Safety issues review of the EU
Helium Cooled Lithium Lead ITER Test Blanket Module

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The Helium Cooled Lithium-Lead (HCLL) breeder blanket concept is one of the two breeder blanket lines presently developed by the EU for DEMO reactor. In the short-term so-called DEMO relevant Test Blanket Modules (TBMs) of these breeder blanket concepts shall be designed, manufactured, tested, installed, commissioned and operated in ITER for first tests in a fusion environment. A review of the safety issues related to this HCLL TBM is presented and discussed in this paper.

A first review of the safety objectives assigned to the test blanket and the compliance with the ITER project safety requirements is presented. Taking into account the ITER basic safety guidelines, a complementary dedicated safety analysis is performed in order to investigate the impact of ITER failures on HCLL-TBM and vice-versa. A list of postulated initiating events has been established following this safety analysis.

Thermo mechanical calculations of the TBM have been performed in order to simulate the accidental conditions following the postulated initiating events. The results are presented and the most challenging parameters that influence the transient are identified.

Special considerations for occupational doses and radioactive releases during normal operation have been addressed and are also presented.

Future work will consist firstly in new refinements due to ITER project data changes and secondly to deal with concerns about the most severe accidental situation which is an ex-vessel LOCA followed by an in-vessel LOCA with plasma disruption and PbLi / water reaction. The different assumptions that have been set up in this scenario will be discussed and the computational tools and models needed to simulate such sequence are presented.
1. **THE HELIUM-COOLED LITHIUM-LEAD (HCLL) BREEDING BLANKET**

Helium Cooled Lithium Lead (HCLL) breeding blanket concept for DEMO has been developed and optimized (with regard to tritium breeding, heat removal and shielding capability), sharing with the Helium Cooled Pebble Bed (HCPB) concept the maximum basic technology (structures fabrication techniques, segment box, He technologies, etc). Previous developed concepts have permitted to identify the basic orientations for a common HCLL/HCPB modular design structure. In particular, the radial orientation of the He cooling in the Breeder Zone has been chosen, which allows the positioning of the collector region in the rear of the module. On the basis of these orientations an HCLL concept has been developed, which seems to be the best compromise with regard to its multiple functional requirements. Neutronic, thermal, thermal-hydraulic and mechanical calculations have been carried out for the dimensioning of the module, a feasibility fabrication study has been performed, and a manufacturing sequence has been envisaged.

2. **HCLL TESTING STRATEGY AND TEST PROGRAMME IN ITER**

- In order to test in a real fusion environment DEMO-relevant blanket concepts before the construction of a DEMO reactor, a HCLL Test Blanket System (TBS) has been developed to be introduced and tested in ITER.

In addition, as the Test Blanket Module (TBM), part of the TBS, is a FW component comparable with the ITER Shielding Blanket, it must fulfil the basic functions common to all in vessel components.

- For the first 10 years of operation, the ITER time-schedule envisages four plasma phases, H-H, D-D, low and high duty cycle D-T with related operating conditions. Because of the differences between the ITER loading conditions and those expected in DEMO, the option of testing several 'act alike' TBMs is selected, which will allow to adapt each module and relevant instrumentation to the ITER parameters in each phase. Moreover, this process will allow to gradually validate the HCLL blanket concept, technologies and design tools while having the minimum impact on ITER safety and availability.

3. **THE HCLL TBM DESIGN**

The TBM looks alike a generic HCLL breeder blanket module for DEMO. It features a steel box cooled by horizontal multi-passes rectangular cross section channels and closed by top and bottom cooled covers and, in the rear, by 4 steel plates acting also as distributing/collecting chambers for the He coolant.
The box is stiffened by poloidal radial and toroidal radial cooled plates (vertical and horizontal stiffening plates, SPs) in order to withstand the internal pressurization at 8 MPa in case of accident (loss of coolant inside the TBM). The grid also stiffens the box against the torques acting on it during disruptions.

The grid forms radial cells in which circulates the multiplier/breeder PbLi, so allowing external tritium extraction. In each cell is inserted a breeder cooling unit (BU), ensuring the heat recovering from the breeding zone. Each BU consists of five radial toroidal plates (Cooling Plates, CPs) cooled by internal double U rectangular channels and welded to the BU back plate. Two BU collectors located behind the BU back plate distribute/collect the He circulating in the CPs.

An exploded view of the latest version of the TBM design is shown in Fig. 1. One He circuit is envisaged to cool both the FW and the breeder zone. In last the DEMO blanket module design, the “cold” He (Tin = 300°C) cools first the FW recovering all the power deposited as heat flux (HF) on the FW and a small percentage of the nuclear power deposited in the breeder zone (BZ). Then the He passes in series in the SPs and then in CPs in which it recovers the largest part of the nuclear power deposited in the BZ and finally it exits at 500°C. For TBM, in which the ratio between the thermal power deposited on the FW and the one deposited on the BZ (0.5/0.78) is slightly different compared to the DEMO one (0.5/2.2). Thus, the use of a by pass to extract a significant part of the He flow rate after the FW cooling is required in order to be able to have a CP's outlet temperature of 500°C. Envisaged He flow path is shown on Fig. 2.

The improved liquid metal flow path allows higher re-circulation rates avoiding excessive PbLi velocities; parallel loops have been chosen rather than a meandering circulation on the whole module height. The liquid metal enters from the external collector and then it is distributed in some intermediate vertical distributing boxes located behind the BU. It enters in a BU and exits from the one below, feeding in this way the BU in parallel (par couple). The PbLi flow path in a TBM vertical column is schematized in the Fig. 3. Assuming 10 recirculations/day, the PbLi mass flow rate will amount to 0.33 kg/s. With this figure, the liquid metal velocity will be ~6 mm/s in the feeding pipes and in the distribution box, ~0.08 mm/s in the BU current section and will increase to ~2.8 mm/s in the front opening between the SP and the FW.
Fig. 1: Exploded view of the HCLL In-TBM

Fig. 2: Envisaged He flow path for the HCLL TBM
4. SAFETY APPROACH FOR HCLL-TBM INTEGRATION

4.1 Main lines of the safety approach

From safety standpoint, the objective of the approach is to confirm the feasibility, i.e. the absence of strong drawback, and to check that the HCLL-TBM integration into ITER does not alter globally the safety level of ITER.

For this purpose, a dedicated approach is built whose main lines are:

- The respect and application of the existing ITER basic safety guidelines,
- The establishment of a list of the additional ‘potential hazards’ for ITER, brought by the integration of the HCLL-TBM,
- The identification of the safety functions assumed or to be assumed by the HCLL-TBM,
- The review of the normal and off-normal operating conditions of ITER including the HCLL-TBM,
- The selection, from the operating conditions and events, of those relevant for definition of the first studies either on safety, dimensioning or operation,
4.2 Coupling aspects of the approach

A general approach, both for initiating the TBM safety analysis and defining safety design requirements, can be split into two sub-approaches:

- Investigating the influence of TBM integration on ITER operation, availability and safety,
- Investigating the impact of ITER system and operation on TBM design, operation and reliability.

These analyses have to be considered in parallel but with possible interactions.

4.3 Mobilized sources and acceptance criteria

The source term and the physical mechanisms that could drive it towards another place, shall be defined.

ITER sources and transport modes:

ITER processes and plant involve potential hazard sources. In accordance with the need for assessment of consequences, the safety approach has to list:

- The nature and quantities of the existing dangerous sources, else with the plant in normal operation, or produced by off-normal operating conditions (e.g. chemical reactions…),
- The possible fault modes that could lead to transport an amount of mobilized source term.

These phenomena involve:

- the energy initiating the transport mode,
- the release pathway including failure of barriers and/or confinement provisions, either as initiating event or as induced event in the considered scenario.

HCLL sources and transport modes:

- The tritium production rate in the HCLL-TBM is 76 mg/day, for a two years period, the inventory is estimated to be about 30g, which is relatively small compared with ITER one (450 g in VV).

But the HCLL-TBM tritium can diffuse through the structures, and the quantities in the diverse loops have to be calculated.

5. HCLL-TBM RELATED SAFETY FUNCTIONS

5.1 Approach of the safety functions

In the "Test Blanket requirements", safety function is allocated to TBM as follows:
### Component and Safety Function

<table>
<thead>
<tr>
<th>Component</th>
<th>Safety function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex-vessel part of Test Blanket components</td>
<td>Part of confinement barrier</td>
</tr>
<tr>
<td>Test Blanket cells</td>
<td>The another (second) confinement barrier</td>
</tr>
</tbody>
</table>

5.2 **Main safety functions**

The ITER safety functions should be supported by components well validated, thus not by experimental components, in particular TBM's parts, as far as possible.

However, if some parts of TBM system are necessarily involved within the ITER safety functions, then the concerned parts must be sufficiently validated in relation with the required reliability.

This approach might be implemented by a progressive HCLL-TBM validation program.

5.3 **Additional safety sub-functions**

The HCLL-TBM system contains breeding and multiplier materials (Li-Pb and maybe Be), pressurized coolants (primary He, secondary $H_2O$) that could challenge the integrity of structures and barriers, either directly (e.g. pressurization) or indirectly (e.g. reactions, $H_2$ production).

Thus, safety provisions must be implemented despite the experimental character of the HCLL-TBM. These provisions should be:

- Safety classified barriers to prevent fluid leakage or chemical interaction,
- Safety classified cooling system, if failure of heat removal can lead to damages.

6. **ABNORMAL OPERATING CONDITIONS AND EVENTS**

The list of events relevant for further studies has to be reviewed, with the two complementary sides: influence of TBM integration on ITER operation/availability/safety, and impact of ITER system and operation on TBM design/operation/reliability.

6.1 **ITER events impacting the HCLL-TBM**

With the ITER list of reference events as a starting point, the table 1, where only useful events are pointed out, shows that relevant events involved in environmental releases (off-site column) and those impacting HCLL-TBM studies (last column) are a priori not the same. This is a positive aspect for the HCLL-TBM.
<table>
<thead>
<tr>
<th>Area</th>
<th>Reference events</th>
<th>Cat.</th>
<th>Off-site</th>
<th>R*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma</td>
<td>Loss of plasma control/exceptional plasma behavior</td>
<td>I, A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>Loss of off-site power for up to 1 h</td>
<td>I</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>In-vessel</td>
<td>Loss of vacuum through a vacuum vessel penetration line</td>
<td>A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Ex-vessel HTS</td>
<td>Heat exchanger tube rupture</td>
<td>A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>Stuck divertor cassette in transport cask</td>
<td>A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintenance accident on vacuum vessel</td>
<td>A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Tritium plant, Fuel cycle</td>
<td>Trinitium process line leakage</td>
<td>I</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Isotope separation system failure</td>
<td>A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuelling line with impaired confinement</td>
<td>A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Magnet</td>
<td>Not relevant for releases, and not for HCLL-TBM studies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryostat</td>
<td>Water/air/helium ingress</td>
<td>A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Hot Cell</td>
<td>Failure of confinement</td>
<td>A</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

I : Incident  A : Accident

Off-site : relevant for environmental releases  R* : relevant for TBM-HCLL studies

Table 1: ITER events impacting the TBM

6.2 HCLL-TBM events with self-impact or impacting ITER

A simple method is proposed in order to define a first list of these events. Its outlines are:

- Define the Postulated Initiating Event (PIE), a priori equivalent to a loss of barrier, and classify it among families: e.g. direct leakage or indirect one (for example, resulting of overheating), confinement barrier or only separating barrier, etc.
- Choose two or three levels of fault severity for each event family
- Prepare the type of aggravating condition that shall be combined with the PIE

7. OCCUPATIONAL EXPOSURE

Dose rate calculations for the PbLi coolant and Eurofer are low, particularly for the PbLi coolant. These dose rates are envelope and do not take into account attenuation factors such as the shields (structure, protection, etc.), distance and time. Within the scope of the ALARA approach and
measures applied to the design of hot cells, the dose rates absorbed by the operators will still be significantly reduced.

The PbLi system represents one of the first barriers against the dose rate resulting from the activation of the PbLi coolant. The Eurofer structural thickness also helps for attenuation. The TBM is 4 cm thick. According to the attenuation curves, a 41 mm thick steel screen is sufficient to reduce the dose rate of $^{54}$Mn by half, whereas a 39 mm thick steel screen will reduce the dose rate of $^{51}$Cr.

Table 2 provides the dose rates obtained for the Eurofer front and rear parts. The parameters taken into account in calculations are the height (about 176 cm) and width (about 131 cm) of the TBM, as well as the 40 mm thick Eurofer screen corresponding to the back plate thickness. All gamma emission lines are taken into account.

<table>
<thead>
<tr>
<th>Nucleide</th>
<th>Activité (Bq)</th>
<th>DDD MICROSHIELD mR/hr</th>
<th>DDD MICROSHIELD mSv/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe 55</td>
<td>3.26E+16</td>
<td>1.11E-18</td>
<td>2.86E-22</td>
</tr>
<tr>
<td>Mn 54</td>
<td>1.82E+15</td>
<td>3.53E+06</td>
<td>9.11E+02</td>
</tr>
<tr>
<td>V 49</td>
<td>5.59E+13</td>
<td>1.34E-21</td>
<td>3.45E-25</td>
</tr>
<tr>
<td>Ta 182</td>
<td>5.53E+13</td>
<td>1.43E+05</td>
<td>3.68E+01</td>
</tr>
<tr>
<td>W 181</td>
<td>3.03E+13</td>
<td>1.66E-01</td>
<td>4.29E-05</td>
</tr>
<tr>
<td>Co 60</td>
<td>1.79E+13</td>
<td>1.20E+05</td>
<td>3.10E+01</td>
</tr>
<tr>
<td>W 185</td>
<td>1.60E+13</td>
<td>1.83E-03</td>
<td>4.71E-07</td>
</tr>
<tr>
<td>Cr 51</td>
<td>4.17E+11</td>
<td>1.12E+01</td>
<td>2.89E-03</td>
</tr>
<tr>
<td>Nb 93m</td>
<td>3.66E+11</td>
<td>2.85E-24</td>
<td>7.35E-28</td>
</tr>
<tr>
<td>Sn 119m</td>
<td>2.85E+11</td>
<td>2.63E-15</td>
<td>6.80E-19</td>
</tr>
<tr>
<td>Co 58</td>
<td>1.92E+11</td>
<td>4.11E+02</td>
<td>1.06E-01</td>
</tr>
<tr>
<td>Fe 59</td>
<td>1.26E+11</td>
<td>3.94E+02</td>
<td>1.02E-01</td>
</tr>
<tr>
<td>Ca 45</td>
<td>8.43E+10</td>
<td>2.39E-31</td>
<td>6.18E-35</td>
</tr>
<tr>
<td>Sr 124</td>
<td>5.37E+10</td>
<td>2.32E+02</td>
<td>5.99E-02</td>
</tr>
<tr>
<td>Sr 125</td>
<td>4.38E+10</td>
<td>2.99E+01</td>
<td>7.71E-03</td>
</tr>
</tbody>
</table>

Table 2 : Dose rate for Eurofer