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Identification of safety gaps for fusion demonstration reactors

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To assist in the development of nuclear fusion as a viable commercial power source, preparation is underway for the fusion demonstration reactor (DEMO), which will build on the work of ITER, the international experimental fusion reactor. Like other advanced nuclear energy systems, DEMO must satisfy several goals including a high level of public and worker safety, low environmental impact, high reactor availability, a closed fuel cycle and the potential to be economically competitive. Yet there are still large scientific and technological safety gaps between the on-going ITER project and DEMO that will need to be addressed. Here we review international fusion safety research and development relevant to DEMO, following the lessons learned so far from ITER. We identify the main scientific and technological safety gaps, drawing on knowledge from the development of fission energy, in particular Generation IV (Gen-IV) fission reactors. From this survey, we discuss the corresponding implications for the design and operation of DEMO.

With greenhouse gas emissions across their total lifecycle similar to those of other renewable energy sources and much lower than for fossil fuels[1], nuclear power can play an important role in efforts to decarbonize the production of electricity[2]. According to statistics from the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD/NEA)[3], nuclear fission power accounted for about 11% of world electricity generation in 2013, and could increase to 17% by 2050. Meanwhile, fusion power — in which light atomic nuclei bind into single, heavier nuclei, releasing a large amount of energy — offers the promise of being the ultimate energy source, mainly owing to the abundance of the fuel, absence of high-level radioactive waste and low greenhouse gas emissions. However, despite extensive research and development being conducted in the fusion community, it remains decades away from deployment.

Safety is considered the top priority in nuclear energy development, in particular after the Chernobyl nuclear accident in 1986 and the Fukushima nuclear accident in 2011. The Chernobyl and Fukushima nuclear fission reactors date from the 1970s and are classified as Generation II (see Box 1 for a description of nuclear reactor generations). Since then, in the further development of Generation III and IV reactors, significant improvements have been proposed and implemented in terms of enhanced safety, minimized waste, high economic competitiveness and proliferation resistance. Fusion energy systems, which will be categorized as the next generation reactor beyond Generation IV, must be even more attractive regarding safety, environmental impact and economic competitiveness if fusion energy development is not to fail in the long run.

A collaboration between 35 nations, the International Thermonuclear Experimental Reactor (ITER)[4,5] is one of the most ambitious energy projects in the world today. It is intended to be the first fusion device to produce net energy and maintain fusion for long periods of time. It will also test the integrated technologies, materials, and physics regimes necessary for the commercial production of fusion-based electricity. The construction of ITER is currently underway in Cadarache, France, and its commissioning is expected to be in 2025.

Progress toward the development of fusion as a source of abundant, safe and clean energy has now advanced to the point where the world community is planning the steps needed for the fusion demonstration reactor (DEMO), which will pave the way for the first commercial reactor by 2050. Accordingly, conceptual designs for DEMO[6–15] are ongoing in several places including China, the European Union, India, Japan, Korea, Russia and the United States. However, fusion energy is not born safe and the correct R&D (research and development) and safety procedures have to be in place to ensure fusion is a safe energy source: accidents could happen with any possible future fusion reactor, potentially resulting in large releases of radioactive materials. Meanwhile, the reactor and its associated systems will eventually become low-level and intermediate-level radioactive wastes, owing to their exposure to high neutron radiation produced in the reactor. As such, it is important to understand and develop safety measures for future fusion reactors.

The ITER project will lead the way for DEMO in developing a safety approach, implementing it in a safety design, performing safety analyses under the scrutiny of a nuclear regulator, ensuring device availability, managing radioactive waste, conducting economic assessments and so on. But it is widely recognized that there will be significant scientific and technological gaps between the current ITER and DEMO in terms of managing safety concerns and developing a safety approach, mainly because ITER is an experimental device whereas DEMO is intended to be much closer to a commercial power plant.

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Box 1 | Nuclear reactor generations.

In 2000, the US Department of Energy (DOE) launched the Generation IV initiative[85]. Subsequently, the commonly used terminology for reactor types became 'Generations'[86].

Generation I (Gen-I). Refers to prototype and power reactors from the 1950s and 1960s, for example the Calder Hall-1 and Wylfa nuclear power stations.

Generation II (Gen-II). Refers to commercial reactors built from the late 1960s to the mid-1990s, for example pressurized water reactors (PWR) and boiling water reactors (BWR). Note that Gen-II reactors form the majority of the over 400 commercial PWRs and BWRs in the world today.

Generation III (Gen-III). Nuclear reactors from mid-1990s to 2010s, for example advanced pressurized water reactors (APWR) and advanced boiling water reactors (ABWR), can be thought of as Gen-II reactors that use a mixture of evolutionary and state-of-the-art design improvements, notably around fuel technology, thermal efficiency, modularized construction, safety systems and standardized design[87].

Generation III+ (Gen-III+). Evolved in terms of safety and economics from Gen-III. Constructed from the 2010s onwards, this class includes the advanced passive PWR (AP1000) and the water–water energetic reactor-1200 (VVER-1200). Notably, some Gen-III+ designs contain passive safety features that rely on gravity or natural convection to mitigate the impact of abnormal events, instead of active controls or operator intervention[87].

Generation IV (Gen-IV). Refers to innovative nuclear energy systems being researched and designed that could be operational by 2030 (ref. 87), for example lead-cooled fast reactors (LFR) and sodium-cooled fast reactors (SFR). The primary goals are to improve the four broad areas of sustainability, economics, safety and reliability, and proliferation resistance and physical protection[42].

Next Generation. These are theoretically possible designs such as accelerator-driven subcritical systems (ADS), and fusion demonstration and commercial reactors. Although such reactors may be built using near-term technology, their economics, practicality or safety mean that they remain of marginal interest[88].

In this Review, we analyse and discuss these gaps in the context of the main scientific and technological challenges of DEMO, incorporating lessons learned so far from ITER and from the development of fission energy systems, in particular Gen-IV fission reactor designs. Based on this analysis, we present an assessment of the implications of these safety issues for the DEMO design and operation, considering that fusion does not yet have its own regulatory framework.

Safety concerns

Safety questions to be considered include, for example, accidents, potential radioactive materials release, occupational radiation exposure and handling of radioactive waste (see also Box 2).

Accidents. According to the International Atomic Energy Agency (IAEA) standard[16], nuclear power plants are divided into operational states and accident conditions: operational states include normal operation as well as anticipated operational occurrences; accident conditions include conditions within 'design basis accidents' and 'design extension conditions'. Design basis accidents are accident conditions against which a facility is designed according to established design criteria, and for which the damage to the fuel and the release of radioactive material are kept within authorized limits. Moreover, design extension conditions (different from what are known as 'beyond design basis accidents', which are accidents that are not fully considered in the design process because they were judged to be extremely unlikely) are accident conditions that are not considered as part of design basis accidents, but that are considered in the design process of the facility in keeping with best estimate methodology, and for which releases of radioactive material are kept within acceptable limits. Design extension conditions could include severe accident conditions, which are characterized in pressurized water reactors (PWRs) as states with significant core degradation in which, for example, core components start to melt. Note that the safety systems for design basis accidents are designed with a set of conservative, prescriptive rules and criteria (for example application of the single failure criterion), whereas the safety features for design extension conditions are not required to be designed to meet the single failure criterion[16,17].

Table 1 summarizes the design basis accidents for different nuclear energy systems. It can be seen that the Gen-II/PWR, Gen-IV, ITER and DEMO systems share similar accident categories, notably: the increase or decrease of heat removal from the reactor coolant system; increase or decrease of the flow rate for the reactor coolant system; anomalies in power supply; and increase or decrease of the reactor coolant inventory. It is also evident that the major difference between fission and fusion nuclear energy systems rests in the transients due to neutron reactivity and safety issues due to the abnormalities of fusion-specific components. Note that the fusion reaction in fusion reactors would intrinsically terminate (and hence produce no runaway reactions) in the event of accidents; and unlike in fission reactors, the supercritical reaction[18] (that is, the conditions in a fission reactor under which the nuclear chain reaction grows without bound and the reactor power rises exponentially) would not happen. From this point of view, fusion is inherently safer than fission.

For ITER[19], postulated events have been considered for design basis accidents, including in-vessel events, tritium events, magnet events, cryostat events and hot cell events. Those events will also be taken into account in the DEMO design. Plasma events have not been categorized as design basis accidents in ITER, as these are expected events in ITER which is designed to achieve inductive plasma burn durations between 300 s and 500 s (ref. 19). By contrast, DEMO is expected to have the essentially steady-state operation required for the efficient extraction of fusion energy, and it is very likely that the frequency of plasma events in DEMO would fall into the category of accidents, thus necessitating the inclusion of possible plasma events (for example disruptions) in the list of design basis accidents. Moreover, given that maintenance activities have to be regularly executed for ITER[19], maintenance-initiated events are included in the list of design basis accidents in ITER, such as a stuck divertor cassette and the failure of its transport cask. However, maintenance-related events have not been considered for design basis accidents in fission PWRs because of their relatively reliable system operations as well as the long service life of their components. It is believed that DEMO may ultimately follow the practices of commercial PWRs, since successful commercialization will depend on the development of highly effective remote handling technology. In addition, tritium breeding blanket events need to be comprehensively investigated as DEMO design basis accidents with respect to possible tritium releases. The above considerations are summarized in Table 1.

For design extension conditions, it is generally considered sufficient to evaluate the robustness of the design and demonstrate an ultimate safety margin[16]. For example, explosions in ITER due to hydrogen or dust are a focus of much attention by the Nuclear Safety Agency (ASN) in France[20]. Such explosions could compromise the integrity of the vacuum vessel and bring about potential release of radioactive materials. This issue should thus be clearly addressed throughout DEMO's lifecycle, not only in the vacuum vessel but also in the tritium handling buildings. 'Beyond design basis accidents' are considered extremely unlikely to happen; however, they do in fact happen, as evidenced by the Fukushima accident. That event resulted in a recommendation by the IAEA that reactor designers attempt to prevent them by introducing design extension conditions[16]. It is most likely that DEMO will follow this approach for future design and operation. As regards extreme external hazards, such as earthquakes, flooding and aircraft crashes, safety standards for DEMO are expected to be the same as those of fission reactors[19,21,22], and the difference in the categorization of these hazards should also be negligible.

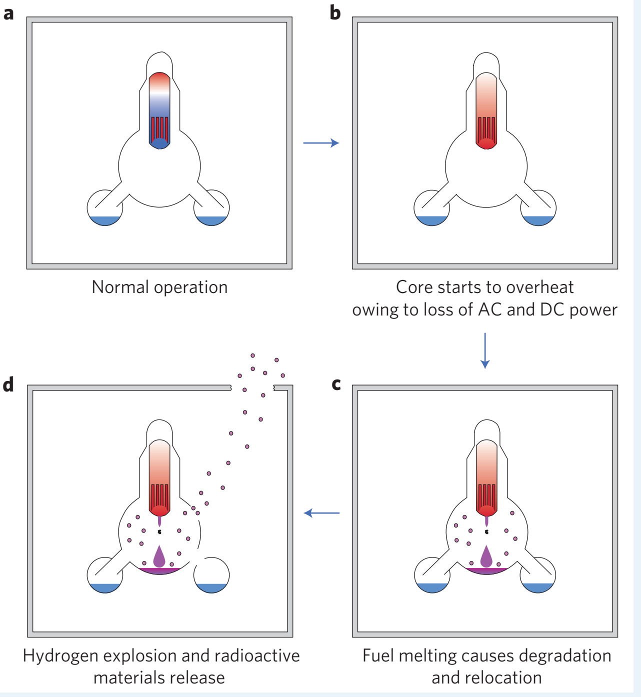
Potential radioactive material release. The radioactive source term (the total radioactivity available for release) in a fission reactor accident is significantly different from that of a fusion reactor, both in terms of radioactive isotopes and their inventories. For today's most common fission reactors, Gen-II/PWR, the main contributors to the radioactive source term are iodine, caesium, noble gases and fission product aerosols. Typical inventories (for example ^{131}I, 3.8×10^{18} Bq; ^{137}Cs, 2.6×10^{17} Bq)[23] are due to fission and activation reactions. This inventory will be broadly similar to that of a Gen-IV reactor depending on the fuel used. In ITER, only a small fraction of the tritium injected in the vacuum vessel is burned, and almost all of it is exhausted through the pumping system and re-used as fuel. Only a small quantity is retained inside the vacuum vessel, but this gradually accumulates to a significant inventory. This trapped tritium can be mobilized under normal conditions including active plasma operation phases and under accident conditions in the case of a significant temperature increase of the surfaces of in-vessel components and also in the case of injection of air or water[19]. Radioactive dust, from the erosion of plasma facing materials (mainly beryllium and tungsten) under normal operations and from evaporation of these materials during plasma disruption phenomena, could be mobilized during maintenance operations or under accident conditions in the case of ingress of water or air[19]. The risk of liquid releases containing tritium water and activation corrosion products is mainly expected in areas and facilities containing the primary cooling systems.

In DEMO, the radioactive materials may be different from those used in ITER, depending on the deployment of plasma-facing materials (for example tungsten or lithium)[24]. For instance, lithium (liquid lithium in particular) could have mitigating effects on the accumulation of dust in the vacuum vessel[25–27], although additional safety measures for lithium have to be considered as it is highly reactive. Moreover, differences may also lie in the possible different inventory of radioactive material for potential release. In ITER the quantity of tritium (~3–4 kg for the total inventory) and the amount of activated dust accumulated inside the vacuum vessel have safety limits of 1 kg and 1 metric tonne[19], respectively. These radioactive materials will be periodically assessed and removed when their inventory, taking into account uncertainties, approaches those limits. In contrast, DEMO may have a larger total inventory of tritium[28], relying not only on the factors of fusion power and tritium burn fraction but the design of the tritium processing system. For the retained tritium and dust in the vacuum vessel, DEMO may present an opportunity to reduce the safety limits in comparison to ITER, considering the adoption of different plasma-facing materials, different plasma edge conditions, higher operating temperature, absence of cryopumps and so on. However, these safety limits have to be carefully chosen to ensure that the balance is fully considered

Box 2 | Safety concerns.

Accidents, radioactive materials release, occupational radiation exposure and radioactive waste are all safety concerns for various applications of nuclear energy. They all need to be effectively assessed, controlled and kept as low as reasonably achievable. All kinds of accidents should be considered in order to restrict the likelihood and/or the consequences of various accident initiators, ensuring that nuclear power plants (NPPs) can be operated safely under all conditions as far as practicable. In addition, large amounts of radioactive wastes are produced in the operation of NPPs. These wastes pose a potential threat to future generations in the long term and require safe disposal methods. Therefore, for nuclear safety it is essential that any hazardous waste should be handled in such a way that it does not pose any risk to human health or the environment.

The example of station blackout (as happened, for example, with the Fukushima accident), illustrated below, can demonstrate the effects of an accident initiator at a NPP. As this example shows, it is of crucial importance to prevent and mitigate accidents and to minimize the release of radioactive materials and radiation exposure to both workers and the general public. These issues must be investigated in depth and clearly understood to ensure the safe design of nuclear systems.



Schematic diagrams of Fukushima nuclear accident process. a, NPPs are generally equipped with on-site d.c. power (batteries) and additional backup a.c. power (that is, gas turbine or diesel engines). **b**, When a NPP loses all d.c. and a.c. power, this situation is referred to as (total) station blackout. If a NPP is in station blackout for a period longer than the design limit, the lack of operating cooling pumps causes the fuel temperature to rise. **c**, If its temperature rises far enough, the fuel begins to melt, resulting in core damage and reactor pressure vessel damage. **d**, Hydrogen may be released from chemical reactions between water and the very hot fuel or fuel cladding in the reactor pressure vessel, leading to explosions that will damage the reactor building[89]. Radioactive materials that are detrimental to human health and the environment will be released to the atmosphere.

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Table 1 | Main design basis accidents for different nuclear energy systems.

	Gen-II/PWR	Gen-IV	ITER	DEMO
Loss of power	Yes	Yes	Yes	Yes
Loss of flow	Yes	Yes	Yes	Yes
Loss of heat sink	Yes	Yes	Yes	Yes
Loss of coolant (with different coolants)	Yes	Yes	Yes	Yes
Reactivity insertion	Yes	Yes	No	No
Plasma events	No	No	No	Yes
In-vessel events	No	No	Yes	Yes
Tritium events	No	No	Yes	Yes
Magnet events	No	No	Yes	Yes
Cryostat events	No	No	Yes	Yes
Hot cell events	No	No	Yes	Yes
Tritium breeding blanket events	No	No	No	Yes
Maintenance events	No	No	Yes	No

between the frequency with which the machine (most likely steady state) is shut down for tritium and dust removal, and the rate of tritium retention and dust generation. Also note that Gen-II /PWR and Gen-IV reactors do not have such safety limits based on the quantities of radioactive materials they contain; rather, their designs concentrate on strengthening multiple barriers to both routine operating and accidental releases. DEMO designs may adopt this approach as shutdowns for radioactive material removal so strongly influence facility availability and maintenance schedules.

Furthermore, owing to tritium breeding in the blanket, DEMO will have a tritium production rate four orders of magnitude greater than that of ITER[29]. This will be a great concern for the confinement of potential tritium releases, posing many challenges for effective tritium extraction, permeation and detritiation systems, as well as the need for multiple confinement barriers. The tritium release limit of ITER may not be feasible for DEMO, as that limit has not yet been verified from the perspective of the tritium technologies of ITER.

Occupational radiation exposure. Occupational radiation exposure is key to evaluating radiation safety not only during routine maintenance but also under accident conditions. In Gen-II/PWR reactors, the main risk of exposure to ionizing radiation in normal operations results from neutrons generated from fission reactions, as well as γ-radiation from the decay of fission and activation products. During shutdown, that risk is mainly associated with γ-radiation from fission and activation products. In contrast, in ITER[19] the risk of exposure comes from fusion neutrons emitted from the plasma, γ-radiation emitted by neutron-activated components, X-rays emitted by some heating and current drive generators, and the β-radiation emitted from tritium.

In DEMO, the occupational radiation risk is supposed to be similar to ITER, and the main difference is the size of the inventories of typical radioactive products[30]. It was calculated in ref. 30 that the radioactivity due to materials activation in a future fusion reactor (1,200 MWe STARFIRE reactor concept with first wall and structure material being stainless steel) may be three orders of magnitude more than that in a typical fission reactor (1,200 MWe light water reactor with structure material being stainless steel) with the same electrical power output, while the total radioactivity is comparable, with order of magnitude of between 10^{10} and 10^{11} GBq. From this point of view, fusion reactors may be potentially unsafe if low-activation materials are not deployed. Note that this finding may also be applicable to the more recent fusion reactor concepts with even low-activation materials adopted. This means that radiation exposure control for fusion reactor design and operation is of critical concern. For DEMO, it is important to take into account the effects of the high fluence of fusion neutrons, to minimize the release of tritium, and to use low-activation materials and remote handling maintenance as much as possible. Thus, several radiation protection provisions, such as confinement barriers, radiation shielding and access control, must be applied in order to meet the maximum public dose limits required by the regulatory body[31] and at the same time to keep individual occupational doses for workers as low as reasonably achievable.

Radioactive waste. Radioactive waste is generated by the operation and decommissioning of all types of nuclear plants. It is commonly classified according to its radioactivity level and decay time. These two characteristics are the principal basis for choosing the optimum method for waste treatment, storage and disposal.

According to the IAEA standard[32], there are six classes of Gen-II/PWR waste: exempt waste, very short-lived waste, very low-level waste, low-level waste, intermediate-level waste and high-level waste. Disposal is considered the final step in the management of radioactive waste. However, this classification scheme can differ widely from country to country. For example, an implementing decree followed by the French Act of 2006 (Sustainable Management of Radioactive Materials and Waste)[33] is applied to Gen-II/PWRs, prescribing requirements for the different categories of radioactive waste and materials from very low-level to high-level long-lived wastes. In the United States, radioactive waste is categorized into Class A, Class B, Class C and waste that is not generally acceptable for near-surface disposal, according to the NRC 10 CFR Part 61 regulation[34]. In China, the classification scheme is given in Chinese nuclear safety codes and guidelines HAD401-04 (ref. 35), categorizing the radioactive waste into exempt waste, low- and intermediate-level short-lived waste, low- and intermediate-level long-lived waste, and high-level waste. Therefore, these schemes could lead to a range of terminologies, differing from country to country and even between facilities in the same country. This situation may also give rise to difficulties in establishing consistent and coherent national waste management policies and implementing strategies, and make communication on waste management practices difficult both nationally and internationally[32].

In ITER, the classification of radioactive waste is based on the French regulation. It is estimated[36] that the operational wastes are roughly 4,500 metric tonnes and dismantling wastes approximately 30,000 metric tonnes. No high-level waste is expected in ITER, whereas Gen-II/PWRs generally produce 20–30 metric tonnes of high-level waste per year in the form of used fuel[30]. High-level waste continues to be a great challenge for Gen-II/PWRs, and it is generally suggested that it could be managed by disposal in a

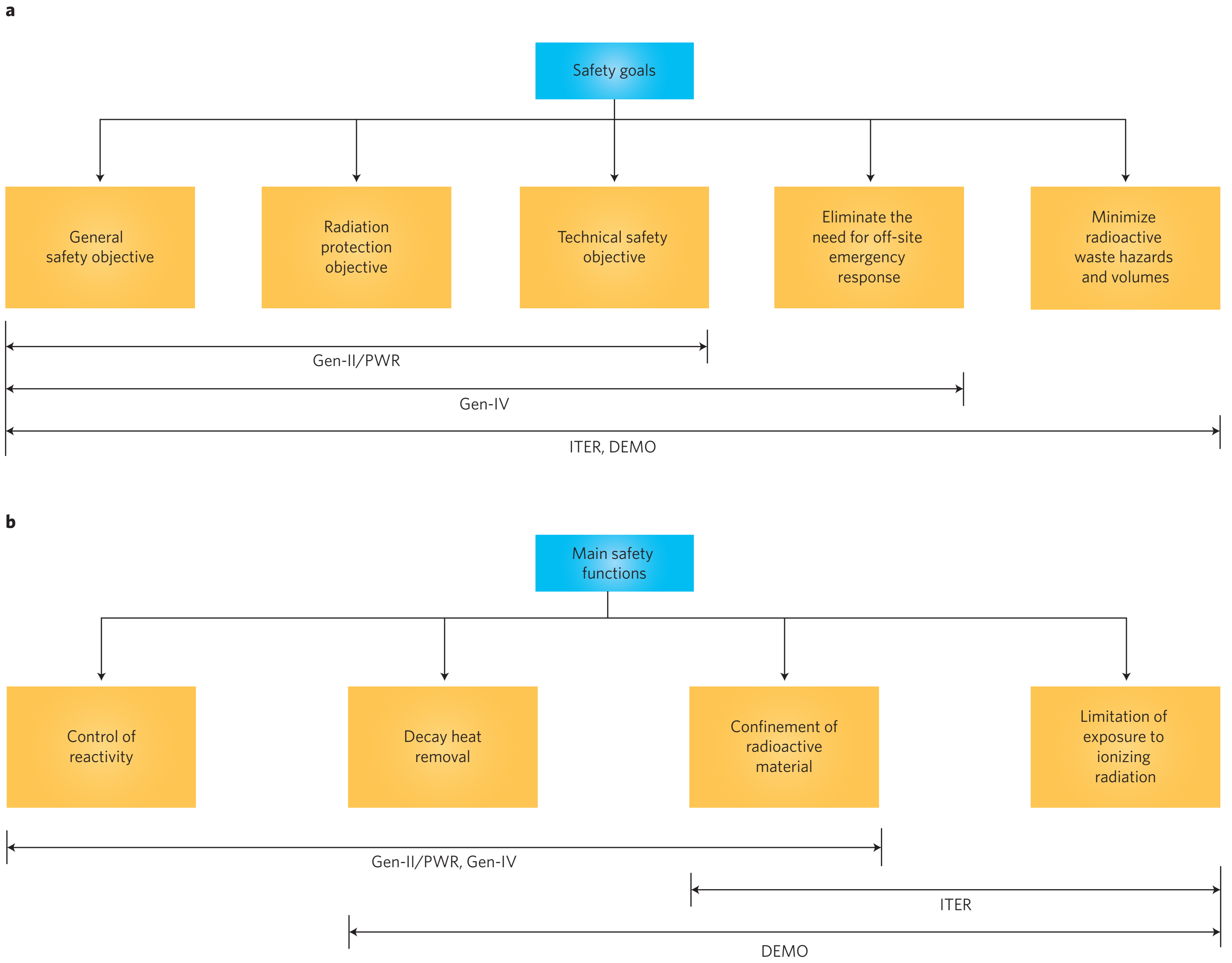

Figure 1 | Safety goals and main safety functions for nuclear energy systems. a, Safety goals for different nuclear energy systems. All such systems must meet the general safety objective. More specifically, Gen-II/PWR safety goals include another two complementary objectives: the radiation protection objective and the technical safety objective. Gen-IV reactors add a new goal beyond Gen-II/PWR safety goals: to eliminate the need for offsite emergency response. ITER adds a further goal: to minimize radioactive waste hazards and volumes. **b**, Main safety functions for different nuclear energy systems. Gen-II/PWR and Gen-IV reactors fulfil the three main safety functions as shown in the first three boxes: control of reactivity, removal of decay heat and confinement of radioactive material. In ITER, two main safety functions are implemented as shown: confinement of radioactive material and limitation of exposure to ionizing radiation. For DEMO, confinement of radioactive material, limitation of exposure to ionizing radiation and decay heat removal are expected to be included in the main safety function. It is also worth pointing out that limiting exposure to ionizing radiation as the main safety function is largely dependent on research and development into highly effective remote handling technology and low-activation materials.

deep (100–800 m) geological formation after a storage period of 30–50 years in adequate engineered structures. Fission fuels may also be reprocessed to remove the fissionable isotopes prior to disposal, with the remaining fission products incorporated into vitrified matrices for disposal. Accelerator-based transmutation or fusion-driven subcritical burners may be promising ways to confront these challenges. For example, China is working on the development of an accelerator-driven subcritical reactor[37]. However, a large quantity of low-level and intermediate-level waste is generated in ITER, mainly owing to the neutron activation of its structures, systems and components as well as tritiated wastes, together posing challenges for waste disposal. The ITER Organization is still working to find suitable places to treat these low-level and intermediate-level wastes[19].

In DEMO, radioactive waste activity after 100 years, assuming that low/reduced-activation materials are used for the first wall and structure material, could be around 20–50 times more than for ITER, owing to higher neutron fluences of 40–150 displacements per atom (dpa)[38]. The larger tritium inventory is also significant for tritiated waste management. In fact, this large amount of radioactive waste and especially tritiated waste will result in a large burden for waste disposal sites in the country where DEMO is located. Therefore, it is important to develop low-activation materials and to control the build-up of tritium inventories in the materials constituting the reactor. Moreover, the construction of special treatment repositories may have to be considered, because of the large amount of low-level and intermediate-level wastes, since conditioning will be needed to ensure that the characteristics of the waste are compatible with the disposal path[39].

Safety approach

Below, we consider the fundamental safety objectives, main safety functions, defence in depth and multiple barriers, and safety assessment methodology for fusion reactors.

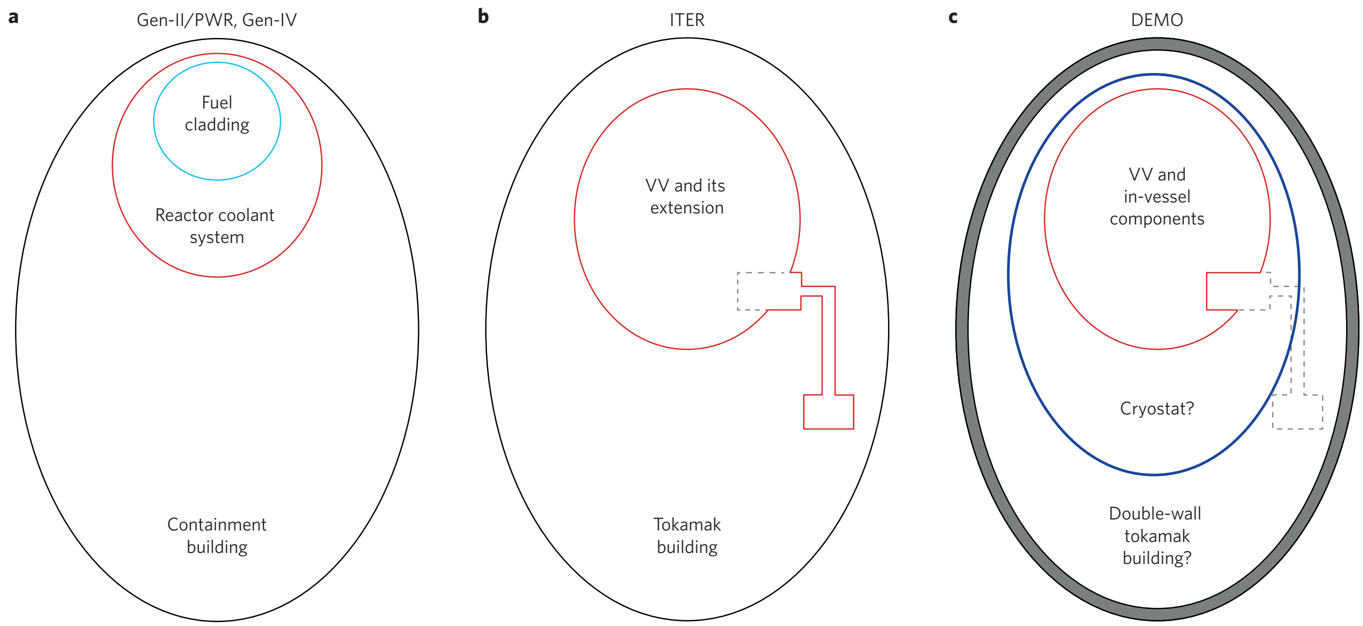

Figure 2 | Confinement and multiple barriers for different nuclear energy systems. a, In fission reactors, such as Gen-II/PWR and Gen-IV, the first barrier is the fuel cladding; the second barrier is the reactor pressure vessel; and the third barrier is the containment building. **b**, For ITER, the first barrier is the vacuum vessel (VV) and its extensions as schematically shown by the inside solid line, and the second barrier is the Tokamak building. **c**, For DEMO, the first barrier may comprise the VV and in-vessel components as schematically shown by the inner solid line. The second barrier may be the cryostat (blue line) or the Tokamak building with a double wall (thick grey line). Note that the main reactor vessel is indicated in red in each panel.

Fundamental safety objectives. According to the IAEA standard[40], the fundamental safety objective is to protect people and the environment from the harmful effects of ionizing radiation. To ensure that facilities are operated and activities conducted so as to achieve the highest standards of safety that can reasonably be achieved, measures must be taken to: control radiation exposures to people and the release of radioactive material to the environment; restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation; and mitigate the consequences of such events if they were to occur. Note that a set of safety goals should be derived at a more technical level to implement the fundamental safety objective. Specifically, the general safety objective is defined for nuclear power plants to protect individuals, society and the environment, generally complemented by the radiation protection objective and the technical safety objective[41].

In Gen-II/PWRs, the foregoing safety objectives are widely adopted by the international community, and after the Fukushima nuclear accident, the trend has been to consider eliminating the need for off-site emergency response including evacuation of affected members of the public. For instance, in the newly published safety standard[16], the IAEA stressed that plant event sequences that could result in high radiation doses or in a large radioactive release have to be "practically eliminated", in order to ensure that the necessity for off-site protective actions to mitigate radiological consequences can be limited or even eliminated in technical terms. Furthermore, the GIF (Generation IV International Forum) clearly put forward "eliminating the need for offsite emergency response" as one of the safety goals in future Gen-IV reactor designs[42], and many countries (for example the United States, Russia, China, Japan, Korea and countries of the European Union) have been making great efforts to achieve this safety goal in their own reactor designs[43]. For ITER, another safety objective is the minimization of radioactive waste hazards and volumes (Fig. 1a). Therefore, the implications of this aspect for DEMO's design may include eliminating the need for off-site emergency response and minimizing the radioactive waste hazards to reasonably achievable levels, and these implications may be further adopted as a DEMO design requirement.

Main safety functions. Based on the IAEA standard[16], the following main safety functions must be fulfilled for all plant states in a Gen-II/PWR: control of reactivity, removal of heat from the reactor and the fuel store, confinement of radioactive material, shielding against radiation, and limitation of radioactive releases from both routine operations and from accidents. Gen-IV systems also aim to follow these principles in design and operation (Fig. 1b). In ITER, two main safety functions are implemented. The first is radioactive material confinement, to ensure protection against radioactive material releases for workers, the public and the environment. The second is limitation of internal and external exposure to ionizing radiation. In contrast to a Gen-II/PWR there is no safety function of 'control of reactivity' in ITER since there is no neutron reactivity issue in a fusion facility. But ITER has the additional safety function of 'limitation of exposure to ionizing radiation' in consideration of radiation protection during its comparatively frequent maintenance activities.

For DEMO, confinement of radioactive material is assumed to be included in the main safety function, as indicated in Fig. 1b, mainly owing to the large tritium inventory. Decay heat removal is also expected to be a safety function, since a fusion demonstration reactor is generally expected to have an order of magnitude more decay heat power than ITER[44], comparable to that of a fission reactor with the same electrical output power[30]. Limiting exposure to ionizing radiation as the main safety function is largely dependent on research and development of highly effective remote handling technology and the low-activation materials.

Defence in depth and multiple barriers. The concept of 'defence in depth' is fundamental to the safety of nuclear installations. It concerns the protection of both the public and workers, and is widely applied to Gen-II/PWRs based on IAEA standards[16,41,45]. There are generally five levels: Level 1 is the prevention of abnormal operation and failures; Level 2 is the control of abnormal operation and detection of failures; Level 3 is the control of accidents within the design basis; Level 4 is the control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents; Level 5 is the mitigation of the radiological consequences of significant releases of radioactive materials. The independent effectiveness of each of the different levels of defence is an essential element of defence in depth at the plant. It is achieved by incorporating measures to prevent the failure of any one level of defence causing the failure of other levels. In Gen-IV reactors and ITER, this concept emphasizes the elimination of the need for off-site emergency response on the basis of INSAG (International Nuclear Safety Advisory Group)-10 by strengthening the first four levels, and is still evolving after the Fukushima accident. According to the newly released IAEA standard[16], design extension conditions will be introduced in order to further enhance the safety of nuclear power plants. DEMO designs may have to adopt these new requirements.

Multiple barriers are designed and constructed in both fission and fusion facilities to prevent the release of radioactive materials and ionizing radiation exposure to the environment and to the public. Their specific design may, however, vary depending on the material activity and on possible deviations from normal operation that could lead to the failure of some barriers. Different barriers are investigated for fusion and fission systems, as shown in Fig. 2. In fission reactors (Fig. 2a), the first barrier is the fuel cladding which confines the UO_2 fuel pellets and has to endure harsh conditions of high neutron flux, coolant corrosion at high temperatures and high mechanical stresses. The second physical barrier is the reactor coolant system, which consists of the reactor vessel and its piping. Special consideration is also given to static and dynamic loads, thermal cycling, and the irradiation effects to which the components will be exposed throughout their lifetime. The third physical barrier consists of containment or confinement structures to prevent the escape of the radiation that constitutes the 'source terms' (that is, the quantities and isotopic compositions of radionuclides that could potentially be the source of exposure to radioactivity). These multiple barriers guard against the possibility of radioactive release in the event of a large variety of abnormal conditions, thereby protecting both humans and the environment.

Significantly different from a Gen-II/PWR, ITER uses two confinement barriers[44,46] (Fig. 2b). The first confinement system is the vacuum vessel (VV) and its extensions to prevent movement of radioactive materials within the facility and thereby protect workers. The VV is a robust double-walled chamber designed to resist, by a large margin, all predictable loads including electromagnetic loads induced by the largest expected plasma vertical displacement event. However, 'extensions' to the ITER VV include not only dozens of ports providing access to the vacuum vessel for remote handling operations, diagnostic systems, heating and vacuum systems, but also hundreds of penetrations through the vacuum boundary for cooling and heating and current drive systems, in-vessel coil feeders and so on. Thus, the first confinement system becomes extremely complicated with hundreds of isolation valves as well as tens of kilometres of pipework, ducts and wave guides[19,44], which is very different from the reactor vessel in the fission reactor. The second confinement system includes all vessels or systems that surround the vacuum vessel. This includes the buildings but also the advanced detritiation systems for the recovery of tritium from gas and liquids, which keep the fusion fuels recycled within a closed system and maintain any releases well below regulatory limits[19,44].

For DEMO (Fig. 2c), in-vessel components may be credited with a confinement function so as to avoid as many extensive and complex ex-vessel parts as possible, as these can complicate ITER's first confinement barrier[44], and thus to enhance the independence of confinement barriers. Considering the large tritium inventory in DEMO, it seems feasible that the cryostat system may also serve a confinement function, or that the tokamak building may have to be strengthened by a reinforced concrete structure and be equipped with more dedicated ventilation/detritiation systems, in order to achieve a highly reliable and robust second confinement barrier specifically designed to prevent, protect against or mitigate accident sequences.

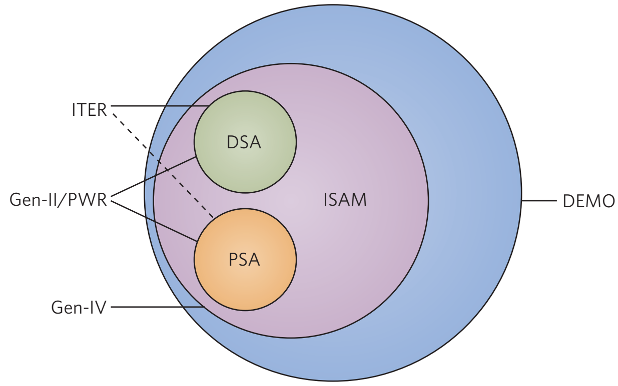

Figure 3 | Safety assessment methodologies for different nuclear energy systems. Traditionally, only deterministic safety analysis (DSA) and probabilistic safety analysis (PSA) are applied for analysis of PWR safety. For Gen-IV systems, the integrated safety assessment methodology (ISAM) has been developed, which contains elements not only of DSA and PSA but also of qualitative safety features review (QSR), the phenomena identification ranking table (PIRT), and the objective provision tree (OPT), to achieve safety that is 'built-in' rather than 'added on'. In ITER, only DSA studies have been performed, and PSA studies are expected to be further strengthened. For DEMO, PSA would receive more attention, and ISAM may be further extended.

Safety assessment methodology. As emphasized in the IAEA standard[19], the objectives of safety assessment are to identify important safety issues and to demonstrate that the plant is capable of meeting any authorized limits on the release of radioactive material and on the potential exposure to radiation for each plant state. In a Gen-II/PWR, both deterministic safety analysis (DSA) methods and probabilistic safety analysis (PSA) methods must be applied to the process of designing and licensing a nuclear power plant. For higher-frequency events, whose acceptance criteria are set in terms of damage allowed, a deterministic analysis is adequate. On the other hand, for low-frequency sequences that lead to barrier damage, PSA may be a suitable risk evaluation tool. Thus, both deterministic and probabilistic analyses provide a comprehensive view of overall reactor safety for the complete range of the frequency–consequence spectrum. Note that DSA methods play an important part in the performance of a PSA as they provide information on whether a given accident scenario will result in the failure of a fission product barrier, whereas, in PSA, a fault tree is a powerful tool that can confirm commonly made assumptions about the availability of systems in the deterministic calculation.

For Gen-IV systems, the GIF collaboration[47] has developed an integrated safety assessment methodology (ISAM), as illustrated in Fig. 3. Its elements include not only DSA and PSA, but also qualitative safety features reviews, phenomena identification ranking tables, and objective provision trees. Its goal is to support the achievement of safety that is 'built-in' rather than 'added on' by influencing the direction of the concept and design development from its earliest stages. For ITER, the fusion component failure rate database[48,49], started as a PSA quantification database, has been generated to support RAMI (reliability, availability, maintainability, and inspectability) studies and design reviews. In ITER, however, there

Table 2 | Main international efforts on DEMO safety R&D.

	Safety programmes and projects	Safety regulation	Safety code and its V&V	Safety design and analysis
China	'Key Technology of Fusion Nuclear Safety & Radiation Protection' within 2014 China Domestic Fusion R&D Program, supported by CN MOST (2014 to 2018). Focus is on fusion safety, environmental and economic studies. Issued and directed by the INEST, CAS with other participants including SWIP, CAEP, CIAE and some universities.	Project 'Key Technology of Fusion Nuclear Safety & Radiation Protection' to investigate adaption of fission safety assessment methodology to DEMO.	INEST, CAS developing HINEG[52] as important experimental platform for fusion neutronics studies. Aims to become a world-class neutron physics research base with the highest neutron intensity. First phase (HINEG-I) completed with neutron intensity up to 1.1×10^{12} n s^{-1}. Feasibility of second phase (HINEG-II, ~10^{14} to 10^{15} n s^{-1}) already experimentally demonstrated. Constructing DRAGON-V (a dual coolant thermal hydraulic integrated experimental loop) to support engineering design validation of Pb–Li breeder blanket[53,54]. Independently developed particle transport simulation software SuperMC[55] as a computer-aided-design based Monte Carlo programme. Now being used in >600 institutions in 50 countries. Developed and employed TAS (Tritium Analysis Program for Fusion Systems) and RiskA (Reliability and Probabilistic Safety Assessment Program) for series of reactor designs[56,57].	Performed preliminary safety analyses for the China Fusion Engineering Test Reactor (CFETR)[58] with different blanket options.
EU	Presented overview of EU fusion safety programmes and projects since 1990 (ref. 23) at the Third IAEA DEMO Programme Workshop covering the SEAFP, SEAL, PPCS and WPSAE projects, with studies concentrating on principal nature, comparative nature and integral design support.	Summarized R&D on safety and licensing of nuclear facilities for fusion[46] to clarify safety approach and regulations. IRSN (Institut de Radioprotection et Sûreté Nucléaire) investigated safety issues possibly to be taken into account in designing future fusion facilities[59].	Investigated adaption of the ASTEC code system to fusion installations[60].	For DEMO blanket safety studies, investigated comprehensive efforts on neutronics analysis and requirements on the HCPB DEMO blanket[61,62]. Conducted preliminary safety studies for blanket concept (including identification of source terms), confinement strategy, and main safety systems[63]. Examined interaction between $Pb^{17}Li$ and water for the water-cooled lead–lithium DEMO blanket[64]. Performed a first safety assessment of the EU DEMO primary heat transfer system with intermediate heat storage, based on a functional failure mode and effects analysis (FFMEA)[65].
Japan	Launched DEMO safety research as part of the Broader Approach DEMO Design Activities (BA-DDA)[66] with the purposes of designing safety systems for preventing and/or mitigating accidents in DEMO; demonstrating the safety of DEMO; and identifying future R&D issues for DEMO safety research.		Developed new version of AINA code for safety studies of a high-aspect-ratio Japanese DEMO design[67].	Explored >20 accident events to address safety issues[68] for water-cooled DEMOs. Conducted basic tritium safety research[69] and management strategy for radioactive waste[70] for DEMO. Analysed major in- and ex-vessel loss-of-coolant accidents (LOCAs) of a water-cooled tokamak fusion DEMO reactor to evaluate responses of DEMO systems to these accidents and pressure loads to confinement barriers[71]. Used modified TRAC-PF1 code to assess functional behaviour and safety-related characteristics, thermo-hydraulic transient analysis[72].
Korea	Safety studies for a fusion DEMO plant (K-DEMO) are on-going with many institutions involved including the National Fusion Research Institute (NFRI), Kyung Hee University, and other groups.	Korea Institute of Nuclear Safety (KINS) is reviewing a technical neutral framework for the safety approach of future nuclear reactors[73] ISAM was used for safety studies on Korean fusion DEMO plants as a preliminary feasibility test[74,75].	KAERI (Korea Atomic Energy Research Institute) developed Multidimensional Analysis of Reactor Safety (MARS-KS) code[76].	Investigated design basis accident scenario for the K-DEMO reactor concept with a fault tree focusing on accident consequences. Performed plant layout study for safety and radiological analyses. Conducting thermal-hydraulic analyses for water-cooled breeding blanket of K-DEMO using the MARS-KS code[76].

Continued

Table 2 | (continued)

	Safety programmes and projects	Safety regulation	Safety code and its V&V	Safety design and analysis
Russia	Studied safety issues for the DEMO-FNS Tokamak[14] for fusion and hybrid technologies, which is planned to be built by 2023 and is the key milestone on the path to the PHP (Pilot Hybrid Plant).			Studied safety issues for the DEMO-FNS Tokamak[14], including distribution of hydrogen isotopes in technological systems and rooms, possibilities and consequences of explosions and fires at the facility, and the maximum emissions of radio-toxicity in case of accident.
USA	Fusion Safety Program (FSP) has historically provided safety design support to a number of national and international conceptual design activities such as ARIES[77].	US DOE fusion safety standards provide general safety requirements and guidance for fusion facilities. They were issued in the 1990s in an effort to develop an official regulation on safety for fusion devices[78–80].	Further development of TMAP and MELCOR for fusion applications[81].	Conducted MELCOR accident analysis for ARIES-ACT[82], followed by the safety assessment of the ARIES Compact Stellarator[83]. Summarized normal operation and maintenance safety lessons from the ITER US Pb–Li TBM programme for DEMO[84].

CAEP, China Academy of Engineering Physics; CIAE, Chinese Institute of Atomic Energy; CN MOST, Ministry of Science and Technology, China; FNS, fusion neutron source; PPCS, Power Plant Conceptual Study; SEAFP, Safety and Environmental Assessment of Fusion Power; SEAL, SEAFP Long-term; SWIP, Southwestern Institute of Physics; TMAP, Tritium Migration Analysis Program; WPSAE, EUROfusion Safety and Environment project; V&V, verification and validation.

is a lack of probabilistic safety analysis studies regarding overall indicators to evaluate the safety level of the fusion facility similar to, for example, the core damage frequency (CDF) and large early release frequency (LERF) for fission reactors. In the long run, PSAs studies are expected to be further strengthened in ITER and then receive more attention in the DEMO design. Furthermore, the ISAM concept may be further extended to DEMO by considering fusion-specific safety characteristics, as indicated in Fig. 3.

Safety R&D activities

Generally, major fusion safety activities in the world can be arbitrarily categorized into ITER and TBM safety-related activities (TBM are test blanket modules, which are inserted and tested in ITER in dedicated equatorial ports directly facing the plasma), and DEMO safety-related activities. The ITER Organization is responsible for ITER safety[36] with the help of domestic agencies as well as other supporting institutions. For major TBM safety studies, the leading institutions are summarized as: Institute of Nuclear Energy Safety Technology (INEST), Chinese Academy of Sciences (CAS) for the Chinese helium-cooled ceramic breeder (HCCB); Fusion for Energy (F4E) for the European helium-cooled pebble bed (HCPB) and the helium-cooled lithium–lead (HCLL); National Fusion Research Institute (NFRI) for the Korean helium-cooled ceramic reflector (HCCR); Japan Atomic Energy Agency (JAEA) for the Japanese water-cooled ceramic breeder (WCCB); Institute of Plasma Research (IPR) for the Indian lead–lithium ceramic breeder (LLCB). Basic safety studies have been on-going for the TBM design reviews. There are also comprehensive efforts involved in the safety analysis of other TBM designs, such as the dual coolant lead–lithium (DCLL) in the United States and dual functional lithium–lead (DFLL) in China.

The IEA (International Energy Agency) and IAEA frameworks have been playing a significant role in DEMO safety R&D. In the IEA framework, the Implementing Agreement on a Cooperative Programme on Environmental, Safety and Economic Aspects of Fusion Power (ESEFP) was established decades ago with eight 'Tasks' mainly focusing on the following: in-vessel tritium source terms; transient thermo-fluid modelling and validation tests; activation production source terms; failure rate database; radioactive waste; socio-economic aspects of fusion power; magnet safety; and fusion power plant studies. The International Workshop on ESEFP has been created in this frame, with the first workshop[50] successfully organized by INEST, CAS, on 13 September 2015 in Jeju Island, Korea. The objectives of this workshop were to establish a platform for scientists and engineers to exchange information and further enhance collaboration; coordinate international efforts to bridge the scientific and technical gaps between ITER and DEMO; and support governmental policies and raise awareness of fusion energy development and its potential to the general public. Its main technical topics included safety issues and environmental impact; availability growth and risk control; socio-economic aspects of fusion power; and fusion power plant studies.

IAEA fusion safety activities up to now include eight previous IAEA Technical Meetings on Fusion Power Plant Safety held between 1980 and 2006. The main technical topics covered at this series of meetings included fusion reactor licensing basis and requirements; power plant safety; test blanket modules; fusion-specific operational safety approaches; computational codes for fusion safety and their validation; accident analysis; tritium safety and inventories; and fusion reactor decommissioning and waste. To further strengthen these activities, the First IAEA Technical Meeting on Safety, Design and Technology of Fusion Power Plants[51] was held on 3–5 May 2016, with topics concentrating on power plant concepts and systems analysis, safety assessment, fuel cycles, management strategies, and socio-economic aspects of fusion.

The main DEMO safety R&D studies in member states are summarized in Table 2. As is clear, these studies are very diverse in range but come purely from ITER members. The IEA and IAEA frameworks may play an important role in combining these efforts to finally realize the goal of fusion power.

Main safety gaps and future outlook

The main gaps required to ensure the safety of DEMO are summarized in Box 3, which also represent the consensus output from the collaboration in the IEA ESEFP IA, particularly during discussions at the First International Workshop on ESEFP[50].

Moreover, code development needs to be well verified and validated; development of safety assessment methodology for fusion installations is needed; and there is a great lack of involvement

Box 3 | Main gaps in ensuring the safety of DEMO.

Accidents

- Large gaps in component failure rate data needed for evaluating accident probabilities must be filled.
- Hydrogen/dust explosions need to be fully addressed to protect confinement barriers such as the vacuum vessel and building walls.
- Electromagnetic loads due to plasma disruptions need to be better understood.
- Decay heat removal may need to be developed as a safety function.
- Comprehensive consideration of design extension conditions and enhanced confinement is required to meet the 'no off-site emergency response' criterion.

Radioactive material for potential release

- Tritium operational release limits in ITER have never been verified, leaving this limit in DEMO unknown.
- R&D on the fraction of tritium burned in the plasma needs to be further enhanced to reduce the tritium inventory.

Occupational radiation exposure

- Remote handling technology required for maintenance operations must be developed and the design choices of DEMO must be optimized, to minimize occupational radiation exposure to workers.

Radioactive waste

- Low-activation materials must be ready for use in DEMO.
- Improved understanding of tritium retention in materials is needed, as is the development of detritiation systems (for example thermal furnace, fusion furnace).

by industry. The feasibility of adapting the fission reactor safety approach to DEMO needs to be further investigated. There are still many unknowns because DEMO is currently a generic concept and not a specific reactor design. The development of innovative technologies (for example advanced plasma-facing materials) may accelerate the filling of multiple gaps.

In this Review, DEMO safety issues have been raised in terms of accidents, radioactive material release, occupational radiation exposure and radioactive wastes in comparison with existing Gen-II/PWRs, Gen-IV reactor designs, ITER. Potential safety approaches for DEMO licensing were also investigated with attention to fundamental safety objectives, the main safety considerations, defence in depth and confinement barriers, and safety assessment methodology. International efforts in fusion safety research towards DEMO were summarized, and then safety R&D gaps were identified. Note that these gaps will be evolving because of the continuous development of advanced fusion science and technology, as well as the increasingly high nuclear safety standards as evidenced by the development of nuclear reactor generations.

Unlike in fission reactors, safety concepts are generally not seriously considered at the very beginning of DEMO designs, and, unfortunately, insufficient attention has been paid to safety culture in the fusion community. In this regard, it is hoped that this Review's findings lay a good foundation for the development of DEMO designs from a safety perspective. Moreover, it will be important for the IEA and IAEA to further enhance collaboration and combine international and national efforts to fill the safety gaps. Importantly, due attention should also be paid to the public acceptance of fusion energy, which presents a challenge on the way to realization of fusion power.

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Competing interests
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