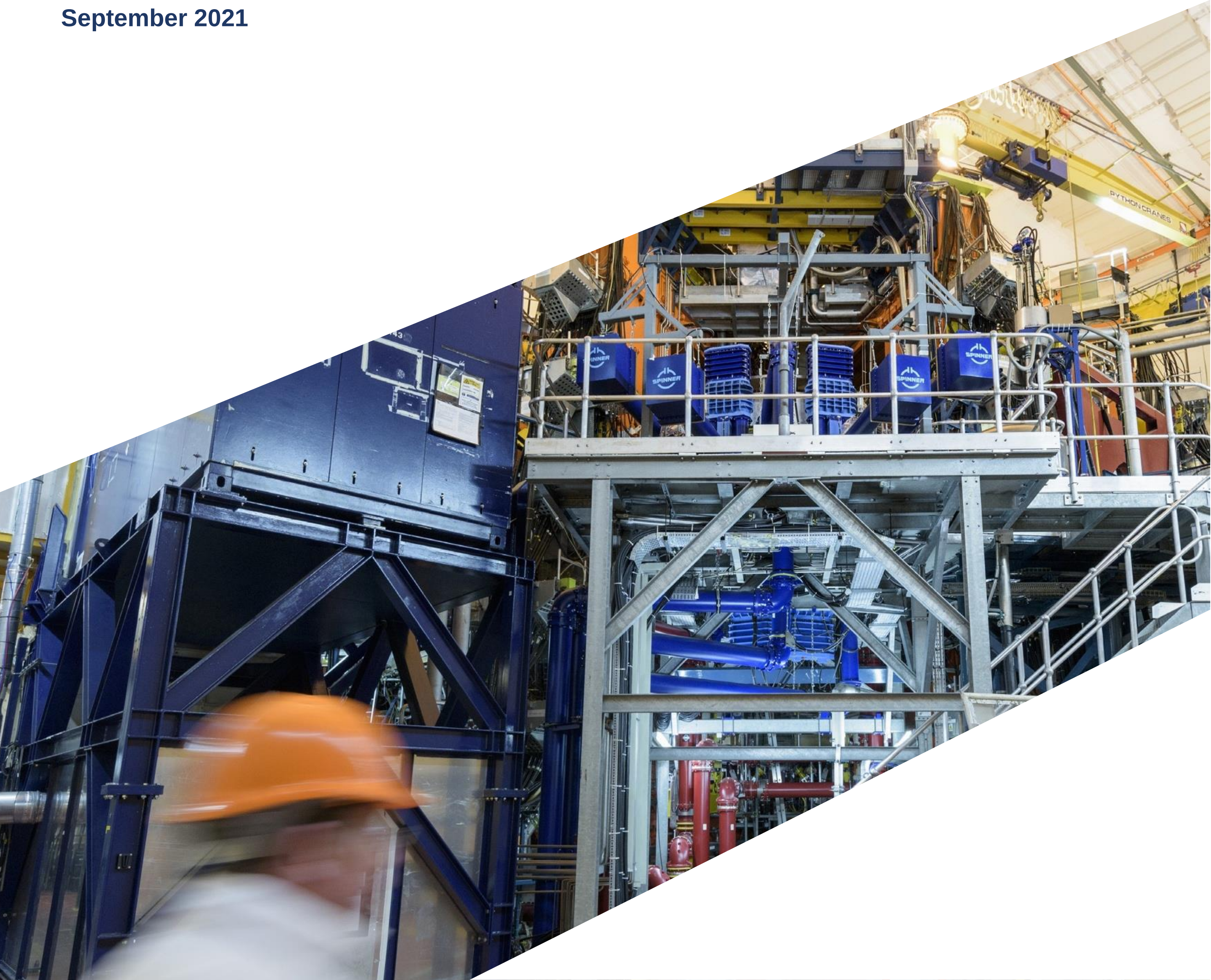
UK Atomic Energy Authority

Technology Report – Safety and Waste Aspects for Fusion Power Plants

Fusion Safety Authority

UKAEA-RE(21)01

Issue 1
September 2021



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Technology Report – Safety and Waste Aspects for Fusion Power Plants

Fusion Safety Authority

Email: FusionSafetyAuthority@ukaea.uk

United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, OX14 3DB, UK

Executive Summary

Over the past six decades, the international fusion community has grown and there are a multitude of organisations around the world carrying out research into the use of fusion as an energy source. There are now several programmes to design and develop demonstration, or prototype, fusion reactors, to test the concepts on the path to realisation of commercial fusion power plant.

This document is written to support the UK Government's consultation on fusion regulation, in the Green Paper "Towards Fusion Energy: The UK Government's proposal for a regulatory framework for fusion energy". The approach to fusion regulation needs to be targeted and proportionate to the level of hazard, protecting people and the environment whilst supporting innovation. This document does not draw any conclusions on a regulatory framework, as how this is achieved is a matter for the Government, in consultation with stakeholders.

The purpose of the Technology Report is to provide a description of the current understanding of the safety hazards, potential radiological doses from accident scenarios, radioactive waste and environmental radioactive discharges of future fusion power plant, to support discussions on the safety and environmental regulatory framework for fusion power plants, by:

- providing supplementary information to support the chapter in the Green Paper on "Fusion Technology and Associated Hazards";
- providing an overview of the different fusion technologies that are being pursued in the UK and internationally, to inform regulatory considerations;
- providing supplementary information and referenced literature on radiological accident scenarios analysis, environmental radioactive discharges and expected radioactive waste for fusion power plants.

The sections of the Report give information for future fusion power plants against the following key messages:

The understanding of the hazards relating to a fusion power plant is well developed.

Published safety analyses for conceptual designs of fusion power plants show that even in the case of major in-plant failures from significant internal or external events, the potential for harm to members of the public is low.

Published assessments of environmental radioactive discharges for conceptual designs of fusion power plant show that the potential for harm to members of the public is very low.

Published assessments for conceptual designs of fusion power plant show that they will not generate a high level radioactive waste legacy burden.

Published analyses of radioactive waste for conceptual designs of fusion power plant illustrate a good capability to estimate the low level waste and intermediate level waste requiring disposal.

An Annex to the Report also provides a brief contextual overview of the fission process, fuels used, and the potential radiological hazards and waste from this technology. This allows the information in this Report on fusion power plant to be set in context, in terms of the levels of hazards and waste potentially arising from the two different technologies, to inform the discussion on the appropriate regulatory framework.

Contents

Acronyms

ALARP	As Low As Reasonably Practicable
ALARA	As Low As Reasonably Achievable
ARIES	Advanced Reactor Innovation and Evaluation Study
Bq	Becquerel (TBq is 10^{12}Bq)
D-D	Deuterium – Deuterium (reaction)
DEMO	DEMOnstration Power Station
EMF	Electromagnetic Field
FFMEA	Functional Failure Modes and Effects Analysis
FPP	Fusion Power Plant
GDF	Geological Disposal Facility
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
HAW	Higher Activity Waste
D-T	Deuterium – Tritium (reaction)
HAZOP	HAZard and OPerability (Study)
HCPB	Helium Cooled Pebble Bed
HLW	High Level Waste
HSE	Health and Safety Executive
HTO	Tritiated Water
HYLIFE	High-Yield Lithium-Injection Fusion-Energy
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate Level Waste
ITER	”The Way” in Latin – an international fusion experiment
JET	Joint European Torus
LLW	Low Level Waste
LLWR	Low Level Waste Repository
LOCA	Loss of Coolant Accident
LOVA	Loss of Vacuum Accident
NDA	Nuclear Decommissioning Authority
NPP	Nuclear Power Plant
PPCS	Power Plant Conceptual Study
REPPIR	Radiation (Emergency Preparedness and Public Information) Regulations
SEAFP	Safety and Environmental Assessment of Fusion Power
SEAL	Safety and Environmental Assessment Long-term
SOMBRERO	Solid Moving Breeder Reactor
STEP	Spherical Tokamak for Energy Production
TFTR	Tokamak Fusion Test Reactor
UKAEA	United Kingdom Atomic Energy Authority
WCLL	Water Cooled Lithium Lead

1. INTRODUCTION

The approach to fusion regulation needs to be targeted and proportionate to the level of hazard, to protect people and the environment whilst supporting innovation. This document is written to support the UK Government's pursuit of fusion energy technology, which is to play an important role over the longer term to decarbonise global energy. This document does not draw any conclusions on a regulatory framework, as how this is achieved is a matter for the Government, in consultation with stakeholders, in the Green Paper "Towards Fusion Energy: The UK Government's proposal for a regulatory framework for fusion energy".

Over the past six decades, the international fusion community has grown, with many organisations around the world carrying out research into the use of fusion as an energy source. The aim is to design and build commercially viable fusion power plant (FPP) that can produce electricity, or other industrial or domestic uses of the power output. There are now several programmes to design and develop demonstration, or prototype, FPP in addition to the next generation of experimental reactors (e.g. ITER) to test the concepts on the path to realisation of a commercial FPP. This move from research to power generation will see fusion reactors that in some instances will be on a much larger scale than the current experimental reactors, and consequently will have an associated change in the level of hazard and waste arisings. The continuing evolution of designs for FPP over the next couple of decades is unlikely to change the overall conclusions of this report.

The purpose of the Technology Report is to provide a description of the current understanding of the safety hazards, potential radiological doses from accident scenarios, radioactive waste and environmental radioactive discharges of future FPP. Although this report will focus on the radiological aspects, there are also other industrial hazards and wastes that need consideration. The role of this Report is to support UK Government and stakeholder discussions on the safety and environmental regulatory framework for fusion power plants by:

- providing supplementary information to support the chapter in the Green Paper on "Fusion Technology and Associated Hazards";
- providing an overview of the different fusion technologies that are being pursued in the UK and internationally, to inform regulatory considerations;
- providing supplementary information and referenced literature on radiological accident scenarios analysis, environmental radioactive discharges and expected radioactive waste for fusion power plants.

This report provides an overview of background and contextual information in the following sections, supporting key messages as highlighted.

Section 2 provides a brief overview of fusion and the history of its development, from the research and development facilities currently operating, to large experimental facilities currently in construction, and the projects to design future fusion power plant.

Section 3 gives an outline of the fuels used in fusion, the fusion process and how this produces energy.

Section 4 includes a description of the different types of fusion technology that are currently being developed, based on the concepts of 'magnetic confinement' and 'inertial confinement'. The focus is on the tokamak, as this is the most prominent design being operated and developed. As well as the technology of the fusion reactor, it also describes the elements that in addition to the reactor, make up the whole FPP.

Section 5 provides information about the main hazards and accident scenarios in a fusion power reactor, focusing on the radiological aspects.

Key message: The understanding of hazards related to a fusion power plant is well developed. This is based on using well-established safety analyses techniques for identifying hazards and assessing their consequences. Onsite hazards associated with the fusion reactor itself are controlled by inherent safety features of fusion reactor dynamics with supplementary passive and active engineered protection systems. Wider plant and off-site hazards are controlled by conventional protection systems and procedures.

Section 6 provides more detail on the analysis of the potential radiological accidents for a fusion power plant, taken from several published studies in this area.

Key message: Published safety analyses for conceptual designs of fusion power plant show that even in the case of major in-plant failures from significant internal or external events, the potential for harm to members of the public is low. These safety analyses indicate that for credible and foreseeable in-plant accident scenarios, no countermeasures involving evacuation of members of the public would be required. In addition, they present an upper bound based on a hypothetical extreme external event scenario (such as a large magnitude earthquake), to illustrate the maximum order of magnitude of dose that might theoretically result.

Section 7 covers the potential level of normal operation doses and environmental radiological discharges that may be expected from a fusion power plant.

Key message: Published assessments of environmental radioactive discharges for conceptual designs of fusion power plant show that the potential for harm to members of the public is very low. Small amounts of liquid and gaseous radioactive effluent will be discharged during normal operations of a fusion power plant, largely from tritium. The analysis of the dose to members of the public from these discharges indicates that they will be well below the level that would require any further significant reduction.

Section 8 outlines the main radioactive waste arisings from a fusion power reactor, giving likely amounts and categories of waste. These arise largely from the decommissioning of the plant at the end of life.

Key message: Published assessments for conceptual designs of fusion power plant show that they will not generate a high level radioactive legacy waste burden. Inherent in the fusion process, there is no build-up of highly radioactive spent fuel, as the by-products of the deuterium-tritium reaction, helium and neutrons, are not radioactive. (See Section 8 for the definition of radioactive waste categories).

Key message: Published analyses of radioactive waste for conceptual designs of fusion power plant illustrate a good capability to estimate the low level waste and intermediate level waste requiring disposal. Radioactive waste will be created by neutron activation of components and tritium contamination of materials. Waste will be minimised by aspects of the design process and by the careful selection of materials.

Section 9 provides some concluding remarks summarising the information provided in this Report on the potential level of radiological hazards and waste from a future FPP. It is recognised that safety and waste analyses are strongly dependent on the type of fusion technology, design of plant and the materials used. The assessment of accident scenarios is dependent on the maximum inventory of radioactive material that could be released, but the worst-case estimates used seek to identify the upper bounds of impacts. The quantities and activities of radioactive waste will also be influenced by choices made at the design stage (informed by the good estimation capability), and by the waste management strategies developed. Future analyses for safety and waste will be underpinned by greater technical certainty and information on inventory levels, which will reduce the uncertainty on the level of hazards and radiological waste.

Annex A to the Report also provides a brief contextual overview of the fission process, fuels used, and the potential radiological hazards and waste from this technology. This allows the information in this Report on FPP to be set in context, in terms of the levels of hazards and waste potentially arising from the two different technologies, to inform the discussion on the appropriate regulatory framework.

2. FUSION OVERVIEW AND HISTORY

The theory that fusion of light nuclei is the process that powers the sun [1] was first proposed in the 1920s, and the first laboratory demonstration of fusion was provided a decade later, with an experiment that showed how helium could be created from the fusion of deuterium. Even at this early stage of fusion development physicists realised that the specific conditions required for fusion to occur were extremely challenging. Since then, various techniques have been explored for achieving these conditions for fusion, and there have been over a hundred experimental plasma devices operated around the world[1], most based on a design known as a tokamak.

Since the 1950's, when the first tokamak (i.e. a magnetic confinement device) was constructed, only two have run in full deuterium-tritium operation (a 50/50 mix required for practical fusion power production), the others being run in non-tritium operations. These two are the Joint European Torus (JET) at Culham in the UK and the Tokamak Fusion Test Reactor (TFTR) at Princeton in the USA.

In the 1970s it became apparent that international collaboration would be key to understanding the complex technical challenges posed to achieve fusion on Earth. This collaboration led to projects such as JET[2], the largest experimental fusion reactor, which has been operating since 1983.

Deuterium-tritium experiments were carried out on JET in the 1990's (processing a few 10s of grams of tritium). A second campaign of experiments is planned in 2021 on JET, with a similar amount of tritium. TFTR also carried out deuterium-tritium experiments in the 1990's, again processing a few 10s of grams of tritium, but is now decommissioned.

The success of JET has paved the way for ITER[3], a much larger and more advanced tokamak. ITER is a multinational collaboration project currently under construction in Cadarache, France [2, 3]. It is currently due to be operational by 2025, and experience gained from ITER and other experimental facilities over the next decade, will be used to develop demonstration fusion power plants. ITER will use quantities of tritium far greater than used in the tokamaks previously built and be more comparable to the magnitudes that will be used in future FPP.

The European DEMO (DEMOnstration power plant)[4] [4, 5] is a proposed FPP that follows on from ITER. DEMO is intended to be comparable in electrical power output to current power plants and to produce its tritium fuel supply. One of the UK's own national programmes to develop a commercial prototype FPP, known as the Spherical Tokamak for Energy Production (STEP)[5], was announced in 2019 and is being developed by UKAEA.

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[1] For more information visit https://nucleus.iaea.org/sites/fusionportal/Pages/FusDIS.aspx
[2] For more information visit https://ccfe.ukaea.uk/research/joint-european-torus/
[3] For more information visit https://www.iter.org/
[4] From herein, 'DEMO' refers to the EU DEMOnstration power plant, unless otherwise stated
[5] For more information visit https://step.ukaea.uk/

3. THE FUSION PROCESS

The fusion of light nuclei (hydrogen) is the reaction that powers the Sun and all other stars. A fusion reactor utilises the fusion reaction between light nuclei, typically two different hydrogen isotopes: tritium and deuterium[6]. In fusion, light nuclei combine to form a heavier nucleus, resulting in the release of energy, which is then used to generate electricity. The fusion process is the opposite of nuclear fission (used in today's nuclear power plants), which releases energy via the splitting of a nucleus to form smaller nuclei (see Annex A).

The fusion of tritium (T) and deuterium (D) yields a helium nucleus and a neutron, which carry the energy from the reaction (see Figure 1). Helium (He), one of the two by-products of fusion, is an inert gas which can be safely released into the environment.

$$\mathbf{D + T \longrightarrow {}^4He + n}$$

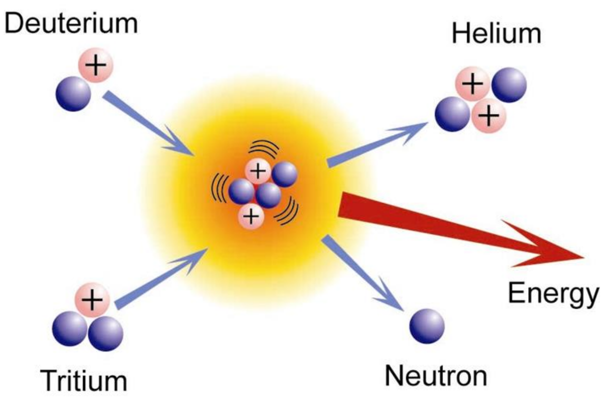

Figure 1: Illustration of deuterium – tritium fusion reaction yielding a helium nucleus and a neutron (Source: ITER)

There is a natural abundance of deuterium from the water in Earth's oceans, which is routinely extracted for industrial applications. However, tritium only exists in very small quantities, with trace amounts being present in the atmosphere. FPP therefore require a supply of tritium. One way to achieve this is via a self-sufficient fuel cycle, whereby the fusion reaction volume is surrounded by a tritium breeder blanket containing lithium (Li). The neutrons from the fusion reaction convert lithium into tritium, which can then be extracted to use as fuel. Lithium is a metallic element that is abundant in seawater in salt form (currently lithium is produced from brine, where it has a larger concentration – large scale extraction of lithium from the lower concentrations in sea water would require industrial development).

To produce energy from fusion on Earth, deuterium and tritium are heated to very high temperatures – around 150 million degrees Celsius – ten times hotter than the core of the sun [1]. Inside the Sun the extremely strong gravitational forces keep the atoms close together. On Earth, where this force is much weaker, fusion only occurs if the particles are moving fast enough to overcome the force of repulsion, which is achieved by elevating the temperature significantly. At the very high temperatures required for fusion, free electrons separate from the atoms and a gas of charged particles known as plasma is formed.

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[6] The nucleus of tritium contains one proton and two neutrons, deuterium contains one proton and one neutron, whereas the nucleus of the common isotope hydrogen-1 contains just one proton.

The complex techniques needed to confine the plasma at the extremely high temperatures required to drive fusion reactions, mean that the development of fusion as a new source of energy is a significant scientific and technological challenge.

Achieving fusion power involves attaining the required density of ions in the plasma, at a high enough temperature. The balance between density and temperature, and their values, affects the choice of fusion reaction and reactor technology.

The fusion reaction with the lowest threshold value uses the deuterium and tritium (D-T) reaction, shown in Figure 1. All other fusion reactions have much higher threshold values than D-T reactions and this considerably increases the technological challenges of designing commercially viable FPP in comparison with D-T FPP.

Using D-D reactions eliminates the challenges of breeding radioactive tritium and it produces lower energy neutrons (although a small amount of tritium is also produced as a by-product of this reaction). However, as the temperature needed for an effective D-D plant is much higher than D-T, it is much more technologically difficult to achieve despite having some advantages over D-T reactions.

The conditions required to achieve fusion are useful in understanding the difference in D-T technologies described in the next section, such as magnetic confinement methods and inertial confinement methods. Magnetic confinement is optimised for longer <u>time</u> duration at the cost of the <u>density</u> of ions in the plasma whereas inertial confinement achieves much higher <u>densities</u> but over much shorter <u>time</u> periods.

4. FUSION REACTOR TECHNOLOGY

There are several different technologies proposed for fusion reactors, with the most prominent design used in experimental machines across the world over the past few decades being the tokamak.

However, two main processes for nuclear fusion have evolved and are currently being developed into designs for fusion power reactors:

- Magnetic confinement – a high temperature light nuclei fuel plasma is contained by a strong magnetic field (e.g. within a tokamak).
- Inertial confinement – a capsule of light nuclei fuel is compressed by laser beams or other means within a chamber to compress and heat the material to ignition.

Further detail on the physics of the different approaches to magnetic and inertial confinement can be found in [6]. Designs involving a combination of these methods are also being developed in what is termed magnetised target fusion.

4.1. General Plant Description

In general, FPP will consist of a vacuum vessel in which the fuel is situated, or injected, and the fusion reactions take place. To generate the tritium fuel for continued operation most designs will incorporate a surrounding tritium breeding blanket. A fuel handling system will also be part of the plant to extract and process the fuel. The vacuum vessel will be housed in a reactor building, typically constructed of concrete, and there will be cooling loops to extract the heat from the fusion reaction.

There will also be conventional power plant, typically consisting of steam generators and electricity producing turbine-generators. Additionally, there will be services and other support buildings on site, such as waste treatment and storage buildings. A typical layout of a magnetic confinement FPP is shown in Figure 2.

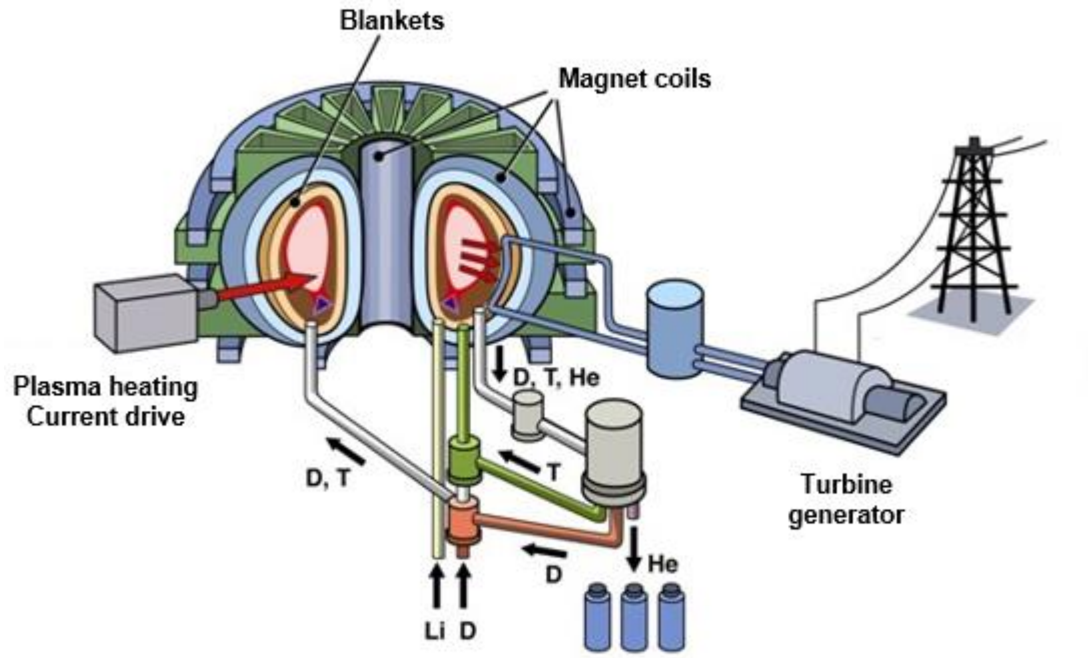

Figure 2: Illustration of a tokamak fusion power plant (components not to scale against each other) (Source: Final Report of the European Power Plant Conceptual Study (PPCS), EDFA(05)-27/4.10)

Vacuum vessel and cryostat

The fusion process occurs within a vacuum vessel of some form in all concepts, and the fuel is also heated and confined (magnetically or inertially or both) within this vessel.

In magnetic confinement devices, the fuel is injected into the vacuum vessel from the fuel handling plant. In inertial confinement and magnetised target devices, fuel may be in the form of sealed capsules, or small confined plasmas in the latter case, transported to the chamber.

In magnetic confinement the fuel can be heated by several mechanisms and is confined by magnetic fields so that the extremely hot plasma does not come into contact with the surrounding materials. In inertial confinement devices, the fuel capsule is compressed using an array of lasers, or other methods, including high velocity projectiles. In magnetised target fusion the fuel is also compressed, but by using magnetic fields in various ways.

For magnetic confinement the plasma is controlled by the magnetic fields, and fusion reactions require a number of key conditions to occur. They are very hard to maintain, so if any key condition is lost, rapid termination of the reaction occurs in a few seconds. In tokamaks, the plasma fuel will be continuously fed into the plasma chamber, whereas in inertial devices fuel is fed into the vacuum vessel in discrete capsules or small plasmas for each cycle of compression. Each cycle is thus independent and again precise conditions are needed for each capsule or plasma to generate energy.

A cryostat is a chamber for ultra-low cooling where the temperature achieved is close to absolute zero (zero degrees Kelvin), typically 4- or 5-degrees Kelvin. The cryostat provides an ultra-cool environment necessary for the superconducting magnets needed for tokamaks.

Tritium breeder blankets

As the tritium fuel is not naturally available in sufficient quantities, a fusion power plant will generally be designed to 'breed' its own fuel [7]. Future FPP concepts commonly use lithium containing materials, deployed in a tritium breeding blanket surrounding the fusion reaction volume, in magnetic confinement this is often referred to as the plasma chamber. The neutrons from fusion react with the lithium in the blanket to produce tritium (plus helium), which will then be extracted for use as fuel in the reactor.

Various solutions to realising this tritium breeding technology are currently being studied, for example, using helium-cooled pebble bed (HCPB) or water-cooled lithium lead (WCLL) tritium breeder blankets [8].

Since the blanket will contain significant amounts of tritium, the minimisation of release will be a primary design objective. The structural materials in the blanket will also contribute to the activated waste, so their activation should be minimised by design (see below).

Fuel cycle plant

The fuel cycle plant handles the injection of fuel (deuterium and tritium) into the reactor, the extraction and recirculation of unfused fuel and storage of tritium fuel. Extraction of tritium from the tritium breeder blankets will also form part of the fuel cycle systems.

Primary / energy extraction circuit

The energy carried by the neutrons from the fusion reaction will be transferred to the materials in the blanket which will have a primary cooling system, which in turn transfers heat to the secondary circuit. The blanket thus combines two functions: conversion of the neutron energy and breeding tritium. In many concepts it also shields the vacuum vessel and magnets.

Activation of the coolant (e.g. by tritium permeation) is a potential hazard to be minimised and managed. The coolant circuits may have to be treated to remove tritium which permeates into them.

Secondary / power generating circuit

In a conventional system, water in the secondary system evaporates in the steam generators heated by the primary system, and the steam drives a turbine coupled to the generator which produces electrical energy. Although it should be noted that other secondary circuit technologies may be used, such as super-heated carbon dioxide.

4.2. Tokamaks – Magnetic Confinement

The tokamak, such as JET [9], is considered here in greater detail as this technology is more developed and has had significant attention within the fusion research community. This section outlines selected confinement concepts as background to the hazard assessment but is not a comprehensive review of magnetic confinement fusion. Other technologies being developed for current designs of fusion reactors and experimental designs that have been built and operated are described in subsequent sections (though most of this section will also apply to stellarators).

One of the main challenges for magnetic confinement fusion is controlling the very high temperature plasma. Scientists in the former Soviet Union overcame this by developing the first successful ring-shaped fusion machine around 1955 which they called a tokamak; an acronym in Russian for toroid-chamber-magnet-coil.

Spherical tokamaks have a configuration of magnets which form a more compact shape than other tokamaks. These take the form of a sphere with a hole through its centre, different from the ring-shaped plasmas of conventional tokamaks, but using the same principles.

The various aspects relating to magnetic confinement technology are outlined below. These focus on a tokamak, but many will be applicable to the different technologies described later in this section.

Plasma confinement – a series of powerful magnets is used to contain and shape the plasma and separate the hot plasma centre from the surrounding materials, since contact stops the fusion process. These magnets require a substantial amount of power to generate the strong magnetic fields required. Superconducting magnets are favoured, introducing the requirement for cryogenic plant, to allow cooling to very low temperatures (around -270ºC). Recent advances have also been made on high temperature superconductors [10], which are being incorporated into designs. Different tokamak geometries (e.g. spherical tokamaks) may allow lower total magnetic energy.

Plasma heating – to achieve the high temperatures and energies required, different techniques have been developed, mainly using beams of high energy neutral atoms and electromagnetic waves in different frequency ranges.

Plasma control – the precise operating conditions mentioned above are attained and sustained with control systems. These systems consist of ‘observers’ (based on measurements) and ‘actuators’ (e.g. heating and fuelling systems, and power supplies for the magnetic field coils) managed by computer systems. There are some control failures that could lead to rapid energy losses and magnetic forces which could in turn damage the plasma facing components. While the structures will be designed to withstand these, there will be active systems to reduce greatly any damage (and thus downtime).

Fuelling – the D-T fuel will probably be in small frozen pellets injected into the plasma at several hundred metres per second [11]. D-T gas will also be injected into the vessel to help manage the power lost naturally from the hot plasma. The two injection systems will determine the tritium throughput, although its relation to the site inventory is highly dependent on the fuel cycle design (some design concepts directly recycle unfused fuel, reducing inventory of the tritium plant).

4.3. Other Fusion Technologies

There are a number of other fusion concepts than the tokamak and some alternative fusion technologies are briefly described here. There are further approaches to fusion under research and development not covered here, as they as not as well advanced. Whilst the summaries focus on the technology of the fusion ‘reactor‘, each would need a means of heat extraction, sustaining fuel cycle (e.g. tritium breeding where tritium is a fuel), and the wider plant. The radiological hazards associated with these is assumed to be similar to those for tokamaks, the main difference expected to be in the quantities of material.

4.3.1. Stellarators - Magnetic Confinement

A stellarator applies the same principles as a tokamak, except with a different shape of vessel and magnetic field coils [12]. These are in the form of a twisted-ring shape of the vacuum chamber and the coils surrounding it to achieve magnetic confinement without the large plasma current needed in the tokamak.

The concept of the stellarator has been around for as long as tokamaks, but it was only with the more recent advances in the computational power of modern computers that modelling of the magnetic field configuration could be carried out to create a design with a good enough magnetic field structure. Their extremely non-uniform shape means that they have different design, construction and maintenance challenges to tokamaks. The hazards are generally similar to tokamaks, although the issues with rapid termination of large plasma currents are avoided.

4.3.2. Laser and Ion Beam Driven - Inertial Confinement

Inertial confinement fusion is achieved by creating a very dense plasma, but for a much shorter time than for the less dense plasmas used in magnetic confinement. The deuterium-tritium fuel is generally in the form of a small capsule placed inside a vessel. The amount of fuel in each capsule is only a few milligrams. A capsule is rapidly compressed by creating shockwaves, which create the heat and fuel density required to initiate the fusion reaction, which is repeated on a pulsed cycle. The hazards beyond those linked with tritium and neutrons relate to the lasers (and the transmission windows into the chamber) and ion beam accelerators.

The most common means of compressing the fuel capsule is by focusing an array of high energy laser beams [12] onto the small target vessel (of the order of one cubic cm). The beams are focused onto the capsule, which causes the capsule to implode, creating the high pressure and temperature required to cause fusion.

The National Ignition Facility (NIF)[7] at the Lawrence Livermore National Laboratory in the USA uses laser based inertial confinement (rather that magnetic confinement). It is the largest experimental inertial confinement fusion device and uses the powerful laser beams to compress and heat the capsule of fuel (deuterium and tritium) to the point of fusion. However, these small capsules consume only micrograms of deuterium and tritium at a time.

4.3.3. Projectile Driven - Inertial Confinement

A different method of compressing the fuel capsule is to use a high velocity projectile, which on impact with the target produces the intense shockwaves required to compress the deuterium-tritium fuel capsule [13]. The implosion created by the shockwaves provide the compression density and high temperatures required to form an inertially confined plasma, again run on a pulsed cycle. The non-tritium/neutron hazards here relate mainly to the mechanism for generating the projectile.

4.3.4. Magnetised Target - Combined Magnetic and Inertial Confinement

Magnetised Target Fusion is based on a combination of concepts taken from magnetic confinement fusion and inertial confinement fusion [12].

In one example, a low-density deuterium-tritium plasma is created and magnetically confined in a separate vessel. This is injected into the reactor vessel, where is it compressed to achieve fusion conditions by fast mechanical compression of a conducting fluid. Other examples achieve compression by a combination of self-pinching of the plasma by a large pulsed current flowing through it and magnetic compression from collapse of an external conducting structure also carrying a large current. The

[7] For more information visit https://lasers.llnl.gov/

hazards beyond tritium and neutrons are mechanical and/or electromagnetic (high current and voltages), lasers and possibly liquid metals.

4.3.5. Field-Reversed Configuration

A Field Reversed Configuration is a magnetic confinement reactor which contains plasma in its own magnetic field by inducing a toroidal electric current inside a cylindrical plasma. Compared to the direction of an externally applied magnetic field, the axial field inside the reactor is reversed by currents in the plasma. An example uses plasma guns to accelerate two plasmas into each other and then heats them with particle beams [14].

The hazards here will relate to the methods to make the high temperature plasma, and in the case of D-T versions, the tritium and neutron-related hazards described for magnetic confinement fusion.

4.3.6. Aneutronic and low neutronicity fusion

The hydrogen (proton) - boron 11 (p-B11) fusion reaction is an example of aneutronic fusion, which is a process whereby the energy created in the fusion reaction is not carried by neutrons, but by charged particles (alpha particles). Since no neutrons are produced directly from this reaction there is little activation of materials, however the reaction does require around ten times the temperature of a deuterium-tritium reaction.

Another reaction, a low neutronicity reaction [8], being studied in a field-reversed configuration is that between deuterium[9] and helium-3 (D-He3) [15], which produces an alpha particle (i.e. He-4 nucleus) and a high energy proton. Some neutrons and tritium are however generated by D-D reactions in the plasma.

Studies into aneutronic and low neutronicity fusion are being pursued at an experimental level and the conditions required to create fusion from these reactions is much more challenging to achieve than for deuterium-tritium reactions.

The hazards for the aneutronic concepts mainly relate to the methods for generating the plasma. For the low neutronicity concepts there will be neutron and probably tritium hazards, but at a lower level than for D-T concepts.

4.3.7. Fusion – Fission Hybrid

This concept is essentially a fission-based system which utilises the neutrons from a fusion reaction to trigger the fission reactions. In one form of this technology the core of the reactor would be a fusion reactor, such as a tokamak, surrounded by a blanket of fissile material. Although the fusion-fission hybrid is an outgrowth of fusion research, it is in essence a fission energy system. Therefore, it is unlikely to be considered under the regulatory framework for pure fusion devices but it is more likely that it would be considered under a nuclear fission regulatory framework.

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[8] A low neutronicity process produces a much lower neutron flux than the D-T reaction but not sufficiently low to be classified as an aneutronic reaction.

[9] The presence of deuterium allows D-D reactions, half of which generate tritium and hence some D-T reactions will occur, depending on the tritium concentration that develops in the time the plasma is contained.

5. MAIN HAZARDS AND ACCIDENT SCENARIOS IN FUSION POWER PLANTS

Developing a robust safety demonstration will be an imperative for the permissioning (or consenting) of future fusion demonstration, prototype, or power plants. Towards this goal, several preliminary safety assessments have been, and are planned to be, performed. A significant step within the EU programme is the currently ongoing preparation of a Generic Site Safety Report for DEMO which will verify that the design will meet all the safety principles and guidelines specifically outlined for DEMO, albeit for a general site. Development of the safety report for DEMO draws on the experience of the licensing of ITER.

It should be noted that some terminology used within safety assessments can have specific definitions varying between country, regulatory body, organisation, etc. This can cause some confusion when reviewing fusion safety study reports and papers, as the use of some terms may not be congruent throughout and/or are different to those more commonly referred to in different industries. Some studies base the terminology on existing regulatory guidance documentation, whilst others have unique fusion-specific definitions. Despite these terminology differences the key considerations for fusion safety and environmental impact in these assessments are broadly similar.

The top-level safety objectives for DEMO, based on international guidelines[10], but which would be generally applicable to all FPP, are [16]:

- 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 (ALARA) [11];
- To ensure that the likelihood of accidents is minimised and that their consequences are low;
- 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.

To achieve the safety objectives, the safety principles of ‘defence in depth’, ‘as low as reasonably achievable’ and ‘passive safety’ underpin the fusion safety approach for DEMO. These safety objectives and principles broadly align with those described in other literature (for example, [17]).

A key safety strategy for an FPP is the confinement of radioactive and hazardous materials, to protect the public and environment. How the confinement strategy is implemented may vary between fusion reactor designs, but in general multiple levels of confinement are likely to be employed and make use of ventilation systems routed through filtration and detritiation systems. Confinement is discussed further in Section 5.5 and more information on the safety measures for an FPP can be found in the following references [17 & 18]. [The principal hazards and safety issues associated with fusion reactors are summarised in the following sections (5 & 6) based on available published literature (see Section 6.1 for a summary of the literature used). Reference is also made to work undertaken for DEMO and ITER, the latter of which has already been the subject of a comprehensive safety assessment as part of its licensing process. However, many of the findings will apply to other FPP using D-T fuel.

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[10] Such as the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP).

[11] ALARA is used here as the safety objectives quoted are for EU DEMO. In the UK specifically, the term ALARP [as low as reasonably practicable] is used, and this is equivalent to the phrase ALARA.

5.1. Radioactive Materials

The amount of radioactive material present in the reactor and associated plant for an FPP broadly determines the level of hazard in an accident scenario. The fusion reaction itself does not directly produce radioactive by-products (the helium nucleus and neutron are not radioactive). Radiation and radioactive material in a fusion power plant comes from two main sources – the tritium used and bred as a fuel, and materials in and around the reactor vacuum vessel that are activated (made radioactive) by the neutrons.

Tritium is a radioactive isotope of hydrogen, which decays by beta emission to form a stable helium atom. Beta particles (electrons) from tritium decay are of low energy and are stopped by about a centimetre of air, or a few micrometres of aluminium. Tritium has a half-life of 12.3 years (i.e. the time taken for half of the tritium atoms to decay to stable helium). As an isotope of hydrogen, it has identical chemical properties to hydrogen, and is therefore highly mobile in biological systems and in the environment. It can be present in the form of gaseous tritium, tritiated water or organically bound tritium.

Tritium is most often found as a gas, which easily diffuses across certain materials, or as tritiated water (HTO). Although the plasma itself will contain only a few tens of grams of injected tritium fuel at any one time, there will be additional tritium in the vacuum vessel of the reactor from (i) tritium created in the tritium breeder blanket, (ii) tritium diffused and trapped in materials surrounding the plasma and (iii) tritium permeated into coolant systems. In addition, a significant proportion of the tritium will be in a tritium handling building (i.e. fuel cycle plant where tritium is recovered from exhaust and waste products, processed for injection and stored in metal hydrides), with smaller amounts in other areas, for example, where maintenance on vacuum vessel internal components is performed and in waste processing facilities.

Neutron activated materials are another key contributor to the radiological inventory. Materials in the vicinity of the plasma become radioactive due to reactions caused by interactions with the neutrons produced from the fusion reactions. Some of the reaction products are radioactive, resulting in activated structural materials (such as in the blanket and other in-vessel components), activated dust (resulting from erosion of the plasma facing components) and activated coolant liquids or gases and any corrosion products in them.

The choice of materials used in the reactor heavily influences the quantities and types of radioactive isotopes that may be produced via neutron activation, which in turn influences the level of hazard resulting from an accident with some activated product release. Processes such as the minimisation of radiologically hazardous material through the optimisation of design decisions is an important element for demonstrating that safety risks are as low as reasonably practicable (ALARP).

5.2. Radioactive Inventory and Source Term

Radioactive inventories will be found in various locations around an FPP. Based on a general description of a future tokamak FPP (Figure 3), the radioactive inventories can be identified in key areas of the plant such as within the vacuum vessel, cooling systems, tritium building / fuelling systems, and the active maintenance facility / radioactive waste building.

The quantitative radioactive inventories will depend on the reactor design, technologies employed, operational scenario, material selection, etc. The later sections of this report focus on accident scenarios related to release of the radiological inventory from the vacuum vessel, as these are the dominant accident scenarios analysed in the literature.

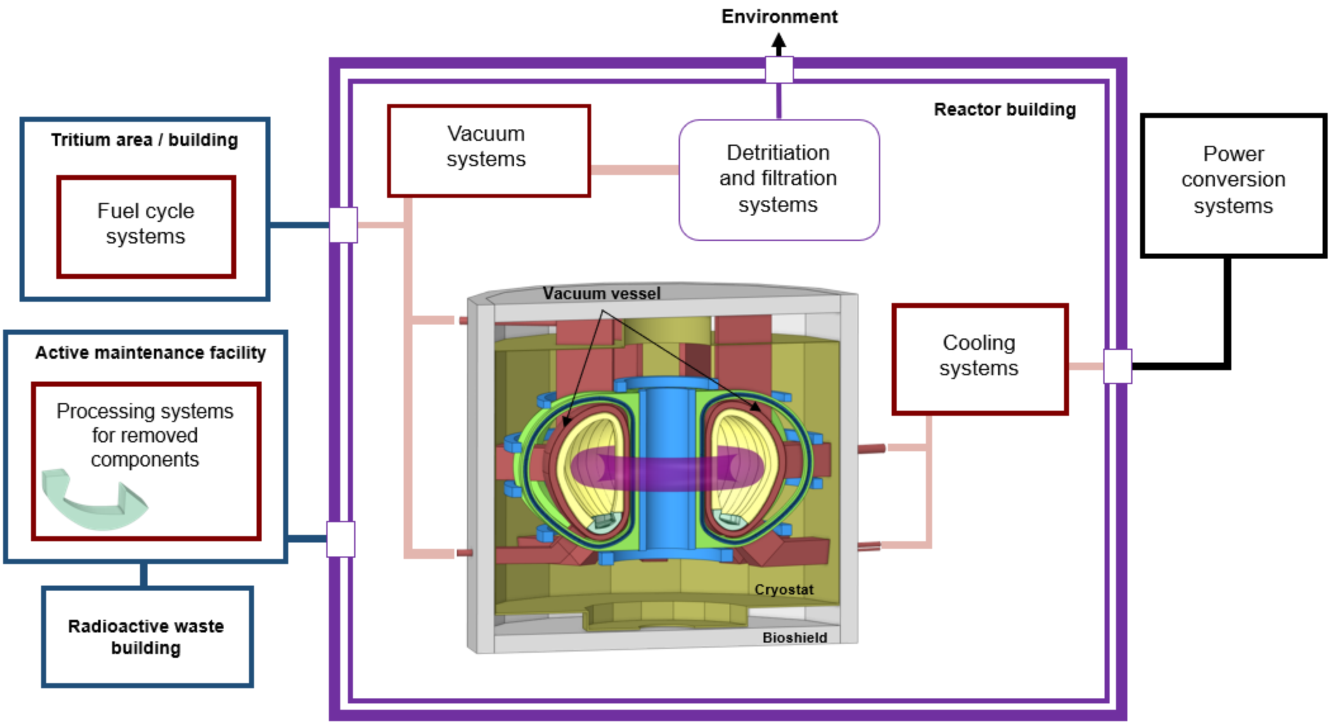

Figure 3: Illustrative representation of a general fusion plant layout (based on a tokamak)

5.2.1. Key Locations of Radiological Inventory

The key areas of plant where the radiological inventory will be located are outlined in the following sub-sections.

Vacuum vessel

Tritium fuel will be continuously injected into the plasma chamber of a fusion reactor, with some fraction of the fuel undergoing fusion reactions. Most of the tritium fuel will remain unfused and be extracted through an exhaust system and recirculated. Some unfused tritium will diffuse into the plasma facing materials and, without intervention, this tritium inventory gradually builds up. Additionally, fusion reactors with tritium breeding blankets will produce tritium within the blanket materials. This bred tritium will be extracted by a tritium extraction system to be used as fuel. Some of the tritium will diffuse into the blanket structural materials and be retained within the blanket.

Activated (i.e. made radioactive) products within the vacuum vessel will build up during the plant operation, due to the continued bombardment of the neutrons from the D-T reactions. Most of the radioactive products will be bound within the solid structures comprising the in-vessel components. Smaller inventories will be found in dust, or corrosion/sputter products circulating in coolants. Dust inventories will increase over the operation of the reactor, produced through several different mechanisms, essentially small pieces of material breaking off from the plasma facing components due to the loads experienced inside the vacuum vessel. The dust will be both radioactive, due to the neutron irradiation, and contaminated with tritium. Additionally, some active products could be mobilised through volatilisation products resulting from oxide-driven mobilisation during some accident scenarios with very large temperature transients.

Minimisation of the vacuum vessel tritium and dust inventories is foreseen through both design and operational planning choices. For example, minimising inventories through material selection to reduce activation, dust production and tritium retention. Vacuum vessel 'cleaning' to remove some of the retained tritium and dust could be included within the maintenance schedule, thereby minimising the inventories within the vacuum vessel. The ITER dust and tritium control strategy is described in [19].

Cooling systems

Tritium from the unfused fuel or bred in the blanket could permeate into the coolant and then be circulated around the cooling system. Additionally, activated products could circulate in the coolant (for example products produced through corrosion). The coolant may also become radioactive due to neutron activation of the coolant.

The tritium and activated products circulating in the coolants are reduced through coolant purification and filtration systems. To reduce the tritium entering the coolant, permeation barriers are also considered and under further development.

Tritium building / Fuelling systems

Tritium will be circulating around the fuelling systems, some moving between the tokamak building and tritium building. Additionally, there could be some tritium in buffer storage, for example an inventory of tritium to cover a delay in the tritium extraction from the tritium breeder blankets. The efficiency of the tritium extraction system will influence the inventory required for the buffer.

The fuel cycle architecture and system efficiencies are developed to minimise inventories, for example use of direct recirculation to minimise isotope separation processes. Tritium extraction systems may be tailored to maximise the recovery of tritium for re-use.

Active maintenance facility / radioactive waste building

Components removed from the reactor vacuum vessel (such as tritium breeder blanket replacement) will be comprised of activated materials and contaminated with tritium. These components will be handled in a facility equipped to work with radioactive materials – here referred to as an 'active maintenance facility'. Similarly, there may be a requirement to store and/or process radioactive materials onsite in a 'radioactive waste building'. Additionally, these facilities/processes will handle the dust and filtration waste extracted from the reactor.

Waste minimisation strategies are constantly being improved to provide designers with choices intended to reduce risks, for example, potential detritiation techniques to minimise the tritium retained within the materials.

5.2.2. Quantitative Radiological Inventories / Source Terms

In an accident scenario some of the radiological inventory could be mobilised. This mobilised quantity is often referred to as the 'source term', or 'mobilised source term'. Depending on the accident scenario and conditions, some of this mobilised source term could be released to the environment – this is often referred to as the 'release source term' or 'environmental source term'.

This report focuses on the vacuum vessel inventories and public dose consequences from the mobilisation of the inventories. Although radiological inventories will be present elsewhere in a FPP, the public dose consequence of a worst-case vacuum vessel accident is indicative of the main plant systems. Additionally, considerably more accident analysis publications are available for the vacuum vessel, although there are some studies of other areas of the plant, for example, the SEAFP study of the fuel cycle [20].

Within the vacuum vessel the key inventories are the tritium and dust, which will build up over the operational life, unless reduced through cleaning techniques. In the studies this report is based upon, the amounts of radioactive material assumed to be mobilised from the vacuum vessel in a worst-case accident is conservatively estimated to be of the order of 1 kg tritium [21, 22] and 10 - 100 kg dust [21, 22]. Whilst a higher value is sometimes quoted of 1000 kg dust inventory in the vacuum vessel for ITER, this is an administrative limit, and assumes a significant number of dust producing plasma disruptions (where there is an instability in the plasma resulting in a rapid loss of energy), as it is an experimental facility [23]. The amount of mobilised material will depend upon several aspects, including the design, technology and material selection, and the accident scenario and conditions. An important focus of much of the research described in many of the references listed in this report is the minimisation of activated materials and the recovery and re-use of tritium to ensure that source terms are minimised.

5.3. Energy Source Terms

The fusion reactor and its supporting systems of an FPP contain several sources of energy. If one or more of the energy sources described below suddenly releases its energy in an uncontrolled manner (i.e. mitigations such as bursting disks fail), damage to confinement barriers could result, leading to release of radioactive and toxic materials into the environment:

- Energy in the plasma – plasma disruption due to loss of plasma control leads to thermal shocks in the first wall, resulting in the production of dust, and the appearance of eddy current and electromagnetic loads in internal components. In some cases, it can result in an electron beam which hits the vacuum vessel wall, resulting in damage potentially causing failure of the cooling system, leading to a loss of coolant accident. Use of a plasma control system is an important mechanism for minimising plasma disruptions and their impact;
- Magnetic energy – the loss of superconductivity in the coils (e.g. due to a leak in the cooling) could lead to the appearance of eddy currents and electromagnetic loads to components or the vacuum vessel. Occurrence of an electric arc could cause local melting and potentially loss of integrity of the vacuum vessel or supporting systems. The ITER design incorporates systems to safely remove magnetic energy in a fault scenario [24], and similar systems could be deployed in other devices;
- Thermal energy – components in the reactor will be at elevated temperatures, so a leak from the primary cooling system into the vacuum vessel causes vaporisation due to these hot components, resulting in a rise in pressure. In addition, the radioactive decay of materials in the plasma facing components and tritium breeder blanket produces heat that must be removed by the cooling systems;
- Explosive energy – from a hydrogen or dust explosion that could occur in the event of ingress of air into the vacuum vessel, or by the oxidation of dust by water in a loss of coolant accident (if water is used as a coolant);
- Cryogenic energy – a leak of liquid helium or nitrogen can cause a sudden vaporisation of the cryogen, with large volumetric expansion and pressure rise in the area with potential loss of integrity of affected confinement barriers.

5.4. Industrial Hazards

A fusion power plant is an industrial site which has other potential industrial hazards. These include: high magnetic fields, lasers, high-power microwaves, high voltages, and hazardous materials such as beryllium and lithium. Some of these are common in other industrial processes and plant. For example, high powered lasers are used for cutting metal and other materials. Plasmas are used for welding purposes, and high electro-magnetic fields (EMF) are used in equipment such as magnetic resonance imaging (medical diagnostic magnetic resonance imaging scanners for example), and induction melting. EMFs are also by-products of all electrical motors and electricity generation and transmission. Many of these industrial activities create significant hazards to workers and members of the public, but they are tolerated by individuals and society because safety controls are put in place to reduce the risks from these activities to workers and the public to a level that is ALARP.

5.5. Confinement of Radiological and Hazardous Inventories

Confinement of the inventory of radioactive and other hazardous material is the key strategy to prevent mobilisation of the materials and to limit any releases to protect the public and environment. The implementation of inventory confinement will vary depending on the type of fusion reactor and some of the design specifics. However, in general, multiple levels of confinement will be employed (e.g. vacuum vessel, reactor building) and make use of a ventilation system with exhaust from ventilation zones routed through filtration and detritiation systems. The confinement strategy would apply to radioactive and hazardous inventories throughout an FPP, including the tokamak building and its ancillary systems, all parts of the fuel cycle, and active maintenance facility.

Although the exact definitions and systems will vary, a general description of the confinement barriers for the reactor/tokamak building is illustrated in Figure 4, where the vacuum vessel (and vacuum extensions and some related systems) and cryostat form primary confinement, and the tokamak building as ultimate confinement. The structures credited in the safety analyses as part of the confinement systems may differ between fusion reactor designs, for example some fusion confinement approaches may not credit the cryostat as part of the confinement. The confinement systems are not single structural barriers, as shown in Figure 4, but will include a diverse set of systems including one or more static (e.g. vacuum vessel, building) and/or dynamic (e.g. ventilation) systems. An example description is given in [17] (p52 - 54) showing the different confinement systems, including those permanently operating and those in stand-by.

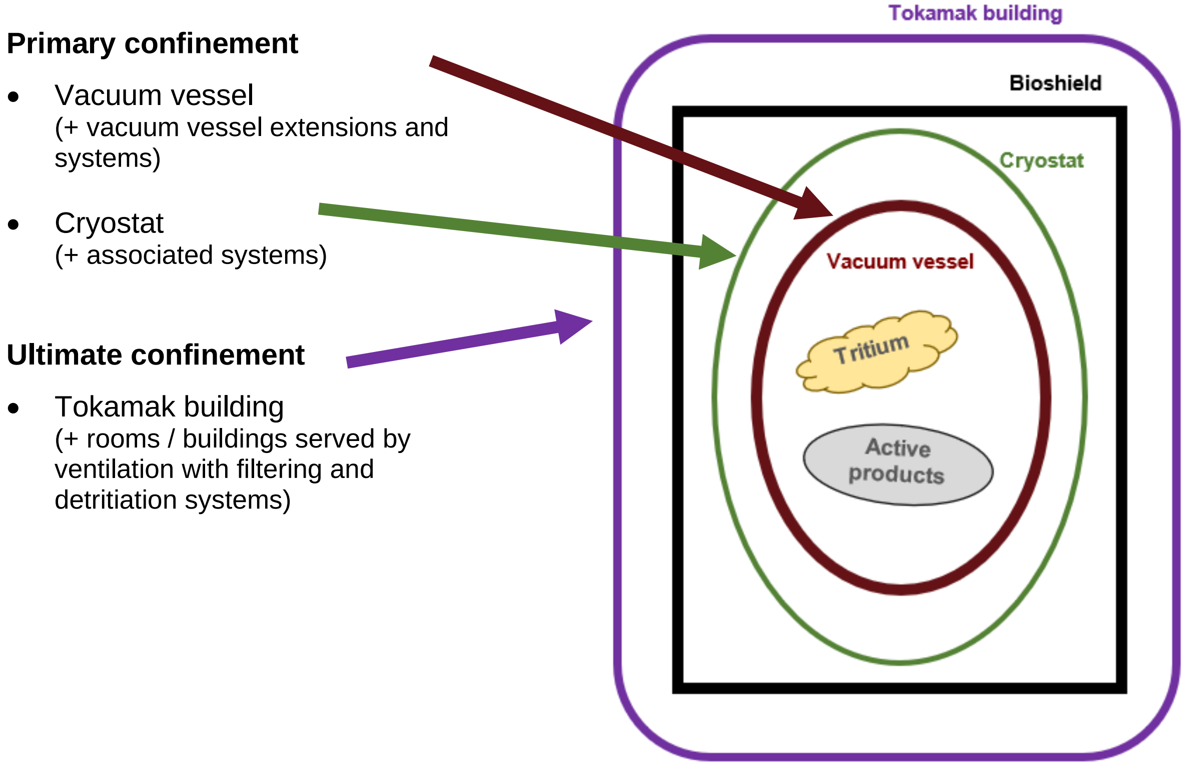

Figure 4: Illustration of multiple layers of protection (based on a tokamak). In this example the vacuum vessel/cryostat forms the primary confinement, and the tokamak building is the ultimate confinement. The bioshield is a thick concrete structure providing protection to personnel from radiation.

DEMO confinement example

The strategy for confinement of radioactive material in DEMO is that any significant inventory of radioactive material is protected by two confinement systems. The main purpose of the primary confinement system is to prevent the mobilisation and spread of radioactive material within the plant, thereby protecting personnel from exposure. The ultimate confinement system prevents or strongly limits any release of radioactive material to the environment if the primary confinement system has failed, thereby protecting plant personnel and the public from exposure. Several barriers may be used within a single confinement system, consisting of passive (static) and active (dynamic) systems to provide redundancy through diversity and increased reliability, consistent with the level of radioactive hazard being protected. The barriers that comprise the confinement systems will be assigned a safety important class based upon the definition used by the IAEA in its document on fusion safety classification [25] and adopted by the EUROfusion DEMO programme. Only systems, structures or components that have an assigned safety important class are credited as performing a safety function in safety analysis. A detailed look at the proposed confinement strategy for DEMO is given in [18].

5.6. Fusion Accident Scenarios

Releases of radioactive and toxic materials in accident scenarios are prevented by multiple barriers. The various types of accidents postulated in a fusion power plant are discussed below and are mainly taken from the SEAFP report [21].

Loss of Coolant Accidents

A Loss of Coolant Accident (LOCA) could involve water, gases (e.g. helium) or liquid metal (depending on the plant design) and can initiate different fault sequences. Loss of coolant into the vacuum vessel will terminate the plasma (if it has not already terminated through a plasma disruption causing the LOCA), resulting in the release of thermal energy and electromagnetic loading of the vacuum vessel. Depending on the type of coolant, a leak could also result in a chemical reaction, e.g. a reaction between water and beryllium or lithium-lead eutectic leading to hydrogen production.

Any water or cryogens that leak into the vacuum vessel will evaporate rapidly and pressurise the vessel. This event could also mobilise a significant amount of the radioactive inventory present (tritium, dusts and activated corrosion products). The design must therefore safely relieve any over-pressure, whilst ensuring that vent paths are carefully designed to limit the spread of radiological material. This is demonstrated in SEAFP [21] showing for significant accidents extremely low levels of radioactivity release.

In current experimental fusion reactors there is very little residual heat to be removed following plasma operation. For a fusion power reactor within a FPP, with much longer plasma operating times and greater fusion power, the residual heat to be removed will be significantly higher. However, this depends on the materials used, and the lower activation materials planned to be used for future reactors should reduce the potential for high levels of residual heat, although the levels would remain much higher than current experimental facilities. The decay heat removal (cooling) system will be a key system for future FPP, both during normal operation and, if required, during in-vessel component replacement and transfer.

Loss of Vacuum Accidents

A Loss of Vacuum Accident (LOVA) occurs when there is an ingress of gas or fluid into the vacuum vessel, for example this could occur due to failure of one of the vessel penetrations or as a consequence of a LOCA. The event could lead to a disruption of the plasma, leading to a rapid termination of the fusion reaction. Similar to the LOCA, the increasing pressure within the vacuum vessel, due to the LOVA, could lead to mobilisation of the radioactive material from the vacuum vessel, and ultimately potential release of radioactive material to the environment.

Explosion

Deuterium and tritium are isotopes of hydrogen, which can form explosive mixtures with air. In the case of loss of coolant (if water), there is the possibility of hydrogen generation from the reaction between steam and the hot metals in the vacuum vessel (e.g. beryllium or tungsten). Within the SEAFP studies this would be a few kilograms of hydrogen isotopes in the worst-case of loss of coolant accident from more than one loop, which is expected to be a very low probability event [21]. Nonetheless, such events will have to be given careful consideration during the design and safety assessment of larger scale fusion reactors.

Within the fuel cycle system, there is also possibility of hydrogen explosion due to the inventories of hydrogen isotopes, which can form explosive mixtures with air. Minimisation of releasable inventories within the fuel cycle systems will be important. Within SEAFP, the quantity of combustible inventories of all hydrogen isotopes is calculated to be a small part (less than 50 g) of the total inventory, but a breach of the primary containment in the fuel cycle system could result in the release of tritium and a resultant radiological hazard [21].

Loss of Plasma Control

Plasma disruptions can lead to physical phenomena that, if the control and mitigation schemes fail, can challenge the integrity of the vacuum vessel (for example, due to electromagnetic loading of the vacuum vessel components), that in their most severe form could potentially lead to a breach of confinement such as the vacuum vessel. Disruptions and other plasma instabilities also have the potential to accelerate production of dust from erosion of the first wall and damage the vacuum vessel cooling system, leading to coolant ingress (i.e. LOCA).

Fire

The risk from fire must be considered and systems put in place to limit its initiation and spread within the facility, as this could result in the release of radioactive material and damage to safety related systems. Within a fusion plant, the hazard from a fire associated with the tritium fuel cycle plant needs consideration. However, SEAFP reports the amount of tritium vulnerable to release is less than for other tokamak related accident scenarios, so the potential radiological hazard is bounded by those in the SEAFP analysis [21].

The ITER facility has implemented a defence in depth approach to protect against fire hazards [26]. Fire prevention is based around the principles of minimising combustible inventories and limiting ignition sources. A comprehensive fire detection and suppression system is provided; the design of the system is location specific, depending on the nature of the fire and equipment involved. If a fire did occur, its propagation between areas is prevented by the area boundaries, which are 'fire rated' so that they can withstand the maximum fire that could occur within. The ITER analysis therefore shows how the application of appropriate fire protection measures can adequately manage the fire risks within a FPP.

External events

External events that must be considered can be divided into two categories: man-made and natural. Man-made hazards include aircraft crashes, explosions from nearby plants and loss of offsite power. Naturally occurring events include phenomena such as extreme weather (wind, precipitation, flooding, and temperature extremes) and seismic events.

For FPP design, the geographical location and local surroundings will determine the range of external hazards to be considered. The consequences of such events must be assessed carefully as coincident failures may occur, e.g. failure of confinement systems and off-site power may both occur due to a seismic event.

6. ACCIDENT ANALYSIS FOR FUSION POWER PLANTS

Fusion 'power plant' specific safety studies performed within the fusion community is in a scoping and/or iterative phase. For example, the conceptual design studies for DEMO include safety studies to guide the design process by assessing the safety and environmental impact of the different design options. A similar process is ongoing for other demonstration, prototype and power plant concepts throughout the world. As discussed in Section 5, the specific approach varies amongst the studies due in part to variations in the assumptions regarding regulatory requirements. A regulator may (or may not) have specific requirements regarding the approach and directly influence the design requirements. The safety analyses methods, type of analysis required, the identification of postulated 'events' and categorisation of events or accidents can vary throughout the available literature. Additionally, the potential accident sequences also vary, as do some of the assumptions regarding the components credited with a safety function, which in turn has a bearing on the accident sequence.

For these reasons it is difficult to give a definitive analysis of the accident scenarios for a FPP without a) inferring some prior decisions on the safety approach and, b) a comprehensive safety assessment requiring a more detailed design than is currently available. A good indication of the key hazards and 'worst-case' type accidents, in terms of off-site releases, can be sought through the safety analyses performed to date, with some key EU studies summarised in the remainder of this section. The various studies take different approaches, accident scenarios and use different tools, so cannot be directly compared (especially between fusion concepts) but they provide a useful view of the situation and there is some consensus on the impact of the worst overall cases.

This report presents the accident scenarios that result in the highest predicted consequences (i.e. 'worst-case') from the different postulated events, along with the expected probability of occurrence per annum of these events. These worst-case accident scenarios generally result from multiple failures, and hence have very low probabilities of occurrence. Further work will be required as FPP design progresses to consider the independence of each failure event in the overall sequence of events to have confidence in the claims on low sequence probabilities. And further work to ensure that there are no single internal or external events at a higher probability per annum that could lead to the same consequences. As with any complex plant there will be numerous other potential accident scenarios with lower consequences, that may have higher probabilities of occurrence, so an analysis of all accident scenarios would need to be undertaken to get a full picture of the overall risk of a future FPP.

This report focuses on the radiological release consequence of accidents relating to the tokamak building, which is assumed to be bounding for other buildings on an FPP site. While it is noted that the fuel handling systems and building could potentially include a significant inventory of tritium and pose a fire/explosion risk (see Section 5.6), based on the amount of vulnerable tritium for release and the combination of highest energy sources and the most challenging operating conditions, the tokamak is assumed to bound the accident consequences to the public [20, 21].

As stated above the accident analysis referenced in this section was undertaken on conceptual FPP designs focussing on worst-case scenarios for each accident type. Many of the conceptual safety analyses referenced in this section used assumptions to give a pessimistic outcome on accident probabilities and radiological consequences. Such assumptions do not fully account for the uncertainties that are inevitable with the design of large and complex plant such as an FPP. To cater for this, at the end of this section where two accidents are shown on a risk matrix diagram, each accident is not represented by a single pessimistic point on the diagram but as a circle of uncertainty with a range of outcomes.

As FPP plant designs develop from conceptual to detailed designs these uncertainties will be better defined without needing to use pessimistic assumptions. These uncertainties do not undermine one of the important key messages of this report, that the hazards from FPP are well understood. Having a good understanding of the hazards from a technology does not eliminate uncertainty, what such knowledge does provide is greater confidence in the range of calculated results. Although each accident shown in this report has a large range of uncertainty, the more detailed safety analysis that will be undertaken as FPP designs progresses from conceptual to a much more detailed level will show that the risks will be within the regions shown in the diagram (Figure 5) and are unlikely to have worse outcomes.

6.1. Brief Summary of Literature

The main sources of information for this report, summarised below, are published documents based on assessment of early conceptual designs of future FPP. The studies, dating back through the past few decades, still have relevance today as they constitute significant efforts in fusion safety research for conceptual FPP, as opposed to experimental facilities, and form the basis for ongoing developments.

A series of studies were undertaken within the European fusion programme, called the Safety and Environmental Assessment of Fusion Power (SEAFP). The first of these studies led to the publication of the SEAFP-1 report in 1995 [21], with the conclusions of the report endorsed by the independent 1996 Fusion Evaluation Board. A series of follow-up studies (SEAL, SEAFP-2 and SEAFP-99) [27, 28, 29] carried forward the further work identified in the earlier study. An integrated summary report for the series was published in 2001 [30].

Following on from SEAFP, the European Power Plant Conceptual Study (PPCS) [22] focused on five power plant models, illustrative of a wider spectrum of FPP design concepts, exploiting the inherent safety features of fusion by appropriate design and material choice. A publication from Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) provides a review of the safety concept for fusion reactors up to 2016 [17].

The European scientific programme ‘EUROfusion’ builds upon the previous work developing concepts for a future demonstration fusion power plant ‘DEMO’. Currently, no single complete conceptual design exists for DEMO and several countries are involved in efforts to design a DEMO or DEMO-like facility. Within the EU, DEMO is an intermediate goal on the roadmap to the commercialisation of fusion, forming a key step between the international fusion facility ‘ITER’ and a commercial FPP [4]. The EUROfusion development of DEMO puts significant emphasis on the safety and environmental considerations, ensuring this is at the heart of the design activities [5], [31]. Although DEMO will not be a commercial FPP, it will demonstrate key aspects for the commercialisation of fusion, including the generation of electricity and operation with a closed fuel cycle. Therefore, the safety studies performed within the EUROfusion programme can provide valuable data to inform on the foreseen safety and environmental aspects for future FPP.

Within the US, a series of FPP studies have been undertaken by the ARIES community (Advanced Reactor Innovation and Evaluation Study) with some initial scoping safety assessments performed. These studies included tokamaks, such as [32], [33], and a stellarator [34]. Additionally, some early safety assessment was performed for the inertial confinement fusion reactor HYLIFE developed by researchers at the Lawrence Livermore National Laboratory [35, 36] and for the laser driven inertial fusion reactor design SOMBRERO [37].

Additionally, there are publications reporting doses to the public from releases which are not specific to a particular design or accident scenario. For example, Idaho National Laboratory produced a report [38] tabulating dose per unit activity for isotopes of interest for several fusion accident release scenarios, based on a future FPP not specific to one design. A paper from Lukacs 2021 [39] provides dose per gram values for a reference case assuming a release of tritium (as HTO) and dust (tungsten) at ground level, over a one-hour release time with conservative weather conditions.

There is also much to be learnt from the licensing of the ITER experimental device as the licence application represents the largest study of fusion safety performed to date [26], [40].

6.2. Safety and Environmental Assessment of Fusion Power (SEAFP / SEAFP2)

The initial Safety and Environmental Assessment of Fusion Power (SEAFP) study [21] based its analysis on the early conceptual design of two variants of large tokamak power plants, with thermal ratings greater than 3 GW. Some additional design variations were also considered within the safety study, including the use of beryllium or tungsten for a plasma facing armour material. The accident examples presented in this report are related to 'Model 2', water-cooled with a tungsten armour, as these were bounding; further information on the models considered can be found in "Section 4" of [21]. The SEAFP study concentrated on identifying potential hazards to the public and ranking the event sequences by importance (to guide the analysis effort). The systematic safety studies were performed based on the method of HAZOP (HAZard and OPerability) assessment. Later updates to the work included use of a systematic 'top-down' accident identification methodology using master logic diagram and functional failure mode and effect analysis (FFMEA) approaches.

Variants of the loss of coolant accident (LOCA) were considered to have the most potential for radioactive releases from an internal initiating event. Two LOCA accident scenario examples from the SEAFP study [21] are summarised here, where Example 1 considers a challenge to the primary confinement, and Example 2 adds additional levels of failure.

The starting point of both examples is a LOCA caused by rupture of a large cooling pipe in the primary heat transfer system. The ingress of coolant into the plasma chamber causes the plasma to terminate and an increase in pressure within the vacuum vessel.

Example 1 considers a major in-vessel LOCA with significant radioactive mobilisation. Some of the mobilised radioactive source term from the vacuum expansion volume is vented through the stack to relieve pressure, via filters and detritiation systems. The released tritium was assumed to be the more hazardous tritiated water (HTO) form of tritium release, and the activated products made up of tungsten dust, and coolant and structure aerosol.

Example 2 considers that in addition to the sequence of Example 1, complete mobilisation of the source term to the expansion volume and additional failures causing a blockage in the path to the stack, so that the volume inside the ultimate confinement would be slightly pressurised for about 2-3 days, resulting in ground level releases of tritium and dust. Again, the released tritium was assumed to be HTO, and the activated products made up of tungsten dust, and coolant and structure aerosol. In the SEAFP report, it is expected that its overall probability occurrence per annum would be less than 10^{-7} (1 in 10 million), although it is acknowledged that such claims of very low probabilities will require rigorous evidence-based safety justification.

The dose consequence to a member of the public, taken to be at a standard 1 km from the source, who receives a dose through exposure and inhalation over a 7-day period is given in Table 1 for the SEAFP accident examples [21].

Table 1: Dose consequence to a member of the public at 1 km from two SEAFP example accidents

Accident	Mobilisable source term	Dose
SEAFP Example 1	1 kg tritium (assumed HTO) ~ 6 kg active products	~ 1 μSv
SEAFP Example 2	1 kg tritium (assumed HTO) ~ 6 kg active products	~ 1 mSv

As part of the follow-up SEAFP-2 study [28], bounding accident temperature transient analyses were carried out for three plant models on the assumption of a hypothetical accident in which there is a prolonged total loss of all active cooling. The models had similar basic features to those in the original SEAFP report with the in-vessel features of the three models differing only by tritium breeder blanket concept. Therefore, the models mainly differ by tritium breeding material, coolant and structural materials selected.

Calculations were performed on the consequences of a hypothetical accident assuming a mobilisable source term of 1 kg of tritium, as HTO, and 10 kg of dust , with all mobilised material transported to the ultimate confinement volume, with subsequent leakage through this confinement barrier. Calculations were performed for this hypothetical accident in detail only for plant models 2 and 3 as "it was clear from scoping calculations that the results for plant Model 1 would be lower" [28]. The resulting temperature rise in Model 3 was such that additional activation products were assumed to be released from the structural materials through volatilisation based on "very conservative estimations" [28]. The dose consequence is shown in Table 2 [28].

Table 2: Dose consequences to a member of the public at 1 km distance

Plant model	Mobilised source terms		Dose
SEAFP-2 Model 2	**Tritium**	1 kg	1.6 mSv
	Tungsten dust	10 kg	
SEAFP-2 Model 3*	**Tritium**	1 kg	2.6 mSv
	Tungsten dust	10 kg	

* In addition to the mobilised tritium and dust, Model 3 also included mobilised activation products from very conservative volatilisation estimations – due to larger temperature rise than Model 2.

6.3. European Power Plant Conceptual Study (PPCS)

Within the European Power Plant Conceptual Study (PPCS), analysis was performed to verify that the new designs and plant parameters [41] did not lead to outcomes that would invalidate the earlier conclusions of SEAFP. PPCS focused on five FPP concepts, ranging from near-term plasma physics and materials (Model A and Model B), to more advanced concepts (Model C and Model D), with an additional near-term concept later added (Model AB). From a safety point of view, the key difference amongst the models was the tritium breeder blanket concepts. Safety assessment focused on the concepts of models A and B, with water cooled lithium lead (WCLL) and helium cooled pebble bed (HCPB) blanket design respectively. Some assessment of the other models was also performed, with further information in [22].

Bounding accident analyses were performed within the PPCS, to establish the bounding consequence of an internally initiated accident in which a very low probability of occurrence per annum event sequence is postulated. Such accident sequences are assumed to be the result of a total loss of active cooling, no active safety system operating and no operator intervention for a prolonged period. The resulting temperature rise is assumed to mobilise tritium and activation products for potential leakage from the plant through successive confinement barriers using conservative assumptions [22]. The mobilised activation products of Model B were assumed to also include volatilisation products as a result of the temperature transients. The fraction of the source term that escapes into the environment is then transported, according to atmospheric dispersion under conservative weather assumptions, to an individual, assumed to be 1 km from the source, who receives a dose through exposure and inhalation over a 7-day period.

Further information on the event sequence, assumptions and detail can be found in Annex 10 of the "Final Report of the European Fusion Power Plant Conceptual Study" [22]. A summary of the mobilisable source term and consequential dose is given in Table 3 for the bounding accident.

Table 3: PPCS bounding accident dose estimations to a member of the public at 1 km

Plant model	Mobilised source terms		Dose
Model A	**Tritium (HTO)**	1 kg	1 mSv
	Dust (steel + tungsten)	10 kg	
Model B*	**Tritium (HT)**	1 kg	18 mSv
	Dust (steel + tungsten)	10 kg	

* In addition to the mobilised tritium and dust, Model B also included mobilised activation products from very conservative volatilisation estimations – due to larger temperature rise than Model A.

6.4. DEMO Reactor Safety and Environment Studies

Within the EUROfusion programme of safety studies performed for the DEMO concepts, a set of reference accident sequences are defined to evaluate the plant response. Functional failure mode and effect analysis (FFMEA) was used as the analytical tool to identify the postulated initiating events – better suited to the design level of DEMO that is not yet mature enough for component level assessment. The set of reference events can be found in [42], [43]. The loss of coolant accident (LOCA) has been classified among the most representative events in terms of challenging conditions for plant safety. The description and analysis of an in-vessel LOCA for DEMO is provided in [44] and [45] for two different concepts. Accident analyses due to external hazards are currently under consideration [43].

6.5. Inventory-Based Worst-Case Estimations

The accidents discussed so far in Section 6 are based on internally generated events. As discussed in Section 5.6 there may be externally initiated events. For the worst-case of such events, SEAFP reports that there may be certain energetic external events (such as large magnitude earthquake) that directly breach all confinement barriers, describing the risk from such events as a "residual risk" [12]. Since there is "no definite upper bound to the energy of such external events, the total failure of confinement cannot be excluded", although this is expected to be a very rare event [21].

The SEAFP report provides an estimate for the public radiological consequence of such an event using an inventory-based approach. With this approach it was assumed that all tritium in the vacuum vessel (1 kg as HTO) [21] was released directly to the environment and the dose estimated to a member of the public located at 1 km distance over a 7-day period was 450 mSv.

At the time of SEAFP the consideration for dust inventory in the inventory-based approach was to "be revisited when data from a next generation fusion device become available" [21]. Using this same approach and taking an indicative dose per gram from [21, 26, 38, 39, 46] of ~ 0.3 mSv/g for tritium and ~ 0.002 mSv/g for tungsten dust, even if the released tritium content doubled to 2 kg, and the tungsten dust increased by factor of 10 to 100 kg, the worst-case dose would be below 1000 mSv (1 Sv).

[12] A residual risk is defined as a level of risk for which it can be demonstrated that the cost of reducing it further is grossly disproportionate to any safety benefit gained.

The total site inventory of tritium across plant such as in the reactor, fuel cycle building, active maintenance facility and radioactive waste building may be a few kg. Whilst a large external event may affect several areas of the plant, the radiological inventory will be in different forms, which will be mobilised to different extents in such an accident scenario. Detailed analyses would need to be carried out on a more realistic basis as part of future safety assessments for such scenarios.

In the references, and this report, using this inventory-based approach to estimating the radiological consequence of an external event that causes failure of all confinement functions and significant radiological release is referred to as 'hypothetical' at this stage. This approach is heavily dependent on the inventory estimations which will depend upon several aspects, including the design, technology and material selection. Furthermore, the entire tritium inventory would not be instantly released directly to the environment in a real accident scenario. Tritium release quantification will form part of future safety assessments, for accident scenarios that are identified.

6.6. Accident Consequences from Other Fusion Reactor Types

This report has focused on the tokamak approach to fusion and most of the safety reports reviewed use this technology and the D-T reaction. However, it is expected that the findings from this report will be applicable to fusion power plant based on different technologies, such as inertial confinement and magnetised target fusion devices using D-T fuel. Although the detailed specifics of many of the accident sequences will be different, the worst-case radiological consequences are expected to be of the same order as those reported for similar accident scenarios. Examples of accident analysis for other reactor types are summarised below.

Stellarator

Accident analyses [34] were carried out for a compact stellarator FPP concept design; the US ARIES-CS stellarator, a 1000 MW (electric) power plant, with a helium cooling and a liquid lithium lead tritium breeding blanket. The accident analyses included loss of coolant flow, ex-vessel loss of coolant and in-vessel loss of coolant with primary confinement bypass. Although no public dose values are given for these accidents, it is stated that no site evacuation plan is needed.

A further scenario was considered involving a loss of coolant accident with bypass of the first confinement boundary (vacuum vessel) and damage to the second confinement boundary (cryostat), such that there is a leak pathway to the environment for tritium and activated dust, with a conservative dose for a member of the public at 1 km calculated at 9.1 mSv [34].

Inertial Fusion Device

HYLIFE-II accident scenario studies [35, 36] report the consequence of an accident involving failure of the fusion chamber and breach of confinement as small, as there is no large source of energy to disperse the radioactive materials, i.e. tritium and activation products. Only a very small fraction of radioactive material would be mobilised and available for release, resulting in an offsite dose less than 0.2 mSv. If the maximum vulnerable tritium inventory in the target factory and tritium handling systems (at a maximum value of 2.5 kg) were released, the quoted offsite dose would be less than 250 mSv.

Accident analysis for SOMBRERO (solid moving [tritium] breeder reactor), a conceptual design of a 1000 MW_e laser-driven inertial fusion power plant, considered a simultaneous loss of flow and loss of vacuum accident produced by failure of the confinement building and consequent air ingress. During the accident, graphite structures suffer oxidation with air, resulting in mobilisation of the carbon structures, including the tritium trapped in it and the xenon gas that fills the reactor. The calculated off-site dose results in 56 mSv, dominated by the activation products of the xenon gas (i.e. iodine and caesium) [37].

6.7. Summary of Indicative Accidents and Consequences

There have been several studies of potential accident scenarios based on evolving conceptual designs of future FPP. One of the main safety features in preventing or limiting the consequence to the public from potential accident scenarios is confinement of the radioactive inventories: tritium and activated materials.

Loss of coolant accidents in the vacuum vessel are taken as representative of the worst-case accident scenarios of the main plant systems, based on the references used (see Section 6.1). The reason for this is that the combination of highest energy sources and the most challenging operating conditions are found in and around the vacuum vessel. However, as part of any future safety demonstration, this would need to be further assessed with a more mature FPP design, including the fuel cycle systems.

Reviewing analyses on the consequence of breaches of successive layers of confinement (for example, the vacuum vessel then the tokamak building) gives indicative conservative doses to the public close to the site[13]. These indicative dose consequences are taken from the analyses described in the above sections and accident frequencies from SEAFP [21]; no credit was taken for actions to mitigate any dose uptake. Definitions of likelihoods used in this section are taken from the Radiation (Emergency and Public Information) Regulations 2019 (REPPIR 2019) [47]. For context, guidance published by Public Health England compares doses of ionising radiation from different sources [48].

Breach of primary confinement (Accident Scenario 1 – Acc1) – a breach of the vacuum vessel confinement but with the tokamak building confinement and its filtration / detritiation systems intact. The worst-case estimated offsite dose to a member of the public is of the order of a few micro-Sieverts (Impact – Limited). This level of radioactive dose is similar to the dose received by a passenger or member of the crew on a single transatlantic flight. Whilst there is no data on the likelihood of occurrence (as this would require a detailed design and analysis), the typical failure rate of a component such as a vacuum vessel or pipework, that has been designed to recognised standards, would be expected to be of the order of from 1 in 2,000 to 1 in 20,000 over a five-year period (Likelihood – Very Low).

Malfunction of ultimate confinement (Accident Scenario 2 – Acc2) – a breach of the vacuum vessel, with additional malfunction of the ventilation system, such that there is leakage through the tokamak building confinement. The worst-case estimated offsite dose to a member of the public is of the order of a few milli-Sieverts (Impact - Minor to low Moderate). A few milli-Sieverts is a typical average annual radiation dose to a member of the UK public. This scenario requires multiple independent failures, so it's likelihood of occurrence is expected to be much less than for Accident Scenario 1 and below 1 in 200,000 over a five-year period (Likelihood – Events not considered in the design).

An extremely unlikely event involving a loss of all confinement (Hypothetical – Hypo) – the inventory based worst-case public dose consequences, 1 km from the source, were estimated to be below 1 Sievert (see Section 6.5), where it was hypothetically assumed that the entire inventory of tritium and large percentage of the radioactive dust was released into the environment due to catastrophic failure of all confinement systems (such as a large magnitude earthquake). (Impact – Significant). A dose of around a Sievert will produce effects including nausea and a reduction in white blood cell count. The likelihood of this extremely unlikely event is presented as much less than 1 in 2,000,000 over a five-year period (Likelihood – Events not considered in the design).

To put these accident scenarios in perspective, Accident Scenario 1 and 2 (Acc1 & Acc2) can be placed on the REPPIR 2019 risk framework matrix, illustrated in Figure 5. The range of risk indicated by the circles represents the uncertainties that remain in the technology and the fact that the existing safety

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[13] Assumed to be 1 km from the source. The distance from the source will affect the dose rates with further analysis on these effects given in [39].

analysis is performed on conceptual designs rather than detailed designs. The position of the worst-case hypothetical scenario (Hypo) is also indicated as below the minimum likelihood used on the REPPIR matrix, however emergency planning would be based on identified and assessed accident scenarios for individual designs. It is important to distinguish a safety risk from a safety hazard. A safety hazard is the potential for harm whereas a risk includes the likelihood that the harm from the hazard is realised.

For comparison, Figure 5 shows the lower and upper emergency reference levels for sheltering are 3 - 30 mSv (i.e. sheltering would not be considered necessary below this range of values), and for evacuation are 30 - 300 mSv averted dose (i.e. the dose that could be received if no actions to shelter/evacuate were taken). It is important to note that for an accident such as the hypothetical accident covered above, early action would be taken to evacuate the members of public most likely to receive a significant radiation dose so the actual dose that they would receive would be much lower. In the accident studies quoted in this report no credit was taken for actions to mitigate any dose uptake.

Note the phrase 'Events not considered in the design' is from taken REPPIR 2019 and covers a wide range of radiation facilities in the UK where indeed no further work needs to be done for accidents in this frequency range for many facilities. The design safety analyses for future FPP will cover the full spectrum of accident scenarios, including those in this very low likelihood but potentially moderate to significant radiological impact range, to identify the provision of protective systems to ensure that risk to workers and the public are as low as reasonably practicable.

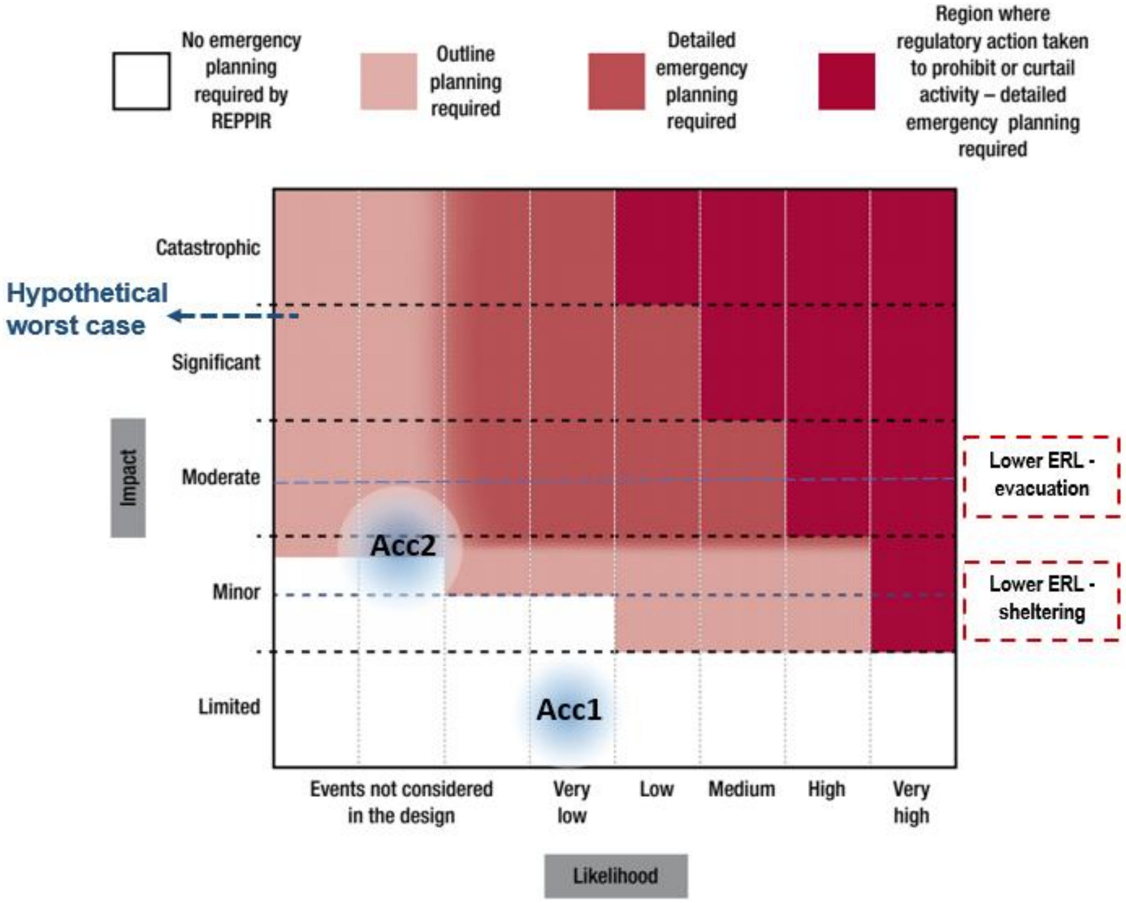

Figure 5: Indicative fusion accident scenarios superimposed on the REPPIR risk matrix, with the Emergency Reference Levels (ERLs) related to the dose averted by sheltering or evacuation. Whether sheltering or evacuation is needed would be addressed in the emergency plan, considering the transient nature of the release [47]. (Source of original risk matrix: The Radiation (Emergency Preparedness and Public Information Regulations 2019, Approved Code of Practice).

7. NORMAL OPERATION RADIOLOGICAL DOSES AND ENVIRONMENTAL DISCHARGES

The previous sections focused on accident conditions but another important aspect of the operation of facilities containing radioactive material is normal operational doses and environmental discharges. This is not as well covered in international publications on safety as the accident analysis. A particular issue to consider in fusion plant is the activation of materials by the neutrons that are produced from the fusion reaction. This process induces radioactivity in the exposed materials. Careful selection of materials is required to minimise the radioactivity of the activated materials.

Research scale reactors operate intermittently, permitting maintenance activities to be undertaken during shut-down periods, with personnel access only being permitted once radiation levels have been allowed to decay to safe levels. For FPP, key components such as blankets and service pipework will require maintenance. As maintenance worker doses should be minimised, and in some cases the dose rate may prohibit personnel access, maintenance and other activities will most likely be performed by remote operations. It is therefore key that provision for such tasks is built into the plant design. Continuing development of technologies for remote maintenance (e.g. manipulator arms and robotic removal and replacement of large components in the vacuum vessel) are vital to ensuring that maintenance tasks can be undertaken safely and reliably.

The SEAFP report [21] provides an indication of future environmental radiological discharges for gaseous and liquid discharges, as shown in Table 4. These are dominated by tritium, and the dose to a member of the public from this level of discharges is less than a micro-Sv per annum [21].

Table 4: Fusion power plant typical annual environmental discharges

	Fusion Power Plant (TBq/year)
Gaseous	255
Liquid	23

8. MAIN RADIOACTIVE WASTE ARISINGS FROM FUSION POWER PLANTS

An important objective for the fusion industry in its development of FPP is to reduce all forms of waste. Radioactive waste is generally considered to be the most problematic form of waste from FPP due to the potential hazard it poses to people and the environment. The radiological hazards from radioactive waste are the same as those from the operational phase covered previously in that if the waste escapes from storage to the environment then it could give rise to elevated radiation doses to members of the public and cause environmental damage. However, the scenarios for release can be very different. A key part of the development of FPP is the optimisation of the use of materials and selection of processes to minimise the creation of all radioactive waste but particularly those radioactive substances with long half-lives.

In the UK radioactive waste currently has three main categories:

- **High-level waste (HLW)** is radioactive waste where the temperature may rise significantly because of their radioactivity. The design of waste storage or disposal facilities has to take this into consideration;
- **Intermediate-level waste (ILW)** exceeds the upper boundaries for low level waste but does not generate a significant amount of heat;

- **Low-level waste (LLW)** contains relatively low levels of radioactivity, not exceeding 4 giga-becquerel (GBq) per tonne of alpha activity, or 12 GBq per tonne of beta/gamma activity.

There is also an overarching higher activity waste (HAW) category, this categorisation is for all radioactive waste not suitable for disposal in the UK's Low Level Waste Repository (LLWR). HAW currently consists of all HLW, all ILW and some LLW. In the UK all HAW must be disposed of in a Geological Disposal Facility (GDF). Note that a radioactive substance does not become radioactive waste until its owner wants to send it for disposal.

Throughout the lifecycle of a FPP, radioactive solid, liquid and gaseous wastes will be generated. During operation of a FPP, a large flux of high energy neutrons will be generated from within the plasma due to deuterium-tritium fusion reactions. These neutrons will cause significant 'activation' of materials in and around the reactor vacuum vessel, giving rise to radioactive components and structures.

The other main radioactive waste source is the tritium fuel and its permeation into components or systems connected to the vacuum vessel. As a result, tritium contamination is likely to be significant in the fuel cycle systems, any off-gas systems, cooling systems, and potentially parts of the downstream power generating systems.

Some quantities of very long-lived radioisotopes are predicted in a FPP through the activation of structural metallic materials, often caused by activation of trace impurities in those materials at typical concentrations in the few parts per million range. The current analysis shows that no high level radioactive waste (HLW) will be produced in fusion power plant [49].

Initial concept estimates for early designs of the DEMO reactor have shown that thousands of tonnes of ILW could be generated within its 20-year lifecycle [49]. Components and structures outside of the vacuum vessel including concrete structures are expected to be disposable either as LLW or not radioactive when operation ceases. However, in-vessel components and some parts of the vacuum vessel could take several hundred years or more to become LLW. The vacuum vessel of the DEMO reactor is presently assumed to be stainless steel while structural components inside the vessel are assumed to be constructed mainly of EUROFER, a low activation steel developed specifically for fusion. Owing to short-lived radioisotopes in activated steels, such as those of iron, cobalt and manganese, the ILW inventory is predicted to at least halve after 100 years [49]. However, without special intervention impurities in alloys of steel can result in long-lived radioisotopes of nickel, niobium and carbon which could mean some portion of the present DEMO reactor concept will be ILW for more than a thousand years; initial indications are that this waste will not meet the strict limits necessary to allow disposal in near-surface or at-surface repositories in the UK. It should be noted that different nations have different radioactive waste classifications, which affect the quantity of waste assigned to each category quite significantly. The UK rules are not the least or most restrictive. There is also a trade between mass of waste and activation level per unit mass depending on the operational approach and waste processing options.

Significant quantities of LLW, typically tens of thousands of tonnes of LLW, could also be generated after shutdown of a future fusion power plant. However, good progress is being made on the development of low activation materials meaning that the current evaluation of quantities of both LLW and ILW are likely to be pessimistic and that there is the potential for reductions in both through the use lower activation materials.

These predictions for an early, not fully waste-optimised, DEMO design show that radioactive waste modelling of this kind will be instrumental in guiding future design development. Fusion reactor design is intended to be continuously informed by rigorous waste modelling to prevent the creation of significant quantities of waste in line with the waste hierarchy[14]. For example, a more detailed analysis of the DEMO predictions than presented above reveals that the threshold for inclusion as LLW (versus waste that can be disposed of or reused by conventional means) is only just exceeded in some situations [50]. In this way, waste prospects for evolving DEMO concepts, and future fusion reactor designs, can be rapidly assessed with guidance provided on the appropriate selection of materials and the careful control of problematic impurities.

In addition, radioactive waste treatment technologies to extract and concentrate problematic long-lived radionuclides are being explored to minimise final waste volumes so far as is reasonably practicable. This will also apply to the management of tritium; despite its relatively short half-life, even minor tritium contamination could have significant waste implications, especially since many storage repositories have imposed strict tritium limits. Therefore, the development of appropriate tritium permeation barriers and waste detritiation technologies will be crucial. It should be noted that the DEMO estimates presented above do not consider any contribution from tritium contamination.

The decommissioning strategy for an FPP can take advantage of the techniques developed for fission decommissioning. Certain ‘operational’ wastes, such as components frequently replaced inside the reactor, waste resulting from accumulation of activated corrosion/erosion products, or spent effluent treatment media, may require prompt packaging and ‘interim’ storage prior to final disposal in a GDF or other suitable repository. However, there is also likely to be significant volumes of activated ILW waste which will require a period of decay storage to reduce the level of activity prior to disposal; this could necessitate a ‘Care & Maintenance’ phase during which waste remains in-situ prior to final reactor dismantling and clearance.

An important principle for the development of FPP is reducing all waste by reusing material in other FPP and this includes re-using radioactive material. For example, some components will have a significant amount of their radioactivity from absorbing tritium. Detritiation of these components is but one of several techniques under development to reduce radioactive waste. The fusion industry has and will continue to be a major investor in remote handling and robotic equipment and will use this expertise to recover and re-use important materials and through this process it will reduce the amount of waste (radioactive and non-radioactive) produced by FPP.

Other FPP technologies based on the D-T fusion reaction will have components surrounding the plasma that will be subject to high energy neutrons and exposure to tritium permeation as in tokamaks. This means that while their technical details will be different from a tokamak design such as DEMO, there will be the creation of radioactivity in their structures, systems and components. It means that as with tokamaks the principles of material and process optimisation to ensure the generation of low quantities of radioactive structures and components together with re-use of material will help to minimise the creation of radioactive waste at these FPP.

[14] The waste hierarchy sets out the priority order for managing waste materials based on their environmental impact: waste prevention, waste minimisation, re-use of materials, recycling and disposal. See https://ukinventory.nda.gov.uk/about-radioactive-waste/what-is-the-waste-hierarchy/

9. CONCLUDING REMARKS

There are a significant number of experimental or research fusion plasma devices operating around the world. Several nations and international collaborations now have projects to design and build demonstration or prototype fusion power reactors, on the path to commercialisation of fusion energy technology. In addition to major government funded projects in the UK and internationally, there are also many private companies working on concepts for future fusion reactors.

Of the existing operational fusion projects in the world, only JET is currently capable of operating with a significant amount of tritium in its fuel. The main radiological hazards from fusion reactors will be the tritium and the activated products created during operations. ITER is a large-scale experimental device that follows on from JET, and in comparison ITER will use larger amounts of tritium. The next stage of prototype and demonstration fusion reactor projects such as STEP from UKAEA and the EU DEMO project will be much more representative of future commercial fusion power reactors.

The level of hazard (e.g. calculated public dose from postulated accident scenarios) from demonstration or prototype fusion power reactors will be higher than for the current experimental facilities, due to the larger source terms of radioactive material involved (i.e. tritium and activation products). Whilst this will scale with attributes of the plant, such as plasma volume and fusion power, other factors will also act to reduce the source term.

There are several different fusion technologies being developed, including magnetic confinement (tokamak, spherical tokamak, stellarator), inertial confinement (laser or projectile driven), or using a combination of both in magnetised target fusion. The majority will use deuterium-tritium fuel and have generally similar hazard profiles. Other technologies will explore aneutronic fusion, and will have a much lower radiological hazard, although these are at a much earlier level of development.

Most of the published safety and waste studies on the concept designs for future fusion power plant are based on tokamak technology, and this report has focused largely on them. They provide indicative inventories of tritium and activated products and are similar to, or bound, results from studies of other technologies.

It is recognised that safety and waste analyses are strongly dependent on the type of fusion technology, design of plant and the materials used. The assessment of accident scenarios is dependent on the maximum inventory of radioactive material that could be released, but the worst-case estimates used seek to identify the upper bounds of impacts. The quantities and activities of radioactive waste will also be influenced by choices made at the design stage, and the waste management strategies developed. Future analyses for safety and waste as the concept designs evolve will have reduced uncertainty on the level of hazards and radiological waste.

This report has provided information based on a number of published studies, which have assessed early conceptual designs of future fusion power plant. From these, the following aspects of fusion safety and waste have been presented:

- an outline of the hazards related to a fusion power plant, focused on the radiological hazards. One of the main safety management strategies to limit any radiological releases from accident scenarios is the design of multiple layers of confinement;

- a summary of the main published safety analyses for conceptual designs of fusion power plant. Illustrative doses to members of the public for postulated accident scenarios from on-site events, where successive layers of confinement are breached, show that the potential for harm is low. In addition, a “hypothetical” worst-case dose from an external event (e.g. a large magnitude earthquake) is estimated, based on the direct release to the environment, of the entire mobilisable tritium inventory of the vacuum vessel;

- an indication of the level of environmental radioactive discharges from conceptual designs of fusion power plant, as reported in published studies, showing that the resulting potential does to a member of the public is very low;

- an assertion from the published assessments for conceptual designs, that fusion power plant will not generate a high level radioactive legacy waste burden;

- an initial estimate from published analyses of radioactive waste for conceptual designs of developmental fusion power plant, showing that low level waste and intermediate level waste will require disposal.

This Technology Report has provided a description of the current understanding of the safety hazards, potential doses from accident scenarios, radioactive waste and environmental discharges of future fusion power plant. It provides supporting information to the UK Government's consultation on fusion regulation, in the Green Paper "Towards Fusion Energy: The UK Government's proposal for a regulatory framework for fusion energy". Future studies will continue to inform the development of the regulatory framework for fusion, as designs for fusion power plant progress from the concept stage. The approach to fusion regulation needs to remain targeted and proportionate to the level of hazard, protecting people and the environment whilst supporting innovation.

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ANNEX A: PROCESS, SAFETY AND RADIOACTIVE WASTE ASPECTS OF NUCLEAR FISSION POWER PLANT

A.1 Introduction

The role of this annex is to briefly outline the processes, radiological hazards, and radioactive waste from nuclear power plant (NPP). This provides context for the processes, hazards and waste from fusion power plant (FPP) that are the subject of the main body of this report.

A.2 The Fission Process

Natural uranium primarily consists of isotopes of U238 (~99.3%) and U235 (~0.70%), but it is only the latter isotope that fissions by absorbing thermal neutrons to sustain a chain reaction and is known as a fissile isotope[15]. U238 is a fertile isotope, because when it absorbs a neutron it can produce fissile isotopes such as plutonium-239 (Pu239).

The key attribute in the nuclear fission process is the release of extra neutrons in addition to the two fission products. These neutrons are used in other subsequent fissions within a reactor thus creating a nuclear fission chain reaction (see Figure A1). These nuclear fission chain reactions produce 'fast neutrons', and to be capable of sustaining a nuclear chain reaction in most NPP designs, they need to be slowed down to 'thermal neutrons'. This slowing of the neutrons is achieved by a moderator, a material with low atomic number such as hydrogen in water or carbon, the latter usually in the form of graphite.

A controlled nuclear chain reaction is used to generate power at a NPP. If uncontrolled, it can lead to a runaway chain reaction, which is self-propagating. Figure A1 is a simplified illustration of a nuclear fission chain reaction. It shows a neutron (the small particle on the left-hand side) being absorbed by the large fissile nucleus which then splits into two smaller nuclei and additional neutrons the latter of which are used to sustain the chain reaction. The two smaller nuclei created by the fission process are the fission products, which are radioactive.

A chain reaction is critical when the number of neutrons in each generation is constant. A chain reaction is sub-critical when it produces fewer neutrons for each succeeding generation and super-critical when it produces more neutrons for each succeeding generation. An NPP reactor operating at constant power is critical, a reactor shutting down by reducing power is sub-critical and a reactor increasing its power is super-critical. An important parameter is known as 'reactivity'. The reactivity of a reactor is zero when the reactor is critical, it is negative when a reactor is sub-critical and positive when the reactor is super-critical. Excessive positive reactivity can be a significant safety challenge in fission reactors, this was one of the technical root causes of the Chernobyl accident in the Ukraine in 1986 [A1].

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[15] Fissile isotopes such as U235 can support a self-sustaining nuclear chain reaction with neutrons of all energies, but predominantly with slow (thermal) neutrons.

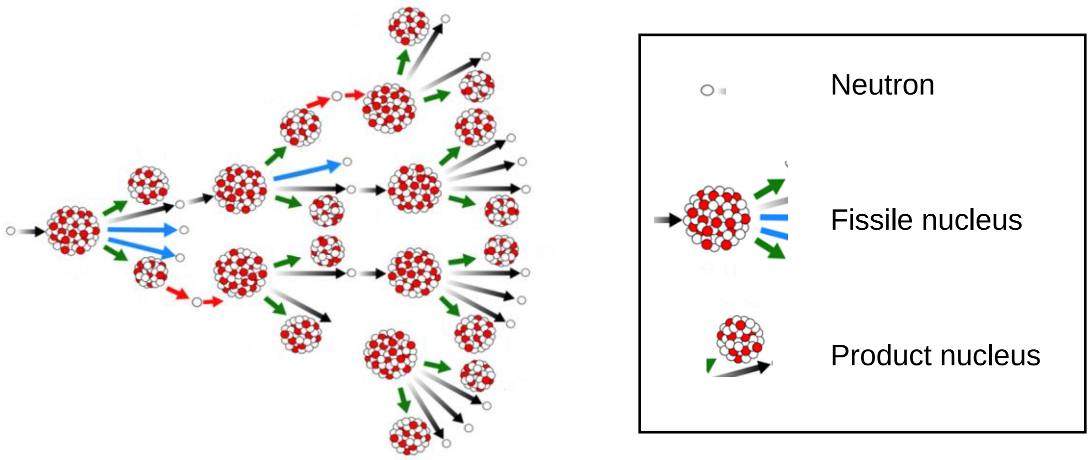

Figure A1: Fission chain reaction (Source: Article in The Conversation, A. Spyrou & W. Mittig, MSU)

A.3 Fission Reactor Technology

There are large number of NPPs operating around the world using different reactor technologies. In general, an NPP consist of a fission reactor core containing the fissile material fuel inside a vessel, cooling loops to extract the heat from the nuclear chain reaction, steam generators and turbogenerators producing electricity. For most NPP the reactor core and reactor vessel are housed in a containment building. Typically, this will be an internal concrete vessel covered by a metallic leak tight skin, and an exterior concrete vessel.

The fuel in most NPP reactors is in the form of fuel assemblies consisting of an array of fuel rods containing ceramic pellets. The ceramic pellets of fuel are sealed in a metallic cladding tube, forming the fuel rod. The metallic cladding of the fuel rod is the first confinement barrier preventing contamination of the primary coolant from the fuel's fission products. Arrays of fuel rods are brought together in a structure known as a fuel assembly and it is in this form that fuel is loaded into the reactor.

A.4 Main Hazards and Accident Scenarios in a [16]Fission Power Reactor

The most significant system failures at NPP have the potential to result in damage to the cladding of the fuel rods in the fuel assemblies and in the worst-case of reactor core meltdown scenarios it will lead to a significant release of radioactive material from the reactor core. If the reactor vessel or primary cooling circuit, which form the second confinement barrier of a typical NPP, is also damaged, then this results in a release of that radioactive material into the containment building. While intact the containment building provides the third confinement barrier preventing the release of radioactive material to the surrounding environment.

A.4.1 Radioactive Materials

In NPP, the fission fragments created by the fission of U235 are radioactive. Additionally, within the NPP fuel, other radioactive isotopes are created by the absorption of neutrons, for example, into U238 to create radioactive transuranic actinides such as plutonium-239 (Pu239) and other actinides in the series. Some of these actinides have very long half-lives measuring in the tens of thousands to hundreds of thousands of years. Also, for NPP to produce the necessary levels of power, they need to have very large quantities of fuel within the reactor core usually measured in the thousands of kilograms;

[16] The descriptions in this section are based on light water reactors as most reactors in operation or under construction internationally use this technology.

for example, Hinkley Point C, currently under construction, will have 127,000kg of fuel[17] [A2] when operational.

For the structures within and surrounding the reactor of an NPP the neutrons produced in fission do make these structures radioactive through the neutron activation process. This means that for NPP many of these structures and components will become either low level radioactive waste (LLW) or intermediate level radioactive waste (ILW) when no longer required at the end of their operational life.

The radioactive materials that can be released in an accident scenario at an NPP when the fuel rod cladding is damaged, are the transuranic actinides created by the non-fission activation of uranium and fission products such as noble gases, strontium, iodine, and caesium. Actinides are alpha emitters with long half-lives, and fission products are mainly beta-gamma emitters with half-lives from a few hours to 30 years.

A.4.2 Fission Accident Scenarios

The fission reactions in the NPP reactor core create energy, which if uncontrolled could cause damage to confinement barriers and lead to a release of radioactive materials into the environment. During a severe accident, extreme temperatures within the reactor could result in chemical species being released which may lead to explosive reactions (e.g. steam or hydrogen). Such explosive reactions could further damage the reactor structures, systems, and components, potentially accelerating the spread of radioactive contamination.

The criticality of a core needs to be controlled, such that the chain reaction can be stopped and the reactor returned to a safe state (i.e. core is sub-critical). This is generally done by two independent neutron absorption systems, such as, for example in light water reactors, a system of control rods and by increasing the concentration of boron in the coolant by injecting boronated water.

The reactor core needs to be cooled to remove the heat produced by fission reactions in the fuel. This ensures that the fuel cladding is not damaged through overheating. Even after the reactor is shutdown residual heat removal is required, as the products of fission ‘decay’ to more stable isotopes they release energy. Removal of this decay and stored heat by the primary coolant is supported by the secondary side coolant by feeding the steam generators with water and removing the steam produced. If there is no residual heat removal, then core damage can occur. Most NPP have at least one single failure tolerant emergency core cooling system independent of the normal primary and secondary cooling systems.

In the case of a fault sequence threatening the safety of the core, the radioactive material needs to be contained by maintaining the integrity of the fuel cladding, the reactor coolant pressure boundary (reactor vessel and pipework) and the containment building.

The most severe types of accidents, leading to a reactor core meltdown, can only occur due to multiple failures of the reactor coolant system and emergency cooling systems, sustained over many hours. Such accidents are considered to be highly unlikely, due to the multiple layers of independent defence mechanisms provided in the design of NPP. It is also highly unlikely that a core melt scenario would occur where there is a high-pressure failure of the reactor vessel and subsequent breach of the containment, leading to a large early release of radioactive material. A possible but highly unlikely accident sequence for a light water reactor is discussed below.

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[17] An equivalent large D-T fuelled FPP would have a few tens of grams of radioactive fuel and up to 1 kg of unburnt tritium fuel absorbed in its reactor vacuum vessel at any one time. This ~1 kg of reactor fuel inventory is more than 10,000 times lower than for an equivalent NPP and is the key reason why the maximum worst-case outcome, as a release of radioactivity to the environment, from an accident, causing major damage to all confinement barriers at an FPP (see Hypo accident in Section 6) is much lower than an equivalent accident at an NPP.

Unmitigated, a gradual loss of cooling water accident would uncover the reactor core, which would then begin to heat up. If the accident continued the fuel rod cladding would melt and fail, if there was sufficient decay or residual heat, resulting in the release of radioactive fission products into the reactor coolant system and the production of hydrogen. Eventually (after many hours) the structural integrity of the core would degrade, and the reactor core would melt to form a molten pool of fuel at the bottom of the reactor pressure vessel. Dependent on the reactor design the molten core is either retained within the reactor pressure vessel (known as in-vessel retention) or where in-vessel retention is not possible the molten core will melt through the reactor pressure vessel which would then flow into a core catcher, which is then passively cooled to remove the decay heat and to prevent degradation of the containment building foundations.

A severe accident[18] at a modern nuclear power plant resulting in a low pressure core melt sequence either contained within the reactor pressure vessel or in a core catcher, would only require protective countermeasures for the public that are very limited both in area and in time, with no need for emergency evacuation beyond the immediate vicinity of the plant, limited sheltering duration for the public close to the site boundary, no permanent relocation and no long-term restrictions on the consumption of foodstuffs.

A.5 Normal Operation Radiological Doses and Environmental Discharges

Most workers at NPP receive very little radiation dose above that of the general population. However, there are some radiation workers, particularly maintenance staff and some plant operators, who due to the nature of their work have the potential to receive additional radiation doses. All radiation doses to workers are closely controlled and monitored.

There is some radioactivity discharged to the environment during operation of an NPP. For illustrative purposes, an EDF report [A3] shows that the annual discharges from Hinkley Point B in 2016 and 2017 were considerably below the authorised discharge limits (e.g. the limit for tritium is 650 TBq/year).

A.6 Main Radioactive Waste Arisings from a Fission Power Reactor

Throughout the lifecycle of a NPP and on its decommissioning at the end-of-life, radioactive solid, liquid, and gaseous wastes are generated.

High level waste (HLW) from a nuclear power plant comes from the reprocessing of spent fuel that has been removed from the reactor, which contains transuranic elements from non-fission neutron absorption and fission products. For a typical NPP about 30 tonnes of spent fuel is created in a year.

Spent fuel produces a significant amount of decay heat, so spent fuel requires cooling in ponds for up to ten years following its removal from the reactor core. The spent fuel is then transferred to, for example, dry casks (steel canisters shielded by concrete) for up to 140 years for interim storage [A4], when the radioactivity has decayed to about 1/1000th of its initial activity. But there is still a level of prolonged radioactivity, and it takes more than 100,000 years for the radioactivity to decay to that of natural ore, so deep geological repositories are required for long-term safety and environmental protection when storing spent fuel and HLW from fuel reprocessing. However, it is worth noting that whilst HLW accounts for most of the radioactivity in waste produced by a typical NPP it only makes up a small fraction of the total waste volume.

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[18] Typical estimates from all accident contributors shows a probability of less than 1 in a million over a year for a modern NPP.

Intermediate level waste (ILW) is generated as a by-product of reprocessing spent fuel from a fission reactor and from activated material surrounding the reactor. During the reprocessing of fuel, significant quantities of contaminated fuel cladding are removed and disposed of in the process of exposing the spent fuel. While ILW can also contain long-lived radionuclides, it differs from HLW in that it generates a limited amount of decay heat.

Significant volumes of ILW also result from the activation of components and structures in and around the fission reactor caused by neutron bombardment. This consists of activated metals from reactor vessels, heat exchangers and, in the case of Magnox and Advanced Gas Reactors, irradiated graphite from core moderators. It is these types of components that make up the bulk of ILW remaining on a site once the spent fuel has been removed.

Low level waste (LLW) consists largely of items that have become contaminated with radioactive material during operations and maintenance, such as protective clothing and filters, and items that have become radioactive from neutron activation, such as equipment and tools. It contains only small amounts of radioactivity, most short lived. LLW is typically compacted (soft waste) and stored in shallow land burial sites.

During final site clearance, the reactor buildings are planned to be dismantled along with any interim storage facilities. It is envisaged that large quantities of LLW, mainly comprising concrete, rubble and contaminated soil, will require packaging and disposal during this phase in suitable near surface LLW repositories. For example, the Magnox reactor site Hinkley Point A is estimated to generate more than 5,000 m^3 of ILW and 40,000m^3 of LLW from decommissioning [A5]. For the Sizewell B site the values are around 1000 m^3 of ILW and 20,000 m^3 LLW [A5]. For illustrative purposes, Figure A2 gives an approximate comparison of the volumes estimated for the different types of radioactive wastes discussed above from a first-generation Magnox reactor.

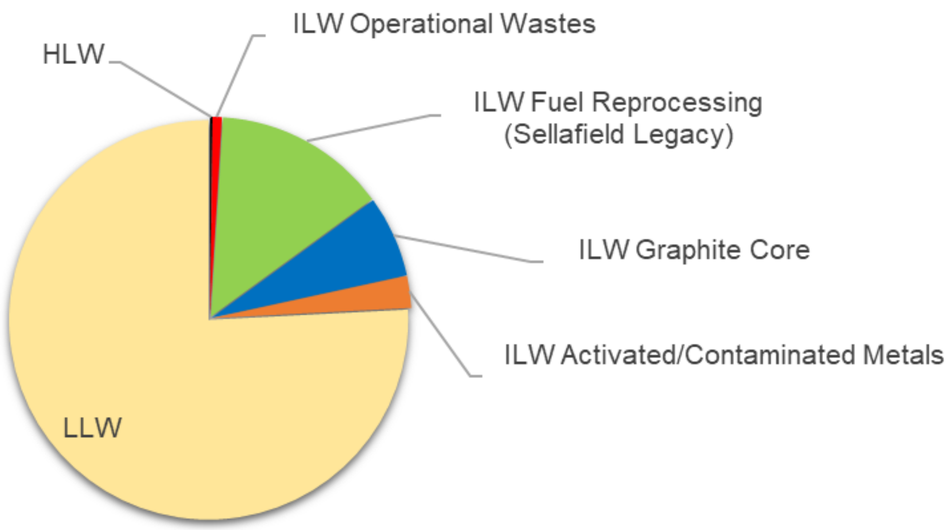

Figure A2: Magnox reactor radioactive waste volumes (Source data from: UK Radioactive Waste Inventory 2019 – Magnox Hinkley Point A, Waste stream data sheets)

The most activated parts of an NPP in the UK will be kept under a care and maintenance regime for several decades before the final stage of decommissioning of the site to green field conditions. This period of care and maintenance will allow most of the material to decay to LLW or lower. However, some ILW will remain and under the current rules as it is classified as Higher Activity Waste (HAW) it will require storing in the UK's future Geological Disposal Facility (GDF).

Some future NPP based on what is known as Gen IV designs may come into commercial operation within the next twenty years [A6]. Some of these NPP are being designed to have a reduced radioactive waste burden. The reason for this is that their designs will be optimised to minimise the build-up of the very long-lived transuranic elements. If this is achieved, then spent fuel from these NPP will pose a much lower radioactive waste burden for future generations and one that will not exist for many millennia as with most current NPP in operation and under construction.

ANNEX A - REFERENCES

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