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Identification of accident sequences for the DEMO plant



Tonio Pinna^{a,*}, D. Carloni^b, A. Carpignano^c, S. Ciattaglia^d, J. Johnston^e, M.T. Porfiri^a, L. Savoldi^c, N. Taylor^e, G. Sobrero^c, A.C. Ugenti^c, M. Vaisnoras^f, R. Zanino^c

^a ENEA FSN, Nuclear Fusion and Safety Technologies Department, Via E. Fermi, 45, 00044, Frascati, Rome, Italy

^b KIT-INR, Institute of Neutron Physics and Reactor Technology, D-76344 Eggenstein-Leopoldshafen, Germany

^c NEMO Group, Dipartimento Energia, Politecnico di Torino, 10129 Torino, Italy

^d EUROfusion Consortium, Boltzmannstr. 2, Garching 85748, Germany

^e CCFE-UKAEA, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom

^f Lithuanian Energy Institute, Breslaujos g. 3, LT-44403, Lithuania

HIGHLIGHTS

- Safety studies for the European Demonstration Fusion Power Plant (DEMO).
- Functional Failure Mode and Effect Analysis (FFMEA) to identify postulated initiating events (PIEs).
- Functional breakdown structure (FBS) of DEMO.
- Reference accident sequences.
- Blanket concepts of the European DEMO reactor.

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ABSTRACT

Safety studies are performed in the frame of the conceptual design studies for the European Demonstration Fusion Power Plant (DEMO) to assess the safety and environmental impact of design options. An exhaustive set of reference accident sequences are defined in order to evaluate plant response in the most challenging events and compliance with safety requirements.

The Functional Failure Mode and Effect Analysis (FFMEA) has been chosen as analytical tool, as it is a suitable methodology to define possible accident initiators when insufficient design detail is available to allow for more specific evaluation at component level. The main process, safety and protection functions related to the DEMO plant are defined through a functional breakdown structure (FBS). Then, an exhaustive set of high level accident initiators is defined referring to loss of functions, rather than to specific failures of systems and components, overcoming the lack of detailed design information. Nonetheless reference to systems or main components is always highlighted, as much as possible, in order to point out causes and safety consequences.

Through the FFMEA a complete list of postulated initiating events (PIEs) is selected as the most representative events in terms of challenging conditions for the plant safety.

All the four blanket concepts of the European DEMO reactor have been analysed.

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1. Introduction

The main systems of the European Demonstration Fusion Power Plant (DEMO) have been analysed to qualitatively evaluate the safety and environmental impact of design options.

The Functional Failure Mode and Effect Analysis (FFMEA) has been chosen as analytical tool because, being based on a top-down approach, it is a suitable methodology to define possible accident initiators and related consequences when no sufficient design detail is available to allow for more specific evaluation at component level.

* Corresponding author.

E-mail address: tonio.pinna@enea.it (T. Pinna).

2. Methodology of analysis

The main process, safety and protection functions related to the plant are defined at first through the functional breakdown structure (FBS). Then, systems and main components of the plant dedicated to perform the above functions are identified in a plant breakdown structure (PBS) through available design information and design intents outlined by the FBS. Each main function is correlated to one or more than one of the components.

Possible failure modes of the functions, related causes, consequences, actions/means set to prevent the occurrence of accident initiators and the progressing of accident chains, mitigating provisions and representative postulated initiating events (PIEs) are identified with the FFMEA.

Final objective of the FFMEA is to provide a complete list of potential initiators of accidental events and give suggestions in order to improve the overall safety of the plant. From the complete list of initiators, a set of postulated initiating events (PIEs) is selected as the most representative in terms of challenging conditions for the plant safety. Being each elementary accident initiator associated to one or more than one PIE, analysing deterministically the accidental plant conditions initiated by the PIEs the compliance of the plant with safety objectives is demonstrated for all the possible events judged to be bearers of safety problems.

3. Functional breakdown structure

The IEC 61226 [1] defines with the term Function, the “*Specific purpose or objective to be accomplished that can be specified or described without reference to the physical means of achieving it*”. Accordingly, three different families of functions were identified for the DEMO plant: process functions, safety functions and investment protection functions.

The main objective of the process functions is to operate the plant and to cover the experimental program, which is to demonstrate the feasibility to produce by a fusion reactor, electrical power to be commercialised.

The main objective of the safety functions is to perform specific actions that prevent or mitigate radiological hazards. Therefore, actions to prevent or mitigate dose uptake to on-site personnel and members of the public and radioactive release to the environments. Additionally, as the objectives of the safety functions have not to be limited to the prevention or mitigation of the radiological hazards, but should include all the actions to prevent the other types of hazards for workers, public and environment, such as chemicals, electric, magnetic, etc. Then, “Safety” describes a condition in which protection from nuclear and non-nuclear (conventional/occupational) hazards is provided for workers, the public and the environment.

The main objective of the investment protection functions is to perform operations dedicated to safeguard investments such as machinery and equipment, as well as to minimize operational costs.

Because of the relationships between the three families of functions, to facilitate and avoid duplications during the assessment with the FFMEA, the core of the analysis is focused on the process functions. The safety and protections functions were considered as supporting functions to be implemented to correctly accomplish the process function.

4. DEMO systems analysed with FFMEAs

Four different concepts are under investigation in Europe for the DEMO plant. They are based on four different concepts of breeding blanket.

Helium-Cooled Pebble Bed concept (HCPB), with a ceramic breeder (Li_4SiO_4 or Li_2TiO_3), Be pebbles as neutron multiplier and helium cooling systems to cool-down the first wall (FW) and the breeder zone (BZ),

Helium-Cooled Lithium Led concept (HCLL), with liquid metal (LiPb) as breeder and helium cooling systems to cool-down the FW and BZ.

Water-Cooled Lithium Led concept (WCLL), with liquid metal (LiPb) as breeder and water cooling systems to cool-down the FW and BZ.

Dual-Coolant Lithium Led concept (DCLL), with liquid metal (LiPb) as breeder, partially self-cooled by a secondary loop, and helium cooling systems to cool-down the FW and part of the BZ structures.

The main systems of DEMO analysed for the four options of reactor models are the following:

- Primary heat transfer systems (PHTS) of FW, BZ, divertor (DIV) and vacuum vessel (VV).
- Balance of plant, i.e. turbine cycle directly used as heat sink for the PHTS and, the alternative design option, of an intermediate heat storage (IHS) system between PHTS and turbine cycle.
- Coolant Purification System.
- Breeding system, i.e. blanket boxes, purge gas circuit for HCPB and LiPb loops for the WCLL, HCLL and DCLL.
- Tritium Extraction System from breeders.
- Fuel cycle, i.e. matter injection (fuelling systems), vacuum pumping, tritium plant.
- Magnet system.
- Vacuum Vessel system.
- Thermal shields.
- Cryostat systems.

5. Postulated initiating events

PIEs are generally determined looking at the set of elementary failures that compromise process functions and induce consequences of safety concern, grouping events that induce similar consequences in the plant and selecting, as representative, the most severe elementary failure of the group of events. Then, all the identified PIEs, are analysed again to identify the overall possible induced accident sequences and to select the minimum set of PIEs that could be taken as reference to evaluate the most challenging plant conditions. Practically, the selection of the reference PIEs is an iterative process: from elementary failures an initial set of PIEs are identified at first, than from this set a reduced set of reference PIEs is selected. From a safety point of view, the reference PIEs selected are the most representative accident initiators, in terms of radiological consequences, between a set of elementary events challenging the plant in similar way and, producing equivalent fault plant conditions.

For each reference PIE, a deterministic analysis will have to verify the plant capacity to mitigate the consequences and, in every case, to verify that consequences are below established safety limits. From the initial large set of PIEs defined by the analyses performed system by system, a reduced set of 21 PIEs has been identified as the most representative for the deterministic assessments to be performed for DEMO, both to check the compliance with safety limits and to give rationales for the selection of the reference DEMO reactor model. The set of these reference PIEs are listed in the following Table 1.

Possible accident sequences and needs of deterministic assessments have been identified in detail for each of the PIEs. Between the 21 events, the HA99 PIE has been recognized as the most severe from the plant safety point of view because all the primary cooling circuit of all plasma facing components (PFCs) are involved in

Table 1
List of reference PIEs identified for the DEMO plant.

PIE	Description
FB1	Loss of flow in the primary cooling loop of the breeder material because compressor or pump seizure
FD1	Loss of flow in the primary cooling loop of the divertor because pump seizure
FF1	Loss of flow in the primary cooling loop of the FW and BZ structures because compressor or pump seizure
FM1	Loss of flow in the liquid metal circuit because electromagnetic pump seizure: the LiPb flow is lost in all blanket modules supplied by the LiPb circuit
HA99	Loss of heat sink in all FW, BZ and divertor primary cooling circuits because loss of condenser vacuum
LFB1	Large loss of coolant from the FW cooling circuit inside the blanket box due to large weld rupture
LBO1	Out-of-vessel loss of cooling accident (LOCA) from the BZ primary cooling loop due to large rupture in the coolant manifold feeder located inside the PHTS building
LBO3	Out-of-vessel LOCA from the breeder primary cooling loop due to large rupture of tubes in a primary heat exchanger (or steam generator)
LFV1	In-vessel LOCA due to a large rupture of the FW structure: complete rupture of the FW
LDO1	Out-of-vessel LOCA from the divertor primary cooling loop due to large rupture in the coolant manifold feeder located inside the PHTS building
LDV1	In-vessel LOCA from the divertor primary cooling loop due to large rupture in the divertor cassette
LMO1	Out-of-vessel loss of liquid metal from the LiPb circuit due to large rupture in the cold leg, downstream the electromagnetic pump (loss of LiPb feeding to all blanket modules supplied by the faulted LiPb line)
LMO2	Out-of-vessel loss of liquid metal from the LiPb circuit due to a leak in the cold leg, downstream the electromagnetic pump
LMO3	Out-of-vessel rupture of liquid metal circuit inside the heat exchanger (HX), i.e. large rupture of tubes
TGG1	Break of tritium gas process line within secondary enclosure (e.g. glove box): cryogenic fluid and fuel gas released into pellet injector guard vacuum volume
TGO1	Out-of-vessel release of tritium gas due to guillotine rupture in the process line of the isotopic separation system (ISS): tritium release inside the building
TGO3	Release of tritiated effluents to environment due to misoperation in the tritium process systems: failure to operate the cryo-distillation columns in ISS
THO1	Guillotine break of the hydrogen gas pipe at the outlet of the electrolyzer of the water detritiation system (WDS). Direct tritium release into the WDS room. Risk of Q2 explosion
TWO1	Rupture of a high activity level holding tank in WDS
VCG1	Loss of cryostat vacuum due to large ingress of gas (He and/or air)
VVA1	Loss of vacuum in VV due to large ingress of air induced by rupture in a VV penetration

the induced accident sequences. The initiator to consider as reference event is the loss of condenser vacuum. Such PIE is discussed in detail in the following section, as an example of the final output of the work.

Furthermore, it is important to note another general output of the work on safety analyses presented in this paper: the deterministic simulations of the accident sequences related to all PIEs shall be performed both considering ON the power supply and other auxiliaries of the systems involved in the accidents and, considering a general long black-out in the supplying of electricity and other services (e.g. $1\text{ h} < t < 32\text{ h}$) to the plant.

6. Possible consequences induced by HA99 PIE

The total loss of heat sink in all primary cooling circuits could be generated by several disturbance in the balance of plant systems. The event selected for the PIE is the loss of condenser vacuum for

rupture of the condenser or of lines interfacing the condenser. The loss of condenser leak-tightness implies the following consequential events:

1. Ingress of air into steam loop towards low pressure section of the turbine inducing the loss of condenser vacuum.
2. Turbine trip for protection intervention.
3. Loss of saturated steam into turbine building.
4. Building pressurization.
5. Release into building of tritium permeated through the steam generators.
6. Direct release of tritium contained in secondary fluid towards the environment if HVAC is not promptly isolated.
7. Fast over-pressurization of primary and secondary loops if plasma is not promptly shutdown.
8. Pressure relief in primary loops (it will assure heat removal from PFCs for a while, giving, even if very short, a period of time in order to operate the plasma shutdown).
9. Leaks/ruptures in ex-vessel and in-vessel sections of primary loops can occur (other leaks/ruptures in secondary circuit can occur too). Both cooling and LiPb loops can be involved.
10. Overheating of the PFC structures.
11. PFC rupture because thermal and/or mechanical stress induced by the overheating and/or by the plasma disruption (the disruption could occur both for an activated fast plasma shutdown or for plasma poisoning induced by the melting of the armour material in the PFC surfaces).
12. Release of breeder material and coolant inside the VV, i.e. Be pebbles and helium for the HCPB; LiPb and water coolant for the WCLL; LiPb and helium for the HCLL and DCLL; water coolant from the divertor of all models.
13. VV pressurization due to the ingress of coolant. Coolant can be released from more than one primary circuit, e.g. two FW loops, one FW and one BZ loop, one FW and one divertor loop.
14. Pressure relief to the expansion volume and/or vacuum vessel pressure suppression system (EV/VVPSS).
15. In case of double rupture from FW, BZ and divertor, possible H₂ production due to Be-water reaction for the HCPB model or LiPb-water reaction for the WCLL, the HCLL and the DCLL models.
16. Radioactive products and tritium contained inside the VV, the coolant loop and the LiPb loop are released towards the EV/VVPSS and towards its surrounding area through containment leaks.
17. Possible loss of VV penetration leak-tightness because the high overpressure inside the vessel.

The following preventing and mitigating features/actions have been identified:

- Redundant control in turbine cycle:
 - Condenser and vacuum line parameters;
 - Hot well and degasser parameters;
 - Pressure relief devices;
 - Turbine parameters;
- Interlocks between plasma operation and turbine and condenser parameters.
- Turbine by-pass.
- Pressure relief devices in primary circuits.
- Soft/Fast Plasma shutdown.
- Pressure relief to the EV/VVPSS by rupture disks.
- Atmosphere detritiation systems.
- Emergency cooling (e.g. VV cooling circuit).

- Cryostat venting to reduce the temperature in the VV and its surrounding structures.

The total loss of the heat sink for the overall PHTS can occur also in the case an intermediate heat storage system with molten salts is used to regulate and stabilize the turbine cycles between plasma pulses. The rupture of a component of the intermediate circuit implies the loss of the entire heat sink, as for the case of loss of condenser vacuum discussed above. The worst case is the rupture of the out-leg of the salts pump. It causes the leakage of molten salt in the containment building and the loss of capability to cool-down all the primary loops.

Deterministic assessment of the accident chains related to the HA99 shall estimate the following phenomenas:

- Trend of pressures and temperatures inside the PFC structures and primary loops after the loss of flow in the steam turbine circuits or in the IHS (all primary loops involved).
- Time to PFC melting (if any) with plasma on.
- Thermal and/or mechanical stress induced by the overheating and/or by the plasma disruption.
- Time available before the collapse of the FW and/or blanket box and/or divertor, if any.
- In case the collapse conditions are reached, transient of the ingress of fluid inside the VV (i.e. cooling and purging helium for the HCPB, LiPb and cooling water for the WCLL, LiPb and helium for the HCLL and DCLL, water from divertor of all models):
 - Emptying rate of fluids;
 - Pressures in the emptying loop;
 - Chemical reactions, if any (e.g. LiPb-water for WCLL, HCLL and DCLL; Beryllium-water for the HCPB).
 - VV pressurization.
- Pressure relief to the EV/VVPSS.
- Amount of radioactive products and tritium released into EV/VVPSS, into building through containment barriers leaks and to environment through building leaks and exhausts of the detritiation systems.
- Worker over-exposure due to the accident sequence.
- Worker over-exposure due to recovering actions.

As the break of PFCs inside the VV could interest most than one circuit (i.e. one of the accident conditions with the largest inventory of fluids with high enthalpy released inside the VV) with different fluids inside (i.e. helium from HCPB, HCLL and DCLL, water from the WCLL and from divertor of all the models, LiPb from WCLL, HCLL and DCLL), the accident chain induced by the HA99 shall be used in “dimensioning” or in “checking correct dimensioning” of the pressure suppression systems for the VV, either they will be EV or VVPSS or a combination of the two.

Since in the accident chain related to this PIE, the possibility to have a release of steam into the turbine building is also identified, deterministic assessment related to the HA99 shall also estimate:

- Maximum amount of tritium contained in the secondary circuit because permeation through SGs and HXs and possible tritium release to turbine building and to environment.
- Turbine building pressurisation due to steam release.
- Need of EV/VVPSS or local cooler for the turbine building in order to limit maximum over-pressure.

7. Conclusions

The main systems of DEMO for the four options of reactor models were analysed by FFMEAs. A reduced set of 21 PIEs has been identified as reference accidents for the deterministic assessments to be performed in the first phase of the DEMO design activities both to check the compliance with safety limits and to give rationales for the selection of the reference DEMO reactor model.

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Reference

- [1] IEC 61226, CEI 61226, “Nuclear power plants—Instrumentation and control systems important to safety—Classification of instrumentation and control functions”, February 2005.