Proposal of the Confinement Strategy for EU DEMO

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Following the European roadmap to the realization of fusion energy, a demonstration fusion power plant (DEMO) is currently in preconceptual design phase until 2020. In this context an external stakeholder group formulated a nuclear licensed manufacturing and construction (M/C) as the top level requirement for a DEMO, translating essentially to the confinement of radioactive and hazardous materials as the most fundamental safety function in normal, abnormal and accidental situations. In a first step energy sources and radioactive source have been assessed for a conceptual DEMO configuration. Based on the European Plant Description Document (PDD) the main systems have been classified as active or passive systems with respect to their confinement functionality. By means of a bottom-up approach at system level, the major DEMO systems are analyzed regarding a potential confinement function. On the basis of those DEMO systems identified as having a confinement function a confinement strategy for EU DEMO has been proposed with respect to confinement barriers and confinement systems. In addition, confinement for the maintenance has been issued as well. The assignment of confinement barriers to the identified sources under abnormal and accidental conditions has been performed, and the DEMO main safety systems have been proposed as well. Confinement related open issues such as discharge of the huge magnet energy in an accidental case, confinement concerning plant states, investigation on further passive and active methods for the confinement, confinement during the procedure of removing and replacing in-vessel components, etc., need to be resolved in parallel with DEMO development.

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Abstract. Confinement of radioactive and hazardous materials is one of the fundamental safety functions in a nuclear fusion facility, which has to limit the mobilisation and dispersion of sources and hazards during normal, abnormal and accidental situations. The confinement function is identified for the main systems of the European DEMO taking a bottom-up approach at system level. Based on identification of the systems possessing a confinement function, a confinement strategy has been proposed, in which DEMO confinement systems and barriers have been defined.

1. Introduction

Following the European roadmap to the realisation of fusion energy, an intense research activity has been started for a DEMOnstration fusion power plant being in the pre-conceptual design phase until 2020. In this context, an external stakeholder group formulated a nuclear licensed manufacturing and construction (M/C) mission statement as the top level requirement for a DEMO, translating essentially to the confinement of radioactive and hazardous materials as the most fundamental safety function during normal, abnormal and accident situations. Hence, the objectives of DEMO confinement are:

- to protect every inventory of radioactive, toxic or hazardous material: to prevent mobilisation into rooms where personnel could be exposed; and to prevent release to the environment that could lead to public exposure;
- to meet DEMO general safety objectives [1] in compliance with the environment in operational or accident situations;
- to reduce potential consequences to the extent reasonably practicable.

Confinement of radioactive and hazardous materials is the first of four fundamental safety functions defined in DEMO Plant Safety Requirements Document (PSRD) [1]. Its supporting safety functions aimed at the protection of confinement during abnormal conditions are identified as control of plasma energy (e.g. fast plasma shutdown), thermal energy (e.g. decay heat removal), confinement pressure, chemical energy, magnetic energy, and coolant energy. Any component or system that provides a safety function must be categorised as Safety Important. Safety Importance Class (SIC) for DEMO components (and systems) is being proposed in [2]. Systems or components that are identified as SIC for the confinement need to comply with the confinement approach identified for DEMO.

Taking a bottom-up approach at system level, the confinement function has been identified for the main systems defined in the plant breakdown structure (PBS) at level 1 [3]. The reference design is EU_DEMO1_2015 [4]. On the basis of those systems possessing a confinement function, a confinement strategy has been proposed. In this context confinement systems and barriers are defined, which are not only for operation but also for maintenance. DEMO main safety systems and devices are proposed. The assignment of a confinement barrier to each the identified source is also performed. DEMO safety approach is based on the identification of potential hazards which could lead to radiological consequences if no protection is defined. Sources and hazards are identified firstly.

2. Sources and hazards

Due to tritium usage and neutron generation in DEMO the radiological safety implications have to be dealt with. Stored energies may have the potential to affect the confinement to destroy the system integrity, and to mobilise radioactive sources that could result in the release of radioactivity. Energy sources identified for DEMO are: enthalpy in structure and coolant, plasma thermal energy, magnetic energy, disruption mechanical energy in operation; decay heat after the plasma shutdown; energy from exothermal chemical reactions between materials in accident situations (reaction of steam / air with tungsten, PbLi, beryllium, etc.), dust explosion, overpressure scenarios, spills of cryogenic / hot helium into the vacuum vessel (VV), etc.; and energy release due to postulated hydrogen explosion.

Radioactive sources identified for DEMO are: (1) tritium inventory in various locations (the VV, the PHTS (Primary Heat Transfer System), fuel cycle components, etc.); (2) dust particles in the VV (mainly tungsten and EUROFER) due to the plasma / wall interaction during normal operation, as well as in other status (e.g. disruption in accident case); (3) Activated Corrosion Products (ACPs) in the PHTS caused by corrosion, erosion (e.g. in water cooled blanket and divertor, in LiPb breeder box); (4) neutron sputtering products (e.g. in gas cooled blanket); (5) activated materials in breeding materials, in the PFC (Plasma Facing Component), in the in-vessel structure, as well as in coolant (e.g. activation in water or liquid metals); (6) possible radioactive isotopes from noble gases (mainly with neon or argon) used for plasma seeding, which may be generated by neutron capture processes, in particular neon, argon, krypton, xenon (these can be easily mobilised and should be quantified); (7) nitrogen seeding for ELM (Edge Localized Mode) mitigation, nitrogen impurity in structures, and injected nitrogen to avoid hydrogen explosion. It is important to estimate inventories of the radioactive sources in the VV and mobilisable fractions for accident analyses in order to assess the consequences of a hypothetical release.

The number of confinement barriers that are required depends on the potential internal and external hazards, and the potential (radiological) consequences of failures. Internal hazards are mainly: internal fire / explosion, thermal releases, plasma transients / disruption, internal flooding, missile effects and pipe whip as well as jet impingement, loss of vacuum (LOVA), loss of coolant (LOCA), loss of heat sink (LOHS), loss of cryogenics, mechanical risks, chemical and toxic risks, and magnetic and electromagnetic risks. The use of halogenated materials at high temperatures has the potential for decomposition to harmful and corrosive products, which could challenge confinement boundaries as well. A complete DEMO safety analysis incorporates an analysis of the impact of external events on the plant. External hazards can occur due to: the natural environment (earthquakes, extreme climatic conditions, notably severe temperatures, snow load, wind and lightning, external flooding, and external fire), or human activities (aircraft crashes, hazards associated with the industrial environment and communication routes, such as external explosions and unauthorized access, station blackout, pressure or temperature shocks from accident in a nearby facility on-site).

3. DEMO main systems and confinement

From the point of view of the confinement functionality, the DEMO main systems at the PBS level 1 are distinguished as either active or passive systems in Table I. The systems have been analysed based on the Plant Description Document (PDD) [5] to identify a potential confinement function. Systems having a confinement function are indicated with symbol (+), and symbol (-) for systems regarded as having no confinement function in the safety case.

TABLE I: DEMO MAIN SYSTEMS AT THE PBS LEVEL 1.

Active system	**Passive system**
• Magnet system (-) • Tritium, fuelling, vacuum (TFV) (+) • Tritium extraction removal (TER) (+) • Electron Cyclotron (EC) system (+) • Neutron Beam injection (NBI) system (+) • Ion Cyclotron (IC) system (+) • Plasma diagnostic and control system (+/-) • Blanket-PHTSs (+) • VV-PHTS incl. emergency cooling system (+) • Divertor-PHTS (+) • VV pressure suppression system (VVPSS) (+) • Remote maintenance (RM) system (+) • Balance of plant (BOP) (-) • Cryoplant & cryodistribution (-) • Electrical power supply systems (-) • Plant Control System incl. Central Safety System, Monitoring System (-) • Auxiliaries (-) • Radwaste treatment (+)	• VV (+) • Divertor (-) • Breeding blanket (BB) system (-): o HCPB (Helium Cooled Pebble Bed) o HCLL (Helium Cooled Lithium Lead) o DCLL (Dual Coolant Lithium Lead) o WCLL (Water Cooled Lithium Lead) • Limiter (-) • Cryostat (-) • Thermal Shields (-) • Buildings (tokamak and tritium buildings) (+) • Radwaste storage (+)

The magnetic energy stored in the magnet system has an impact on the confinement in accident situations. A huge amount of magnetic energy is accumulated in the superconducting coils (e.g. ~135 GJ in toroidal field (TF) coils). It has to be evacuated outside the coils and the tokamak building in case of malfunctions or coil failures. The safety risks associated with the magnets originate from quench development without energy discharge, and short circuit of the (TF) coils and consequent arcing towards confinement barriers and release of 4 k helium. The credible magnet system failures under normal or abnormal conditions (including earthquake) must not cause damage to the confinement barriers.

The VV ensures two safety requirements: confinement and support function. It is classified as SIC1 in [2] and should be capable to withstand pressures and environments loads resulting from off-normal events. The confinement barrier is formed by the outer shell of the vessel double wall, the single wall of ports and the connection between ports and port plugs. The entire vacuum boundary also provides the confinement function including seals, feedthroughs, (ceramic) windows, bellows, etc., which are more vulnerable to failure than the vessel itself.

In the blanket-PHTS, water or helium as coolant can be contaminated by permeated tritium produced in the BB; by ACPs caused by corrosion, erosion with water as coolant and PbLi as breeder; by dust and neutron sputtering products that are accumulated as well. The blanket-PHTS has to provide confinement for the coolant and radioactive sources, and it is classified as SIC1 in [2]. Also the divertor- and VV-PHTS have to confine the coolant and potential radioactive sources. The VV-PHTS is classified as SIC2 in [2]. The emergency cooling system is activated to remove decay heat on failure of the VV-PHTS.

The tokamak building forms the final barrier between the tokamak and the environment, and it is classified as SIC2 in [2]. Three alternative wall design concepts have been proposed: 1. high reinforced concrete building, 2. single-walled containment with steel liner, 3. double-walled containment. Concept 1 adopts the ITER concept. Concept 2 adopts the containment concept for the European pressurised reactor [6]. For Concept 3 the inner pre-stressed concrete wall withstands high pressure in case of accident, and the outer reinforced concrete shell withstands external aggression. A proper liner concept should be selected with respect to tritium behaviour, leak rate, coolant and accident conditions. The options of a metallic liner, a composite liner from homogeneous fibres or composite laminate, or no liner are being considered.

In the TFV, the vacuum pumping system enables isolation of tritium and dust inventories during off-normal conditions. Leaks into the system would be inward and would result plasma termination due to unsuitable vacuum conditions. It is classified as SIC2 in [2] for loss of vacuum. The fuelling system confines gases (e.g. H, D, T, He) within the TFV, and it is classified as SIC1 in [2]. A fusion power shutdown system and a Disruption Mitigation System (DMS) are included in this system. In the tritium plant systems, the coolant purification system (CPS) which removes the tritium from the BB coolant, the tritium extraction and processing system (TEPS) which processes the outlet stream from the BB tritium extraction system (TES) of the TER, and the tokamak exhaust processing (TEP) system which removes impurities and plasma enhancement gases, are relevant for the confinement function [7]. During the plant shutdown the exhaust detritiation system (EDS) needs to be functioning to process off-gassing tritium from sources to be reserved / recycled as potential fuel.

4. DEMO confinement strategy

Starting with the DEMO systems that have been identified as possessing a confinement function, multiple confinement systems / barriers are required for DEMO as a nuclear facility, in order to protect the personnel, public and environment against radioactive material releases. The confinement function should be ensured for events exceeding level three of defence in depth [8], which may require measures to mitigate the consequences of accidents that result from failure of the third level of defence. Hence, radioactive releases must be kept as low as reasonably achievable (ALARA). The sequential barriers associated with the confinement systems are essential to confine hazards and minimise tritium release. The principles to take into account for confinement systems are: independency among confinement systems, passive safety methods, high reliability of components, and accurate monitoring and control.

4.1.Confinement systems and barriers

Two confinement systems have been proposed for the European DEMO. The first confinement system prevents releases of radioactive and hazardous materials during normal plant operation into the accessible working areas in order to protect personnel. The second confinement system prevents environmental releases of these materials to the working areas accessible by non-classified radiological workers, the general public and the environment in the event of failure of the first confinement. The outer wall of the second confinement system has to withstand external aggression.

A confinement scheme is shown in Fig. 1 identifying those systems providing the major safety functions of DEMO. Four blanket concepts using different breeding materials and coolants necessitate the implementation of different technological solutions matching the confinement target. The PbLi breeding loop is schematised for the HCLL, DCLL and WCLL concepts, which is not required for the HCPB concept. PbLi is also used as coolant, together with helium, in the blanket-PHTS for the DCLL, while the blanket-PHTS consists of only a helium loop for the HCPB and HCLL, and of only a water loop for the WCLL. The PbLi breeding loop in the HCLL and WCLL has a heat exchanger (HX) to the side of the TES, which is not shown in the figure. The first confinement system consists of the first and second barriers. High reliability of the first confinement barrier for enclosing radioactive inventories is required. The second confinement barrier maximizes separation and independence from the first barrier, in order to prevent a common mode failure. In these two barriers penetrations of ducts, pipes, etc. must be handled with care that the confinement function is not therefore affected. In addition, key sub-systems having a confinement function are assigned to the confinement barriers. The first barrier contains the VV, its extensions (including NB cell, the VVPSS in case of accident), the blanket-, the VV- and divertor-PHTS, fuelling line, tritium systems and components. The second barrier includes the VVPSS, the drain tank, the PHTS-HX, glove boxes, the CPS, the TES, the emergency cooling system, and isolation valves. The third barrier provides the second confinement system which contains active systems such as the HVAC system, the Normal Vent Detritiation System (N-VDS), the S-VDS, the TEP system, the EDS, the common discharge point, and the tokamak and tritium buildings.

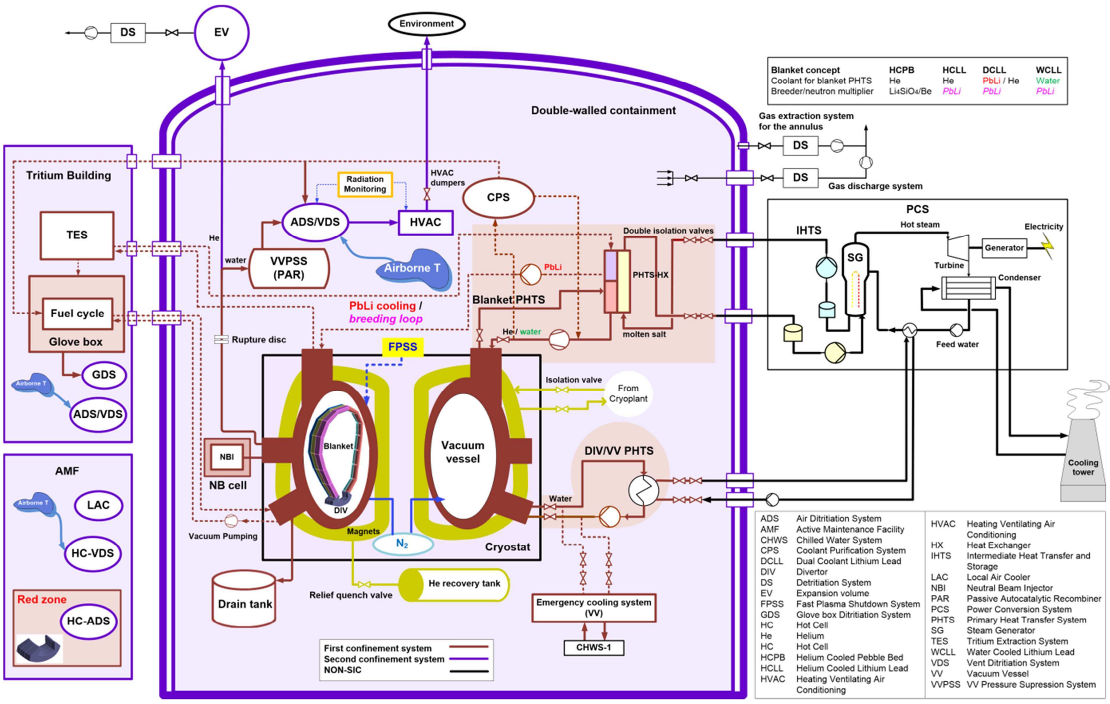

FIG. 1. EU DEMO confinement Scheme.

The VVPSS is classified as SIC1 in [2], since it limits the VV pressure in the event of in-vessel LOCA and confines radioactive sources in the system. For the helium cooled blanket concepts (HCPB, HCLL and DCLL), an expansion volume (EV) with a passive safety feature is required. This is tentatively placed outside the tokamak building because of its potentially huge volume. The EV is assumed to be part of the second confinement system. A combined VVPSS and EV concept is being explored in the EUROfusion safety program [9]. Isolation valves are considered as SIC1 for the VV or as SIC2 for other barriers which maintain confinement in the system's own volume in order to avoid a release to the next system / room. Double isolation valves are installed at the interface to the NON-SIC side (IHTS and PCS of the BOP) in order to prohibit, limit, or spatially divert the release of radioactive sources.

4.2. Confinement during maintenance

Maintenance requiring remote removal and replacement of the in-vessel components (IVCs) and in-cryostat components has relevance for the confinement. Since the VV is opened during maintenance such that it is no longer a confinement barrier, systems working in maintenance, which are part of the second and third barriers during normal operation, become the first and second barriers respectively. Thus keeping two confinement systems, each confinement system containing one barrier is proposed for maintenance. The first barrier contains the VVPSS, the drain tank, the emergency cooling system, and also the cryostat (if its vacuum is unaffected). In addition, adopting the ITER maintenance cask concept, the contamination control door [10] and the transport cask are also part of the first barrier. The transfer structure for transportation of the transport cask from the tokamak building to the Active Maintenance Facility (AMF), the AMF for dismantling, maintenance and storage, the HVAC system, the ADS, the VDS, the EDS, and the tokamak building and the common discharge point are part of the second barrier in the second confinement system. An advanced maintenance concept with a robust hot cell structure above the bioshield which connects directly to the AMF is being developed [11]. In this case the hot cell replaces the casks as the first barrier and the transfer structure is removed.

4.3.Main safety systems and devices for DEMO

The systems and devices implementing the major safety functions in Fig. 1 are proposed in Table II and are classified as passive or active systems. In ITER, the fast plasma shutdown system (FPSS) is classified as active system that is actuated by a passive logic; however in DEMO its design can follow the criteria of passive components specified in [12] to be classified as passive. For the DMS, the safety function has not been assigned in ITER, but it could be assigned in DEMO [9].

TABLE II: PROPOSAL OF THE MAIN SAFETY SYSTEMS AND DEVICES FOR DEMO.

System / device	**Safety function / Call on service / Consequence by failure**
VV and its extensions (passive)	Confinement / Always / Loss of 1st confinement barrier
VVPSS (passive)	Confinement / In-vessel LOCA / Loss of 1st confinement barrier
Tokamak / tritium Building (passive)	Confinement / Always / Loss of 2nd confinement system
FPSS (passive)	Plasma termination / Severe events / Partial failure of the PFC
DMS (active)	Avoid or reduce disruptions / Abnormal operation / Large disruption, damage of the IVCs
Emergency cooling (active)	Decay heat Removal / Unavailability of the PHTS / Failure of active heat removal
HVAC (active)	Condition room air, maintain depressurized atmosphere, and isolation in case of tritium released in the building/ Normal operation / Pressure increase of the building encompassed by the pressure relief and subsequent filter system
N-VDS (active)	Collect tritium released / Normal operation / S-VDS starts
S-VDS (active)	Collect tritium released in abnormal scenario, pressure control / High level of radioactivity inside the 2nd confinement / Pressure increase of the building, possible tritium release.
Common discharge point (passive)	Control pressure by release through the stack / 2nd confinement overpressure signal / 2nd confinement overpressure
N_2 injection (active) / PAR (passive)	Avoid H_2 explosion / Passive / H_2 generation / H_2 explosion limited to small scale not affecting barrier integrity
Magnet energy fast	Avoid arc or short in magnets, release of 4 k He / Temperature

discharge system (active)	increase in magnets / magnets quench, possible damage to the confinement barrier
Emergency Power Supply (active)	Supply emergency safety systems / Loss of power / No power supply to safety systems (station blackout)
Central Safety System (active)	Monitor the overall plant status, coordinate actions to bring the plant into a safe status / When the plant goes out of the safety operation domain / The plant is brought to the safe status through separate actions via Plant Safety Systems
Monitoring System (active)	Detect the radioactivity concentration in all nuclear buildings and through the common discharge point / All time / Lost the monitoring also of the releases to the environment through the common discharge point
Fire barriers / suppression (passive/active)	Prevent propagation of fire / Fire / Propagation of fire and possible release
EV (passive)	Protection of the VV, room and building / Always / Overpressure of the VV, cooling system room and building
Isolation valve (active)	Confinement / LOCA / Release of the source terms to the BOP

4.4.Assignment of confinement barriers to the sources

It is important to ensure that each source is confined by suitable active / passive barriers. Table III shows the assignment of confinement barriers to each of the sources shown in section 2. Only systems and devices being activated under abnormal and accidental conditions are listed. Not every source is confined by both active and passive barriers as expected. More passive barriers are required for the confinement in accident situations.

TABLE III: ASSIGNMENT OF SOURCES TO CONFINEMENT BARRIERS.

Source		**Barrier**	
		active	**passive**
Energy	Decay heat	Emergency cooling system	PCCS[1] (WCLL)
	Chemical reaction	Emergency cooling system	PCCS (WCLL)
	Dust explosion	N_2 dilution, O_2 limitation	VV
	Overpressure scenarios	VVPSS, drain tank	VV, EV, rupture disc
	Spills of cryogenic or hot helium into the VV	-	VV, EV, rupture disc
	H_2 explosion	N_2 injection	VV, PAR
Radioactive source	Tritium	S-VDS, EDS, isolation valve	VV, emergency storage system
	Dust	Isolation valve	VV
	ACPs	Isolation valve	VV
	Activated materials	-	VV

5. Conclusions

The confinement study for the European DEMO has been investigated for the main systems at the PBS level 1 taking a bottom-up approach. Consequently, a confinement strategy has been

[1] Passive Containment Cooling System (PCCS) is widely used for water cooled nuclear power plant (NPP), and it is considerable for the WCLL concept.

proposed, in which two confinement systems and three associated barriers have been defined. For maintenance two confinement systems containing one barrier in each confinement system has been proposed. The main safety systems and devices have also been proposed. The assignment of confinement barriers to the sources shows that not all sources are covered by both passive and active barriers. The confinement function is being identified for sub-systems and components accompanying the development of PBS levels in the EUROfusion safety program. The following open issues need to be resolved in priority from the confinement point of view: (1) define inventories for all mobilisable radioactive sources; (2) the provision of the helium EV; (3) provide discharge capability for the potentially huge amount of magnet energy in accident scenarios; (4) select wall and composite liner options for the tokamak building taking into account cost implications; (5) define leak rate conditions for confinement; (6) explore additional passive / active methods for confinement barriers; (7) maintain confinement for different plant states (including cold and hot standby, and maintenance).

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