Preliminary Safety Analysis for the Chinese ITER Dual-Functional Lithium-Lead Test Blanket Module

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Abstract. Safety analysis is a part of the ITER Test Blanket Module (TBM) design process to ensure that the TBM does not adversely affect the safety of ITER. To get the license for TBM as a whole with International Thermonuclear Experimental Reactor (ITER), the relevant safety analysis is required for each TBM system proposed by each party. The safety analysis for the Chinese Dual-Functional Lithium-Lead Test Blanket Module (DFLL-TBM) has been performed based on the latest DFLL-TBM design. In this paper, the following safety considerations, such as source terms, operational releases, accident sequence analyses and waste assessment, have been analyzed. Both deterministic approach and complementary systematic approach starting with FMEA (Failure Mode and Effects Analysis) studies have been adopted in the accidental analysis. The preliminary results show that the DFLL-TBM system at normal operating conditions and under accident scenarios does not add additional safety hazards to ITER machine and can meet the ITER safety requirement and additional safety requirements for TBM system.

Keywords: DFLL-TBM; Safety analysis; Source term; Accident sequence

1 Introduction

It is one of the missions of International Thermonuclear Experimental Reactor (ITER) to act as test bed for various breeder blanket test modules to explore their potential for a demonstration reactor. A Dual Functional Lithium Lead (DFLL) Test Blanket Module (TBM) [1-2] concept has been proposed in China for testing in ITER to demonstrate the relevant technologies of the Chinese series FDS liquid lithium-lead (LiPb) breeder blanket concepts for fusion power reactors [3-6]. The design of DFLL-TBM concept, with emphasis on the balance between the risk and the potential attractiveness of blanket technology development, is flexible to test both He-cooled quasi-Static Lithium Lead (SLL) blanket concept and the He/LiPb Dual-cooled Lithium Lead (DLL) blanket concept.

The TBM is subjected to special safety requirements and shall not compromise the safety objectives, principles, requirements and guidelines of ITER. Safety considerations are part of the design process to ensure that the TBM does not adversely affect the safety of ITER. For licensing of ITER construction, the preliminary safety analysis report (RPrS) for DFLL-TBM system is required.

The safety analysis of the DFLL-TBM has been performed based on the latest DFLL-TBM design, which has been updated according to the design requirements of ITER. To get the license for DFLL-TBM as a whole with ITER, the relevant safety analysis has to be consistent with the system safety analysis as presented in ITER safety analysis report and further safety analysis defined also to answer to French Nuclear Safety Authority (NSA) requests.

In this paper, the general description of DFLL-TBM system has been presented. The safety-related source terms, operational releases, accident sequence analyses and waste assessment have been analyzed. Both deterministic approach and complementary systematic approach starting with FMEA studies have been adopted in the accidental analysis. An assessment of waste arising during operations and decommissioning has been made to investigate the feasibility of recycling and clearance for the materials in the DFLL-TBM.

2 DFLL-TBM System Description

The design of DFLL-TBM, based on the common architecture that was developed for DEMO blankets [3-6], is planed to be tested in one vertical half of a designated test port of ITER. The DFLL-TBM consists of a $484 \times 1660 \times 585$ mm^3 rectangular steel box with a faceted first wall (FW) designed to match the surface of the ITER shielding blanket. A 3D view of the structure design with LiPb flow for DFLL-TBM is shown in FIG.1. The box is reinforced by one radial-poloidal and four '˥' shape toroidal-poloidal stiffening plates, containing the LiPb flow channels. It is closed in the rear by the back plates also acting as helium manifold. The structure material is made of China Low Activation Martensitic steel (CLAM)[7], and the FW is plated with 2mm thick beryllium armor.

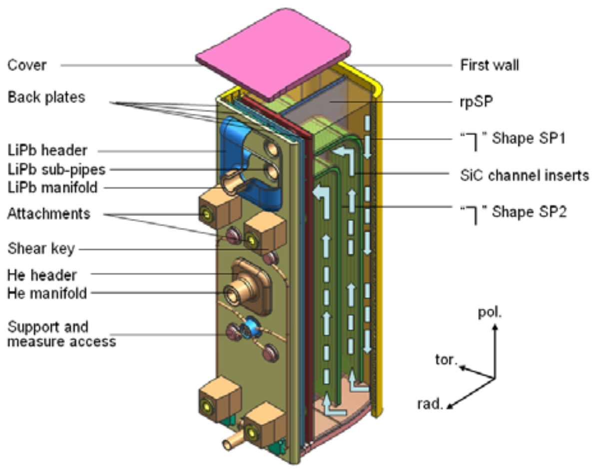

FIG.1 3D Structure View of the DFLL-TBM

The TBM FW and structure are cooled by 8MPa helium, which enters the module at 340 °C and leaves the module at 402 °C. The helium is delivered to the TBM by outer annular channel of the concentric pipe at the back of the TBM and flows out of the module through the inner one. Once outside of the TBM, the helium directly goes to the ITER tokamak cooling system (TCWS) through the pipes to exchange heat with water.

The LiPb enters the module at the top from the outer annular channel of the concentric pipe at 480 °C, and leaves the module through the inner channel. A lower exit temperature of ~480 °C under velocity of ~1mm/s of LiPb flow and a higher exit temperature of ~700 °C under LiPb velocity of ~100mm/s are designed to feature the dual functions of DFLL-TBM. A bypass loop is adopted to allow the hot LiPb from the TBM to be mixed with the cold LiPb, resulting in only a lower temperature LiPb going to the tritium extraction system (TES) and the heat exchange system (HES).

The detailed design on TBM and He/LiPb auxiliary systems can be found in Ref.[1-2].

3 Source Terms

3.1 Tritium

The nuclear design requirements for ITER are determined from the operational phases that are envisioned. The entire operation phase will last about twenty years and will involve a few thousand hours of D-T operation with the tritium supplied from external sources. The tritium production calculations in the DFLL-TBM have been performed with the Monte Carlo code MCNP/4C [8] and the nuclear cross-section data library FENDL-2.1 [9] based on the ITER neutronics model “FDS-Brand20”.

The local TBR and tritium production with natural and enriched LiPb are calculated. The daily tritium production is ~19.81mg/FPD and 56.46 mg/FPD in the DFLL-TBM at natural and 90% Li-6 enrichment, respectively. The corresponding daily tritium production at typical duty factor ~22% (burn time ~400s and repetition time ~1800s) is 4.36 mg/day and 12.42 mg/day in DFLL-TBM with FCIs at natural and 90% Li-6 enrichment, respectively.

3.2 Activation Products

The activation calculations were performed to assess the activation inventories of the DFLL-TBM by using the code system VisualBUS [10]. The total activation product inventories in the TBM were assessed after shutdown. Also assessed was the activation product mobilization. After 0.0841 MWa/m^2 pulsed average fluence at shutdown, the total activity level in the TBM is 4.90×10^{16}Bq with a contribution of 6.97×10^{15}Bq from the structure, 3.95×10^{16} Bq from LiPb and 2.81×10^{15}Bq from SiC_f/SiC inserts, respectively. A few minutes later, the structure dominates the total activity inventory thereafter. Most of activated product is tightly bound to the metal structures and a small portion of the total activation product inventory is in a form that could be mobilized in accident conditions including dust, activated corrosion product, high volatilizable isotopes Hg-203 and Po-210 in LiPb and oxidation products.

3.3 Energy Source Terms and Hydrogen

The decay heat is existed after shutdown and the total decay heat generated in the TBM and contribution from each material as a function of time is shown in FIG.2. A total decay heat of 0.013MW is attained at shutdown with a contribution of 1.40×10^{-3}MW from the CLAM structure, 0.01MW from LiPb breeder and 1.37×10^{-3}MW from SiC_f/SiC inserts, respectively. The large contribution from LiPb is due to the generation of ^{207m}Pb ($T_{1/2}$=0.8s), which drops rapidly after shutdown. During the short period (<100 seconds) after shutdown, the contribution from the SiC_f/SiC inserts is also significant for the total decay heat. But after 100 seconds, the afterheat in the SiC_f/SiC inserts declines rapidly and is 2~6 orders of magnitude lower than the level in the structure while the attainable level in LiPb is ~2-3 orders of magnitude lower than that of the structure. The contribution from the coating to the total afterheat in the TBM is not significant and not considered due to its very small volume.

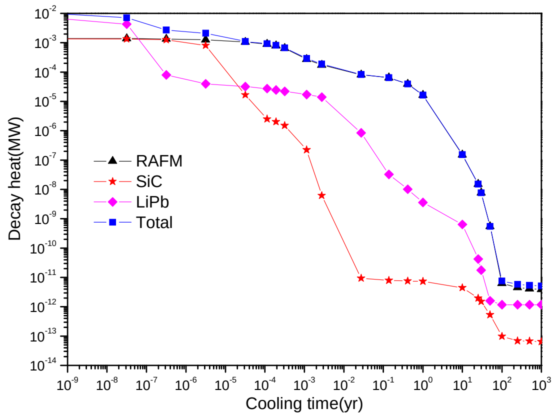

FIG. 2 Total decay heats generated in the DFLL-TBM and contribution from each material

The chemical energy and hydrogen are possibly occurred when LiPb comes in contact with water during accident scenarios. ITER has specified a TBM LiPb inventory limit of 0.28 m^3 based on the assumption that 100% of the lithium in this volume will react to produce hydrogen limit 2.5 kg. The other chemical energy and hydrogen generation source is the reaction between the TBM FW beryllium cladding and steam. The quantity of beryllium on the FW clad is about 4.6 kg, which is less than the 10 kg beryllium limit set by ITER. So the mass of hydrogen generated by the DFLL-TBM FW beryllium is not a significant safety concern, while the chemical energy heat generated is a safety concern considering the thermal integrity of the TBM FW.

4 Operational Releases

4.1 Tritium Release

A tritium permeation model of the entire DFLL-TBM system was developed, which included the structural material associated with the TBM and major components of the TBM auxiliary system, e.g. pipes and heat exchangers etc.

In normal operation, the analyses results show that tritium release into environment as HT is ~1.353mg-T/yr, which is much lower than the total TBM annual release limit of 10mg-T/yr as HT, and the tritium permeation inventory into the ITER heat removal system through the TBM He/H_2O heat exchanger is ~0.010mg-T/yr as HTO, which is much lower than the total TBM annual release limit i.e. 1mg-T/yr as HTO. The amount of tritium which could be liberated from the beryllium is bounded, and the tritium release from the TBM system is inherently small. The total tritium inventory is ~111mg in TBM systems, which is less than the tritium inventory of 450g contained within the VV during normal operation of ITER. The DFLL-TBM is safe from the viewpoint of the tritium according to the ITER TBM safety guideline.

4.2 Occupational Radiation Exposure (ORE)

The ORE assessment of the DFLL-TBM plays an important role in the replacement and maintenance. It is important to note that, from an ORE assessment perspective, we are still at the early stages of design. A reasonable ORE assessment requires information that is normally lacking at this stage of the design. The lack of detailed design and maintenance information, however, means that, we can't provide any estimate of worker doses, such as the estimation of worker dose for maintenance of helium ancillary sub-system components installed in TCWS vault, tritium processing sub-system components installed in tritium plant.

The workers dose for replacement of DFLL-TBM and for inspection and repair of LiPb ancillary system are 18.32 p-mSv and 0.24 p-mSv, respectively. The other worker doses are on going, such as the estimation of worker dose for maintenance of helium ancillary sub-system components installed in TCWS vault, tritium processing sub-system components installed in tritium plant.

5 Accident analysis

5.1 FMEA analysis

To help ensure that all aspects of plant operation have been considered, the component-level (bottom-up) approach has been applied to the identification of potential event initiators. The principal technique used in the bottom-up studies is Failure Mode and Effects Analysis (FMEA), which is based on the application of systematic methods which seek to catalogue all potential faults in the DFLL-TBM components and sub-systems, and to consider the conceivable consequences of these faults. The focus is on the failure of individual components, and is based on the design in as much detail as is available. The work thus provides a comprehensive analysis of the DFLL-TBM and the detailed accident initiating events that could occur. These are grouped together into families of events.

From FMEA analysis, 20 Potential Initiating Events (PIEs) is identified. PIE-Potential Impacts Table (PIE-PIT) provides not only a useful presentational tool for the result of event identification studies, but has also yielded 6 Bounding Events for DFLL-TBM proposed as the basis for future event analyses. The correspondence of PIEs and Bounding Events with earlier reference event selections gives confidence in the justification of the selection.

5.2 Accident sequences analysis

The emphasis of the safety assessment is placed on the analysis of off-normal events. The objective is to demonstrate that the introduction and operation of the test modules does not add significantly to the risk of the basic machine. Three groups of accidents are judged to cover all accident scenarios envisaged in incidents and accidents involving the TBMs. Some limited effort has been spent to also address behavior of the TBMs under hypothetical accident scenarios to assess the ultimate safety margins of the TBMs. The three groups of accidents investigated with their parametric variations are summarized below.

Case1: in-vessel TBM coolant leaks

Case2: in-TBM breeder box coolant leaks

Case3: ex-vessel TBM coolant leaks

The assessment addresses a number of concerns or issues that are directly caused by the TBM system failure. The concerns addressed for the different event sequences, where applicable, are the following: (a) vacuum vessel pressurization, (b) vault pressure build-up, (c) purge gas system pressurization, (d) temperature evolution in the TBM, (e) decay heat removal capability, (f) tritium and activation products release from the TBM system, and (g) hydrogen and heat production from chemical reactions.

The accident sequences were examined using computer code, such as ANSYS code for heat transfer analysis, or analytical methods with conservative assumptions for the pressure and activation products release assessment.

The accident analyses are concluded as follows:

An in-vessel TBM coolant leak event makes the plasma disruption immediately. Only decay heat source exists in the reactor. The highest pressure in TBM is estimated as 22.4 KPa and the maximum temperature in TBM is 620°C. The FW temperature reaches the 225°C after 10 days. The beryllium armor and FW temperature evolutions during 10 days after in-vessel loss-of-coolant accidents (LOCAs) are shown in FIG. 3. The decay heat removal capacity of DFLL-TBM can meet the ITER safety requirement. The hydrogen production is insignificant under this accident. Tritium and activation products released from the TBM into the VV are insignificant compared to the total amount mobilized from non-TBM components.

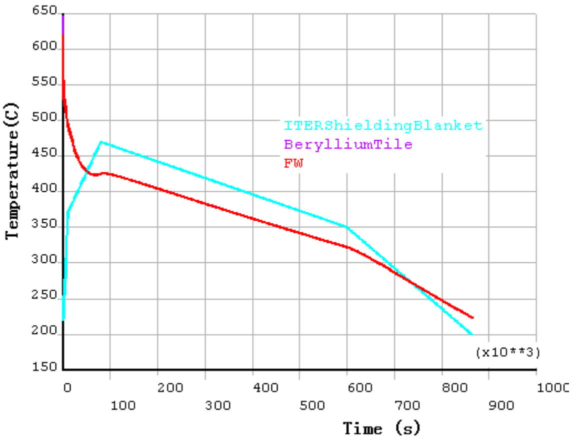

FIG. 3 The Be armor and FW temperature evolutions during 10 days after in-vessel LOCA

In case of no active plasma termination and in-TBM loss of coolant event, the FW temperature evolution during 10 days is shown in FIG. 4. The temperature of FW peaks above 1395 °C, resulting potentially in significant hydrogen production. But the hydrogen production is less than the ITER limit. Tritium and activation products released from the TBM into the VV are insignificant compared to the total amount mobilized from non-TBM components. In case of active plasma termination and in-TBM loss of coolant event, the temperature of the FW and TBM is estimated below 573 °C, resulting in insignificant consequence. The temperature evolution during 10 days can be shown in FIG. 5.

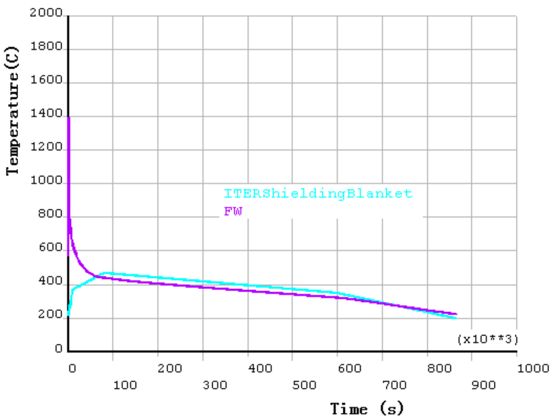

FIG. 4 The FW temperature evolution during 10 days after the in-TBM LOCA without detection

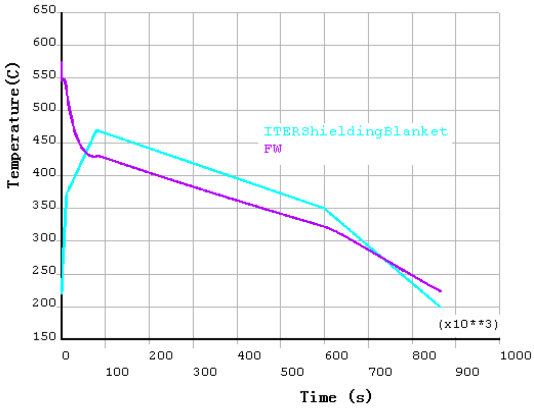

FIG. 5 The FW temperature evolution during 10 days after in-TBM LOCA with detection

An ex-Vessel loss of coolant event causes the no significant pressure increase in the TCWS vault. The temperature rising and hydrogen production and activation products release are similar to the in-TBM loss of coolant event.

6 Wastes

The activated materials are classified into three classes: permanent disposal waste (PDW), recyclable material and non-active waste (NAW). Two categories of recyclable materials are envisaged, complex recycle material (CRM) and simple recycle material (SRM), according to the more or less demanding requirements of remote handling recycling (RHR), with upper limit of D of 20 and 2 mSv/h, respectively. Adopting and extending the concepts developed in SEAFP [11] analyses, the feasibility of recycling and clearance for the materials in the TBM is investigated and all the materials can be managed by hands-on recycling except Al_2O_3 after 100 years'cooling.

7 Conclusions

The activated materials inventory in DFLL-TBM system is insignificant compared with ITER. The potential hydrogen production will be less than the limit of 2.5kg. The DFLL-TBM is safe from the viewpoint of the tritium according to the ITER TBM safety guideline. The concerns identified for the individual event sequences have been revealed to be non-critical. The analyses on off-normal events demonstrate that the introduction and operation of the test modules does not add significant risk to ITER. After 100 years' cooling, all the materials can be managed by hands-on recycling except Al_2O_3. The preliminary analysis shows the DFLL-TBM system can meet the ITER safety requirements for license.

Acknowledge

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