Lessons learned for the Breeding Blanket designers from the design development of the European Test Blanket Module Systems (He, Tritium, Liquid Metal Systems)

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ABSTRACT The TBM Program is the answer to the ITER mission of testing tritium breeding concepts that would lead in a future reactor to tritium self-sufficiency, the extraction of high grade heat and electricity production. The objective of the ITER TBM Program is to provide the first experimental data on the performance of several breeding blanket concepts in an integrated fusion nuclear environment. Such data are essential to design and predict the performance of DEMO and future fusion reactors.

To achieve this objective, the TBM Program plans to: i) test and validate DEMO relevant technologies and materials; ii) validate and qualify predictive tools in view of their use for the design of the breeding blankets in DEMO and power plants. To comply with this mission, the TBM Program envisages to test, for each breeding blanket type, several different TBM versions specifically instrumented to operate in the various ITER phases. This diversification is foreseen in the TBM Program in order to maximize the ROX (Return on Experience) for each ITER operational phase in view of the DEMO breeding blanket design.

Although the design of the two European TBS (Test Blanket System) is only at a preliminary stage, different design aspects have been already managed which deserve the attention of the DEMO breeding blanket designers. These aspects range from safety requirements implementation to licensing process, from the implementation of safety functions to the integration issues. They are presented and discussed in this paper with the objective to provide relevant suggestions to the DEMO breeding blanket designers.

1. Introduction

The testing of Tritium Breeding Blanket concepts as part of the ITER mission has been recognized as an essential milestone in the development of a future fusion reactor ensuring tritium self-sufficiency, extraction of high grade heat and electricity production. The TBM Program in ITER has been established by decision of the ITER Council (IC-3, 19-20 November, 2008). Upon recommendation of the TBM Program Committee, the ITER Council has noted the proposed TBM port allocation which foresees the installation and testing of two European Test Blanket Modules (TBMs) in ITER equatorial port #16.

The design of the two European Test Blanket Systems (TBS), based on the Helium Cooled Lithium Lead (HCLL) and Helium Cooled Pebble Bed (HCPB) breeding blanket concepts, has completed its conceptual phase. Several "lessons learned" can be already now brought to the attention of the designers of a DEMO breeding blanket. They deal with:

- Licensing process and compliance with regulations: impact on the design requirements and implementation
- Safety functions: impact of their implementation on the design
- Design of the instrumentation
- Integration issues: tritium contamination in the rooms hosting the blanket systems

After a synthetic recall of the main design features of the HCLL and HCPB-TBS, all above mentioned topics are discussed in this paper, addressing the analysis onto the original inputs and ROX for the designers of a breeding blanket for DEMO from the current TBM systems design experience.

2. Recall of HCLL and HCPB-TBS main features

In Fig. 1 are shown the block diagrams of HCLL and HCPB-TBS. Their main features in terms of materials, technologies and operating conditions are derived from the corresponding breeding blanket concepts developed in the two past decades in Europe. Both concepts envisage the use of EUROFER reduced activation ferritic-martensitic steel as structural material and pressurized helium for heat extraction (8 MPa, 300–500˚C).

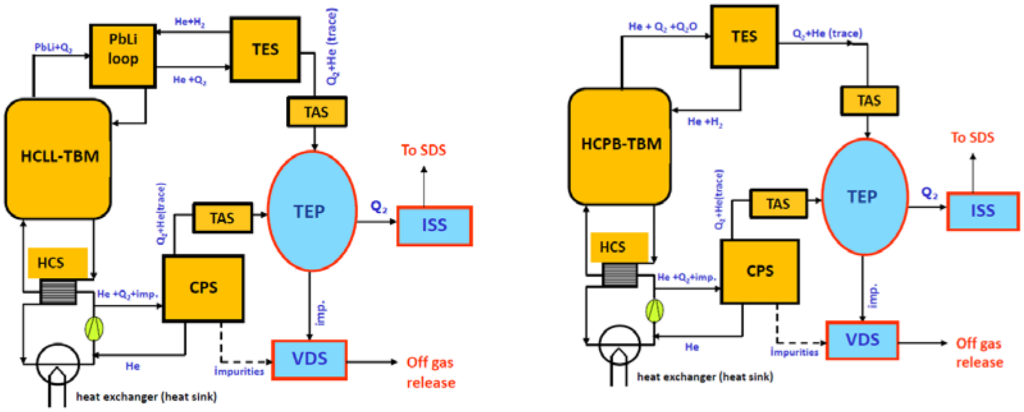

Fig. 1 Block diagram of HCLL-TBS (left) and HCPB-TBS (right); Q = H, D, T

In fig. 1 it is possible to identify: i) HCLL-TBM, with the box made of reduced activation ferritic-martensitic steel Eurofer-97, cooled by pressurized He at 8 MPa, and containing slowly flowing Pb-16Li alloy that acts as tritium breeder and neutron multiplier; ii) the Pb-16Li loop, for recirculation of Pb-16Li alloy externally to the TBM and vacuum vessel; iii) HCS (Helium Cooling System), the primary cooling circuit with high pressure He (8 MPa) for the extraction of the thermal power from the TBM; iv) CPS (Coolant Purification System), for the extraction and recovery of tritium permeated into the primary cooling circuit and to control the TBM coolant chemistry; v) TES (Tritium Extraction System), for the tritium recovery from Pb-16Li and tritium concentration in gas phase (He); vi) TAS (Tritium Accountancy System), for the tritium accountancy prior tritium is routed to the ITER Tritium Plant. TEP (Tokamak Exhaust Processing System), DS (Detritiation System) and ISS (Isotope Separation System) belong to the ITER Tritium Plant.

The HCPB-TBS layout and main features are the same as for HCLL-TBS. However, in this case, a low pressure He purge stream, doped with hydrogen, extracts the tritium generated in the TBM ceramic pebbles. The HCLL and HCPB TBSs are completely independent from each other at the functional level, only sharing physical space and supporting structures. The HCLL and HCPB-TBS sub-systems are deployed in different areas of the Tokamak complex, as shown in fig. 2 [3].

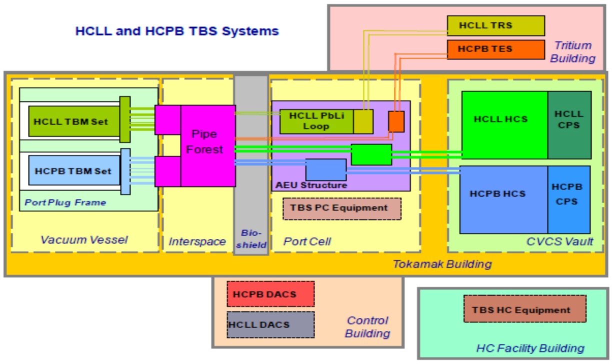

Fig. 2 HCLL and HCPB-TBS sub-systems in the Tokamak Complex areas [3]

3. Lessons Learned from TBS design for a DEMO breeding blanket

This section presents and discusses some design issues of different nature which are being managed during the preliminary design of HCLL and HCPB-TBS and can be already brought to the attention of the DEMO breeding blanket designers.

3.1 Licensing process and compliance with regulations: impact on design requirements

Building ITER, the basic nuclear installation (BNI) n. 174, was authorized by the “Creation Decree” on November 2012, after the issue of the Preliminary Safety Report by the Operator, ITER Organization. In the framework of the French regulations applicable to BNI, the order 07-February 2012 (BNI order, [4]), sets the general rules relative to the organizational aspects of the lifecycle of a BNI. In line with the French Environmental Code, in order to get the license to operate the BNI order requires the Operator (ITER Organization) to carry out a Nuclear Safety Demonstration in which the risks originated from the BNI operation are identified together with the provisions to either prevent or limit them. To do this, the Operator must identify Structures, Systems and Components (SSC) which have safety functions to remove or mitigate the foreseen hazards. Under the BNI Order these SSCs are identified as Protection Important Components (PIC), while the Protection Important Activities (PIA) are the processes related to the design and manufacturing of the PICs.

As part of the Nuclear Safety Demonstration the BNI order prescribes that for PIC and PIA the (safety) “defined requirements” are first of all identified and then propagated in the design through the whole supply chain. Through the allocation of suitable verification activities, the Operator will be able to demonstrate to the Nuclear Safety Authority that the Defined Requirements, identified in the ambit of the Nuclear Safety Demonstration, have been correctly propagated.

Establishing suitable safety analysis methodology and compliance with nuclear pressure equipment regulation are an important part of the Nuclear Safety Demonstration.

- *Establishment of safety methodologies and their applications*

Safety studies for fusion facilities are commonly conducted using codes originally developed for fission reactor accident analysis. Some of these codes have been modified with the inclusion of physical models to treat fusion-relevant phenomena. The F4E TBS accidents analyses methodology addressed the challenge in performing accident analysis for the EU TBS having available only limited experimental data on TBS-related phenomena [5]. The developed HCLL and HCPB TBS MELCOR and RELAP5 models have been evaluated via a test matrix that includes:

i. comparisons of the MELCOR and RELAP5 predictions with available finite-element analysis results from the TBM design description documents in steady state, pulsed plasma operations and MARFE (Multi-Faceted Asymmetric Radiation From the Edge) power excursion;
ii. further MELCOR and RELAP5 comparisons in normal operations and test transients designed to cover a representative range of accident-relevant phenomena;
iii. sensitivity and uncertainty studies in more complex accident scenarios;
iv. code-to-code comparison for the 32h LOOP (Loss of Power) accident analysis as the final step of the qualification.

It is clear that the qualification of the TBS models is limited at this stage to generic models developed and whenever needed for the analyses of specific accidents an additional effort will be undertaken. It is doubtful that such an approach would work for DEMO and future fusion power plants. Experimental data for the validation of the safety codes in much wider application domain that covers both fusion related phenomena and specific plant range of parameters will be needed for DEMO licensing. Due to the higher inventories of tritium, of tritium breeder and of neutron multiplier materials in DEMO, the acceptable conservatism in safety analyses of any fusion plant will be much lower than the one used in the ITER. This might be achieved by using new or improved modelling tools and safety codes and best-estimate uncertainty methods. The efforts in developing these tools, their verification and validation, relevant methodologies has to be of high priority in preparing the safety case of DEMO.

- *Compliance with the nuclear pressure equipment (ESPN) regulations*

The TBS are nuclear pressurized equipment which must fulfil the requirements contained in the French Regulations, essentially the ESP decree (December 1999) and ESPN order (December 2005), in order to assure the quality of the design, manufacturing and operation. Following these regulatory documents the TBM are classified as multi-chamber pressure equipment with common boundaries and on the basis of preliminary evaluation it belongs to the following classifications: the HCPB TBM would be classified in Cat. IV against risk of pressure (ESP), and the HCLL TBM would be in Cat. IV level N2 according to ESPN order. The ancillary system components have different ESP/ESPN classification depending on the operating conditions, radioactive inventory and volume.

The regulatory documents do not mention how to fulfil the given technical requirements and conformity assessments but only refer to professional guides leaving the manufacturer of the equipment the choice of the design and manufacturing codes. However, the manufacturer shall demonstrate the conformity of the selected codes and standards to the technical requirements and to the ESR (Essential Safety Requirements) contained in the ESP decree. The French nuclear code RCC-MRx has been chosen for the European TBMs as the reference code taking into account the operational conditions such as the irradiation and high temperature environment in an experimental reactor like ITER. Furthermore, it is important to point out that RCC-MRx Section II, specifically REC3200, lists the specific mandatory provisions for design and manufacturing, matching all the applicable rules of RCC-MRx to those in the ESP decree and the ESPN order. In addition the specific design rules for box structures (RB3800) are well adapted to the TBM structural layout.

In light of the considerations developed in this section, the DEMO designers have to consider the following points:

- It is requested by the licensing process to present to the Regulator and the Agreed Notified Body, along with design and safety analyses, supporting data like materials data and design limits, qualified fabrication procedures specifications and validated modeling tools that can go over the today’s state-of-the-art of nuclear industry.
- It is highly recommended to start already during the conceptual design a close interaction with a Notified Body in order to better understand and implement the Regulator constraints and requirements along the whole design process. Among the specific matters of discussion, one can mention: i) the possibility to get an exemption of conformity from ESP; ii) the in-module box pressurization and related definition of the maximum allowable pressure, when the equipment does not return into service; iii) the issue of low ductility materials like 9Cr ferritic-martensitic steels with respect to the regulation; iv) the implementation of alternative measures to fulfill inspection obligations that are not feasible by classical means.
- Being the licensing process a long lasting endeavor that requires significant efforts, it is highly recommended to the DEMO designers to study in detail and take into account the international (including European) nuclear fission safety standards, good practices and Generation IV methodologies for the Nuclear Safety Demonstration.

3.2 Safety functions: impact of their implementation on the design

When designing the systems of the breeding blanket for DEMO, the designers have to take into account the implementation of safety functions in order to ensure appropriate reactions to potential incidents and accidents like loss of coolant, loss of flow, loss of heat sink, etc. These are critical both for the management of abnormal situations and for the mitigation of their consequences, like minimizing the effect of loss of confinement and of the spread radioactivity. Three safety functions are identified specifically for the TBS, which are called upon detection of abnormal conditions by safety relevant instrumentation:

- isolation of TBS sub-systems;
- pressure release in case of over-pressurization;
- plasma termination requested by the TBS Plant Safety System to the Central Safety System.

An example of the impact of the implementation of the safety functions on the design development is the case of instrumentation and control system. The design against the single failure criterion, implementing the principle of defense-in-depth, requires the redundancy of safety devices (isolation and pressure relief valves), sensors, actuators and I&C cubicles. On top of redundancy, the use of 2oo3 (two-out-of-three) logic for sensors triggering the safety functions is highly recommendable to avoid that spurious signals may lead to unjustified shutdown of ITER. This logic has been implemented in the current design of the HCLL and HCPB-TBS in order to minimize the impact of TBS operation on ITER availability. As an example, this means that six pressure sensors located, distributed in pair in three different locations, will have to be implemented in the HCS loop to close the isolation valves in case of an ex-vessel LOCA. The two sensors belonging to each pair shall be physically separated and connected to independent plant safety cubicles. Taking into account that this approach is applied to all TBS sub-systems, there is proliferation of sensors and cables in the Port Cell, with integration issues and lack of space. Additionally, only instrumentation resisting to radiation field shall be used, in particular in the Port Cells. This is even a heavier limitation if one considers that on top of the safety functions sensors have to implement also investment protection functions. Using for the investment protection the same instrumentation adopted for the safety functions is a design solution for the two European TBS implementing a signal duplicator, located in the PSS cubicle, whose architecture is shown in fig. 3. This allows reducing the number of sensors, then lowering cost and integration issues.

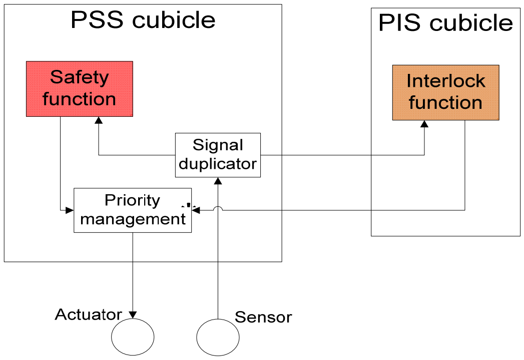

Fig. 3 Signal duplicator scheme for investment protection and safety functions

Two messages can be important for the DEMO designers. The first one is that the safety functions and their implementation have to be considered early in the design. In addition, this implementation has to be done already at the early stage with a quite significant level of detail, including the selection of the safety devices with the appropriate performance features.

As a matter of fact these are of critical importance to the setting up the two essential parts of the TBS safety case – i.e. implementation of the defense-in-depth and the accident analysis [5]. The sensors response, actuation time and set-points of isolation valves, as well the set-points of pressure relief devices, dump tanks capacity and liquid metal draining sequence are examples of key features. The second message is that the correct definition and implementation of the safety functions could massively impact the breeding blanket systems design due to the components redundancy, complexity of I&C configuration and space constraints, as already experienced in the first phase of the HCLL and HCPB-TBS design.

3.3 Design of the Instrumentation

TBS instrumentation must perform reliably in the ITER challenging environmental conditions. Depending on the sub-system, the number of physical parameters and range of measurement in the TBM set and ancillary systems is vast [6]. Some are recalled here:

- temperature, 300÷900 ˚C, for TBM structural and functional materials and ancillary system process fluids
- mass flow-rate of the process fluids, from few Nl/s to some thousand Nl/s
- pressure of the process fluids, from ambient pressure up to 8 MPa
- magnetic field, up to 5 Tesla in the TBM location
- electrical current, up to several thousand A for the eddy currents
- neutron flux, up to 10^{18} $n/m^2 s$ in the TBM
- neutron spectrum, from eV to MeV
- gamma radiation field, from10^{-5} to some Sv/h
- displacement/position, from 10^{-3} to some mm
- tritium concentration/partial pressure, from 10^{-2} to 10^{2} Pa, in the process fluids

The main challenges common to most ITER instrumentation are due to radiation (both direct from plasma and secondary emission from activated materials) and magnetic field effects. Both fields can cause in many conditions a real time, instantaneous drift in the sensor signal. This not only reduces the accuracy of the measurement but for instrumentation related to a control function it can also incorrectly activate control functions, with impact on machine availability. In addition, radiation effects cause damage in the sensors materials that could lead to long term, irreversible degradation of the performance. In the case of several TBS components (and in particular the TBM) field conditions are further complicated by high operating temperatures. A second issue to be considered for the selection of sensor technology is the integration in the component, sub-system and overall ITER design. The case of the TBM set (the in-vessel part of the TBS) is particularly challenging, giving the space limitations and the necessary penetration thru the main ITER confinement barrier (the vacuum vessel).

Following the ITER recommendation, sensors and related instrumentation chain have been categorized in three tiers: safety, investment protection, and conventional control (for system control and data acquisition for scientific mission). Depending on the tier to which they belong, different requirements in terms of accuracy, reliability, quality assurance, resistance to radiation, must be considered.

Moreover, for the TBS ancillary systems an additional issue is that the components are spread in several areas of the ITER complex, generating many interfaces with ITER systems and related specific requirements which have to be accounted for in selecting and designing the instrumentation.

Based on the experience gained in the TBM Project, the DEMO designers are suggested first of all to categorize the instrumentation needs in the three tiers above mentioned and to identify clear performance requirements. Moreover, depending on the typology and location of the instrumentation, several aspects have to be taken into account while designing the instrumentation for a breeding blanket: i) EM noise: both pulsed operation and fast transients due to plasma disruption imply the generation of time dependent magnetic fields and, then, eddy current. This can lead to spurious signals in instrumentation electronics which require appropriate shielding provisions; ii) brazing techniques: most commercial brazing techniques include the use of silver, which in principle should be avoided because of the transmutation to cadmium under neutron irradiation. Alternative materials must be considered for instrumentation design and their performance must be then validated against applicable requirements (vacuum, etc); iii) use of optical fiber systems: their application as transmission lines and specialized sensors in ITER components is very attractive to avoid the issue of EM noise reduce integration problems in case of limited space. However, their applicability must be carefully analysed because of the possible impact of high temperature and radiation field on basic properties, such as transmissivity, luminescence and refractive index.

3.4 Integration: tritium contamination in the areas hosting the systems

Already during the TBS conceptual design phase, the TBS integration in ITER has strongly impacted the design. A relevant example of this is related to the difficulty to respect the authorized level of tritium concentration for the C3 ventilation level (maximum 1 DAC during operation/maintenance; 1 DAC due to tritium contamination: $3.4\text{x}10^5$ Bq/m^3) foreseen for the Port Cell#16, where a substantial part of the HCLL and HCPB-TBS sub-systems is located. This is mainly due to the significant amount of tritium permeated from the TBM systems into the Port Cell areas, particularly through the piping and components of the PbLi loop and the two HCS. In spite of the presence of a continuously running DS, the global tritium permeation rate into the Port Cell, which might be a relevant fraction (up to 3%) of the HCLL and HCPB-TBM tritium generation rate, leads to a high tritium concentration in the room housing the systems, well beyond of the target of 1 DAC during plasma operation. Moreover, the tritium absorbed in the epoxy painted walls is slowly released, impairing possible hands-on maintenance activities.

Fig. 4 shows the calculated evolution of the tritium concentration in the Port Cell with a value of 40 m^3/h of DS flow-rate in the 12 days of plasma operation and in the subsequent days where plasma is supposed shut-down. This preliminary analysis was carried out through the TMAP simulation tool with the support of INL scientists. Based on the experience gained in the conceptual design of the HCLL and HCPB-TBSs the DEMO designers should consider different possible countermeasures, like:

- to implement in the design provisions to strongly reduce the tritium permeated into the areas hosting the breeding blanket systems. They are, essentially:
  - design of a tritium extractor from Pb-16Li with high extraction efficiency (>80%) to lower the tritium partial pressure in the liquid metal, then reducing the tritium permeation rate into the relevant rooms;
  - use of tritium permeation barriers on the inner walls of the piping;
  - adoption of suitable operating conditions: i) PbLi flow-rate as high as possible to reduce the tritium partial pressure in Pb-16Li; high CPS flow-rate to keep low the tritium partial pressure in the main cooling system.
- to increase the DS recirculation rate, as the steady state tritium concentration in the air is inversely proportional to the DS flow-rate for a given tritium source rate;
- to use a wall epoxy liner characterized by a very low HTO solubility;
- to wrap with enclosures piping and components which are the higher contributors to the tritium permeation, connecting the DS directly to the enclosures.

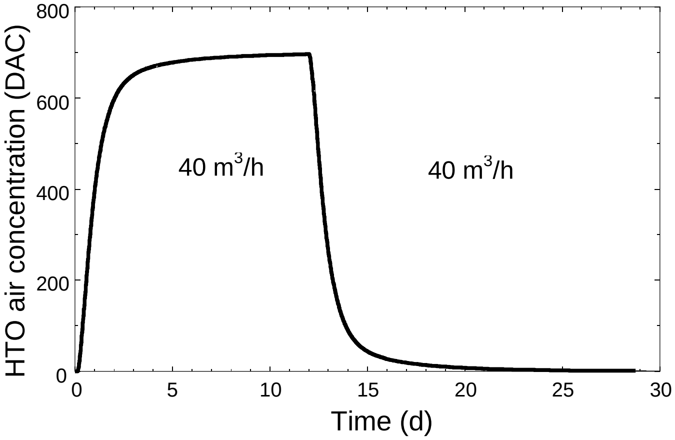

Fig. 4 Tritium concentration evolution in the Port Cell#16 during plasma operation

4. Conclusions

The design of HCLL and HCPB-TBS has completed its conceptual phase. Already at this stage, the return on experience for the DEMO breeding blanket design is relevant in different ambits. Preliminary lessons learned for the breeding blanket designers deal with the implementation of the TBS licensing procedure, the design of the safety functions with the related impact on the instrumentation integration, the design of instrumentation for the different functions (safety, investment protection, conventional control) and the impact of the integration of the TBS in the ITER environment on several design aspects: in this paper the example of the management of the tritium contamination in the areas hosting the breeding blanket systems has been described.

The design provisions described in this paper have been implemented in the European TBM project to solve several issues related to the above mentioned items. Based on the experience gained in conducting the TBS design, specific recommendations are given in this paper to the DEMO designers in order to guarantee a consistent approach to the breeding blanket design from the early stage.

Disclaimer

The views expressed in this publication are the sole responsibility of the authors and do not necessarily reflect the views of Fusion for Energy and ITER Organization.

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