Preliminary Failure mode and effect analysis on Chinese ITER helium cooled solid breeder test blanket design concept

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Abstract:

The complexity of the ITER TBM (International Thermonuclear Experimental Reactor Test Blanket Module) and the inventories of radioactive materials involved in its operation require a systematic approach to perform detailed safety analyses during the various stages of the project in order to demonstrate compliance with the safety requirements. A Bottom-Up methodology based on component level Failure mode and effect analysis (FMEA) has been applied to perform the safety analyses for Chinese ITER TBM design with helium-cooled solid breeder (HCSB) concept for testing in ITER device. The main purposes of the work are: to identify important accident initiators, to find out the possible consequences for the TBM deriving from component failures, identify individual possible causes, identify mitigating features and systems, classify accident initiators in postulated initiating events (PIEs), define the deterministic analyses which allow the possible accident sequences to be quantified, and consequently, to ascertain the fulfillment of ITER safety requirements.

1. Introduction

The complexity of the ITER TBM (International Thermonuclear Experimental Reactor Test Blanket Module) and the inventories of radioactive materials involved in its operation require a systematic approach to perform detailed safety analyses during the various stages of the project in order to demonstrate compliance with the safety requirements. The main purposes of such analysis are: to identify important accident initiators, to find out the possible consequences for the TBM deriving from component failures, identify individual possible causes, identify mitigating features and systems, classify accident initiators in postulated initiating events (PIEs), define the deterministic analyses which allow the possible accident sequences to be quantified, and consequently, to ascertain the fulfillment of ITER safety requirements. TBM being a important part of ITER, little or no information is available on expected accidents, so that a systematic analysis is very useful from the early phase of the TBM design. In our previous work, some concrete analyses on several accidents are performed [1,2]. Now with the design activities being further advanced, and many systems having been clearly defined, a bottom-up methodology based on component level failure mode and effect analysis (FMEA) can be applied to perform the safety analyses for Chinese ITER TBM design with helium-cooled solid breeder (HCSB) concept for testing in ITER device.

For years, FMEA has been an integral part of engineering designs. For the most part, it has been an indispensable tool for industries such as the aerospace and automobile industries.

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Government agencies (i.e., Air Force, Navy) require that FMEAs be performed on their systems to ensure safety as well as reliability. Most notably, the automotive industry has adopted FMEAs in the design and manufacturing/assembly of automobiles. Although there are many types of FMEAs (design, process, equipment) and analyses vary from hardware to software, one common factor has remained through the years—to resolve potential problems before they occur. So it is very important and necessary to apply FMEA method to the fusion design, such as TBM design.

2. HCSB TBM Systems Descriptions

TBM has itself complex systems. For the FMEA analysis, it was required to deeply familiarize with the TBM systems so that the consequences of possible failures based on a component-by-component can be able to predict. Then the first step of the analysis is to identify all the components included in the systems. The functions performed by each component have to be identified as well, together with the basic parameters. For this purpose, the process schemes and the design description documents (DDD HCSB) are used [3].

The helium cooled solid breeder (HCSB) ceramic test blanket is one of two blanket concepts chosen in the frame of the China blanket program as a China DEMO relevant blanket. Distinguish features of this concept are the use of the ceramic breeder and the beryllium multiplier in form of pebble beds, which are separated and cooled by cooling/stiffening plates. The coolant helium at high pressure (8MPa) and high temperature flows in the first wall and the breeding zone in small channels, while the beds self are purged by a low pressure helium (0.1MPa) flow. This independent purge flow can remove the tritium produced in the beds, carry it to a tritium extraction system (TES) and keep low the tritium partial pressure at the interface with the coolant channels reducing the permeation flow to the main coolant system. Hence, permeation barriers (coatings) are not necessary between the two loops.

The structure of HCSB TBM module self is consisted of the following main components: first wall (FW), caps, grids, manifolds, attachments, cooling pipes, purge gas pipes and sub-modules (see Fig.1). A dual-layer structure with the thickness of 30mm is used in FW design. A U-shaped helium cooling channel in series connection is used in the cooling circuit design. The grids and caps with their own helium cooling channels are considered. The grids are welded on FW, which will enhance the safety and reliability of structure. The integral HCSB TBM consists of 12 sub-modules. Each sub-module has an independent cooling circuit and a purge gas circuit. The cooling and tritium extraction paths with parallel connection are designed for each sub-module.

The HCSB TBM related systems consist of helium cooling system (HCS), pressure control system (PCS), coolant purification system (CPS), tritium extraction system (TES) and so on. Schematic concept of the TBM systems is shown in Fig.2. For each one of these system, pipes, guard pipes, manifolds, pumps, pressurizers, heat exchangers, coolers, tanks, isolation valves, control valves and relief valves has been identified as single components.

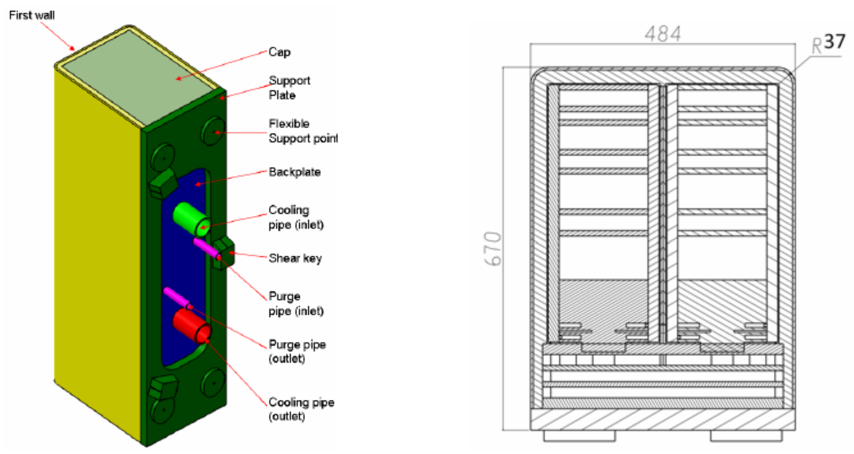

Fig.1 Overall isometric view of the HCSB TBM

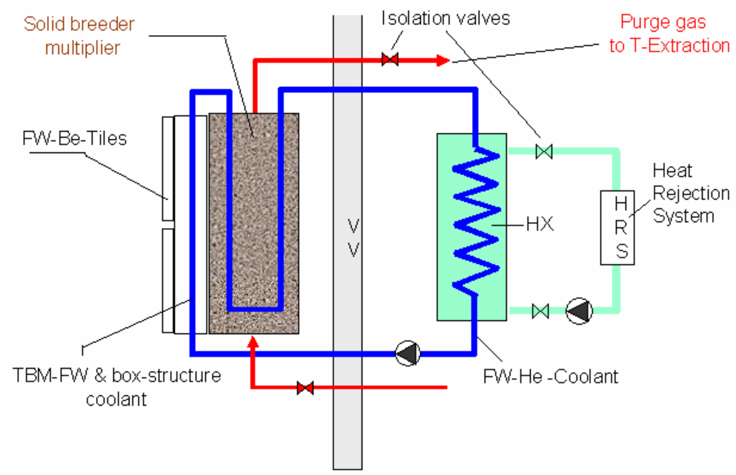

Fig.2 Schematic concept of the TBM systems (Reference: presented by M. Iseli in TBWG Safety workshop meeting, July 18, 2006, Garching)

3. Operation Conditions

The operation conditions of each component have to be identified in order to perform the analysis in all possible working phase. This is important because some failure can be more challenging for the safety, or can only be possible, in phases different from normal operation. The PI-TBM (Plant Integration module), which will operate in the last period of the high duty cycle D-T phase of ITER-FEAT life, has been considered in the assessment because it is the most representative from a safety point of view. The burning and dwell operating, the so call “Normal Operation”, have been considered in identifying possible elementary failures and related consequences.

4. Failure Mode and Effect Analysis (FMEA)

After all the components of the CH HCSB TBM systems have been identified, the detailed analysis for the components have been done with FMEA methodology in order to find out the possible safety consequences for the TBM deriving from their failures, identify possible cause, and define mitigating features and systems appointed to cope with the accidents. For each component, all the possible failure modes that could occur in the operating states are evaluated in terms of: accident frequencies and relative category classification, failure cause and possible action to prevent the failure, consequences and actions to prevent and mitigate the consequence. Also, and this is a characteristic feature of this FMEA, each elementary accident initiator is classified in a postulated initiating event (PIE) since it is not practical to consider each basic failure as an accident initiator.

From a safety point of view, the PIEs are the most representative accident initiators, in terms of radiological consequences, between a set of elementary events challenging the plant in similar way and, producing equivalent fault plant conditions. In this way each defined PIE is characterized by:

(1) A representative event, which usually is one of the contributors (generally, the one posing the most severe challenging conditions);

(2) A set of elementary accident initiators grouped under this PIE; take into account the similarity of accident development in terms of mitigating features and possible consequences.

The PIEs definition is useful to limit the set of accident initiators to be taken into account in the deterministic transient analyses. In fact, they are representing the most challenging conditions for the ones that could concern all elementary initiators grouped on them.

In general, FMEA analysis results were filled in a table. A first list of possible PIEs for the various systems was identified in the first step of the safety analysis. Since the first objective of the analysis, an assessment of the completeness of such a set of PIEs, is already taken into account, as the single component failures are investigated and the accident evolution is examined, the PIE that could be considered to encompass this particular accident is searched in the list and assigned to the component failure in case it is found out. In case the accident is not included in the already defined list, a new PIE is defined and added in this list. Also, since the most challenging event is usually taken as representative of the related PIE, the PIEs can be modified by changing their representative event downstream of the assignment of retrieved accident sequences to a particular PIE. As a result, each determined PIE is the most representative accident initiator in terms of expected frequency and radiological consequences, between several single component failures which could produce equivalent fault plant conditions. This is a conservative approach, which can be refined if it should lead to a heavy burden on the system from the safety point of view, for instance if frequency-consequence limits are overrun.

5. Postulated Initiating Event (PIE) Analysis

The total list of PIEs recognized by the FMEA on Chinese HCSB TBM systems is reported in the following Table 1. PIEs were pointed out by assessing elementary failures related to the different components of HCSB TBM systems during normal operation. Accident sequences arising from each PIE have been defined.

Four of these PIEs were already identified by the FMEA on other ITER systems and already documented in [GSSR] [4]. Six of the other PIEs are taken into account and judged to cover all the most demanding accidents, Such as LFC-1, IBB-1, LVV-3, LVP-1, IVC-1 and

LTP-1. All elementary failures not inducing safety relevant consequences have been classified in a PIE named N/S (Not Safety Relevant). Even if such failures are not important from a safety point of view, they will be important on defining plant operability and maintenance strategy, as well as they will be useful in evaluating worker safety.

Table 1 Total list of PIEs identified by the FMEA on CH HCSB TBM model

PIEs	**Description**
LFC-1	Loss of flow in a TBM cooling circuit
LFC-2	Partial flow blockage in a TBM cooling circuit
LHS-1	Loss of heat sink in TBM coolant-He
IBC-1	In breeder region loss of TBM coolant-He: Rupture of a sealing weld
IBC-2	In breeder region loss of TBM coolant-He: Leak of a sealing weld
LVV-1	LOCA out-VV: large rupture of TBM coolant pipe in TWCS room
LVV-2	LOCA out-VV: small rupture of TBM coolant pipe in TWCS room
LVV-3	LOCA out-VV: rupture of tubes in a primary TBM-HCS HX
LVP-1	LOCA out-VV: rupture of TBM coolant pipe in Port Cell
LVP-2	LOCA out-VV: small rupture of TBM coolant pipe in Port Cell
IVC-1	In-VV loss of TBM coolant-He: Rupture of TBM-FSW
IVC-2	In-VV loss of TBM coolant-He: leak from TBM-FSW
LVC-1	LOCA out-VV: small rupture of PFW/BLK coolant pipe in Port Cell
LIV-1	LOCA in-VV small PFW/BLK: equivalent break size-a few cm^2
RVP-1	Small rupture of VV coolant pipe in Port Cell
RVV-1	Small rupture in the internal VV shell-equivalent break size: a few cm^2
LTG-1	Leak of TBM-TES process line in Glove Box containment
LTP-1	Leak of TBM-TES process line in Port Cell
VBG-1	Loss of vacuum in VV: break inside the VV of TBM purge gas system
VBG-2	Loss of vacuum in VV: leak inside VV from TBM purge gas system
AVV-1	Ingress of air in the VV-small leakage
N/S	Not safety relevant

(Note: VV means Vacuum Vessel; HX means Heat Exchanger; PFW means Primary First Wall; BLK means Blanket.)

The PIEs have been discussed to qualitatively define possible accident evolutions.

Just as an example, for one of the PIEs: the LFC-1, its fault condition is loss of flow in a TBM cooling circuit because of circulator /pump seizure. The severe loss of flow in the TBM cooling circuit could be determined by a seizure of the circulator or malfunctions in some valves located in the HCS circuit. The reference event selected to represent the PIE is the circulator seizure. Loss of He coolant flow under this fault condition will result in the following events: HCS loop over-pressurization, increase of temperature in TBM box, increase of temperature in HCS loop and so on. Then other series of accidents will follow: such as pressure relief towards PCS, swelling of Be pebbles, swelling of ceramic breeder pebbles, break in TBM structures if plasma is not shutdown, loss of purge gas into VV, loss of He coolant into VV, plasma disruption, VV pressurization, pressure relief towards VV pressure suppression system (VVPSS), etc. In order to prevent environmental release, some mitigating actions will be considered at first. For example, TBM coolant inlet flow-rate and temperature should be monitored. Plasma should be shut downed promptly. VVPSS should be designed to treat over pressurization generated be He gas. Broken circuits should be isolated promptly to reduce the coolant released in VV. However in this case of LFC-1 initiator Be pebbles get higher temperature before the module in-vessel breaks. On the other hand, the detection of the loss of flow should be quite rapid and sufficient time should be available to intervene shutting down the plasma. Anyway LFC-1 followed by TBM in-vessel break because contemporaneous failure to shutdown the plasma can be considered as one of the bounding accidents for the ITER TBM.

It’s important to note that the discussion on PIEs focuses on consequences related to public safety. But, it has to be considered that any failure that could occur in the TBM systems could have significant consequences in terms of occupational radiation exposure, both to perform recovery actions and to perform decontamination, if it needs. Dedicated studies have to be done on the matter and detailed procedures, in an ALARA context, have to be defined to perform the different recovery and/or maintenance activities.

6. Conclusion and Summary

The FMEA methodology has given a complete screening of the various causes that could induce failures in the plant or simply a stop in the operating phases because of failures in CH HCSB TBM and interfacing systems. Also a qualitative overview on accident sequences arising from each elementary failure could be derived from the FMEA tables looking at consequences description and preventive/mitigating actions.

A list of 21, public safety relevant PIEs has been set assessing elementary failures related to the different components of CH HCSB TBM systems. Each PIE has been discussed in order to qualitatively identify accident sequences arising from each PIE itself. Deterministic analysis will have to demonstrate the plant capacity in mitigating and, in every case, in withstanding accident consequences, arising from the overall set of PIEs, below fixed safety limits.

In addition, important feedback to the design activities will from the FMEA study performed for safety assessment purpose. Design modification could be required to improve: prevention against the accident initiators, the effectiveness of mitigations, the system control, and the system availability with planned test and maintenance during operations.

This work is just underway. Many further researches are required.

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