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Safety assessment for EU DEMO – Achievements and open issues in view of a generic site safety report

Maria Teresa Porfiri[a], Neill Taylor[b,*], Sergio Ciattaglia[c], Xue Zhou Jin[d], Jane Johnston[b], Bethany Colling[b], Tim Eade[b], Dario Carloni[b], Tonio Pinna[a], Egidijus Urbonavicius[e], Robert Vale[b], Andrija Volkanovski[f], Gianfranco Caruso[g]

[a] ENEA UTFUS-TECN, Via Enrico Fermi, 45, 00044, Frascati, Roma, Italy
[b] Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK
[c] EUROfusion Consortium, Boltzmannstr.2, Garching, 85748, Germany
[d] Karlsruhe Institute of Technology (KIT), Institute of Neutron Physics and Reactor Technology (INR), Herrmann-von-Helmholtz-Platz 1, D-76344, Eggenstein-Leopoldshafen, Germany
[e] Lithuanian Energy Institute, Breslaujos g. 3, LT-44403, Kaunas, Lithuania
[f] Jožef Stefan Institute, Jamova cesta 39, SI-1000, Ljubljana, Slovenia
[g] Sapienza University of Rome, Department of Astronautical Electrical and Energy Engineering, Corso Vittorio Emanuele II, 144, 00186, Rome, Italy

A R T I C L E I N F O

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A B S T R A C T

The way to arrive at a licensing phase for a nuclear fusion installation is not straightforward mainly because of the lack of operating experience and of dedicated nuclear regulations. In fact, only small/medium experimental facilities exist with limited licensing processes and only one large experiment, ITER, has obtained a construction license. Therefore, the safety assessment and the preparation of the preliminary safety report is almost a first of a kind for DEMO. Taking advantage of the fission power plants experience and considering to the maximum extent the ITER safety studies, the preparation of a Generic Site Safety Report (GSSR) has begun. It will require some years to be completed; however currently, at the starting point, the strategy to develop it is clear and well defined. This paper considers all the safety issues that will be included in the GSSR because they have been clarified in the frame of the European Workprogramme for DEMO from 2014 up to 2018, and should not be modified in the future, such as the safety requirements for the plant and the systems, the tools to be used for the safety assessment, the procedures for the selection of the reference accidents, and so on. Together with these topics, considered as goals achieved, there are others for which an additional effort is necessary because they do not cover all the expected requirements of the likely licensing procedures applicable for DEMO. A complete spectrum of Design Basis Accidents and Beyond Design Basis Accidents that can determine the risk of releases from the main systems of the power plant is still incomplete together with the safety classification of most of the Structures, Systems and Components, and the feasibility and analyses of some accident mitigation systems.

The outcome of this study is the quantification, when possible, of the gap between the results achieved and the goals established in the power plant guidelines.

It will help also to qualify the effort required in terms of studies, experiments and human resources to reach a good stage for successful DEMO licensing.

1. Introduction

DEMO is an intermediate goal in the path towards the construction of a fusion power plant able to supply electricity to the grid. Several countries (EU, China United States, India, Japan) are involved in efforts to design a demonstration facility. In this context EU DEMO is in the phase of the so called pre-conceptual design. It means, for example, that the selection of a breeder concept is not yet finalized. In the past years four breeder blankets: 1) Helium Cooled Lithium Lead (HCLL), 2) Dual Cooled Lithium Lead (DCLL), 3) Water Cooled Lithium Lead (WCLL) and 4) Helium Cooled Pebble Bed (HCPB) have been proposed and studied. Up to 2021 (Pre Concept Design Phase – G1), the two that demonstrated better chances to be realized, WCLL and HCPB, will be developed and designed in more detail and integrated in the adapted

* Corresponding author.
E-mail address: mariateresa.porfiri@enea.it (N. Taylor).

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primary heat transfer system (PHTS) coupled with the optimized balance of plant (BoP).

As for any nuclear new build, EU DEMO also needs the safety assessment in order to fulfil the licensing requirements. In this context an iterative process has been started to prepare a generic site safety report (GSSR), a basic document before the site selection for the construction. This will verify that the design of the fusion power plant meets all the safety principles and guidelines specifically outlined for the plant itself.

At the same time verification of the safety requirements for the DEMO systems and components will be carried out together and reported in the GSSR to avoid any conflict between design exigencies and safety rules.

The current status of the EU DEMO GSSR is documented in this paper.

The reference design is DEMO 2017: 2000 MW plasma power, 9 m major radius, aspect ratio 3.1 and pulse length 2 h.

The DEMO design is focused currently in the optimization of the BB performances and in the implementation of the limiters for FW protection.

2. GSSR structure

Following DEMO features, the GSSR assigned in the frame of the Eurofusion Workprogramme, is structured in 11 volumes:

Volume 1 - Safety principles and approach. This includes safety objectives, principles and criteria.

Volume 2 - Overview of design and the safety features. This contains the description of the design features for the main DEMO systems that affect safety and have a potential environmental impact.

Volume 3 - Radiological and energy source terms. This collates the radioactive inventories, the origins and magnitude of energies available which could be released in off-normal situations that represent a risk for the workers, the population and the environment.

Volume 4 - Occupational safety. This refers to the systems that are the major contributors to occupational radiation exposure and strategies for minimizing them.

Volume 5 - Environmental impact of normal operation. This deals with the environmental impact of gaseous and liquid releases including those during routine maintenance.

Volume 6 - Accident sequence identification. This contains the description of systematic identification of initiating events and sequences (e.g. from Functional Failure Mode and Effects Analysis, FFMEA studies).

Volume 7 - Analysis of accident scenarios within design basis. This presents the details and results of analyses of all Design Basis Accidents (DBAs)

Volume 8 - Analysis of beyond design basis events. This contains the description and the evolution and results of analyses of all Beyond Design Basis Accidents (BDBA).

Volume 9 - Assessment of impact of external hazards. This describes the consequences of external events (e.g. seismic) and proposes solutions for their mitigation.

Volume 10 - Safety models and codes. This deals with the list of models and codes used in the safety analyses and the status of their validation.

Volume 11 - Strategies for reducing radioactive waste hazard. This contains the preliminary evaluation of radioactive waste arising from DEMO together with some selected approaches and techniques to reduce the radioactive waste burden.

3. Achieved safety issues in GSSR

Among the achieved safety issues in EU DEMO it is possible to consider the topics treated in GSSR Volumes 1, 2, 6, 7, 8 and 10. They are discussed in more detail in this section.

The top-level Safety Objectives for DEMO are clearly stated (GSSR - Vol. 1): protect workers, the public and the environment from harm assuring that the power plant has controlled and minimized radioactive inventories, that in case of accidents the radiological risk is minimized within the power plant limits and the waste burden is reduced as much as achievable. The no-evacuation criterion must be met in case of any accident, BDBAs included. In pursuing the above Objectives, use is made of well-established Safety Principles, in particular Defence in Depth, ALARA, and passive safety.

In order to ensure that the Safety Objectives are achieved, with the application of the Safety Principles, a set of Safety Requirements are elaborated, and set out in a Plant Safety Requirements Document (PSRD). Including shielding requirements. This document has its basis in IAEA [1], EPA US [2] and DOE [3] standards for fusion. PSRD states also quantitative limits and targets that can be used as Safety Criteria to assess the extent to which objectives are being met.

Amongst the quantities for which quantitative limits and targets are to be set as the design and analyses progress there are:

- Personnel maximum individual dose, currently proposed at 20 mSv/y and 100 mSv/5 years.
- Maximum collective dose for the facility (i.e. the sum of all personnel individual doses in the power plant). 700 p-mSv/y is proposed at this design stage.
- Maximum dose rates in different zones of the facility, according to a radiological zoning scheme. At present in the controlled zones they are: 25 μSv/h in green zones, 2 mSv/h in yellow zones, 100 mSv/h in orange zones, above 100 mSv/h in red zones.
- Maximum releases to the environment in one year, of radioactive material in gaseous and liquid form, during normal operation and maintenance. There is a requirement for potential releases to be demonstrated to be ALARA, however 50 μSv/year is identified as an equivalent maximum dose target for releases.
- Maximum predicted individual public dose resulting from an accident. An early dose (7-day uptake) of 50 mSv/event is assumed at the site boundary for the nearest resident population at 1 km, to meet the requirement for no evacuation. In case of DBA the objective dose is 5 mSv/event (1E-02 ÷ 1E-04 accident frequency), 10mSv/event early dose and 50 mSv/event chronic dose (1E-04 ÷ 1E-06 accident frequency). Avoiding counter-measures is basic in this context.

The compliance of the design solutions of all the systems in the reactor with the safety requirements (*GSSR Vol. 2*) are verified and documented step by step according to the evolution of the project, by means of a systematic and exhaustive procedure through the verification of interfaces, fault conditions, status of safety important components and so on. Any design change request proposed by the design teams is implemented in the GSSR together with the safety implications.

The Functional Failure Mode and Effect Analysis (FFMEA) (*GSSR Vol. 6)* based on a top-down approach was selected as the reference method to identify accident initiators and related sequences. FFMEA is a suitable methodology when insufficient design detail is available to allow for more specific evaluation at component level later.

The FFMEA, an updating of [4], performed for the DEMO plant identified 21 postulated initiating events (PIEs) as critical for the power plant and specifically

- 4 PIEs caused by a loss of flow (F)
- 1 PIE caused by a loss of heat sink (H)
- 9 PIEs caused by a loss of coolant (L)
- 5 PIEs caused by the tritium system failure (T)
- 2 PIEs caused by a loss of vacuum (V).

Accidents relating to the magnet system, maintenance procedures, hot cell system and fire and explosion occurrences, caused by H_2 generation due to the reaction of water with tungsten or LiPb, will be added

Table 1
Events analyzed.

Category	Analysed event	Important parameters	Important phenomena
LOFA	Station blackout – HCPB	- He loop pressure, temperature, control - Blanket pressure, temperature	- Loss of cooling ability - Heat up of the **First Wall** (**FW**) and **Breeder Zone** (**BZ**)
	Station blackout – WCLL	- Water loop pressure, temperature, control - Blanket pressure, temperature	- Loss of cooling ability - Heat up of the FW and BZ
In-BB LOCA	HCPB	- BZ pressure, temperature - **Purge gas** (**PG**) system pressure, temperature	- Effect of He discharge from loop into PG line - Loss of cooling ability - Heat up of the FW and BZ
	WCLL	- BZ pressure, temperature - LiPb loop system pressure, temperature	- Effect of water discharge from cooling loop into LiPb line and LiPb-water reaction - Heat up of the damaged module
In-VV LOCA	HCPB	- FW cooling loop pressure, temperature - **Vacuum Vessel** (**VV**) pressure, temperature - **Vacuum Vessel Pressure Suppression System** (**VVPSS**) pressure, temperature	- Effect of He discharge from loop in VV - Loss of cooling ability - Heat up of the damaged module - Source terms trapping in VVPSS
	WCLL	- FW cooling loop pressure, temperature - VV pressure, temperature - VVPSS pressure, temperature	- Effect of water discharge from loop into VV - H_2 production of Tungsten-water reaction - Heat up of the damaged module - Source terms trapping in VVPSS
Ex-vessel LOCA	HCPB	- **Tokamak Cooling Room** (**TCR**) pressure, temperature - FW temperature	- Effect of discharge of He from loops into TCR - Loss of cooling ability - Heat up of the FW and BZ
	WCLL	- TCR pressure, temperature - FW, BZ temperatures	- Effect of discharge of water from loops into TCR - Loss of cooling ability - Heat up of the FW and BZ
Plasma Events	Plasma Thermal Quench	- Plasma disruption energy and deposition time	- FW temperature and failure criteria

in the future to this first PIE selection.

The FFMEA will be complemented by the FMEA when DEMO design at component level will be available together with the HAZOP analysis approach to identify fault sequences. The combination of small incidents leading to critical consequences will be assessed as well.

The full spectrum of the accident analyses (*GSSR Vol. 7&8*) identified by the FFMEA have not yet been completed. The selection of the accident analyses followed, at first, the criterion to support the DEMO design. Then the breeder blanket accidents (in-box LOCA), in-vessel LOCA, ex-vessel LOCA, loss of flow accidents, plasma events have been analyzed up to now (Table 1) for the two concepts WCLL and HCPB.

Results of the accident analyses performed are shown in detail in [5] and [6] for WCLL and in [7] for HCPB. Others will be published in the future. Among the main outcomes obtained there is the demonstration that the maximum pressure during an in-VV LOCA DBA is well below the VV design pressure (200 kPa) if it is supported by a suitable vacuum vessel suppression system (VVPSS).

In the WCLL concept the isolation valves must be foreseen because only one loop cools all the First Wall segments.

Also the effectiveness of event mitigation by means of the VVPSS without the need of isolation valves for HCPB and with the intervention of the isolation valves for WCLL was shown for BDBA ex-vessel LOCA.

A screening of 30 safety codes, able to perform the analyses necessary for the assessment (*GSSR Vol.10*) in the frame of nuclear fusion has been performed highlighting the application field, the validation and verification status and the requirements for further improvements.

4. Open safety issues in GSSR

Open safety issues identified in the GSSR that require further consideration relate to the source terms (*GSSR Vol. 3*), the occupational safety (*GSSR Vol. 4*), the environmental impact of normal operation (*GSSR Vol. 5*), the external hazards (*GSSR Vol. 9*) and the waste assessments (*GSSR Vol. 11*).

The distribution of the source terms (*GSSR Vol. 3*) such as tritium (T), dust (APs) and activation corrosion products (ACPs) inside the power plant is well known because they are located mainly inside the vacuum vessel (T, APs), in the breeder blanket (T, ACPs), in the cooling loops (T, ACPs) and in the tritium building (T). The inventories themselves are quite complex to define with sufficient accuracy at the present time. The typical phenomena inducing source term production and deposition such as the plasma sputtering on the PFCs, the T diffusion in the depth of the material and its release during baking or the corrosion of the cooling pipes have different features in comparison with those monitored in existing experimental machines (JET, ASDEX, DIII-D etc.).

Direct extrapolation of the experimental data is not appropriate and a tentative scaling from ITER data [8] resulted in a large range of uncertainties. A new assessment is in progress [9] to link experimental data with plasma-wall interaction and tritium behavior modeling. The scope is to verify whether some of the conservatism adopted in [10] and used in [8] have to be reduced.

For occupational safety assessment (*GSSR Vol.4*) the problem is related to the lack of definition of the maintenance procedures and the lack of dose rates around main components and systems. Provisionally an approach that defines the most demanding systems from the maintenance point of view is adopted and a first occupational radiation exposure (ORE) evaluation has been done. This first step is necessary to focus attention on the optimization of the procedures and of the design also from the maintenance point of view. Further assessments will be carried out as the design progresses and the radiation fields in the zones affected by maintenance will be available, as well as when the needs for remote maintenance will be defined.

The first ORE evaluation has been performed for the PHTS and energy storage systems (ESS) of the two BB concepts (Table 2), using a parametric dose rate in the green zones affected by the maintenance.

The two systems give a significant contribution to the collective dose because the target for the entire EU DEMO is 700 p-mSv/year,

Table 2
Collective dose in PHTS&ESS.

BB Model	Collective dose (p-mSv/year)	
HCPB	10 µSv/hr in green zone 433	5 µSv/hr in green zone 242
WCLL	25 µSv/hr in green zone 255	10 µSv/hr in green zone 152

average overall several years. Optimization, reduction of hands on activities and use of remote handling as an alternative will be the goal to minimize exposure and stay below the limits established.

The environmental impact of normal operation (NO) (*GSSR Vol. 5*) is dependent on the source term inventories that are under evaluation (*GSSR vol. 3*), the pathways they follow in the plant and the release fraction typical of the components through which the source terms pass. In addition the design of the lay-out of the plant, still in the preliminary phase, affects the type and quantity of the releases in NO. As a consequence the definition of the environmental impact of normal operation is still far from completion.

The accident analyses due to external hazards (*GSSR Vol. 9*) have not been started currently but one case is foreseen to be studied before the EU DEMO Gate Review (November 2020), during which the continuation of the project will be decided by the European Commission. The relevant external hazards that commonly refer to extreme environmental conditions, seismic, flooding, aircraft crash and site-specific events such as explosions represent the spectrum of the external hazards to be faced. The selection of the case to assess first will be carried out including a combination with internal hazards, for example earthquake + vertical plasma displacement + fire, to avoid what occurred in Fukushima, as suggested by a Design Review of the WPSAE work, recently.

The waste management strategy (*GSSR Vol.11*) is the last open issue because the replacement policy of the components is not yet fully defined. As a consequence, the waste streams expected and methods to store the waste is premature.

The virtual cycle of the waste management (Fig. 1) must foresee several steps in which the detritiation, reuse and recycling have to be optimized through applying a waste hierarchy of preferential options. In this context techniques for detritiation, smelting [11], chlorination and decarburization [12] have been investigated [13] together with processes to reduce as much as possible the impurities in the pre-use materials, being, in most cases, the causes of the higher activation.

Following an effective recycling treatment, the vast majority of materials would not require long-term disposal in a geological repository. For the components requiring disposal, long lived radionuclides would be removed where possible. As a first evaluation utilizing neutronics studies out of 484 − 560 tonnes of beryllium, around 3 − 4 kg represents the mass of the most harmful radionuclides; for tungsten, where 1960 tonnes will be used, around 59 tonnes will represent long-lived radionuclides.

The difference in the amount of disposed material is due to the origin of radionuclides because tungsten itself will create harmful transmutation products whereas beryllium's radionuclides arise from impurities (uranium, cobalt).

Recycling is not envisioned for lead and disposal would be the final route for the majority of PbLi. During DEMO's lifetime, an estimated 30,000 tonnes of lead will be used for the HCLL concept, compared to a maximum of 210 tonnes of lithium.

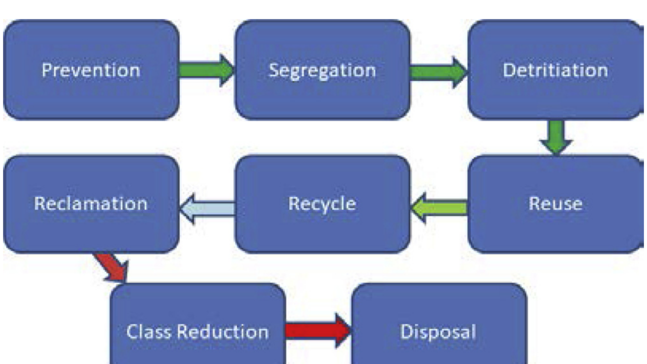

Fig. 1. Waste management: steps from dismantling to disposal.

5. Plan for GSSR completion

The EU DEMO project is ongoing and GSSR is following and revealing the key issues of the reactor in respect of safety. The plan for the completion of the safety report has to fulfil all the missing data and the pending accident analyses as described in §3 and solve the challenges highlighted in §4.

Together with the research of suitable solutions for outstanding technical problems (e.g. waste management), the retrieval of data arising from the experience and knowledge of the other DEMO working groups, such as the materials or the plasma-wall interaction teams is essential to build a coherent data base for source terms definition.

In parallel an R&D program is outlined dealing with

- the explosion risk due to possible chemical reactions and H_2 production by means of dedicated experiments,
- the dust and tritium inventory control inside the VV by means of the development of diagnostic and monitoring equipment,
- the implementation of codes for the modeling of the activated corrosion products in the PbLi circuits.

In addition, and as a consequence of the new approach to the risk management of all industrial plants, the issue of security has to be addressed and placed side by side with the nuclear safety.

6. Conclusions

An ambitious program for the safety of fusion power plants is to realize a machine that is suitable not only to produce energy and fuel to be burnt in the plant itself, but also to reach the highest safety standards. This means that the reliability of the plant has to provide stable energy production where the need for normal maintenance required infrequently, the risk of accident reduced to the minimum achievable, and the dose to the workers low enough to be comparable with the existing nuclear power plants and lower if achievable. It must be possible for the radioactive waste to be placed in low or intermediate level storage in small amounts, and for the most part of it to be reused and recycled.

The safety analysis, in this frame, has the duty to verify that the solutions proposed for:

- reducing the activation of the material,
- increasing the strength of the components,
- minimizing the complexity of the machine,
- optimizing the maintenance activities and reducing them,
- improving the confinement systems,
- implementing the remote maintenance

are adequate to avoid incident and accident conditions, and to reduce as much as reasonably achievable the doses to workers, the population and the environment in any case.

The Generic Site Safety Report (GSSR) has a role to demonstrate that all the goals can be achieved with significant margins.

A robust R&D program will accompany the GSSR evolution for the following years, dealing with the pending issues.

In the meantime, a high-level approach for the fusion power plant security will be outlined to complement the safety assessment.

CRediT authorship contribution statement

Maria Teresa Porfiri: Conceptualization, Writing - review & editing. **Neill Taylor:** Supervision, Methodology. **Sergio Ciattaglia:** Supervision. **Xue Zhou Jin:** Conceptualization, Investigation, Formal analysis. **Jane Johnston:** Conceptualization, Investigation. **Bethany Colling:** Validation. **Tim Eade:** Validation. **Dario Carloni:** Conceptualization. **Tonio Pinna:** Conceptualization, Formal analysis.

Egidijus Urbonavicius: Data curation. **Robert Vale:** Conceptualization, Investigation. **Andrija Volkanovski:** Conceptualization. **Gianfranco Caruso:** Conceptualization, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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