Development of load specifications for the design of the breeding blanket system

Gandolfo Alessandro Spagnuolo[a], Lorenzo Virgilio Boccaccini[a], Gaetano Bongiovì[a], Fabio Cismondi[b], Ivan Alessio Maione[a]

[a] Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[b] EUROfusion Consortium, Boltzmannstr.2, Garching, 85748, Germany

The Breeding Blanket (BB) system with a volume of about 1700 m^3 and a plasma front surface of about 1400 m^2 represents the largest In-Vessel component of DEMO reactor. Due to its position and its key functions (e.g. tritium production, thermal power removal and shielding), the BB is also one of the most critical component. The single loads acting on the BB can be of different nature (inertial, pressure, thermal and electromagnetic, for instance) and their combination may produce high stresses jeopardizing the BB structural integrity if not carefully taken into account during the design. For these reasons, within the EUROfusion consortium, the development of BB system load specifications has been pursued since the early pre-conceptual design phase.

The main goals of this work are: (i) to list all relevant single loads and their combinations to be considered for the verification of BB structural integrity, and the categorization of these relevant load combinations, (ii) to identify the short list of load combinations relevant to the pre-conceptual design review phase in sight of 2020 Gate Review. Particular emphasis is also given to the most representative postulated initiating events, which drive the design of the BB, providing their respective load combination.

Keywords: DEMO, Breeding Blanket, load specifications, postulated initiating events.

1. Introduction

The European DEMOnstration Fusion Reactor (DEMO) represents an important step of the Roadmap to Fusion Electricity [1]. Its ambitious schedule is approaching an important step with the conclusion of the Pre-Conceptual Design (PCD) phase in 2020, when the project's Gate Review will take place, and with the starting of the Conceptual Design (CD) one in 2021 [2]. This programme affects also an essential DEMO component such as the Breeding Blanket (BB). In this regard, the Helium Cooled Pebble Bed [3] (HCPB) and the Water Cooled Lithium Lead [4] (WCLL) BB concepts have been selected as possible candidates to become driver BB for DEMO. Hence, they will face the Gate Review process aimed at assessing and validating the progress/achievements of their design [5]. For these reasons, a set of documents has to be prepared with the aim to substantiate the work already done and to provide indications useful for the next CD phase.

Within this framework, the BB Load Specifications represents one of the key documents. It includes:

- the list of all relevant single loads and their combinations to be considered in order to verify the structural integrity of the HCPB and WCLL BB;
- the categorization of these relevant load combinations;
- the number of load cycles;
- the description of the states of the HCPB and WCLL BB concepts during their life-time.
- the description of the load events significant for the HCPB and WCLL BB concepts.

The preliminary description of the DEMO BB Load Specifications is herewith reported, together with a purposely identified short list of load combinations relevant to the PCD phase. To this end, a description of the load categories and damage levels is given in Section 2 whereas operational and accidental single loads are described in Sections 3 and 4 respectively. Lastly, the identified load combinations are reported in Section 5 and conclusions are given in Section 6.

2. Load categories and damage levels

On the basis of the occurrence frequency (f), each event that affects the BB System is classified according to the load categories defined in [6, 7]. Starting also from the work done in ITER [8], four different event categories are identified for DEMO BB. They go from the operational events, where all the system conditions planned for the DEMO normal operation are included, to the extremely unlikely event sequences, which includes all the postulated events that are not likely to occur during the plant life (10^{-4}/y > f > 10^{-6}/y). In between, one can find the likely sequences, in which all the event sequences that are not planned but likely to occur several times during the life of the system (f > 10^{-2}/y) are considered, and the unlikely sequences, where some postulated events (10^{-2}/y > f > 10^{-4}/y) are assumed. Events with f < 10^{-6}/y are not considered within the design basis and, therefore, they are not assumed for the system design. Such kind of events are usually identified as beyond design and taken into account for the verification of the system safety. The unlikely and extremely unlikely sequences correspond to the accidental DEMO plant conditions. To each load category, a corresponding damage limit at component level is associated. Four damage limits are identified:

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author's email: alessandro.spagnuoloakit.edu

normal/test, upset, emergency and faulted. For the normal damage, the component should maintain its service functions. The upset limit includes all the not-significant damages that do not require any inspection or repair of the component. In the emergency damage limit, large deformation could arise and the component may necessitate removal for inspection and/or repair. In this case, the general strain should be within the elastic regime (i.e. insignificant permanent deformations). The faulted damage represents the most dangerous situation where the component faces gross general deformation and its functions as well as structural integrity is strongly degraded (only the safety function is still maintained).

Usually, the Codes & Standards (C&S) define the link, in terms of “criteria levels”, between the event occurrence frequency and the damage limits. Regarding the DEMO BB, the selected C&S is the RCC-MRx [9] (in this code, the structural material EUROFER97 is reported). In Table 1, the criteria levels defined in RCC-MRx are reported.

Table 1. RCC-MRx criteria levels [9].

Loading Category	Damage Limit	Criteria Level
Category I: Operational Loading Conditions	Normal/test	Level A
Category II: Likely Loading Conditions	Upset	Level B
Category III: Unlikely Loading Conditions	Emergency	Level C
Category IV: Extremely Unlikely Loading Conditions	Faulted	Level D

Moreover, the Category Test is introduced for DEMO BB in order to evaluate some operational test to be performed prior to the operational phase.

3. Main design driving single loads

3.1 Integrated approaches and load paths

The BB is a complex system that will be operated in a harsh environment. It interfaces several systems (e.g. Remote Maintenance, Balance of Plant, Vacuum Vessel attachment, Heating and Current Drive and Fuelling Lines Systems) [10] and has to fulfill important key functions like tritium breeding and thermal power removal [11]. Indeed, the BB is subjected to different and simultaneous loads (e.g. high heat and neutron fluxes, variation with space and time of strong magnetic field as well as radiation damage [12]) that drive its design. For these reason, in the definition of the load combinations and in the design analysis, the use of a holistic approach is becoming a mandatory [13, 14]. An example of the interfacing systems and their relations with the BB in terms of mechanical and ferromagnetic force transferred from the ground up to the BB through the DEMO reactor is reported in Fig. 1. The ultimate goal is to be able to identify the major loads, which form the design basis, that can be superimposed in order to determine the load combinations to be used for the BB design. The single loads are divided in: inertial, pressure, thermal, electromagnetic loads. Other loads (single or their combination) can arise during accidental events. In the following paragraphs, an overview of the single loads is presented.

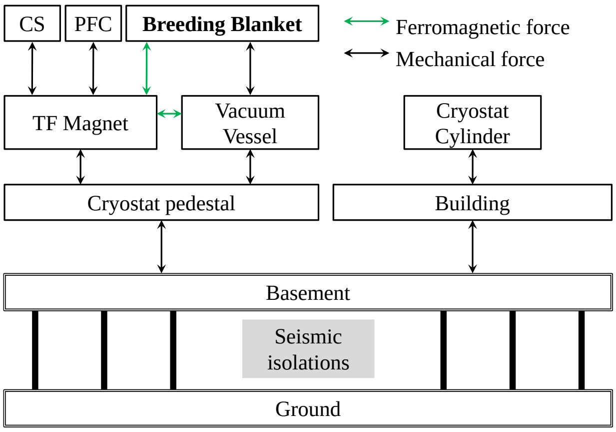

Fig. 1. Load path in DEMO reactor.

3.2 Inertial loads

Due to the size of the BB, inertial loads represent an important contribution in the design, for instance, of the support system. Two kind of inertial loads (L_{inert}) have been so far identified for the BB: the dead weight and the seismic loads. The first represents the mass of the BB with a vertical acceleration of 9.806 m/s^2 and it is included in all load combinations. The room temperature must be considered as reference one in structural calculation (volume estimation and no thermal stress conditions). The inertial load can vary according to the operation state from 39 tons (WCLL Inboard Blanket, IB, without LiPb) to 179 tons (WCLL Central Outboard Blanket, COB, with LiPb) [15] or from 49 tons (HCPB IB) to 55 tons (HCPB COB) [3]. Regarding the seismic loads, as stated in [7], three levels of ground motion are considered: SL-2 as Cat. IV event (extremely unlikely), SMHV (Maximum Historically Probable Earth-quake) as Cat. III event (unlikely) and SL-1 as Cat. II event (likely).

3.3 Pressure loads

The pressure loads (L_{press}) are exerted within the BB under normal and accidental conditions by the operational fluids coolants and/or breeder. The main pressure loads for the HCPB and WCLL First wall (FW) and Breeder Zone (BZ) are reported in Table 2. Considering that the "Design" pressure is the value of the pressure that the BB system must safely withstand under operating conditions, this value must include any normal excess pressure that can occur during the system's operation. This is a discretionary value that depends on the foreseen operational transients plus the margin provided by C&S. For DEMO BB load specifications, an increment of 15% over the operational pressure has been assumed in order to define the Design Pressure value. The same value is used also for the design pressure applied for the Primary Heat Transfer System (PHTS).

Table 2. Pressure loads with temperature in each state.

Component		Fluid	Pressure test	Normal Operation[1]	Maintenance	Maximum allowable	Design value
HCPB BB	FW+ BZ	He	17.801 MPa 20 °C	8.0 MPa 300 °C	TBD	9.2 MPa 550 °C	9.2 MPa 550 °C
	PB[2]	He	0.445 MPa 20 °C	0.2 MPa 450 °C	TBD	0.23 MPa 550 °C	0.23 MPa 550 °C
WCLL BB	FW	H_2O	25.570 MPa 20 °C	15.5 MPa 295 °C	TBD	17.825 MPa 344.8 °C	17.825 MPa 344.8 °C
	BZ	H_2O	25.570 MPa 20 °C	15.5 MPa 295 °C	TBD	17.825 MPa 344.8 °C	17.825 MPa 344.8 °C
		PbLi[3]	0.742 MPa 20 °C	0.45 MPa 326 °C	TBD	0.5175 MPa 344.8 °C	0.5175 MPa 344.8 °C

[1] The pressure and temperature are inlet pressure and inlet temperature.

[2] Pebble bed

[3] The design and maximum allowable pressures do not take into account the weight of the fluid column.

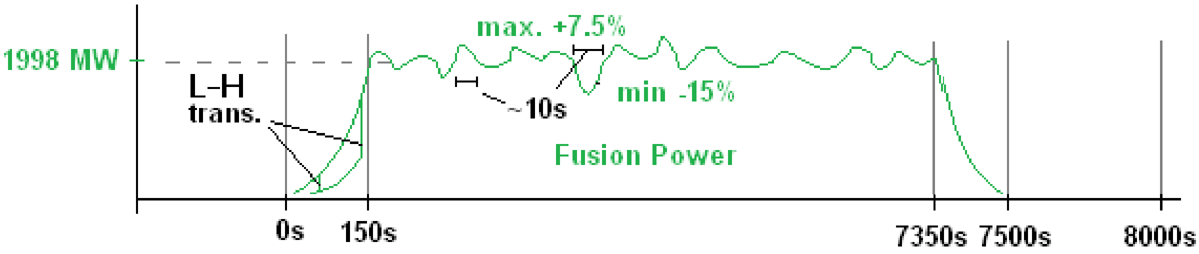

Fig. 2. Plasma pulse profile with power excursion during flat-top [16].

The Normal Operation pressures and temperatures are considered at the inlet of the component. The Design temperature is, as to HCPB, the Eurofer maximum allowable temperature whereas, as regards WCLL, it is the water saturation temperature at the Normal Operation pressure. These temperatures have been assumed as design ones also for purge gas and PbLi. The Maximum Allowable Working Pressure (MAWP) is defined, according to the used C&S, as the maximum vessel or equipment pressure at which the component is allowed to function considering a specific temperature. Currently, the maximum allowable pressure and temperature have been assumed equal to the design ones.

The test pressure has been calculated following the hydrostatic test (REC 3257.4) of RCC-MRx [9] for the WCLL BB and the pneumatic test (IC3231.2) of SDC-IC [17] for the HCPB BB.

3.4 Thermal loads

Thermal loads (L_{ther}) are the most relevant loads for the dimensioning of the blanket structures during normal operation. The considered thermal loads are the Heat Flux (HF) coming from the plasma and acting on the FW and the volumetric Nuclear Heating due to the nuclear reactions inside the blanket materials because of the neutron flux. Due to the pulsed nature of DEMO machine, the thermal loads may vary in space and time according to plasma operation (Fig. 2). For this reason, it is possible to identify an asymptotic case (steady state loads) that should be reached during the plasma flat-top (including controlled perturbations), and time varying load cases (transient loads) which are either normal (rump up/down, due to the pulsed nature of DEMO) or off normal transients (disruptions, VDEs, loss of confinement etc.).

3.5 Electromagnetic loads

Electromagnetic loads (LEM) arise from the interaction of the ferromagnetic/conductive structure with the currents and the magnetic field generated inside the tokamak and act on the BB structure during both normal and off-normal operations. In particular, their distribution and magnitude strongly depends on the tokamak magnetic configuration, BB segments design and their electrical connections with the other conductive structures, as well as on the considered plasma scenario.

Following the categorization given in [18], two main EM loads have been identified: 1) ferromagnetic loads, due to the magnetization of the ferromagnetic materials (i.e. EUROFER); and 2) Lorentz loads generated by the interaction of currents that flow through the BB structure with the external magnetic field.

Due to their nature, ferromagnetic loads act during all the operational states of the machine in which a magnetic field is present. With respect to the BB system, the main component of these loads is a radial force directed towards the inner leg of the TF coils (due to a predominant 1/r toroidal magnetic field), whose intensity is mainly driven by the amount of ferromagnetic material and the intensity of the magnetic field and its gradient.

On the other side, Lorentz loads arise during off normal operations in which a magnetic transient is triggered. Such events, as plasma vertical displacement

(VDE), plasma disruptions (e.g. MD), coils discharges, etc., are characterized by a change in the magnetic flux (both toroidal and poloidal) that consequently induce currents in the conductive structure. Moreover, an additional contribution is given by the HALO currents that flow from the plasma edge to the BB walls. With respect to the ferromagnetic forces, the behaviour of Lorentz forces is quite complex and strongly depends on the particular scenario considered for the analysis.

4. Loads due to accident events

Although the BB is not classified as Safety Important Class (SIC) component [19], it can support the mitigation of accidents that could jeopardize SIC components like the Vacuum Vessel (VV) to which is associated the function of primary confinement. Currently, the relevant types of accidents considered in the BB design include the In-box LOCA (leak of coolant from the FW or blanket structure cooling circuits inside BB box) and the Ex-Vessel LOCA (leak of coolant from the primary circuit in ex-vessel environment). The mitigation of these accidents could avoid the propagation of domino effect that might compromise the reactor safety and investment. Indeed, if the structural integrity of the segment box is not maintained during an In-Box LOCA, the accident can propagate in an In-Vessel LOCA (leak of fluid inside plasma chamber) jeopardizing the VV. On the other hand, the increase of BB temperature, due to the loss of coolant during the Ex-Vessel LOCA, could cause the uncontrolled expansion of the BB segment and, then, damage of supports attached to the VV with the possible consequent deterioration of primary confinement. For these reasons, these accidents have been considered and analyzed in the following.

4.1 In-box LOCA

According to the Postulated Initiating Event (PIE), a small and large In-Box LOCA can be defined for the BB depending on the size of the cooling channel break within the BB box. The reference event for this PIE is the small or the large loss of coolant from the FW or blanket structures cooling circuits inside the BB box because of a sealing weld rupture.

According to the strategy already adopted for ITER TBM programme [20], large In-Box LOCA can be considered as Design Basis Accident and therefore it is classified in event category IV. For this case the peak pressure is determined conservatively assuming that the PHTS can ensure the “nominal” coolant pressure with +/- 5% accuracy with an additional +/- 5% for the burst disc in case of PHTS failure (Table 5). The small in-Box LOCA (in ITER TBM of Cat. III) can be enveloped in the large one under certain conditions, namely assuming that the box is designed at the peak pressure for Cat. IV conditions and that primary stresses are directly proportional to pressure. In ITER TBM, the “allowable” pressure in Cat. III conditions (namely for the small In-box LOCA) is defined by the ratio of the corresponding allowable stresses defined by Level C and Level D criteria times peak pressure for Cat. IV.

A validation of this procedure is under discussion in DEMO. In fact, the present estimated frequency of small in-box-LOCA is too high, leading to a classification of this event into Cat. II, Level B (see Table 3 taken from preliminary reliability, availability, maintainability and inspectability (RAMI) analysis performed on HCPB and WCLL BB [21]). Therefore, in order to envelope the small In-Box LOCA in the large one, the pressure relief systems on the tritium carrier loop must ensure that the pressure of 4.65 MPa (HCPB) and 9.01 MPa (WCLL) is never exceeded during the accidental Cat. II transient (Table 5).

Table 3. Event category for the small and large In-Box LOCA events.

	HCPB		WCLL	
	Freq. [y^{-1}]	Cat.	Freq. [y^{-1}]	Cat.
Small In-Box LOCA	5.9	II	0.3	II
Large In-Box LOCA	-	IV	-	IV

In DEMO this failure frequency should be reduced in any case with an improvement of the BB design and related fabrication technologies. Dedicated studies have to be performed in order to evaluate the peak pressure within the BB box occurring during the In-Box LOCA transient.

4.2 Ex-Vessel LOCA

According to the PIE, a small and large Ex-Vessel LOCA can be defined for the BB depending on the size of the break on the BB primary cooling circuit. Using a deterministic assessment, the trend of temperatures inside the blanket box and the thermo-mechanical stress on the blanket box structures and attachment, due to the expansion in absence of the coolant, have to be estimated. The RAMI analysis [21] has shown a very high occurrence frequency of the small Ex-Vessel LOCA, as reported in Table 4. Considering that the main difference between small and large Ex-Vessel LOCA is the transient velocity, it can be conservatively assumed that the small Ex-Vessel LOCA is enveloped within the Large Ex-Vessel LOCA that, as done before, can be considered as Design Basis Accident and therefore it is classified in event category IV regardless of its frequency of occurrence.

Table 4. Event category for the small and large Ex-Vessel LOCA events.

	HCPB		WCLL	
	Freq. [y-1]	Cat.	Freq. [y-1]	Cat.
Small Ex-Vessel LOCA	0.1	II	0.6	II
Large Ex-Vessel LOCA	-	IV	-	IV

5. BB load combinations

In order to define the load combinations that should be taken into account in the BB design, several analyses are currently ongoing for establishing the probability that one condition triggers another loading event. More than

130 load combinations have been identified starting from the definition of plasma and cooling states and taking into account the initiating and concatenate events. The design driving load combinations so far recognised for the design of the BB are 54. The information given in the load combinations tables is structured as following:

- Category & id: these two columns provide the coding corresponding to each load combination;
- DEMO Plant Operation State: this column reflects the DEMO Plant Operation State compatible with the corresponding load combination, in accordance to those defined in [6], namely, Plasma Operation State (PO), Testing & Conditioning (TCS), Short Term Maintenance (STM) and Long Term Maintenance (LTM);
- Pressure/Magnets/Seismic: this column highlights the existence within each load combination, of abnormal events associated with the pressure, magnetic and seismic load cases;
- Initiating and Concatenated events: these two columns provide information about the events initiating the sequence that leads to the corresponding load combination, as well as any other concatenated events;
- Cooling and tritium carrier state: these columns describes, in terms of circuit pressure and inlet temperature, the state assumed for each specific load combination.
- PHTS Operating mode: This column defines the operating mode assigned to the PHTS;
- No events: This column shows the number of events associated to each category I or II load combination (this information is still missing for the PCD phase).

For the load combination cases, a short list of 10 load combinations to be used for the PCD phase is here indicated based on engineering judgment about enveloping cases (Table 6).

6. Conclusion

The identification of the single loads as well as their combinations represents a basic input for the assessment of BB structural integrity in sight of the end of the DEMO PCD phase. The preliminary definition of the main loads both during normal and accidental conditions affecting the BB design has been performed and reported in this work. Starting from the definition of plasma and cooling states and taking into account the initiating and concatenate events, it has been possible to identify more than 130 load combinations, of which 54 have been recognised as design driver. The preliminary short list with 10 load combinations both for HCPB and WCLL BB for the PCD phase has been then identified.

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Table 5. Pressure loads in In-Box LOCA.

	P_{nom}	P_{peak} in BB box (Cat. IV)	S_m^B @500 °C	S_m^D @500 °C	$P_{relief\ valve}$ (Cat. II)
HCPB	8 MPa	8.82 MPa	145 MPa	275 MPa	4.65 MPa
WCLL	15.5 MPa	17.09 MPa			9.01 MPa

Table 6. Short list of load combinations for the HCPB and WCLL BB for the PCD phase.

Cat.	DEMO Plant operation state	Plasma state	Pressure/ Magnets/ Seismic	Initiating event	Concatenated event	Cooling state (P,T,q)	Tritium carrier state	PHTS Operating mode	no. Events
I	POS	Normal cycle	-	-	-	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-
I	POS	Fusion power excursion	-	-	-	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-
II	POS	MD II	-	MD II	-	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-
II	POS	VDE II	-	VDE II	-	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-
II	POS	MD I	SL-1	SL-1	MD I	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-
III	POS	MD III	-	MD III	-	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-
III	POS	VDE III	-	VDE III	-	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-
IV	POS	Normal cycle	SL-2	SL-2	-	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-
IV	POS	Normal cycle	-	-	Ex-Vessel LOCA	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-
IV	POS	Normal cycle	-	In-Box LOCA	-	9.2/17.825 MPa, 300/295°C, q_{nom}	in BB, P_{nom}	Plasma operation	-

MD = Major (or central) disruption of Category I,II or II.

VDE = Vertical displacement event of Category I,II or II.