# SIMULATION OF HEAT EXCHANGER TUBE RUPTURE EVENT FOR CN HCCB TBS

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**Abstract**

In accordance with local French legal requirements, it is required to submit a safety analysis report of the testing blanket system (TBS), detailing the safety design and potential radiological consequences before its installation into the International Thermonuclear Experiment Reactor (ITER). In this paper, the heat exchanger tube rupture event was simulated employing distinct break areas and fusion power stop mode. The results confirm the safety of the Chinese Helium Cooled Ceramic Breeder Test Blanket System (CN HCCB TBS) under the simulated scenarios, and support the modification of the operation scheme to use normal fusion power stop mode instead of Fusion Power Terminated System (FPTS).



## 1. INTRODUCTION

The current fusion technology route mostly adopts the deuterium-tritium fusion program, which requires a large amount of tritium to generate fusion power, which requires self-sustaining tritium fuel in the fusion reactor. The International Thermonuclear Experimental Reactor (ITER) program aims to explore the feasibility of magnetic confinement controlled fusion technology, and one of the most important goals is to test the tritium-breeding blankets to verify the feasibility of tritium self-sufficiency and the maturity of the associated technologies. At present, five basic blanket design concepts have been proposed [1]: helium-cooled solid breeder, helium-cooled liquid lithium-lead, water-cooled solid breeder, self-cooled liquid lithium-lead, and self-cooled molten salt. China has chosen the first two options for the development of its own experimental blanket technology, building on years of domestic research and the national strategic goal of advancing fusion energy [1]. Among them, the helium-cooled solid-state breeder (HCSB) experimental blanket has been chosen as the option for testing on ITER.

The safety of ITER as a nuclear facility is of paramount importance. According to the local French legal requirements, tritium-breeding blanket systems must be supported by safety analyses that demonstrate the robustness of their designs and assess potential radiological consequences prior to installation in the ITER device. Moreover, this analysis, and their conclusions, provide valuable references for the formulation of national laws, norms and standards for fusion reactors [2]. Currently, all ITER participants have conducted safety assessments covering a range of accidents, including a variety of ITER Design Basis Accidents (DBAs) and some Beyond Design Basis Accidents (BDBAs), involving multiple systems and components [3-8].

China's Helium-Cooled Ceramic Breeder Test Blanket System (CN HCCB TBS), as a key component of ITER, also requires accident analyses. In this paper, one representative design-basis accidents, the heat exchanger (HX) tube rupture accident, is selected for modelling and analysis, with the following objectives:

(1) To verify the reasonableness and safety of the CN HCCB TBS design, ensuring compliance with ITER acceptance criteria under accident conditions;

(2) To identify potential weaknesses in the design and propose improvements;

(3) To provide supporting data for subsequent studies

## 2. DESCRIPTIONS

### 2.1. CN HCCB TBS

The China Helium-Cooled Ceramic Breeder Test Blanket System (HCCB TBS) was developed by the team at the Southwestern Institute of Physics of China National Nuclear Corporation (CNNC). It will be installed in the ITER facility to verify the engineering feasibility of tritium production through the reaction of Li-6 and neutrons, as well as the efficiency of the helium coolant heat transfer.

The HCCB TBS system consists of several sub-systems: (1) the Test Blanket Modules (TBM-set), (2) the Helium Cooling System (HCS), (3) the Tritium Extraction System (TES), (4) the Coolant Purification System (CPS) and other ancillary systems. These sub-systems are arranged in different rooms within the ITER building and interconnected by pipelines. The general layout of the systems in the building is shown in Fig. 1. In the preliminary design phase, the main objects of accident analysis are the TBM-set and the HCS; therefore, these two subsystems will be emphasized.

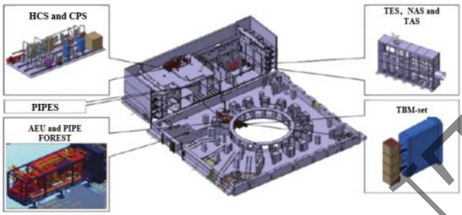
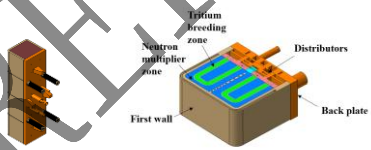



*Fig.1 General configuration of CN HCCB TBS in ITER facility[9]*

The blanket module is a fundamental element of the system, and is installed within the vacuum vessel of the ITER facility. The TBM-set comprises several sub-modules, and each integrating the first wall (FW), back plates, cavities, ribs, pebble-bed regions filled with beryllium pebbles and Li4SiO4 pebbles, and U-shaped cooling channels separating and cooling the pebble bed regions. The general layout and details of the TBM-set are depicted in Fig. 2.




*A TBM-set* *b sub-module*

*Fig.2 Layout and the internal structure of TBM sub-modules[10]*

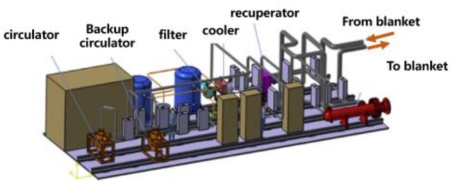



*Fig.3 General configuration of HCS[11]*

The Helium Cooling System (HCS) represents a crucial component of the Test Blanket System, responsible for heat transfer. A typical HCS developed by SWIP is shown in Fig. 2. It consists of various components, including a helium circulator, a heat exchanger, a filter, a recuperator, an electric heater, and other auxiliary equipment. The blanket module is connected to the HCS via the back plate. The operational pressure at the inlet of the HCS is 8MPa with a flow rate of 1.04 kg/s.

### 2.2. Heat Exchanger tube rupture event

The internal tube rupture event within the heat exchanger is a typical event in helium cooling circuits (HCS) [12]. It begins with a rupture or leakage in the cooling channel of the heat exchanger between the primary and secondary sides of the HCS. Subsequently, high-temperature and high-pressure coolant from the primary loop enters the secondary loop of the heat exchanger through the rupture, resulting in a rapid pressurization in the secondary loop, triggering a high-pressure signal. In this accident, the FW temperature, the mass flowrate via the break and the pressurization in the secondary loop should be monitored.

### 2.3. RELAP5/MOD3.4

In this article, the RELAP5 code was employed to perform one-dimensional simulations. The internal non-condensable gas (NCG) subroutine was used to designate helium as the working fluid, enabling the simulation of both steady-state and transient scenarios [13]. The Dittus-Boelter formular is adopted for single phase forced convection model under the scenarios where Re is greater than 1×104, which is appropriate for the HCS. The Trapp and Ransom Model was adopted for the simulation of a choked flow of nonequilibrium two-phase coolant, with the water phase fraction set to zero to represent the helium cooling circuit. In the past decades, scholars have conducted research on MELCOR code and RELAP5 code, finding that discrepancies in simulating LOCA scenarios are negligible[14].

## 3. MODELS AND ASSUMPTIONS

### 3.1. HCS MODEL

For the main pipeline and branch pipeline of the circuit, this paper adopted the pipe module for modelling, and its parameters are assigned according to the actual design. For the internal pipeline of the TBM, due to the complexity and variability of its internal flow path, simplifications were applied.

Considering the main structure of TBM targeted in the actual analysis, in this paper, the TBM was divided into the first wall, multiple rear plates, fascia boards, upper and lower covers and other structures in the modelling. Pipelines were integrated within these structures. The circulation area was represented by the sum of the overall cross-sectional area, ensuring that flow rate, pressure drop and temperature variations were preserved. The circulation length was determined as the actual circulation length of the TBM. The TBM thermal components are established in accordance with the actual position and the left and right boundaries. The TBM thermal components were defined according to their actual positions and boundary conditions, and their lengths, thicknesses and materials were determined according to the actual design.

The HCS is designed as a loop with ‘figure-eight’ configuration, and the cold leg and hot led is connected for heat transfer via a recuperator. The main equipment of the HCS includes recuperator, heat exchangers, electric heaters, the main fan of the circuit, the pressure control system, safety isolation valves and associated pressure, temperature and flow measurement control systems. The components are categorized into (safety importance component) SIC grade and (safety related) SR grade according to the safety function the component executes. In this article, in order to obtain conservative results, only the SIC class components, such as the isolation valves, are modelled, and other components, such as the electric heater and the pressure control systems, are ignored. The external connecting pipes of the HCS are modelled and arranged according to the realistic configuration, and the length, cross-sectional area, resistance coefficient, wall roughness and angles are consistent to the design.

The RELAP5 nodes of the HCS are shown in Fig. 5. Among them, the upper M1, FW, CAP, RIB, etc. indicate the internal structure of the TBM, namely the back plate, first wall (FW), cover plate, and fascia plate. Nodes 14 and 6 indicate the structure of the return heaters, 16 and 102 indicate the structure of the heat exchangers, 2 indicates the main fan of the HCS circuit, 082, 088 and 085 are the safety isolation valves, and node 21 indicates the HCS voltage regulator. To meet the requirement that the TBM waste heat can be exported by radiative heat transfer under the accidental working condition, several vacuum chamber components were built inside the vacuum chamber to export waste heat from the TBM, as shown in Fig. 4. At present, 6 groups of thermal radiation model are added, which are the thermal radiation model between the TBM and the upper/lower/left/

right in-vessel components, the vacuum chamber and the shielding respectively. The thermal radiation model between 4 TBM sub-modules are neglected due to similar temperature [5].

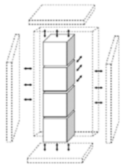


*Fig.4 Thermal radiation model for TBM in-vacuum-vessel[5]*

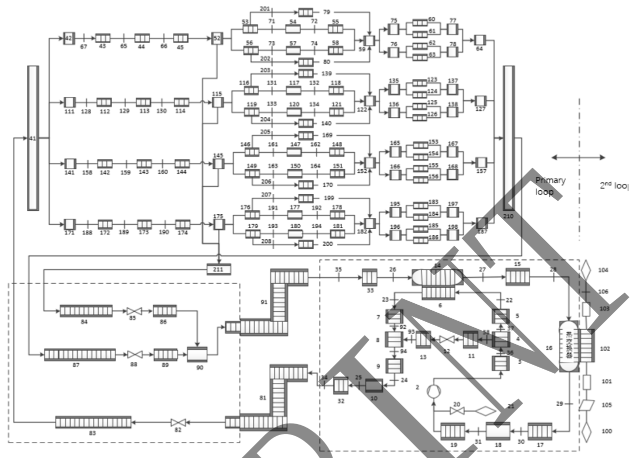



*Fig.5 Node diagram of HCS primary loop[15]*



Based on the preliminary design scheme of ITER component cooling water system (CCWS), a complete secondary loop model was established in this study, including the branch for transferring the heat from the HCS as well as the set of branches for the rest of the cladding loops, as shown in Fig. 6. Among them, P228 represents the secondary side of the HCS heat exchanger, P251 and P252 are the inlet sections separated by two-loop isolation valves, and P253 and P254 are the outlet sections, with an additional isolation valve installed.

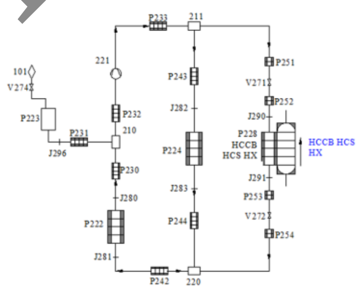



*Fig.6 Node diagram of HCS secondary loop[15]*

According to the system modelling scheme, the calculated values of key parameters under full power operation of the helium cooling system are presented in Table 1. By comparison, the calculated values are very close to the design values, confirming the validity of the system model.

Table 1 Key parameters under full power steady-state

| Parameters | Design value | Calculated value |
|---|---|---|
| Pressure at blanket inlet/MPa | 8.0 | 8.06 |

| | | |
|---|---|---|
| Main flow rate/（kg·s-1） | 1.04 | 1.04 |
| Coolant temperature at blanket inlet/°C | 300 | 298.1 |
| Coolant temperature at blanket outlet/°C | 550 | 548.4 |
| Water temperature at secondary loop inlet/°C | 30.0 | 30.4 |
| Helium temperature at HX inlet | 210 | 205.6 |

### 3.2. Assumptions and acceptance criteria

For the simulation of a heat exchanger rupture accident, with reference to the guidelines for accident analysis of blanket systems proposed by ITER [12], the following assumptions are formulated in this paper:

(1) Initial conditions: Prior to the accident, the loop operate at full power, with parameters consistent with design values. Considering the plasma power drift, it is assumed that the heat flux density and neutron nucleation heat applied to the first wall increases by 20% starting 10s before the accident and continues until the plasma rupture.

(2) Safety control logic: When the pressure of the second circuit exceeds 1.8 MPa, the high-pressure signal of the second circuit is triggered, leading to fusion power termination and closure of the isolation valves in 2nd circuit. When the pressure of the first circuit falls below 6 MPa, a low-pressure signal of the first circuit is triggered, resulting in the first-circuit fan stopping and the isolation valve being closed.

(3) Fusion power termination modes: Three termination modes are considered.

In the fast fusion power stop mode (NFPS) and normal fusion power stop mode (NFPS), the plasma pulse is interrupted, allowing the plasma control system (PCS) to execute a termination sequence, determined by the PCS. The heat load on FW is assumed to decrease linearly to zero in 2 s (FFPS) or 10 s (NFPS).

In the safety fusion power stop mode (SFPS), the Fusion Power Termination System (FPTS) will operate, resulting in a major disruption of plasma. At the same time the first wall heat flux density is raised to 5.52 (MW-m-2) and held for 0.1 s, then reduced to 0.72 (MW-m-2) and sustained for 0.9 s, and finally drops to zero.

All three modes mentioned above will be triggered by the 1st loop low-pressure signal or the 2nd loop high-pressure signal, and a 3s delay time is considered conservatively.

(4) Isolation valves response: Signal transmission time is assumed to be 2 s and the operation time is 3s, that means the isolation valves are completely closed 5 s after the signal is triggered.

(5) Decay heat: Decay heat of each material of the TBM module is calculated by neutronics [16].

Since fusion reactor safety is still under research and no consistent safety acceptance guidelines have been agreed upon. For heat exchanger tube rupture accidents, ITER has developed the following general acceptance guidelines [12], which will be continuously refined based on materials, design improvements, etc:

(1) Blanket structural material temperature must not exceed the design temperature for a long period of time to ensure the integrity of the blanket structure.

(2) Consequence of radioactive release must remain within acceptable limits.

(3) The pressure of the second circuit must not exceed the design limit.

With these assumptions, the general accident sequence could be obtained and is displayed below.

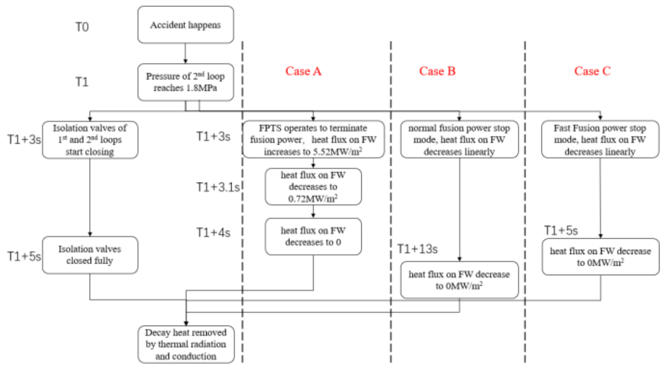



*Fig.7 General accident sequence*

4. RESULTS

### 4.1. LOCAs in Case A

In this section, the 1% section area small break LOCA and the double ended guillotine LOCA were simulated under the assumptions for Case A.

The discharge velocity of helium coolant at the leak location is presented in Fig. 8, categorized according to the magnitude of the leak as either large or small. In the small breach accident scenario, following the occurrence of the accident, helium coolant flows from the primary circuit to the secondary circuit at a rate of approximately 0.2 (kg·s$^{-1}$) via the rupture, with this discharge persisting for approximately 20 seconds. It is assumed that, in the event of a small breach accident, the primary circuit fan and isolation valve are not immediately shut down, as they are triggered only by a low-pressure signal from the primary circuit. As a result, the primary circuit fan continues to operate and the isolation valve remains open. Consequently, after the closure of the secondary loop isolation valve, the pressure on the secondary side of the heat exchanger undergoes an increase, reaching approximately 7 MPa after approximately 20 seconds (Fig. 10). At this stage, due to the secondary side pressure being higher than the primary side pressure, the helium-water two-phase mixture flows back into the primary side from the secondary side, as demonstrated in Fig.7. In the event of a major leak accident, the discharge rate of helium coolant is substantially higher and subject to considerable fluctuations. This is due to the large-scale outflow of helium, which causes substantial fluctuations in secondary-side pressure (Fig. 11), strongly affecting the discharge flow rate. As the primary circuit isolation valve closes (at approximately 6.5 seconds), the helium discharge flow rate decreases rapidly, and the discharge process ceases at approximately 10 seconds.

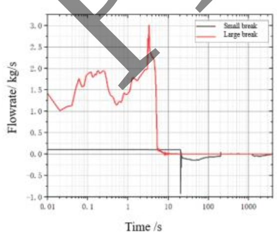



*Fig. 8 mass flowrate via break*

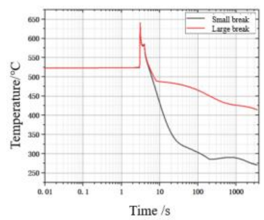



*Fig. 9 FW temperature*

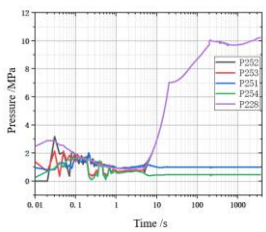



*Fig.10 Pressurization in secondary loop in SB accident*

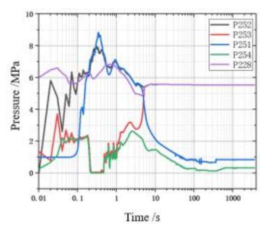



*Fig.11 Pressurization in secondary loop in LB accident*

As illustrated in Fig.9, the temperature of the first wall material (the plasma-facing portion of the blanket) varies under accident conditions. During the initial stages of both accident conditions, the temperature trends of the first wall material were consistent, with similar peak values. This is because, in both cases, the FPTS was triggered by high-pressure signals from the secondary circuit at nearly same time, resulting in consistent peak temperatures and initial temperature trends. In the large breach accident, the wall temperature decreases rapidly at first, followed by a slower decline. This is attributable to the closure of the primary loop isolation valve at 6.5 s, which led to the primary wall being cooled exclusively by thermal radiation, thereby reducing the overall cooling capacity. In the small breach condition, the rate of temperature decrease slowed at approximately 200 s, when the primary loop fan was manually shutdown. At that point, coolant circulation transitioned from forced to natural circulation, thereby reducing the cooling capacity. The maximum temperature recorded for the first wall reached 641.3 °C, briefly exceeding the design limit of 550 °C. However, experimental studies conducted at the Southwest Institute of Physics demonstrated that the blanket structural material can withstand temperature above 650°C for more than 30 h while maintaining a stable microstructure and favorable mechanical properties. Consequently, it can be deduced that the first wall material temperature remains within the permissible range, the first wall structure will not be damaged, and the integrity of the radioactive containment function remains intact [17][18].

## 4.2. LOCAs in Case A/B/C

In this section, LOCAs in case A, B and C scenarios were simulated to investigate the influence of different fusion power stop modes on the FW temperature, which is critical for maintaining blanket integrity.
As depicted in Fig. 12, the FW temperature varies across the three cases due to the distinct termination modes. In case A, the Safety Fusion Power Stop (SFPS) mode is adopted, employing the FPTS to terminate the burning plasma. It results in the major plasma disruption leading to a dramatic increment of FW heat load aforementioned. In case B and case C, the Fast Fusion Power Stop Mode (FFPS) and the Normal Fusion Power Stop Mode (NFPS) are applied, respectively. In both cases, the combined effect of helium spray and the gradual reduction in heat load cause the FW temperature to decreases smoothly, indicating that integrity of the blanket can be ensured.

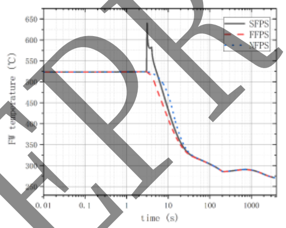



*Fig.12 FW discrepancy in Case A/B/C*



## 5. CONCLUSIONS

This study is based on the preliminary design scheme of CN HCCB TBS, with the RELAP5/MOD3.4 program employed to model and analyse heat exchanger tube rupture accidents. The main findings are as follows:

(1) The overheating duration of the blanket structure material is relatively brief, with a maximum temperature of approximately 641.3°C. Therefore, the structural integrity of the cladding is not compromised.

(2) During the early phase of a large-break accident, significant pressure fluctuations occur in the secondary pipes of the heat exchanger. However, during the later stages of a small-break accident, the secondary-side pressure becomes higher because the isolation valve between the primary and secondary loops remains open. This allows continuous heat and mass transfer between the loops, leading to pressure buildup.

(3) In case B and C, which adopt the Fast Fusion Power Stop (FFPS) and the Normal Fusion Power Stop (NFPS) modes, respectively, the FW temperature decreases smoothly, ensuring that blanket integrity is maintained.

Looking ahead, the CN HCCB TBS design team will apply coupled computational methods to calculate the three-dimensional flow field and temperature field inside the heat exchanger. This will enable a more comprehensive safety evaluation of the CN HCCB TBS and provide a stronger basis for the future design of the heat exchanger and the system.

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