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Resolving Safety Issues for a Demonstration Fusion Power Plant

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The conceptual design studies for a European DEMO, include safety studies and analyses, to help guide the design process and start preparation for eventual licensing. A safety approach has been adopted that is expected to satisfy a nuclear regulator, but at this early stage it is difficult to anticipate the safety concerns that may be raised. Potential safety issues for DEMO that have been listed by a regulatory technical body include decay heat removal following an accidental loss of cooling or during blanket module replacement, the minimization of occupational radiation exposure, the comprehensive identification of postulated accident scenarios, the environmental release of gaseous tritium during normal operation, and the management of radioactive waste, particularly where contaminated with tritium. Here we explain how these issues are being addressed in the safety programme for a EU DEMO, and are taken into account in the design from the beginning of its conception.

Keywords: DEMO, safety, environment, licensing.

1. Introduction

The conceptual design studies for a European DEMO include a programme of safety studies and analyses, to help guide the design process by assessing the safety and environmental impact of design options under consideration. It also begins to prepare for the eventual licensing of DEMO construction and operation by a European nuclear regulator. A safety approach has been adopted that is expected to satisfy a regulator, but at this early stage it is difficult to anticipate the safety concerns that may be raised, or to predict changes in regulations that may occur the licensing of DEMO.

The French nuclear safety authorities and their technical advisors, having licensed the construction of a nuclear fusion facility, ITER, have acquired expertise in examining the safety case for a fusion facility. It was therefore useful that the technical advisors, Institut de Radioprotection et de Sûreté Nucléaire (IRSN) presented the safety issues that they perceive as important in a future nuclear fusion facility such as DEMO [1]. The issues that were raised are listed in below in section 2. In section 3 each one is discussed, explaining how it is being addressed in the conceptual design of a EU DEMO and the related safety analyses.

2. Safety issues for DEMO

IRSN have presented an overview of their views of the safety issues facing DEMO and other nuclear fusion facilities [1]. The motivation is to identify "the safety issues which seem necessary to take into account right from the earliest design phase of these DEMO facilities".

The main safety issues noted in [1] are on the following topics: decay heat removal following a loss of coolant accident (LOCA), or during replacement of blanket sectors, personnel exposure to ionizing radiation, comprehensive identification of accident scenarios, releases of tritium during normal operation, particularly as gaseous effluent, and the management of radioactive waste. In the next section, each of these issues is discussed to note how it is being addressed in the currently planned EU DEMO safety studies.

3. Safety issues and how they are addressed

3.1 Decay heat

3.1.1 In-vessel LOCA

Heat generated by the decay of radionuclides from neutron activation of in-vessel components is likely to be higher in DEMO than in ITER. In ITER it has been demonstrated that even a long-term total loss of cooling does not cause temperature rises that would challenge the integrity of any safety important components [2]. Decay heat removal is therefore not designated as a primary safety function for ITER, but an increased level of decay heat in DEMO may lead to a different conclusion.

The structural material in DEMO, will be reduced activation ferritic-martensitic steel (EUROFER), compared with the austenitic stainless steel used in ITER. This will yield a substantially lower activation and decay heat, per unit neutron fluence. However the integrated neutron fluence in DEMO will be larger, due

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to the higher fusion power, longer operating periods and duty cycle. Thus there are competing factors affecting the decay heat compared with ITER.

Activation analyses have been carried out to evaluate decay heat in all four blanket concepts [3]. The results show some variation, but the lowest, in the Helium-Cooled Lithium Lead (HCLL) blanket, is initially 17 MW total. This compares with around 10 MW in ITER [2]. The consequence of this modest increase in total heat, distributed in a larger mass, depends on other design details that will influence the peak temperatures reached in a LOCA.

Some initial accident analyses have been carried out for the scenario of the failure of the coolant-retaining structure inside a blanket module [4]. These suggest that the consequences will be limited, but a more complete range of scenarios will be analysed before conclusions can be reached on the need for decay heat removal as a safety function. If it is needed, efforts will be made to provide cooling by passive means.

3.1.2 Transfer of blanket segments to the Active Maintenance Facility (AMF)

The concept for the replacement of blanket segments is discussed below in section 3.3.7. There is a possible need to maintain cooling of the blanket segments during removal and transport. Using the new decay heat data mentioned in section 3.1.1, an evaluation of the temperatures in a blanket segment during transportation and storage will be done. This will reveal whether active removal of decay heat is required. If so, a safety-class cooling system will be provided for the transporter.

3.2 Occupational Radiation Exposure

The principle adopted for the exposure of personnel to ionizing radiation is to maintain doses as low as reasonably achievable (ALARA). Ref. [1] expresses concerns that activation levels in some DEMO components will be increased compared with ITER, and that there may be additional personnel challenges present in some concepts, such as ^{210}Po from blankets with lithium-lead breeder. These potential increases are partly offset by the use of low-activation materials, and some sources of radiation may be eliminated, for example the use of helium coolant instead of water removes the intense gamma radiation from ^{16}N generated by neutron activation of ^{16}O in water. If a water-cooled blanket option is selected, design to minimize the impact of ^{16}N will be taken into account from the start of the design.

Extensive use of Remote Maintenance techniques will be used to avoid personnel exposure, and there will be fewer requirements for routine personnel intervention due to the less experimental nature of the plant. As a guideline, remote maintenance is considered for any identified activity where the dose rate for personnel exposure would exceed 100 μSv/hour and the activity may exceed one hour per week, consistent with IAEA recommendations for nuclear power plants [5].

Despite the early stage of the DEMO conceptual design project a study of occupational radiation exposure has been launched. The aim is to identify the potentially largest doses that may arise from routine activities, and ensure that design provisions are incorporated so that doses are ALARA.

3.3 Identification of accident scenarios

The postulated accident scenarios to be studied by full analyses (the "reference events") have been selected by systematic methods to ensure a comprehensive coverage of potential events. In the absence of a detailed design, this has been done using Functional Failure Modes and Effects Analysis (FFMEA). A total of 21 Postulated Initiating Events (PIEs) are selected for the reference events [6].

The specific areas in which accident potential in DEMO may differ to that of ITER raised in [1] are the subject of discussion in the following sections.

3.3.1 In-vessel dust and tritium inventory

An assumption that the inventory of dust and tritium inside the DEMO vacuum vessel (VV) will rise faster than that of ITER is unduly pessimistic. It is currently the expectation that the in-vessel inventory of both dust and tritium can be maintained no higher than that of ITER, and there are reasons for anticipating that they may be lower, for example the expected lower erosion rate of tungsten compared with beryllium as the plasma-facing surface, and the more stable plasma operating scenario with fewer disruptions [7].

A significant part of the in-vessel retained tritium inventory in ITER is that accumulated in cryopumps. The absence of cryopumps in DEMO (according to the current pumping system concepts) will eliminate this inventory. The absence of a beryllium surface in the plasma chamber, replaced by tungsten, should also reduce the amount of tritium retained. Furthermore, the plasma-facing components will be operated above 500 °C, significantly higher than the 140 °C in ITER, and even well above the 350 °C that ITER will use to bake its divertor specifically to remove accumulated tritium. At the higher operating temperatures of DEMO components, it can be expected that retained tritium will be lower.

It can be concluded that the source term for postulated accidents involving the in-vessel inventory of dust and tritium will be no higher than the corresponding value in ITER, and that smaller inventories can be reasonably expected. This will be confirmed in due course by the planned studies.

3.3.2 Tritium breeding blankets and related systems

The introduction of breeding blankets into the DEMO design brings additional hazards and accident scenarios compared with those analysed for ITER. The first accident analyses performed have already been those related to failures within blanket modules [4]. FFMEA studies of the blanket systems and tritium extraction systems have been performed and the identified events are grouped in the selected PIEs of the reference events [6].

The additional tritium inventory present within the blanket modules is not mobile within the VV, and only a small fraction may be feasibly involved in a postulated accident, but it does represent one of the most significant source terms for accidents in DEMO. The modules are designed to be robust against failures, whether or not they have a safety importance assigned to them.

3.3.3 Loss of plasma control

Another concern raised in [1] is that there may be more possible cases of loss of plasma control in DEMO than in ITER. However, DEMO operation will benefit from a further 20 years or more of operational experience on current tokamaks and, later, ITER. As at ITER, the safety approach for DEMO puts no dependence on plasma control. However a severe disruption could potentially cause damage to the first wall and thereby initiate an in-vessel LOCA.

Because of its experimental nature, a disruption mitigation system (DMS) for ITER is given no credit in the safety analysis. However, after further development and experience of DMS use on ITER and other tokamaks, it is likely that for DEMO a DMS could be sufficiently reliable to be assigned a safety function. By avoiding, or reducing the severity of disruptions, the damage caused by rare plasma events could be limited.

3.3.4 Magnet stored energy

A large amount of energy is stored in the superconducting coils. In the ITER safety case it was shown that a failure in magnet systems leading to discharge of this energy in arcs cannot lead to significant damage to the confinement barriers. Ongoing studies are confirming this with more detailed modelling [8]. The total stored energy in DEMO magnets is likely to be higher than at ITER, but the approach to avoiding any safety consequences of a fault is the same: the design will be optimized to minimize the potential for magnet arcs to impact on confinement barriers or other safety systems. As at ITER, a fast discharge system will be included to safely dump the stored energy if a superconductor quench is detected, and there should be a larger margin to the detection of a quench event.

3.3.5 Accidental release of helium coolant

A DEMO with one of the helium-cooled blanket concepts will have rather a large total inventory of helium coolant, between 10 – 14 tonnes depending on the blanket design concept. In an event such as an in-vessel LOCA, the escaping coolant must be contained to avoid a leak to the environment of gas containing radioactive material (principally tritium). In a water-cooled design such as ITER, steam escaping in a LOCA can be routed to a suppression tank where it can be condensed and readily contained. For a plant cooled by a non-condensable gas such as helium a much larger volume is required – the PPCS study concluded that an expansion volume (EV) of at least 50,000 m^3 would be needed [9].

An initial parametric assessment of the issue has been performed for the EU DEMO concept, concluding that the EV required lies in the range 17,000 to 200,000 m^3 depending on cooling system design parameters and options such as cooling the helium on its path to the EV. Design studies are now exploring a number of options for volumes within the plant that could be used to contain the escaping coolant, or by a dedicated external structure.

3.3.6 Potential for hydrogen explosions

A concern is expressed in [1] that the inventories of hydrogen isotopes in rooms outside of the tokamak – particularly those housing the fuel cycle systems – will be larger in DEMO than in ITER and therefore the hydrogen explosion risks may be higher. Mentioned in particular is a large inventory in the isotope separation system (ISS).

However there is a fundamental difference between the fuel cycle system in ITER and that currently conceived for a EU DEMO. At ITER, the exhaust gas from the tokamak is separated into deuterium and tritium, stored, and then mixed together again as fuel. In contrast, at DEMO, the D-T mix extracted from the tokamak exhaust gas will be directly recycled as fuel without isotope separation [10]. Only a small additional T or D component will be added to adjust the mixture, if necessary. Thus the ISS at DEMO will be very much smaller than that at ITER, and the D and T inventories very much lower.

The quantity of D and T in storage at DEMO may be higher than that at ITER, in order to support the greater daily throughput in the plasma and to manage the balance of tritium coming from the breeding blankets. But there is no reason, *a priori*, to assume that the hydrogen isotope inventories in the fuel cycle systems will be significantly higher than those at ITER. The minimization of these inventories is an important safety requirement.

3.3.7 Vertical removal of blanket segments

In contrast to the scheme for blanket replacements in ITER, where individual blanket modules will be removed through a horizontal equatorial VV port, in the EU DEMO concept a string of blanket modules is withdrawn through a vertical VV port and an opening in the bioshield lid [11]. The height of this string requires substantial space above the bioshield to load into a cask or transporter to carry it to the AMF for dismantling, maintenance and storage. There are a number of potential safety issues associated with this procedure, including that raised in ref. [1] of the potential for an aircraft crash during the removal operation, which could potentially damage confinement barriers.

Maintaining confinement of the in-vessel inventory during the blanket replacement process, with or without an external aggression, is being addressed by the evaluation of a number of design concepts. During the blanket removal operations, the risks of mobilizing the in-vessel inventory of tritium and active dust are somewhat lower than during plasma operation, because a high-pressure coolant LOCA is not possible.

One of the design concepts being evaluated is a robust “hot cell” structure above the bioshield, providing the first confinement barrier during removal of the blankets. This could be strong enough to resist an aircraft crash. If this hot cell also includes the route to the AMF, transport of the blanket modules could be done by a transporter with no need for a cask.

3.4 Environmental releases of tritium

The importance of minimizing routine releases of tritium to the environment, particularly in gaseous form, during normal operation and maintenance has been highlighted in [1]. Reducing tritium inventories is an important part of this minimization, as is the restriction of potential routes to the environment from each significant inventory. Ref. [1] mentions three such inventories that need attention: the breeding blanket cooling circuits, equipment that transfers in-vessel components to the AMF, and waste detritiation systems.

A systematic approach is being taken to this issue. All systems and components in which a tritium inventory may be present have been identified, to the extent possible given the present design maturity, starting from the DEMO plant breakdown structure. Each is assessed to identify those which have potential release pathways that may make a significant contribution to the overall plant tritium release. Strategies and design options for minimizing each of these contributions will be developed. This will lead to a plant design in which all potential paths for release have been optimized, leading to a minimum routine tritium effluent.

3.5 Radioactive waste management

Ref [1] also points out that the contamination of radioactive waste with tritium has led to difficulties in disposal of some of the active material from ITER, leading to plans for dedicated interim storage facility to allow some tritium decay [12]. The quantity of material, particularly structural steel, with tritium absorbed in the bulk could indeed be higher in DEMO than in ITER.

To avoid or minimize this problem for waste from DEMO, an R&D programme is under way on detritiation techniques for solid wastes. A comprehensive survey has been completed of potential detritiation techniques. Each has been evaluated and compared in a systematic way, according to the destination of the material: re-use, recycling, or disposal. For the techniques with the greatest potential of success, an R&D programme is being launched, and will make use of synergies with other detritiation facility developments such as that at JET [13]. Another study is considering the best techniques for waste that is contaminated with tritium, but without induced radioactivity [14]. These programmes should lead to the ability to reduce the tritium content of waste without the need for medium-term storage to allow decay.

In addition to the reduction of tritium content, DEMO waste management studies include optimization of the design to minimize radioactive waste quantities and hazard levels, for example by proposing composition limits for some key materials such as the structural steel Eurofer [15].

4. Conclusions

It is essential to consider the safety and environmental impact of a DEMO plant throughout its life cycle, starting at the conceptual design stage. This is being done in the EU DEMO project, with full involvement of design engineers in the setting of safety requirements. Account is being taken in the design and safety analyses of a number of potential safety issues that have been raised. Optimization to maximize the safety performance will continue throughout the design activities.

Acknowledgments

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