cooled Ceramic Breeder Testing Blanket System Heat Release and Tritium Release for the ITER New Baseline DT-1 Scenario in the Port Cell

Ruyan Li, Long Zhang, HongXiang Zhang, Jie Liu, XingHua Wu, FengChao Zhao, Jun Wang, ZhiFei Zhang
Southwestern Institute of Physics
liry@swip.ac.cn

ABSTRACT

- For HCCB TBS during the ITER DT-1 scenario, heat release and tritium release within PC (Port Cell)#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 confirm the heat release and tritium release under the updated v2024 baseline DT-1 scenario, heat release remains below 31 kW and tritium release maintains <1 DAC.

BACKGROUND

- ITER has established an updated baseline (v2024) to address emerging technical challenges with 3 operational phases: SRO, DT-1, and DT-2.
- 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.
- 80 kW of electric heating may be added in the breeding zone
- The shared PC#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.

METHODS

TriSim (Tool)

• 0D control volume models

Main fluid (He):

$$\frac{dm}{dt} = \sum_{inlets} F_{in} - \sum_{outlets} F_{out} + m_{source}$$

$$mC_p \frac{dT}{dt} = \sum_{inlets} F_{in} h_{in} - \sum_{outlets} F_{out} h_{out} + Q$$

$$p_j = \zeta \frac{\rho v^2}{2} \quad p_f = \lambda \frac{l}{d_e} \frac{\rho v^2}{2}$$

Transport of the diluted species (T/H):

$$m\frac{d\chi_i}{dt} = \sum_{inlets} F_{in}\chi_{i,in} - \sum_{outlets} F_{out}\chi_{i,out} + s_i$$

Source:

$$\frac{\partial c}{\partial t} = \frac{G_T}{V_b} - \frac{c}{\tau} \quad J = \frac{cV_b}{\tau}$$

Isotope exchange (Additions):

$$H_2 + T_2 \rightleftharpoons HT$$

Decay:

$$dc = -\lambda_d c dt$$

• 1D solid models

Heat conduction:

$$\frac{\partial T}{\partial t} = a^2 \frac{\partial^2 T}{\partial x^2}$$

Tritium diffusion:

$$\frac{\partial c}{\partial t} = -D\nabla^2 c$$

Plasma implantation (Additions):

$$J_P = D\frac{c_R - c_0}{R} + D\frac{c_R - c_x}{R}$$

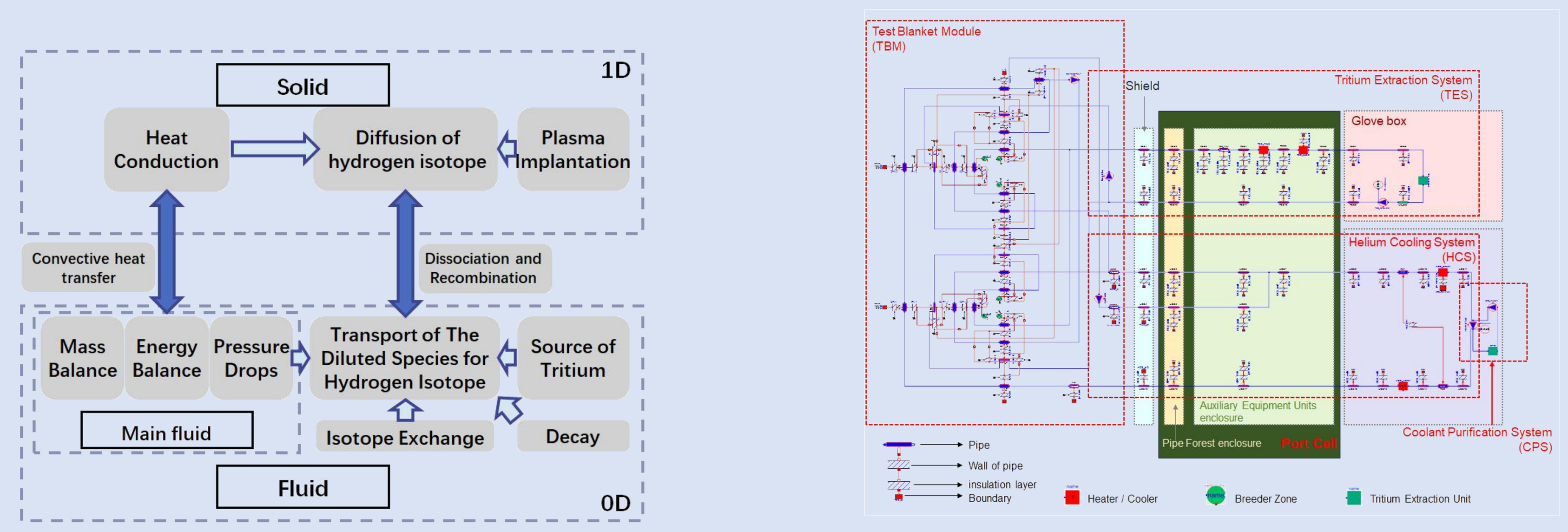
• solid-fluid coupling models

Convective heat transfer (Additions):

$$Qflow = Ah(T - T_{wall})$$

Dissolution and Recommbination (Additions):

$$J = J_d - J_r = 2K_d p - 2K_r c^2$$



Structure of TriSim

OUTCOME

HEAT RELEASE

- The heat release in PC#18 is much lower than the limit value 31kW.
- Even if electric heating is added, the heat release remains below 31 kW.

TRITIUM RELEASE

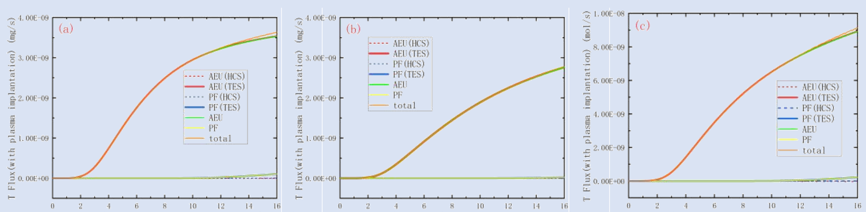
- The tritium concentrations in the PF and AEU <1 DAC, which meets the requirements of ITER.
- During the 16-hour operation of DT-1, whether plasma implantation is considered or not, its impact on tritium release is negligible
- Plasma-implanted tritium release to PC18 requires:
  - -Time of permeate into the HCS.
  - -Additional timescales for environmental release
- Validation of implanted tritium permeation necessitates extended computational duration.

Heat release in PC#18

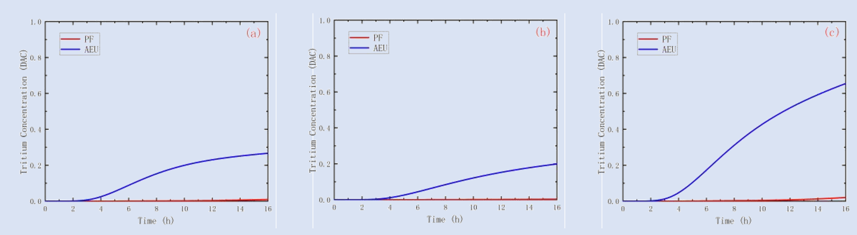
Cases		Air Temperature (C)	System	PF (W)	AEU (W)	PC (W)	Total (kW)
Design temperature		35	HCS	842.93	1410.04	2252.97	2.62
			TES	-199.52	562.16	362.64	
		60	HCS	1165.43	933.98	2099.41	1.92
			TES	-95.07	-84.78	-179.85	
		80	HCS	1100.12	877.17	1977.29	1.37
			TES	-275.89	-334.35	-610.23	
		100	HCS	1034.84	820.34	1855.18	0.81
			TES	-456.67	-583.93	-1040.60	
Fusion power 500MW (v2016 baseline) Surface heat 0.3MW/m²	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) Surface heat 0.26MW/m²	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) Surface heat 0.32MW/m²	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	

Heat release in PC#18 with electrical heater

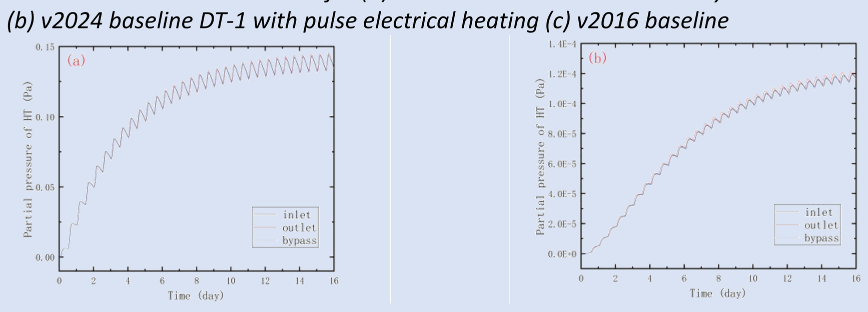
Cases		Air temperature (C)	System	PF (W)	AEU (W)	PC (W)	Total (kW)
Fusion power 250MW (v2024 baseline) Surface heat 0.32MW/m² Pulse operation (16h max)	With steady electrical heating	35	HCS	926.3	785.2	1711.4	2.0
			TES	97.4	208.5	305.9	
	With pulse electrical heating		HCS	957.5	800.1	1757.6	2.1
			TES	103.5	213.0	316.5	



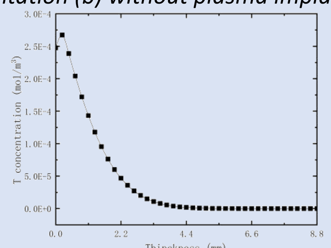
Tritium release in PC#18 for (a) v2024 baseline DT-1 with steady electrical heating (b) v2024 baseline DT-1 with pulse electrical heating (c) v2016 baseline



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



P_{HT} in HCS for v2024 baseline DT-1 considering steady electrical heating (a) with plasma implantation (b) without plasma implantation



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

CONCLUSION

- The heat release remains within ITER-specified limits (<31 kW)
- Tritium concentration 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 th HCS.
- Tritium implantation from the plasma side may significantly influence tritium release in PC18 in Long-term Operation.

REFERENCES

[1]Croset J.- P., ITER Research Plan (IRP) - Level 1 - ITER Research Plan, ITER Organization, 2024.
[2]R. Villari ,et al., "Neutronics for iter nuclear phase: Insights and lessons learnt from JET DT operation", Chengdu, 2025(in press).
[3]P. Barabaschi ,et al.,"Progress of ITER and its value for Fusion", Chengdu, 2025(in press).
[4]L. Zhang,etal., "Overall Progress for the Design and R&D of CN HCCB TBM Design and challenge for ITER Divertor Langmuir Probe", Chengdu, 2025(in press).
[5]X.H Wu, etal., "Preliminary engineering analysis for CN HCCB TBM regarding ITER new baseline scenario Poster", Chengdu, 2025(in press).
[6]Li Ruyan, Wang XiaoYu , Zhang Long ,et al., Development of Tritium Dynamic Transport Analysis Tool for Tritium Breeding Blanket System Using Modelica, Fusion Eng. Des. (2020) 112023.
[7]R.A. Causey, R.A. Karnesky, C. San Marchi, 4.16 - Tritium Barriers and Tritium Diffusion in Fusion Reactors, Comprehensive Nuclear Materials, (2012) 511-549.
[8]L. Sedano, Adolfo Perujo, Kevin John Douglas ,et al.The Deuterium Recombination and Dissociation Constants in MANET Derived from Plasma Implantation Experiments. EUR-OP (1997).
[9]Ying A, Zhang H, Merrill B, et al. Breeding Blanket System Design Implications on Tritium Transport and Permeation with High Tritium Ion Implantation: A MATLAB/Simulink, COMSOL Integrated Dynamic Tritium Transport Model for HCCR TBS. Fusion Eng Des. (2018) 1153-1160