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EU DEMO safety and balance of plant design and operating requirements. Issues and possible solutions

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The DEMO preliminary safety and operating design requirements are being defined aiming at obtaining the license with a relatively large operational domain.

The DEMO design approach is being organized, by taking into account the Nuclear Power Plant, ITER and Generation IV lessons learnt. Outstanding challenges remain in areas exhibiting large gaps beyond ITER. Those require a pragmatic approach, especially to evaluate and improve the readiness of technical solutions through dedicated physics and technology R&D. Therefore, a system engineering approach is adopted based on an integral plant design analysis which follows clear defined goals as safety, availability and power provision to the grid. This ensures not only the identification of critical interfaces but also the margin of possible solutions and, moreover, the definition of target parameters for technical systems to be met in order to arrive at a feasible DEMO design.

The overall DEMO plant design has to be strongly safety and operation-balance of plant (BoP) oriented.

The paper describes a set of important aspects of safety and BoP that require early attention and a continuous reanalysis at any significant design change. This includes: (i) safety provisions required by the coolant options following some reference accidents; (ii) tritium inventory limit control considering the substantial throughput; (iii) permeation of tritium through the Primary Heat Transfer System; (iv) conditions for a plasma shutdown, (v) pulsed operation and relevant interfaces with the grid and BoP systems; (vi) layout of the tokamak building to accommodate Remote Maintenance meeting layout and safety criteria.

Any effort to reduce the complexity of a Fusion Power Reactor design through simplification and rationalization of the design and operation of the main systems translates into a more robust plant configuration enlarging safety margins and operational thresholds.

Keywords: Fusion reactor, nuclear safety, design objectives, operating requirements, balance of plant, licensing.

1. Introduction

Initial DEMO conceptual design studies are being conducted in Europe as part of the EU roadmap which aims at the demonstration of electricity produced by nuclear fusion around the middle of this century. DEMO in Europe is the nearest-term reactor design to follow ITER, under construction in France, and capable of demonstrating production of electricity, operating with a closed fuel-cycle and to be a facilitating machine between ITER and a commercial reactor [1].

The aim of this paper is to introduce a few design and operational challenges relevant to safety and balance of plant (BoP) and to present possible solutions and general criteria to minimize and control the complexity of the plant aiming at facilitate licensing and improving machine availability.

The preliminary safety and design requirements have been defined aiming at obtaining the license for construction (and license for operation later) with a relatively large operational domain.

The DEMO design approach is being organized, by taking into account the Nuclear Power Plant (NPP) experience and the lessons learnt from ITER and Generation IV. Outstanding challenges remain in several areas with potentially large gaps beyond ITER that need to be overcome and that require a pragmatic approach, especially to evaluate and improve the readiness of the foreseeable technical solutions through dedicated R&D. Integrated plant design assessments are essential from the early phase to ensure a better integration of engineering and operational challenges, safety, power conversion aspects and reliability of the power plant: control of system interfaces, e.g. primary heat transfer systems (PHTS) and plasma facing components (PFC), plant electrical system (PES) and all active system of DEMO, space allocation, layout and hands-on and remote maintenance (RM) criteria.

In other words the overall DEMO plant design has to be strongly safety and operation-BoP oriented; this represents a significant culture change within the fusion community which previously concentrated mainly to plasma performance optimization.

The article highlights some important aspects of safety and BoP, such as the plasma instabilities, the radioactive and energy inventories, PHTS and the relevant power conversion system (PCS), PES and the tokamak layout that require early attention and a continuous reanalysis at any significant design change because of their impact on licensing or on their dimensions and relevant complexity.

The requirements of these systems and structures (PHTS, PCS, PES and tokamak building) are challenging compared to similar systems of nuclear fission power plants. Different cooling fluids, different temperatures and pressures, pulsed operation, formulate extreme demands for the design of heat transfer and power conversion

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systems (PCS) as well as the very large and in part pulsed electrical power requested by the numerous equipment necessary for the fusion reactor (several times bigger than the recirculating power in a nuclear or conventional power plant) require particular attention in the relevant design and continuous interaction with the reactor system designers in order to control the dimension and feasibility of these systems.

Any effort to reduce the complexity of DEMO through simplification and rationalization of the design and operation of the main reactor systems will translate into beneficial returns on the safety and on the operation of the plant.

2. Main Objectives of DEMO

The overall final objectives of DEMO are a long plasma operation time, tritium self-sufficiency and net electricity output. In order to reach them two essential design drivers are necessary to be pursued since the early stage of the design and to be verified throughout the DEMO design development: i) a feasible and easy licensing for construction and operation, ii) an acceptable availability of the plant.

3. NPP and ITER experience of design, construction and operation

The design, construction and operating experience is fundamental for the design, fabrication, operation and licensing of a complex nuclear power plant like DEMO.

ITER is the closest plant, therefore a close attention is paid to the ITER design solutions, the results of R&D ongoing, the licensing commitments and relevant solutions. The lessons learned in each phase of ITER development are considered by DEMO designers to the maximum extent, e.g. the layout and environment of the tokamak building, the nuclear shielding of critical areas, the identification and control of radioactive source terms, the management of energy inventories, the safety important classification (SIC) of structures, systems and components (SSC) and relevant implications.

DEMO presents a few significant differences in comparison to ITER. The main ones are the Breeding Blanket with the relevant systems to recover the produced tritium, the associated fuel cycles, that having to deal with a much higher throughput of deuterium (D) and tritium (T), should recirculate as much as possible the D-T mixture extracted from the vacuum vessel (VV), the complex plasma heat transfer and power conversion chain with the connection to the grid through its own electrical generator.

Two main concepts for PHTS are presently being studied: helium cooled pebble beds (HCPB) and water coolant lithium lead (WCLL). They are significantly different, therefore auxiliaries, safety analyses, tokamak building, etc., are being defined for each model.

The operating experience of the NPPs and a reference for DEMO for the PHTS and PCS and those auxiliary systems common in fusion and fission plants, for example building layout, qualification, maintenance and inspection of components.

The DEMO preliminary plant site layout (Figure 1) makes basically reference to that of ITER with few adaptations: the turbine/generator building, close to the tokamak building and to the switchyard because the PCS, PHTS and their auxiliaries, require significant electrical power and also the generator has to deliver the power to the grid. The most demanding buildings from design point of view are those of the nuclear island: having to perform the secondary confinement function, they should resist all external and internal design basis events (DBE) while maintaining the safety function. Hosting all the radioactive inventories, they have to meet general safety principles such as the separation between redundant SIC systems, limitation of radioactive and energy inventories that can be involved in a single DBE, maintenance and human factors requirements. The safeguards buildings should host all the other SIC components not contained in the nuclear island. Such buildings have to withstand to the DBEs in order to protect the SIC components and the relevant safety functions. All non-SIC components and those not necessary to be close to the torus, should be located outside such buildings in order to reduce their volumes, the risk of accidents and the radiation dose to the staff.

4. Safety and BoP issues and possible mitigation

Eight key design integration issues (KDII) that affect the whole plant architecture have been identified [2] and are being studied during the DEMO pre-conceptual design phase: (i) feasibility of wall protection limiters during plasma transients, (ii) integrated design of breeding blanket and ancillary systems, (iii) power exhaust taking advantage of advanced divertor configurations, (iv) tokamak architecture based on vertical blanket segments, (v) power conversion concept (direct or indirect), (vi) configuration of plant systems in the tokamak building, (vii) feasibility of hydrogen separation in the torus vacuum pump and direct recirculation, and (viii) development of a reliable plasma scenario including supporting systems like heating current drive (HCD) and diagnostics systems..

These KDII are treated in other papers of the conference, e.g. [2, 3]. Below we discuss briefly issue (v) and few general aspects affecting safety and BoP that are important to consider and control at any stage of the project.

4.1 Plasma instabilities: control and mitigation

In contrast to existing fusion experiments and ITER, being experimental devices exploiting the plasma physics development, DEMO shall operate with a validated, stable and safe plasma scenario [4]. Nevertheless, with the present knowledge, instabilities and plasma disruptions

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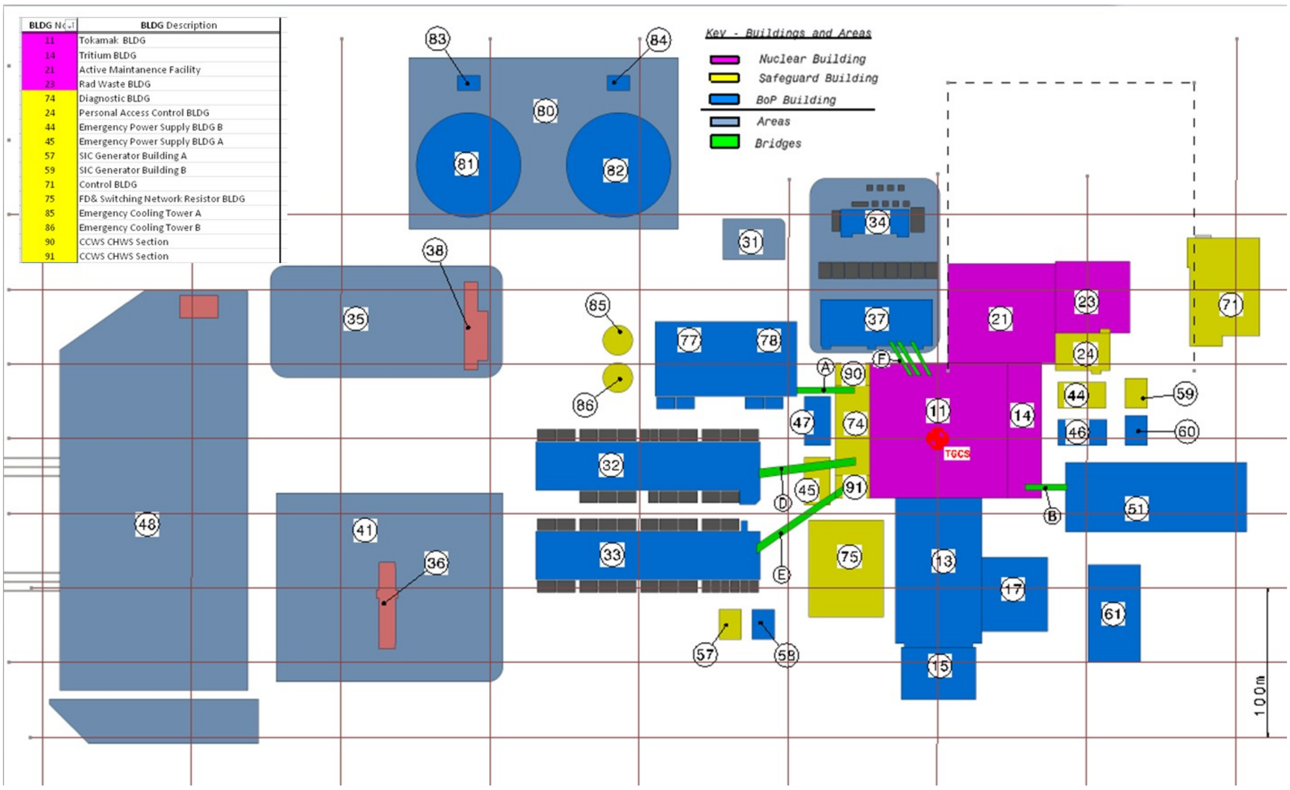
cannot be excluded a priori [4]: the present objective is to have a plasma disruption rate less than 1 event/fpy. That asks for provisions to reduce such risk and also to implement mitigation systems to prevent accident sequences [5] initiated by them as e.g., a damage on the FW or on DV with a possible in-VV loss of coolant accident (LOCA) and thereby allowing for a safety demonstration. Because of the relevant enthalpy, that accident implies the adoption of an expansion volume (EV) or of a VV pressure suppression system (VVPSS) for HCPB and WCLL respectively to be connected through valves and rupture disk to the VV to accommodate the overpressure through the extension of the VV volume. That is a complex and large system as it is the first static containment barrier with capability to control the VV radioactive products, including the risk of dust-H/D/T-air explosion [6]. Furthermore instabilities and plasma disruption are the main contributors to the in-VV dust production that has to be measured and maintain below the safety limits.



BLDG No	BLDG Description
11	Tokamak BLDG
14	Tritium BLDG
21	Active Maintanence Facility
23	Rad Waste BLDG
74	Diagnostic BLDG
24	Personal Access Control BLDG
44	Emergency Power Supply BLDG B
45	Emergency Power Supply BLDG A
57	SIC Generator Building A
59	SIC Generator Building B
71	Control BLDG
75	FD& Switching Network Resistor BLDG
85	Emergency Cooling Tower A
86	Emergency Cooling Tower B
90	CCWS CHWS Section
91	CCWS CHWS Section

Figure 1. DEMO preliminary plant site layout

Currently, design provisions are under consideration to protect the FW [6]. Further experience on the present experiments and those foreseen on ITER might help in defining a safe plasma scenario, as well as an effective and reliable way to control instabilities in an intrinsic way or through SIC systems. That might reduce significantly the inventory of the fluid entering the VV and then the dimension of VVPSS or EV. A simplification of the EV/VVPSS might come also from the possible increase of the design pressure of the VV and its extensions (presently limited to only 2 bar because mainly of the ceramic windows on a few VV connections). The qualification tests on-going for ITER and the R&D on materials should contribute to this issue.

4.2 Radioactive inventories: minimization and control

Dust in the VV, tritium in the VV, breeding blanket (BB), fuel cycle, PHTS and hot cell and activated corrosion products (ACP) in PHTS for the WCLL are the main inventories. They change along the operating time and their map needs to be identified with accuracy and maintained updated at any time up to plasma pulse by pulse. Any uncertainty on the inventory figures will reduce the operating domain and then the availability of the plant.

Tritium in DEMO is the dominant radioactive inventory because of the the huge throughput necessary to sustain the fusion reaction (the burning factor of very few % of the DT throughput). Very important is the design of a system allowing for a direct recycling of unburnt DT fuel pumped from the VV and thereby minimising the throughput of gas to be reprocessed to the tritium building (in ITER that is 100%) [8]. One licensing criterion is posed by the limit of chronic releases which in ITER restricts the allowable tritium releases to the atmosphere to about 1g/y). The tolerated accidental release is of few g/event in ITER [9] and should involve only limited volumes of the buildings to avoid the need of

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a very large detritiation system that has implication on several aspects, including auxiliaries and space needed. Being a SIC system this needs to be redundant and requires to be supplied by the emergency diesel generators (in ITER is the biggest electrical load). The inventories and the releases must meet the ALARA criterion.

4.3 Inventories of Energies: control and mitigation

DEMO presents some significant energies that in accident conditions might mobilise part of a radioactive inventory or/and challenge some safety functions, e.g. primary or secondary confinement systems (i.e. VV or tokamak building). The PFC-PHTS coolant, the S/C magnet, the large 4K He cryo-mass and the PFC decay heat are the main energy sources present in the tokamak building. The former can cause, in case of a LOCA, an overpressure inside the VV above the design pressure on several components that have to assure the VV integrity to guarantee the first confinement barrier. The decay heat needs to be removed also in case of station blackout. The substantial magnetic energy is removed through resistances, sized considering the S/C coils inductance, in order to avoid any risk of electrical arc or short circuit. The energy of the huge mass of He at 4K will be controlled through isolation valves in order to limit the maximum amount releasable into the tokamak building and through a SIC quench line to discharge the He into a He recovery tank outside the tokamak building. The over-pressurization of the VV and of its extensions following an in-VV LOCA might be limited by assuring a more stable plasma (see above) and with the adoption of isolation valves (IV) that will reduce the discharged coolant inventory. Such valves provide a contribution also in case of an ex-VV LOCA limiting the over-pressure of the tokamak building and the volume where it is accommodated. IVs can be postulated either on manifolds for each sector or on Hot/Cold Legs; on manifolds they are more effective (see Table 1).but the number of valves is large (few hundreds against few tens).

Table 1 In-vessel LOCA-WCLL/VVSPT 1.5 bar (m^3)

Valve Position	**5 s closure**	**10 s closure**
Hot / cold legs	258 (57%)	297 (65%)
Manifolds	160 (35%)	217 (50%)
No isolation valves	456 (100%)	456 (100%)

IV failure to close probability is not negligible when many redundant valves are installed. Loss of flow is expected to be manageable through the fast plasma termination system for which intervention is fast (e.g. 3s in ITER) without damaging PFCs. Such a SIC system is necessary also for a few other accidents that may endanger PFC integrity.

A preliminary design of the decay heat removal system (DHRS) foresees a fully redundant active system consisting of an emergency heat exchanger (HX) and emergency safety grade pump installed in each VV PHTS loop in parallel with the main VV PHTS HX and the main pump. As in ITER, the venting of the Cryostat is likely to be adopted in DEMO, considering it as a redundant, diversified and passive DHRS, thanks to the huge cryogenic mass of the superconductor (S/C) coils. Table 2 reports a few elements of the active DHRS design power determined through an in-VV model describing radiative heat transfer and conductive heat transfer between BB and VV walls (4/3 MWth for HCPB/WCLL, considering that the decay heat at plasma shut down is about 1% of the fusion power and quickly decreases). From the elements above, the DHRS function is not critical, exhibiting several hours grace time hours for intervention.

Table 2. Heat Exchanger of DHRS

DHRS HX	**WCLL**	**HCPB**
Pth (MW)	3	4
W (Kg/s)	67,3	89,7
T in/out DHRS	200/190	200/190
T in/out CHWS	6/12	6/12
Pressure drop (bar)	0,1	0,05
Pitch diameter	1,5	1,5
# Active tubes	133	133
Length (m)	O,820	0,941
Tube	¾” BWG 18	¾” BWG 18
Material	Inconel 690	Inconel 690

4.4 Primary Heat Transfer System and Power Conversion System

A preliminary design has been performed [9] as well as the localization of the main PHTS systems and components. The design is quite challenging for the different main circuits (BB, Divertor, VV and others not yet designed) and their integration.

The possibility of a direct coupling of PHTS with PCS, with the elimination /or minimization of the energy storage system (ESS), identified as one of the eight major design issues [2] is under analysis with support from nuclear Industry. The aim is to maintain the turbine at its nominal speed with the generator synchronized with the electrical grid, to provide the minimum steam to the turbine necessary to avoid thermal stress. A few technical options are feasible and currently assessed: an auxiliary boiler, a small thermal storage system in PCS and the motorization of the electrical generator during the dwell time.

PCS and PHTS have to face the pulsed operation and the fast increase and decrease of fusion power that is not compatible with the main components design, particularly the turbine. Detailed analyses of the thermal dynamic and hydraulic transients are providing the basis for the design solutions.

A recent reduction of the dwell time to the minimum possible (10 minutes), make this proposal interesting.

4.5 DEMO plant electrical loads

Another large and complex system is the plant electrical system (PES), serving the Tokamak that fundamentally can be assimilated to a large “electromagnetic machine”. The electrical buildings are 17, 31, 32, 33, 36, 38 of Figure 1, dedicated to the Magnets, NBI and

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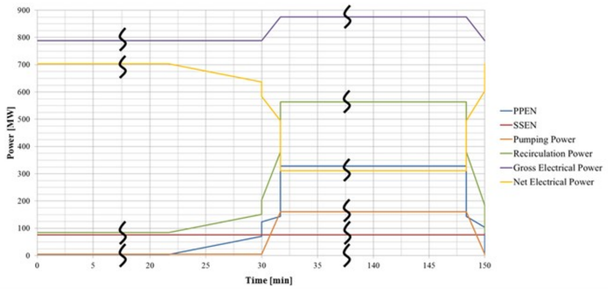
radiofrequency needs. The large area including buildings 77, 78, 81, 82 is the electrical switchyard where DEMO will receive and deliver power to two 400-kV transmission lines. It includes the compensation of the significant reactive power required by the inductive loads and bridge converters.

DEMO will require a recirculating electrical power in the range of 300-500 MW (almost one order of magnitude bigger than the recirculating power of a NPP). This large value, together with that relevant to the pulsed operation (Figure 2), necessitates a site close to very well interconnected electrical nodes of the EU grid.

Considering the experience of ITER [10], some mitigation solutions are being assessed: i) bigger integration of pulsed and steady state electrical systems, ii) pulsed active power of a short duration (e.g. ECH support to plasma breakdown) provided by electrical storage systems on-site, e.g. supercapacitors, iii) reduction of the reactive power (750 MVAR in ITER) if Active Front End thyristor development will be successful [11].

Figure 2. DEMO preliminary electrical power (HCPB)



4.6 Tokamak building layout and environmental conditions

Two tokamak buildings layout are being developed [12] considering the two options for the breding blanket: HCPB and WCLL. The building requires large space especially for the case of He as a coolant to integrate a large number of PHTS loops as well as a large expansion volume (tens of thousands m^3) in case of an in-VV LOCA, the need of large size (>1 m) and long pipes (~9 km) transporting high temperature He gas. WCLL production of radionuclides N^{16} and N^{17} due to interactions of high energy neutron with water and resulting radiation doses in areas where PHTS is localized, requires shielding and accurate layout of the PHTS versus sensible equipment as I&C. Open is still for both coolant options how large installations are required for coolant purification systems to keep below radiation protection standards.

The tokamak building layout takes advantage of the ITER design and lessons learnt and of the nuclear Industry support. The systems being studied first include cooling, particularly for PFC, PHTS, magnets, including feeders and quench protection systems, RM, He 4K cryodistribution lines, AH, cable trays, diagnostics. Most of them, excluding for the time being diagnostics and cable trays have been represented on a CAD model: considering the DEMO specific preliminary design (e.g. cooling system) otherwise on first extrapolation from ITER (e.g. feeders). Installation, maintenance and inspection criteria are considered. Space reservation is considered for huge or numerous systems as diagnostics, ventilation and air conditioning, cable trays and I&C cubicles. Particular attention is given to layout safety criteria as separation or segregation between redundant systems, low magnetic and radiation field, pipe whipping protection, etc. The definition of the layout is being accompanied by the first definition of the environmental conditions, particularly the magnetic field, the radiation dose rate and the temperature, pressure, humidity. In a fusion reactor the accidental conditions affect only the last three parameters.

6. Synopsis and outlook

DEMO has to produce electricity in a safe and reliable way. Therefore, the entire project must be oriented on safety and power provision to the grid.

The design of all main systems must be advance in a progressive way taking into account all the interdependencies and considering two major objectives: to acquire a nuclear license allowing for a wide operation domain and an adequate availability of the plant. The safety requirements have been issued since the first phase of the project, safety analysis launched from the preliminary definition of the main systems: mayor accident sequence identified. The relevant deterministic analyses on-going, accompanied by the safety classification in close discussion with the plant designers, are providing important guidelines to the design of safeguards and mitigation systems and to the definition of the nuclear island. A continuous iteration between designers of the main systems and safety allow to maintain this objective and also to create the safety culture among the designers as it has been often recommended by the review Committees of ITER. Identification of source terms and their control with an adequate accuracy, together with their segregation, is essential to maintain an adequate operation domain.

The preliminary plant site layout has been defined with efforts devoted to the most critical aspects as building and tokamak.

A sufficient availability asks for stable, predictable plasma and for a simplification of the plants systems as much as possible: relevant efforts are ongoing in all the system design..

Acknowledgments

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