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Failure mode and effect analysis for the European test blanket modules

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ABSTRACT

A failure mode and effect analysis (FMEA) at component level was done to study possible safety relevant implications arising from failures in European test blanket modules (TBMs) for ITER: the helium cooled pebble bed (HCPB) and the helium cooled lithium lead (HCLL) TBMs.

The following sub-systems have been analysed by this study: TBM, TBM port plug (PP), inter-space and Port Cell equipment, Helium Coolant System (HCS), Coolant Purification System (CPS), coolant pressure control system, PbLi ancillary system and tritium extraction system. The present study is focused on the modules that will operate in the last period of the high duty cycle D–T phase of ITER, the plant integration TBM (PI-TBM) for the HCPB and the integral TBM (IN-TBM) for the HCLL.

For both modules, six PIEs have been highlighted as the ones more relevant to be studied with deterministic assessments.

1. Introduction

The design of the equipment and confinement barriers of ITER should be consistent with the basic safety requirement that no emergency plan involving evacuation of the nearby population is required in case of the worst credible accident.

Extensive analyses have been done to point out the overall abnormal event sequences that could arise from failures or malfunctions in the plant systems, to verify and ensure that all potential consequences are within project guidelines. Such analyses require the definition of the overall possible accident initiators and the selection of the most relevant in terms of safety concerns for the plant. They are called postulated initiating events (PIE) and are the ones that could determine accident sequences with some potential for radiological damages. Deterministic studies, done by the use of computer codes, will have to demonstrate capability of safety measures in terms of prevention and mitigation of the consequences and the respect of prescribed safety limits.

A bottom-up methodology based on component level failure mode and effect analysis (FMEA) has been applied to point out a complete and detailed list of accident initiators.

This paper addresses the identification of PIEs arising from failures in European test blanket modules (TBMs) for ITER: the helium cooled pebble bed (HCPB) [1] and the helium cooled lithium lead (HCLL) [2] TBMs. The design of the two systems used for this analysis is based mainly on the two design description document issued at end of 2005 [3,4], the ones available at the moment of the study.

2. Failure mode and effect analysis

The FMEA methodology is based on the study of the possible failure modes of plant components. Therefore, the first step of the work is to identify the complete list of the components to be analysed, trying to trace a deeper breakdown of the systems, sub-systems, main components and sub-components as the possible failures need to be detailed because of differentiation of the failures and/or of the effects of the failures. For each one of the identified components, the possible failure modes that could occur in the interested operating phases have to be evaluated. In our case the burning and dwell operating phases have taken into account because they are the most challenging operating conditions in terms of performance of the systems and inventories of energy involved. For each failure mode, the possible causes and possible actions to prevent the failure, consequences and actions to prevent and mitigate the consequences, PIE in which the elementary failures is grouped are pointed out.

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. By this method each defined PIE is characterized by:

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- a set of elementary accident initiators grouped under the PIE;
- a representative event, which is one of the contributors (generally, the one posing the most severe challenging conditions).

The definition of PIEs 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 plant, guessing that consequences from PIEs are the most severe (upper limit) of the ones that could concern all the elementary initiators grouped on them.

3. Identification of EU TBMs and related systems

The Test Blanket System (TBS) is an experimental device for the testing in a real fusion environment DEMO-relevant blanket concepts before the construction of a DEMO reactor.

The breakdown of components to be analysed has been prepared assigning identification labels, description, useful comments and figures [3,4].

Both HCPB and HCLL European concepts use a reduced activation ferritic martensitic (RAFM) steel as structural material, the EUROFER. The blanket structures are mainly made by plates with internal cooling channels; these plates are joint together to form a box that contains the breeder materials: in the channels helium at high pressure (8 MPa) and high temperature (outlet 500 °C) flows cooling a first wall (FW) in direct contact to the plasma surface irradiation and the internal breeding zone heated by neutrons. Distinguish features of the HCPB concept are the use of the Ceramic Breeder and the Beryllium Multiplier in form of flat pebble beds, which are purged by a low pressure Helium flow. This independent purge flow removes the Tritium produced in the beds. In the HCLL TBM case, the liquid eutectic lead lithium (PbLi) is used as tritium breeder and carrier and as neutron multiplier.

The TBS is composed by the elements listed below and their components.

3.1. The test blanket module

The test blanket module encompasses the function of the FW, breeding blanket, shield and structure. Its principal functions in ITER are, besides serving as test module, to remove surface heat flux and energy from plasma during normal and off-normal operational conditions, and to contribute to the shielding to the vacuum vessel (VV) and super-conducting coils. It will be inserted in an equatorial port of ITER inside the vacuum vessel in front of the plasma.

3.2. The TBM port plug (PP)

The PP contains the TBMs and provides thermal and neutronic insulation from the ITER basic machine. It allows the TBM replacement through the port itself. The front part (called “frame”) has also FW functions. The mechanical interface with the ITER machine will be provided by the PP rear part (“flange”); this flange is supported by the VV port extension. The PP provide also neutron shielding; a thick water cooled “shield” is placed behind the TBM. The pipes coming from the TBMs and crossing the PP up to the boundary with the inter-space are considered part of the PP.

3.3. The interspace and Port Cell equipment (IPCE)

Piping and loop components belonging to the main Helium Coolant System (HCS) and connecting the PP with the shaft wall, where the interface of the Tokamak Cooling Water System (TCWS) is set.

3.4. The Helium Coolant System

This system shall provide the He coolant at the characteristic of pressure, temperature and mass flow required by the TBM for the testing and for the extraction of the heat produced. The components (compressor, heat exchanger, etc.) and the piping allocated in the TCWS vault are part of this system.

3.5. The Coolant Purification System (CPS)

Function of the CPS is to remove the Tritium that can permeate in the coolant and other impurities, and control the gas composition in the HCS (partial pressure of H_2, H_2O and impurity control). This system is connected to the HCS and its allocation is anticipated in the TCWS.

3.6. The PbLi ancillary system

This is only for the HCLL TBM. The PbLi circuit is a closed loop with a forced circulation of the liquid metal. It includes the main circuit, detritiation unit and cold trap, dosing and sampling systems, heating and cooling systems, and shielding and insulation. From the PbLi storage tank, liquid metal is pumped into the TBM where tritium is produced. The flow velocity in the PbLi system is controlled in the range of 0.1–1 kg/s. PbLi outlet temperature from the TBM is 550 °C. Tritium is removed from PbLi in a detritiation unit (tritium extractor) connected to the Tritium Recovery from Purge Gas System (TRPS). Corrosion products and impurities are removed in a cold trap.

3.7. The Tritium Extraction System (TES)

The function of the TES is to remove the Tritium produced in the TBM from the He carrier. The TES of the HCPB is directly connected to the TBM: the He purge gas flows directly through the pebble beds. The TES of the HCLL is made by the Tritium Extractor in the PbLi loop and the TRPS. TES of HCPB and TRPS of HCLL are supposed to be allocated in the Tritium Building.

3.8. Other systems

Measurement or helium conditioning systems, instrumentation control and management. These systems will be allocated in front of the VV Port and almost integrated in the IPCE.

Three of the equatorial ports (2, 16 and 18) are dedicated for blanket test modules. The EU HCPB TBM is supposed to be allocated in Port 16, sharing the place with another blanket with similar characteristic (helium cooled solid breeder blanket). The EU HCLL TBM is supposed to be allocated in Port 18, sharing the room with another blanket with similar characteristic (Helium cooled, PbLi breeder blanket) or with Water-cooled Ceramic Breeder TBM.

During the ITER life several plasma phases are foreseen: H–H, D–D, low and high duty cycle D–T with related operating conditions. Different types of TBMs will be used for the various phases. For both the HCPB and HCLL TBMs, the present study is focused on the models that will be used in the last period of the high duty cycle D–T phase, because the operating conditions are the most relevant from a safety point of view.

4. Postulated initiating events

On sets of about 230 and 250 elementary failures, 21 and 22 PIEs have been identified, respectively, for the HCPB and HCLL TBM systems (see Table 1). For both of them, four PIEs were already identified by the FMEA on other ITER systems and already documented