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Safety and environment studies for a European DEMO design concept

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ABSTRACT

Pre-conceptual design studies for a European Demonstration Fusion Power Plant (DEMO) have been in progress since 2014. At this stage, while a range of design options are being considered, assessments of the safety and environmental impact of these options are carried out. This is to ensure that the DEMO plant is optimized for safety performance, and that it will demonstrate the favourable safety and environmental characteristics of fusion energy as part of its mission.

To this end, safety studies have been under way since the start of the project, to set clear safety objectives and requirements, to analyse the response of the plant to off-normal events, to assess hazardous inventories, to develop strategies to minimize them, and to identify the main potential contributors to environmental releases and to occupational radiation exposure. Development of computer codes and models for safety analysis is accompanied by selected experimental activities focused on improving their validation, and these models have been used for initial studies of postulated accident scenarios, selected by a formal methodology. Studies of key aspects of waste management are also performed, to minimize the waste burden of DEMO and of fusion power plants that will follow.

1. Introduction

Pre-conceptual design studies for a European Demonstration Fusion Power Plant (DEMO) have been in progress since 2014 [1]. At this stage in the development of a conceptual design, while a range of options are being considered, it is essential that assessments of the safety and environmental impact of these options are carried out. It is necessary not only to ensure that the DEMO plant is optimized for safety performance, but also that it will demonstrate the favourable safety and environmental characteristics of fusion energy as part of its mission.

Safety studies have been under way since the start of the project, to set clear safety objectives and requirements, to analyse the response of the plant to off-normal events, to assess environmental releases and strategies to minimize them, to identify the main potential contributors to occupational radiation exposure, and to engage in a number of R&D activities focused on improving the evaluation of safety impacts. Safety analysts have engaged with design teams with the aim of selection of design options to achieve the highest safety performance. At the same time, key aspects of waste management are studied to minimize the waste burden of DEMO and of fusion power plants that will follow.

2. Safety objectives and requirements

2.1. Safety objectives

A first step is to establish the safety approach to be used, to set the top-level objectives and the safety principles that will be employed in meeting them. For EU DEMO, similar objectives have been set as those

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adopted for ITER, consistently with international guidelines [2]. They are:

- To protect workers, the public and the environment from harm;
- To ensure in normal operation that exposure to hazards within the facility and due to release of hazardous material from the facility is controlled, kept below prescribed limits and minimized to be as low as reasonably achievable;
- To ensure that the likelihood of accidents is minimized and that their consequences are bounded;
- To ensure that the consequences of more frequent incidents, if any, are minor;
- To apply a safety approach that limits the hazards from accidents such that in any event there is no need for public evacuation on technical grounds;
- To minimize radioactive waste hazards and volumes and ensure that they are as low as reasonably achievable.

The fifth bullet corresponds to the “no-evacuation criterion” commonly applied to fusion facilities. It effectively gives a quantitative limit to the consequences of any accident scenario, no matter how unlikely.

The means to achieving these objectives is primarily by application of a nuclear safety approach based on the key principle of Defence in Depth, which requires multiple levels of protection to prevent deviations from normal operation, to detect and control any such deviations, to avoid the propagation of an accident in the unlikely event that one is initiated, and to mitigate the consequences of any accident sequence by ensuring that confinement of radioactive inventories is maintained.

2.2. Safety requirements

Plant level safety requirements have been defined at the top level. This been done in consultation with design teams to ensure that, whilst challenging, the requirements are realistic. Involvement of the designers also helps the requirements to be fully understood and the process contributes to a good safety culture.

The requirements are particularly focused on the design phase of the project, but also include operational limits, constraints and targets, so that assessments can be made of the performance of the evolving design in meeting these targets. For example, occupational dose limits and targets have been specified, see Table 1, as well as limits of the consequences of postulated accident scenarios in different categories of event frequency.

Safety requirements have been entered into a DOORS database used to manage all requirements for the DEMO project, ensuring that these plant level requirements are cascaded down to those at system and component level.

3. Safety functions and classification

3.1. Safety functions

In order to understand the role that any system, structure or component (SSC) has in ensuring the safety of the facility, it is essential to first define the safety functions that must be fulfilled. For EU DEMO the top-level safety functions have been defined as

- Confinement of radioactive and hazardous materials;
- Limitation of exposure to ionizing and electromagnetic radiation;
- Limitation of the non-radiological consequences of conventional hazards;
- Limitation of environmental legacy

For each of these there is a set of supporting functions, for example for the first it is necessary to control energies from all sources that may lead to a challenge to confinement barriers. These supporting functions, in turn, will lead to more detailed safety functions at the component level, defining what each is required to fulfil for safety.

3.2. Radioactive material inventories

The most important of the safety functions is the confinement of hazardous materials, particularly radioactive materials. The inventories that need confinement are primarily tritium and the products of neutron activation. Tritium is retained in the vacuum vessel, on surfaces, permeated into structural materials, and absorbed into dust. It is also present in the entire fuel cycle equipment including pumping systems, fuelling systems, the fuel processing plant and in the breeder blankets with their tritium extraction system. Tritium will also contaminate remote maintenance systems used to replace in-vessel components. These components introduce a tritium inventory into the Active Maintenance Facility where they are stored and maintained. The atmosphere of any room housing components with a tritium inventory may also have some tritium present due to permeation, as will coolant fluids due to permeation through coolant channel walls.

Neutron activation products are present in the materials of all in-vessel components after irradiation, and in dust from the erosion of plasma-facing surfaces and accumulated in the vessel. The vessel itself, and some ex-vessel components, will also become activated albeit at a lower level.

The minimization of these inventories is an essential safety requirement, and this is being fully taken into account in the design activities. For example, in new concepts for the fuel cycle [3], tritium inventory needs have been reduced from tens of kilograms to hundreds of grams. Their confinement is provided by robust barriers, utilizing existing barriers such as the vacuum vessel itself, and will be supplemented by ventilation, filtering and detritiation systems.

Table 1
Dose limits provisionally adopted for EU DEMO.

	Normal operation		Anticipated events / Incidents	Unlikely events	Extremely unlikely events	Hypothetical events
	Limit	Target				
Accident Frequency /year			$f > 10^{-2}$	$10^{-2} > f > 10^{-4}$	$10^{-4} > f > 10^{-6}$	$f < 10^{-6}$
On-site Dose	50 mSv/year 100 mSv/5 years	5 mSv/year	5 mSv/year	20 mSv/event		
Off-site Early Dose	1 mSv/year	0.1 mSv/year			10 mSv/event	50 mSv/event
Off-site Chronic Dose			1 mSv/year	5 mSv/event	50 mSv/event	No cliff-edge effects. Limited countermeasures

3.3. Safety classification

SSCs are assigned a safety classification that indicates their importance for safety and thereby determines some specific requirements. For EU DEMO three levels of Safety Importance Class (SIC) have been defined:

SIC-1:required to bring and maintain DEMO in a safe state;

SIC-2:needed to prevent, detect or mitigate incidents or accidents (but not required to reach the safe state);

SIC-3:not *needed* to prevent, detect or mitigate, but helps to further reduce the consequences of an incident or accident.

Quantitative definitions of these classes, based on the consequence of the failure of the SSC to provide its safety function(s), have been defined to assist with the process of assigning SIC levels [4]. This process has been completed at the system level and is now being done at the component level where the design maturity allows – the classification of the primary heat transfer systems' SSCs has been completed [4].

4. Accident analyses

4.1. Selection of reference events

The definition of postulated accident scenarios to be analysed is achieved by a formal, systematic methodology to ensure completeness. At this early stage in the design process, with many systems lacking detail, a Functional Failure Modes and Effects Analysis (FFMEA) has been done. This has been completed for all key systems and has led to the determination of 21 Postulated Initiating Events (PIEs) that envelope all identified failures [5].

These PIEs provide the basis for the event sequences, the Reference Events, that are the subject of detailed analyses to establish their consequences and to reveal design choices that can limit their likelihood and severity.

4.2. Source terms for accident analyses

While it is an important requirement for the design to minimise all inventories of radioactive materials, for the purposes of accident analyses it is necessary to make conservative assumptions about the quantity of material that may be vulnerable to release, i.e. the source terms. For postulated events inside the vacuum vessel, this is primarily retained tritium and accumulated active dust originating from plasma-facing surfaces.

For dust in the vessel, some insight can be gained from measurements made at JET, where a small amount of dust (typically < 2 g) is recovered from the divertor region after each operating period [6]. The composition includes beryllium, tungsten, nickel and even carbon, a legacy of earlier operations when graphite tiles were in the vessel. The dust appears to originate from melting and delamination of surfaces, but only 2–4% of this material becomes mobile dust particles. It is difficult to use these measurements to infer dust quantities in DEMO, as JET has mainly beryllium plasma-facing surfaces whereas DEMO will be all tungsten. But studies will continue with the aim of understanding more about dust generation and mobilisation.

To make assumptions for tritium and dust source terms in the DEMO accident analyses, an approach has been used to scale the corresponding assumption used for ITER. By identifying a range of parameters believed to influence these inventories, and scaling appropriately, a range of tungsten dust quantity, 690–1379 kg, and of tritium, 671–4676 g, have been estimated [7]. These are dependent on factors such as the expected number of unmitigated disruptions and the tritium permeation in tungsten compared with beryllium. These are working assumptions for the interim, until more detailed studies can provide improved estimates.

In addition to dust and tritium, in scenarios involving a leak of water coolant, activated corrosion products in the coolant are taken into account, according to a separate analysis of these [8].

4.3. Analysis of reference events

At this pre-conceptual design stage, deterministic accident analyses have focussed on scenarios where the results may give important feedback to the design choices and concepts. So far, analyses have been performed for the Reference Events involving the cooling systems of in-vessel components. These include a range of loss of coolant accident (LOCA) scenarios. Failure of a coolant channel inside a breeder blanket module, leading to pressurization of the blanket box (in-BB LOCA), failure of one or more first wall cooling loops into the vacuum vessel (in-vessel LOCA), and failure of a cooling loop outside the vessel, in the room housing the heat exchangers (ex-vessel LOCA), have all been studied. Additionally, some loss of flow accident (LOFA) scenarios have been studied.

These analyses employ models using thermal-hydraulic codes such as the fusion version of MELCOR 1.8.6 [9] and represent the cooling loops in as much detail as the design allows. Failures are postulated, with a range of assumptions, for example, the expected first wall damage area due to a plasma event such as a vertical displacement, which is between 1 and 10 m^2. For the larger break sizes more than one cooling loop may be involved and are assumed to discharge their complete coolant inventory.

Although these studies are preliminary and further scenarios need to be completed, some observations can be made from the results. For both in-BB LOCA [10,11] and in-vessel LOCA [12], exceeding the design pressure limit of the blanket box or vacuum vessel can be avoided by the use of a pressure suppression system using rupture disks. The requirements for this system depend on details of the blanket design concept and the associated primary heat transfer system under study, and in particular the coolant type (water or helium). For ex-vessel LOCA it is likely that over-pressurization of the affected room can be avoided.

It has become clear that in the case of helium coolant a very large expansion volume is required to confine the escaping coolant, at least 50,000 m^3. Moreover, the size of the duct connecting the vessel to this volume needs to be large, more than 2 m^2 cross-sectional area. Accommodating these within the tokamak may be a challenge, and studies are currently under way to explore options for their location.

4.4. Validation of codes and models

The computer codes and models used in the safety analyses require validation, particularly for calculations that will eventually form part of a DEMO licensing submission. To progress this, a number of experimental activities are underway to provide data for comparison with model computations. These include simulations of loss of flow in a first wall mock-up [13], studies of water/liquid lithium-lead interaction in a water-cooled lithium-lead blanket concept [14], and measurements of hydrogen permeation in blanket structural materials [15].

5. Other safety assessments

5.1. Routine environmental releases

Amongst other safety assessments being performed are provisional assessments of gaseous and liquid effluent during normal operation. In order to prevent such releases, a comprehensive survey of potential sources has been performed, with identification of possible pathways to the environment, so that design provisions can be proposed to eliminate or minimize them.

5.2. Occupational radiation exposure

In a similar way, potential contributors to occupational doses are identified, insofar as the current design maturity allows, to guide design choices to minimize them with adequate shielding provisions and optimized maintenance procedures.

6. Radioactive waste management

6.1. Radioactive waste assessments

Studies of neutron-activated material in the facility at end of life or in components replaced during operation reveal a substantial quantity, mainly steel, that would be classified as low or intermediate level radioactive waste [16]. To minimize the amount needing long-term storage or disposal, studies are performed on key aspects of radioactive waste management.

6.2. Detritiation

Tritium that diffuses into the materials of in-vessel components, in particular structural steel, represents an inventory that must be reduced before a component can be maintained or its materials sent for recycling or disposal. A comprehensive review of potential techniques for detritiation of solid materials was performed [17] and R&D on selected candidates is now under way. This includes techniques for melting or for baking of components, and consideration of scaling-up the process to an industrial scale. It is anticipated that detritiation factors in excess of 95% can be achieved.

6.3. Recycling

The possibility of recycling active material from fusion plant has long been an aspiration [18]. But the feasibility of recycling processes on the industrial scale has not yet been established. Together with industrial partners, the required technologies are being studied, based on fully remote-handling procedures.

The first stage after dismantling and separation is the melting of the materials to put into ingot form for interim storage to allow decay of short-lived nuclides. The feasibility of this melting has been established after assessing a range of possible techniques, and furthermore the removal of some unwanted nuclides such as ^{14}C at this stage has been shown to be feasible [19]. Experimental programmes are under way to test the candidate melting technologies [20].

The identification of uses to which the recycled materials could be put, together with the needed refabrication processes, are now under investigation.

7. Conclusions

Safety and environmental studies within the pre-conceptual design activities for a European DEMO are covering a range of topics to ensure that the design evolution optimizes the safety performance and minimizes the environmental impact. Involvement of the design teams in the safety work is essential to establish a good safety culture in the project and to ensure that safety is taken as a priority from the beginning of the design.

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