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Identification of the Postulated Initiating Events of Accidents Occurring in a Toroidal Field Magnet of the EU DEMO

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Abstract — *The design of the European Union (EU) DEMO reactor magnet system, currently ongoing within the EUROfusion consortium, will take advantage of the know-how developed during the design and manufacturing of ITER magnets; however, DEMO will suffer some new, more severe challenges, e.g., larger tritium inventory and higher neutron fluence, both having an impact on safety functions accomplished, among the other systems, also by the magnets. For these reasons, and in view of the need to demonstrate a high availability of the reactor (aimed at electricity production), a new, more systematic assessment of the system safety is required. As a contribution in this direction, the initiating events (IEs) of the most critical accident sequences in the EU DEMO magnet system (with special reference to the toroidal field magnets) are identified here, adopting first a functional analysis and then a failure mode, effects, and criticality analysis. In particular, the following are provided: (1) the EU DEMO magnet system is subdivided into functionally independent subsystems and components (e.g., the magnets, their cooling circuits, and their power supply system); (2) the relevant failure modes of each subsystem are systematically identified, together with the corresponding causes and consequences; (3) a list of IEs is compiled, leading to scenarios that may compromise the magnet safety and availability. Finally, the so-called postulated IEs are selected as the most challenging IEs for the safety of the magnet system. This analysis initializes a path leading to a risk-informed design, i.e., the identification of safety issues that could be addressed at the design level instead of introducing expensive mitigation measures after the design completion.*

Keywords — *EU DEMO, superconducting magnets, safety, FMECA, postulated initiating events.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

According to the roadmap toward electricity from nuclear fusion[1,2] that is driving the research in that field in Europe, the ITER experiment will be followed by a plant—the European Union (EU) DEMO (Ref. 3) —aimed at demonstrating the possibility to produce net electricity from fusion reactions.

The design and manufacturing of the EU DEMO magnets will take advantage of the know-how developed for the ITER construction, introducing however some new features that call for a new, more systematic assessment of system safety. Table I (Ref. 4) reports the main differences between ITER and DEMO directly relevant for safety analyses: With respect to the former, the latter will be equipped with a breeding blanket for the tritium on-site production, so the magnets will be part of a reactor where a proper confinement of the tritium must be ensured (any catastrophic failure of a magnet on the primary containment may have radiological consequences). Moreover, DEMO will have to demonstrate a high availability of the machine[4,5] (for power production

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TABLE I

Main Differences Between ITER and EU DEMO Relevant for Safety Analyses*

ITER	EU DEMO
Experimental device	Demonstrate plasma operation and electricity production for several full-power years
Outages for maintenance foreseen	Maximize availability
Large design margins	Smaller design margins thanks to experience
Small tritium breeding in test blanket module	Tritium breeding needed for self-sufficiency
Modest neutron fluence and dpa	High neutron fluence and dpa

*Reference 4.

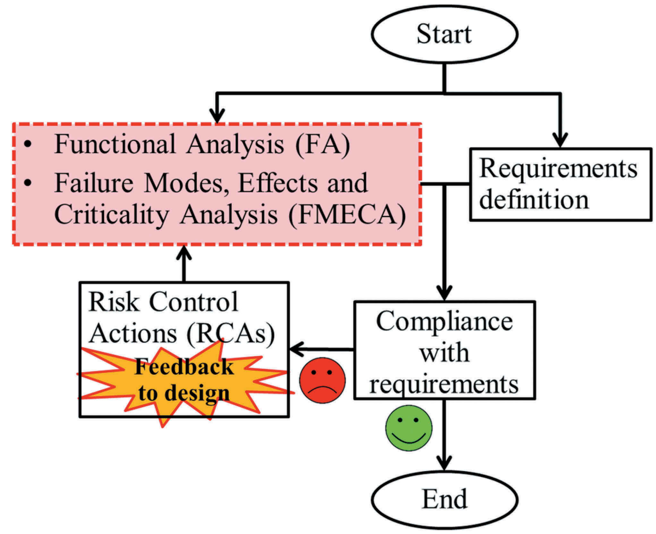

Fig. 1. The most important actions to be undertaken in the safety analysis of a power plant, with special reference here to a fusion reactor.[13]

purposes). Correspondingly, the higher utilization factor will lead to a higher neutron flux, with a consequent increase of the displacements per atom (dpa) and of the damage to the structural materials. Safety analyses have already been carried out for ITER (Refs. 6 and 7), including its magnet system,[8] but in view of the above-mentioned differences (impacting on plant safety) and of the different design solutions foreseen for some of the magnets, they must be repeated for EU DEMO (Ref. 9) and must be tailored to its peculiar characteristics. The early stage of the EU DEMO design will allow pursuing the so-called risk-informed approach,[10,11] aimed at identifying safety issues that could be addressed in a structured iterative framework at the preliminary design level instead of introducing (expensive) mitigation measures only at a later stage of reactor design.

As a first step in that direction, the potential initiating events (IEs) of accident sequences in the EU DEMO magnet system, currently in its preconceptual design phase within the EUROfusion Work Package MAGnets[12] (WPMAG), will be identified in this work in order to provide safety insights and to highlight open points in the preliminary design of the reactor.

II. METHODOLOGY

In order to perform safety analyses of a fusion reactor, the methodology described by Alzbutas and Voronov[13] and sketched in Fig. 1 can be adopted:

1. The system is decomposed into safety functions, to be accomplished by the different subsystems and components by means of functional analysis (FA).

2. The negation of these functions (i.e., the system failure mode) is systematically analyzed by means of the failure mode, effects, and criticality analysis (FMECA).

3. The FMECA results allow judging whether the current magnet system design is compliant with the safety requirements,[14] i.e., the acceptance criteria for the consequences (or risk levels) that must be defined in parallel with the FA and FMECA.

4. If not, the design team should take into account the feedback from the safety analysis and update the design of the system, of its subsystems, and/or of the single components in order to try to meet the requirements.

5. A new FA and FMECA will then be performed to again systematically assess the compliance, and the iterations will proceed until all safety requirements are met.

We concentrate here on the first steps of the safety analysis that will be applied to the EU DEMO magnet system. The safety requirements needed to proceed with the subsequent steps are currently under definition,[14] and the steps followed in the present work will thus lead to the definition of the most relevant IEs:

1. An operational mode of the magnets is identified as reference for the analysis (e.g., pulsed plasma operation, failed or maintenance states, etc.), as the same component may accomplish different functions depending on the operational mode.

2. Functional analysis is applied to the EU DEMO magnet system, subdivided into functionally independent subsystems and components (e.g., the magnets, their cooling circuits, and their power supply system).

3. Concentrating on the toroidal field (TF) magnets, for which the preconceptual design stage is well defined, the FMECA is performed.

The strategy followed to carry out the FMECA will be the following:

1. All the relevant failure modes (negation of the accomplished function) of each TF magnet component will be systematically identified for the chosen operational mode together with the corresponding causes and consequences. Suggestions will be given on if and how the failure can be (easily) detected, and possible prevention and/or mitigation actions will be proposed.

2. Among the IEs of the resulting list, those leading to accident conditions, i.e., scenarios that may compromise the magnet safety and availability and are thus the most representative IEs in terms of challenging conditions for the safety of the magnet system, will finally be selected as postulated initiating events[15] (PIEs).

III. RESULTS

According to the action plan presented in Sec. II, we first address the selection of the reactor operational mode, during which the function of the subsystems and components must be defined. According to the EU DEMO plant description document,[16] during its operation phase (which will follow the construction and assembly phase and the commissioning phase), the machine will face the following operational states:

1. plasma operation state
2. testing and conditioning state
3. scheduled maintenance state
4. failed state (unscheduled maintenance state).

The (nominal) plasma operation state is selected here as the reference state, as DEMO should demonstrate high availability factors in this operating mode. It consists of the following main substates, as sketched on a timeline in Fig. 2:

1. dwell substate, during which the nominal operating parameters of the reactor are recovered after a plasma pulse
2. standby substate, during which the start of the next plasma pulse is prepared

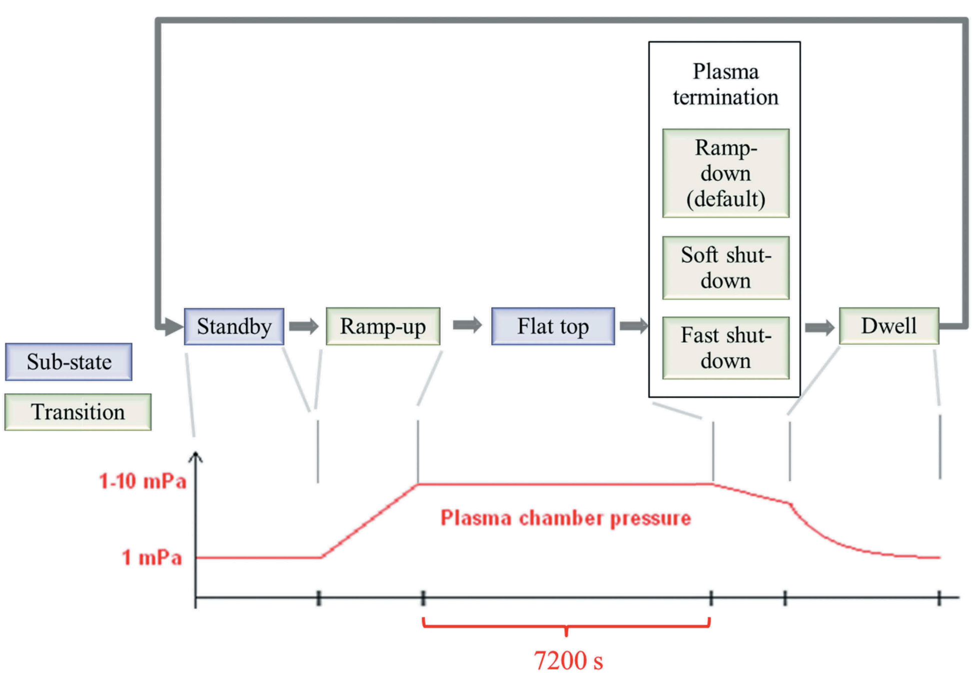

Fig. 2. Substates and transition phases during the plasma operation state[16] selected as reference operational mode for the present safety analysis.

3. pulse substate (including the initial plasma current ramp-up), during which most of the fusion power is generated (in the EU DEMO, it is foreseen to last up to ~2 h)
4. terminate pulse state, during which the plasma current is ramped down.

III.A. Functional Analysis

After the definition of the operation mode, the magnet system (whose main function is to confine and control the plasma inside a toroidal plasma chamber) can now be subdivided into the following subsystems, reported in Fig. 3 and accomplishing different functions:

1. *superconducting (SC) magnets*: to generate the time- and space-dependent magnetic field within a given tolerance and without joule losses (excluding those localized in the joints or due to alternating-current (AC) losses)
2. *cryoplant*: in turn composed of
   a. cooling loops to provide the nominal coolant mass flow rate at the design inlet temperature and pressure to operate the magnets in SC mode
   b. refrigerator to provide the cooling power to the cooling loops
3. *power supply*: to provide the rated current to the coils
4. *control system*: to control the magnet system parameters (manipulating suitable actuators in order to keep the parameters close to their desired operating values) and to provide signals to safely switch off the power supplies. The latter is a safety important class[17] (SIC) function. It deals with the removal of the magnetic energy stored in the coils that, if released in an uncontrolled way, instead of being safely discharged, can damage the primary containment barrier, i.e., the vacuum vessel (VV).
5. *protection system*: to protect the system during transients that can lead to severe conditions.

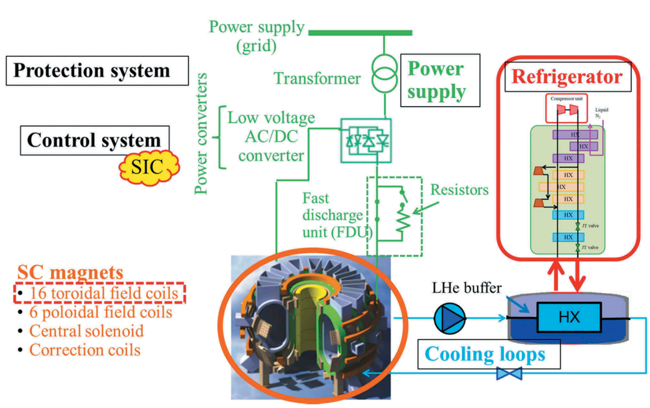

Fig. 3. Functional breakdown of the EU DEMO magnet system. The main subsystems are reported in boldface, while the subject of the safety analyses reported here is highlighted in a dashed rectangle. (DC = direct current; LHe = liquid He; HX = heat exchanger.)

Concentrating now on the TF SC magnets, Fig. 4 shows their functional breakdown. The main function of the TF magnets is to contain the plasma by means of the toroidal magnetic field, with a toroidal ripple of less than 0.6% (Ref. 16). Each TF magnet can be split into two main parts, namely, the winding pack (WP) and the structures, in turn constituted by several components accomplishing different functions:

1. *winding pack*: to generate the rated toroidal magnetic field
   a. cable-in-conduit conductor (CICC)
      i. jacket to confine the He flow and withstand Lorentz forces on the cable
      ii. strands to transport the current in SC mode
      iii. helium flow area to provide space for coolant flow with low hydraulic impedance
   b. electrical insulation to electrically insulate the conductor turns and the WP
   c. joints to electrically connect two conductor lengths with low resistance
   d. helium inlets/outlets to connect supply/return pipes from/to the cooling loops with the CICCs
2. *structures*: to provide mechanical support to the WP and to the VV, the latter being contained in the toroidal space inside the TF magnets and distributing on them part of its weight
   a. casing to provide mechanical support to the TF WP and to the poloidal field coils against Lorentz forces
   b. cooling paths to cool the structures by means of suitable pipes attached on the casing surface or fixed in dedicated grooves inside the casing

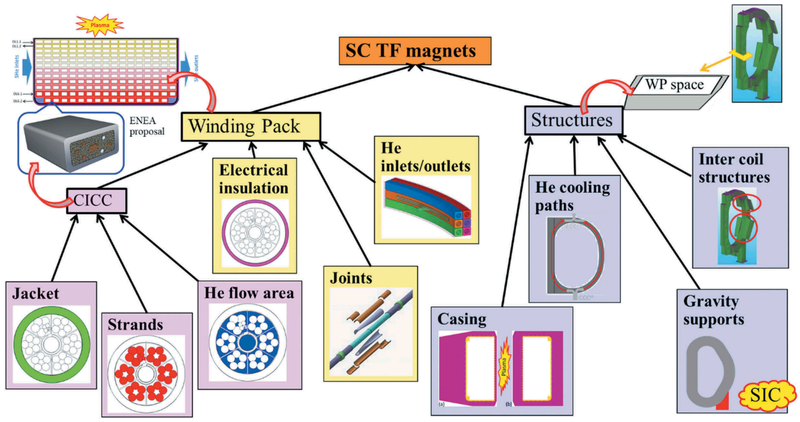

Fig. 4. Functional breakdown of the TF magnets of EU DEMO.

c. intercoil structures to connect the outer leg casing of adjacent coils to create a unique robust structure capable to withstand the Lorentz forces

d. gravity supports to provide mechanical support to the magnet and to the VV against gravity (the latter is a SIC function, as it deals with the mechanical integrity of the primary containment barrier).

III.B. Results of the FMECA

Starting from the functions defined in Sec. III.A, and with respect to the operational mode chosen, the FMECA is carried out here for both the WP and the structures of an EU DEMO TF magnet. The results of the analysis are collected in Tables II and III for the WP and the structures, respectively. For each TF component, the failure mode is identified as the negation of the function accomplishment.

The causes of the failures listed in Tables II and III are to be found in equipment failure; causes that are internal to the magnet system (e.g., electromagnetic and thermal cycles); and external causes (hazards), i.e., not directly related to the magnet system itself, such as abnormal heat loads, impurities, neutron fluence, falling objects, or earthquakes (the latter being a natural hazard).

The main consequences highlighted in Tables II and III are the following:

1. *Catastrophic failure*: This is catastrophic failure of the magnet (caused, e.g., by mechanical failure of the casing or gravity support) collapsing on the VV, which will then lose its containment function releasing the tritium with on-site radiological consequences.

2. *Electric arcs*: Electric arcs in the coils or between the coil and the ground, leading to serious (possibly unrepairable) damage to the coil itself. Detailed analyses have been carried out in ITER on this topic.[8]

3. *Quench of the coil*: Note that the quench is in principle not included in the plasma operation state but, rather, in the failed state; it is considered here only because the consequences of a quench (heating of the He and of the cold masses) prevent the plasma operation state to be recovered, reducing the plant availability in that state. Moreover, it should be noted that according to the DEMO Plant Safety Requirements Document,[14] the SC coils shall be designed to avoid quench during the plasma operation state.

4. *ITER*: With respect to ITER, the need for long recooling times after thermal-hydraulic transients (e.g., fast discharges or quenches) causing a heating of the He and of the cold masses is also considered a consequence relevant for the plant availability.

5. *In-cryostat loss of coolant (He)*: The severity of such a consequence is due to the loss of vacuum in the cryostat; the pressure increase reduces the voltage threshold needed to induce electrical arcs in the coils.[20]

Concerning the detection strategies, while in some cases they can be useful to quickly intervene on the operational parameters to avoid more severe damage, in other situations (especially in the case of catastrophic failures of the structures), they only allow to assess the entity of the failure.

Prevention and mitigation actions constitute feedback to the magnet designers in this preliminary design stage. Some of them are worth mentioning, in particular, the following:

TABLE II

Failure Mode, Effects, and Criticality Analysis of the TF WP

Process Function	Associated Components	Failure	Cause	Consequence	Detection	Prevention	Mitigation
Generate the rated toroidal magnetic field with a TF ripple of less than 0.6%	CICC	Superconducting strand break (= degradation)	Electromagnetic fatigue, thermal fatigue, unprotected quench	Magnet unrepairable failure	Early voltage development during charge	Redundancy of quench protection, conductor R&D	Develop procedure for fast TF coil replacement[a]
		Temporary loss of SC conditions (= quench)	Abnormal heat load (from thermal shield cooling anomaly, nuclear shielding reduction)	Loss of plasma confinement	Dedicated quench detection system	Improve the neutron shielding, specify a proper margin during the design	Design the first wall to withstand loss of plasma confinement
			Abnormal heat load (from plasma disruption)	Helium venting to quench tank → need time for recooling		Reduce the foreseen number of disruptions	Size the refrigerator to accelerate recooling/venting strategy redesign
		Loss of cooling (loss-of-flow accident[18,19])	Cooling channel occlusion by impurities/power supply failure	Temperature increase (→ quench, failed state)	Reduction in the mass flow rate/increase in differential pressure across conductors	Helium purification, cold test of all conductors/electrical power backup	Increase pumping power
	Jacket	Loss of He confinement (= jacket rupture)	Thermal/mechanical/electromagnetic fatigue or overload, presence of defects/electrical fault	In-cryostat LOCA (→ loss of vacuum), magnet unrepairable failure	Cooling loop depressurization	Quality checks on CICCs and weldings, proper safety valve set point	Develop procedure for fast TF coil replacement[a]
	Ground and interturn/layer/pancake insulation	Loss of electrical insulation of the conductor	Loss of vacuum, thermal/mechanical/electromagnetic fatigue, dpa, overvoltage, in-cryostat LOCA	Electrical fault[8]	Voltage/current measurements	Quality checks on materials, R&D, Paschen tests[20]	Develop procedure for fast TF coil replacement[a]
	Helium inlet/outlet pipes	Break/leak	Thermal fatigue/welding defects	Loss of CICC cooling/in-cryostat LOCA	Cooling loop depressurization	Quality checks on weldings	Accessibility to He inlet region for repair
	Internal joints	Loss of electrical connection in the WP	Mechanical loss of integrity of the joint	No current in the magnet, need for joint replacement (long outage)	Voltage measurement on all joints, power supply voltage	R&D on joint topology	Design joint for easy replacement
		Increased joint resistance	Partial loss of integrity, poor Cu quality, manufacturing/installation defects	Additional heat deposition in joints (possible quench development)		R&D on joint topology, set proper thresholds for joint quality	Design joint for easy replacement, install joints in low field regions and at outlet

[a]Currently not considered an option.[16]

TABLE III

Failure Mode, Effects, and Criticality Analysis of the TF Structures

Process Function	Associated Components	Failure	Cause	Consequence	Detection	Prevention	Mitigation
Provide mechanical support to the WP and VV	Casing	Partial loss of mechanical integrity	Fatigue (electromagnetic, thermal), DPA, impact of falling objects, electric arcs	Larger magnet displacements (→ change in ripple)	Displacement sensors, suitable cameras	Introduce sufficient safety factors, proper design of the casing, use of high-quality materials, avoid presence of objects that can damage the casing	Local repair or develop procedure for fast TF coil replacement[a]
		Total loss of mechanical integrity		Magnet catastrophic failure (VV break → loss of tritium confinement)	Displacement sensors, suitable cameras, loss of vacuum		Develop procedure for fast TF coil/VV replacement,[a] foresee secondary confinement barriers
	Cooling paths	Flow blockage (loss-of-flow accident)	Presence of impurities	Increased (re-) cooling time, higher heat load to the WP	Pressure drop/temperature measurements	Proper quality settings for He, installation of purifiers	Develop procedure for fast TF coil replacement,[a] design cooling pipes for easy maintenance/replacement, foresee additional cooling by backup cooling or possibility to increase mass flow
		Detachment from the structures	Fatigue (electromagnetic, thermal), dpa		Temperature measurements	R&D on pipe-to-casing attachment strategies, quality checks on weldings	
		Pipe break		Increased (re-) cooling time, higher heat load to the WP, in-cryostat LOCA (→ loss of vacuum)	Pressure drop/temperature measurements, in-cryostat pressure measurement	Proper mechanical checks	
	Gravity supports	Lack of mechanical support to the magnets and VV against gravity	Structural failure	Catastrophic failure of the magnet (VV break → loss of tritium confinement)	Displacement sensors, suitable cameras, loss of vacuum	Introduce sufficient safety factors, R&D on materials	Develop procedure for fast TF coil/VV replacement,[a] foresee secondary confinement barriers
			Earthquake			Suitable definition of the maximum earthquake to be withstood	
	Intercoil structures	Partial loss of connection between the coils	Fatigue (electromagnetic, thermal), dpa, impact of falling objects	Larger magnet displacements	Displacement sensors, suitable cameras	Introduce sufficient safety factors, proper design of the intercoil structures, use of high-quality materials, avoid presence of objects that can damage the casing	Local repair or develop procedure for fast TF coil replacement[a]
		Total loss of connection between the coils		Magnet catastrophic failure (VV break → loss of tritium confinement)	Displacement sensors, suitable cameras, loss of vacuum		Develop procedure for fast TF coil replacement,[a] foresee secondary confinement barriers

[a]Currently not considered an option.[16]

1. *To develop a procedure for the fast TF coil replacement, as a mitigation for a coil unrepairable failure*: Since the TF coils are currently being designed as unreplaceable components,[16] the unrepairable failure of one TF coil implies the definitive loss of availability of the machine. In order to avoid such a condition, the (presently pursued) solution is to push on the prevention measures, such as research and development (R&D), quality checks, redundancies, etc. As a complement to the current solution, it is proposed here to develop a procedure allowing a (relatively) fast replacement of the TF coils, at least in the perspective of a power plant, extending the reactor lifetime in case of a TF magnet unrepairable failure.

2. *To develop mitigation actions aimed at reducing the unavailability of the plant after minor accidents*: One example of these mitigations is the sizing of the refrigerator for a fast recooling after a thermal transient that increased the He and cold mass temperature. This is directly connected to the need of DEMO to demonstrate high availability factors.

Most of the prevention actions listed in Tables II and III take advantage of the lessons learned during the ITER design (e.g., the definition of adequate safety margins and redundancies), the ongoing ITER manufacturing (e.g., the development of suitable quality checks and qualification tests), and the R&D efforts carried out in the EUROfusion WPMAG.

III.C. Postulated Initiating Events

Among the events listed in Tables II and III, the PIEs of accidents occurring in the TF magnets are identified as those leading to the most severe consequences; here, only the consequences are considered for determination of the PIEs even though risk should be used to define PIEs. This is done because risk is the product between the consequence caused by the failure and the probability of the failure,[13] but the latter is not defined due to the lack of details on the components at this design stage.

The following PIEs for the WP have been identified:

1. loss of electrical insulation, for which R&D on insulation materials is foreseen
2. break of SC strands (causing the so-called "degradation" of conductor performance), currently being addressed by means of R&D on several conductor samples[21]
3. jacket rupture, namely a loss-of-coolant accident (LOCA), for which suitable analyses are required in order to assess the consequences with more detail
4. quench of the magnet, for which, with respect to the ITER experience, a detailed assessment of the recooling time and a redesign of the venting strategy are needed to meet the DEMO availability targets.

The following PIEs for the structures have been identified:

1. total loss of mechanical integrity of the casing and of the intercoil structures
2. lack of mechanical support to the magnets and VV against gravity.

Both structure PIEs are currently being addressed by R&D activities including detailed mechanical analyses[22,23] and studies on new structural materials.

Note that the PIEs are caused both by events internal to the magnet system (electromagnetic/thermal fatigue, overvoltage) and by external hazards (abnormal heat load, neutron fluence, impact of falling objects, earthquake), while there are not human-induced events.

IV. CONCLUSIONS AND PERSPECTIVE

With respect to ITER, in the EU DEMO fusion reactor, currently being designed within the EUROfusion consortium, reliable operation of the SC magnet system is crucial for reactor availability and to maintain operating conditions that are significantly more challenging than those foreseen in ITER. A safety-informed design is proposed here as a viable approach, introducing safety aspects already in the preconceptual design phase, so that the design choices can take advantage of feedbacks from the safety analysis and avoid the introduction of expensive mitigation measures in the advanced engineering design phase.

The methodology for the FA and the FMECA and the determination of the PIEs in the EU DEMO magnet system have been described in detail.

As a result of the application of the FMECA to the TF magnets (WP and structures), the following PIEs have been highlighted:

1. loss of electrical insulation of the conductor
2. break of SC strands
3. loss of structural integrity.

Research and development is already ongoing/foreseen for these PIEs, as well as for

1. quench, which will need a careful assessment of the recooling time and a redesign of the He venting system to reduce unavailability
2. in-cryostat LOCA, which will deserve detailed analyses.

The analysis of events leading to unrepairable failures of the TF magnets highlighted the possible need to consider the option of designing a suitable strategy for the TF replacement during the reactor lifetime in order to extend its availability in case of severe accidents to the magnets.

When more detailed information will be available on the components (e.g., even rough indications on the failure frequencies), the present safety analysis could then be refined and extended by means of a risk matrix, providing semiquantitative input to the designers for the selection of the critical events.

Acknowledgments

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