Identification of the postulated initiating events of accidents of a CPS-based liquid metal divertor for the EU DEMO fusion reactor

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A preliminary but systematic safety analysis of a Liquid Metal Divertor (LMD) for the EU DEMO, performed by means of the Functional Failure Mode and Effect Analysis (FFMEA), is presented. This methodology is suitable for the analysis of the LMD, which is undergoing pre-conceptual design. In fact, the FFMEA compensates for the lack of detailed design information by postulating the loss of a system function, rather than a specific component failure.
The implementation of the FFMEA led to a better understanding of the safety issues associated to the system and to the identification of a list of Postulated Initiating Events (PIEs), i.e., the most challenging conditions for the plant. The PIEs, together with their possible consequences, represent an input for future quantitative safety analyses. Due to the early design stage of the LMD and the iterative nature of the methodology, this list will evolve alongside with the design detail and with improvements in the understanding of phenomena driving reactor behaviour.
The study highlighted some safety-relevant issues, e.g. those related to materials compatibility and system modularity, to be addressed in the perspective of a safety-driven design evolution.

Keywords: *Nuclear Fusion, EU DEMO, Liquid Metal Divertor, Power Exhaust, Safety assessment, FFMEA, Postulated Initiating Event*

1. Introduction

In a tokamak fusion reactor, the divertor targets might be subject to heat fluxes that could reach peak values as large as 10 MW/m^2 in steady state and 20 MW/m^2 during slow transients [1]. For fusion to be economically feasible, these conditions must be withstood without the need to frequently replace the Plasma-Facing Components (PFCs). A reliable solution for this power exhaust problem is among the milestones indicated in the European Research Roadmap for the Realisation of Fusion Energy [2]. The “baseline” strategy, relying on actively cooled solid Tungsten (W) PFCs (called W monoblocks), will be employed for the ITER experiment, currently under construction in France [3,4]. However, it is presently unclear whether this strategy can be extrapolated to a future fusion reactor, such as the EU DEMO, whose pre-conceptual design is ongoing within the EUROfusion consortium. For this reason, alternative solutions are under study, which will eventually be tested in a dedicated experiment in Italy, namely the Divertor Tokamak Test (DTT) [5]. Liquid Metal Divertors (LMDs) based on Capillary Porous Structures (CPS) are among the concepts being considered [6], [7]. With respect to solid divertors, CPS-based LMDs have the potential to guarantee a longer divertor lifetime and a superior resilience to transient events [6].

The working principle of an LM-filled CPS is based on capillary forces which allow to passively re-wet the divertor target Plasma-Facing Surface (PFS), thereby compensating for the erosion induced by the plasma heat and particle fluxes. Moreover, using a CPS to constrain the LM prevents droplets ejection and splashing phenomena which could occur if a free LM surface was adopted [8]. The LMs being considered for the EU DEMO LMD are Li and Sn [9].

Due to the very slow flow of LM in the CPS (of the order of few mm/s [10]), the LM can be considered almost stagnant. Therefore, the only physical mechanisms available for exhausting the power coming from the plasma are LM evaporation (latent heat) and vapor shielding [11], which are not sufficient alone. For this reason, active cooling of the component is necessary, as for a solid divertor. To ensure the correct operation of an LMD, however, additional functions must be performed, which are related to the specific physical phenomena involved in this divertor design. The CPS must be connected to an LM-filled reservoir which needs to be constantly replenished, to prevent the dryout of the PFS due to LM unavailability. Moreover, LM freezing must be avoided everywhere in the system during operation, thus requiring an LM heating strategy. Additionally, issues associated to the specific physical/chemical behaviour of the LM when interacting with other fluids (e.g. Li-water exothermic reaction) and with solid surfaces (e.g. metal corrosion/erosion) must be taken into account, as well as the potential retention of Tritium (T) and impurities in the LM [12]. Co-deposition of eroded metal and fuel species, including T, can also occur on the tokamak First Wall (FW) [13].

Within the framework of the preliminary design of an LMD for the EU DEMO, safety issues must be considered at an early stage. This work is aimed at:

- Performing a preliminary but systematic safety analysis for this system, by means of the Functional Failure Mode and Effect Analysis (FFMEA).

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- Identifying a list of Postulated Initiating Events (PIEs) and formulating recommendations which could possibly be accounted for in the design process. The PIEs represent in turn the starting point for the Probabilistic Safety Assessment (PSA) that will be performed in later phases of the design.

To the best of the authors' knowledge, this is the first time that a systematic safety assessment of an LMD is performed.

The paper is organised as follows. In section 2, the preliminary design of the LMD system (divertor target and auxiliary circuits) is described. In section 3, the FFMEA methodology adopted for the present work is recalled. In section 4, the results of the safety assessment, in terms of PIEs and of the possible development of the associated accidental scenarios, are reported. Finally, conclusions are drawn and possible future activities related to this subject are proposed.

2. System description

This section describes the preliminary design of the LM (Li or Sn) divertor target and auxiliary circuits considered for the safety study, which is based on [14]. The divertor functions and operational modes are first clarified. Successively the confinement strategy for the radioactive inventory is addressed. Finally, the components are briefly described, distinguishing between those located inside and outside the Vacuum Vessel (VV).

2.1. Divertor process functions and operational modes

During the normal operation of the reactor (and in particular during the flat top phase of the plasma pulse, lasting ~2 h in the EU DEMO reference scenario [15]) the major function of the divertor is to exhaust the non-radiated fraction of the power associated to the alpha particle source and conducted and advected by the plasma along magnetic field lines in the scrape-off layer. In the LM concept considered in the present study, this is achieved by actively cooling the PFCs by means of pressurized water [14]. The correct water flow and cooling parameters are guaranteed by the presence of a water circuit.

Moreover, it is necessary to constantly wet the plasma facing CPS with LM, to avoid the latter to be directly exposed to the plasma heat and particle flux, which would lead to its melting, with consequent need for replacement of the involved component(s). To this purpose, material losses associated to LM surface erosion are compensated by passive (capillary effect) pumping to the PFS of the LM contained in a nearby reservoir. The reservoir is in turn refilled by means of an LM circuit.

To guarantee the LM flow it is necessary to prevent the LM freezing everywhere in the LM circuit. This is ensured by heating at least the local reservoir and the LM tank by means of a hot gas. The correct gas flow, pressure and temperature (the latter being sufficiently larger than the LM melting point) are guaranteed by the presence of a heating circuit.

Should any of the three functions mentioned above (cooling, heating, refilling) be not satisfied, a massive plasma contamination could occur, leading to the reactor unplanned shut-down, together with the structural damage of the divertor and possibly of other tokamak components, as it will be explained in section 4.2. The effects of the loss of each function are an output of this study.

Other reactor operational modes are:

- Plasma start-up: before the reactor operation, the divertor heating circuit must be activated to melt the Sn or Li. At this point the LM circuit can be activated. Before the start of the plasma pulse, the water circuit must then be switched on. Further details on the start-up procedure (e.g. associated to the CPS wetting) and compliance of the LMD with e.g. the reactor baking phase [16] are currently under discussion within the EUROfusion consortium.
- Reactor shut-down: at the end of the reactor operation, also the divertor circuit must be shut-down. Since the details on this procedure are still unknown (e.g. the management of LM inventory), it is not possible to identify which of the circuits operate during each step of this phase.

Additional operational modes, such as tests (e.g. non Deuterium-Tritium operation), reactor temporary shut-down for inspections or divertor maintenance, are characterized by significant uncertainties which would make the safety analysis at this stage not valuable.

2.2. Radioactive inventory and confinement barriers

From a safety point of view, it is fundamental to identify the sources of radioactivity. In a fusion reactor, alongside with activated materials, these sources are mainly associated to Tritium (T). As far as the LMD is concerned, depending on the specific design choices, T retention in the LM and/or T co-deposition on the FW can occur. In these cases T is transported in the LM circuit, thus calling for purification systems to avoid the build-up of the radioactive inventory (in compliance with the corresponding limit, whose value is still under discussion). Therefore, T can be present both inside and outside the VV.

Two confinement barriers have been proposed for the EU DEMO. A complete panorama of this confinement strategy is reported in [17]. From the point of view of the LMD, two physical barriers can be identified:

- The first confinement barrier is composed by the VV walls and the divertor LM circuit and cooling water system.
- The second confinement barrier is represented by the containment building.

In the light of these considerations, it is important to distinguish between events occurring inside the VV (associated to *in-vessel components*) and outside the VV, but still inside the containment building (associated to *ex-vessel components*). In particular, the in-vessel components and the specific solutions adopted for the LM PFC are addressed in 2.3, while the ex-vessel circuits serving the LM divertor systems are discussed in 2.4.

2.3. In-vessel components (IVCs)

The LMD design considered in this work is taken from [18] and [14], and complemented with suitable assumptions in case of missing information. The design, which is briefly described in the following, is highly modular. The divertor is subdivided into 54 *cassettes*, covering the entire toroidal extension of the tokamak. In each cassette there are two *Vertical Targets* (VTs), i.e. the components directly exposed to the plasma heat and particle loads. Each VT is covered by 24 *modules*, each containing 3 *units*.

It should be noticed that the one here analyzed is not the only LMD design currently under investigation for EU DEMO. For instance, concepts where the heating and cooling fluids coincide, possibly characterized by a lower degree of modularity, are being considered [19].

The CAD of a single divertor cassette is shown in Figure 1a. In the current EU DEMO divertor design, the cooling water inlet to each cassette is connected to a Bottom Ring Collector (BRC), see Figure 1b. Correspondingly, the water outlet from each cassette is connected to a Top Ring Collector (TRC). BRC and TRC are in turn connected to an ex-vessel water circuit, see section 2.4. For the present study, it has been assumed that both inlet and outlet LM and heating gas pipes for each cassette are connected to a corresponding BRC and TRC, respectively, see again Figure 1b. LM and heating gas BRC and TRC are in turn connected to external circuits, described in section 2.4. In the following, it is assumed that the heating gas is pressurized He.

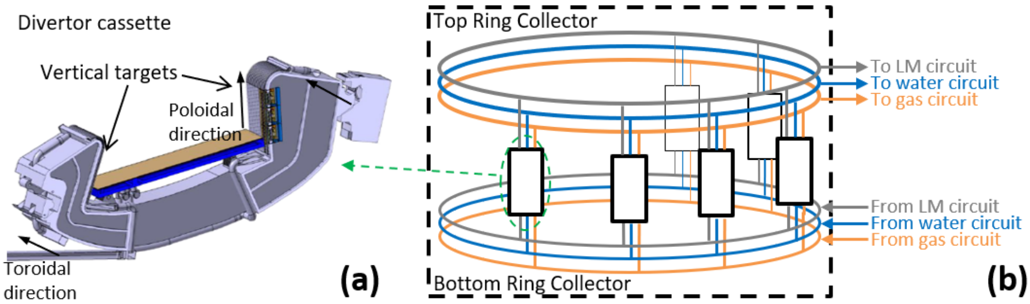

Figure 1: CAD of a single cassette of an LMD for the EU DEMO (a), adapted from [18]*, and schematic representation of the hydraulic connections of the cassettes to the BRC and TRC (b). Note that, for the sake of simplicity, only 6 divertor cassettes out of the total 54 are shown.*

In a divertor cassette, the surface of each VT is covered by 8 (toroidal)x3 (poloidal) divertor modules. The three modules in the poloidal direction are connected in series, whereas all the eight series of three modules each are connected in parallel. The CAD of a single module is shown in Figure 2a. Each module is connected to the cooling water inlet (in blue) and outlet (in orange) lines, to the heating gas inlet and outlet lines (in yellow) and to the LM refill line (in grey). The PFS of each module is composed by three units, juxtaposed in the toroidal direction. The schematic of the hydraulic connections of the modules for a single VT is shown in Figure 2b.

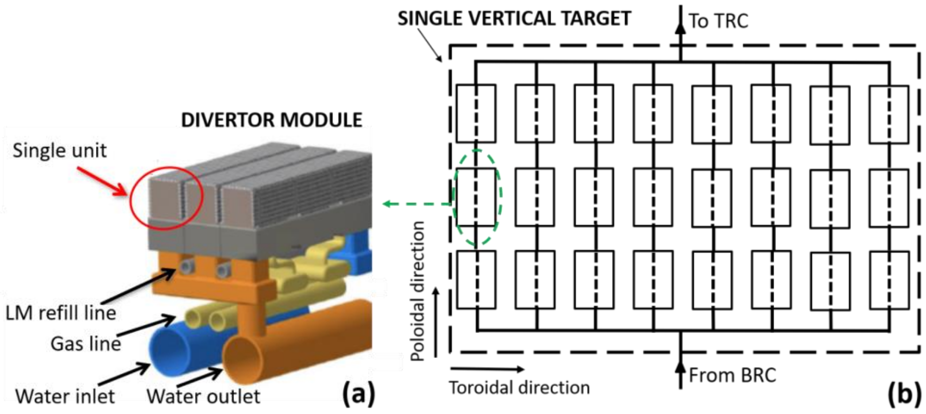

Figure 2. CAD of a single module of an LMD for the EU DEMO (a), adapted from [18] *and schematic representation of the hydraulic connections of the modules to the inlet and outlet collectors of the cassette (b). Note that, for the sake of simplicity, the water, LM and gas lines have not been explicitly indicated.*

Figure 3 shows the cross section of one of the three units on top of each module. The CPS (in blue) is made of a W mesh or felt. It extends up to an LM reservoir (in green) to allow for capillary forces to passively replenish the PFS. The reservoir is connected to the LM refill line shown in Figure 2a. Being located away from the PFS, the reservoir is not reached by the plasma heat. The water cooling channels, connected to the water inlet and outlet lines shown in Figure 2, are located near the CPS to optimize the heat removal. The gas heating channels, connected to gas inlet and outlet lines shown in Figure 2, are located in proximity of the reservoir to avoid LM freezing. The specific LMD design here considered is hence based on decoupling the functions of cooling and heating.

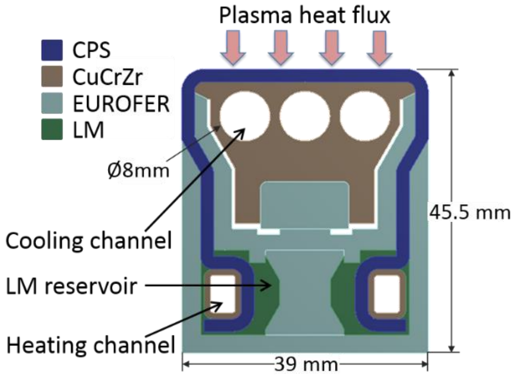

Figure 3. Cross section of a single unit of an LMD for the EU DEMO, adapted from [14].

2.4 Ex-vessel components

The ex-vessel circuits for the cooling water, the replenishing LM and the heating gas feeding the LM divertor are schematically indicated in Figure 4. For the purpose of this preliminary safety assessment, and in the absence of a detailed design, only the subsystems essential to achieve the required functions for each circuit have been considered.

The LM flow from an LM tank towards the BRC is promoted by means of an Electro-Magnetic (EM) pump. The LM flowing out of the VV from the TRC is first treated by means of an LM purification system to remove impurities (e.g. due to the erosion/corrosion of piping materials), which could be activated, and Tritium; then, it is heated by means of a heat exchanger to compensate for the heat losses from the pipes. The LM eventually flows into the above-mentioned LM tank. Although more detailed design information would be required to quantify the total LM inventory, it can be estimated that the total LM volume constrained by the CPS inside the VV will be ~10 litres. The water circuit is composed by a pressurizer, a pump and a purification system, alongside with a heat exchanger to discharge the heat absorbed by the PFCs. The water circuit operational pressure is ~50 bar and the inlet temperature to the cassette is ~140 °C. The temperature increase induced by the plasma power is small (~ 10 °C), thanks to significant water flowrate (the velocity in the cooling channels is ~12m/s) [14]. The He flowrate in the gas circuit is promoted by a compressor and heated by means of a heat exchanger. A He tank is necessary to ensure pressure control (the He operating temperature is ~ 350 °C [20]).

The LM eroded from the PFS due to the plasma heat and particle flux is, at least partially, recondensed on the FW and recollected. The recollection line features a purification system (to remove impurities and co-deposited Tritium) and an EM pump, and is connected to the LM tank.

The LM tank, the water pressurizer and the He tank are connected to external refill lines, which are however beyond the scope of the present study.

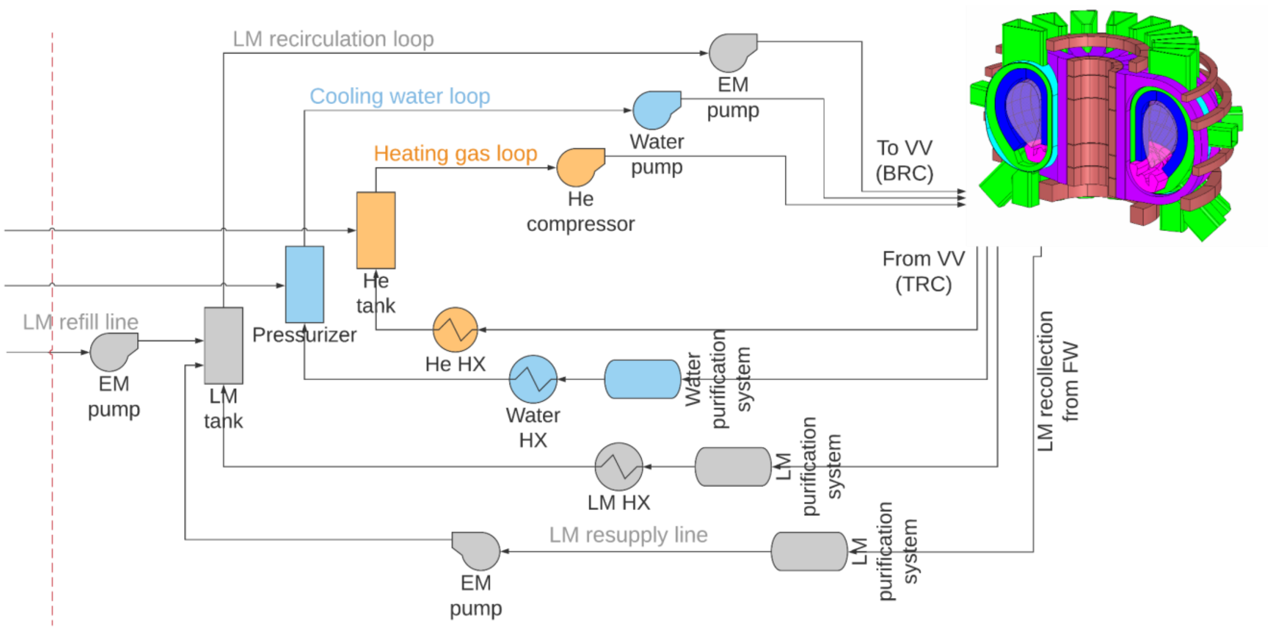

Figure 4. Schematic representation of the ex-vessel LMD circuits. CAD of the EU DEMO tokamak reproduced from [21].

3. Methodology

3.1. Assumptions

In a safety study, it is fundamental to specify the battery limits, i.e. the boundaries between the analyzed system and the rest of the plant. With reference to section 2, the analyzed domain includes the following:

- Divertor in-vessel components;
- LM recirculation/purification loop;
- LM heating circuit;
- LM cooling circuit.

Only internal events, in terms of major components failures, are taken into account and security issues are neglected.

Among the operational modes identified in section 2.1, the reactor nominal operation, during a plasma pulse (flat-top phase) has been selected for the present analysis. In fact, this operational mode involves the largest heat fluxes to the divertor (except for off-normal events such as plasma disruptions). Moreover, this condition occupies the largest fraction of the reactor operational time and is characterized by the most detailed information currently available (e.g. concerning phenomenology, design, operation). Off-normal situations, e.g. plasma disruptions, are currently under investigation through punctual deterministic evaluations (e.g. TOKES code simulations [22]).

3.2. Steps and objectives of the FFMEA

In order to fulfill the objectives of the paper, the FFMEA has been selected. This methodology has already been successfully implemented for the study of other conceptual designs of both fusion and fission reactor components ([23–25]) and for the identification of the associated PIEs.

The FFMEA methodology is indeed particularly suitable for the analysis of systems at a preliminary design stage, when the insufficient design detail does not allow for more specific considerations at the component level. In fact, the starting point of the analysis is not constituted by the failure modes of the specific component/system, but by postulating the loss of the systems functions. In this way, it is possible to overcome the lack of information in the design and the possibly incomplete knowledge of the physical phenomena driving the system behavior [24].

The FFMEA methodology involves the following steps [24]:

- Definition of the main functions of the plant and their specification into sub-functions (Functional Breakdown Structure -- FBS), knowing that the loss of a low-level function implies the loss of all the correspondent higher level functions.
- Systematic and comprehensive listing of all the components of the system (Plant Breakdown Structure -- PBS), collecting all the available information on the design and on its plausible evolution.

- Compilation of the FFMEA table for identifying functional deviations which could compromise system safety, to
    - list their causes (Initiating Events, IEs),
    - sketch their consequences, identify potential preventive and mitigative barriers and, eventually,
    - suggest supplementary safety provisions.
- Grouping the IEs into families according to the way they challenge the system, to the plant response, and to the plant status after the occurrence of the event itself. For each group of IEs, a PIE is selected as the most severe event in terms of consequences.

The FBS is organized into 5 main functions. The loss of each of them implies the unplanned reactor shutdown. In particular, two of them are mainly related to the operation of the divertor (i.e., to exhaust the plasma heat and particles load and to avoid excessive plasma contamination), two of them to the LMD geometrical configuration (i.e., to guarantee the integrity of the divertor structure and to properly intersect the magnetic field lines) and one of them to the safety requirements (i.e., to control T inventory). Each section is in turn specified into sub-functions, some of them up to the 6th level. It is important to underline that the present analysis focuses on the functions which are specific of an LMD, since the functions that are in common with a conventional (solid) divertor have already been analyzed in a previous work, as well as safety and investment protection functions that characterize the entire reactor [25]. An extract of the FBS is reported in Appendix A.

The PBS is organized into 7 parts, one for each main part of the LMD according to the latest available design information. Each section is in turn subdivided into sub-components, to organize them in a systematic way. This also allows to highlight the open points in the design to be further specified. In fact, it should be stressed that the PBS list is a clear example of the iterative nature of the FFMEA methodology. Indeed, as the design detail increases, the PBS will evolve as well. An extract of the PBS is reported in Appendix B.

Table 1 shows an extract of the FFMEA table compiled for the process functions of the LMD concept. The actual table contains four additional columns, namely “Detection type”, “Preventing action”, “Mitigation action”, “Notes”, not shown here due to space constraints. It is worth to note that the entire table, not reported here, is composed by a total of almost 200 rows.

Table 1. Extract from FFMEA table

Process function	**PBS elements**	**Op. Md.**	**Failure**	**Cause**	**Failure Consequences**	**PIE**
2.1.5.1.1. To guarantee integrity and leak-tightness of divertor cooling circuit	1.4.4.Pump (water circuit)	NOp - flat top	Loss of Cooling	Pump rupture without external leakage	Cooling water flowrate suddenly stops (conservatively the pump inertia is not considered); All the modules composing the LM divertor are not effectively cooled, while being exposed to undiminished heat loads; Etc.	CW01: Loss of cooling because of water pump rupture with external leakage

4. Results

4.1. List of PIEs

The list of PIEs is compiled starting from the entire set of elementary failures identified during the compilation of the FFMEA table (which is not included in this work due to space constraints). Among all the events inducing similar consequences, the most severe event is selected as representative. From a safety point of view, the PIEs are the most challenging conditions for the plant in terms of reactor operability, potential monetary losses and radiological releases and are assumed to summarize all the IEs consequences.

The definition of PIEs limits the size of the set of accident initiators, for which deterministic analyses will be performed to quantitatively estimate the corresponding consequences. The results of deterministic analyses eventually allow to assess the plant compliance with safety criteria/limits and its capability to mitigate the consequences, thereby driving the definition of the reference design. Nevertheless, at this stage, it is not always obvious to identify the most severe events. For this reason, in the present study a relatively large number of IEs has been retained as PIEs. This aspect of the analysis could be refined at a later stage.

Table 2 presents the list of the 11 PIEs identified. Due to the early design stage and the iterative nature of the methodology, this list will evolve alongside with the design detail and phenomenological studies. The PIE identified by the label HB99 has been inherited by a previous study on the EU DEMO balance of plant [25].

Table 2. List of PIEs for the LMD concept

PIE	**Description**
WC01	Loss of wetting control because of LM tank overfill

WC02	Loss of wetting control because of LM tank rupture
ICM01	Loss of inventory control because of fissured LM collector at the bottom of the FW
CW01	Loss of cooling because of water pump rupture with external leakage
CW02	Loss of cooling because of external leakage from coolant collector/distributor of the divertor module or connection pipes inside the VV
CW03	Loss of cooling because of internal leakage in the heat exchanger (with primary and secondary coolants mixing)
HB99	Loss of heat sink in all FW, breeding zone and divertor primary cooling circuits because trip of both high pressure and low pressure turbines due to loss of condenser vacuum [25]
CCW01	Loss of cooling water chemical control because of purification system internal rupture
CCM01	Loss of chemical control of LM because of malfunctioning of LM purification system on the LM resupply line
HH01	Loss of heating because of compressor rupture
HH02	Loss of heating because of rupture of penetration pipe inside the VV

For each PIE, a plausible accidental sequence has been qualitatively described, together with possible detection methods and mitigative and preventive systems. The nature of the accidental sequence following each PIE is reflected by the label associated to each of them:

- WC: accidental sequences characterised by the loss of wetting control of the porous matrix facing the plasma, either in excess (WC01) or in defect (WC02). An excess of LM can be caused e.g. by an overpressure in the LM circuit or by an overfilling of the reservoirs/tank present in the circuit. The WC01 has been selected as PIE because it involves the entire toroidal extension of the divertor. On the other hand, the CPS dryout can be caused e.g. by the rupture/obstruction of a component of the LM circuit. The WC02 has also been selected as PIE because it involves the entire toroidal extension of the divertor.
- ICM: accidental sequences characterised by the loss of inventory control of the LM. This may be due e.g. to an incorrect recollection of the LM condensed/deposited on the FW.
- CW: accidental sequences characterised by the loss of cooling. This may be due to e.g. the rupture/obstruction of a component of the water circuit. The three PIEs CW01-03 have been selected based on the location of the rupture, taking into account the confinement barriers (see section 2.2): CW01 considers an event outside the VV, CW02 considers an event inside the VV and CW03 considers an event involving the mixing of the divertor cooling water, which possibly contains activated corrosion/erosion products, with the secondary fluid. The secondary circuit, being a part of the balance of plant, will likely be outside the containment building.
- CCW/CCM: accidental sequences characterised by incorrect purification of the working fluids (water or LM).
- HH: accidental sequences characterised by the loss of heating. This may be due e.g. the rupture/obstruction of a component of the He circuit. The two PIEs HH01 and HH02 have been selected based on the location of the rupture, taking into account the confinement barriers (see section 2.2): HH01 considers an event outside the VV, while HH02 considers an event inside the VV.

4.2. Example of accidental scenario

Due to space constraints, in the following only two among the PIEs listed in Table 2 are described in detail (accidental sequence, detection methods, preventive and mitigative systems, additional considerations):

- CW01: Loss of cooling because of water pump rupture with external leakage.
- CW02: Loss of cooling because of external leakage from coolant collector/distributor of the divertor module, or connection pipes inside the VV.

These PIEs have been chosen because of their significance for the present analysis. In particular, CW01 is significant because it implies the sudden loss of the largest number of LMD functions, namely three out of five: to exhaust the plasma power, to avoid excessive plasma contamination and to guarantee the structural integrity of the system. CW02 is significant because it highlights issues possibly driving the successive design evolution, in terms of, e.g., the choice of the LM. Moreover, it is illustrative to consider both CW01 and CW02, because they imply different consequences on the confinement barriers: in fact, CW01 jeopardizes the first confinement barrier, whereas CW02 does not imply the direct loss of confinement.

4.2.1. CW01: Loss of cooling because of water pump rupture with external leakage

The loss of cooling in the LMD can be generated by several disturbances in the cooling loop. One of the events selected as PIEs is the rupture of the water pump with loss of leak-tightness. This implies the following consequential events:

1. Pump stops working (conservatively the pump inertia is not considered).

2. The pressure difference between the water circuit and the primary containment drives some coolant flow, providing a finite grace time.
3. Pressurized and activated water containing activated corrosion/erosion products will be released in the primary containment.
4. Pump fragments may be transported in the cooling circuit and potentially obstruct pipes or damage components (e.g. coolant collector and distributor).
5. All the modules composing the LM divertor are not effectively cooled, while being exposed to undiminished heat loads.
6. The PF-CPS temperature of the entire LM divertor increases and at the strike point it can reach the melting point.
7. LM and W (from the molten CPS) droplets/fragments are ejected in the plasma (splashing phenomenon).
8. Plasma contamination.
9. End of plasma pulse.
10. The LM and W droplets/fragments act as projectiles in the plasma chamber; it is highly plausible that the impact of these droplets with the chamber walls may cause structural damages.
11. The affected divertor modules need to be replaced.
12. Maintenance actions will have to be performed to re-establish the plasma chamber.

It is noticed that, for this accidental scenario, the plasma contamination acts as a safeguard for the CuCrZr substrate on top of which the PF-CPS is placed. If the plasma shut down occurs too late, the melting of the CuCrZr substrate is highly probable due to the reduced heat sink provided by the coolant. In this case, the cooling water will be released in the plasma chamber with its consequent pressurization. In case Li is used as an LM, it will react exothermically with the water. The pressure will be released to the VVPSS (Vacuum Vessel Pressure Suppression System). Radioactive products (e.g. activated LM and W) and Tritium will be released in the VVPSS and possibly in VVPSS surrounding area through containment leaks [25]. The loss of VV penetrations leak-tightness may also occur because of the high overpressure inside the vessel.

As stated in section 2, designs using either Li or Sn are currently being considered. This accidental scenario points out relevant safety issues that could be useful to drive the choice between Li and Sn.

Since the presence of a single cooling circuit has been assumed, this initiating event affects the entire toroidal extension of the divertor.

In order to detect this event, it could be advisable to:

- Equip the water circuit with flowmeters or pressure sensors (whose compatibility with the external environment should be verified);
- Detect primary containment pressurization;
- Measure radioactivity inside the primary containment;
- Detect the increase of divertor superficial temperature through an IR camera [26].

Additionally, after the unexpected plasma shutdown, a spectroscopy analysis could be performed to investigate the presence of W and LM droplets, knowing that the presence of W is symptomatic of a degradation of the PF-CPS.

In the case of cooling water release, the presence of water in the VVPSS will indicate the in-vessel LOCA.

The installation of a redundant pump in the water circuit can prevent the loss of divertor cooling, thus reducing the frequency of occurrence of this event. Furthermore, all the identified plausible detection methods could trigger the immediate shutdown the plasma, mitigating the consequences and avoiding the exposure of the CuCrZr substrate to plasma heat loads.

In case of cooling water release in the plasma chamber, the VVPSS prevents the escalation of the accident (e.g. structural damages to the VV). Moreover, a depressurization system for the water circuit could be implemented to reduce the amount of released water.

4.2.2. CW02 Loss of cooling because of external leakage from coolant collector/distributor of the divertor module, connection pipes inside the VV

Regarding the loss of cooling of the LMD, another event selected as a PIE is the external leakage from coolant collector/distributor of the divertor module or connection pipes inside the VV. This implies the following series of events:

1. Water leakage from coolant collector/distributor of divertor module, connecting pipes and/or valves;
2. The cooling water will be released in the plasma chamber with its consequent pressurization;
3. End of plasma pulse;
4. In case Li is used as an LM, it will react exothermically with the water;
5. The pressure will be released to the VVPSS; radioactive products (e.g. activated metal) and Tritium will be released in the VVPSS and potentially in VVPSS surrounding area through containment leaks;
6. The loss of VV penetrations leak-tightness is possible because of the high overpressure inside the VV. Since many systems of collectors/distributors will be present, the affected collector/distributor, connection or valve

will determine the severity of the damages. The rupture of larger channels is presumably more probable than the rupture of smaller channels;
7. The affected divertor modules need to be replaced;
8. Maintenance actions will have to be performed to re-establish the plasma chamber.

It is noticed that, due to the system modularity, the frequency of occurrence of a water leakage inside the VV could be significant, since the failure rate also depends on the total length of the pipes and the number of connections. Proper design evaluation, material selection and maintenance actions will be necessary to manage the associated risk, being aware that even a small leakage will be able to compromise the reactor operation and will require the restoration of the affected components, especially in the case Li is used as LM. As for the accidental scenario described in section 4.2.1, relevant safety issues connected to the LM physical properties emerged from this analysis.

This accidental scenario is supposed to evolve rapidly. Nevertheless, after the plasma shutdown, some features of the post-accident conditions could help to investigate the causes:

- The unplanned plasma shutdown following the release can be traced back to the massive plasma pollution associated to water ingress in the chamber.
- The presence of water in the VVPSS will indicate the in-vessel LOCA.
- Through visible cameras, the affected sector can be identified.

Even in this case, the VVPSS prevents the escalation of the accident (e.g. structural damages to the VV).

5. Conclusions and perspective

In this work, a functional safety analysis of a preliminary design of an LMD for the EU DEMO has been performed for the first time.

The implementation of the proposed FFMEA methodology for the safety assessment has allowed to systematize the safety-relevant information and to highlight possible consequent issues as exhaustively as allowed by the current level of design detail.

A limited number of PIEs have been identified, together with their possible consequences. The list of PIEs collects both events that are specific to the LMD concept, e.g. the dryout of the CPS, and events that were already highlighted for a conventional (solid) divertor, e.g. the in-vessel LOCA, albeit with a different accident evolution.

Additionally, the LMD could originate initiating events already identified for other reactor systems, thus increasing the frequency of occurrence of the above mentioned events. For instance, in case the HCPB (Helium Cooled Pebble Bed) option is selected for the Breeding Blanket (BB) [27], He could be released inside the VV both from the BB and from the LMD.

This list of PIEs can represent an input for successive deterministic safety analysis (e.g. CFD simulation of in-vessel LOCA [28]) and the starting point for the PSA to be successively performed.

The outputs of this work could be further refined with the evolution of the design and knowledge of physical phenomena involved in an LMD, as suggested in [29]. It is plausible that some of the hazardous events could be removed from the list if successive analyses show their total or partial inconsistency. Moreover, there are some open points of this LMD design that would affect the evolution of the accidental sequences, while leaving the list of PIEs unchanged. An example that clearly emerged from the analysis is the impact of the LM choice (Li or Sn) on the accidental sequence following CW02: the water ingress in the VV will be more severe in case Li is used instead of Sn, mainly because of the exothermic Li-water reaction.

The analysis has also pointed out that the system modularity – which is significant in the specific LMD design here considered– may increase the frequency of some accidental scenarios while possibly limiting the associated damage. Nevertheless, even a small leakage will lead to the interruption of the reactor operation and require the restoration of the affected components.

In case a different LMD design is chosen, the list will need to be revised, because on one hand some events could become inconsistent (e.g. physically impossible), on the other hand additional events will have to be included.

In perspective, some of the assumptions listed in section 3.1 could be relaxed. In particular, other operational phases should be analysed (e.g. maintenance with the issues associated to the potential LM freezing). Moreover, it will be necessary to consider how the presence of an LMD can modify the PIEs identified from the safety study of other systems (e.g. the BB).

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Appendix A. Extract of Functional Breakdown Structure

An extract of the FBS is here reported.

To operate the reactor
To operate the divertor

1. To intersect magnetic field lines (general characteristic of divertor not specific of Liquid Metal –LM- divertor)
2. To avoid excessive plasma contamination
    - 2.1. To limit sputtering, evaporation and splashing of divertor LM
        - 2.1.1. To appropriately manage/limit plasma temperature at target (out of the battery limits)
        - 2.1.2. To minimize plasma ion flux at target (out of the battery limits)
        - 2.1.3. To avoid LM excess on CPS surface
            - 2.1.3.1. To ensure control of LM inventory
            - 2.1.3.2. To balance LM flow with the liquid inventory necessities (e.g. avoid pumps over-running)
            - 2.1.3.3. To guarantee LM recollection downstream the CPS
        - 2.1.4. To keep the correct geometry ensuring capillarity (i.e. to guarantee the correct pore dimension of CPS)
        - 2.1.5. To keep the LM in the correct temperature range (part of sputtering and evaporation depend on superficial LM temperature)
            - 2.1.5.1. To provide cooling of divertor structures (function of water circuit)
                - 2.1.5.1.1. To guarantee integrity and leak-tightness of divertor cooling circuit
                - 2.1.5.1.2. To provide coolant flow in the divertor cooling circuit
                - 2.1.5.1.3. To allow for coolant circulation (i.e. to guarantee availability of flow paths)
                - 2.1.5.1.4. To provide pressure and coolant inventory control
                - 2.1.5.1.5. To provide Heat Sink for the divertor cooling circuit (out of the battery limits)
                - 2.1.5.1.6. To provide coolant purification for the divertor cooling circuits
            - 2.1.5.2. To avoid excessive plasma heat load (out of the battery limits)

[…]

Appendix B. Extract of Plant Breakdown Structure

An extract of the PBS is here reported.

1. Liquid Metal divertor system
    - 1.1. Cassette (structural components)
    - 1.2. Target (PFC)
      […]
    - 1.3. Recirculation loop (LM resupply system)
      […]
    - 1.4. Cooling system (water circuit)
        - 1.4.1. Coolant pipe (the tube inside the CuCrZr heat sink)
        - 1.4.2. Coolant collector at the bottom of the divertor cassette
        - 1.4.3. Coolant distributor at the top of the divertor cassette
        - 1.4.4. Coolant Pump
        - 1.4.5. Coolant heat exchanger
        - 1.4.6. Pressurizer
        - 1.4.7. Pipelines & valves
        - 1.4.8. Purification system
    - 1.5. Heating system
      […]
    - 1.6. Pumping protection system
    - 1.7. Divertor enclosure system

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