Transient Safety Study of Chinese Helium Cooled Solid Breeder Test Blanket Module for ITER

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Abstract

This paper introduces the transient accidents analysis for Chinese Helium Cooled Solid Breeder Test Blanket Module (CN-HCSB TBM) and its cooling system using RELAP5 code. The sub-modules bypass is used to control the first wall (FW) coolant temperature increase. The In-Vessel Loss of Coolant Accident (LOCA) results indicate that the induced over-pressurization of the vacuum vessel is within the ITER design limit pressure 200kPa. The Ex-Vessel LOCA will induce the melting of FW beryllium armor after 86s of this LOCA beginning. The In-Box LOCA will induce the pressure increase of the purge gas to about 7.3MPa within one second. Installing the fast isolation valve for tritium extraction system (TES) and pressure relief valve to TBM box are very important. The maximum temperature of FW beryllium armor induced by Loss of Flow Accident reaches 764^{o}C and the final pressure of vacuum vessel is 28kPa. The Loss of Heat Sink accident induces the FW beryllium armor maximum temperature of 877^{o}C, and then the armor temperature decreases. The coolant water of heat exchanger (HX) secondary side begins to evaporate after 415s accident beginning.

1. Introduction

The Test Blanket Module (TBM) is used to test the technological feasibility of breeding blankets for future fusion reactor on the International Thermonuclear Experimental Reactor (ITER). Its corresponding thermohydraulics design and transient safety analysis are the inevitable work for insuring the safe operation of TBM and ITER [1-3]. These studies have been carried out in all of the ITER Parties. The European Union performed the thermohydraulics analysis using ANSYS and the transient accident analysis using RELAP5 and ANSYS codes together [4-7]. This is a good method because the RELAP5 code can give the systematic information and the ANSYS can give the relatively accurate local materials temperature. Moreover, South Korea also did the transient accident analysis using RELAP5 code [8]. For the Chinese Helium Cooled Solid Breeder Test Blanket Module (CN-HCSB TBM), the preliminary transient accident analysis has been carried out since 2005 using RELAP5 code [9]. In 2007, the design of TBM first wall (FW) coolant pipe dimension was changed. In this paper, we develop a RELAP5 model for the 2007 version of the CN-HCSB TBM and its cooling system to calculate the thermal-hydraulic situation of the cooling loop for steady-state and accidents conditions. Five postulated initiating events are analyzed, and these are the In-Vessel loss of coolant accident (LOCA), Ex-Vessel LOCA, In-Box LOCA, Loss of Flow Accident (LOFA) and Loss of Heat Sink (LOHS). The three kinds of LOCAs have been analyzed in the previous paper for the old FW design [9], and in this paper, these LOCAs are also analyzed for the new FW design.

2. System Description and Heat Source

The CN-HCSB TBM will be installed in one half of an ITER test port. The TBM is contained in an insulation frame and this frame provides a standardized interface with the ITER vacuum vessel and thermal isolation from the basic machine. The CN-HCSB TBM is 1.66m×0.67m ×0.484m (poloidal×radial×toroidal), and includes the FW, sub-modules, caps, grids, manifold, purge gas pipes, back plate and support plate. The FW is made up of 29 cooling pipes, and the plasma facing FW is covered with a 2mm beryllium. The plasma facing FW area is 0.803m^2. There are 12 sub-modules and they are arranged as 2×6 structure. The TBM inlet/outlet temperatures are 300^{o}C/500^{o}C, respectively. The tritium breeding material is Li_4SiO_4 and the neutron multiplier is beryllium. A Reduced Activation Ferritic-Martensitic Steel CLF-1 (Chinese Low Activation Ferritic/martensitic) is used as the structural material, and its limit operational temperature is 550 ^{o}C. The helium coolant flows through the following path: firstly it flows into the FW, and then flows into the sub-modules, caps and grids in parallel. The tritium extraction system (TES) is used to extract the tritium from Li_4SiO_4 pebble bed through 0.1MPa helium purge gas [10]. The CN-HCSB TBM is used to test the tritium production rate, nuclear energy production rate and check the analysis codes and data for fusion reactor breeding blanket analysis.

The CN-HCSB-TBM Cooling System includes the primary side helium cooling system and the secondary side water-coolant Heat Rejection Systems (HRS) furnished by ITER. The helium cooling system is made up of pump, heat exchanger (HX), pressuriser, dust filter, cold and hot legs, etc. The ITER water cooling system supplies the heat sink to the primary cooling system and the inlet/outlet water temperature are 35 ^{o}C/75 ^{o}C, respectively. The cooling system RELAP5 model is shown in Figure1. The HX is modeled with two pipes to simulate the primary and secondary sides. The pressuriser is connected to the hot leg. The volume is 250m^3, pressure is 7.7MPa and the temperature is 500 ^{o}C for steady state operation. The pressuriser will be opened when the HX inlet pressure is greater than 1MPa.

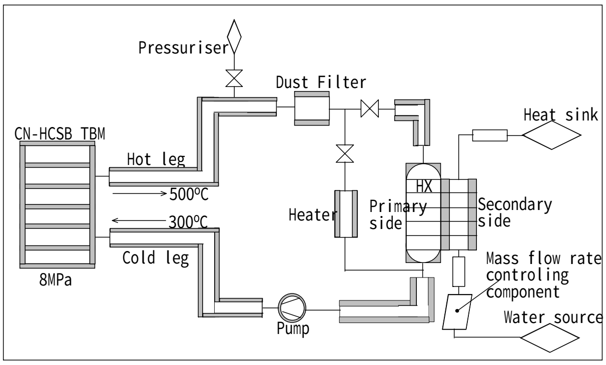

FIG. 1. RELAP5 nodalisation of TBM Cooling System.

The nuclear and decay powers in the TBM have been calculated [11-12]. In this analysis, 3D MCNP nuclear power results have been used. The neutronics calculation is performed for normal operation at 0.78 MW/m^2 neutron wall load for the NT-TBM, which is a neutronics testing TBM operated during the D-D phase and possibly the very beginning of the low duty cycle D-T phases. The total TBM nuclear power is 0.593MW. The decay heat is calculated by FDKR code. The total shutdown afterheat and one hour afterheat are 2.09×10^{-2}MW and 1.96×10^{-2}MW, respectively. The surface heat flux is 0.3 and 0.5MW/m^2 in ITER normal and extreme operation state. The FW heat flux will be 1.8MJ/m^2 within one second when the plasma is disrupted [13]. Table I shows the energy sources results for the NT-TBM.

TABLE I: ENERGY SOURCES IN THE CN-HCSB TBM.

Sources items	**Energy Deposition**
FW heat flux (normal/extreme)	0.3/0.5MW/m^2
Plasma disruption FW heat flux	1.8 MW/m^2 (ave. within 1s)
Nuclear heating	0.593MW
Shutdown afterheat	2.09×10^{-2}MW
1 hour afterheat	1.96×10^{-2}MW

3. Results and Analysis

3.1. Steady State Analysis

Because of the FW structural material temperature limit, the FW coolant temperature increase has to be controlled. At the same time, the sub-modules bypass, which is a bypass between FW and hot leg paralleling to the sub-modules for the distribution of redundant coolant from FW, has to be used to control the sub-modules coolant temperature increase. The RELAP5 PUMP control component and VALVE control component are used to control the FW and sub-modules coolant mass flow rates, respectively. With the controlled mass flow rates, the FW and sub-modules coolant temperature increase are controlled.

When the FW coolant temperature increases are 40^{o}C and 60^{o}C (FW inlet coolant temperatures are both 300^{o}C), the FW structural material maximum temperatures are 487^{o}C and 544^{o}C, respectively at the FW heat flux of 0.5MW/m^2 (ITER extreme operation). Because the FW structural material maximum temperature has relatively larger margin for 40℃ FW coolant temperature increase, this design is chosen for the current transient calculation. In this situation, the FW and sub-modules coolant mass flow rate are 1.9kg/sec and 0.5kg/sec, respectively.

With the 40^{o}C FW coolant temperature increase and at the FW heat flux 0.3MW/m^2 (ITER normal operation), the FW structural material maximum temperature is 449 ^{o}C, having 101^{o}C margin comparing the limit temperature 550^{o}C. The FW beryllium armor, beryllium pebble bed and Li_4SiO_4 pebble bed maximum temperatures are 456 ^{o}C, 522 ^{o}C and 712 ^{o}C, respectively. Figure 2 shows the coolant temperature results at CN-HCSB TBM steady state operation. The obtained temperatures at TBM inlet/outlet are approximately to be the designed 300^{o}C/500^{o}C. The pressure drops are about 0.09MPa in the FW, about 0.00372MPa in the sub-modules, and 0.12MPa in the whole TBM. The flow velocities of coolant in the FW and sub-modules are about 51m/sec and 9m/sec, respectively.

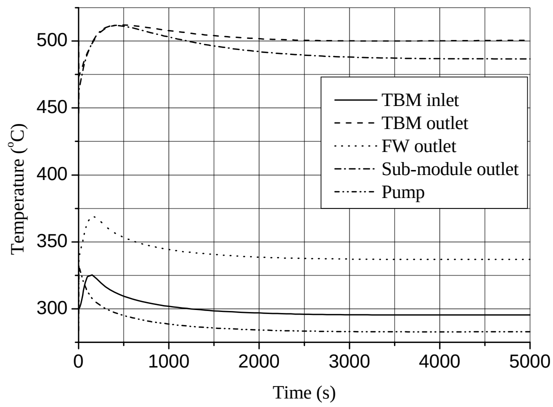

FIG. 2. Helium Temperature of Steady State.

3.2. In-Vessel LOCA

This postulated event assumes a rupture of the FW cooling pipes, and the primary side coolant leaks directly into the vacuum vessel and the plasma is inherently shutdown by the ingress of coolant. Because of the quenching of plasma, the FW is deposited with 1.8MJ/m^2 heat flux within one second. Then the production of neutron is stopped, and the TBM heat source mainly comes from the decay of radioactive isotopes. The area of broken pipes is 0.00084m^2. This LOCA is simulated for 69 seconds.

Figures 3 and Figure 4 show the results of materials temperature and helium pressure in vacuum vessel. The temperature of FW beryllium armor increases from 456 °C to 531 °C within 1.5s because of the large FW heat flux induced by plasma quenching, and then the armor temperature decreases. The Li_4SiO_4 and beryllium pebble bed materials temperature decreases when this LOCA happens. This means that the heat of the TBM can be removed passively. The 1350m^3 ITER vacuum vessel (VV) is pressurized to the small value of about 26kPa, which is much less than the ITER VV pressure design limit of 200kPa.

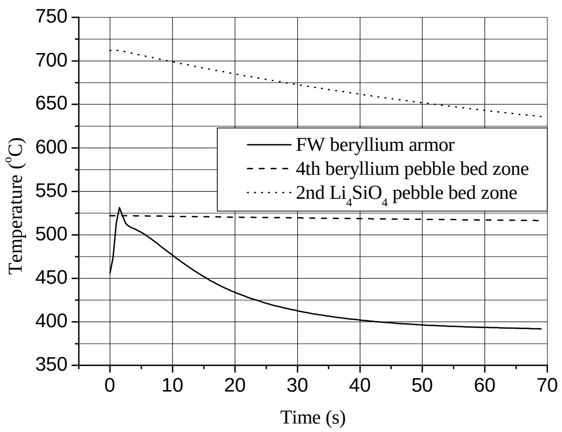

FIG. 3. Materials Temperature for In-VV LOCA.

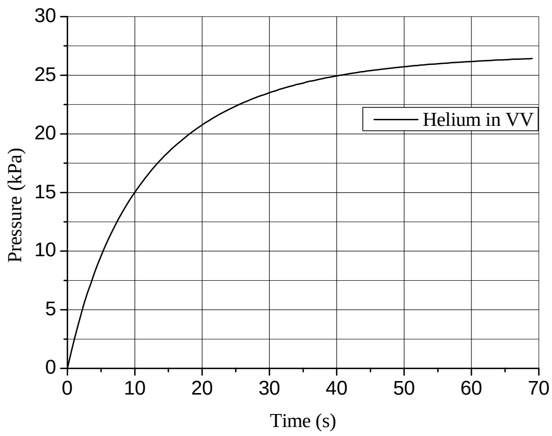

FIG. 4. Helium Pressure in VV for In-Vessel LOCA.

3.3. Ex-Vessel LOCA

This postulated event assumes that the helium cooling system hot leg is broken, and the coolant erupts out of the loop and leaks into the ITER TCWS vault. The fusion plasma will not quench and it produces neutron continually based on the assumption of the Fusion Power

Termination System failure. Finally, the temperature of FW beryllium armor increases until melting. The area of broken pipe is 0.0314m^2. In this analysis, an ultimate passive shutdown has been assumed to occur when the melting point of the FW beryllium armor is reached at 1290 ^{o}C. The over-pressurization of TCWS vault is assumed insignificant because of its large volume.

Figure 5 shows the results of materials temperature. It's obvious that the FW beryllium armor will melt at 86 seconds after this LOCA initiation and the pebble bed materials temperature also increase. Some passive or active measures have to be taken to shut down the plasma before the beryllium armor melting.

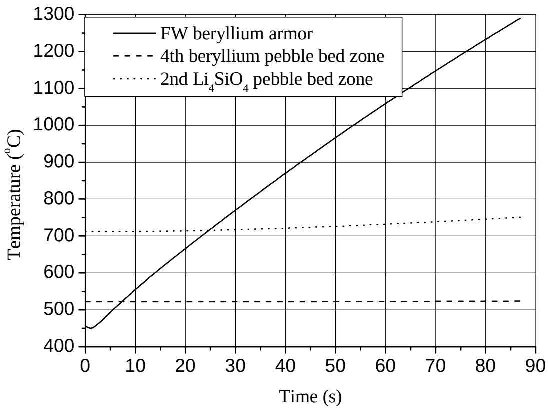

FIG. 5. Materials Temperature for Ex-Vessel LOCA.

3.4. In-Box LOCA

This event postulates that the cooling pipes of the sub-module are broken, and the helium leaks into the purge gas (PG) loop of TES, which has an operational pressure of 0.1MPa. A pressure relief valve is mounted between the TBM box and VV and it is opened if the PG pressure is higher than 1MPa. After the opening of pressure relief valve, the helium will leaks into the VV and the plasma is quenched with a 1.8MJ/m^2 heat flux on FW within one second. Then the supply of neutron energy is stopped. The inlet of TES is mounted with a fast isolation valve which will be closed when the PG pressure is higher than 0.2MPa. This accident is simulated for 8 minutes.

Figure 6 and Figure 7 show the pressure results of PG/TBM inlet coolant and materials temperature. This accident will lead to over-pressurization of the PG pipes to the pressure of 7.3MPa within one second, and so the helium leaks into the VV through the pressure relief valve. The plasma is quenched and the VV is pressurized to 43kPa after 8 minutes. At the same time, the TES inlet fast isolation valve is closed because of the over-pressurization of the PG system.

The maximum temperature of FW beryllium armor increases to 526 ^{o}C within 1.5 seconds due to the large FW heat flux induced by plasma quenching. Then the beryllium armor temperature decreases because of the end of plasma quench process and the decrease of the coolant pressure. The materials temperature of sub-modules pebble beds decrease at the course of this LOCA.

For this accident, the pressurization of TES is very critical and the TES fast isolation from TBM has to be done quickly, or the 0.1MPa PG loop will be over-pressurized.

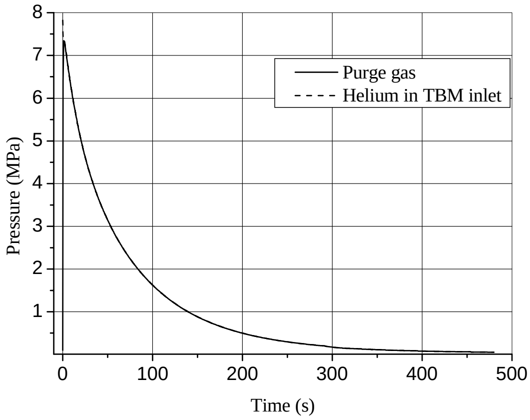

FIG. 6. Helium Pressure of PG and TBM inlet for In-Box LOCA.

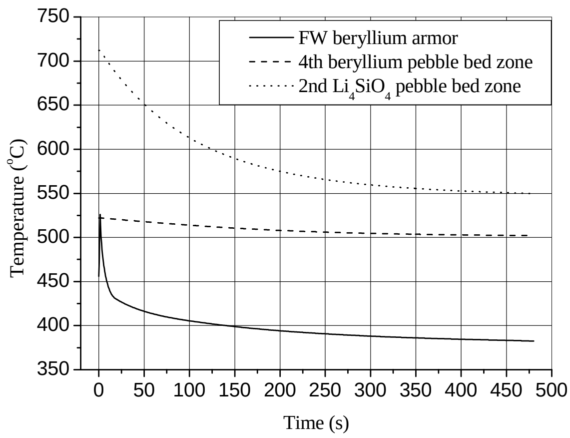

FIG. 7. Materials Temperature for In-Box LOCA..

3.5. Loss of Flow Accident

The Loss of Flow Accident (LOFA) postulates that the electrical power of the pump is lost, and the pump is coast down. The coolant mass flow rate decreases quickly. The plasma will not quench and nuclear heat is continually deposited on the FW. The beryllium armor temperature increases. The In-Vessel LOCA is assumed continually happened when the beryllium armor temperature reaches to 700 ^{o}C, and then the plasma is quenched and 1.8MJ/m^2 heat flux is deposited on the FW within one second. The accident is simulated for 95s.

The pump slows down to half speed in about 2 seconds. The system mass flow rate decreases to about zero after 20 seconds of LOFA happening. Then after 27.5 seconds, the FW beryllium armor temperature reaches to 700 ^{o}C and the In-Vessel LOCA is assumed happened continually. The maximum temperature of FW beryllium armor reaches to 764 ^{o}C after the In-Vessel LOCA happens. The temperature of pebble beds materials has a slight increase before the In-Vessel LOCA and then decreases after the In-Vessel LOCA happens. The VV is over-pressurized because of the continued In-Vessel LOCA. The final pressure of vacuum vessel is 28kPa, and has a large margin comparing the ITER vacuum vessel design limit pressure 200kPa.

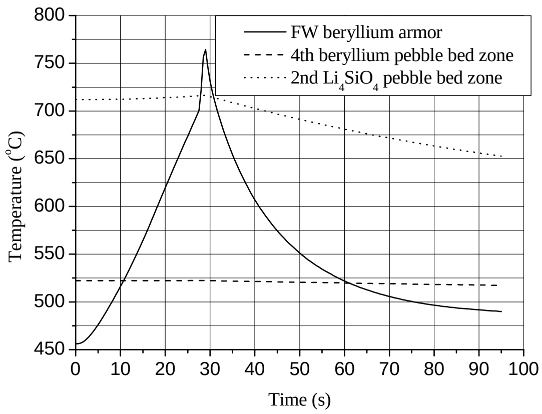

FIG. 8. Materials Temperature for LOFA.

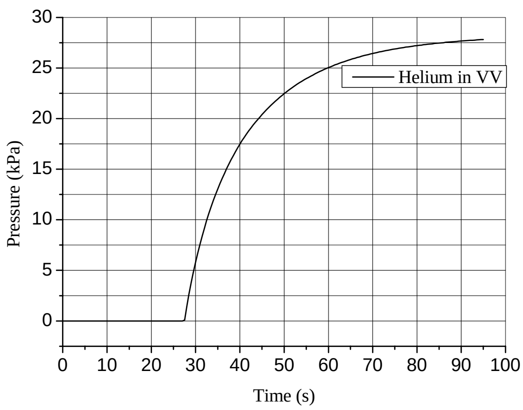

FIG. 9. Helium Pressure in VV for LOFA.

3.6. Loss of Heat Sink Accident

Loss of Heat Sink accident is characterized by a total loss of flow on the HX secondary side, which will be probably caused by inadvertent valve closures in secondary loop. The stagnant water in the HX on the secondary side will heat up in the course of the transient, and the normal plasma shutdown happens after 1s delay (which is defined as a coast down of FW heat flux and nuclear heat from normal value to zero and the decay heat value within 100s). The pump is also coast down at the beginning of this accident.

The LOHS induces the FW beryllium armor maximum temperature of 877 ^{o}C within 90 seconds because of the normal plasma shutdown process, and then the armor temperature decreases. The pebble beds temperature increases continually at the end of this accident. The coolant water of HX secondary side begins to evaporate after 415s accident beginning when it reaches its saturation temperature of 180 ^{o}C. Because of the large time scale of LOHS, the system has enough time to shutdown the plasma operation.

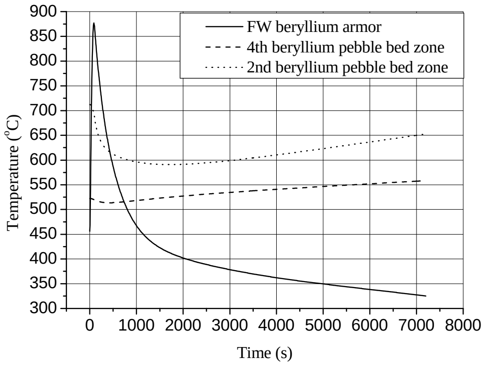

FIG. 10. Materials Temperature for LOHS.

4. Summary

Two kinds of steady state situations are analyzed for the CN-HCSB TBM and the sub-modules bypass is used to control the FW coolant temperature increase. In the case of 40^{o}C FW coolant temperature increase, the FW mass flow rate is 1.9kg/sec, and the FW structural material maximum temperature is 449 ^{o}C, having a larger margin to the limit temperature 550 ^{o}C. The pressure drops in the FW, sub-modules, and the whole TBM are 0.09MPa, 0.00372MPa and 0.12MPa, respectively. The flow velocities of coolant in the FW and sub-modules are about 51m/sec and 9m/sec, respectively.

The results for In-Vessel LOCA reveal that the FW beryllium armor has a peak temperature of 531 ^{o}C within 1.5 seconds because of the plasma quench. The pebble beds temperature decreases when this LOCA happens and the over-pressurization of VV is well within the allowable value of ITER design. The results for Ex-Vessel LOCA without plasma termination reveal that the FW beryllium armor will melt after 86 seconds LOCA initiation. The plasma has to be shut down before the beryllium armor melting. For In-Box LOCA, the PG is pressurized to 7.3MPa within one second and the helium is leaked into the VV and the plasma is quenched. The FW beryllium armor temperature increases to 526 ^{o}C within 1.5 seconds and then this temperature decreases. In order to avoid the damage of the TES, it has to be isolated from the TBM just after this LOCA beginning. When the LOFA happens, the In-Vessel LOCA is assumed continually happens when the FW beryllium armor temperature reaching to 700 ^{o}C. The FW beryllium armor maximum temperature is 764 ^{o}C and VV is pressurized to 28kPa at the end of the LOFA, which is well within the ITER VV pressure limit. The LOHS will induce the FW beryllium armor maximum temperature 877 ^{o}C and the secondary side coolant water evaporation after 415 seconds. Because of the large time scale, the system would have enough time to shutdown the plasma operation.

The further analysis for ITER pulse operation scenarios is ongoing.

Acknowledgement

This report was prepared as an account of work by or for the ITER Organization. The Members of the Organization are the People's Republic of China, the European Atomic Energy Community, the Republic of India, Japan, the Republic of Korea, the Russian Federation, and the United States of America. The views and opinions expressed herein do not necessarily reflect those of the Members or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the ITER Joint Implementation Agreement.

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