Fusion Engineering and Design 124 (2017) 633–637

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Initial definition of structural load conditions in DEMO

C. Bachmann[a,*], W. Biel[b], S. Ciattaglia[a], G. Federici[a], F. Maviglia[a], G. Mazzone[c], G. Ramogida[c], F. Villone[d], N. Taylor[e]

[a] EUROfusion Consortium, PPPT Department, Boltzmannstr. 2, Garching, Germany
[b] Institute of Energy and Climate Research, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany
[c] ENEA Fusion and Technology for Nuclear Safety and Security Department, ENEA C. R. Frascati, 00044 Frascati, Italy
[d] ENEA-CREATE Association, DIEI, Università di Cassino e del Lazio Meridionale, Italy
[e] Culham Centre for Fusion Energy, Abingdon, UK

HIGHLIGHTS

- Load event probabilities definition in DEMO.
- Damage limits for DEMO systems.
- Seismic spectrum on DEMO site.
- Main parameters of plasma disruptions to be considered in the design of DEMO systems.
- Load combinations to be considered in the DEMO conceptual design.

ARTICLE INFO

Article history:
Received 19 September 2016
Received in revised form 7 February 2017
Accepted 16 February 2017
Available online 11 March 2017

Keywords:
DEMO
Tokamak
Load
Electromagnetic
Disruptions

ABSTRACT

An essential goal of the EU fusion roadmap is the development of design and technology of a Demonstration Fusion Power Reactor (DEMO) to follow ITER. A pragmatic approach is advocated considering a pulsed tokamak based on mature technologies and reliable regimes of operation, extrapolated as far as possible from the ITER experience. The EUROfusion Power Plant Physics and Technology Department (PPPT) started the conceptual design of DEMO in 2014, see Federici et al. (2014) [1].

This article defines, based on ASME III, the categories of loads to be considered in the design of the DEMO components, defines the categorization of load conditions based on their expected occurrence and provides the correlation of acceptable component damage levels. It furthermore defines the load combinations to be considered in the conceptual design phase of DEMO. Furthermore, with exception of heat loads from plasma particles and radiation to the plasma facing components, the most important load cases are described and quantified. These include (i) electromagnetic (EM) loads due to toroidal field coil fast discharge, (ii) EM loads in fast and slow plasma disruptions due to eddy and halo currents, (iii) seismic loads, and (vi) pressure loads in the dominant incident/accident events.

1. Introduction

1.1. DEMO parameters

The EUROfusion Power Plant Physics and Technology Department (PPPT) started the conceptual design of DEMO in 2014, see [1]. The main parameters of the DEMO tokamak machine are listed in Table 1. Their definition is described in [2].

1.2. Load cases abbreviations

MFD: Magnet fast discharge
MD: Major (or central) disruption
VDE: Vertical displacement event
In-vessel LOCA: In-vessel loss of coolant event
Cr ICE: Cryostat ingress of coolant event
Ex-vessel LOCA: Loss of coolant event outside the vacuum vessel
LOCA NB: Loss of coolant event in NB cell
VV LOVA: Loss of vacuum event in plasma chamber
Cr LOVA: Loss of vacuum event in cryostat
LOOP: Loss of offsite power
LOSP: Loss of site power (incl. emergency generators)

* Corresponding author.
E-mail address: christian.bachmann@euro-fusion.org (C. Bachmann).

http://dx.doi.org/10.1016/j.fusengdes.2017.02.061

Table 1
Parameters of the DEMO tokamak.

Major radius, R	9.07 m
Minor radius, a	2.93 m
Plasma current, I_p	19.6 MA
Plasma cross section, A_p	44.8 m^2
Vacuum toroidal field at R, B_0	5.667 T
Number of TF coils	18
Total current in single TF coil	14.28 MA

2. Load categories and damage limits

2.1. Load categories

Being a nuclear device in the design of DEMO the design practice defined for nuclear components is adopted to allow licensing through a Nuclear Regulator. This includes distinguishing load conditions depending on their expected occurrence according to a nuclear code. Four categories of load conditions in DEMO are therefore defined based on [3] (subsection NB-3113). The indicated frequencies of occurrence associated to categories II and III are based on the IAEA definitions [4]:

Cat I includes *operational* loading conditions, i.e. conditions intentionally triggered by the plant operator.

Cat II includes *expected* loading conditions, i.e. conditions that are expected to occur in the life of the plant up to about 100 times.

Cat III includes *possible* loading conditions, i.e. conditions that are expected to occur less than about once during the plant life.

Cat IV are *unlikely* loading conditions, i.e. conditions with an expected frequency of occurrence of less than once every 10,000 years.

2.2. Damage limits

A structural design code must be selected for the design of each DEMO component. Design codes define different *criteria levels* each aiming at preventing specific structural damages of a component. Based on ASME Sec. III NCA-2142.4 the following damage limits are defined:

- Level A and B: No damage requiring repair occurs. The plant shall be able to resume operation without special maintenance or test.
- Level C: Large (plastic and hence permanent) deformations permitted in areas of structural discontinuity. Shutdown for component inspection and repair may be required before proceeding operation.
- Level D: Gross general (plastic and hence permanent) deformations permitted including some loss of dimensional stability, e.g. local buckling. Component repair or replacement may be required.

The default association of loading conditions to damage criteria in DEMO is as follows:

- Cat I loading condition → damage criteria level A
- Cat II loading condition → damage criteria level A
- Cat III loading condition → damage criteria level C
- Cat IV loading condition → damage criteria level D

Based on specific requirements of a component regarding safety or investment protection a modified approach can be adopted.

3. Single load events

3.1. Normal operation loads

Operational loads on a component such as coolant pressure may vary depending on the component's state. These component-specific loads need to be specified individually and are not described in this article.

3.2. Magnet fast discharge

A magnet abnormal condition or fault will induce a quench that will actuate a fast discharge of the huge coils' magnetic energy into resistors. The fast discharge of the PF and CS coils (MFD I) is not considered in this article since the effect on the DEMO structures of the fast discharge of PF, CS *and* TF coils (MFD II) is typically more severe. During an MFD II electrical currents are induced in all tokamak structures offering a poloidal or toroidal current path, in particular in the vacuum vessel.

3.3. Plasma disruptions

3.3.1. Main parameters

Plasma disruptions can cause a variety of electrical currents flowing in the tokamak components during the disruption. Electromagnetic (EM) forces are generated as these currents cross the magnetic field. Three phenomena occur during disruptions: (i) During a rapid *thermal quench* the plasma current profile flattens causing an increase of the plasma toroidal current (by ~5–10%) and also affecting the poloidal plasma current. The change of plasma current induces (eddy) currents in the surrounding passive structures. (ii) During the *current quench* the plasma current decays inducing currents in the passive structures. In this phase the plasma may move vertically. A disruption is referred to as MD if the thermal quench occurs before plasma vertical control is lost. During an MD the plasma vertical movement is moderate and generates significant eddy currents only locally. If instead initially the plasma vertical control is lost and the thermal quench occurs during plasma vertical movement the event is considered a VDE. The plasma vertical movement in a VDE is significant, see Fig. 2. (iii) In the later phase of a disruption the plasma will usually be in contact with the wall. In this phase currents flowing in the outer (halo) region of the plasma partly exit and re-enter the plasma running through the passive structure. These currents are referred to as halo currents, I_{halo}. In particular in slow VDEs, i.e. VDEs with a low plasma current decay rate, halo currents can be significant.

In DEMO eddy currents are typically design drivers of the in-vessel components (IVCs) and port plug components. Halo currents are typically design drivers of the IVCs, the vacuum vessel (VV), and the magnet system.

3.3.2. Parameter scaling

The initial specification of the thermal quench time t_{TQ} and the current quench time t_{CQ}, see Table 1, is based on the ITER specification, [5]. The thermal quench time was scaled as suggested in [6] with the plasma minor radius (2.93 m/2 m). The minimum current quench time was scaled as suggested in [6] with the plasma cross-sectional area (44.8 m^2/22 m^2). Given the early phase of the DEMO development for simplification no exponential but only linear current quench profiles need to be considered in the design development. Halo currents were often observed with a toroidally non-uniform magnitude. Toroidal peaking of I_{halo} affects in particular the design of the toroidally discrete IVCs. The toroidal non-uniformity, i.e. the ratio of the local to the average halo current

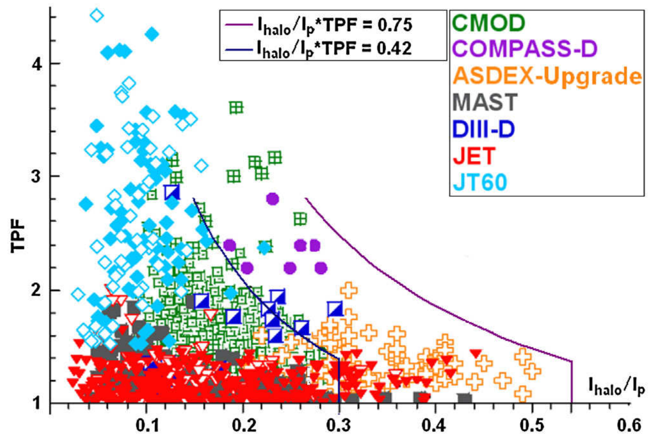

Fig. 1. Experimental data from different tokamak machines on the relationship of I_{halo}/I_p with the TPF as in [8] with Cat II and Cat III envelop lines.

Table 2
Specified minima of thermal and current quench time (t_{TQ} and t_{CQ}) and specified halo current maxima.

Unit	t_{TQ} [ms]	t_{CQ} [ms]	I_{halo} (360°) [MA]	peak I_{halo} (ψ = 6.7°) [kA]	$TPL \cdot \frac{I_{halo}}{I_p}$
MDI	4.4	97	2.12	54	0.15
MDII	1.5	70	2.12	54	0.15
MDIII	0.7	70	2.12	54	0.15
MDIV	0.7	51	2.12	54	0.15
VDEII fast up	1.5	70	2.74	73	0.202
VDEII fast down	1.5	70	3.43	91	0.252
VDEII slow up	1.5	70	4.57	122	0.336
VDEII slow down	1.5	70	5.71	152	0.42
VDEIII fast up	0.7	70	5.08	131	0.36
VDEIII fast down	0.7	70	6.35	163	0.45
VDEIII slow up	n/a				
VDEIII slow down	n/a				
VDEIV fast up	0.7	51	5.08	131	0.36
VDEIV fast down	0.7	51	6.35	163	0.45
VDEIV slow up	0.7	51	8.46	218	0.60
VDEIV slow down	0.7	51	10.58	272	0.75

density, is described through the toroidal peaking factor (TPF) that is considered in the definition of the halo current severity:

$TPF \cdot I_{halo}/I_p$.

For a large number of disruption cases observed in existing tokamaks the halo current severity has been collected, Fig. 1. In ITER, based on the definition of 300 expected VDEs, probabilistic assessments have led to the definition of the halo current severity of Cat II VDEs to be $TPF \cdot I_{halo}/I_p = 0.42$, [5]. Data points in Fig. 1 below the blue line are considered for the definition of the category II load severity. All data points are considered for the definition of the category III load severity. In DEMO, initially, the same halo current severity of Cat II VDEs is defined. In addition the following halo current scaling is applied in DEMO based on [5]: In fast VDEs the halo current peak is reduced to 60% of that in slow VDEs. For upward VDEs the halo current peak is reduced to 80% of that in downward VDEs. An overview over the main parameters of different types of disruptions is provided in Table 2.

3.3.3. Disruption mitigation

To reduce the number of disruptions to be considered in the design a disruption mitigation system is considered in DEMO. At this point this is assumed to mitigate *most* disruptions and in addition to limit the severity of the structural loads of *all* slow VDEs to the severity defined for Cat II events. The latter is a working assumption that will require validation before the conclusion of the DEMO

Table 3
Fraction of total halo current defined in Table 2 entering/exiting the component and absolute magnitudes during VDEII slow down.

Component	Toroidal extent, ψ	VDE up	VDE down	VDEII slow down
Vacuum vessel	360°	30%	20%	1.2 MA
Inboard blanket	10°	30%	20%	46 kA
Outboard blanket	6.7°	100%	100%	152 kA
Div. outer target	6.7°	0%	30%	46 kA
Div. inner target	6.7°	0%	10%	15 kA

licensing process. The time scale to detect such slow VDEs is an order of magnitude longer in slow VDEs compared to fast disruptions (in DEMO >100 ms based on [7]); hence a reliable detection is considered technically feasible, e.g. by installing independent and hence redundant detection systems. High reliability of the mitigation system itself might also be achieved installing different types of mitigation systems, e.g. a massive gas injection system (MGI). MGI is reported to inject within 10 ms reducing halo current magnitude by at least 50% and the TPF to unity [8]. Hence in DEMO no Cat III slow VDEs are specified. The *unlikely* event of an unsuccessful disruption mitigation of a slow VDE is considered through the definition of Cat IV VDEs with a severity of $TPF \cdot I_{halo}/I_p = 0.75$. This is consistent with the ITER specification [5] and envelops the most severe VDEs in the ITER physics basis database, [8].

3.3.4. Halo currents in IVCs

The magnitude of the halo current in an individual IVC is an important design parameter for the IVC structure, its supports and its electrical connection to the VV. These currents cross the toroidal field generating EM loads that in many cases are design-driving. Based on DEMO plasma disruption simulations for a moderately slow current quench time of 200 ms carried out with an evolutionary equilibrium code [9], see Fig. 2, the fraction of the halo current defined in Table 2 as “peak I_{halo}” entering IVCs is given in Table 3. It is worth noting that unlike in ITER the main halo current source and sink are on different poloidal locations of the same outboard blanket, hence in these particular events the major part of the halo current will flow within the outboard blanket and not enter into the VV. This peculiarity is probably due to the specific pre-disruption magnetic flux map and to the excitation used to trigger the VDE (voltage kick in one of the PF coils). In order to consider reasonable deviations from the plasma trajectories found in these simulations some fraction of the halo current is specified to enter also the inboard IVCs.

3.4. Seismic loads

The DEMO site not being identified, initially the ITER seismic loads [5,10] (in French) are defined for DEMO. Three levels of ground motion are considered for housing safety critical equipment (SL-2, SMHV, and SL-1). A SL-2 is a category IV event and corresponds to the seismic level required by French nuclear practice [10]. The DEMO SL-2 soil response spectra are shown in Fig. 3 and are based on those defined for the ITER buildings on the Cadarache site (rock soil) [11]. A SMHV (Maximum Historically Probable Earthquake) is a Cat III event and is the most penalizing earthquake liable to occur over a period of about 1000 years. The accelerations of a SMHV are roughly half of the SL-2 values for frequencies up to 0.4 Hz and ~70% of the SL-2 values for frequencies above 2 Hz. A SL-1 is a category II event with a probability of occurrence in the order of 10^{-2} per year and represents an investment protection earthquake level. The accelerations in the SL-1 spectra are 1/4 of those in the SL-2, however smaller damping need to be considered. To avoid performing specific analyses for SL-1 and SMHV the results obtained in the SL-2 analysis can be multiplied by 0.34 and 0.73, respectively [12].

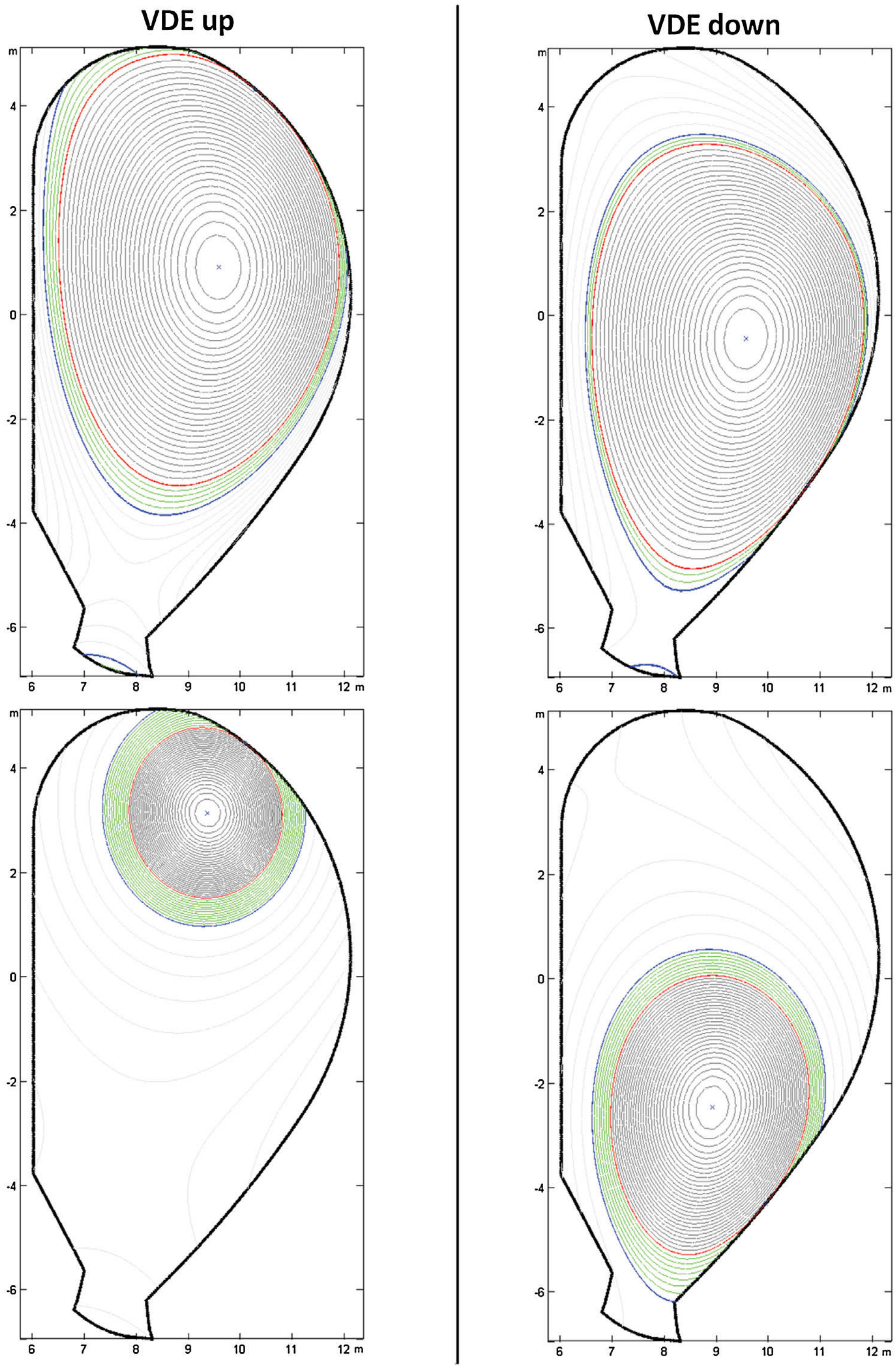

Fig. 2. Plasma boundary at specific instants during upward and downward VDEs with t_{CQ} = 200 ms, (halo region indicated in green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The floor response spectra at the *basemats* of nuclear buildings shall be defined assuming the buildings to sit on ITER-like seismic isolation pads. Seismic loads on other buildings are defined in Eurocode 8 [13].

3.5. Pressures loads and leak incidents/accidents

During plasma operation all zones of the tokamak building outside the cryostat are at atmospheric pressure (~95 kPa). All zones inside the cryostat, the plasma chamber, and the vacuum vessel pressure suppression system (VVPSS) are at vacuum pressure (0 kPa). The transient conditions during incidents/accidents events involving leaks are assessed and defined through accident analyses that have so far not been concluded. The extreme pressures listed in Table 4 are preliminary recommendations to guide the design progress and based on the ITER specifications [5] and the following assumptions:

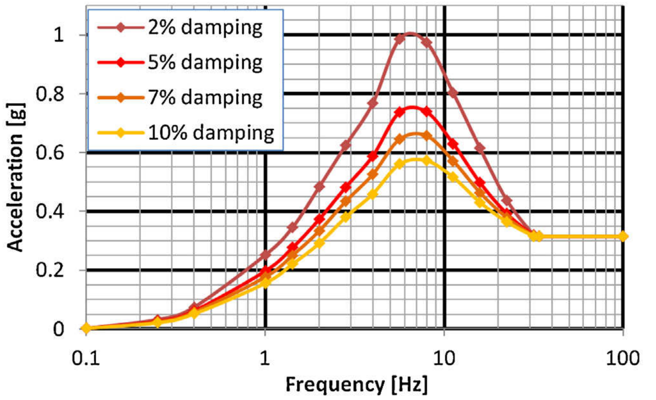

Fig. 3. DEMO horizontal ground design response spectrum for SL-2 for different damping values; vertical design soil spectra are equal to 2/3 of the horizontal ones.

Table 4
Overview over leak incidents/accidents and recommendations for associated design pressure values.

Event	Abs. pres.	Zone
In-vessel LOCA II	~1 bar	Plasma chamber
In-vessel LOCA III	>1 bar, tbd	Plasma chamber + VVPSS
In-vessel LOCA IV	>1 bar, tbd	Plasma chamber + VVPSS
Cr ICE II	~30 kPa	Cryostat
Cr ICE III	~1 bar	Cryostat
Cr ICE IV	tbd	Cryostat
LOCA NB III	~1.6 bar, [12]	NB cell
Ex-vessel LOCA III	tbd	Parts of tokamak building including port cells

Table 5
Postulated events combination and classification in plasma operation state.

Cat.	Initiating event	Potentially triggered events
I	MDI	
II	SL-1	MDI or MFD II
II	Cr ICE II	MFD II
II	In-vessel LOCA II	MDII or VDEII
II	MDII	In-vessel LOCA II
II	VDEII	In-vessel LOCA II
II	MFD II	MDI
III	SMHV	Cr ICE II and/or MFD II or LOOP
III	SL-1	(MDII or VDEII) and/or MFD II
III	SL-1	MFD II + MDII
III	MDIII	In-vessel LOCA III
III	VDEIII	In-vessel LOCA III
III	MFD II	MDII or VDEII
III	In-vessel LOCA III	MDIII
III	Cr ICE III	MFD II
III	Ex-vessel LOCA III	
III	LOCA NB III	
IV	SL-2	Cr ICE III or MDI or Ex-vessel LOCA III or LOOP
IV	SL-1	MDIII
IV	MDIV	In-vessel LOCA IV
IV	VDEIV	In-vessel LOCA IV
IV	Ex-vessel LOCA III	In-vessel LOCA II
IV	Airplane crash	

3.5.1. *In-vessel LOCA*

Initiating events of an in-vessel LOCA are breaks of plasma-facing components cooling channels or – with lower frequency – breaks of IVC cooling pipes. The coolant discharging into the plasma chamber causes the plasma to disrupt very quickly, hence the triggering of a disruption is considered. VV LOVA events are considered enveloped by in-vessel LOCA events assuming similar transients as in ITER, [12].

3.5.2. *Cr ICE*

The cryostat vacuum may be lost due to air ingress (Cr LOVA), a helium-, or cooling water leak. In case of Helium ingress the Helium remains in gaseous state causing convective heat transfer between the cryostat (20 °C) and the magnets (4 K), hence the triggering of a magnet fast discharge is considered when the leak is significant. Cr LOVA events are considered enveloped by Cr ICE event assuming similar transients as in ITER, [12].

4. Load combinations and classification

The load combinations to be considered in the design of the tokamak components and the equipment inside the DEMO nuclear buildings during plasma operation are listed in Table 5. This is based on [11]. All of these load combinations include the operational loads that are present at the time the event combination occurs, e.g. dead weight, coolant or vacuum pressure, thermal loads, etc.

5. Conclusions

The definition of the main loads affecting the conceptual design of DEMO is provided in the DEMO Plant Structural Load Specification, which is an annex to the DEMO plant requirements document and a parent document to all load specifications of DEMO components. It is a common reference for all structural verifications of the DEMO components. A summary has been provided in this article quantifying key load cases, defining the load combinations to be considered and highlighting the correlation between categorization of load combinations with their expected occurrence and the associated acceptable damage level.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] G. Federici, et al., Overview of EU DEMO design and R&D activities, Fusion Eng. Des. 89 (2014) 882–889.
[2] R. Wenninger, et al., The physics and technology basis entering European system code studies for DEMO, Nucl. Fusion 57 (2017) 016011.
[3] ASME Boiler & Pressure Vessel Code Section III-Rules for Construction of Nuclear Facility Components-Division 1-Subsection NB-Class 1 Components.
[4] IAEA Safety Standards Series No. SSG-2, Deterministic, Safety Analysis for Nuclear Power Plants, 2010.
[5] G. Sannazzaro, et al., Structural load specification for ITER tokamak components, 23rd IEEE/NPSS Symp. Fus. Eng. (2009), http://dx.doi.org/10.1109/FUSION.2009.5226521.
[6] Progress in the ITER physics basis, Nucl. Fusion 47 (12) (2007) S168, Par. 3.2.
[7] M. Sugihara, et al., Disruption impacts and their mitigation target values for ITER operation and machine protection, Nucl. Fusion 47 (4) (2007).
[8] T. Hender, et al., Chapter 3: MHD stability, operational limits and disruptions, Nucl. Fusion 47 (2007) S128.
[9] F. Villone, et al., Coupling of nonlinear axisymmetric plasma evolution with three-dimensional volumetric conductors, Plasma Phys. Control. Fusion 55 (2013) 095008.
[10] Règles fondamentales de sÛreté relatives aux installations nucléaires de base – RFS no 2001–01.
[11] ITER Load Specifications v. 6.0, ITER_D_222QGL.
[12] J.-M. Martinez, et al., Structural analysis of the ITER vacuum vessel regarding 2012 ITER project-level loads, Fusion Eng. Des. 89 (7–8) (2014) 1836–1842, http://dx.doi.org/10.1016/j.fusengdes.2014.02.066.
[13] Eurocode 8, Design of structures for earthquake resistance, EN 1998.