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The Development of a Regulatory Framework for the Licensing of a Fusion Power Plant

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Abstract

Determining an appropriate regulatory framework for fusion power plants (FPPs) is a key step in the development of fusion power. Decisions made in the near future regarding fusion regulation will have a significant impact on the deployment of FPPs in years to come, not just in the UK but internationally too. Whilst many countries are yet to decide on the best approach to regulating fusion, there are some countries (France, Canada, etc.) that have already decided FPPs will be regulated under the same framework as nuclear fission power plants (NPPs). The widespread adoption of an NPP approach could lead to unnecessarily onerous regulatory practices that are not justified by the hazard potential of FPPs. This thesis aims to draw on the current knowledge of FPPs and current regulatory regimes, both national and international, to determine an appropriate regulatory framework for FPPs. The key safety issues relating to FPPs are explored, including the current approach to fusion safety and methods of accident identification. The results of a sensitivity analysis to gauge the hazard of potential of FPPs are reported. When considering what is an appropriate regulatory system, it is important to remember that regulation should be based on the hazard potential (the unmitigated risk to the public) and not the mitigated risk. On the basis of FPP hazard potential and associated safety, security and safeguards analysis, four main FPP regulatory options for the UK are mapped out and analysed against criteria that are necessary to deliver an effective and efficient regulatory system. The most appropriate option, based upon a proportionate regulatory approach, suggests that a nuclear licensing framework should be adopted. This thesis then develops this proportionate licensing approach and explores how it can fit within the UK legal system.

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Statement of Originality

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

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List of Abbreviations

ACPs	Activated corrosion products
AEA	Atomic Energy Act of 1954
AEA46	Atomic Energy Act 1946
ALARA	As low as reasonably achievable
ALARP	As low as reasonably practicable
ASN	Autorité de sûreté nucléaire (Nuclear Safety Authority)
BDBA	Beyond design-basis accident
BEIS	Department for Business, Energy and Industrial Strategy
BNI	Basic nuclear installation
BWR	Boiling water reactor
CCFE	Culham Centre for Fusion Energy
CDM	Construction (Design and Management)
CFETR	China Fusion Engineering Test Reactor
CNSC	The Canadian Nuclear Safety Commission
CPPNM	The Convention on the Physical Protection of Nuclear Material and Nuclear Facilities
CRNL	Chalk River National Laboratories
DBA	Design-basis accident
DBT	Design-basis threat
DCF	Dose conversion factor
DCLL	Dual-coolant lithium lead
DEMO	European demonstration fusion reactor
DF2	Weak atmospheric diffusion
DN5	Normal atmospheric diffusion
DN5P	Normal atmospheric diffusion with rain
DOE	The Department of Energy
DU	Depleted uranium
EA	Environment Agency
EIM&C	Enhanced implementation monitoring and control
ELM	Edge-localised mode
EnA	Energy Act 2013
EPR	The Environmental Permitting (England and Wales) Regulations 2016

ERLs	UK Emergency Reference Levels
FMEA	Failure Mode and Effects Analysis
FPP	Fusion power plant
FPTS	Fusion Power Termination System
GDF	Geological disposal facility
GF	General Fusion
GNSCR	General Nuclear Safety and Control Regulations
GSSR	Generic Site Safety Report
HCLL	Helium-cooled lithium lead
HCPB	Helium-cooled pebble bed
HLW	High level waste
HSE	The Health and Safety Executive
HSWA	Health and Safety at Work etc. Act 1974
HT	Tritium gas
HTO	Tritiated water
IAEA	International Atomic Energy Agency
IC	Inertial confinement
ID	Inhalation dose
ILW	Intermediate level waste
IO	ITER Organization
IRRs	Ionising Radiations Regulations 2017
IRSN	Institut de radioprotection et de sûreté nucléaire
JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus
LC	Licence condition
LI	Licence instrument
LLW	Low level waste
LOCA	Loss-of-coolant accident
LOCE	Loss-of-coolant event
LOVA	Loss-of-vacuum accident
LWR	Light water reactor
MAST	Mega Ampere Spherical Tokamak

MC	Magnetic confinement
MLD	Master Logic Diagram
NBIs	Neutral beam injectors
NIA	Nuclear Installations Act 1965
NII	HM Nuclear Installations Inspectorate
NISR	The Nuclear Industries Security Regulations 2003
NNSA	National Nuclear Safety Administration
NPP	Nuclear fission power plant
NRC	Nuclear Regulatory Commission
NRW	Natural Resource Wales
NSA	Nuclear Safeguards Act 2000
NSA18	Nuclear Safeguards Act 2018
NSCA	Nuclear Safety and Control Act
NSR	Nuclear Safeguards (EU Exit) Regulations 2019
NSTX	National Spherical Torus Experiment
NTM	Neoclassical tearing mode
ONR	The Office for Nuclear Regulation
PCmSR	Pre-Commissioning Safety Report
PCSR	Pre-Construction Safety Report
PDmSR	Pre-Decommissioning Safety Report
PF	Poloidal field
PFCs	Plasma facing components
PG	Pasquill-Gifford
POSR	Pre-Operations Safety Report
PPCS	European Fusion Power Plant Conceptual Study
PSR	Preliminary Safety Report
PWR	Pressurised Water Reactor
REPPIR	The Radiation (Emergency Preparedness and Public Information) Regulations 2019
RHC	Regulatory Horizons Council
RPrS	ITER Preliminary Safety Report
RP	Regulatory principle
RPV	Reactor pressure vessel

RSR	Radioactive Substances Regulations
SAPs	Safety Assessment Principles
SEAFP	Safety and Environmental Assessment of Fusion Power
SEPA	Scottish Environmental Protection Agency
SI	Statutory instrument
SICs	Safety important components
SNF	Spent nuclear fuel
SQ	Significant quantity
ST	Spherical tokamak
ST-VS	Suppression tank detritiation system
START	Small Tight Aspect Ratio Tokamak
TAGs	Technical Assessment Guides
TBR	Tritium breeding ratio
TE	Tokamak Energy
TECDOC	Technical document
TF	Toroidal field
TFTR	Tokamak Fusion Test Reactor
TIC	Time integrated concentration
TOR	The Tolerability of Risk from Nuclear Power Stations
TRF	Tritium removal facility
TRISO	Tri-structural isotropic
TSN	Transparency and Security in the Nuclear Field
UKAEA	United Kingdom Atomic Energy Authority
VLLW	Very low level waste
VV	Vacuum vessel
VVPSS	Vacuum vessel pressure suppression system
WCLL	Water-cooled lithium lead

List of Definitions

Hazard potential - The potential consequences (both radiological and non-radiological) that can be caused by a facility or an accident scenario, assuming that no safety and protection systems operate as intended (note in this thesis hazard potential is used interchangeably with unmitigated risk, see below).

Inventory - Inventory of all radionuclides present in the facility or building to be assessed against nuclear safety criteria.

Mitigated risk - The risk of an event occurring multiplied by the consequence of failure, assuming that safety and protection systems operate as intended.

Nuclear facility - A facility (including associated buildings and equipment) in which nuclear material is produced, processed, used, handled, stored or disposed of [1].

Nuclear fuel - Fissionable nuclear material in the form of fabricated elements for loading into the reactor core of a civil nuclear power plant or research reactor [1].

Nuclear fuel cycle - All operations associated with the production of nuclear energy [1].

Nuclear material - Plutonium except that with isotopic concentration exceeding 80% in 238Pu; 233U; uranium enriched in the isotope 235 or 233; uranium containing the mixture of isotopes as occurring in nature other than in the form of ore or ore residue [1].

Nuclear safeguards - Measures to verify that countries comply with international obligations not to use nuclear materials from civil nuclear programmes for non-peaceful purposes.

Nuclear safety - The achievement of proper operating conditions, prevention of accidents and mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation risks [1].

Nuclear security - The prevention and detection of, and response to, criminal or intentional unauthorized acts involving nuclear material, other radioactive material, associated facilities or associated activities [1].

Releasable inventory - The amount of inventory present in the facility or building that is able to be mobilised and can therefore potentially be released.

Risk - Probability of event occurring multiplied by the consequence of failure.

Source term - The amount and isotopic composition of radioactive material released (or postulated to be released) from a facility.

Unmitigated risk - The risk of an event occurring multiplied by the consequence of failure, assuming that no safety and protection systems operate as intended, and there are no barriers between the inventory and the environment.

Preamble

Literature review and radiological inventories used in analysis

This thesis was written between Oct 2018 and Apr 2022, and an attempt was made to use best available information at all times. However, the information and figures used in the thesis were limited by what was publicly available at the time the work took place. Throughout the thesis, reference is made to the 1 kg of tritium and 1000 kg of dust inventories used in the ITER Preliminary Safety Report (RPrS), and these values are used in the thesis as reference values for a fusion power plant (FPP). Through conversations with peers and conferences focused on fusion safety and regulation, it is often said that these values are administrative values, calculated using old models, and that the "real" expected inventories at ITER (and therefore what should be expected at an FPP) will be much lower.

Whilst this may be the case, it will be up to designers/licensees of FPPs to demonstrate that the inventories of tritium or dust will be much lower than the values taken at ITER. This thesis makes no claim to the likelihood of any releases of radioactive material; rather, it demonstrates the quantities of materials that, if released under certain accident scenarios, could potentially trigger emergency countermeasures being implemented. Further, given that the safety analysis performed in the licensing of ITER RPrS currently provides the most comprehensive view of a fusion safety concept in the world, it seems reasonable to use the values taken in the RPrS as representative values for an FPP and to comment upon them.

Unmitigated risk/hazard potential At various points in the thesis, both the unmitigated risk and hazard potential of fusion power plants (FPPs) are referred to. In the thesis, these terms are used interchangeably and refer to the maximum potential consequences (both radiological and non-radiological) that can be caused by a facility, assuming that no safety and protection systems operate as intended and that there are no barriers between the inventory and the environment (however unrealistic this scenario may be).

The majority of the tritium inventory within the vacuum vessel is assumed to be stuck within the plasma facing components and will take time to outgas. Much of the tritium will also be in the form HT rather than the much more dangerous HTO (the inhalation dose conversion factor for HTO is 10,000x larger than for HT). Further to this, if in an accident scenario some tritium does manage to

escape out of the vacuum vessel, it will then likely need to travel through rooms and down corridors before it reaches the environment, providing further opportunities for the tritium to be absorbed into walls and components, therefore reducing the amount that reaches the environment. These have points have been raised to contend that the amount of radioactive material that could ever credibly reach the environment in an accident scenario at an FPP is significantly lower than the inventories used in fusion studies and in the ITER RPrS. However, if any safety analysis is *relying* on tritium outgassing slowly, or becoming stuck in the walls as it travels away from the vacuum vessel, or that much of the tritium remains in the form HT and not HTO, then the analysis would need to *demonstrate* that this was the case. If the walls absorbing/adsorbing tritium is a key element of demonstrating that the design is safe, then in this sense the walls would become safety important components and designers would need to demonstrate how much tritium is retained under a variety of conditions. As detailed information such as this is not yet (publicly) available for FPPs, it is still useful to discuss the unmitigated risk/hazard potential, as it allows an honest discussion regarding the inventories present within an FPP and the consequences they can bring about. Whilst the design of an FPP and the materials/configurations chosen will determine the amount of radioactive material that will reach the environment during any accident scenarios, these things will need to be demonstrated in some form of analysis or safety case.

Chapter 1

Introduction

1.1 Project Motivation and Aims

Fusion power has long been promoted as the solution to the world's energy problem. Being low carbon, low hazard potential and producing manageable amounts of radioactive waste, fusion power plants (FPPs) present an ideal solution to ever increasing energy demands. Despite research into fusion power starting in the 1940s, progress has been slow and commercial FPPs have still not been realised.

Recent advancements in materials science and increasing interest by state and private enterprises in the development of small, prototype spherical tokamak FPPs means that fusion power is closer than ever before to becoming a reality. A key question that remains is: How should FPPs be regulated? An overly strict regulatory framework may inhibit fusion innovation at a time when many ideas need to be tested and fine-tuned. A lax regulatory framework may not sufficiently protect the health and safety of workers and the public. The answer to this question will have far-reaching consequences not only for the development of fusion power programmes in the UK but fusion power internationally and its place in the world's energy mix.

This project aims to answer the question of how FPPs should be regulated. Drawing on the characteristics of FPPs and the technologies involved, the key safety issues of fusion power are identified and reviewed and a sensitivity analysis is performed in order to gauge the importance of key parameters in relation to the hazard potential of FPPs. This information is then used to determine an appropriate regulatory framework for FPPs in the UK, with an in depth analysis of the various

regulatory options available. Following this, an appropriate regulatory framework is selected and developed within the UK legal system.

1.2 The Need for Fusion Energy

As inventories of fossil fuels deplete, worldwide energy demand continues to rise. In its *International Energy Outlook* produced in 2013, the U.S. Energy Information Administration predicted that the world electricity consumption will double between 2010 and 2040 (see Figure 1.1) [2].

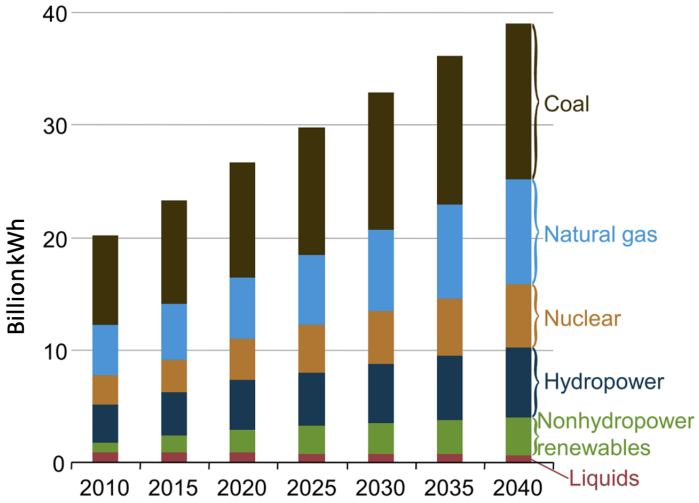


Figure 1.1: Predicted world electricity consumption by fuel type. Source: [2]

Ref [2] also predicts that half of the increase in energy consumption between 2010 and 2050 will be caused by India and China. A massive 80% of this increase will be provided for by burning fossil fuels, which will lead to a 46% increase in the release of CO_2 reaching a value of 40 billion metric tons in 2040. Predictions such as these have led countries to try and limit their greenhouse gas output and reduce environmental damages to preserve the world for future generations.

One of the ways to mitigate the damaging effects of greenhouse gases from rising energy demands is to change to low-carbon technologies for power generation such as renewables and nuclear energy. Renewables are currently receiving plenty of investment and are expected to grow their output 2.5% year-on-year until 2040 [2]. Nuclear power is gaining more importance in countries such as China, India and South Korea, who see nuclear as the ideal way to satisfy their huge energy demand. However, there are deficiencies to these technologies: renewables have yet to find a convincing solution of how to store energy for use on days where the sun is not shining or the wind is not

blowing, and nuclear power has the major disadvantage of producing very long-term radioactive waste as well as a negative public image from major accidents such as Chernobyl and, more recently, Fukushima.

A potential solution to these problems is the emergence of FPPs. Using isotopes of hydrogen as fuel, FPPs do not produce the same amounts of radioactive waste as nuclear power plants and have a much lower hazard potential.

1.3 Thesis Structure

To answer the question "*How should fusion power plants be regulated?*", it is necessary to first understand the characteristics of FPPs and the technologies and safety issues involved, including the differences between the technologies and safety issues involved in fusion and fission power. This will help determine whether the current regulatory framework in place for nuclear installations is applicable to fusion power or whether other frameworks will need to be considered. To this end, the thesis first explores the characteristics of FPPs and the technologies and hazards associated and how these differ to those associated with nuclear fission power plants. The key safety, security and safeguards issues for FPPs are then reviewed, with a focus on gaps in current knowledge together with areas for future work. International approaches to fusion regulation are explored to gain an understanding of existing regulatory approaches and potential regulatory options for fusion power in the UK.

Following this, a sensitivity study is performed to gauge the importance of key parameters that may significantly influence the hazard potential of FPPs. Identifying the factors that significantly influence the hazard potential helps determine what the safety critical areas are that are therefore of greater regulatory concern. Building on this knowledge, the various regulatory options for fusion power in the UK are analysed and an appropriate regulatory framework is developed.

Part I

Part I - Review of Literature - FPP Characteristics

Chapter 2

Characteristics of Nuclear Fusion and Proposed FPPs

This chapter introduces the physics and major characteristics of FPPs and provides an overview of the various approaches to fusion being pursued.

2.1 Physics of Nuclear Fusion

Nuclear fusion involves the joining together or *fusing* of two atomic nuclei at high temperatures, with a large release of energy. The most studied reaction is the joining of deuterium and tritium ions - both isotopes of hydrogen. This reaction (see below) results in the formation of a helium nucleus and a fast neutron, with kinetic energies of 3.5 MeV and 14.1 MeV, respectively. The reactants are kept at a high temperature (usually around 100 million K) in order for the corresponding nuclei to have high enough thermal energies to overcome their electrostatic repulsion and fuse. At these temperatures the reactants strip off their outer electrons and form a *plasma*.

$$^{2}_{1}\mathrm{D} + ^{3}_{1}\mathrm{T} \longrightarrow ^{4}_{2}\mathrm{He} + \mathrm{n} + 17.6\,\mathrm{MeV} \tag{2.1}$$

This reaction is most common as it has a high nuclear cross-section (probability that the reaction will occur) and deuterium is naturally abundant (mainly in seawater). Tritium on the other hand does not occur naturally and must be made, most commonly through neutron capture in lithium (see below). Tritium is also radioactively unstable with a half-life of 12.3 years.

$$^{6}_{3}\mathrm{Li} + \mathrm{n} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{T} \tag{2.2}$$

$$^{7}_{3}\mathrm{Li} + \mathrm{n} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{T} + \mathrm{n} \tag{2.3}$$

There are other fusion reactions in which it is not necessary to breed tritium:

$$^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \longrightarrow {}^{3}_{2}\mathrm{He} + \mathrm{n} + 3.27\,\mathrm{MeV} \tag{2.4}$$

$$^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \longrightarrow {}^{3}_{1}\mathrm{T} + {}^{1}_{1}\mathrm{H} + 4.03\,\mathrm{MeV} \tag{2.5}$$

$$^{2}_{1}\mathrm{D} + {}^{3}_{2}\mathrm{He} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} + 18.3\,\mathrm{MeV} \tag{2.6}$$

However, the nuclear cross-sections for these reactions are low except at exceedingly high energies. For example, to achieve high levels of D-D fusion would require temperatures of over 500 million K, much higher than the 100 million K that can be achieved with current technologies. Note, D-D fusion has been achieved at lower temperatures than 500 million K; however, only with a low density plasma and a short confinement time (the time the plasma is maintained at a temperature above the critical ignition temperature). To gain net power from a fusion reaction, the "triple product" of plasma density, plasma temperature and confinement time must be greater than a certain value (known as the Lawson criterion). Therefore, to achieve fusion with a sufficient plasma density and confinement time, much higher temperatures are required for D-D fusion when compared to D-T fusion. Due to this, the majority of the world concentrates on D-T fusion.

A standard $1\mathrm{GW}_{\mathrm{fus}}$ reactor is expected to consume around 150 g of tritium per day, which amounts to around 56 kg per year [3], [4]. As things stand, no production method exists that will be able to sustain an FPP over its lifetime - a key issue facing FPP designers.

Currently, tritium is either produced directly (for use in nuclear weapons) or occurs as a byproduct of nuclear fission power plants (NPPs). Today in the U.S., tritium is produced by irradiating

absorber rods in a single light water reactor (LWR) run by the Tennessee Valley Authority (TVA). A second LWR run by TVA planned for operation early next decade will also have tritium production capabilities. Whilst the amount of tritium produced in the U.S. is not readily available, it is worth making clear that tritium that is produced this way is produced for the sole purpose of stockpiling components for nuclear weapons, and not in quantities large enough to sustain an FPP. An alternative method of tritium production occurs in CANDU-type reactors due to neutron capture in deuterium present in the coolant and moderator; however, each of these reactors produces only approximately 130 g per year [5], the majority of which will be used to fuel ITER for its D-T campaign.

The current fusion philosophy is an FPP must be able to breed its own tritium. The preferred approach is that specially designed lithium blankets will surround the plasma, absorbing the high energy neutrons produced from the fusion reactions and forming tritium which can then be extracted and used to refuel the plant.

In order to contain the plasma, a confinement system must be employed. The two main routes currently being researched are magnetic confinement (MC) and inertial confinement (IC). MC uses powerful magnetic fields to confine the plasma in the shape of a torus, whilst IC uses the compression of a small fuel target to start the fusion process. In this chapter, the MC concept is focused on as this is the approach currently in development in ITER and the vast majority of plans for FPPs.

2.2 Magnetic Confinement (MC) Options

2.2.1 Tokamaks

A tokamak is a device that uses powerful magnetic fields to confine a hot plasma in the shape of a torus. The plasma is contained in this way by magnetic field lines that wrap around in a helical shape. These externally generated fields are then coupled with a self-generating magnetic field that arises when a current is ran through the plasma, resulting in both toroidal (parallel to lines of latitude) and poloidal (direction of magnetic field) components to the field (see Figure 2.1).

These fields effectively pinch the plasma and allow it to travel in a circular path in the torus. The initial plasma current, generated by a central solenoid coil through transformer action, has a secondary use as it also provides for the initial heating of the plasma (see Figure 2.2).

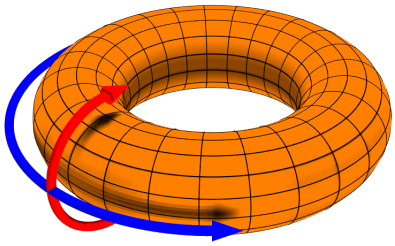


Figure 2.1: Diagram depicting the poloidal direction (red arrow) and toroidal direction (blue arrow). Source: [6]

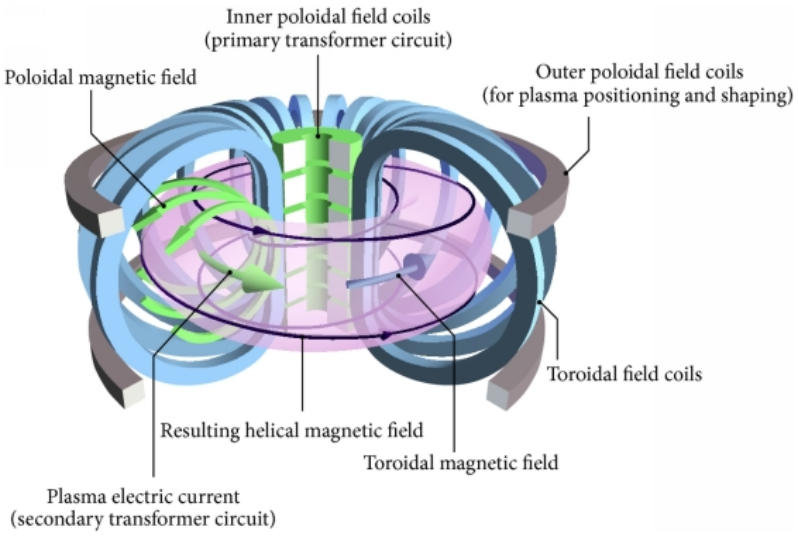


Figure 2.2: Schematic of magnetically confined plasma in a tokamak. The rotational transform of the helical magnetic field is formed by a toroidal field (generated by external coils) together with a poloidal field (generated by the plasma current). Source: [7]

The plasma equilibrium, however, is prone to various 'disruptions', usually caused by a rapidly growing instability, that result in a sudden loss of thermal energy and an immediate termination of the plasma. Two types of instability that are relevant to tokamak plasmas are the edge-localised mode (ELM) and the neoclassical tearing mode (NTM). ELMs result in a sudden, violent ejection of heat and particles from the plasma surface in a short time frame (around 100 microseconds). There is concern that these sudden eruptions may affect the performance of large-scale tokamaks and even damage structural walls. The cause of these instabilities is difficult to pinpoint, and research is ongoing in this area. As things stand, major work is being put into methods of maintaining a steady-state plasma, in which the likelihood of these instabilities is significantly reduced.

Tokamak plasmas are generally stable to NTMs unless given a 'kick' from another instability. The cause of this kick could be the ELM (detailed above) or a third type of rapid instability in the plasma called a 'sawtooth' (similar to an ELM but in the core). NTMs result in filamentary currents in the plasma which cause magnetic field lines to break and reform, creating large structures called magnetic islands. These magnetic islands are much less effective at confining heat and particles, which is a concern for MC plasmas. As mentioned above, a major area of work is developing the conditions for a plasma to exist in a steady-state mode, in which the number and severity of these disruptions is reduced [8].

In order to maintain this steady-state equilibrium and avoid instabilities or at least limit their consequences, a considerable amount of active feedback control must be present within the tokamak [9]. An example of this is work done by Nazikian *et al.* [10] which aims to suppress large amplitude ELMs by producing small magnetic ripples known as resonant magnetic perturbations (RMPs). Increasing the overall pressure of the plasma results in a plasma that is far more responsive to the ripples to better control ELMs and produce steady-state conditions [10].

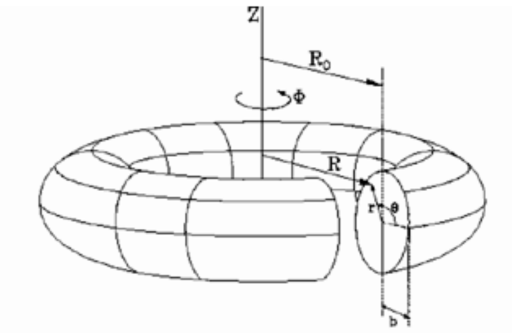


Figure 2.3: Basic geometry of general tokamak design displaying both the major radius R_0 and the minor radius b. Source: [11]

Figure 2.3 illustrates the basic geometry of a tokamak, including the major radius R_0, and the minor radius b, so that a corresponding aspect ratio $A = R_0/b$ can be defined. These properties, along with the fusion power and magnetic field strength B, will be used to describe the tokamaks referenced throughout this chapter.

2.2.2 Stellarators

The main challenger to the tokamak for the design of a commercial FPP employing an MC approach is the stellarator. Similar to the tokamak, the stellarator incorporates a torus shape; however, it only uses externally generated magnetic fields, i.e. no current is run through the plasma.

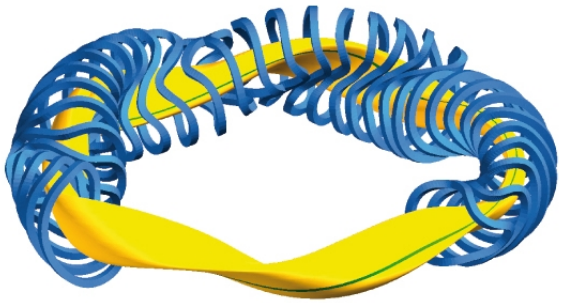


Figure 2.4: Schematic of stellarator design. The twisting field is produced entirely by non-axisymmetric coils. Source: [12]

These magnetic field lines twist around the torus in such a way that the plasma is forced to follow a twisting path (see Figure 2.4), cancelling out plasma instabilities found in the tokamak design [13]. For example, in tokamaks the NTM can be excited by the perturbation of a bootstrap current (a current proportional to the pressure gradient that arises due to collisions with trapped particles and passing particles within the plasma) [14]. When a magnetic island forms, this causes a drop in the local pressure gradient parallel to the flux tube of field lines, causing a reduction in the bootstrap current. In tokamaks, this drop in bootstrap current causes the magnetic island to grow, resulting in reduced confinement of the plasma [14]. In stellarators, the configuration of the global magnetic shear means that a drop in the bootstrap current with a magnetic island results in the island shrinking rather than growing. This way, the plasma pressure in stellarators often works to 'self heal' magnetic islands [12], [15]. Stellarators can also operate at higher plasma densities than tokamaks due to the lack of a Greenwald-like density limit (a maximum operational density limit in MC devices) [16].

2.2.3 Comparison of Tokamak and Stellarator Options

The tokamak found more favour than the stellarator due to its improved performance with plasma confinement and the fact it was easier to build. The main disadvantages for stellarators arise from

the non-axisymmetric 3-D magnetic field configuration, which results in ions drifting radially and leaving the confinement region [12]. On top of this, the divertor configurations for stellarators have not yet been sufficiently explored. The density and impurity control in stellarators is also a concern. However, since the observation of the H mode (high confinement mode) of the W7-AS stellarator in 1993 [17], there has been a resurgence of interest in the stellarator design. Main examples include the Wendelstein 7-X in Germany, the helically symmetric experiment in the U.S. and the large helical device in Japan [13], [18], [19].

Due to the similarities in the components and materials used in tokamaks and stellarators, the safety considerations are expected to be very similar. The event sequences, however, are more complex in tokamaks, due to the different approaches to magnetic confinement [14]. The disruptions present in tokamaks are expected to compound event sequences, requiring more sophisticated design solutions.

2.3 Tokamak-Based Fusion Facilities

In this section, the various tokamak-based facilities carrying out fusion research are reviewed, along with currently proposed electricity generating FPPs.

2.3.1 JET

It seems sensible to begin with the largest and most powerful tokamak currently operating: the Joint European Torus (JET). Located at the Culham Centre for Fusion Energy (CCFE) in Oxfordshire, UK, JET began operation in 1983 and currently holds the record for the closest approach to breakeven via fusion (i.e. when the power being released by the fusion reactions is equal to the required heating power) - outputting 16 MW of power from an input of 24 MW (the initial heat is required to produce the initial current, drive the magnets and heat the plasma to fusion temperatures) - with an energy gain factor Q of 0.67. JET has a major radius of 2.96 m, a minor radius of 1.25 m, a plasma volume of 100 m^3 and a toroidal magnetic field strength of 3.45 T. The magnetic field strength corresponds to the density of the magnetic field lines and, as detailed in Section 2.2, the magnetic field ensures the plasma doesn't make contact with the walls and instantly cool. JET was one of the first tokamaks to utilise a D-shaped vacuum vessel: initially chosen as a method of improving the safety factor (the ratio of the number of times a magnetic field line travels around toroidally

compared to poloidally), it also made the machine simpler to build mechanically.

JET is currently the only operational facility that can test deuterium-tritium (D-T) fuel mixes (as will be used in commercial FPPs). At the current time, JET is carrying out work to assist in the design and construction of ITER. This involves testing plasma physics, material properties and various systems that are planned for ITER. As an example, since 2011, JET has successfully tested ITER first wall materials in over 60 hours of plasma operation [20]. Ongoing experiments at JET are also key to further understanding the plasma-wall interaction and disruptions that ITER will face [21]. The team at JET are currently carrying out another D-T campaign, which aims to test multiple fusion technologies in ITER scenarios with the ITER material mix.

2.3.2 ITER

The next stage in the EUROfusion roadmap is the ITER project. Proposed in 1987 and situated at Cadarache in southern France, ITER is the culmination of decades of research and will be devoted to validating the models needed to design the demonstration fusion reactor (DEMO) and to demonstrate sustained fusion. ITER will also be used to test material behaviour of the main reactor components and develop operating procedures for DEMO. To do this, ITER will test physics and engineering issues, as well as various plasma configurations and plasma operation modes such as inductive high Q (high energy gain factor) modes, long pulse hybrid modes and non-inductive steady state modes, testing large ranges of plasma currents, densities, betas and fusion powers [22].

The primary objectives of ITER are:

- Produce 500 MW of fusion power for pulses of 400 s (Q value of 10)
- Demonstrate the integrated operation of technologies for an FPP
- Achieve a D-T plasma in which the reaction is sustained through internal heating (albeit thermal power will still be injected into the plasma to maintain operations)
- Test tritium breeding
- Demonstrate the safety characteristics of a fusion device

The second objective is particularly crucial as the integrated technologies tested at ITER such as heating, control, diagnostics, cryogenics and remote maintenance will enhance understanding in

areas that will be beneficial to future fusion technologies. Currently, ITER is over 10 years behind its original schedule (and more than €15 billion over budget) and the value of the data it will produce may be diminished by newly emerging programmes. Construction of ITER is now expected to finalise in 2025, with D-T reactions not scheduled until 2035.

ITER has a major radius of 6.2 m, a minor radius of 2.0 m, a plasma volume of 830 m^3 and a toroidal magnetic field strength of 5.3 T. Much larger than JET, the increased volume will allow the production of a 'burning plasma', in which the majority of heat required to sustain the temperature of the plasma is produced by the alpha particles created during the fusion process - a feat which has not yet been achieved. The first wall of ITER will be composed of primarily beryllium, whilst the divertor will be primarily tungsten, with future options to test various materials such as tungsten alloys, steels and even flowing liquid metal walls. The European development of EUROFER steel [23], a reduced-activation (low neutron capture and absorption cross-sections) martensitic steel, will also be tested in plasma facing components (PFCs) and test blanket modules in advance of DEMO.

2.3.2.1 Breeder Blanket Types

A key area of research for ITER is the testing of various breeder blankets. Multiple blanket types are being designed for the facility to allow testing of various configurations and makeups. In order to choose a particular blanket design for use in DEMO, the blanket must ensure tritium breeding self-sufficiency, show good power conversion efficiency and be able to withstand high neutron fluence [24]. A brief summary of blanket types will be discussed here.

Helium-Cooled Lithium Lead (HCLL)

In the HCLL blanket, liquid lithium lead (PbLi) serves solely as a breeder material whilst the entire thermal power released in the blanket is removed by a helium cooling system [25]. In this blanket, there is no liquid metal flow required to remove the heat. The helium coolant is in the temperature range 300-500 °C with an average pressure of 8 MPa. As the PbLi is not required for heat transfer, the PbLi flow speed can be low (0.1-1 mm/s) to maximise tritium extraction and PbLi purification processes [25]. Permeation of tritium from PbLi into helium flows is a major safety issue for the HCLL blanket - a focus of current R&D.

Helium-Cooled Pebble Bed (HCPB)

The HCPB concept incorporates alternate layers of solid static Li_4SiO_4 (breeder material) and layers of beryllium (neutron multiplier), both in pebble bed form. These are separated by arrangements of parallel cooling plates that allow helium to flow to remove heat [26]. The beryllium neutron multiplier layers are required to ensure the tritium breeding is sufficiently high to reach the tritium self-sufficiency goal for FPPs. An early design of this blanket was used in the European Fusion Power Plant Conceptual Study (PPCS) in the early 2000s [27].

Water-Cooled Lithium Lead (WCLL)

The WCLL concept is characterised by the use of water at similar conditions to pressurised water reactors (285–325 °C at 15.5 MPa) as coolant and PbLi as liquid breeder [28]. The PbLi characteristics are similar to those of the HCLL (see above). The water coolant has a flow velocity less than 2 m/s. Thermo-mechanical studies have been performed on the water cooled first wall to ensure cooling is sufficient to cope with the reference thermal load of 0.5 MW/m^2 as indicated in the design requirements [28].

Dual-Coolant Lithium Lead (DCLL)

Blankets in which a liquid metal serves as breeder and coolant are particularly attractive, mainly due to the high heat transfer coefficients of liquid metals and their high tritium breeding ratio. However, cooling of the first wall and blanket structure is difficult due to the magnetic field present degrading the heat transfer and causing a large pressure drop [29]. To overcome this, the DCLL blanket was proposed - using helium to cool the first wall and blanket structure, with PbLi as a self-cooling breeder material. This concept has the potential to operate at high PbLi temperatures (up to 700 °C) which allows a high efficiency of power conversion [28]. To prevent large pressure drops, the PbLi velocity is low inside the modules (2-3 cm/s).

2.3.3 DEMO

The next step in the EUROfusion roadmap following ITER is to build an experimental demonstration FPP (DEMO) capable of electricity generation. In this thesis, the term DEMO will refer to the European DEMO, as described in the EUROfusion roadmap [30], [31].

The aim of DEMO is to demonstrate that fusion can be done on a commercial scale, with a minimum 2 GW_{fus} power output, continuous pulses of plasma and self-sufficient tritium breeding. The success of DEMO will act as proof that fusion can operate on a scale large enough to supply significant amounts of energy to the grid. There are a number of significant material challenges that designers of FPPs such as DEMO will need to overcome; an overview of these is given in Section 2.4.

DEMO is only in the early design stage but a number of general features and objectives have been identified [32]:

- Plasma volume ∼1000-3500 m^3
- Fusion power output ∼2000-4000 MW
- Long pulses, quasi-steady state
- Tritium breeding
- Plasma density ∼30% greater than ITER
- Q-value >25

Figure 2.5 illustrates the differences in scale between JET, ITER and DEMO. As shown, DEMO is significantly larger than both JET and ITER and will pose significant design and structural challenges.

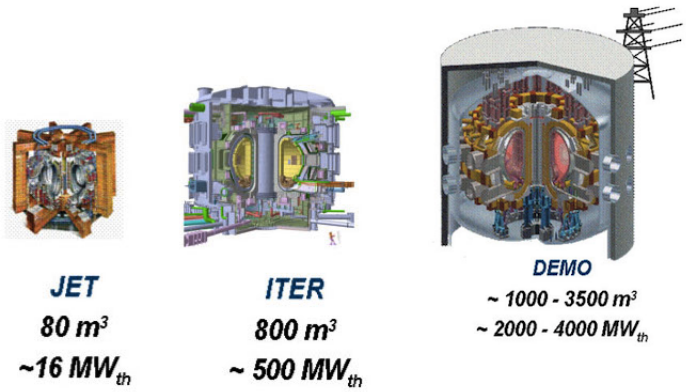


Figure 2.5: Expected size differences between JET, ITER and DEMO. Source: [33]. Edited to reduce expected size of DEMO machine.

One of the main challenges facing the designers of DEMO is the choice of material for the first wall of the vacuum vessel, divertor and breeder blankets. The first wall will undergo significant structural

damage due to the high energy neutron bombardment, with an estimated displacements per atom (dpa) value of 150 [34]. To allow comparison, the expected dpa value in ITER is expected to be around 2-3, whilst the most damaged component in an NPP is typically the zircaloy cladding which reaches a dpa value of around 15, although this is usually replaced every $\sim$5 years [35]. Current initial designs for DEMO use specially designed EUROFER steel as the structural material for components such as the divertor and blankets, with plated tungsten armour on any plasma facing surfaces. The general design features and material challenges facing DEMO are given in Section 2.4.

In the original EUROfusion roadmap, DEMO was scheduled to begin the first construction phase in 2024, with the first phase of operation scheduled to begin in 2033 [30]. However, due to delays in the ITER schedule, the first construction phase of DEMO is now not scheduled to begin until 2041, with the first phase of operation delayed until after 2050. Frustration at the lack of progress in the 'standard' approach to fusion (JET-ITER-DEMO), coupled with significant advances in both tokamak physics and superconductor technology, has led many in the field to consider alternative approaches to fusion.

2.3.4 Spherical Tokamaks

Spherical tokamaks (STs) operate very similarly to conventional tokamaks; however, they have a very small aspect ratio (A<2) which proponents claim gives improved confinement and allows a simpler build of the machine. STs have shown to display a high β (ratio of plasma pressure to magnetic pressure) [36]. MC devices generally aim to have as high a β as possible, as this reduces the magnetic force required for confinement. STs have also been shown to operate at steady-state in a compact configuration at a reduced cost [37]. This reduced cost, coupled with the flexibility of working with smaller devices (faster implementation times, lower input power required, etc.) makes STs a particularly attractive option for the fusion community.

2.3.4.1 START

The history of STs can be traced back to the Small Tight Aspect Ratio Tokamak (START) that was developed at Culham in 1990. Built primarily out of spare parts, START had a much lower aspect ratio (A=1.3) compared with conventional tokamaks and was much less costly to build. The

START experiment was housed in a 2 m diameter, 2 m high, 0.038 m thick aluminium vacuum tank, incorporating an internal system of stainless steel jacketed poloidal field coils.

Whilst initial results were promising (START displayed high temperature discharges with good global stability properties and typical tokamak characteristics) [38], the installation of divertor coils resulted in frequent disruptions of the plasma and the experiment finished in 1998 with the dismantling of the machine.

2.3.4.2 MAST

The next ST to be built at Culham was the Mega Ampere Spherical Tokamak (MAST) in 1999, which operated until 2013. MAST had a similar design to its predecessor, incorporating a spherical shape with a major radius of 0.9 m, a minor radius of 0.6 m, a plasma volume of 8 m^3, and a toroidal magnetic field strength of 0.55 T. The objectives of MAST were to attempt to reproduce the already promising results of START on a larger device, as well as carry out vital research that could aid in the design and build of ITER. Due to MAST, significant advances have been made in key research areas including start-up methods and plasma instabilities, particularly in understanding the mechanisms behind Halo currents that cause immediate termination of the plasma [39].

MAST recently underwent a major upgrade that included:

- Increased pulse length by up to a factor 10
- Improvements to neutral beam heating system
- Super-X divertor - plasma escaping the core will spread over a larger area, reducing the impact on the wall
- Improved control and pumping necessary to contain higher temperature plasmas

The objectives of the upgraded MAST are to add to the knowledge base for ITER, test equipment for potential use in DEMO (such as the Super-X divertor and innovative plasma exhaust systems) and hence make the case for a fusion component test facility (CTF) - a facility that would allow the testing, development and validation of ideas to aid with the design and construction of DEMO and future fusion facilities [40].

2.3.4.3 Commercially Funded ST Programmes

The renewed interest in STs has led to a number of commercially funded programmes to pursue the goal of fusion power for electricity generation. These programmes offer more flexibility than the larger state or internationally financed programmes; they also provide more optimistic delivery dates.

Tokamak Energy

Tokamak Energy (TE), based in Oxfordshire, UK, developed a fusion programme with the aim of having fusion energy on the grid by 2030. The current iteration of its machine, ST40, achieved a plasma temperature of 15 million °C during its first round of testing in June 2018. After this, it was rebuilt with the aim of achieving a plasma temperature of 100 million °C - the temperature required for D-T fusion. Following this, TE are aiming to develop a larger fusion device, STF1, which will be used to demonstrate fusion power from D-T fusion. The STF1 design will provide the fusion core of the commercial FPP design, STE1.

International Programmes

As well as TE in the UK, there is General Fusion (GF) based in Canada who are aiming to use a blend of inertial and magnetic confinement to achieve what they call magnetised target fusion (MTF). This approach involves confining a hydrogen plasma in strong magnetic fields, before compressing it with an array of pistons to greatly increase fuel density and temperature.

Princeton Plasma Physics Laboratory has also upgraded its National Spherical Torus Experiment (NSTX). The upgrade doubled the toroidal field, plasma current and heating power and increased pulse duration by a factor of five. The upgrade will initially focus on contributing to the development of predictive capability for ITER, DEMO and the Fusion Nuclear Science Facility (a nuclear facility designed by the U.S. that will act as an intermediary between ITER and DEMO). The upgrade will also be used to test the effectiveness of the spherical tokamak shape on plasma energy confinement properties.

Massachusetts Institute of Technology (MIT) has also recently collaborated with private company Commonwealth Fusion Systems, with funding from Italian energy company Eni, to fund a fusion reactor called SPARC. The primary aim of SPARC is to produce 100 MW of fusion power for ten

second bursts, more than twice the power used to heat the plasma. If successful, there are plans to produce a second reactor, around twice the diameter of SPARC and capable of producing 200 MW of electricity. A power output of this size is hoped to be demonstrated within 25 years [41].

2.3.4.4 Licensing and Regulation

ST designs offer many advantages, not only because they are smaller and potentially easier and cheaper to construct, but also because dynamic private sector companies are more able to adapt to rapidly changing technologies. The ability to test multiple configurations and materials in a relatively short time frame is in stark contrast to larger devices such as ITER, in which progress is currently moving at a painfully slow rate.

The prospect of fusion power for commercial exploitation in the early 2030s compared to the 2060s offered by the EUROfusion roadmap has implications for the development of regulation. The overarching safety legislation involving fusion power will therefore need to address the prospect of compact STs.

2.4 General Design Features of an FPP

An FPP producing $\sim 1GW_{electric}$ is expected to require a fusion power value of $\sim 3GW_{fusion}$ [42]. Detailed designs do not currently exist for an FPP, but the majority of preliminary plans, including those for experimental reactors such as DEMO, suggest that secondary power conversion will be via either a steam Rankine cycle or a gas Brayton cycle. In these cycles, the heat generated by the fusion reactions is removed from the plasma chamber by a cooling system that uses either water, helium, liquid metal, etc. as the coolant. The secondary system enables this heat to be converted into electricity via a turbine generator.

The main technology challenges are discussed below and include choosing a resilient enough material to coat the plasma chamber, choosing a suitable coolant that can withstand intense neutron bombardment without undergoing activation and how to efficiently separate the useful hydrogen isotopes from the exhaust gas. The DEMO design is used as an example to illustrate the current gaps in knowledge/technology, but any FPP will have many if not all of the outlined challenges.

2.4.1 Vacuum Vessel

The vacuum vessel (VV) is an area of huge importance as it not only contains the plasma but also encloses two major components: the breeder blanket and divertor (see Figure 2.6).

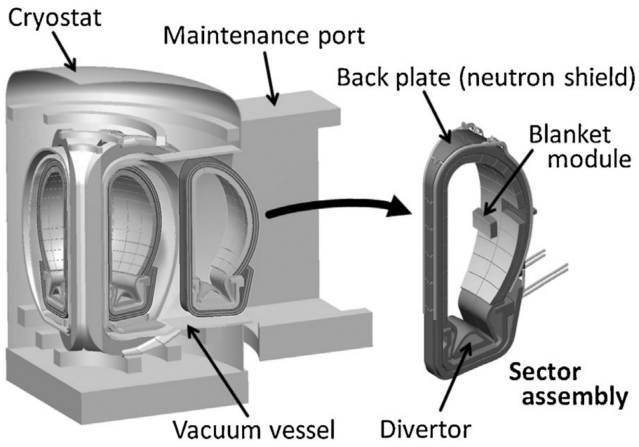


Figure 2.6: Schematic of vacuum vessel, blanket and divertor in DEMO Source: [43]

The VV is a hermetically sealed steel container that houses the plasma and acts as the first confinement barrier. It has a double steel wall in which the coolant flows to extract the heat from the fusion reactions. The space between the double walls is also filled with borated stainless-steel blocks which provide neutron shielding together with the blanket (see Figure 2.7) [44].

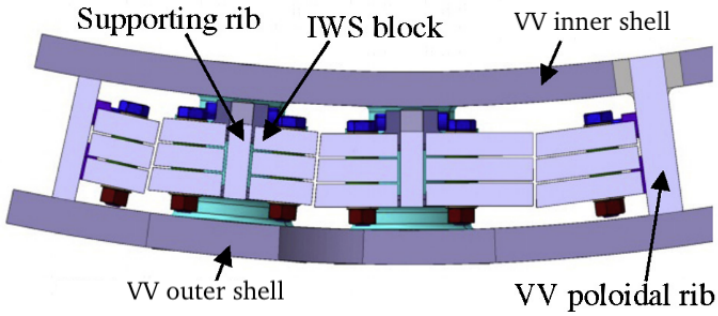


Figure 2.7: Basic configuration of VV and borated stainless steel blocks used for neutron shielding. Source: [44] (Edited)

The shielding acts to protect the external steel structure from the high energy neutrons produced in the plasma and is able to do this as boron possesses a large neutron absorption cross-section. The design of the wall incorporates ports for equipment for monitoring plasma behaviour, additional heating, fuelling the plasma and cooling and vacuum systems [45]. Additional ports will also be

installed for maintenance and removal of components such as the blankets and divertor.

2.4.2 Breeder Blankets

The breeder blanket modules run around the VV, providing protection for the metal VV walls from the neutron bombardment. The heat deposited in the blanket via the radiative heat from the plasma (along with the heat from the slowing down of the neutrons) is removed via a coolant (most likely helium, water or liquid metal). The choice of coolant will play a significant part in the safety case and each option has its drawbacks. Helium cooling is noncorrosive and so is less likely to degrade the pipework; however, helium is a light gas and hence to remove the heat at the required rates it will need to be pressurised. It also leaks easily through small cracks. Therefore, the high flow rates needed to transport the heat from the blanket and other parts of the VV to the turbines require considerable pumping power (several hundreds of MW) [46]. Water, on the other hand, has efficient heat removal capabilities and therefore requires lower flow speeds and hence the required pumping power is much less than that of helium cooling systems [47]. However, water will need to be kept at a high pressure and will be subject to a phase change in a loss-of-coolant accident (see Section 4.5.2.1); water is also corrosive and leakage into the VV could have significant safety implications. Liquid metal coolant also has efficient removal capabilities (the front runner for this type of coolant is a PbLi eutectic alloy); however, the high magnetic fields of a tokamak will induce eddy currents in moving metals, generating magnetic forces which act to impede flow [48]. These metals can also be activated which causes additional problems.

Activation characteristics of the coolant are a significant safety factor. Activation of helium coolant produces tritium via ${}^{4}_{2}\mathrm{He}(\mathrm{n},\mathrm{p}){}^{3}_{1}\mathrm{T}$, but only in small quantities. This amount is considered negligible compared with the amount of tritium which diffuses through the VV into the cooling system via the walls. β-decay of tritium produces low energy electrons and low energy γ radiation, both of which will not damage the structure. Therefore, the activation of a helium coolant should not pose a significant safety concern.

Activation of PbLi results in large quantities of tritium produced which will need to be extracted for re-fuelling of the plasma. Conservatively assuming that all this tritium can be extracted, the activity of the coolant is then largely dominated by Pb activation products: $\mathrm{Pb207}^{\mathrm{m}}$ ($\mathrm{T}_{1/2} = 0.8$ s), Pb203

($T_{1/2}$ = 51.9 h) and Ti204 ($T_{1/2}$ = 3.78 yr). Activation of PbLi coolant also produces Hg203 and Po210, whose respective dose factors per ingestion are 100 and 100,000 times higher than tritiated water [45]. PbLi activation also results in high levels of γ radiation being released. Due to this, a PbLi coolant has high activity and dose rate levels during operation and at shutdown (due to Pb activation products).

Activation of water results in high activity at short times due to the production of N16 via $^{16}O(n,p)^{16}N$ ($T_{1/2}$ = 7.1s). β-decay of N16 results in high energy γ rays which can damage surrounding structures (mainly via gamma heating and ionisation processes). Therefore, shielding of water pipes is required. Activation of water will also result in production of tritium, C14 and N17; therefore, tritium extraction will also need to be performed in a water-cooling system. Delayed neutron radiation from N17 decay is another area for concern. Water is also corrosive and can result in corrosion products circulated in the coolant. These corrosion products can become activated and present a radiological hazard. The activation of materials in the coolant system and the production of activated corrosion products may be a significant issue for FPPs, particularly when considering workers and their occupational radiation exposure. They may require significant shielding and safety and protection measures in place to reduce any occupational dose received. Further work is required to fully understand the behaviour of activated corrosion products, water chemistry, radiolysis and the potential for tritium to permeate into the water coolant.

In the reference DEMO concept, the blanket and first wall are helium cooled [49]. In other concepts, the blanket and first wall are either water cooled or cooled by PbLi [28]. The current proposal involves the plasma facing side of the blanket (the first wall) to be made of beryllium or tungsten. This will be subject to high energy neutron bombardment, thermal flux and thermal shocks. During operation, tritium adsorption will occur on this wall. All of these factors will, over time, cause the wall to erode and create activated dust, requiring blanket sectors to be changed multiple times over the course of the plant's life. Due to the high radiation levels in the VV, maintenance will need to be undertaken remotely using robotic systems. The blankets will be removed through specially designed ports in the VV roof and transferred to the hot cells. Several different blanket concepts are currently being developed, and these will be tested in the ITER facility.

2.4.3 Divertor

The divertor is located at the bottom of the VV and aims to extract all the helium (produced in the fusion reactions), unused fuel (deuterium and tritium) and any other impurities (primarily dust produced from erosion of the first wall of the blankets and divertor). A significant amount of the energy produced from fusion is also extracted via the divertor. As such, the divertor requires cooling not only for its protection but also to recover the energy for power generation. A primary concern with the choice of material for the divertor is the retention of tritium ions on the surface (reduction of tritium inventories in the VV is a key safety issue). Tungsten is the leading candidate for the material for the divertor, as it has lower open porosity and co-deposition rates compared with beryllium which results in lower amounts of tritium being retained on the surface of the divertor [50]. The first wall of the divertor will also have to be changed during the lifetime of the plant due to the intense neutron bombardment and thermal fluxes incident on the surface. In DEMO, the divertor will most likely be cooled by water, although helium cooling is being developed [51]

2.4.4 Magnetic System and Cryostat

The magnetic system is comprised of toroidal field (TF), poloidal field (PF) and central solenoid (CS) coils. Six PF coils are installed to the outboard leg of sixteen identical D-shaped TF coils, providing the vertical and radial magnetic field (see Figure 2.2). The CS is a stack of coils in the centre of the torus [46]. These coils will be manufactured out of cryogenic steels which have excellent structural performance at low temperatures, but this performance drastically degrades with temperature rises. It is therefore paramount that the steels remain at ultra-cool temperatures of around 4 K [52].

As in ITER, DEMO will incorporate superconducting magnets to control the plasma in the VV and ensure the plasma makes no contact with the vessel wall (as it will cool instantly). The superconducting magnets are located within a second vacuum chamber called the cryostat. Made entirely of stainless steel and representing the largest component of the tokamak, the cryostat provides the ultra-cool liquid helium (around 4.5 K) required to cool the superconducting magnets [45]. The magnets will be enclosed between the hot VV, with operational temperatures of around 450 K, and the cryostat [53]. In the initial plans for DEMO, the magnets will be made primarily of Nb_3Sn superconducting strands that are twisted together to form a high current-carrying cable.

These strands are then inserted into steel jackets for coil windings [54]. More advanced cables are being developed to reduce cost and performance degradation under cyclic operation [55].

The maximum TF strength for DEMO is expected to be in the same order as the TF at ITER at 13.45 T and 11.8 T, respectively. Currently DEMO doesn't use high B TF coils as any increase in B inherently leads to higher stresses ($\sigma \propto B^2$). To cope with these higher stresses, higher strength cryogenic steels will need to be developed (research in this area is ongoing).

To protect the magnets from the high levels of radiative heat transferred from the VV, thermal shields will need to be placed on both sides of the magnet system [53]. To effectively reduce thermal heat, it is crucial that the shields have low emissivity and are actively cooled in the temperature range 80-120 K [53], [56]. The cryogenic cooling plant therefore has to overcome the heat loads on both the magnets and the thermal shields. To help reduce heat loads on the thermal shields, designers are investigating the effects of covering the shields with passive multi-layer insulation. This would then reduce the refrigeration power needed to maintain the operating temperatures of the cold systems - an important design objective of DEMO if it is to achieve efficient electricity production [53].

The primary safety concern with the magnetic system is how to deal with the discharges of magnets with large stored energies. Studies have estimated the TF coils will have energies up to 180 GJ [57]. Energies of this order can locally distort reactor geometry and damage confinement barriers. To compensate for this in ITER, mitigation systems are incorporated in the design which can rapidly detect magnet faults (e.g. a quench) and can safely discharge the energy into large resistors. High current cables will be required to limit the coil inductance and thus limit terminal and ground voltages during safety discharges of the magnets [58]. It is expected that similar mitigation systems will need to be included in designs for FPPs as well.

2.4.5 Pumping Systems

FPPs need to be cooled to extract heat and maintain structural integrity. To maintain a burning plasma, helium ash must also be removed from the plasma, along with unused deuterium and tritium. The presence of impurities in the plasma can affect plasma burn and significantly reduce the efficiency of the plant. In ITER, mechanical and cryogenic pumps evacuate the air from the VV

and cryostat until the pressure has dropped to one millionth of normal atmospheric pressure. This low pressure is a key condition for plasma burn and for the superconducting magnets to operate effectively. The pumps in ITER are composed of stainless steel, cooled with supercritical helium and coated with activated charcoal as sorbent material. Research has shown charcoal has the correct density and porosity for capturing helium particles.

Cryopumps have some significant limitations. They require massive amounts of energy to maintain their low temperatures and they must undergo regeneration: a process in which the cryopump is heated to above room temperature to extract the tritium and deuterium to reuse in the plant. In ITER, this is expected to occur once every 24 hours of plasma operation. Due to this, alternative designs are currently being explored for future fusion facilities.

For DEMO, advanced solutions such as mercury pumps and pumps based on enhanced permeability are expected to be employed. Mercury pumps can be used on a continuous basis and do not require the regeneration process that cryopumps do. These pumps are fully developed and have been delivered to JET for their latest tritium campaign [59]. The number of pumps required for DEMO is not yet specified and, unlike ITER, must be defined from an assessment of required particle throughput [60]. The development of a linear mercury diffusion pump at a scale similar to DEMO, including the corresponding infrastructure systems, is looking promising [61]. It is difficult to identify the main safety concerns regarding the pumping systems as detailed designs are yet to be published.

2.4.6 Fuel Cycles

The fusion fuel cycle is an important auxiliary system for an FPP. The conventional approach is for FPPs to breed their own tritium. As such, there are two parts to the fuel cycle: the *inner fuel cycle* and the *outer fuel cycle*. The inner fuel cycle is associated with the supply of tritium to the plasma chamber and the recovery of unused tritium from the exhaust. This exhaust material is then processed in the tritium recovery plant, where the unused deuterium and tritium is returned along with fresh supplies of fuel to the plasma chamber. The outer fuel cycle is associated with the breeding of tritium in the breeder blankets and all tritium extraction systems [62].

2.4.6.1 Inner Fuel Cycle

The main objective of the inner fuel cycle is to recover the unused tritium from the exhaust material. Once the exhaust gases have been pumped to the on-site tritium plant, the impurities are separated from the fuel mixture. For DEMO, the proposed approach uses a multi-stage membrane reactor. This process involves the permeation of pressurised hydrogen through a thin palladium membrane at around 700 K [63]. The hydrogen is then bound to the membrane and removed from the exhaust stream. Catalysts and purge gas are then used to crack the chemically bound hydrogen from the membrane. Final detritiation of the exhaust gas makes use of a combined electrolysis and catalytic exchange (CECE) process. The isotopic exchange process takes place in a liquid chemical exchange column and an electrolyser [63]. Once this process is complete, cryogenic distillation is used to separate out the isotopes with high purity levels, if required. To achieve this, multiple rectification columns are operated at around 20 K using the different boiling points of deuterium and tritium to create very high purities. The deuterium and tritium is then stored in the form of uranium hydride in so-called 'getter beds' (see Section 2.4.6.4), ready to be injected back into the plasma.

Advanced designs in which a metal foil pump close to the divertor separates the hydrogen from all other gases and thus the main load to the fuel clean-up systems is a smaller, helium-rich gas stream are currently gaining traction [64]. Known as Direct Internal Recycling (DIR), this process is essentially a shortcut in the fuel cycle, producing two flows: a pure fuel flow (that is directly recycled back to the plasma), and a residual gas flow (that is sent to the tritium plant for processing). This process is gaining interest as it leads to a strong reduction of the tritium inventory in the pumping system [62]. The next stage is for the metal foil pumps required to be developed in a laboratory environment and fully optimised [63]. If this technology can be confirmed, the complexity of the auxiliary systems (tritium plant, cryoplant, etc.) can be drastically reduced [64]. It is worth noting, however, DIR is still a new concept and needs further R&D to confirm its feasibility.

The separated isotopes are then transferred to a pellet source which creates frozen mm-sized pellets from the gas mixture. These fuel pellets are then injected into the VV by pellet injectors on the torus inboard side. The pellets are propelled to velocities of 1000 m/s by means of gas pressure or centrifugal force in order to reach the plasma core more efficiently [65]. The ITER design is

based upon classical pellet injection and the focus so far has been concentrated on supporting ITER. Further R&D may be required in this area for future FPPs.

2.4.6.2 Outer Fuel Cycle

An outer fuel cycle is also required if an FPP is to demonstrate tritium self-sufficiency. Tritium bred in the breeder blankets must be extracted, purified and sent to the inner fuel cycle (see above). The blanket modules must be cooled in order to extract the heat from the plasma and to keep the modules from overheating. Due to the high operational temperatures, there is the potential for tritium to permeate into the coolant loop. To avoid a build-up of tritium in the loop, the coolant is purified [63]. Therefore, the outer fuel cycle comprises the breeder blankets and all ancillary systems required for tritium extraction.

In ITER, there is no need to breed a large quantity of tritium as the tritium required will be supplied by the current global fleet of CANDU reactors. As such, the outer fuel cycle will be limited for experimental purposes (i.e. demonstration of the breeding concept) [62]. An FPP on the other hand, if it is to demonstrate tritium self-sufficiency, requires a much larger and more complex outer fuel cycle (estimated throughput 10^4 times higher than ITER) [62].

There are currently four major design concepts for the breeder blanket, each with different coolants and a liquid or solid breeder (see Section 2.4.2). Until a final design is chosen, there can be no decision made on the technology used for tritium extraction and coolant purification [63]. If a liquid breeder is chosen, permeation against vacuum (PAV) is considered the leading candidate for tritium extraction by bringing the mixture into contact with a membrane (similar to the process described above). Enhanced permeation can be achieved by applying vacuum conditions on the opposite side of the membrane [63]. If a solid breeder is chosen, however, cryotraps are the leading candidate to extract tritium from the helium purge gas.

2.4.6.3 External Fuel Cycle

To avoid the added complexities that come with attempting tritium self-sufficiency (robust design of blankets, safety concerns with blanket removal, etc.) and taking into account the limiting resources of tritium, an external fuel cycle (in which tritium is created off-site) should be considered.

The majority of the world's supply of tritium is produced in CANDU-type reactors through the interaction of fission neutrons and the heavy water moderator and coolant. A tritium removal facility (TRF) is required to extract the tritium, of which there are only two in operation: one in Canada and one in South Korea (note there are plans for a third TRF to be built in Romania) [5], [66]. It is estimated that the quantity of tritium that can be generated with the current fleet of CANDU-type reactors is sufficient to meet ITER's tritium needs throughout its lifetime (roughly 18 kg of tritium is required) [67]. However, uncertainties around the lifespans of the current fleet of ageing reactors, coupled with uncertainties over the future of TRFs, means that any proposed external fusion fuel cycle would require a new fleet of CANDU-type reactors (or other technology) to generate the large amounts of tritium required.

A typical CANDU reactor can produce approximately 130 g of tritium per year and a standard $1GW_{fus}$ FPP will consume around 55 kg of tritium per year. Fuelling a single FPP would therefore require hundreds of CANDU-type reactors producing tritium, which is evidently unfeasible. Despite the impracticality of using CANDU-reactors to produce tritium to be used as fuel for FPPs, alternative methods of off-site tritium production should still be investigated due to the multitude of drawbacks associated with on-site breeder blankets.

2.4.6.4 Tritium Storage

Currently, the preferred approach to tritium storage is to use uranium 'getter beds', in which the tritium bonds with depleted uranium (DU) to form uranium tritide, UT_3. This approach allows large quantities of tritium to be stored in small volumes, with the tritium easily dissociated from the uranium by applying heat. On cooling, the uranium quickly reabsorbs the tritium resulting in a fast uptake even at low pressures. DU also has potential for high pressure delivery rates due to a high equilibrium pressure at elevated temperatures [68]. DU is currently a strong candidate for tritium storage in an FPP, despite its radioactivity and potential restrictions in handling. A potential drawback is that the storage ability does not scale proportionately with the amount of tritium that will need to be stored for commercial deployment [65]. A single bed can be loaded with approximately 1.86 kg of DU which equals a tritium capacity of 70 g in the form of UT_3 [68]. A $1GW_{fus}$ FPP will consume around 55 kg of tritium per year, but the storage requirements will

depend upon the strategic stocks needed to meet security of supply requirements. A strategic stock of six weeks' supply would require around 90 parallel uranium beds. Due to the large bed expansion upon tritide formation, coupled with the need for cooling during tritium absorption, this number of beds is not ideal for an FPP. They would also require around 167 kg of uranium to operate. As there are regulatory restrictions around the use of uranium as a controlled nuclear material[1] (in some countries it is banned), this may be a concern. For these reasons, developing an alternative solution of tritium storage that is based on non-nuclear materials is an important area of ongoing R&D.

2.4.7 Plasma Heating

In an FPP, the plasma has to initially be heated to start the fusion reactions. If the temperatures are below a certain value, the ions do not have enough thermal energy to overcome their repulsion and fuse. For an FPP, one of the main tools to heat the plasma is the injection of beams of high energy deuterium neutrals (D^0) into the plasma. The incoming particles must first be neutralised before injection as charged particles will not be able to penetrate the plasma and transfer their energy (due to the strong magnetic fields). The ion beam must therefore be injected into a region of high gas density to be neutralised [62]. Tangential injection of these high energy neutrals also contributes to maintaining the high-power current drive required to sustain the plasma for long pulses.

Neutral beam injectors (NBIs) tend to require a high vacuum pump with large pumping speeds (range of several 1000 m/s) to accelerate the ions and guarantee the required density profile along the beam line [62]. NBIs have already been developed, with 34 MW (beam power supplied to plasma) positive ion-based (P-NBI) beams currently installed at JET. To ensure the particles reach the centre of the burning plasma, larger devices require higher neutral beam energies. High energy systems (>100 keV) require the use of negative ion technology (N-NBI). In ITER, the precursor ion beams are D^- with a beam energy of 1000 keV. It follows that an FPP will also make use of N-NBIs.

One of the challenges for DEMO designers is to improve the efficiency of the neutralised component to ∼70% (in ITER this value is expected to be ∼55%) The efficiency is defined as the ratio between the power flux of neutral particles at the exit of the neutraliser and the negative ions at the entrance [69]. Another technical challenge for DEMO designers is to try and reduce the beam losses in the

[1] DU is an alpha emitter and if ingested or inhaled is a serious health hazard. It is also chemi-toxic.

beam duct - the area that connects the NBI with the plasma chamber. There is no official beam energy value specified for DEMO; however, for the current conceptual design a value of 800 keV has been chosen, slightly less than for ITER [69]. Both ITER and DEMO plan to incorporate three separate injectors at different locations in the VV. Figure 2.8 is a schematic of the main features expected in an FPP.

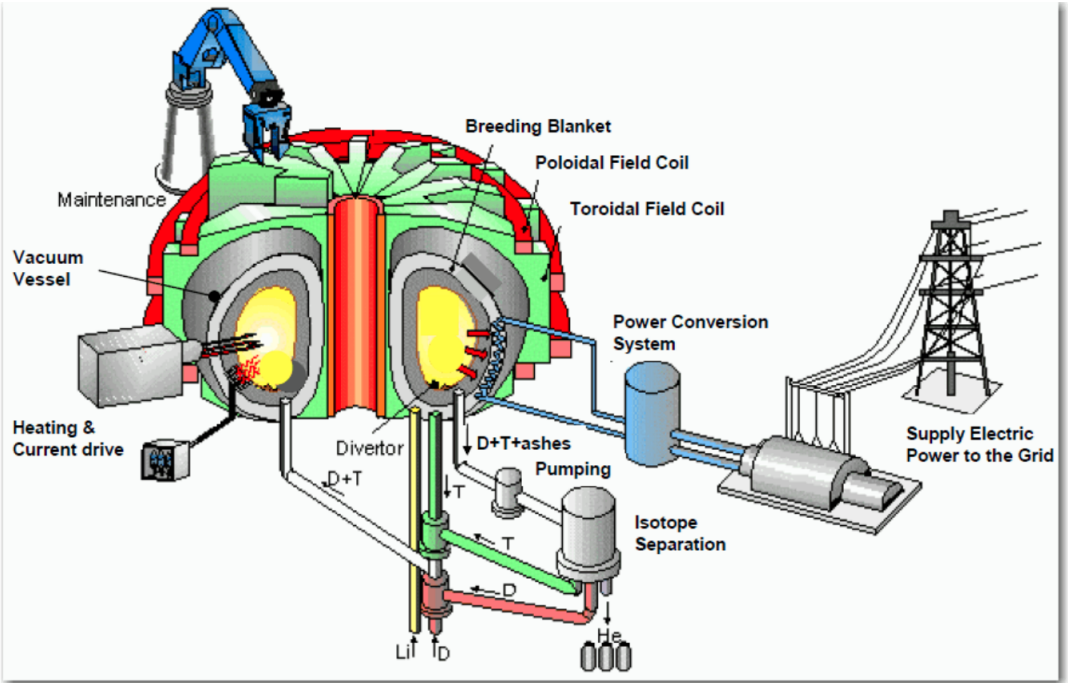


Figure 2.8: Schematic of main components and systems expected in an FPP. Source: [27]

Chapter 3

Technology Differences between FPPs and NPPs

This chapter illustrates the main technology differences between FPPs and NPPs, focusing on fuels, operating temperatures, pressures, neutron fluxes, materials behaviour and radioactive waste. Illustrating the primary differences between FPPs and NPPs will help determine whether the current regulatory framework for NPPs is appropriate for FPPs. Note only a brief overview of NPP technologies and inventories is introduced here, as the primary goal is to illustrate the key differences between FPPs and NPPs.

3.1 Fuels and Radioactive Materials Inventories

3.1.1 Radiological Inventories

In an NPP, the fuel is a heavy fissile actinide element (generally U233, U235 or Pu239) that, when hit by a slow-moving neutron, splits into two nuclei releasing large amounts of energy. This process usually produces two or three more neutrons, with average energies of $\sim$2 MeV. These neutrons then go on to cause further heavy nuclei to split and thus a *chain reaction* is formed (see Figure 3.1). Note U233, U235 and Pu239 all decay via α-emission and all have extremely long half-lives of 160,000 years, 703.8 million years and 24,100 years, respectively.

The fissile isotopes of uranium and plutonium used in NPP fuels are usually in the form of oxide powder (e.g. UO_2) that is then processed into pellet form. These pellets are sintered and undergo a

grinding process to achieve a uniform pellet size. They are then inserted into fuel rods - long tubes of a corrosion-resistant metal alloy (usually stainless steel or zirconium). In a large pressurised water reactor (PWR), there are roughly between 180-270 fuel rods per bundle and between 150-200 fuel bundles in a reactor core (these are roughly 4 m long). The zirconium alloy tubes are pressurised with helium to act as a filling gas. In a boiling water reactor (BWR), the process is similar: fuel rods are bundled together and each rod is backfilled with pressurised helium.

Following fission of the fissile nucleus, highly radioactive fission products are formed, primarily Cs137, Sr90 and I131. These primarily decay by β-decay and have half-lives of 30.2 years, 28.8 years and 8 days, respectively. However, there are over 60 different fission products that can form with some having very long half-lives, e.g. I129 has a half-life of 15.7 million years.

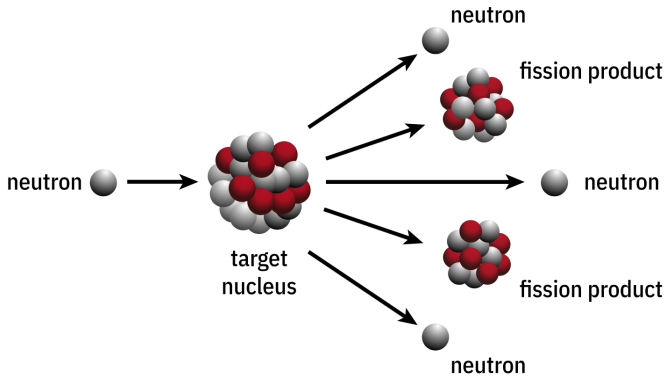


Figure 3.1: Diagram depicting the fission process. Source: [70]

In an FPP, the fuel is generally two isotopes of hydrogen: deuterium and tritium. These are joined together at high temperatures, producing a helium nucleus, a fast neutron (average energy ∼14 MeV) and releasing large amounts of energy (see Figure 3.2). Deuterium is naturally occurring and abundant (found in seawater, typical values of 150 ppm), whereas tritium is man-made and is most commonly formed by bombarding lithium with neutrons in an NPP (see Section 2.1). There are other reactants that can be used in fusion; however, these tend to have lower cross-sectional areas at attainable temperatures and so D-T reactions are favoured. Note tritium decays via β-decay and has a half-life of 12.3 years.

In the proposed plans for DEMO, the fuel will be mm-sized frozen pellets of a D-T mix. As detailed in Section 2.4.6, these pellets will be fired into the VV by pellet injectors on the torus inboard side.

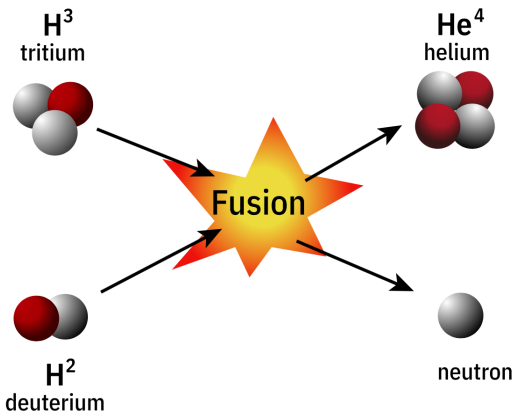


Figure 3.2: Diagram depicting the fusion process. Source: [71]

They are then propelled to velocities of 1000 m/s by means of gas pressure or centrifugal force, in order to reach the plasma core more efficiently [65]. Typically, there is around 1 gram of fuel in the plasma chamber at any one time – enough to sustain the reaction for a few seconds only [72].

Activated dust particles (formed from plasma-surface interactions) and activated corrosion products (if water is chosen as the primary coolant) are also expected to be present in an FPP. The dust particles expected in an FPP will generally have the same composition as the walls that make up the plasma-facing surfaces [73]. The walls of the PFCs in ITER will be made of tungsten and beryllium; however, the isotopes generated from the activation of tungsten dominate over those from activated beryllium (in terms of activity released). If water is chosen as the primary coolant, the activation of oxygen can form isotopes N16 and N17, both of which have very short half lives (7.1 s and 4.2 s, respectively) [74]. Moreover, corrosion of the materials used in the pipes and valves can form inventories of activated corrosion products (ACPs) in the coolant that may be significant. Without detailed designs of a plant, however, it is difficult to accurately identify the composition of these inventories or determine which radioisotopes will be present (see Section 4.4.2.2).

3.1.2 Health Issues

Each of the heavy fissile isotopes used as fuel in an NPP is inherently unstable and chemically toxic. Whilst they generally decay via α-decay and α particles shouldn't penetrate through skin, inhaling or ingesting these isotopes can significantly damage organs and surrounding tissues, potentially increasing the risk of lung cancer, liver cancer and bone sarcoma [75]. If fission products are released,

they can travel great distances (by attaching themselves to fine particles such as water vapour) and contaminate local soil and water deposits [76]; they are then taken up by living organisms and passed up the food chain. Upon ingestion, Cs137 decays by both β-decay and γ emission from an intermediate state, potentially depositing energy in regions of human tissue. Sr90 behaves similarly to calcium in the human body and is deposited in bones. Cs137 has a much lower biological half-life (time taken for half of the material to be excreted due to bodily processes) than Sr90, 70 days compared with 50 years; however, both radioisotopes can significantly damage nearby cells and increase the risk of developing cancer. I131 is considered less of a safety concern as it has a much shorter half-life (8 days); however, upon ingestion, iodine is quickly transported to the thyroid, where build-up can lead to thyroid cancer. Cs137 and Sr90 are considered the most harmful radioisotopes to the environment due to their approximately 30 year half-lives and biological uptake. As an NPP continues operation, these fission products build up in the reactor core, increasing in concentration until part of the core is replaced (generally around one third of the core is replaced every 18-24 months). Therefore, there is always a standing inventory of radioactive fission products in the core of an NPP that provides a significant radiological inventory in the event of an accident.

In an FPP, the main material inventories that can have an impact on safety are tritium, activated dust and ACPs. The deuterium fuel is both non-radioactive and non-toxic. The high-energy α particles produced in fusion reactions either give up their energy to the tritium and deuterium ions, transfer their energy by contact with the first wall or are removed by the divertor. If an accident scenario occurred that resulted in the release of high-energy α particles from the VV, they would travel only a few cm in air before losing their kinetic energy and capturing two electrons to form stable helium [77]. The tritium fuel, activated dust particles and ACPs produced are radioactive, however, and can be a cause for concern. Note the radioactivity of the tritium and activated dust inventories is generally orders of magnitude higher than that of ACPs; hence, these radioactive inventories give rise to the most significant safety concerns. Tritium and most activated dust isotopes decay via β-decay and hence do not pose a significant external hazard (the β particle produced from tritium decay has a low energy and penetrating power $\sim$5.7 keV). The most common form of tritium entering the body is ingestion of tritiated water (HTO). However, HTO and its vapour can be absorbed through skin [78]. Tritium can also contaminate local soil regions and be taken up the food chain

via similar processes discussed above for fission products. Once inside the body, tritium does not accumulate in any one area or reside in the body for long periods as it has a biological half-life of 7 to 14 days. However, the ionising radiation released inside the body due to tritium can increase the probability of a person developing cancer in their lifetime [79]. HTO tends to behave in a similar way to ordinary water in the body, evenly distributing itself throughout the body and then excreted via the same pathways as water, primarily through urine [79]. The main activation products of water (if water is chosen as coolant), N16 and N17, can also be a safety concern. N16 is a strong γ emitter and N17 emits neutrons that can cause secondary activation. The γ radiation emitted by N16 and particularly the high energy neutrons produced in the plasma have the potential to damage safety-critical electronic equipment and will require workers to be shielded from the cooling pipes. Any safety related electronics that could be subject to incoming neutrons will either need to be designed in such a way that they can withstand these neutron fluxes or will need to be shielded from them. Whilst FPPs do not build up radioactive products as they continue operation in the same manner as NPPs, in the event of an accident there may be a significant radiological inventory in the activated dust particles that have eroded from PFCs, ACPs that have formed and tritium that has migrated into structural components (there is only expected to be a few grams of tritium in the plasma at any time). The majority of the tritium inventory is not instantly mobile, however, as it will take time to migrate out of structural components.

Whilst the radiological consequences of ingesting/inhaling the radioactive inventories of an FPP can be significant, they are generally considered less severe than ingesting/inhaling the radioactive inventories of an NPP, primarily due to the decay processes that occur and the energy that is then deposited in the body. Nevertheless, inhaling 0.001 g of tritium (in the form of tritiated water) is sufficient to provide a lethal dose[1]. Whilst this quantity may seem small, the preliminary safety report for ITER [80] estimates that in an accident scenario the most-exposed person is only likely to inhale quantities of the order 1×10^{-8} g of tritium due to the safety and protection systems in place, the limited tritium inventory in the VV and the dispersion of tritium in air.

[1]Based on the activity of tritium, the dose conversion factor for tritiated water and a lethal dose estimate of 5 Gy

3.2 Key Operating Characteristics

3.2.1 NPPs

The coolant temperature in a PWR is generally around 550-590 K, but the fuel cladding will be continuously exposed to high temperatures and high heat fluxes (typical value of 1 MW/m^2 throughout its lifetime, equivalent to $\sim$1% of the heat flux at the surface of the sun) [34]. As the cladding contains the radioactive fuel and harmful fission products, designers of NPPs must ensure that it operates reliably in a high temperature/high radiation environment and doesn't undergo significant dimensional changes or degradation in mechanical properties due to stress corrosion cracking or radiation damage [34]. Structural components in an NPP can reach a radiation damage value of 70 dpa (average number of times each atom is displaced from its initial lattice site) over a typical 40-year lifetime [34]. The zircaloy cladding is typically the most damaged component with damage exposures of around 15 dpa, although this is usually replaced every $\sim$5 years [35]. Key safety concerns with the fuel cladding include oxidation, hydriding, build-up of low thermal conductivity corrosion deposits and the effects of hydrogen on cracking and corrosion [34].

The reactor pressure vessel (RPV) in an NPP acts as the primary barrier between the reactor core and the environment. Typically composed of an Mn-Mo-Ni low-alloy steel, the RPV is an irreplaceable component and the lifetime of the vessel tends to define the lifetime of the reactor itself (typically between 40-60 years). Throughout its lifetime, the RPV walls are expected to receive a neutron fluence of 4×10^{23} n/m^2, with an average neutron energy of $\sim$2 MeV [81]. The primary safety concerns with the RPV involve the consequences of intense radiation damage including loss of fracture toughness, embrittlement and cracking [82]. Failure of the RPV can result in the catastrophic release of radioactive inventories to the environment. Due to this, designers and operators of NPPs place heavy emphasis on ensuring the RPV is built exactly to specification and that it is properly inspected and maintained to ensure failure is not credible throughout the lifetime of the reactor. Key safety concerns for the cooling system materials include thermal ageing and complex water chemistry effects that can induce stress corrosion cracking, reducing ductility and increasing the risk of sudden failure of the main cooling pipes [34]. Failure of the main cooling pipes in a PWR can result in a loss of cooling, failure of the fuel and the release of harmful fission

products stored in the reactor core.

As well as loss-of-coolant accidents, NPPs, if not correctly designed or operated, also have the potential for reactivity insertion accidents which can result in a rapid increase in thermal power and fuel failure, again with the resultant release of the fission products in the reactor core. NPP designers/operators must ensure there are sufficient control and protection systems in place to ensure the likelihood of these accidents occurring is acceptably low. Multiple control and protection systems (defence in depth) are also employed at NPPs to prevent or mitigate the consequences of these accidents. The primary approach to safety in NPPs is therefore: control/cool/contain.

3.2.2 FPPs

The temperature of the plasma in an FPP will generally be over 100 million K (approximately six times hotter than the core of the sun). To prevent the structural materials from melting, the plasma is confined with powerful magnetic fields (see Section 2.1). Several studies have been published that provide estimates for first wall thermal loads in DEMO [83]. Radiated power was estimated to reach up to 450 kW/m^2 [84], and additional peak loads by thermal charged particles were estimated up to 650 kW/m^2 [85]. These values are lower than the heat fluxes the fuel cladding in an NPP is exposed to (see above). However, some studies estimate the thermal loads in an FPP could reach the several MW/m^2 region for cases where the first wall surfaces intersect with magnetic field lines [83], [86]. The major safety concern with the VV walls and PFCs is the bombardment of 14.1 MeV neutrons that are produced in the fusion reactions. Upon impact, these neutrons cause severe displacement damage and can result in transmutation which can lead to aggravated degradation effects [34]. The first wall is expected to undergo significant structural damage due to the high energy neutron bombardment, with an estimated dpa value of 150 [34]. This dpa value is significantly higher than that for the most damaged structural materials in an NPP (see above). The divertor is another area which is expected to be subjected to extremely high fluxes, radiation damage, and hydrogen and helium implantation. The challenge for FPP designers is not only choosing a suitable material that can withstand these high heat fluxes and intense neutron radiation damage, but also designing a cooling system that can transfer heat away to maintain their temperatures at sustainable levels under normal operation. For materials making up the first wall, there is very little that can be done

to reduce the initial displacement damage of the incoming neutrons knocking atoms out of their lattice sites. However, methods are currently being studied that effectively recombine many of these vacancies and self-interstitial atoms, so the retained displacement damage in the material is much lower than the initial dpa value [34].

Despite the high temperatures at the core of the plasma in an FPP, the pressure inside the VV is generally much lower than atmospheric pressure (the pressure in the centre of the plasma approaches atmospheric pressure), which, coupled with the volume of the VV, results in a plasma with low density. This results in the nuclear power densities in an FPP being low compared to an NPP [3]. The pressure in the cooling system in an FPP depends significantly on the type of coolant chosen. In the WCLL blanket concept, the cooling water has a temperature of around 300 °C and an average pressure of 15 MPa, similar to the operating conditions of a PWR. In the HCPB blanket concept, the helium has a temperature in the range 300-500 °C with an average pressure of 8 MPa. In the HCLL blanket concept, the heat is removed by circulation of the PbLi itself and helium coolant passing through channels in the structure. The PbLi has an inlet temperature of 450 °C and an outlet temperature of 700 °C, which is above the maximum permissible temperature for the EUROFER steel [27]. Therefore, the PbLi channels are lined by silicon carbide composite inserts, which provide thermal insulation and allow for higher operational temperatures of the PbLi for improved thermodynamic efficiency [27]. Conceptual studies suggest that the tungsten outer walls of blanket modules should not reach temperatures close to the melting point of tungsten during normal operation or during a total loss-of-coolant accident (LOCA) - see Section 4.5.2.1 [27]. However, there are other factors aside from melting point that may impact the suitability of tungsten as a structural material in FPPs. The primary concerns following radiation damage in tungsten are changes in thermal conductivity and embrittlement. The combination of these mechanisms, coupled with the thermal cycling that tungsten will be exposed to in an FPP, can lead to cracking [87], [88]. Research is ongoing in this area to try and limit the effects of these mechanisms.

In an FPP, there is no danger of a criticality accident occurring as there are no fissile materials expected in an FPP. However, uranium impurities in the blanket materials could introduce small quantities of fissile material (Pu239 and U235m can both form from the 0.004 weight % uranium impurity in beryllium [89]). Current focus is on reducing the impurities within materials so as to

not build up inventories of fissile material or problematic radionuclides. The plasma in the VV also exists under extremely precise conditions - any slight changes to these conditions and the plasma dies. In the case of an event or accident scenario that would impair the integrity of PFCs or cause their overheating, impurities from the wall would enter the plasma, causing an immediate thermal quench (generally in the time frame of a few seconds) [3]. The safety analysis at ITER investigated the scenario of over-fuelling the plasma to see if it resulted in any power excursions [80]. However, the analysis found that any over-fuelling of the plasma may temporarily increase fusion power but will quickly lead to plasma instabilities and immediate termination of the plasma. There is clearly no possibility of a core meltdown occurring at an FPP as there is no core to melt. Once the plasma is terminated there is no residual energy in the fuel and hence no decay heat (as is the case in an NPP). However, there will be a small amount of decay heat in the breeder blankets and from tritium absorbed in PFCs. It is clear that some of the primary safety goals when designing and operating an NPP - preventing criticality and core meltdown - do not apply to FPPs; however, as discussed later, the hazard potential of FPPs is not trivial and will need to be managed.

3.3 Radioactive Waste

3.3.1 NPPs and Fuel Cycle Facilities

Radioactive waste in the UK is divided into four distinct categories based on the activity and heat generation level: high level waste (HLW), intermediate level waste (ILW), low level waste (LLW) and very low level waste (VLLW). Spent Nuclear Fuel (SNF) is not technically classed as radioactive waste in the UK, unlike in some other countries, but it is produced in NPPs and is highly radioactive and thermally hot due to fission product decay. HLW is waste which is significantly heat generating ($>$2 kW/m^3) and highly radioactive ($\sim$10^4 TBq/m^3). The UK's HLW results from the reprocessing of SNF where the highly radioactive fission products and some minor actinides are separated from the residual uranium and plutonium in the spent fuel. The separated fission products are vitrified and stored in passively safe stainless steel containers pending disposal. HLW requires significant levels of shielding for hundreds of years. ILW is waste that has a higher activity than LLW but generally requires shielding only and no cooling. LLW and VLLW do not require shielding or cooling.

HLW and SNF are the main areas for concern when considering the waste produced at NPPs and fuel cycle facilities, due to their radioactivity and heat generation. In HLW, borosilicate glasses and ceramics are used to immobilise the unstable fission products recovered from the SNF (e.g. Cs137 and Sr90). Current UK policy states that HLW will be sent to a geological disposal facility (GDF), a waste repository excavated deep within a stable geological environment that is capable of delivering 'passive safety' (i.e. safety and protection measures which do not require human intervention, directly or indirectly) for over hundreds of thousands of years [90]. No GDF currently exists in the UK, however, and the majority of the HLW inventories in the UK are currently in the Vitrified Product Store at Sellafield. The main safety concerns associated with HLW involve ensuring the inventory is isolated from the environment for a time frame that ensures the radioactivity levels of the inventory decrease to levels that are considered non-hazardous for people and the surrounding environment.

SNF typically contains fission products as well as transuranic elements and accounts for over 95% of the total radioactivity produced in NPPs. As stated above, SNF is not classed as radioactive waste and hence is not yet destined for permanent disposal in a GDF in the UK. It is currently stored in interim storage facilities such as reactor ponds - specially designed pools of water (usually built at the same site as the NPP) that provide shielding and cooling capabilities. SNF is typically stored in these pools for periods of up to five years (for PWRs), before being transported to a reprocessing facility or dry cask storage. Reprocessing facilities in the UK, however, have either already closed (THORP in 2018) or are due to close soon (Magnox due 2021). If the SNF can no longer undergo reprocessing, it is instead moved to long-term storage. The behaviour of SNF whilst in long-term storage poses safety concerns because it is not passively safe. If the storage canisters fail in the presence of water, the radionuclides in the SNF are released in two stages: easily accessible radionuclides (mainly from pellet-clad, fracture surfaces, grain boundaries, etc.) are rapidly released; occurring simultaneously but at a much slower rate, the fuel matrix dissolves with simultaneous release of fission products, activation products and actinides. The dissolution of the fuel matrix depends heavily on the redox chemistry of the system [91].

The main safety concerns associated with SNF are similar to those for HLW: ensuring the radioactive inventory is not released before the radioactivity levels have decreased to tolerable levels. The time

frame required for radiation levels to decrease to a level such that the SNF can be handled is around 1000 years [92]. During that time, it is vital that the SNF remains isolated from the public and the environment; this is typically achieved through the use of sophisticated engineered barrier systems. As chemistry with the environment plays a vital role in determining the processes that describe the corrosion of SNF, careful consideration of material properties and the geological disposal conditions (both of which evolve over time) must be taken [92].

3.3.2 FPPs

The main bulk of the radioactive waste produced in an FPP is not related to its fuel (as it is in an NPP); rather, it is primarily related to tritium that has migrated into structural components, breeder materials and structural materials that have undergone neutron-induced activation [93]. FPPs are also expected to produce routine radioactive effluents that are released into the environment; however, these are expected to be controlled at very low levels that will be in accordance with environmental regulations.

Quantifying the total inventories of radioactive waste expected to be produced at FPPs is difficult due to the lack of detailed designs. Recycling processes for the materials at FPPs are also currently being researched and improved upon (e.g. detritiation processes) which will likely significantly reduce the amount of radioactive waste that will be produced [94]. Nevertheless, Gilbert *et al.* have estimated the quantity of radioactive waste produced at DEMO using various breeder blanket concepts, with a focus on the length of time required before the components will be classed as LLW and can be disposed of without the need for shielding or cooling [89].

FPPs are not expected to produce any HLW (as this is produced from the reprocessing of SNF); however, they are expected to produce thousands of tonnes of ILW [89], the majority of this being the breeder blankets, divertor, PFCs and some parts of the vacuum vessel (VV). Whilst this is a significant amount, Ref [89] estimates that radial sub-division of the VV (i.e., separating the VV into higher and lower activity radial regions rather than treating the entire VV as a homogenised mix prior to further processing) should result in a VV that is more than 50% LLW within 100 years (regardless of blanket choice) [89]. FPPs are also expected to produce tens of thousands of tonnes of LLW during their operation and decommissioning, similar to the amount of LLW generated at an

NPP producing equivalent power [95].

The choice of breeder blanket design in an FPP will also influence the amount of ILW produced. Figure 3.3 shows toroidal cross-sections through three DEMO concept models - the helium-cooled pebble bed (HCPB), helium-cooled lithium lead (HCLL) and water-cooled lithium lead (WCLL) - and the predicted time taken for each cell to decay to a point where it can be classified as LLW (as opposed to ILW) [89].

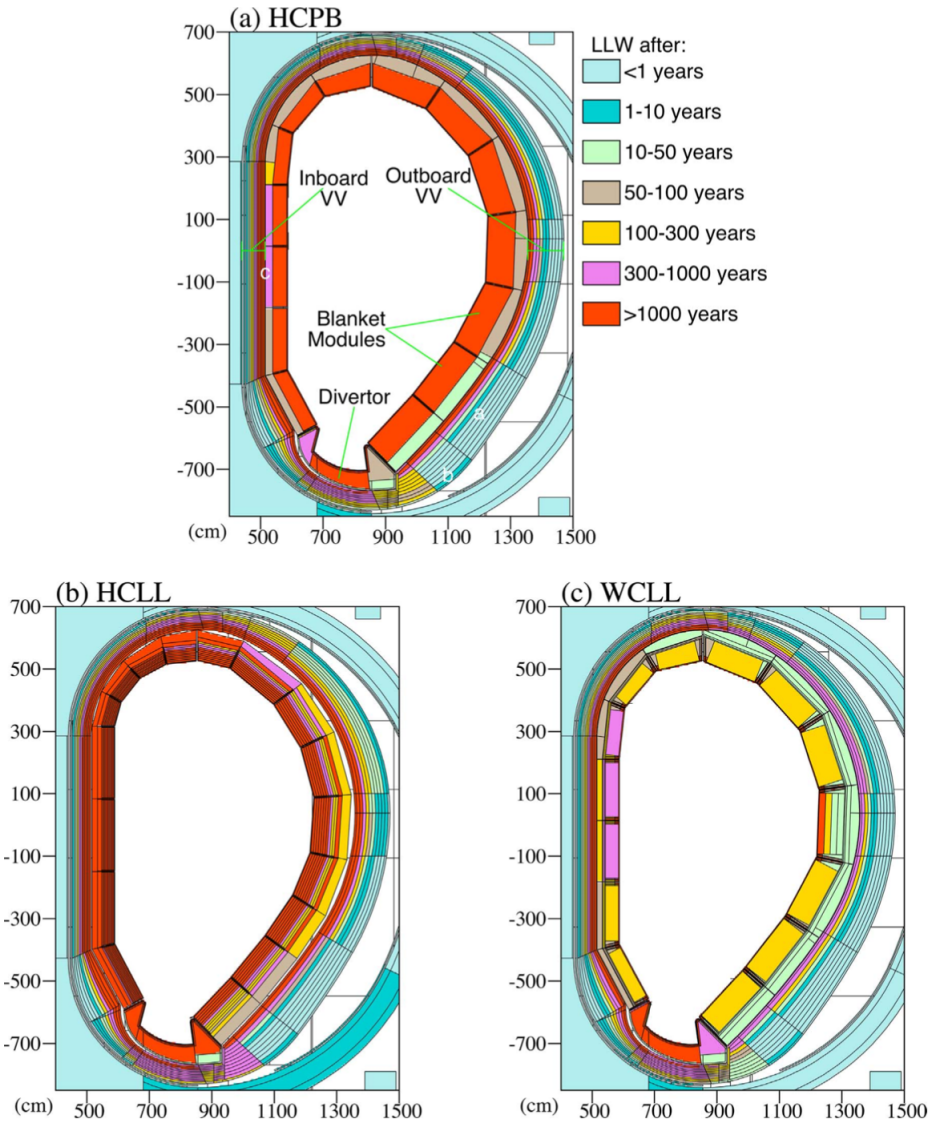


Figure 3.3: Toroidal cross-sections of the DEMO model for (a) the HCPB breeder blanket concept, (b) HCLL and (c) WCLL. The colouring identifies the time interval during which each cell is predicted to satisfy the limits to be classified as LLW (as opposed to ILW). Source: [89]

Figure 3.3c shows that the majority of the WCLL blanket is predicted to be LLW within a time interval of 100-300 years, whereas both the HCPB and HCLL are predicted to remain ILW for over

1000 years [89]. The cause for this is the slight difference in the amount of residual C14 β-activity in the blanket module materials [89]. It should be noted that the blanket designs used in this analysis suffer from a lack of detail; it is expected a more realistic model (in which the blanket components are divided into different material regions) will reduce the time taken for the components to be classified as LLW [89].

Careful consideration of the materials (e.g. low activation) used in an FPP can also significantly reduce the quantity of radioactive waste produced, as can restoring processes such as segregation, detritiation, decontamination and recycling (some of which will be tested at ITER) [94]. Materials are defined as 'low activation' if they either a) display low neutron capture and absorption cross-sections, b) produce stable, short-lived activation products or c) some combination of the two [96]. To avoid the formation of long-lasting radionuclides in structural materials, it is important to maintain low levels of impurities in the materials, as these can activate readily and form activation products that are difficult to remove (such as impurities of iron and molybdenum in the nominally pure tungsten that contribute to the majority of the activity of the divertor armour beyond around 10 years of decay [97]).

It is clear that whilst an FPP is not expected to produce any significantly heat generating HLW that will need to be isolated from the public for hundreds of thousands of years (as is the case with an NPP), the large inventories of ILW waste produced will need to be dealt with at the end of the facility's life. The quantities and types of radioactive waste produced are significantly influenced by design and material choices; hence, FPP designers have the opportunity to minimise the waste produced. A lot of emphasis is placed on improving the economy and efficiency of various recycling and restoring processes (see above) in order to reduce the amount of radioactive waste produced at an FPP. The processes tested at ITER will have to be scrutinised in order to gain an accurate picture of how effective these will be.

Part II

Part II - Review of Literature - FPP Safety, Security and Safeguards

Chapter 4

Nuclear Safety, Security and Safeguards for FPPs

This chapter builds on the work knowledge gained in researching the earlier chapters to review the key nuclear safety, security and safeguards issues for FPPs. Drawing on major studies of FPP concepts and the current work being undertaken for the ITER project, gaps in current knowledge are identified along with areas for future work. Understanding the major nuclear safety, security and safeguards issues and hence the main hazards and risks at FPPs will be crucial when determining the most appropriate regulatory framework for FPPs.

Nuclear Safety for FPPs

4.1 Background

The passing of the *Nuclear Energy Innovation and Modernization Act* [98] in the U.S. in 2019 marked a significant milestone in the development of fusion power, as it required the U.S. Nuclear Regulatory Commission (NRC), one of the world's leading nuclear safety regulators, to develop a regulatory approach for FPPs. Various safety concepts for FPPs have been developed, concurrent with plant design, and these have allowed multiple approaches to be considered.

The aim of this chapter is to provide an analysis of some of the key approaches that are likely to be part of a safety case for an FPP. Key safety gaps are highlighted together with analysis of the applicability of the current safety objectives (see Section 4.2). Where the current objectives are

questionable, recommendations are given on how best to resolve the issues. A literature review was performed to establish the current progress on fusion safety and the critical areas that need to be focused on.

Various European studies were reviewed, including the *Safety and Environmental Assessment of Fusion Power* (SEAFP) [57], [99], [100] and the *Safety and Environmental Assessment of Fusion Power - Long Term Programme* (SEAL) [99], [101]. The *Power Plant Conceptual Study* (PPCS) was used as a basis for FPP designs and for identifying key safety factors and blanket types [27], [102]. The preliminary safety analysis performed in the licensing of ITER (RPrS) [80] was also used as a major reference point, as this currently provides the most comprehensive view of a fusion safety concept in the world.

4.2 Nuclear Safety Objectives

The top-level safety objectives for DEMO are based on international guidelines and similar to those adopted by any nuclear facility [103]. These are:

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

These are worthy high-level goals and are consistent with those adopted for the PPCS; hence, similar objectives would be appropriate for an FPP.

4.3 Risk Analysis

Defence in depth is the basic nuclear safety principle used in NPP design [104], [105]. This approach utilises multiple levels of defence (e.g. confinement barriers/protection systems), so that if one system fails, another will be in place to ensure the safety consequences are limited. This concept of defence in depth can be applied to FPP designs to deliver high levels of nuclear safety, nuclear security and the protection of the environment. In line with good safety practice, the number and extent of barriers required will depend upon both the frequency of the initiating event and its consequences. Whilst the role of these barriers is to prevent the release of radioactive material, there are accident scenarios where the integrity of these barriers will be challenged, hence the need for multiple independent barriers.

Defence in depth requires knowledge of the probabilities of the initiating events, the probabilities of failure of the various barriers and the consequences of failure. For example, events that have a significantly likely probability of occurrence should have minor or no radiological consequences, whilst events that have the potential to result in significant radiological consequences should have a very low probability of occurrence [3]. This is illustrated in Figure 4.1.

The figure depicts the relationship between acceptable risk and not acceptable risk in relation to expected dose to the public and probability of occurrence (risk is defined as probability of occurrence $\times$ consequence of failure). An accident can be plotted on the graph (see red circle) with its expected dose and probability and it can be determined if the risk is acceptable, depending on which zone it lies in. The red line on the graph marks the boundary between these zones. As shown, as the probability of occurrence increases, the dose to the public must significantly decrease in order to remain in the acceptable risk zone. Note both the dose and probability are on a logarithmic scale.

When constructing an FPP safety case, a deterministic approach, complemented when necessary by a probabilistic approach, can be used to identify additional accident sequences to be further considered. If an accident scenario lies outside the acceptable risk zone, there are a number of steps that the designer can take. If the radiological release cannot be reduced, then either an additional containment structure must be provided or another mitigation tactic to reduce the consequences

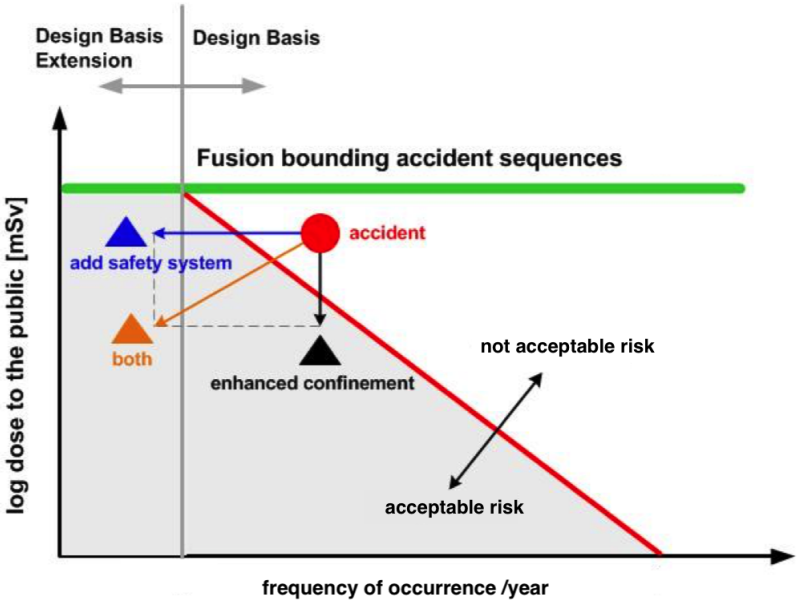


Figure 4.1: Risk approach to safety. Source: [3]. Original: [106] (Edited)

must be employed. Alternatively, additional protection and safety systems can be provided to reduce the probability of the release occurring. Judging what is acceptable is not easy and is often based on public acceptance of a risk of harm when compared to the benefit they gain from the activity that is producing the risk. For NPPs operating in the UK, the law requires risks to be reduced to 'as low as reasonably practicable' (ALARP) and hence there is no simple demarcation between what is acceptable and what is not. Note the ALARP principle is a UK concept that is broadly accepted, which is similar to the principle 'as low as reasonably achievable' (ALARA) used in relation to ionising radiation exposure by other bodies nationally and internationally [107]. The Health and Safety Executive (HSE) document *The Tolerability of Risk from Nuclear Power Stations* (TOR) [108] addresses public perceptions and gives guidance on how these perceptions can be translated into risk. Although originally produced for NPPs, TOR is equally applicable to FPPs and any safety case for an FPP would need to demonstrate that the risk was either broadly acceptable (10^{-6} chance of death/year of operation to a member of the public) or within the ALARP region (less than 10^{-4} but greater than 10^{-6} chance of death/year). See Figure 4.2 below.

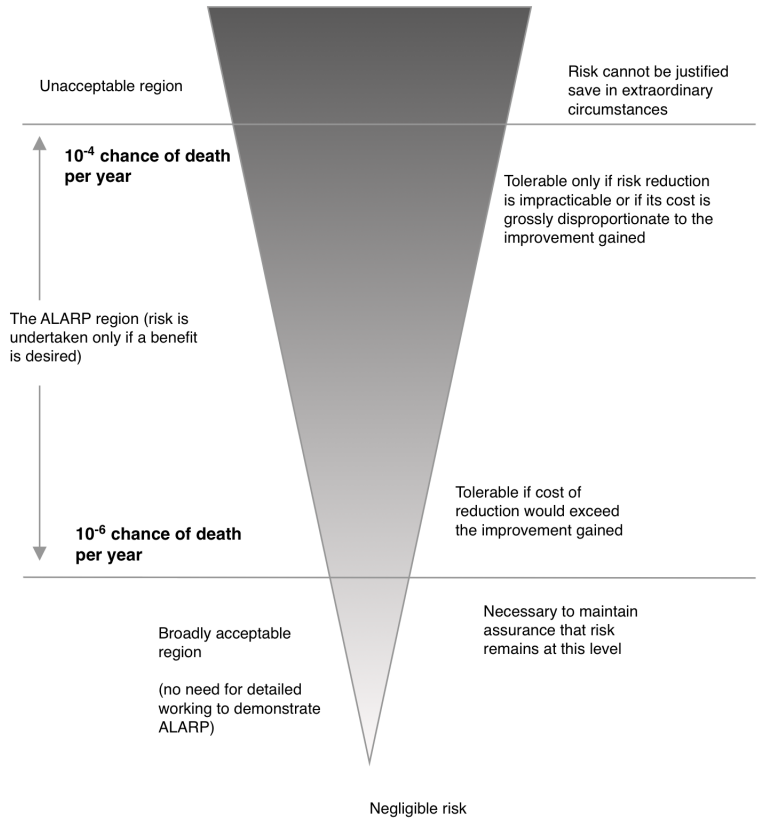


Figure 4.2: Levels of risk and ALARP. Source: [108] (Edited)

4.4 Safety Related Inventories

To meet the above principles the design of FPPs must take account of the hazard potential that results from a number of features, some unique to fusion power. The inherent features of an FPP that give rise to these hazard potentials are the energy and radioactive materials inventories.

4.4.1 Energy Inventories

Energy inventories play a crucial role in the safety analysis of an FPP. Stored energies have the potential to break confinement barriers and mobilise radioactive elements, releasing them into the environment.

4.4.1.1 In-Vessel Fuel Energy

The SEAFP and SEAL studies [57], [99] identified the various energy sources present in a commercial FPP concept. These studies produced conservative estimates of the significant energy sources and

showed that the in-vessel fuel inventory was not a primary safety concern. This finding was based upon the fact that in the event of a plant malfunction or accident, the fusion process would be terminated by shutting off the fuel supply to the plasma. The estimated maximum energy that could be released from the residual fuel in the plasma chamber was estimated to be some 6.5 GJ (equivalent to the energy released when a barrel of oil combusts); this is not sufficient to challenge the integrity of the vacuum vessel (VV). Note this value does not take into account the additional energy from potential combustion of adsorbed hydrogen on PFC surfaces. Further work is needed to accurately determine these additional inventories and evaluate their energy release. The studies also found that the plasma thermal energy is not a primary safety concern: its stored energy was estimated to be only 1–2 GJ.

4.4.1.2 Magnetic Energy

The magnetic energy in an FPP is expected to be relatively large, with toroidal and poloidal coils having energies up to 180 GJ and 50 GJ, respectively [57]. Failure of the magnet systems could result in the discharge of this energy into the wall of the first confinement barrier (the VV) or structural components of the containment system. It is worth noting that multiple penetrations will be present in the VV wall (for auxiliary systems such as heating and diagnostics) and these are the weakest sections of the wall. If the energy from the magnets is discharged into a small area of the VV wall (or its penetrations), it can result in melting of the steel and the initiation of a loss of vacuum accident (LOVA) [57]. Coil quench occurs when part of the superconducting coil suddenly enters the resistive stage as a result of excursions over limits of temperature, magnetic field and current density [109]. In this situation, the magnetic energy from the coil must be removed as soon as possible in order to prevent arcing and damage to adjacent structures. This accident scenario is recognised in the ITER safety case and the ITER design has included an accident mitigation system.

This potential hazard is common to any magnetic confinement FPP and hence all FPP designs will need to have a similar mitigation system to that proposed for ITER. The ITER system includes real-time monitoring, plasma control and stabilisation of magneto-hydrodynamic (MHD) modes [110]. As an example, in the case of coil quench, ITER's superconducting magnets are fitted with a fast discharge system for quench protection; this system dumps the energy safely through the use of

energy dump resistors. During a quench, the flow of current is interrupted and dumped into Fast Discharge Units (FDUs). These are energy dump resistors that discharge the magnets and dissipate the stored magnetic energy as heat [109]. In ITER, the toroidal field FDUs are classified as safety important components (SICs) and perform the safety function of protecting the VV [109].

As the magnetic energy inventories in DEMO (or any other FPP) are expected to be larger than in ITER, the coil quench protection system will be an essential safety design feature, and the substantiation of its performance a major component of the plant's design and operational safety case.

4.4.1.3 Plasma Facing Component (PFC) Stored Heat

The heat generated from the radioactive decay of activated PFCs must be taken into account because of its potential to magnify consequences of accidents. The major structural material expected to be used in FPPs is the reduced activation martensitic steel EUROFER [23], due to its expected performance under fusion conditions. In order to reduce the erosion rates of the first wall, the current approach is to have tungsten tiles form a protective layer (or armour) on the PFCs. Tungsten (W) is also expected to be the main structural material used in the divertor, an area of the plant that will be exposed to extremely high heat fluxes (up to 20 MW/m^2 [111]) and intense radiation damage. The incoming neutrons not only cause cascades of damage in the PFCs but also result in activation and transmutation of the structural materials.

Activated tungsten decays via β-decay to form small amounts of rhenium (Re) and osmium (Os) (expected concentrations in tungsten armour after 5 years in an FPP are 3.8% and 1.4%, respectively) [87], [112]. Tungsten can also transmutate to form trace amounts of tantalum (Ta) (expected concentration after 5 years 0.8%) [87]. The decay heat density of tungsten is expected to be modest, with a value for the first 12 hours after shutdown between 0.2 and 0.3 kW/kg [112]. The structural material of the blankets (typically EUROFER) is expected to be a more significant source of decay heat compared with the tungsten armour, as is, possibly, the breeding materials themselves. The EUROFER first wall is expected to have a decay heat of around 0.1 kW/kg [112], albeit with a much higher inventory than the tungsten armour. The impact of this decay heat will depend upon the accident scenarios that are identified in the design safety case. Further work is needed to ensure

that decay heat effects can be accurately modelled in accident scenarios that have the potential to thermally threaten the integrity of the VV.

4.4.2 Radioactive Materials Inventories

As detailed in Section 2.1, fusion is a nuclear process that uses deuterium and tritium as fuel and results in the production of high-energy (14.1 MeV) neutrons that can activate non-radioactive materials. Tritium is a major radioactive inventory in an FPP and can be found in the VV, coolant, breeder blankets and tritium plant. Understanding and quantifying the potential radioactive inventories from neutron-activated materials is another crucial safety analysis requirement. The amount of radioactive material present determines the hazard potential of an accident, not only to workers but also to the public if radioactive material is released into the atmosphere. The other major inventories identified are activated dust (tungsten or Be) and activated corrosion products (ACPs). Dust refers to the products formed due to the erosion of plasma facing components, whilst ACPs are defined as the products of corrosion within the cooling loops. Depending on the breeder blanket type used in an FPP, there may be additional inventories that are not mentioned here. As things stand, there are four design options with different levels of design and technology readiness being considered for DEMO using helium, water or lead-lithium (PbLi) as a potential coolant (see Section 2.3.2.1) [55]. Until a final decision is made on the breeder blanket type, it remains difficult to identify the radioactive inventories present in FPP blanket architecture.

4.4.2.1 Tritium

Whilst there is only a few grams of tritium fuel in the plasma at any one time, the tritium consumption in the VV amounts to $\sim$165 kg per year (in a standard 1GW$_e$ FPP) and can lead to a build-up of tritium in the VV and fuel and coolant system over time. The use of reduced activation martensitic steel in the VV should result in a relatively low level of tritium absorption, due to its high diffusion coefficients under conditions expected in an FPP. However, the majority of tritium build up will be due to absorption in the W/Be armour and co-deposited tritium in dust [113]. In the PPCS and SEAFP studies [27], [57], the maximum tritium inventory that is able to be mobilised in the event of an accident is assumed to be 1 kg, which results in an inventory of 3.57E+17 Bq.

4.4.2.2 Activated Dust and ACPs

Quantifying the inventories of radioactive dust and ACPs in an FPP remains problematic. Due to the lack of information over the wide range of phenomena taking place during dust and corrosion product production, mainly the plasma-material interactions and the physical and chemical processes involved, the inventory at any one time is based on approximate assumptions and does not take into account the engineering parameters of different plant designs [114]. Nevertheless, an attempt has been made in [115] to identify the potential inventories that can be produced in an FPP along with their activity.

The maximum expected inventory of dust in DEMO has been estimated at 1000 kg [32], [113]. Whilst it remains unclear which isotopes will make up this 1000 kg at any time, a conservative assumption that the entire dust inventory is composed of W185 (this isotope has the highest activity and decays on the timescale of days rather than minutes) would suggest that the inventory of dust available for mobilisation would be in the region of 3.7E+16 Bq. Whilst this inventory is still lower than the inventory of tritium (see Section 4.4.2.1), it is still a significant amount and the potential production of activated dust and ACPs must be taken into consideration at the design stage as this could influence component material selection. Dust will also be produced from materials other than the armour on PFCs, such as stainless steel used in instruments in the walls. Note, at ITER the 1000 kg dust inventory is a maximum administrative limit; dust cleaning during maintenance periods should act to remove much of the dust inventories present in the VV. Further work will need to be carried out to accurately estimate the composition of the activated dust and ACPs to determine an accurate source term that can be used in fault analysis. This can then be used to fully evaluate the consequences of radioactive dust dispersion (as a result of fusion accidents) on the public and the environment.

4.4.2.3 Chemi-Toxic Dust

Identifying and quantifying the chemi-toxic materials in an FPP that can be released in the event of an accident is also problematic, mainly due to the lack of final designs and final choice of materials used. In ITER, the Be dust from PFCs can form chemically toxic beryllium oxide (BeO). In an FPP this is expected to be less of an issue as tungsten is the currently preferred candidate for PFCs rather

than Be. Tungsten can, however, form tungsten trioxide[1] (WO_3) under certain conditions, which can be mobilised by sublimation at temperatures of around 1170 K [116]. The effects of a release of WO_3 need to be better understood, particularly in the case of a LOCA (see Section 4.5.2). Until final designs are completed the use of Be cannot be ruled out and, given that a large quantity of Be may be used in the breeder blankets in some of the design concepts, an understanding of the effects of a release of Be dust is necessary. Further work is required to gain a better understanding of the potential chemi-toxic inventories and their expected compositions in an FPP. Further work is also required to better understand the consequences for the public and the environment of the release of these materials in an accident scenario.

4.5 Key Nuclear Safety Issues

Nuclear safety can be regarded as all those activities that are necessary to protect workers, the public and the environment from a release of radioactivity from a nuclear facility under both normal and accident conditions. Nuclear safety therefore requires a detailed knowledge not only of the radioactive inventory within the facility at any point in time but also of how the facility will handle routine releases, as well as how it will behave under accident conditions. A list of postulated events that could cause a nuclear safety concern in an FPP has been produced utilising the methods of Failure Mode and Effects Analysis (FMEA) and Master Logic Diagrams (MLDs) in [117]. It is claimed that the use of both of these methods ensures a comprehensive list of postulated events.

A selection of design issues and accident scenarios is presented here with a focus on nuclear safety concerns, along with comments on the status of current understanding and the actions needed to resolve them. Whilst this selection is not exhaustive, the accident scenarios detailed below were chosen because they are deemed to be either a primary safety concern or, because there is currently insufficient information available to judge their significance, they have the potential to become a primary safety concern.

It is worth noting that in the accident scenarios considered below, it is assumed that many of the safety and protection systems (e.g. detritiation systems and vacuum vessel pressure suppression

[1] WO_3 has a melting point of 1746 K and a boiling point of 1970 K

system) operate as intended. The risks considered below are therefore mitigated risks, rather than unmitigated risks.

4.5.1 Thermal Inertia

During normal operation the walls of the VV and the breeder blankets store energy. Heat is removed to maintain a steady state temperature profile via the coolant. There is therefore always the potential for a power coolant mismatch should there be an unplanned loss of cooling. If such an event were to occur, there are two possible outcomes. The first is that the loss of cooling protection system fails to terminate the fusion process; the second is that the loss of cooling protection system successfully terminates the fusion process. The consequences of the former are discussed later. In the case of the latter, the loss of cooling capability, even when the fusion process is terminated, will result in a transient change in the temperature of the wall of the VV and the breeder blankets. The safety analysis will need to demonstrate that the temperature transients do not challenge the integrity of the VV (or its penetrations), its supporting structure, the breeder blankets or other key safety related components. The extent and impact of the thermal inertia stored in these key components will need to be taken into consideration in the detailed design of the plant.

4.5.2 Decay Heat Removal

In an FPP, decay heat is not associated with the fuel, as is the case in an NPP, it is associated with the breeder blankets, tritium that has migrated into the structural components and the activated materials in the PFCs. The impact of decay heat removal in the breeder blankets will be discussed later. In relation to the PFCs and other structural components that have become impregnated with tritium, the impact of decay heating arising from the activation of the EUROFER steel, the breeder material, tungsten or tritium will depend upon the activation levels (sustained power levels) and the accident scenario. Decay heat in this context is the heat that is produced in the activated or impregnated materials after shutdown of the fusion process. As shown above in Section 4.4.1.3, the decay heat density from activated tungsten is around 300 W/kg. The decay heat density from tritium is similar at 325 W/kg [118]. However, due to the low levels of tritium present, the overall decay heat from tritium is expected to be low. Whilst the decay heat density from EUROFER steel appears low at 100 W/kg, the large inventories expected means that the overall decay heat from EUROFER

will be significant. The impact of decay heat on the course of accident scenarios, especially in relation to the release of radioactive materials, needs further investigation. The following sections on LOCAs look at the impact of decay heat.

4.5.2.1 Loss-of-Coolant to Breeder Blanket and Divertor

The breeder blankets contain structural materials (EUROFER steel) as well as breeder materials (e.g. Li_4SiO_4) that contribute to the overall decay heat. From Ref [117], the primary safety concern with this decay heat is a potential LOCA. Coolant in this sense refers to the fluid (water, helium, liquid metal etc.) that is used to cool the breeder blankets or divertor during normal operation. The PPCS study [27] investigated a bounding LOCA, resulting in a total loss of cooling from all loops in the plant, with added assumptions of no active cooling, no active safety system operation and no intervention for a prolonged period. Temperature transients in the blanket structures were then obtained for a period of 100 days after the accident, with contributions due to thermal inertia in the structure, decay heat, and tungsten activation and subsequent decay heat. Figure 4.3 shows the poloidal temperature profile in PPCS Model A 10 days after the hypothetical accident.

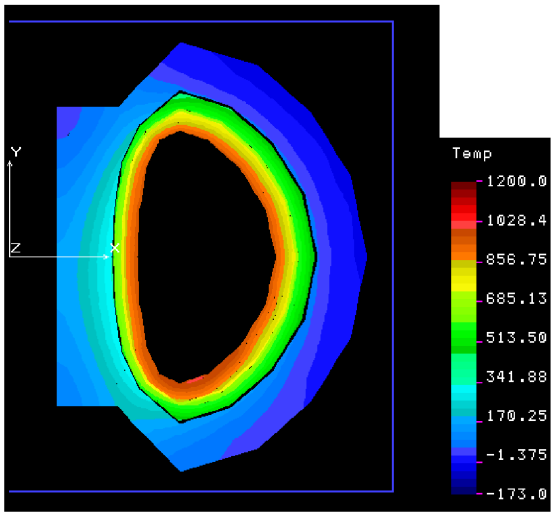


Figure 4.3: PPCS Model A poloidal temperature profile 10 days after a total LOCA occurs. Source: [27]. Note, the temperature scale is in degrees Celsius and Y denotes the vertical direction

The PPCS analysis shows that the tungsten first wall is expected to reach a maximum temperature of ∼1200 °C 10 days after the postulated LOCA. This value is significantly lower than the melting point of W, inferring the component should not fail at this temperature. The EUROFER steel has a melting point of 1325-1530 °C and should also not melt at this temperature; however, there are

other factors that have to be taken into account when substantiating the adequacy of the design in the safety case. One such factor is the formation of WO_3. Analysis by the Materials Assessment Group (as part of the EUROfusion roadmap process) found that in the event of air ingress into the VV (probable due to failure at penetration at this temperature), significant quantities of highly volatile WO_3 could form at a rate of 10-100 kg/h for a surface area of 1000 m^2. It is clear therefore that if a LOCA challenged the integrity of the VV and caused deterioration of confinement barriers, a fraction of this radioactive WO_3 could escape and disperse into the environment [45], [119], [120]. Further work on this is needed to evaluate the likelihood of this event, the amount of WO_3 that could be released, its radioactivity source term and the associated impact on people and the environment resulting from exposure to WO_3. It would be expected that the safety case would be based upon worst-case weather conditions in order to calculate the expected doses to the most-exposed individual at the site boundary. If the level of risk to the public was too great, the design would need to include the provision of an emergency cooling system to remove the decay heat and limit the PFC temperatures to reduce the production of WO_3. Further work is needed on the range of potential accident scenarios to examine not only WO_3 releases but also the potential for hydrogen explosions due to air ingress into the VV (see Section 4.5.4).

4.5.2.2 Loss-of-Coolant to Vacuum Vessel

An in-vacuum vessel loss-of-coolant accident (in-VV LOCA) has been identified as one of the key safety concerns for an FPP. As the accident sequence in an FPP for electricity generation is expected to be similar to that used in the ITER safety analysis (due to the similarities in expected initial plant designs and the final design for ITER), the analysis performed for ITER has been used here as a basis to investigate the impact of a LOCA to the VV and provide an estimate for the radiological consequences.

The key steps and safety responses to an in-VV LOCA scenario are detailed in the ITER RPrS [80]. Initially, a coolant pipe rupture causes the LOCA. This results in coolant ingress into the VV, which in turn causes a plasma disruption: terminating the plasma with a rapid release of thermal energy and potentially resulting in electromagnetic loading on the VV and its supporting structural components. These loads would need to be substantiated to give confidence that the integrity of

the primary confinement barrier (the VV) is not significantly challenged. In order to be explicit, in ITER the primary confinement barrier is defined as the VV and any extensions (i.e. any system that enters the VV or has a barrier that may fail such as first wall/blanket cooling loops).

The hot water entering the VV undergoes rapid evaporation, producing steam which pressurises the vessel. To reduce the potential to over-pressurise the VV, drain and suppression tanks, connected to the VV via rupture discs, are used to enable the steam in the VV to be drained and the steam to be condensed. This is known as the vacuum vessel pressure suppression system (VVPSS). However, these actions result in a significant inventory of radioactive material (maximum estimates are almost 1 kg of tritium and hundreds of kilograms of dust) being transferred to the drain and suppression tanks.

It is expected that the mobilised radioactive inventory of tritium, ACPs and dust will be initially trapped in both the drain and suppression tanks. On the basis of assumptions used in the analysis, it is suggested that the pressure increase in either the drain or suppression tanks will be such that pressures will be maintained below atmospheric pressure (the pressure in the VVPSS is maintained at the level of about 4 kPa to effectively depressurise the VV). The implications resulting from the removal of contaminated liquors from the tanks will need to be assessed, especially in relation to the need for shielding and radioactive waste treatment, which could influence the design of any commercial FPP.

From the analysis in the ITER RPrS, the mobilised radioactive inventory is not released from the drain or VVPSS tanks in the adjacent rooms since pressure remains below room pressure. Given that there are no workers present in the VVPSS tank room or the drain tank room during plasma operation, and that the return to safe state does not require the presence of workers in these rooms, there are no significant radiological consequences for workers [80]. Following the event workers will be exposed to ionising radiation as part of the clean-up and plant recovery activities. However, during these activities worker exposure will be controlled by normal radiation protection procedures, which in the case of ITER will limit worker doses to less than 10 mSv/year [80].

Given that there is no failure of primary confinement barrier (the radioactive inventory cannot escape the VV or travel further than the cooling pipework which, as defined earlier, is part of the primary

confinement), and hence there are no leaks into adjacent rooms and no uncontrolled leaks into the environment, the only potential environmental releases are controlled releases via the suppression tank detritiation system (ST-VS). The calculated radiation doses for most-exposed persons arising from the radioactive release associated with this accident are 9.7E-05 mSv at 200 m and 6.6E-05 mSv at 2.5 km [80]. Such exposures are very low when compared with the 1 mSv limit for members of the public and are orders of magnitude below the evacuation limit (50 mSv).

Whilst the 1 mSv dose limit for the public is generally associated with routine releases during normal operation, comparing this value with the dose predicted for members of the public arising from accident scenarios is useful as it puts the postulated consequences into perspective. As the predicted inventories of DEMO and ITER are expected to be similar, it seems reasonable to assume that even with the added complexity of an advanced reactor (longer running times, presence of breeding blankets etc.), the radiological dose from an in-VV LOCA would not reach levels where an evacuation may be necessary.

There is another accident scenario in which the VVPSS fails to activate (e.g. a mechanical fault occurs in which the rupture discs fail to burst at the specified pressure); the consequences of this could lead to a higher release. This accident needs to be investigated to demonstrate that either 1) the VV will not reach overpressure in the absence of this safety system, or 2) the radiological release due to overpressure has no significant impact on workers or the surrounding public. Until one of these points is met, it remains unclear if an in-VV LOCA is a primary safety issue, or whether the response satisfies the safety objectives outlined.

4.5.2.3 Loss of Cooling During Transfer of Blanket Sectors

The role of the breeder blanket in an FPP is to absorb high-energy neutrons produced in the plasma, extracting heat as well as producing tritium to be used as fuel (see Section 2.4.2). Due to this intense neutron bombardment and the activation of materials in the first wall, the blanket sectors will need to be removed and replaced at various points throughout the lifetime of the plant. The current conceptual design for DEMO suggests that specially designed ports in the roof of the VV will be used for the remote removal of the breeder sectors (or half-sectors). Given the levels of radioactivity of these reactor components (dose rates of DEMO half-sectors during maintenance

have been estimated at around 3 kGy/h [121]), and given that the lethal dose is 5 Gy, changing of the sectors will have to be performed using robotic handling (RH) to ensure worker exposure to ionising radiation is kept ALARP.

Due to their large size, it is expected that the decay heat of each blanket sector will be significant (around 4.55 MW per sector just after shutdown [43]) and therefore will require active cooling during their transfer from the VV to the hot cells. Ref [43] investigated the decay heat of plant components following shutdown on the former Japanese SlimCS DEMO reactor project. This analysis showed that to ensure the decay heat of the blanket had reduced to acceptable levels (< 0.5 MW per sector), it was necessary to wait at least one month after shutdown before transfer of any sectors is carried out. The availability of a power plant is a hugely significant factor and whilst this paper focuses on safety, it seems likely that new solutions will need to be found for tritium breeding in order to reduce this outage time significantly, if fusion is to be economically competitive.

Assuming the current conceptual design for DEMO requires breeder blanket sectors to be removed, it would appear that some form of active heat removal will be necessary during the blanket transfer process. Analysis in Ref [43], [45] and [122] suggests that without this the temperature of the blanket could reach $\sim$1000 °C after around 40 days – a figure considered too high for a component in a zone outside the primary confinement barrier. Designing a safety critical active cooling system for the breeder sectors to enable removal transport to the tritium treatment plant will be challenging. The complexity of such a system will inevitably give rise to safety challenges associated with loss of cooling as shown above.

The safety analysis will require an evaluation of the potential causes of failure of the transport-specific cooling system along with their consequences. However, as this will be a new concept, there will be little if any component failure rate data; as such, a reliable probability of failure analysis will be difficult to obtain. When studying the potential consequences of this loss of transport-specific cooling, a number of factors will need to be considered, namely: recovery times, transient temperatures within the breeder sector, tritium release pathways, location of blanket sectors within the building and the building containment and ventilation capability.

The decay heat removal system is clearly safety critical. The substantiation of the design of the

system will be a major part of the safety case for an FPP and it is clear that the analysis of potential consequences of a LOCA, either during normal operation or during breeder blanket transfer, needs further work.

4.5.2.4 Loss of Cooling in a Dual Coolant Lead Lithium (DCLL) Blanket

The makeup of the breeder blankets can have a significant effect on the safety case. For example, activation of the DCLL blanket produces Hg203 and Po210, whose respective dose factors per ingestion are 100 and 100,000 times higher than for tritiated water [45]. The primary concerns with these radioisotopes are potential spills and releases during maintenance operations. For the test DCLL blanket module (TBM) being developed for DEMO, the end-of-life production of Hg203 and Po210 equates to activities of 1332 GBq and 66.6 GBq, respectively [123]. If an accident were to occur that resulted in the deterioration of confinement barriers and the release of the entire Po210 inventory to the environment, assuming average weather conditions (PG stability conditions D with a wind speed of 4 m/s), the dose at the site boundary would be 0.08 mSv [123]. Similarly, if the entire Hg203 were to be released, the dose at the boundary would be 0.002 mSv. Whilst these doses are low, it is worth bearing in mind these estimates are for a single blanket module. Investigation of the potential consequences of an unplanned release of inventories of Hg203 and Po210 in an FPP needs further work, in order to inform the design of the blanket cooling systems to avoid a LOCA resulting in an unacceptable release of radioactivity.

During operation, the only release pathways for the PbLi coolant in the DCLL blanket are through potential leaks in the pumping systems. This is a similar concern for the release of tritium during operation and will need to be addressed in the pre-construction safety case. Potential spills of the PbLi during maintenance activities will also need to be investigated in order to protect workers. Ref [124] reports work on the modelling of the blanket in a conceptual 1000 MW_e FPP design to identify safety issues and develop mitigation strategies. The most promising approach is the introduction of online bismuth removal to 1 ppm. As Bi209 acts as a precursor to Po210, reducing the Bi209 can limit the Po210 inventory. Due to the volatility of these radioactive isotopes, there is a potential for an off-site release. A detailed safety analysis of the accident scenarios is required in order to determine the appropriate containment system for an FPP.

4.5.3 Loss of VV Integrity

Failure of penetrations in the VV can result in a loss of vacuum and ingress of air into the vessel itself. These are typically called loss of vacuum accidents (LOVA). As part of the RPrS at ITER [80], an assessment of a LOVA found that if a single penetration line is assumed to fail, the resulting air ingress will trigger a disruption, resulting in an immediate termination of the fusion power.

From the analysis, the engineered barriers and protection systems ensure that the tritium and dust masses in the vessel that are likely to escape outside the bioshield are very small (0.32 mg and 6 mg, respectively). Given that there are no workers present in these areas during operation, and the return to safe state does not require workers to be in these areas, there are no significant radiological consequences for personnel.

The calculated radiation doses for most-exposed persons arising from the radioactive release associated with this accident are 0.012 mSv at 200 m (short term) and 0.013 mSv at 2.5 km (long term) [80]; such exposures are very low when compared with the 1 mSv limit for members of the public and are orders of magnitude below the evacuation limit (50 mSv). As the predicted inventories of DEMO and ITER are expected to be similar, it seems reasonable to assume the radiological dose from a single failure of penetration would not reach levels where an evacuation may be necessary.

4.5.4 Hydrogen and Dust Explosion

Within an FPP where there is tritium and deuterium there is the potential for an energetic hydrogen interaction should a failure of the VV result in significant air ingress. Failure of the VV causing significant ingress of air resulting in a combined hydrogen and dust explosion was considered to be a beyond design-basis event for the ITER design. Nevertheless, this event was considered in the ITER safety analysis [80]. The accident sequence chosen considered multiple failures in one of the penetration lines connecting the VV to a port cell, resulting in rapid air ingress into the VV. Hydrogen from the cryopumps was assumed to mix with the air. As the ignition energy required for a hydrogen explosion in air is so low (0.02 mJ), an explosion can spark on any hot surface.

Within the VV of an FPP there is the potential for a large quantity of dust to accumulate. This dust is composed of Be and tungsten that is eroded when the plasma hits the VV walls; in ITER and in

DEMO the maximum limit for dust in the VV is 1000 kg. In the ITER analysis, it is assumed that the hydrogen explosion provided enough energy to initiate a more severe dust explosion (expected energy of around 14 GJ). The combination of these explosions resulted in multiple failure of confinement systems (windows or valves) between the VV and several Port Cells, providing a release pathway for any radionuclides into the atmosphere. Note in this scenario that despite there being a direct release pathway for radionuclides into the environment, it is still assumed that safety and protection systems such as the suppression tank and detritiation systems operate as intended; therefore, this scenario is still not considering an unmitigated risk.

In the ITER analysis, as this scenario was classed as a beyond design-basis accident, no worker doses were calculated; however, the calculated radiation doses for most exposed persons are 0.33 mSv at 200 m and 0.20 mSv at 2.5 km. Radiation doses at this level would again not result in the need to evacuate people in the surrounding areas. Given that the probability of the initiating event is extremely low, even at these dose levels the risks are likely to be in the broadly acceptable region. However, for a commercial FPP, the probability of the initiating event would need to be evaluated to demonstrate this is the case, and that any additional safety measures needed to reduce the risk further would need to satisfy the ALARP criteria.

Nevertheless, such explosions have the potential to compromise the integrity of the VV and the containment/confinement vessel and result in multiple release pathways for radioactive materials. Given the larger size and added complexity of DEMO, or other FPPs, the consequences of a potential hydrogen/dust explosion could be more severe than that shown in the ITER safety analysis. Whilst avoiding ignition sources is not a practical solution (the ignition energy required for a hydrogen explosion is extremely low), mitigation systems that aim to limit the consequences of an explosion are currently being explored. Examples of mitigation tactics for future FPPs include igniters within the VV (which ignite a small amount of hydrogen/air mixture as soon as the lower flammability limit is reached resulting in a less severe combustion), or rapid injections of inert gas to reduce the rate of pressure increase [32]. Another option for designers is to reduce the potential for dust accumulation through material selection for components within the VV and dust extraction systems.

4.5.5 Loss of Plasma Control

Plasma instabilities and disruptions can lead to physical phenomena such as thermal shocks, electron beams, eddy currents, etc. that can, if uncontrolled, threaten the integrity of the VV (e.g. due to electromagnetic loads in VV components and on the vessel itself) [45]. Such instabilities also have the potential to accelerate production of dust from erosion of the first wall and damage the VV cooling system causing coolant ingress (as discussed above).

The ITER safety analysis looked at a scenario that began with an "over-fuelling" of the plasma, resulting in a loss of plasma control and an increase in fusion power. A simultaneous failure of the Fusion Power Termination System (FPTS) and failure of all three first wall cooling loops into the VV were postulated as aggravating factors. This scenario was chosen as a bounding case for events related to loss of plasma control to demonstrate the safety margins of the plant design.

In the event, it is assumed the FPTS fails to stop the plasma on the indication of an increase in fusion power. If this occurs, the FPTS has a backup system in which it stops the plasma burn after receiving a signal that the outlet (VV) water coolant temperature exceeds 170 °C. As it takes roughly 40 s to reach this temperature, it is assumed that both the coolant spilled inside the VV and the in-vessel components are at significantly higher operational temperatures than normal. Future work should investigate the consequences of a loss of plasma control in which the FPTS fails completely.

The ITER RPrS [80] finds that both the temporary increase in fusion power and the increase in temperature and pressure have no significant effect on the VV. Whilst the failure of the cooling loops demonstrate failures of safety critical components, assuming the VVPSS operates correctly, the VV will not reach overpressure and there is no significant release of radiological material.

Similar to the point made in Section 4.5.2.2 (above), further work on accidents/events in which the VVPSS fails is necessary to fully evaluate the potential threat from these types of event. The safety analysis for an FPP must be able to demonstrate that in the event of a loss of plasma control (resulting in an in-VV LOCA), failure of the VVPSS system will not result in overpressure of the VV, or result in a radiological release that has a significant impact on workers or the surrounding public.

4.5.6 External Hazards

In addition to designing FPPs to cope with a range of plant modifications and accident initiating events, it is necessary to consider the challenges posed by external hazards [125]. External hazards can generally be split into two categories: natural events such as earthquakes, extreme temperature, high winds, flooding, precipitation, forest fires, etc.; and man-made events such as aircraft crashes, external explosions, loss of off-site power, etc. [126]. In the SEAFP studies [57], only preliminary consideration was given to the role of external events such as those described above.

4.5.6.1 Bounding Event

In the SEAFP studies [57], an unspecified ultra-energetic event was postulated, resulting in the complete destruction of confinement barriers. In this scenario, the radiological consequences of a ground level release of the full inventory of tritium (in HTO form) would result in a dose to a most-exposed member of the public at 1 km up to about 450 mSv[2] [57]. In this sense this scenario considers the unmitigated dose, i.e. the dose received when no safety or protection systems operate and there are no barriers at all between the radionuclide inventory and the environment, however unrealistic this scenario may be. In order to prevent this scenario, it is clear that any FPP would need to be designed to limit this uncontrolled release of radioactivity in line with the Tolerability of Risk concept [108] and in conformance with Figure 4.1 (above). Consideration of this worst-case scenario is useful to put the potential consequences into perspective and enable appropriate protection and confinement systems to be built into the design [3].

In Ref [57], it was concluded that only certain ex-plant events have a potential for breaching the primary radioactivity confinement barrier. It was suggested that aircraft impact and earthquakes be covered by the design-basis [3]. However, for any FPP design, the range of external hazards to be considered will depend upon the country and location that the plant is sited in.

4.5.6.2 Seismic Events

The design requirements to withstand seismic events depend upon a number of factors including the consequences of an uncontrolled release of radioactive materials and the seismicity of the area

[2]It should be noted that such an event is not based on any realistic assumptions; rather, it demonstrates the maximum radiological consequences of a release of the entire tritium inventory

in which the plant is located. In the case of ITER, the French regulators required that buildings that contain radioactive inventories have earthquake protection [74]. This was to ensure that, in the event of an earthquake, safety important components are not impaired and retain their function. The analysis performed at ITER found that an earthquake itself would not initiate an accident that has not already been covered by the safety case; however, internal and external hazards can act as aggravating factors in an existing situation, for example loss of electric power following an earthquake [80].

The approach adopted for ITER is understandable, but it should not be regarded as a precedent for future fusion facilities. Seismic protection can be costly and can increase design complexity. To justify special design measures to withstand seismic events, it is essential to understand the potential consequences of failure. As such seismic design requirements for FPPs should be risk based, designers of future FPPs will need to evaluate containment integrity based on the radiological release consequences. It is entirely possible that enhanced seismic design requirements may not be justified on safety grounds alone but rather for asset protection reasons.

4.5.6.3 Aircraft Impact

Prior to the attacks on the Twin Towers in New York in 2001, the traditional approach to aircraft crash assessment was to consider the likelihood of an aircraft falling out of the sky and impacting on a facility. These probabilities were generally very low and hence in most, but not all, cases no special design measures were required. However, things have changed, and NPPs now need to demonstrate resilience against a direct aircraft impact. Assessments of aircraft impacts on plant buildings were performed in the safety analysis at ITER [80]. A range of aircraft families were analysed and the probability of a hazard relating to general aircraft impacting on the Tokamak Building was calculated at 1.2×10^{-6} per annum. As this value was above the 10^{-7} per annum limit for a radiologically controlled building (as stated in the Fundamental Safety Rule (RFS) [127]), the hazard must be taken into account in the design of the facility. The analysis showed that the design and layout of the buildings ensures that any impact from a general aircraft would not impair SICs or result in a release of radioactive material. This is generally due to the concrete in the roofs and walls of the tokamak building being sufficiently thick to withstand an aircraft crash or the impact

of structures, liable to fall on them, without causing major cracks or perforations [80].

However, aircraft impact protection is costly and can increase design complexity and hence aircraft protection for any future fusion facilities must be justified. The potential radiological consequences of an aircraft crash must determine the extent to which the plant is designed to protect against them.

4.5.7 Internal Hazards

4.5.7.1 Fire Hazards - Reactor (Tokamak) Building

Fire within a power plant is a recognised internal hazard and, as such, all nuclear installations are designed to limit the initiation and consequences of fire. The preliminary safety analysis (RPrS) of the ITER design [80] addressed the fire risk and showed that it is possible to design a fusion facility so that a fire in the tokamak building (i.e. the building housing the fusion reaction) would not result in a loss of VV integrity, and that the loss of safety functions from damage to SICs was very unlikely [80]. This analysis has shown that with the application of the appropriate fire standards, the risks associated with internal fire hazards in FPPs can be managed. The radiological consequences of a fire breaking out in the tritium plant are discussed in Section 4.5.7.2 (below).

4.5.7.2 Fire Hazards - Tritium Plant

The impact of a fire in the tritium plant was modelled as part of the RPrS at ITER [80]. The analysis assumed the failure of a glove box confinement which resulted in a release of tritium. It was assumed that the entire tritium inventory in the glove box (70 g) was instantaneously released into the room as the fire began. The temperature increase led to a pressure increase; however, it was assumed that the detritiation systems will be able to cope with the room pressurisation during the fire and maintain it under depression. The maximum quantity of tritium (in HTO form) released into the environment was calculated to be 7.3 g.

The calculated radiation doses for most-exposed persons arising from the radioactive release associated with this accident are 1.07 mSv at 200 m and 0.17 mSv at 2.5 km. Whilst these exposures are on the same order as the 1 mSv limit for members of the public, they are significantly below the evacuation limit (50 mSv). Given that this is classed as a beyond design-basis accident, i.e.

a hypothetical event sequence postulated by adding a series of independent aggravating failures, the likelihood of the overall sequence transpiring is extremely low [115]. The objective must always be to make any fault sequence extremely low if the consequences result in the risk not being ALARP/ALARA.

For ITER there is a comprehensive fire detection and suppression system together with a robust defence in depth approach to fire protection [80]. It is clear that there is a potential for radiological release from a fire in an FPP tritium handling plant and hence the fire safety design will require robust substantiation.

4.5.7.3 Electromagnetic Discharge

The magnetic energy inventory in an FPP is expected to be large, with toroidal and poloidal coils having energies up to 180 GJ and 50 GJ, respectively. Failure of the magnet systems can result in discharge of this energy in arcs leading to significant damage to the first confinement barrier (the VV wall). Energy from the magnet is discharged in a small area and can result in a hole forming in the wall, initiating a LOVA [57]. As detailed in Section 4.4.1.2, ITER's magnet system incorporates separate monitoring, fault detection and protection systems that act to minimise the likelihood of magnetic energies damaging the first confinement barrier.

A bounding accident related to this hazard was included in the ITER RPrS [80]. In the scenario, two 1 m^2 holes appear simultaneously, one in the wall of the VV and one in the wall of the cryostat, providing potential release paths to the environment. The hole in the VV wall causes coolant ingress into the VV, causing a pressure rise and effects similar to those discussed in the in-VV LOCA in Section 4.5.2.2. As this scenario was classed as a beyond design-basis accident, no worker doses were calculated; however, the calculated radiation doses for most-exposed members of the public are 3.0 mSv as 200 m and 0.13 mSv at 2.5 km. Radiation doses at this level would again not result in the need to evacuate people in the surrounding areas. However, the safety case for any future FPP will need to address this accident scenario to ensure that the design is robust to reduce the consequences of this type of accident such that the risks to workers and the public are ALARP. FPPs are also expected to have larger magnetic energies compared to that in ITER. Additional work in this area is currently being carried out [3].

4.5.8 Component Failure Rates

Evaluating risk requires knowledge of the probabilities of the initiating event and the subsequent performance of the protection systems. Currently there are large gaps in component failure rate data for evaluating accident probabilities. Failure rates are generally based on empirical data where available. A fusion-specific database has been developed as part of an international collaboration, based on data from typical equipment used in other areas of engineering (such as pipes, valves, ducts, etc.) [128]. Many fusion-specific systems, however, have no empirical data (as they are new) and hence cannot be assigned an accurate component failure rate. In these circumstances judgement has to be used to assign failure rates. In the SEAFP studies [57], failure rates were used to form bands of probabilities defining events as:

- incidents - 1 to 10^{-2} per annum;
- design-basis accidents - 10^{-2} to 10^{-7} per annum; and
- beyond design-basis accidents - $< 10^{-7}$ per annum.

The current international fusion safety community, as illustrated in the ITER project, uses a similar technique but without indicating numerical values for occurrence rates [3]. Instead, ITER defines an incident as an unplanned event that can nevertheless be expected to occur at least once in the lifetime of the reactor. An accident is defined as an event that is not expected to occur; however, precautions are taken in the design to mitigate the consequences if it does. A beyond design-basis accident is defined as an accident with multiple aggravating factors that is not expected to occur and has such a low probability that it is generally not taken into account during design [80].

Looking towards DEMO and other FPPs, it is imperative that the consequences of accidents where safety systems are impaired or fail to act are established. Using the in-VV LOCA as an example (see Section 4.5.2.2), if the VVPSS rupture discs fail to burst, the consequences of an unmitigated pressure rise need to be established. The design pressure limit of the VV will be verified (e.g. in ITER it is expected to be 200 kPa), but there will need to be an analysis of what the peak pressure would be in an in-VV LOCA with failed VVPSS rupture discs and if this peak pressure is sufficient to cause failure of the VV. Whilst rupture discs tend to have a low rate of failure, in order to determine

if this rate is acceptable, one would need to know the probability of the initiating event coupled with the probability of the failure of the bursting disc, as well as the consequences of the likely release. The assumptions around the size of the water ingress in the case of an in-VV LOCA will also need to be substantiated, along with the ability of the VVPSS to cope with a range of water ingress events. This will ensure the VVPSS has been designed to cope with the design-basis event and there was no cliff edge present beyond the design-basis. Given this it is not unreasonable to suggest that more work is needed to identify the range of challenges from the design-basis water ingress assumptions to the VVPSS and the ability of the proposed design of the VVPSS to cope with the design-basis challenge.

As discussed above, the reliability of the plasma control system is vital to the safe operation of an FPP. In an FPP, the control and protection system is likely to be more complex than that in ITER and hence the potential for malfunctions of the plasma control system could potentially increase. Initiating events could result in a rapid increase in fuelling rate or a rapid increase in auxiliary heating [129]. New systems will probably have to be developed that can monitor and control the plasma to limit the likelihood and consequences of these types of events. As these will be new fusion-specific systems, again there will be little empirical failure rate data which will make reliability assumptions difficult to verify in the early stage of FPP development.

Without accurate system and component failure rates, the reliability of FPP control and protection systems will be difficult to verify. To compensate the lack of component failure rates, the operations at ITER will have to be scrutinised in order to provide further input to be used for safety and reliability assessments at future fusion facilities. This work is vitally important to the demonstration of the safety of fusion power and can be used to help develop, build and maintain a comprehensive failure rate database for evaluating accident probabilities.

Nuclear Security for FPPs

4.6 Background

Identifying the issues surrounding nuclear security for FPPs is challenging as there is a lack of open-source material on this area. There are three possible reasons for this: 1) FPPs have not been

close to being realised before now and hence the security concerns surrounding FPPs were of little interest; 2) since the events of 9/11, security requirements for nuclear facilities are generally kept confidential and; 3) a security breach at an FPP is perceived to be a significantly lower threat than a breach at an NPP and hence not a significant concern. To explore the security issues that may be associated with FPPs, it is helpful to first look at the security issues surrounding nuclear facilities currently.

In the UK, the *Nuclear Industries Security Regulations 2003* (NISR) [130] sets out the security requirements for nuclear facilities in the UK, such as the requirement that a security plan is drawn up for each facility and that arrangements are in place to ensure the physical protection of all nuclear material. However, the NISR currently only applies to nuclear licensed sites, sites in which sensitive information is held or sites in which special nuclear material (generally isotopes of uranium, plutonium or other actinides) is used or stored and hence it doesn't apply to FPPs. Likewise, the *Convention on the Physical Protection of Nuclear Material and Nuclear Facilities* (CPPNM) is an international convention requiring the protection of nuclear material and nuclear facilities; however, due to the current definitions of "nuclear material" and "nuclear facilities" within the CPPNM, FPPs and fusion materials (i.e. tritium) are currently excluded from its remit.

NPPs are expected to have robust defence and protection systems to ensure the physical protection of the facility from sabotage and control and protection measures over inventories of nuclear materials. These include but are not limited to: fences with anti-vehicle barriers, motion sensors, advanced detection systems, restricted access zones and armed guards present at all times [131]. The NISR sets out the requirement that NPPs must have an approved security plan that set outs the protection measures in place at the facility. These protection measures are designed to cope with a 'design-basis threat' (DBT). In the U.S., the current DBT for NPPs generally assumes a large paramilitary force with four-wheel drive vehicles, weapons, explosives and assistance from an insider, intent on gaining access to the facility to commit radiological sabotage [131], [132]. In the UK, the DBT is known as the Nuclear Industries Malicious Capabilities (Planning) Assumptions (NIMCA). The security plan must therefore demonstrate that the security measures in place at the facility are sufficient to repel a force as set out in the NIMCA until external assistance arrives[3]. These measures are onerous,

[3]The specific details of the NIMCA are classified and are not made public for obvious reasons

time-consuming and costly, but they are considered proportionate to the high hazard potential of NPPs and the catastrophic radiological consequences of the potential sabotage of an NPP or the theft of special nuclear materials and technology. Whilst the hazard potential of FPPs is significantly lower than that of NPPs, FPPs will contain radiological inventories that, if released due to an act of sabotage, could present a significant radiological hazard. There are also political issues relating to the theft or sabotage of tritium on a facility that could threaten national security and potentially the security of supply of electricity. Due to these factors, it is worth considering the potential security issues associated with FPPs.

4.7 Key Nuclear Security Issues for FPPs

When constructing a safety case for a nuclear facility, it is necessary to demonstrate that the risks to workers and the public from design-basis accidents are sufficiently low. Design-basis accidents are not worst-case accidents; rather, they are judged to be of a high enough probability (coupled with a high enough radiological dose if not prevented) that they require design measures and substantiation in the safety case. Typically, in a design-basis accident it is assumed that all automatic safety systems, emergency core cooling systems and confinement barriers operate as expected, and that operators can intervene to mitigate any effects [131]. Beyond design-basis accidents go further than this and assume multiple system failures and generally result in a greater radiological release. Beyond design-basis accidents in general do not require specific design measures to prevent or mitigate their consequences. However, emergency arrangements and emergency operating procedures are required to mitigate the consequences of these events. When considering the security issues at a nuclear facility, however, it is necessary to consider events that have a significantly low probability of occurrence. Whilst these events may be extremely unlikely to occur as part of an accident scenario, they could be caused by saboteurs intent on causing a large radiological release [131]. Therefore, when considering security at an FPP, it is necessary to consider how the safety of the FPP could be compromised via sabotage of the plant and whether this could result in a significant radiological dose to the public.

4.7.1 Loss-of-Coolant Events (LOCE)

Section 4.5.2 demonstrated that, provided all emergency safety systems operate as intended, a LOCA to the VV or breeder blankets and divertor would not result in significant off-site radiological consequences. The design of the VV (and its corresponding drain and suppression tanks) and the detritiation system ensures that there would be no uncontrolled releases of radioactive material into the environment. When considering security, however, it is necessary to consider scenarios in which some emergency safety systems are rendered inoperable, either by a physical attack (i.e. explosives) or human intervention. Saboteurs could also damage confinement systems (e.g. the VV wall) providing a direct release pathway into the environment. The feasibility and radiological consequences of a loss-of-coolant coupled with acts of sabotage, a loss-of-coolant event (LOCE), needs to be analysed to determine whether this is a key security issue. If the probability of saboteurs being able to disable safety protection systems and initiate a LOCE is extremely unlikely or the radiological consequences of such an event are low, then it may not need to be considered in any security plan. However, if the probability is not too low or the radiological consequences are unacceptable, then security measures must be taken to ensure that the likelihood of saboteurs gaining access to the plant is extremely low. This can be achieved by the use of armed guards, advanced surveillance systems, restricted access, etc.

4.7.2 Direct Attack on the Vacuum Vessel (VV)

In an NPP, a direct use of explosives on the reactor core in an attempt to release the radiological inventories within would not be worthwhile because of the lack of accessibility to the core and that disabling safety systems would be sufficient due to the high levels of decay heat within the core. Given that commercial FPPs will not have a standing inventory in the VV, the focus could be on using explosives to breach the VV wall and outer confinement buildings to provide a direct release pathway into the environment. Section 4.4.2 highlighted the radiological inventories that are expected to be present in an FPP; if these inventories have a direct pathway into the environment the consequences could be significant. Further work is needed to evaluate the likelihood and radiological consequences of such an event. If the risks are intolerable, then FPPs may need strict security measures, not dissimilar to those found at NPPs, in order to deter terrorists from attempting to

produce an uncontrolled release of radioactivity.

4.7.3 Control of Tritium / Sabotage of Tritium Plant

Currently, tritium is not classed as a "nuclear material" by the International Atomic Energy Agency (IAEA) and does not come under the remit of the CPPNM, nor is it controlled under the *Treaty on the Non-Proliferation of Nuclear Weapons* (NPT) [133]. The regulatory regime governing the security and control measures over stockpiles of tritium is therefore considerably less stringent than for nuclear materials such as uranium or plutonium. Whilst tritium cannot be used to produce a nuclear weapon in the absence of fissile materials, it can be used to boost the yield of fissile weapons, including those based on reactor grade plutonium [134].

Up until now, there has been no demand for strict security over stockpiles of tritium, as the primary method of producing tritium is by irradiating absorber rods in an NPP (see Section 2.1) which undoubtedly already has strict security measures. However, if FPPs are successfully deployed, there will be significant quantities of tritium stockpiled at every site (current estimates are a $1GW_{fus}$ FPP will require a strategic stockpile of 5-10 kg of tritium to meet security of supply requirements [135]). Moreover, the tritium plant at an FPP is expected to cycle through large inventories of tritium and will likely be much more accessible than the tokamak building or the VV, making it a possible target for potential sabotage.

Given that tritium can be used to boost the effectiveness of nuclear weapons and a large release of tritium can result in significant radiological consequences for the public, it therefore seems reasonable to suggest that there will need to be some form of security requirements to demonstrate adequate control over inventories of tritium at FPP sites and to deter potential sabotage of the tritium plant or tritium storage facilities.

4.7.4 Political Effect

Another factor that must be taken into consideration when examining security issues at FPPs is the political effect that sabotage or occupation of an FPP by terrorists or other activists may engender. Whilst analyses may demonstrate that the radiological risks due to sabotage of an FPP are not severe, the political consequences of such an event may be significantly more damaging than

the radiological consequences. It would be a huge political embarrassment for any government if terrorists (or a political organisation) managed to successfully infiltrate and take control of an FPP, irrespective of the potential harm to the public. In view of this, politicians may require an FPP to have sufficient security measures in place to deter potential saboteurs to provide both public and political confidence in the use of the technology.

Nuclear Safeguards for FPPs

4.8 Background

As with nuclear security, there is little open-source material addressing nuclear safeguards issues at FPPs. This again may be due to FPPs not being close to the point of being realised before now and the perception that the absence of fissile materials such as uranium or plutonium in the fusion fuel cycle means that there are no safeguards issues worth considering. However, there are safeguards concerns that need to be addressed. To explore the safeguards issues that may be associated with FPPs, it is helpful to first look at the safeguards issues surrounding nuclear facilities currently.

Although the NPT doesn't require its five nuclear-weapon states (UK, U.S., China, France and the Russian Federation) to adopt safeguard agreements, they all have voluntary offer safeguards agreements (VOAs) with IAEA to accept safeguards over some or all of their civil nuclear activities. The UK VOA [136] stipulates the UK shall accept the application of safeguards on nuclear material and facilities and will co-operate with IAEA to ensure appropriate safeguards are implemented[4]. The *Nuclear Safeguards Act 2000* (NSA) [137], the *Nuclear Safeguards Act 2018* (NSA18) [138] and the *Nuclear Safeguards (EU Exit) Regulations 2019* (NSR) [139] set out the safeguards requirements for nuclear material and facilities in the UK, such as implementing accountancy and control measures over inventories of nuclear material, granting inspections and verification processes by the UK nuclear safeguards regulator (ONR) and IAEA, and abiding by import/export controls when consigning or receiving nuclear materials. However, due to the current definitions of "nuclear facilities" and "nuclear material" by IAEA, FPPs and fusion materials are currently excluded from any safeguards obligations.

[4]The UK has also agreed an Additional Protocol with IAEA that goes beyond the provisions set out in the VOA

Operators of NPPs and fuel cycle facilities are expected to maintain high standards of nuclear material accountancy and control to ensure that nuclear material is not diverted unlawfully into military or weapons programmes. Operators/licensees of NPPs and fuel cycle facilities are required to declare to ONR the basic technical characteristics of the facility and must submit to ONR an annual outline of a programme of activities indicating provisional dates for taking a physical inventory. ONR may then impose safeguards obligations based on the type of facility and type and quantity of nuclear materials present. Operators must also submit operating records and material accounting records to ONR to show all material balances and inventory changes that have occurred. ONR then submits nuclear material accounting reports and basic design information to IAEA for the application of safeguards. Operators are required to grant ONR and IAEA access to facilities and nuclear materials to allow verification activities to take place, which may include real time monitoring and physical inspections. If operators wish to consign or receive nuclear material to/from outside the UK, they must give advance notice to ONR and abide by import/export controls. These measures are onerous, time-consuming and costly, but they are taken due to the potentially catastrophic consequences of diversion of nuclear material. If inventories of uranium or plutonium are diverted they can be utilised by a rogue state or a terrorist organisation in such things as improvised nuclear devices (INDs), fission weapons or thermonuclear weapons with devastating consequences. Whilst FPPs are not expected to have inventories of uranium or plutonium on site, there are still safeguards concerns that need to be addressed.

4.9 Key Nuclear Safeguards Issues for FPPs

A selection of nuclear safeguards issues for FPPs is detailed below. This list is by no means exhaustive; rather, it is meant to demonstrate that there are safeguards concerns that will need addressing if FPPs are to be successfully deployed.

4.9.1 Control over Tritium Inventories

As discussed above, tritium is not currently classed as a nuclear material by IAEA and inventories of tritium are not controlled under any safeguards obligations. The rationale behind this is that tritium cannot be used to produce a nuclear weapon in the absence of fissile materials [134]. Nevertheless,

tritium can be used to boost the yield of nuclear weapons and is a key component in the production of thermonuclear weapons. As demonstrated in Section 4.7.3, if FPPs are successfully deployed there will be multiple sites in the UK with significant quantities of tritium stockpiled and as tritium can be used to boost the effectiveness of nuclear weapons, it seems reasonable to suggest there may need to be a safeguards regime implemented to ensure sufficient control over these tritium inventories.

4.9.2 Using an FPP to Produce Fissile Materials

Since the events of 1974, in which India detonated a nuclear weapon containing plutonium produced from CANDU heavy water reactors sold by Canada, there have been concerns that civil nuclear reactor technologies sold to foreign countries could be adapted and used to produce nuclear weapons. Given the materials and neutron fluxes expected in FPPs, there is the concern that FPPs may be adapted and used for this very purpose. Ref [135] looked at the potential methods of using FPPs to produce fissile materials and determined that there are three primary approaches worthy of consideration: 1) clandestine production of fissile material in an undeclared facility; 2) covert production of fissile material in a declared facility and; 3) use of a declared facility in a breakout scenario. These scenarios will be briefly examined here.

4.9.2.1 Clandestine Production of Fissile Material in an Undeclared Facility

The first scenario postulated in Ref [135] is the clandestine production of fissile material in an undeclared facility. Whilst it is generally acknowledged that there is no credible risk that a GW-scale FPP could be built and operated in a covert fashion (the size and power consumption of such a facility would make it simple to detect), there exists the possibility that smaller FPPs could be built and operated covertly [135].

Ref [140] investigated the possibility of using an FPP with special breeder blankets containing fertile material to maximise production of Pu239 and U233 (using the 14.1 MeV neutrons produced) to use as fuel for NPPs. Known as a fission-fusion hybrid system, a facility such as this was estimated to be able to use each neutron to produce up to 0.64 Pu239 or U233 atoms, with a tritium breeding ratio (tritium nuclei produced per neutron) of 1.06 [135], [140]. However, the analysis showed that no experimental fusion facility currently in operation could credibly be used for these aims. Current

fusion experiments can produce D-T fusion powers of around 10 MW but generally for time frames of less than a second [135]. These facilities are also extremely easy to detect. As an example, the Tokamak Fusion Test Reactor (TFTR) at the Princeton Physics Laboratory required up to 1000 MV A of pulsed magnet power for its D-T experiments [7]. The facility requires significant energy storage equipment and the site has an area of around 100,000 m^2, not including the control room or cooling tower, making it easily identifiable on public satellite imagery [135]. It is therefore increasingly unlikely that an experimental fusion facility similar to those currently in operation could be constructed and operated in a clandestine fashion to produce fissile material.

A more likely scenario is the use of a compact fusion device (e.g. an ST) to generate the neutrons required to produce fissile material. Ref [135] investigated the possibility of using a small ST with breeder blankets containing fertile material to produce significant quantities of Pu239 or U233. Note IAEA, under the NPT, has defined "significant quantity" (SQ) as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded... [taking] into account unavoidable losses due to conversion and manufacturing processes" [135], [141]. The current SQ for both Pu239 and U233 is set at 8 kg [141]. The analysis in Ref [135] found that it would take over two years of operation to produce an SQ of either Pu239 or U233 in an undeclared compact ST. However, to achieve this the facility would need a continuous power supply of 40 MW which would require large electrical supply lines and power conversion buildings, as well as a substantial cooling system and a reactor building with significant shielding, all of which would make the facility quite visible [135]. In addition, trace amounts of tritium that escape from the facility (unavoidable for any fusion facility operating with tritium) would be detectable for a distance of tens of kilometres (due to its environmental signature) [135]. The fertile material that would need to be added to the breeder blankets would most likely be U238 or Th232, each of which would need to be diverted from a pre-existing nuclear fuel cycle facility (under IAEA safeguards) or produced in a separate covert facility [135]. Due to these factors, the construction and operation of an FPP in a clandestine fashion to produce fissile materials is considered extremely unlikely.

4.9.2.2 Covert Production of Fissile Material in a Declared Facility

Another safeguards issue worth considering is the possibility of covertly adding fertile uranium or thorium into the breeder blankets or coolant, allowing the uranium or thorium to transmutate into fissile material and then chemically extracting the fissile material at a later stage. Ref [135] investigated the feasibility of inserting micro-fuel (TRISO) particles containing fertile uranium or thorium into the coolant of the DCLL blanket (see Section 2.3.2.1) to produce inventories of either Pu239 or U233. The analysis found that there are two limiting factors which ultimately limit the amount of fuel particles able to be added to the coolant: reduction in the tritium breeding ratio (ratio of the rate of tritium production to the rate of tritium burned in plasma) and increased heat load in the blanket. Figure 4.4 shows simulation results illustrating the effect of increasing the concentration of TRISO particles on the tritium breeding ratio (TBR) in the DCLL blanket.

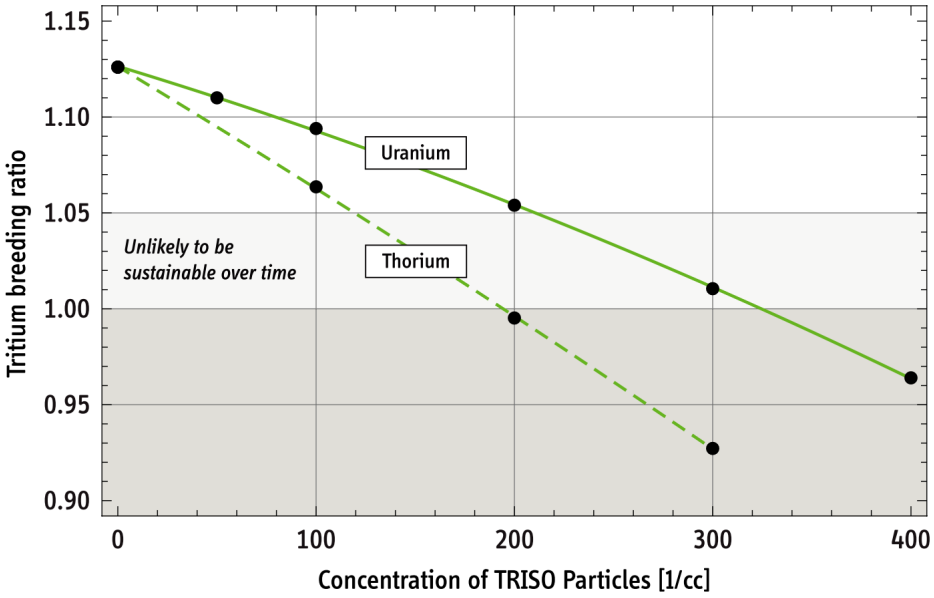


Figure 4.4: Impact of TRISO particles on tritium breeding ratio. Source: [135]

From the figure, it can be seen that increasing the concentration of TRISO particles containing fertile uranium or thorium causes a steady decrease in the TBR. An FPP operating at steady state must be capable of breeding a sufficient quantity of tritium to replace the tritium consumed in the plasma. A TBR value < 1.1 is considered an insufficient buffer to maintain tritium self-sufficiency and protect against losses during extraction and transport. A loss of 5-10% in the TBR is likely to be unsustainable in an FPP operating at steady state and would require a reduction in operational power

[135]. The increased heat load (caused due to additional neutrons produced in uranium fast-fission events going on to interact with lithium) would also be problematic. Increasing the concentration of TRISO particles results in increased heat deposition in the blanket, which would result in operators needing to reduce the fusion power in order to maintain a steady state temperature profile via the coolant. It is currently unknown whether an FPP could operate under a significant reduction in fusion power. Ref [135] estimates that a reduction of more than 50% fusion power will be difficult to achieve whilst the plant remains operational.

Despite these hurdles, it is still feasible that rogue states could attempt to use FPPs to covertly produce fissile materials in a manner similar to that discussed above. It therefore seems reasonable to suggest there will need to be some form of safeguards applied to FPPs to deter rogue states from attempting this strategy (or similar strategies). Ref [135] highlights the relatively simple steps that ONR/IAEA could take to regulate safeguards to recognise when fissile material is being produced covertly (take random samples of coolant and test for quantities of fertile material, use detectors to detect large gamma emissions that occur due to the decay of U238 or U232, undertake routine inspections to ensure there are no undeclared coolant injection/extraction systems, etc.). Whilst the use of a declared FPP to covertly produce fissile material is considered a possibility, the application of some form of safeguards should ensure that the proliferation risk is kept low.

4.9.2.3 Use of a Declared Facility in a Breakout Scenario

The final scenario considered in Ref [135] is a 'breakout scenario', in which a nation or state exiles IAEA inspectors and uses FPPs to rapidly produce and stockpile weapons-grade material. A breakout scenario is a significant international concern for countries that operate fleets of NPPs due to the devastating effect of nuclear weapons. The main difference between a breakout scenario with a fleet of NPPs and a fleet of FPPs is the availability of nuclear material at the time of breakout. With NPPs, it is expected that at the time of breakout a substantial amount of weapons-grade material has already been produced. However, with FPPs, assuming IAEA safeguards are implemented and are operating effectively, there should be no fissile material produced at the time of breakout [135].

The two most likely methods of producing fissile material in an FPP in a breakout scenario are identified in Ref [135] as: 1) increased loading of TRISO particles into breeder blankets or coolant

to maximise fissile material production or 2) plant shutdown and restart with alternative blanket modules containing fertile material in solid form. Ref [135] analysed both scenarios and found that it would take at least one month for a nation or state to adapt an FPP to be able to produce an SQ of Pu239 or U233, provided safeguards were operating effectively before the point of breakout. This would give the international community at least one month to be able to respond to this threat. Ref [135] also points out the relative ease with which FPPs should be rendered inoperable as they require multiple supporting facilities to operate (huge power supply units for magnets, cryoplant, external cooling towers, etc.). Disabling any one of these should render the plant inoperable and, based on the generic site layout for ITER, these buildings should be situated far enough away from the tokamak building that disabling them shouldn't pose a significant risk of exposure to harmful levels of radiation [135]. However, it should be noted that commercial FPPs may have a significantly different design and site layout to ITER and therefore rendering the plant inoperable may prove more challenging.

Further work is needed in these areas to accurately determine the proliferation risk from FPPs; however, it can be seen that the proliferation risk is not zero, and there will need to be some form of safeguards in place to deter states from using FPPs or fusion materials to produce nuclear weapons. The proliferation risks from FPPs appear to be lower than from NPPs, primarily due to the amount of fissile material expected to be present on site. However, it can be seen that without a proper accountancy system and safeguards in place, FPPs can be adapted to produce weapons-grade material in a relatively short time frame. It is therefore reasonable to suggest that there will need to be some form of safeguards in place at FPPs that are proportionate to the proliferation risk that FPPs pose.

Part III

Part III - Review of Literature - FPP Regulation

Chapter 5

Mapping International Approaches to Fusion Regulation

Before mapping out the regulatory options available for FPPs in the UK, it is useful to first look at how different nations are planning to regulate FPPs, particularly whether they are planning to regulate them in a similar manner to NPPs or adopt an entirely new approach. This information will be used to help map out the regulatory options available in the UK.

5.1 Background

Mapping how major nations plan to approach fusion regulation provides not only a crucial insight into the current international mood surrounding FPPs, but also a glimpse of the roadmap that designers, operators and regulators of FPPs will need to traverse as the technology is realised. As will be shown in this chapter, some nations have already decided their approach to fusion regulation whereas other nations are still undecided. Nevertheless, the fact that some nations have already decided their approach does not imply that this approach is correct or that it should set a precedent in how FPPs should be regulated.

This chapter will focus on international approaches as well as national legislation and regulations. The licensing of ITER will also be used as a major reference point, as this is the only example of the licensing of a fusion facility that currently exists. Note this chapter focuses mainly on nuclear safety

rather than nuclear security and safeguards, as the approach to regulating nuclear safety has a much bigger impact on the regulatory framework overall when compared to security and safeguards.

5.2 IAEA

There is limited information regarding fusion regulation published by the International Atomic Energy Agency (IAEA). The only related document is a recently published technical document (TECDOC) on an *Integrated Approach to Safety Classification of Mechanical Components for Fusion Applications* [142]. A key area of the TECDOC highlights the use of a zoning scheme that identifies areas of different radiation levels in order to limit exposure to ionising radiation within an FPP. The zoning scheme summarised in the TECDOC is the scheme used at ITER and DEMO and is based on French regulations [142]. However, whilst this document provides guidance on how to design components, how to select appropriate design codes and how to classify components using a graded approach based on their importance to safety, it fails to give an insight into how IAEA will approach regulating FPPs. Due to the accelerated development of FPPs in recent years, it is expected that IAEA will publish material on fusion regulation imminently, with two separate TECDOCs expected at the end of 2021.

5.3 U.S.

5.3.1 Background to U.S. Legal Framework

To properly understand whether or how FPPs are to be regulated in the U.S., it is necessary to examine the statute which "establishes the national regulatory framework governing radioactive materials and significant uses of atomic energy" [143] - the Atomic Energy Act of 1954 (AEA) [144]. The AEA provides the general rules for all civilian uses of radioactive materials and nuclear energy ranging from low-range medical devices to large-scale NPPs. The AEA has a vast range of regulatory frameworks for regulating different types of materials or facilities: 10 CFR Part 30 involves the licensing of byproduct materials (see below); 10 CFR Part 50 involves the licensing of production and utilisation facilities (e.g. NPPs); and 10 CFR Part 70 involves the licensing of facilities that manage or handle special nuclear material but are not classed as utilisation facilities (e.g. fuel cycle facilities). These frameworks will be explored further in this chapter.

The AEA covers facilities that use, produce or manage radioactive materials, as well as facilities that use "atomic energy in such quantity as to be of significance to the common defense and security, or in such manner as to affect the health and safety of the public" [144]. NPPs are regulated facilities under the AEA (these are termed "utilization facilities" [144]), as are medical isotope and fuel cycle facilities [143]. The AEA also controls all civilian use of radioactive materials, including byproduct materials (i.e. naturally radioactive materials, materials that have been made radioactive by use of a particle accelerator, and other materials, such as low level radioactive materials that have been produced via irradiation, nuclear decay or transmutation) [143], [144]. Tritium is currently regulated under the AEA and by the Nuclear Regulatory Commission (NRC) as a byproduct material. The extent to which FPPs will be regulated in the U.S. is based on the interpretation of the wording of the AEA and the perceived hazard potential of FPPs. Before exploring the potential approaches to fusion regulation in the U.S., it is worth expanding on the roles of the regulators.

5.3.2 Department of Energy (DOE)

Created in 1977 with the *Department of Energy Organisation Act 1977* [145], the Department of Energy (DOE) is a department of the U.S. Government concerned with energy policy, national security, environmental challenges and radioactive waste disposal, as well as overseeing the nation's nuclear weapons program and NPP production for the U.S. Navy [146]. The DOE is also a central hub of scientific research and innovation, providing funding for and overseeing a wide range of renewable technology programmes, plans for advanced NPPs and fusion energy projects. This last point is achieved through its Fusion Energy Sciences (FES) program that manages three major experimental facilities: the National Spherical Torus Experiment (NSTX) at Princeton, Alcator C-Mod at MIT and the DIII-D tokamak at General Atomics in San Diego. The DOE also funds multiple fusion-related projects and is responsible for the U.S.' participation in ITER [146]. The DOE therefore has decades of experience managing fusion devices and acutely understands the technical challenges involved with fusion, having published documents outlining safety requirements of magnetic fusion facilities and supplementary handbooks on fusion safety standards [147], [148].

The DOE has played a crucial role in advancing the U.S. fusion power programme and has successfully managed and operated multiple experimental fusion facilities whilst ensuring the safety of workers

and the public [146]. Whilst the DOE has experience in approving and supervising experimental fusion facilities, it does not issue nuclear licences; rather, it authorises the necessary activities [146]. This approach is taken in other countries (UK, Canada, etc.) that manage experimental fusion facilities as "low hazard facilities more akin to radiological laboratories" than large power plants. [149].

5.3.3 Nuclear Regulatory Commission (NRC)

The Nuclear Regulatory Commission (NRC) was created in 1974 with the *Energy Reorganisation Act of 1974* [150] as an independent agency of the U.S. Government tasked with overseeing safety and security at NPPs and other nuclear installations, issuing reactor licenses and supervising their renewal, and regulating the recycling and disposal of spent nuclear fuel [146]. Prior to the formation of NRC, all military and civil use of nuclear power was governed by the U.S. Atomic Energy Commission (AEC). The Act divided the functions of AEC into two separate entities: the Energy Research and Development Administration (now the DOE) and NRC [146].

Under the AEA, NRC can delegate regulatory authority to so called "Agreement States" [144]. These are state regulators that are handed responsibility for regulating certain lower-risk activities (e.g. activities involving byproduct materials, applications for medical devices or cancer treatments), as well as source materials and small amounts of special nuclear materials [151]. Most U.S. states are Agreement States; therefore, in these states the state regulator is the primary nuclear regulator-in-practice for any proposed activities. However, Agreement States are prevented from exercising regulatory authority over NPPs, high-level nuclear waste or large amounts of special nuclear material - jurisdiction over these facilities and processes remains with NRC [146].

5.3.4 U.S. Regulatory Frameworks

The wording of the AEA allows for varying levels of regulation dependent on the hazard potential of the activity/facility being regulated [144]. As a result, NRC has developed various regulatory frameworks for different types of activities/facilities. The frameworks that may be relevant to FPPs will be expanded upon in this section.

5.3.4.1 10 CFR Part 30

This regulatory framework (spans through 10 CFR Parts 30 to 37, but here is referred to as "Part 30" [152]) covers all aspects of civilian use of radioactive materials from exit signs to industrial gauges to complex medical equipment [143]. Part 30 is exclusively applied to a large group of materials called "byproduct materials"[1] which are essentially all radioactive materials that are not uranium, plutonium, thorium or other fissile materials (tritium is defined as a byproduct material in Schedule B of Part 30 [152]) [143]. There are more than 20,000 active source, byproduct and special nuclear materials licences in place in the U.S., a quarter of which have been administered by the NRC whilst the rest are administered by Agreement States [143]. The delegation of the jurisdiction of activities involving these materials to Agreement States acknowledges the limited nature of risk that small amounts of these materials pose.

Part 30 is much less onerous than the 10 CFR Part 50 framework used in the licensing of NPPs (see below) and places far fewer obligations on the licensee, commensurate with the reduced risk that activities regulated under Part 30 pose to workers and the public. As part of the application process, licence applicants are expected to show that certain safety analyses have been performed and that they satisfy certain requirements within the framework, e.g. establishing an emergency plan to mitigate the consequences of a potential release of radioactive material if any inventory limits given in Schedule C of Part 30 are exceeded (unless it can be demonstrated that the maximum dose to a person offsite due to a release of radioactive materials would not exceed 1 rem [10 mSv] effective dose equivalent of 5 rems [50 mSv] to the thyroid) [152]. Part 30 also requires that safe shutdown protocols are in place to restore the facility to a safe condition after an accident and that all site personnel are appropriately trained for their roles.

Medical cyclotrons used to produce high yields of short-lived radioactive materials are licensed under Part 30. These are usually installed in hospitals or specialist clinics and in some cases require shielding of over a metre as well as significant worker safety measures [143], [153]. It is worth noting that some of these clinics lack large radiation-shielded areas and will continuously be visited

[1] Definition of byproduct material in Part 30 is "any radioactive material (except special nuclear material) yielded in, or made radioactive by, exposure to the radiation incident to the process of producing or using special nuclear material."

by members of the public with little radiation protection awareness. This is in stark contrast to an NPP or fuel cycle facility in which every member of staff/visitor will be acutely aware of the radiation hazards present. It is therefore crucial that hospitals and clinics that operate these devices have an appropriate level of radiological shielding in place along with a well-planned building design in order to ensure the safety of workers and the public [153]. Part 30 has already been used to licence fusion systems such as the DT110-14 MeV Neutron Generator [154]. This utilises the D-T fusion reaction to produce 14 MeV neutrons; as such, it requires a Type A broad scope specific licence authorising possession of tritium. These cases serve as examples where, despite the radioactive materials present, the radiological risk to workers and the public is limited, allowing a regulatory approach that is less strict and places fewer duties on operators/designers.

5.3.4.2 10 CFR Part 50

Currently, there are two main licensing paths to license an NPP in the U.S.: 10 CFR Part 50 and Part 52 [155]. All of the NPPs operating in the U.S. have been licensed under the two-step Part 50 framework, which requires both a construction permit and an operating licence. In 1989, to increase regulatory efficiency, NRC established the Part 52 framework which essentially combines a construction permit and an operating licence into what is known as a combined licence and allows for early site permits (which allows an applicant to obtain approval for a reactor site for future use) and a standard plant design certification process (which allows for pre-approved designs to be authorised) [146]. Whilst the rules under both licensing paths do differ, many of the burdens imposed under Part 52 refer directly back to Part 50. For the purposes of this work, mapping the key provisions required under each framework, both parts will be subsumed under "Part 50".

Part 50 provides for the "licensing of production and utilization facilities" [155]. The term "utilization facility" is defined in the AEA as facilities that use "special nuclear material" or "atomic energy" in such quantity "as to be of significance to the common defence and security, or in such manner as to affect the health and safety of the public" [144]. Despite there being some room for interpretation as to what types of facilities this would apply to, the NRC has traditionally limited the definition of utilisation facility to NPPs and one separate facility that uses special nuclear material (see below) [143], [155].

Part 50 is one of the NRC's strictest regulatory frameworks due to the hazard potential of NPPs and the radiological consequences of an unplanned release of radioactive material. Part 50 requires that each application for a construction permit includes a preliminary safety report (PSR) giving a description and safety assessment of the facility. The PSR is expected to show that through the plant's "design, construction and operation" there is "an extremely low probability for accidents that could result in the release of radioactive fission products" [155]. Part 50 is entirely driven by the safety issues that are unique to NPPs, such as preventing the release of fission products, ensuring core cooling and preventing super-criticality [143]. To achieve this, Part 50 contains a section titled *Appendix A to Part 50 – General Design Criteria for Nuclear Power Plants* in which it sets out the minimum requirements that must be met in order to apply for a construction permit (note Part 52 obligates applicants to meet the same criteria) [155]. These principles are generally prescriptive in nature (e.g. the maximum fuel element cladding temperature shall not exceed 2200 °F) and include using certified codes to evaluate the safety functions of various components, designing reactor control and protection systems to ensure fuel design limits are not exceeded and ensuring that fuel criticality in fuel storage and handling systems is prevented.

5.3.4.3 10 CFR Part 70

This regulatory category (spans through 10 CFR Part 70 to 76, but here is referred to as "Part 70" [156]) covers the possession of special nuclear materials (e.g. enriched uranium, plutonium and thorium) and is also used to license fuel cycle (including fuel fabrication) facilities [143]. Part 70 is stricter than Part 30 but not as strict as Part 50 and is largely concerned with safety issues that arise from storing, producing or managing unirradiated fissile materials. As such, the provisions set out in Part 70 are focused on preventing criticality, guarding against diversion of special nuclear material and protecting the health of workers on-site [156].

Each licensee/licence applicant is expected to conduct and maintain an integrated safety analysis that takes into account radiological hazards, chemical hazards and potential accident scenarios caused by on-site and off-site phenomena. However, commensurate with the limited range of hazards that arise from storing large quantities of unirradiated fissile materials, the obligations within the framework are not as onerous as those under Part 50 and are largely concerned with accident scenarios that

result in criticality of the fissile material. Part 70 illustrates how nuclear installations with limited radiological risks can be subjected to less onerous criteria than those found in Part 50 and still deliver high levels of safety and protection of workers and the public.

5.3.5 NRC's Approach to Fusion Regulation

In 2009, NRC staff produced a memorandum titled *Regulation of Fusion-Based Power Generation Devices* in which the topic of whose jurisdiction fusion power should come under was discussed [157]. In the memo, NRC proposed two possible sources of jurisdiction: the first would involve classifying FPPs as utilisation facilities and thus subjecting them to the rigorous measures required under Part 50; whilst the second would involve indirectly regulating FPPs as a result of their byproduct materials (i.e. tritium and activated dust inventories) [146].

The staff recommended that NRC assert regulatory jurisdiction over commercial FPPs and expand the definition of "utilization facilities" to include FPPs, subjecting FPPs to the onerous Part 50 framework [143]. An example of this can be seen in the approach NRC took in reviewing the construction permit for a medical isotope facility designed by SHINE Medical Technologies, Inc., who are intending to use the D-T fusion reaction to generate neutrons aimed at a uranium target to produce the isotope Molybdenum-99, used in nuclear medicine diagnostic procedures [158]. NRC determined that the facility should be defined as a utilisation facility and should be regulated under Part 50; however, a key factor in this decision was the presence of the uranium target [143]. Nevertheless, the Part 50 framework was amended and the definition of "utilization facility" now includes the SHINE facility [155].

Whilst a final decision on how FPPs are to be regulated in the U.S. has yet to be made, it is expected that NRC will give this matter serious consideration in the next few years due to the passing of the *Nuclear Energy Innovation and Modernization Act* in 2019 [98]. Section 103 in the Act instructs NRC to establish stages in the licensing process for commercial "advanced nuclear reactors", a term that is defined in the Act to specifically include FPPs and prototype plants. The Act also instructs NRC to complete a rulemaking to establish a regulatory framework for advanced nuclear reactors (including FPPs) by no later than 31st December 2027 [98]. The NRC's current target for this is now 2024.

5.4 France

5.4.1 Background to French Legal Framework

Currently, the only fusion facility that has undergone a licensing process is ITER in France. ITER has been licensed as an *installation nucléaire de base* (basic nuclear installation or "BNI"), primarily due to its tritium inventory and expected levels of neutron activation [159]. Under French legislation, BNIs are defined as either: NPPs; facilities that produce, process or store nuclear fuels or radioactive waste; facilities that contain radioactive or fissile substances beyond a specific threshold; or particle accelerators meeting characteristics defined by a State Council decree [160]. It is expected that ITER will set a precedent and that any future FPPs in France will also be licensed as BNIs (due to their inventories of tritium); hence, they will be regulated in a similar manner to NPPs.

The licensing process for a BNI is formalised by two decisions at government level: the first is the *Décret d'Autorisation de Création* (DAC) which authorises construction of the facility; the second is the *Décret d'Autorisation de Rejets et de Prélèvements d'Eau* (DARPE) which is related to preventing or limiting radiological effluents from the facility and is required to start operation [159]. Whilst the final stage of obtaining a licence involves an extensive examination of safety documentation by the nuclear regulator coupled with a local public enquiry, the entire process is based on a continuous dialogue between the operator and the safety authorities [159].

5.4.2 ASN

Created in 2006 with the *Transparency and Security in the Nuclear Field Act* (the "TSN Act" [160]), the Autorité de sûreté nucléaire (Nuclear Safety Authority or "ASN") is an independent administrative authority responsible for the regulation of nuclear safety and radiation protection, replacing the General Direction for Nuclear Safety and Radioprotection. ASN currently regulates all areas of 58 NPPs (including the Gen III+ EPR currently under construction), all fuel cycle facilities (including enrichment and reprocessing facilities) and several thousand activities using sources of ionising radiation for medical, industrial or research purposes. ASN are also tasked with implementing the "BNI Order" at all nuclear facilities (see Section 5.4.3.2). When regulating nuclear facilities, ASN receives assistance from the French public expert in nuclear and radiological risks, the Institut

de radioprotection et de sûreté nucléaire (IRSN), who act as the ASN technical support organisation assisting in the evaluation of nuclear safety issues for potential sites for nuclear facilities.

5.4.3 French Regulatory Framework

5.4.3.1 The TSN Act

The primary legislation under which BNIs are licensed in France is the 2006 TSN Act [160] (now codified in books I and V of the Environment Code by ordinance 2012-6 of 5th January 2012) [161]. Upon ratification, the TSN Act extensively overhauled the BNI legal system and established the formation of ASN, as well as implementing the "BNI Order" (see Section 5.4.3.2). The TSN Act also implements various elements of the French legal system including article L. 1333-1 of the Public Health Code, concerned with the general principles of radiation protection (justification, optimisation and limitation), and articles L. 593-1 and L.110-1 of the Environment Code, concerned with public safety and environmental protection, respectively.

5.4.3.2 The BNI Order

Following the ratification of the TSN Act and the subsequent overhaul of the BNI legal system, a Ministerial Order setting out the general technical regulations applicable to BNIs was published in 2012. The BNI Order, taken in application of Article L. 593-4 of the Environment Code, sets out the criteria applicable to BNIs considered essential to protect public health and safety and the environment [161], [162]. The Order prescribes a large number of criteria for designers/operators of BNIs whilst also providing a legal basis for several of the requirements expressed by ASN following the Fukushima accident.

Part 3 of the BNI Order ("Demonstration of Nuclear Safety") sets out the requirements concerning the demonstration of control of accident risks (both radiological and non-radiological) that the licensee must provide [161], [162]. This includes applying the principle of defence in depth with the aim of detecting incidents and applying measures that will prevent them from leading to an accident, controlling accidents that could not be avoided and limiting their aggravation, or managing accident scenarios that could not be controlled as to protect the public and the environment [162]. The Order also demands a cautious design approach in which sufficient design margins are integrated

and, wherever necessary, the implementation of redundancy, diversification and physical separation of components required to provide the safety function. Defence in depth is the basic nuclear safety principle used in NPP design and is consistent with IAEA standards and the ASN technical directives for the latest generation of NPPs [161]. The BNI Order goes on to define the various internal and external hazards that need to be considered in the demonstration of nuclear safety including pressure equipment failures, explosions, fires, hazardous substance emissions, floods, earthquakes, airplane crashes, lightning and electromagnetic interference and any other internal hazard identified by the licensee or, if appropriate, that ASN determines must be taken into consideration [162]. The licensee/licence applicant must include an assessment of both the radiological and non-radiological consequences of each accident using validated codes and modelling tools, as well as a description of the necessary protection measures in place for the hazards that lead to large releases of hazardous substances [162]. The severity of each accident considered is defined with respect to reference values expressed as levels of intervention by the local authorities as defined by ASN in application of article R. 1333-80 of the public health code [162]. Whilst the BNI Order highlights areas that need to be taken into account in the safety analysis of a nuclear facility, it is up to the licensee to develop its own arrangements for managing safety.

5.4.4 Timeline of Licensing ITER

The first step in the licensing of ITER began in 2002 with the preparation of the *Dossier d'Options de Sûreté* (Main Safety Objectives or "DOS") which defined the major risks in the facility and the protection measures in place to avoid or mitigate these risks. Prepared by the French Alternative Energies and Atomic Energy Commission (CEA) on behalf of a future ITER Organization (as ITER Organization did not exist as a legal entity at the time), the DOS provides a brief description of the installation and proposes the general safety objectives and how they are going to be implemented [163]. The DOS was largely based on the Generic Site Safety Report (GSSR) produced by ITER in 2001. This was then followed by the *Rapport Préliminaire de Sûreté* (Preliminary Safety Report or "RPrS") which contains a detailed description of the facility and a comprehensive safety analysis. The RPrS is the most comprehensive document regarding the safety of the facility prior to the construction phase and was submitted to ASN for examination in January 2008. Upon reviewing the document, ASN sent several questions and requests for improvements to be made in July

2008 [159]. ITER Organization (IO) responded to these queries and resubmitted the RPrS with additional information and design data in March 2010 [164]. In December 2010, ASN sent a letter to IO confirming the RPrS is "receivable", meaning ASN can start to fully examine the report - with assistance from IRSN - and the public consultation phase may begin [80], [164].

The "Enquête Publique" (public consultation) phase involved IO organising public debates (as required by French law) to present the ITER project to local communities (within a 10-15 km radius of the site) to discuss the project's socio-economic and environmental advantages and disadvantages. The main areas for concern were the external effects resulting from the construction and operation of the facility [163]. Technical questions were asked during these meetings; however, no new technical issues were introduced [165]. IO also started to prepare the documents required to obtain the DAC and DARPE licences around this time. Much of the content required for these applications were lifted from the RPrS, such as the design justification study, accident analyses study and environmental study, amongst others [163].

Following the public consultation phase, in June 2012 ASN gave their final approval to the ITER project, and in November 2012, ASN signed the official decree declaring ITER a BNI as well as providing the organisation with the DAC licence [166]. It is worth noting that all of the above was carried out in accordance with the TSN Act (2006) but before the BNI Order (2012) was established.

5.5 UK

In the UK, there is currently no mention of fusion power in any legislation/regulations. In fact, the primary legislation under which nuclear installations are licensed, the *Nuclear Installations Act 1965* [167] (see Section 5.5.5.5), definitively excludes FPPs from its definition of nuclear reactors which only includes plants that produce "atomic energy by a fission process" [167]. However, Part 1(3)(a) of the NIA allows installations to be prescribed as licensable if they are "designed or adapted for producing or using atomic energy" where atomic energy has the meaning assigned to it in the *Atomic Energy Act 1946* (AEA46) [168] which is "the energy released from atomic nuclei as the result of any process..." Fusion is a process that results in the release of energy from atomic nuclei; therefore, the NIA covers fusion energy and it allows ministers to prescribe FPPs as licensable installations.

The UK Government has recognised that the issue of how FPPs should be regulated will need to be decided soon; hence, in October 2021 it published a green paper on the various proposals for regulating FPPs in the UK [95]. In addition, a recent report by the Regulatory Horizons Council (RHC) [169], an independent committee made up of members from a variety of sectors, highlighted and analysed some of the regulatory options for FPPs and came to the conclusion that a light-touch regulatory approach in which FPPs are classed more as radiological laboratories rather than power plants would be most appropriate. However, this recommendation is not UK Government policy and the UK Science Minister has responded that the UK Government "cannot yet take a firm view on the RHC's recommendations" [170]. Given that the UK Government has yet to take a final position on the regulation of FPPs, it is worth exploring the relevant legislation/regulations to help determine the options for the regulation of FPPs.

5.5.1 Background to UK Legal Framework

The legal framework for the nuclear industry in the UK is based around the *Health and Safety at Work etc. Act 1974* (HSWA) [171], the *Energy Act 2013* (EnA) [172] and the *Nuclear Installations Act 1965* (NIA) [167]. Environmental protection legislation is largely based around the *Environmental Permitting Regulations 2016* (EPR) [173]. The relevant regulators in the UK are the Office for Nuclear Regulation (ONR), the Health and Safety Executive (HSE) and the relevant environmental regulators: the Environment Agency (EA) for facilities in England, Natural Resources Wales (NRW) for facilities in Wales and the Scottish Environment Protection Agency (SEPA) for facilities in Scotland.

5.5.2 Office for Nuclear Regulation (ONR)

ONR is an independent organisation that is responsible for the regulation of the UK's nuclear industry. Established in 2013 with the ratification of the EnA, ONR regulates all nuclear installations for nuclear safety, security, safeguards, transport of nuclear and radioactive materials, and industrial health and safety (including radiation protection) on nuclear licensed sites. ONR is regarded as one of the world's leading nuclear safety regulators and is held in high regard within IAEA and its peers. ONR succeeded HM Nuclear Installations Inspectorate (NII). NII was founded in 1960 and built up decades of experience successfully regulating the UK's nuclear installations. ONR/NII has

experience of regulating a wide range of nuclear facilities/activities with varying hazard potentials ranging from NPPs, fuel cycle facilities, radioactive waste management facilities, nuclear submarine refuelling, nuclear weapons production, research reactors and other research facilities. ONR is also responsible for the granting of nuclear site licences to corporate bodies - a necessary precursor to constructing or operating a nuclear installation in the UK.

5.5.3 Health and Safety Executive (HSE)

HSE is a UK Government non-departmental public body (NDPB) responsible for regulating occupational health and safety across all sectors. Created by the HSWA, HSE is responsible for implementing the relevant provisions of the Act, as well as any regulations that come under the Act, such as the *Ionising Radiations Regulations 2017* (IRRs) [174], the *Radiation (Emergency Preparedness and Public Information) Regulations 2019* (REPPIR) [175] and the *Construction (Design and Management) Regulations 2015* (CDM Regulations) [176]. Note that on a nuclear licensed site it is ONR that implements the relevant provisions of the HSWA and its corresponding regulations, not HSE. HSE is responsible for the enforcement of the HSWA on the UKAEA Culham site which hosts the JET facility (see Section 5.5.6).

5.5.4 Environmental Regulators

5.5.4.1 Environment Agency (EA)

EA is an independent Government agency responsible for the protection and enhancement of the environment in England. Established by the *Environment Act 1995* [177], EA is a large organisation with a variety of functions ranging from regulating rivers, fishing, managing and regulating flood protection, regulating industrial pollution, regulating the use and security of sealed radioactive sources, regulating radioactive discharges from nuclear installations and the disposal of radioactive waste. EA is also responsible for enforcing the EPR at the UKAEA Culham site, including at the JET facility. The primary role of EA is enforcing the relevant provisions of the EPR.

5.5.4.2 Natural Resource Wales (NRW)/The Scottish Environment Protection Agency (SEPA)

Natural Resource Wales (NRW)/The Scottish Environment Protection Agency (SEPA) are the environmental regulators for Wales and Scotland, respectively. In relation to licensed nuclear installations, the primary role of NRW is implementing the relevant provisions of the EPR for facilities in Wales, whilst the primary role of SEPA is implementing the relevant provisions of the *Environmental Authorisations (Scotland) Regulations 2018* (EASR) [178] for facilities in Scotland. Note the passing of the EPR and the EASR repealed the provisions of the *Radioactive Substances Act 1993* [179].

5.5.5 UK Regulatory Framework

5.5.5.1 The Health and Safety at Work etc. Act 1974

The HSWA [171] is an enabling Act that requires that all employers, including those in the nuclear industry, implement measures to look after the health and safety of their employees and the public who may be affected by their activities. It also introduces the concept of reducing risks to as low as reasonably practicable (ALARP). This concept of reducing risks to ALARP is a key component in delivering safety in nuclear facilities and is used throughout safety cases for nuclear facilities. Generally the Act is enforced by HSE, but on a nuclear licensed site, as discussed above, it is enforced by ONR. Under the HSWA there are specific regulations that are concerned with nuclear related activities - the IRRs and REPPIR - and these would apply to FPPs due to the presence of ionising radiation.

5.5.5.2 The Ionising Radiations Regulations 2017

The IRRs provide the main legal requirements for the use and control of ionising radiation in the UK. They place duties on the employer to ensure that appropriate measures are in place to protect workers and the public from any health and safety risks associated with ionising radiation.

The IRRs also place duties on employers to carry out radiation risk assessments, take steps to restrict the extent to which its employees and other persons are exposed to ionising radiation, provide appropriate personal protective equipment, maintain and examine engineering controls, and

ensure employees and other persons are not exposed to ionising radiation to an extent that a pre-defined dose limit is exceeded in a calendar year. The IRRs are generally enforced by HSE, but, as stated above, on nuclear licensed sites they are enforced by ONR.

5.5.5.3 The Radiation (Emergency Preparedness and Public Information) Regulations 2019

REPPIR ensures that arrangements are in place to protect surrounding populations should an accident result in the uncontrolled release of radioactive material from a nuclear installation. REPPIR usually requires an operator to draw up emergency plans to make use of countermeasures to limit radiation exposure, which generally involve sheltering or evacuation of local populations.

5.5.5.4 The Energy Act 2013 (EnA)

The EnA [172] established ONR as a statutory body (effective from 1st April 2014). ONR was formed as a merger of: HSE's Nuclear Directorate, the Office for Civil Nuclear Security, the UK Safeguard's Office and the Department for Transport's Radioactive Materials Transport Team [180]. ONR's duties are detailed in Section 5.5.2.

5.5.5.5 The Nuclear Installations Act 1965 (NIA)

The NIA [167] sets out the requirement that no person may construct or operate a nuclear installation unless a licence has been granted by the appropriate authority (ONR). This nuclear site licence can only be granted to a corporate body and is non-transferable. Each nuclear site licence has 36 attached licence conditions (LCs) that licensees must comply with. Failure to comply with the LCs is a criminal offence. The 36 LCs aim to envelope all the requirements needed to effectively manage nuclear safety including the control of the design, construction, commissioning, operation and decommissioning of each facility. The 36 conditions are a mixture of prescriptive and goal setting requirements. The goal setting conditions require the licensee to make and implement adequate arrangements to meet the intention or goal of the LC [181]. This goal setting approach is consistent with the HSWA which places the responsibility for safety on the duty holder, i.e. the licensee in the case of a nuclear licensed site. The strength of the UK's goal setting approach to nuclear safety regulation is that the licensee has the freedom to put forward its own arrangements for managing safety. The legal basis for these LCs is set out in Section 4 of the NIA "Attachment

of conditions to licences" [167]. This Section specifically allows ONR to attach conditions that it considers "necessary or desirable in the interests of nuclear safety" [182]. Section 4 also allows ONR to attach conditions it considers appropriate to the handling, treatment and disposal of nuclear matter. These powers enable ONR to have regulatory control over every stage of the life cycle of the facility including the "design, siting, construction, installation, operation, modification, maintenance and decommissioning" of nuclear installations [167]. The non-prescriptive nature of the licensing approach allows ONR to proportionately regulate facilities according to their hazard potential.

5.5.5.6 Permissioning

Permissioning is a key part of the regulation of nuclear installations in the UK as it enables ONR to apply regulatory control to various stages of the licensing process. Permissioning starts with the granting of the licence. A regulatory schedule is then developed through discussion between ONR and the licensee. Depending on the type of permissioning, the licensee generally cannot move past a pre-defined "hold point" without the permission of ONR. To obtain permission from ONR, the licensee is required to produce safety documentation to demonstrate that the activity for which permission to proceed is being requested can be safely carried out and will deliver the required levels of nuclear safety as set out in the safety case. Permissioning requires the regulator to have legal powers and ONR has a range of powers at its disposal. These powers are explored further in Section 7.2.4

5.5.6 Regulation of JET

The construction and subsequent operation of JET was undertaken by UKAEA, which at the time of construction was exempt from nuclear site licensing under the NIA. However, UKAEA was required to ensure safety to an equivalent standard to licensed nuclear installations and hence JET's design, construction and operation followed UKAEA internal procedures. Industrial health and safety was regulated by HSE and environmental discharges and radioactive waste were managed by EA's predecessors. The UKAEA exemption from nuclear site licensing was removed in 1989, but it was decided that as the nuclear licensing regime only related to fission technologies, JET would remain outside the nuclear safety licensing regime and the day-to-day operations at JET would continue to be regulated by HSE and EA. Proponents of a light-touch approach for regulating FPPs point to

the example of JET, arguing that a regulatory approach led by HSE/EA has been broadly effective so far [169]. However, as stated above, whilst JET did not at the time of its construction require a nuclear site licence, it was subject to a Ministerial Direction on UKAEA to provide an equivalent safety regime to that of licensed nuclear installations and hence HSE and the environmental regulators at the time had limited influence or control over the design, construction or commissioning of JET. The suitability of regulating FPPs in a similar manner to how JET is regulated is discussed in Chapter 7.

5.6 Canada

5.6.1 Background to Canadian Legal Framework

Under Canadian law, FPPs are to be regulated under the same framework as NPPs. The relevant legislation and regulations are the *Nuclear Safety and Control Act* (NSCA) [183], the *General Nuclear Safety and Control Regulations* (GNSCR) [184] and the *Class I Nuclear Facilities Regulations* (C1NFR) [185]. The nuclear regulator is the Canadian Nuclear Safety Commission.

5.6.2 Canadian Nuclear Safety Commission (CNSC)

Established in 2000 with the passing of the NSCA, the Canadian Nuclear Safety Commission (CNSC) is an independent federal government agency charged under the NSCA with the authority to regulate the development, production and use of nuclear energy and nuclear materials in Canada. CNSC regulates a variety of facilities/activities ranging from NPPs and fuel cycle facilities to the operation of uranium mines to the use of radioactive sources in oil exploration. CNSC also conducts environmental assessments at sites and implements Canada's bilateral agreement with IAEA on nuclear safeguards verification.

5.6.3 Canadian Regulatory Framework

5.6.3.1 The Nuclear Safety and Control Act (NSCA)

The NSCA [183] came into force on May 21st 2000, replacing the *Atomic Energy Control Act* [186], and established CNSC and set out its responsibilities and powers. Similar to the UK regulatory

framework, in Canada no person may construct or operate a nuclear facility unless a licence has been granted by the appropriate authority (CNSC). In the NSCA both the terms "nuclear facility" and "nuclear energy" specifically include fusion or fusion power and hence CNSC have regulatory jurisdiction over FPPs and they are subject to the same suite of legislation/regulations that NPPs and any other nuclear facilities are [183].

5.6.3.2 The General Nuclear Safety and Control Regulations (GNSCR)

Under the NSCA, CNSC has implemented regulations and by-laws with the approval of the Governor in Council. This includes the *Radiation Protection Regulations* [187], which sets prescribed dose limits and stipulates that the dose received by any exposed persons is kept ALARA (as low as reasonably achievable), and the GNSCR [184], which provides the general criteria with respect to licence applications and renewals and the obligations of licensees. Similar to the UK approach, the regulatory framework allows a primarily goal setting approach towards nuclear safety and security, rather than prescriptive, by ensuring that every licensee shall "take all reasonable precautions to protect the environment and the health and safety of persons and to maintain the security of nuclear facilities..." and "take all reasonable precautions to control the release of radioactive nuclear substances" [184]. As in the UK, the licensee is ultimately responsible for safety and security and the licensee may implement adequate arrangements to deliver specific safety related activities, provided they can demonstrate that "all reasonable precautions" have been taken [184].

5.6.3.3 Class I Nuclear Facilities Regulations (C1NFR)

The C1NFR [185], mandated under the NSCA, defines both "nuclear fission reactors" and "fusion reactors" as "Class IA nuclear facilities" and sets out the general requirements needed for a licence applicant to be awarded a licence at each stage of the facility's life cycle. Whereas in the UK a single nuclear site licence is granted for the lifetime of the facility, under C1NFR a licence applicant must apply for a separate licence at each stage of the facility's life cycle: preparing the site, construction, operation, decommissioning and abandonment [185]. At each stage the same general criteria need to be shown by the licence applicant (albeit to varying degrees commensurate with the hazard potential of the activity being proposed). These include:

- A detailed description of the site and of the design and design operating conditions

- A safety analysis report demonstrating the adequacy of the design in relation to the activity being proposed
- The proposed measures to prevent or mitigate the effects of accidental releases of radioactive material to protect workers, the public and the environment
- The proposed security policies and procedures, including an emergency response plan

These measures are again non-prescriptive and it is up to the licensee to implement adequate arrangements to deliver safety and security. Upon receiving the relevant licence application, CNSC will make a judgement on the adequacy of the design and safety case. The separate licence applications operate in a similar fashion to the UK's permissioning hold points, in that the licensee/licence applicant cannot progress past each stage without the granting of the licence by CNSC.

5.7 China

5.7.1 Background to Chinese Legal Framework

There is currently no fusion-specific legislation or regulatory framework in China, despite the accelerated development of its flagship China Fusion Engineering Test Reactor (CFETR) which has completed its conceptual design phase and is expected to begin construction within the next decade [188]. CFETR is an experimental fusion reactor aiming to bridge the gap in fusion experiments between ITER and DEMO. Due to the lack of fusion-specific regulations, there are concerns that CFETR will be subject to the strict regulatory framework that currently exists for NPPs [189]. The current framework for nuclear facilities is explored below. It is worth noting China is currently contributing to the current IAEA work on FPP regulation.

5.7.2 National Nuclear Safety Administration (NNSA)

Established in 1984, the National Nuclear Safety Administration (NNSA) is a central government agency responsible for the regulation of nuclear safety, radiation safety and environmental protection at all civilian nuclear facilities in China. No person may construct or operate a nuclear facility in China without holding a nuclear site licence granted by the appropriate authority (NNSA).

5.7.3 Chinese Regulatory Framework

The current nuclear regulatory framework in China includes two laws related to nuclear safety (with another one in the process of enactment), 7 administrative regulations, 27 department rules, around 90 safety guides and over 180 technical documents [189]. Among these, the national laws and administrative regulations have a legal basis, whilst the safety guides and technical documents are general references rather than legal requirements. The two laws that relate to nuclear safety are the *Law of the People's Republic of China on Prevention and Control of Radioactive Pollution 2003* (LPC) [190] and the *Nuclear Safety Act 2017* (NSA) [191]. In addition to these, the *Atomic Energy Act* has been drafted by the Standing Committee of the National People's Party and is due to be enacted soon.

5.7.3.1 Law of the People's Republic of China on Prevention and Control of Radioactive Pollution 2003 (LPC)

The LPC sets out the criteria that must be followed to prevent or mitigate the effects of a release of radioactive material from a nuclear facility, with a focus on protecting the public and the environment. It also sets out the requirement that no person may construct or operate a nuclear facility without a licence. The term "nuclear facility" is defined in the NSA as NPPs, research reactors, fuel cycle facilities and facilities that treat, store and dispose of radioactive waste. [190]. Article 6 of the LPC states that every "individual shall have the right to report to the authorities and bring a charge against any act that causes radioactive pollution" [190]. The Law also grants the Department for Environmental Protection under the State Council (under which reports NNSA) the responsibility to "exercise unified supervision over the prevention and control of radioactive pollution" as well as the power to create "national standards for prevention and control of radioactive pollution [190]. Article 13 of the Law states that operators of nuclear facilities must "adopt safety and protective measures to prevent the occurrence of any kind of accident that may lead to radioactive pollution" [190]. Article 19 stipulates that an operator must apply for a licence prior to construction, fuel loading, operation or decommissioning of nuclear facilities. As part of the licence application, an operator must prepare an environmental impact report and submit it to the Department for Environmental Protection under the State Council for examination and approval. The Law then sets out a list

of criteria that must be taken into account by designers/operators of nuclear facilities in order to deliver safety including where to store radioisotopes during plant operation, the need to monitor radioactive effluents and the manner of which radioactive waste is disposed, amongst others [190].

5.7.3.2 Nuclear Safety Act 2017 (NSA)

The NSA was passed in 2017 to provide more powers to the regulator (NNSA) and to strengthen China's nuclear safety regime [192]. Whether the LPC and NSA will apply to CFETR and FPPs depends on the wording of the NSA. In the NSA [191], the definition of "nuclear facility" includes NPPs, "nuclear plants producing heat and power" and "nuclear plants generating steam and heat". The definition of "nuclear material" is limited to U235, U238, Pu239 or "other nuclear material that is subject to control in accordance with laws and administrative regulations" [191]. Despite tritium not being clearly defined as a nuclear material in the NSA, it is explicitly defined as nuclear material in the *Control Ordinance for the Nuclear Material of the People's Republic of China (HAF501)* [193]. As CFETR and FPPs for electricity generation will produce heat and power and store and use nuclear material (tritium), it is expected that these laws will be applicable to both. The NSA stipulates that the "operator of a nuclear facility assumes overall responsibility for nuclear safety" and sets out the need for a clear organisation structure that prioritises safety [191]. It also sets out the requirement that operators must establish security measures to prevent the facility and nuclear material from "destruction, damage and theft" [191]. Articles 18 and 19 require the operator to ensure dose limits are not exceeded by personnel and to monitor the concentration of radionuclides in the environment and report these values to the relevant authorities. Article 38 states that an operator must also obtain a licence to possess nuclear material and ensure the safety and lawful use of nuclear material on-site [191]. Both the NSA and LPC require that restricted areas around nuclear facilities are clearly demarcated and that an on-site emergency response plan is developed in the case of accidents; this emergency response plan will be required for CFETR even if the goal to eliminate the need for an emergency off-site response is achieved [189].

5.7.4 Approach to Fusion Regulation

The nuclear regulatory framework in China appears to be more goal setting rather than prescriptive, which may allow for FPPs to fall under the same jurisdiction as NPPs but require less onerous

measures be implemented. Article 8 of the NSA places the duty on the State to "establish a system of nuclear safety standards at highest and strictest levels... in accordance with the development of the economy and society and the advancement of science and technology" [191]. It is expected that these safety standards will incorporate characteristics of fusion power due to the progress made with CFETR [189]. Whilst the LPC and NSA are essentially technology-neutral, there are multiple safety guides and technical documents in place to assist with the design, siting, construction, operation and decommissioning of nuclear facilities, some of which are translated from IAEA technical reports [189]. The contents of these safety guides and technical documents are specific to NPPs; as such, many of the insights and recommendations are not suitable for FPPs. Due to this, there have been calls to develop new design requirements for components unique to fusion systems [189].

5.8 Commonalities and Differences in Approach to Regulating Fusion

This chapter has demonstrated that there is currently no agreed approach to how FPPs should be regulated. Whilst IAEA has published extensive guidance on how NPPs and other civil nuclear installations associated with nuclear fission should be regulated - which countries then take into account and use to draft their national legislation and regulations - there is a dearth of published material on how FPPs should be regulated. This may be due to a few factors: a lack of urgency, the inordinately slow pace of international projects such as ITER and DEMO and the lack of detailed designs and therefore a clear idea of the hazard potential of FPPs. The lack of published material on the regulation of FPPs by IAEA has resulted in a lack of consensus on how FPPs should be regulated. Some countries have adopted a similar approach to regulating NPPs; others, concerned about the onerous requirements for NPP regulation, have hinted that they will take entirely different approaches to regulating FPPs. The U.S. NRC is conducting public hearings to help them on the most appropriate way to regulate FPPs and the UK Government is consulting on the matter. IAEA is producing a TECDOC on fusion regulation to capture current knowledge and it is holding a consultant meeting to explore the regulatory options. All the major nuclear countries are involved in these activities.

Some countries (France, Canada) have already developed the regulatory framework that FPPs will be subject to and decided that they will be regulated under the same framework as NPPs and other civil nuclear facilities. FPPs are to be classed as BNIs and Class 1A nuclear facilities in France and Canada, respectively. This means that FPPs will be subject to a licensing regime and that no person may construct or operate an FPP unless a licence has been granted by the appropriate authority (ASN/CNSC). Whilst in these countries the regulatory framework surrounding NPPs is (rightly) extremely strict (due to the severe radiological consequences of a catastrophic uncontrolled release of radioactive material), the frameworks themselves are primarily goal setting. It is the licensee who is ultimately responsible for safety and hence the licensee can put forward its own arrangements for managing safety. Nevertheless, in these countries there are certain criteria that designers of FPPs are expected to take into account when demonstrating the safety of FPPs, e.g. in France designers of FPPs will be expected to demonstrate that the facility can withstand earthquakes, airplane crashes, lightning and other external hazards, despite the potential for the radiological consequences being significantly lower than in NPPs. The suitability of applying an NPP-based regulatory approach to FPPs is explored in Chapters 7 and 8.

Other countries (U.S., UK and China) have not finalised their approach to regulating FPPs; however, there is concern in each of these countries that the authorities will follow suit and decide that FPPs should be licensed in a similar manner to that applied to NPPs. Whilst the UK and China have primarily goal setting approaches to regulating NPPs, the U.S. has an extremely prescriptive approach to regulating NPPs laid out in its Part 50 framework. The U.S. nuclear regulator NRC has indicated that it plans to assert regulatory jurisdiction over FPPs and to expand the definition of "utilization facilities" in order to incorporate FPPs and subject them to the Part 50 framework (as seen by its approach to regulating the D-T fusion machine developed by SHINE); however, this is under review and the regulatory approach has yet to be determined for FPPs. Application of Part 50 would result in designers of FPPs having to adopt strict processes and arrangements for delivering safety that were developed for NPPs, despite the significantly reduced hazard potential of FPPs. There are some in the U.S. that fear this approach will stifle promising fusion technologies and argue that FPPs should be treated as low risk facilities and regulated under the less onerous Part 30 framework [143]. Their argument is based on the assertion that FPPs have such a low hazard potential that

they do not require rigorous regulatory oversight.

The approach that will be taken to regulating FPPs in the UK is less clear. The nuclear regulator ONR has made no statement on whether it plans to regulate FPPs and the UK Government has yet to make a final decision on the subject. It is clear that there are a range of options and the UK has an opportunity to promote a regulatory framework that will enhance fusion innovation whilst also providing confidence that the health and safety of the public is protected. The options available for regulating FPPs in the UK are mapped out in Chapter 7.

Part IV

Part IV - Analysis - FPP Hazard Potential

Chapter 6

An Analysis of the Hazard Potential of FPPs

This chapter provides an insight into the hazard potential of FPPs and the factors that can influence the assessment of risk. Understanding the hazard potential is essential when determining what type of regulatory approach will be appropriate for FPPs.

6.1 Background

In order to determine an appropriate regulatory framework for fusion power, it is vital that the hazard potential of FPPs is properly established and that any factors that can significantly influence the hazard potential and consequent risks to the public are sufficiently understood. From Chapter 4, it is clear that there are certain accident scenarios in which a part of the radiological inventories in an FPP can be released into the atmosphere, potentially posing a risk to workers and members of the public. The actual radiological risk to an exposed person depends on a multitude of factors including type of inventory released, quantity released, height of release, weather conditions and age of person exposed, amongst others. Detailed evaluations of risk will depend upon the FPP design and as there is no final design of an FPP, risk has been evaluated in relation to doses that would trigger the emergency reference levels (ERLs) for sheltering and evacuation of the public in the event of an accident that results in the release of radioactive material. The aim of this chapter is to assess the radiological dose received by an exposed member of the public under a variety of conditions and determine the quantities of radioactive material that would need to be released to trigger the ERLs. These quantities are then put into context in relation to the expected inventories in FPPs.

A sensitivity study has been performed to evaluate the influence of the key parameters/assumptions in the dose calculations.

As detailed in Chapter 2, the radiological inventories expected in an FPP that have the potential to give rise to an off-site hazard are tritium (used in fuel), activated dust (formed due to the erosion of plasma facing components) and activated corrosion products (formed due to corrosion within the water cooling loops if water is chosen as the primary coolant). Depending on the breeder blanket type chosen for the FPP, there may be additional inventories that are not mentioned here. The atmospheric dispersion modelling tool ADMS-STAR was used to evaluate the impact of a release of radionuclides on the risks to workers and the public. Given that the radioactivity of the tritium and activated dust inventories is generally orders of magnitude higher than that of ACPs, this chapter focuses on the impact of releases associated with tritium and dust.

6.1.1 Overview of the Analysis Model

ADMS-STAR (**S**hort-**T**erm **A**ccidental **R**eleases) [194] is a relatively nascent atmospheric modelling tool developed as part of the ADMS suite, which is used by a number of regulatory authorities in the UK including HSE, EA, SEPA and the Northern Ireland Environment Agency (NIEA). ADMS-STAR differs from standard air dispersion modelling tools in that standard models use a single parameter Pasquill-Gifford stability class to define dispersion parameters. ADMS-STAR, however, characterises the boundary layer structure with two parameters: the boundary layer height and the Monin-Obukhov length; this allows for more accurate dispersion modelling particularly when elevated sources are considered. It is worth noting that ADMS-STAR can only model short-term releases and doesn't factor in processes such as ingestion or re-emission. However, for the purpose of this work, illustrating the quantities of radioactive materials in the form of HTO and activated dust that would need to be released in order to trigger the lower sheltering and evacuation ERLs, this limitation was deemed an acceptable omission.

6.1.2 Atmospheric Stability Classes

The transport and dispersion of radionuclides through the atmosphere depends primarily on the speed and direction of the wind, but the vertical mixing of pollutants is strongly influenced by

differences in temperature with altitude (known as the lapse rate) [195]. The lapse rate is generally used as an indicator of atmospheric stability, which can essentially be thought of as the tendency of the atmosphere to enhance or resist vertical mixing [195]. Simple dispersion models use stability categories to define atmospheric stability, with the most common being the Pasquill-Gifford (PG) scheme [196]. The PG scheme defines seven atmospheric stability categories ranging from A (very unstable) to G (very stable). These are displayed in Table 6.1.

Stability class	**Definition**	**Most likely occurrence**	**Frequency of occurrence in central England** (%)
A	Extremely unstable	Late morning to mid-afternoon in spring and summer	0.6
B	Moderately unstable	Daytime transitions all year	6
C	Slightly unstable	Daytime transitions all year	17
D	Neutral	Daytime/cloudy; night-time/cloudy; high wind, day transition all year	60
E	Slightly stable	Night-time transition all year	7
F	Moderately stable	Night, clear skies, light winds, all year	8
G	Extremely stable	Night, clear skies, light winds, all year	1.4

Table 6.1: Pasquill-Gifford (PG) stability classes. Source: [195]. Copyright (2013) by Imprint. Reproduced by permission of Taylor & Francis Group.

Traditional approaches to dispersion modelling used the seven PG stability classes to define boundary layer stability. The advantage of this method is that it requires minimal input data and is a typically empirical approach. It is based on the assumption that the plume (in our case the volume of air that is contaminated with radionuclides that have escaped from an FPP following an accident) concentration distribution follows a normal (or Gaussian) distribution in both the horizontal and vertical directions in all stability conditions (see Section 6.2). However, field experiments have shown that this is an overly simplistic model, as the lapse rate results in convective eddies of turbulence that grow and rise over time and this adjusts the vertical mixing of pollutants [197]. A more modern

approach to dispersion modelling, used in ADMS-STAR and led by recent advances in the field of atmospheric physics, characterises the boundary layer using different parameters. The ADMS-STAR approach does not require PG stability categories as inputs as it combines a range of meteorological conditions to represent different atmospheric stabilities [197]. The two most important parameters in the ADMS-STAR model are the Monin-Obukhov length L_{MO} and the boundary layer height h.

6.1.2.1 The Atmospheric Boundary Layer

The atmospheric boundary layer, also known as the planetary boundary layer, is the lowest part of the troposphere that directly experiences surface effects due to friction (cause by roughness at the earth's surface) and heating or cooling [195]. The boundary layer generally exhibits turbulence and has a strong diurnal cycle of temperature, wind and related meteorological variables [198]. Changes across the boundary layer occur with timescales typically between a fraction of a second and an hour, whilst the height of the boundary layer also exhibits a pronounced diurnal cycle and varies between tens of metres up to kilometres. The main meteorological factors affecting the depth of the boundary layer are the amount of insolation (sunshine) and wind speed. The state (or stability) of the boundary layer (amount of turbulence, meteorological conditions, etc.) will greatly influence the dispersion characteristics of any plume within it.

From a modelling perspective, the most important atmospheric processes that need to be parametrised are vertical mixing and the formation, sustenance and dissipation of clouds [199]. Surface properties that also have a significant effect on boundary layer stability include albedo (fraction of incident sunlight that the surface reflects), roughness, moisture content and vegetation cover [199]. There are two types of turbulence that dominate throughout the boundary layer: convective turbulence (due to surface heating) and mechanical turbulence (generated by shear at surface). The state of the boundary layer and dispersion behaviour of any pollutants within the boundary layer depend significantly upon which turbulence effect is dominant.

6.1.2.2 The Monin-Obukhov Length

The Monin-Obukhov length gives a relative measure of the significance of buoyancy (generated by heating of the surface) and mechanical turbulence (generated by friction at the surface) and is given

by

$$L_{MO} = \frac{-u_*^3}{\kappa g F_{\theta_0}/(\rho c_p T_0)} \tag{6.1}$$

where u_* is the friction velocity at the earth's surface, κ (= 0.4) is the von Karman constant, g is the acceleration due to gravity, F_{θ_0} is the surface sensible heat flux, ρ is the density of air, c_p is the specific heat capacity and T_0 is the near surface temperature. To simplify, we can substitute in a term for buoyancy, B given by

$$B = \kappa g F_{\theta_0}/(\rho c_p T_0) \tag{6.2}$$

Then the Monin-Obukhov length becomes

$$L_{MO} = \frac{-u_*^3}{B} \tag{6.3}$$

Physically, the Monin-Obukhov length can be thought of as representing the depth of the boundary layer in which mechanical turbulence dominates [197]. Note in equation 6.3, the friction velocity will increase with increasing wind speed and surface roughness, whilst the buoyancy will increase with increasing surface heat flux. From these parameters, we can define three main categories of stability: unstable, neutral and stable.

6.1.2.3 Unstable Conditions

Convective (unstable) conditions (PG cat A-C) tend to occur on hot sunny days with light winds and strong heating of the earth's surface. This generates warm thermals which rise from the ground and form large convective eddies, resulting in strong convective turbulence. This results in both a large vertical and lateral spread of the plume as it travels downwind. In unstable conditions, the Monin-Obukhov length is negative and the magnitude of L_{MO} represents the height above which convective turbulence dominates over mechanical turbulence. Typically, $|L_{MO}|$ is < 10 m in unstable conditions, whilst the boundary layer depth is large (usually between 1000–2500 m). Therefore, convective turbulence dominates throughout almost the entirety of the boundary layer,

with only a shallow layer close to the surface in which mechanical turbulence has a significant role. The more unstable the conditions, the shallower the layer dominated by mechanical turbulence, and the smaller the magnitude of L_{MO}. Note extremely unstable conditions are infrequent in the UK, occurring for less than 1% of the time.

6.1.2.4 Neutral Conditions

Neutral conditions (PG cat D) commonly prevail on cloudy days with medium to strong wind speeds which cause vigorous mixing of the lower atmosphere. In this case, mechanical turbulence dominates throughout most or all of the depth of the boundary layer, whilst the cloud cover inhibits any heating or cooling off of the ground, reducing any convective eddies of turbulence that would otherwise occur [197]. The vertical and lateral spread of the plume is lower under neutral conditions than in the convective case. In neutral conditions L_{MO} may be either positive or negative but the magnitude of L_{MO} will be very large, demonstrating that mechanical turbulence dominates throughout most or all of the boundary layer, with little effects due to convective turbulence. The magnitude of L_{MO} is generally greater than the height of the boundary layer (typically around 800 m) meaning buoyancy effects do not dominate at any height [197]. Note this is the broadest category and neutral conditions occur over a wide range of times of day and times of year.

6.1.2.5 Stable Conditions

Stable conditions (PG cat E-G) occur on clear, calm nights with strong cooling of the ground and the lower layer of the atmosphere caused by long wavelength radiation to space. In stable conditions the boundary layer tends to form into layers of different densities, such that the denser layers are closer to the ground. These layers act to resist any vertical motion caused by friction effects at the surface, although these layers assembling on top of each other will cause weak turbulence [197]. Temperature inversions typically occur in stable conditions, due to the strong cooling at the surface, and the vertical and lateral spread of the plume is lower in the stable case compared to the neutral and unstable cases. In this case, L_{MO} is a measure of the height above which vertical turbulent motion is considerably suppressed by the stable stratification. Despite the small value of L_{MO} (typically less than 20 m) in stable conditions, mechanical turbulence still dominates throughout a significant portion of the boundary layer due to the reduced boundary layer height (typically between

100–200 m) [197]. Note in the UK very stable conditions occur only a few percent of the time.

6.2 Code Methodology

6.2.1 Puff Dispersion Model

ADMS-STAR employs a puff model to simulate the dispersion of a release. The release is represented as a series of instantaneous puffs, which may increase in number over time; these puffs are then advected independently in a manner defined by the local meteorological conditions. In order to calculate the activity/concentration field at any particular time, the model simply sums the activity/concentration field from each puff at that time [194]. The instantaneous puffs are characterised by their position and size, which are given as spread parameters; these spread parameters are updated on a timescale shorter than the timescale on which the meteorology changes.

6.2.1.1 Concentration

Each individual puff is described by its centre position (x_c, y_c, z_p) and spread parameters σ_x, σ_y, σ_z. These parameters represent the lateral and vertical spread of the release of the plume centreline and have units m/s. The model represents the activity/concentration distribution for each individual puff as Gaussian in the along-wind and cross-wind directions and Gaussian or skewed-Gaussian in the vertical. The concentration due to an individual puff at a given time is given by

$$\begin{aligned} C(x,y,z,t) = & \frac{M_s}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} \exp\left(\frac{-(x-x_c)^2}{2\sigma_x^2}\right) \exp\left(\frac{-(y-y_c)^2}{2\sigma_y^2}\right) \\ & \{\exp\left(\frac{-(z-z_p)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+z_p)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z-2h+z_p)^2}{2\sigma_z^2}\right) + \\ & \exp\left(\frac{-(z+2h-z_p)^2}{2\sigma_z^2}\right) \exp\left(\frac{-(z-2h-z_p)^2}{2\sigma_z^2}\right)\} \end{aligned} \tag{6.4}$$

in neutral and stable conditions in the presence of an inversion, where M_s is the total mass in the puff and h is the boundary layer height [194]. For convective conditions, stable conditions with no inversion, or for a puff that penetrates through the boundary layer the term in curly brackets is replaced with appropriate vertical terms for plumes.

6.2.1.2 Advection

The model then updates the puff properties based on the meteorological conditions at the position of the puff at that time at the mean puff height. In the presence of an inversion, the mean puff height z_m is given by

$$z_m(t) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{h} z\, C(x,y,z,t)\, dz\, dy\, dx}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{h} C(x,y,z,t)\, dz\, dy\, dx} \tag{6.5}$$

Note the upper limit of the integral in z is given by h as material that passes through the boundary layer height is dealt with separately.

Position

The position of the centre of the puff is given by

$$\begin{aligned} x_c(t+\Delta t) &= x_c(t) + \Delta t\, U_x(z_m, t) \\ y_c(t+\Delta t) &= y_c(t) + \Delta t\, U_y(z_m, t) \\ z_c(t+\Delta t) &= z_c(t) + \Delta t\, (U_z(z_m, t) - v_s + w_{pr}) \end{aligned} \tag{6.6}$$

where U_x, U_y, U_z represent the wind speed components at the mean puff height at time t, and the vertical term contains components for gravitational settling v_s and plume rise w_{pr}. The vertical position must always be greater than or equal to $1.5z_0$, where z_0 is the local roughness length [194].

Spread Parameters

To update the spread parameters, the model calculates the change in the standard ADMS spread parameters that would have occurred during the same time step assuming the current meteorological conditions (at the mean puff height) experienced by the puff had been experienced since the start of the release. The spread parameters are given by

$$\begin{aligned} \sigma_x^2(t+\Delta t) &= \sigma_x^2(t) + \Delta t \frac{\partial \sigma_x^2}{\partial t} + \Delta\sigma_{pr}^2 \\ \sigma_y^2(t+\Delta t) &= \sigma_y^2(t) + \Delta t \frac{\partial \sigma_y^2}{\partial t} + \Delta\sigma_{pr}^2 \\ \sigma_z^2(t+\Delta t) &= \sigma_z^2(t) + \Delta t \frac{\partial \sigma_z^2}{\partial t} + \Delta\sigma_{pr}^2 \end{aligned} \tag{6.7}$$

where σ_{pr} is the change due to plume rise (in which the volume of air contaminated with radionuclides is raised up higher into the atmosphere).

6.2.2 Dry Deposition

In the model, the rate of dry deposition is assumed to be proportional to the near-surface concentration, as given by

$$F_{dry} = v_d \, C(x, y, 0) \tag{6.8}$$

where F_{dry} is the rate of dry deposition per unit area per unit time, v_d is the deposition velocity (either specified or calculated within the model) and $C(x, y, 0)$ is the predicted concentration at ground level [194]. The deposition velocity actually contains two components, the diffusive velocity $v_d^{'}$ (usually referred to as deposition velocity only) and an additional element due to gravitational settling that in the model depends on a single parameter v_s, the terminal velocity of a particle. Note in all releases considered, v_s was not a fixed parameter and was calculated within the model as a function of the diameter and density of the particles released.

The overall deposition velocity v_d is expressed as

$$v_d = \frac{v_s}{1 - \exp(-v_s/v_d^{'})} \tag{6.9}$$

Note in the limit $v_s \to 0$ we find $v_d \sim v_d^{'}$.

6.2.3 Wet Deposition

As the plume travels, the amount of material incorporated into any falling precipitation is ΛC per unit area per unit vertical distance per unit time, where Λ is the washout coefficient and C is the local airborne concentration [194]. Assuming no re-emission, the total wet deposition rate per unit horizontal area per unit time is expressed as

$$F_{wet} = \int_0^{\infty} \Lambda \, C \, dz \tag{6.10}$$

where z is the vertical direction. It follows that the plume strength decreases with downwind distance. Note in the model, Λ takes into account both in-cloud scavenging (rainout) and below-cloud

scavenging (washout). The washout coefficient Λ varies with the nature of the isotope modelled, precipitation rate, droplet size distribution, and isotope concentrations in the air and in raindrops. In the model, it is estimated as

$$\Lambda = AP^B \tag{6.11}$$

where P is the precipitation rate and the values of A and B for all isotopes are 0.0001 and 0.8, respectively [194].

6.2.4 Radiological Dose

The short-term (early) dose is calculated for an exposure time of 48 hours and takes into account the following:

- internal exposure induced through inhalation of radioisotopes
- external exposure to deposits on the ground
- external exposure to radioactive plume
- absorption of tritium through skin

The calculations involved in these processes will be discussed briefly here.

6.2.4.1 Inhalation Dose

The model calculates the inhalation dose (ID) for each isotope as follows

$$ID = TIC \times ir \times DCF \tag{6.12}$$

where TIC is the time integrated concentration for the isotope, ir is the inhalation rate and DCF is the dose conversion factor for inhalation of the isotope. The default inhalation rate (1.2 m^3/hr in accident conditions) and dose coefficients are taken from ICRP 119 [200]. In this chapter, the dose coefficient values are taken from Table G.1 – *the effective dose coefficients for inhalation (activity median aerodynamic diameter = 1 μm) of radionuclides for members of the public up to 70 years of age*, with the worst cases for adults selected. Note for tritiated water (HTO) the inhalation dose is multiplied by 1.5, in order to account for the dose due to absorption of HTO through skin [201].

6.2.4.2 External Exposure to Ground Deposits

To calculate this dose contribution, we must first calculate the total ground deposition by integrating over the exposure time

$$\text{Time integrated ground deposition} = \int_0^t D(x, y, z, t)\, dt \tag{6.13}$$

where $D(x, y, z, t)$ is deposition as a function of position and time. Then for each isotope we must introduce a dose coefficient for exposure to contaminated ground surfaces $h_{T_{ground}}$ (taken from Federal Guidance Report No. 12 [202]) to calculate

$$\text{Dose due to ground deposits} = \text{Time integrated ground deposition} \times h_{T_{ground}} \tag{6.14}$$

6.2.4.3 External Exposure to Plume

Similar to above, for each isotope we must introduce a dose coefficient for air submersion $h_{T_{air}}$ (taken from Federal Guidance Report No. 12 [202]). Then

$$\text{Dose due to exposure to plume} = TIC \times h_{T_{air}} \tag{6.15}$$

The total dose is then calculated by summing all these doses.

6.3 Model Validation

To give confidence in the model prediction, it was decided to try to validate the developed model. Ideally, to validate the model it should be compared with either experimental data, or, if this is not possible, with predictions from other models. In the case of tritium releases it was possible to validate the model by comparing its predictions with measurements derived from experimental field studies. The validation of the model for dust releases was more problematic, as it was not possible to obtain experimental release data for dust particles that are likely to be produced in FPPs. To get around the lack of experimental data, the model predictions were compared with the dust calculations reported in the ITER Preliminary Safety Report (RPrS), as this is regarded as the

most comprehensive safety analysis for a large fusion facility that is currently available [80]. The RPrS data was also used to validate the model for tritium releases.

6.3.1 Model Validation Using the Canadian HT Study

An experimental release of tritium (in the form HT) was carried out at the Chalk River Meteorological Field in Canada in June 1987 [203]–[205]. The purpose of this experiment was to understand how tritium would behave if released under accident conditions and to develop further knowledge about the dose conversion values of HT. Around 3.54 TBq of HT was released at 15:20 on June 10th 1987 at a steady rate over a 30 minute period from a height of 1 m above the surface. The whole field consisted of a grassy circular section with a diameter of 183 m and a sparsely vegetated patch 226 m long [204]. The temperature and humidity were measured at a distance of 100 m from the release point and had values of 21 °C and 34%, respectively. The mean wind speed was measured at 2.4 m/s and was roughly 20° off the field centreline (see Figure 6.1).

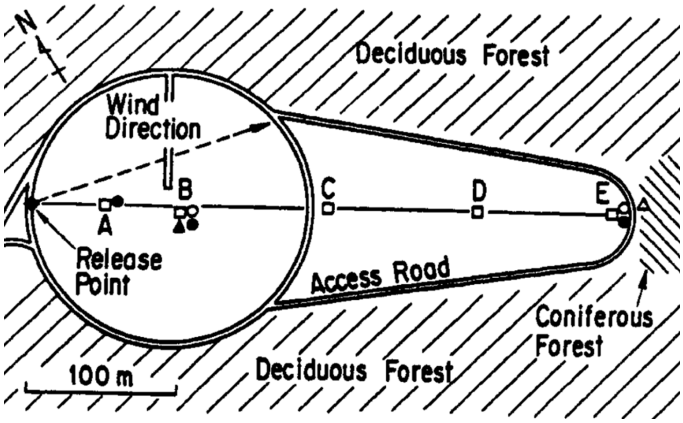


Figure 6.1: Chalk River Meteorological Field illustrating field centreline and various receptor points. Source: [204]

Air samplers for tritium gas (HT) and tritiated water vapour (HTO) were located at distances ranging from 50 m to 400 m from the release point. Japan Atomic Energy Research Institute (JAERI) also participated in this experiment to compare HT concentrations with those predicted by its Gaussian plume dispersion model and to observe HT and HTO deposition and re-emission rates from soil [204]. The ADMS-STAR model was used to predict the results of this experiment using the experiment source term and meteorological conditions. Figure 6.2 shows the results generated by the ADMS-STAR model.

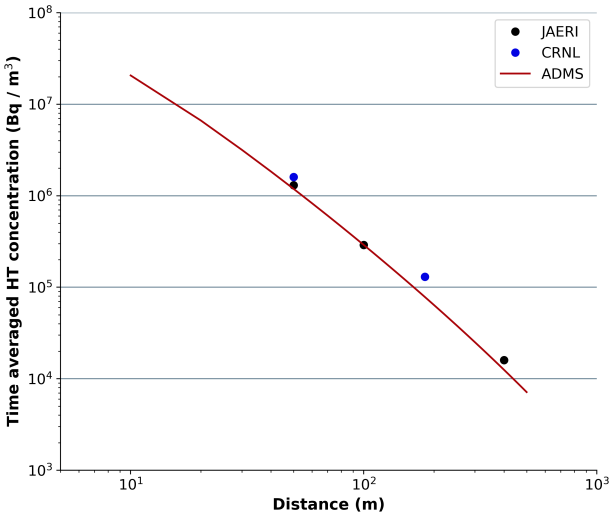


Figure 6.2: Comparison of ADMS-STAR model with Chalk River National Laboratories (CRNL) and JAERI's experimental results. Note both axes are on a logarithmic scale

It can be seen from Figure 6.2 that the model agrees well with experimental data at all distances from the source. It is worth noting that whilst a fraction of the released HT is converted into HTO in air, this fraction is relatively small, and has no significant effect on the average HT concentration in air. A process that may have a significant effect on dose, however, is the conversion of HT to HTO in soil, followed by re-emission of HTO to the atmosphere (HTO's dose conversion factor is 10,000 x larger than HT's) - a process that ADMS-STAR does not account for. Nevertheless, it will be shown that, as a conservative assumption, any tritium released from an FPP in an accident scenario is assumed to already be in HTO form. In this case, deposition and re-emission of HTO does still occur; however, it results in a negligible increase in dose received by an exposed person [201]. For the purposes of this work, assessing the magnitude of risk to workers and the public that an FPP poses, this re-emission process can be overlooked.

6.3.2 Model Validation Using the ITER RPrS

The RPrS [80] used the CERES and GAZAXI codes to study the effects of tritium and dust releases (these are established codes and are approved for use by the French regulatory authority ASN) [115].

6.3.2.1 Weather and Dose Assumptions

The RPrS incorporates the Doury dispersion parameter set [206], which consists of only two different stability categories: normal diffusion and weak diffusion. Normal diffusion corresponds to unstable or neutral atmospheric conditions (PG classes A to D) and is characterised by a vertical temperature gradient less than or equal to -0.5 °C/100 m. Weak diffusion corresponds to stable or very stable atmospheric conditions (PG classes E to G) and is characterised by a vertical temperature gradient greater than -0.5 °C/100 m [207]. In the RPrS, calculations are performed for:

- weak atmospheric diffusion and a wind speed of 2 m/s, so called DF2
- normal atmospheric diffusion DN and a wind speed of 5 m/s, so called DN5
- normal atmospheric diffusion DN and a wind speed of 5 m/s, with rain (5 mm/hr), so called DN5P

In addition to this, the air temperature and relative humidity are assumed to be 20 °C and 80%, respectively.

Early dose (as defined in the RPrS) considers an exposure time of 48 hours at a short distance. Receptor points are located at distances of 200 m, 1 km, 2 km, 2.5 km and 3.5 km; however, only the measurements at 200 m consider wholly early dose effects; measurements at all other distances take into account long-term effects such as ingestion. Early dose takes into account:

- internal exposure induced through inhalation of radioisotopes
- external exposure to deposits on the ground (dust only)
- external exposure to radioactive plume
- absorption of tritium through skin (HTO only)

6.3.2.2 Release Characteristic Assumptions

If the ratio between stack height and height of the surrounding buildings is less than 2.5, building wake effects can potentially occur. This creates a turbulent zone in the near-field, resulting in increased vertical mixing close to the building, effectively creating a downwash effect and dragging

the plume down in the near-field [115]. In order to account for this, the effective release point is calculated by dividing the stack height by a factor of 2.

In the design of ITER considered in the RPrS, the release is from a stack that protrudes about 4 m above the roof of the tokamak building, which itself is 54 m above ground, giving a release height of 58 m. The surrounding buildings, however, have a height of around 54 m, meaning building wake effects have to be considered. In the RPrS, the effective release height is taken to be 30 m (roughly half of the actual release height). Note in certain accident scenarios, some of the release may be leakage through building walls; this is represented as a ground level release [80]. For all releases considered, a nominal release duration of one hour and an adult breathing rate of 1.2 m^3/hr have been assumed.

6.3.2.3 Source Term Assumptions

A number of assumptions have been made in the RPrS in relation to the source terms for tritium and activated dust.

Tritium

Whilst there is only expected to be a very small amount of tritium actually in the plasma at any one time (∼1–2 g), tritium can accumulate both on the surface of and inside plasma facing materials. In the event of an accident, this tritium can mobilise and potentially follow a release pathway out to the environment. In the RPrS, the tritium inventory is estimated at 1 kg with an activity of 3.57E+17 Bq (note this takes into account both tritium in the cryopumps and tritium in the co-deposited layer of plasma facing components). In each accident scenario considered, this inventory is mobilised and assumed to be entirely in the form of HTO. This is a conservative estimate, as HTO is not only the most mobile form of tritium but also has the largest inhalation dose coefficient (1.8E-11 Sv/Bq) [200]. Note only a fraction of this 1 kg inventory is assumed to escape to the environment in the scenarios considered, as the ITER design employs multiple engineered barriers and defence in depth.

Activated Dust

In the RPrS, the activated dust is assumed to be tungsten from within the VV as this provides conservative radiological consequences (due to the high activation of tungsten). The maximum

dust inventory that can be accumulated inside the VV in ITER is assumed to be 1000 kg, and this is used to determine the dust source term considered [80]. Note if the accident scenario also triggers a large plasma disruption, an additional 5 kg of tungsten dust is assumed to be produced, increasing the dust inventory to 1005 kg. Similar to the tritium case, it is assumed that only a fraction of this inventory actually escapes to the environment in the scenarios considered because of the effectiveness of ITER's engineered barriers.

Generally, the dust found in fusion devices has the composition of the walls that make up the plasma-facing surfaces [73]. The wall of the PFCs in ITER will be made of tungsten and beryllium; however, the isotopes generated from the activation of tungsten dominate over those from activated beryllium (in terms of activity released). Therefore, neutron activation calculations have been performed on tungsten (as part of the ITER safety case) in order to estimate the quantities of each expected radionuclide present in activated tungsten dust (see Table 6.2). Note in the RPrS the dust particles are all assumed to be 1 micron in diameter.

6.3.2.4 Additional Input Assumptions

For all releases, surface roughness length is set at 0.3 m (standard value for this parameter), surface albedo is set at 0.23 (model default) and deposition velocity is calculated within the model for each run. The boundary layer h and the Monin-Obukhov length L_{MO} values depend significantly on the atmospheric stability type being simulated and were initially set as follows:

- DF2 (weak diffusion/stable conditions): $h = 100$ m, $L_{MO} = 20$ m
- DN5 (normal diffusion/neutral conditions): $h = 800$ m, $L_{MO} \rightarrow \infty$
- DN5P (normal diffusion/neutral conditions with rain at 5 mm/hr): $h = 800$ m, $L_{MO} \rightarrow \infty$

In both DN5 and DN5P stability conditions, L_{MO} tending to infinity is a representation of mechanical turbulence dominating throughout the entirety of the boundary layer, with little effects due to convective turbulence. Note these values are merely input values for these parameters; as the model iterates through time these values will change. DF2 conditions are represented by relatively clear skies (1 okta), whereas DN5 and DN5P conditions are characterised by cloudy skies (8 oktas). For a release of dust, the half-life, density, particle size and DCF for inhalation of each radioisotope had

Nuclide	Activity (Bq/g)	DCF for inhalation (Sv/Bq)
W187	1.04E+11	2.00E-10
W185	3.72E+10	1.47E-10
Re186	1.97E+09	1.10E-09
Ta182	1.67+E08	9.70E-09
Re188	1.19E+09	5.50E-10
W181	1.43E+10	2.80E-11
Ta183	6.40E+07	2.00E-09
Co60	1.27E+06	2.90E-08
Re184	1.99E+07	1.80E-09
Ta184	4.33E+07	4.40E-10
Ta179	2.74E+07	5.20E-10
$Ag110^{m}$	3.72E+05	1.20E-08
Co58	1.14E+06	2.00E-09
Ta186	6.40E+07	1.90E-11
Mn54	2.57E+05	1.50E-09

Table 6.2: Nuclide composition of activated dust source terms in RPrS. Note activity is given in Bq per gram of dust released; DCF for inhalation of particles of diameter 1 micron taken from ICRP 119. Source: [115], [200]

to be entered. All dust particles were assumed to be 1 micron in diameter (as in the RPrS) and their respective half-lives and DCFs were taken from ICRP 119 [200].

6.3.2.5 ADMS-STAR Model Comparison with ITER RPrS Predictions

Elevated Releases

Table 6.3 shows a comparison between the model and the RPrS early dose predictions for a 1 g release of both tritium (in HTO form) and activated dust from a 58 m stack (30 m effective) under DF2, DN5 and DN5P conditions.

Table 6.3 shows that for an elevated release the model is in reasonable agreement with the ITER RPrS early dose predictions for both HTO and dust at a distance of 200 m. It can be seen that for DF2 weather conditions, the model and the RPrS agree well. For DN5 weather conditions, however, the model overpredicts the doses at 200 m by a factor of about 2. For DN5P weather conditions, the

	Weather conditions					
	DF2		DN5		DN5P	
Source	ADMS	RPrS	ADMS	RPrS	ADMS	RPrS
HTO	2.81E-08	2.50E-08	5.40E-02	2.10E-02	5.33E-02	2.10E-02
Dust	1.91E-10	1.80E-10	4.15E-04	2.00E-04	3.17E-03	4.00E-03

Table 6.3: Comparison of ADMS-STAR and RPrS early dose (mSv) predictions for a 1 g release from 58 m stack; dose is calculated at a distance of 200 m from the source

model again overpredicts the HTO dose at 200 m by a factor of 2, but slightly underpredicts the dust dose. Given the uncertainty in the meteorological conditions considered in the RPrS calculations, this seems an acceptable level of accuracy for the model. Hence, for the purposes of this work, it seems reasonable to assume that the model can be considered to be validated for elevated releases under the DF2, DN5 and DN5P weather conditions.

Ground Releases

Table 6.4 shows a comparison between the model and the RPrS early dose predictions for a 1 g release of both tritium (in HTO form) and activated dust from ground level under DF2, DN5 and DN5P conditions.

	Weather conditions					
	DF2		DN5		DN5P	
Source	ADMS	RPrS	ADMS	RPrS	ADMS	RPrS
HTO	4.79	4.50	0.20	1.90	0.20	1.80
Dust	3.05E-02	3.80E-02	1.55E-03	1.70E-02	3.53E-03	2.40E-02

Table 6.4: Comparison of ADMS-STAR and RPrS early dose (mSv) predictions for a 1 g release from ground level; dose is calculated at a distance of 200 m from the source

Table 6.4 shows that for ground level releases under DF2 conditions, the model slightly overpredicts the HTO dose and slightly underpredicts the dust dose at 200 m when compared with the RPrS values. For the DN5 and DN5P conditions, the ADMS model underpredicts both the HTO and dust doses by a factor of about 10. This may be due to the lack of detailed information available on the meteorological data used in the RPrS, or due to the advanced modelling processes that are taken into account in the model and absent from the CERES/GAZAXI codes (such as characterising the

boundary layer using h and L_{MO}). However, given that a robust safety analysis of any potential releases of radionuclides would take into account worst-case weather conditions, it can be seen in Table 6.4 that for the ground level worst-case weather conditions (DF2), there is a good fit between the ADMS-STAR prediction and the RPrS result. Given this, it is not unreasonable to assume that for the purposes of this work, the ADMS-STAR model can be considered validated for use in the analysis of risk reported in this chapter.

6.4 Reference Case

The work reported in this chapter was to provide an insight into the hazard potential of FPPs and to investigate the factors that can influence the assessment of risk. In the absence of an FPP design, a reference case risk calculation was performed. The reference case was based on realistic assumptions for an FPP accident analysis. Given the validation results in Section 6.3.2.5, the following scenario was used as the reference case for a representative FPP:

- Release of 1 g of activated dust/tritium in HTO form
- Release period of 1 hr
- Ground level release
- DF2 weather conditions
- Particle size of 1 μm
- Dust nuclide composition (see Table 6.2)
- Adult breathing rate of $1.2m^3/hr$

This scenario can be considered to provide a best estimate calculation for a representative FPP, as it provides a realistic set of assumptions that are likely to result in a maximum dose to exposed individuals. Figure 6.3 illustrates the early dose received by an adult as a function of distance from the source for this reference scenario – the distances of 200 m and 1 km have been highlighted to represent the site boundary and the closest expected population, respectively.

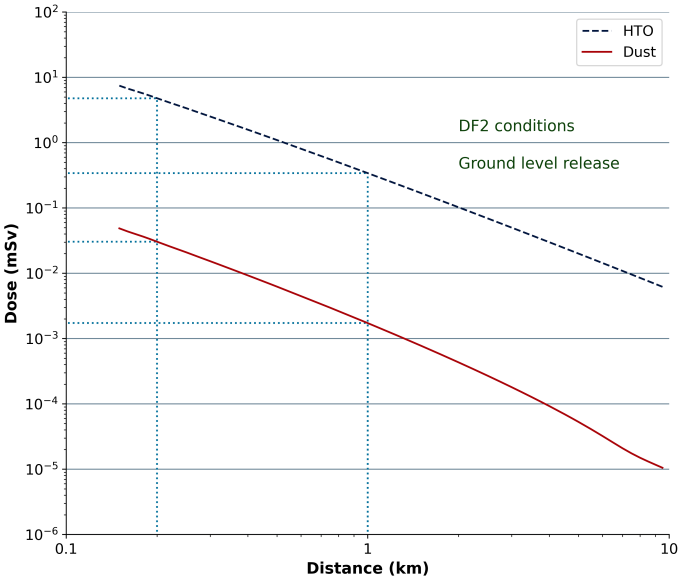


Figure 6.3: Early dose for 1 g release of dust and HTO from ground level under DF2 conditions

6.5 Sensitivity Analysis

Given the lack of a detailed design for an FPP, it is important to consider the sensitivity of the risks predicted in the reference case to changes in the key assumptions in order to see if any have a significant effect on the risk outcome. The key parameters investigated in the sensitivity study were:

- Release height
- Dust particle size
- Release time
- Weather conditions

6.5.1 Release Heights

6.5.1.1 Overview

Section 6.3 showed that release height can have an effect on the dispersion behaviour of a release of HTO or dust which in turn impacts the dose received by an exposed population. The purpose here

is to investigate the effect of the release height on the dose received by the public. Various release heights have been investigated rather than just the two release heights considered in the RPrS [80].

In a number of accident scenarios considered in the RPrS, hot water enters the VV and undergoes rapid evaporation, producing steam which pressurises the vessel. As a result, any mobilised inventories of tritium and dust are initially transferred to the drain and suppression tanks. Given that there is no failure of the primary confinement barrier and hence there are no leaks into adjacent rooms and no uncontrolled leaks into the environment, the only potential environmental releases are controlled releases via the suppression tank vent system (ST-VS) and associated detritiation systems, i.e. via the stack. It is therefore crucial to understand what effect the stack release height has on any potential releases. This information will be useful to FPP designers whose challenge involves ensuring the radiological consequences of any accident scenarios are minimised.

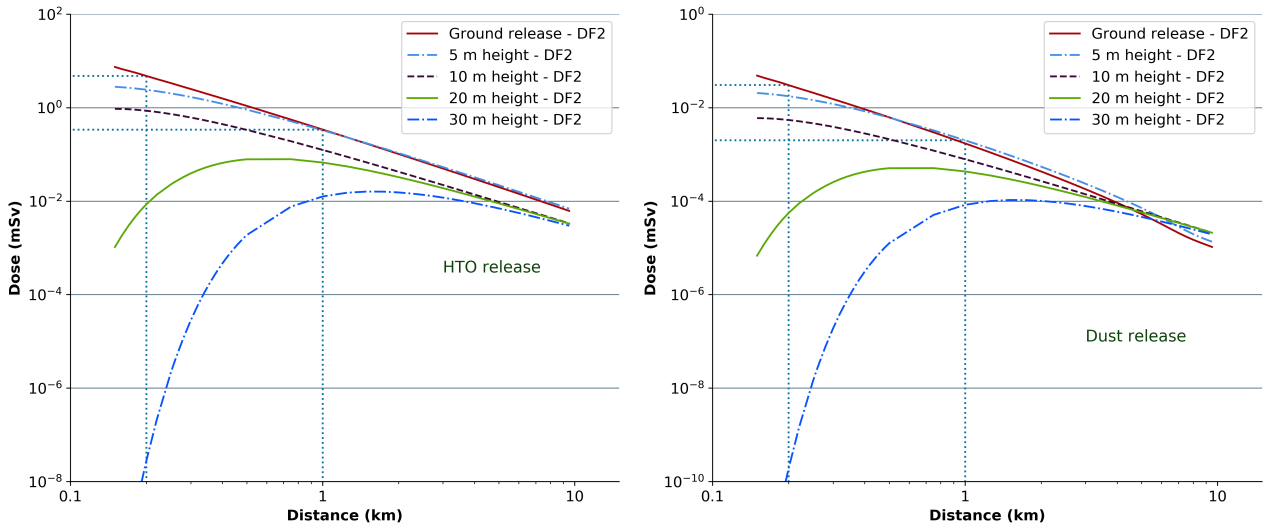
6.5.1.2 Release Characteristics

If the ratio between stack height and height of the surrounding buildings is less than 2.5, building wake effects can potentially occur [115]. In order to account for this, the approach taken in the ITER RPrS was to calculate the effective release height by dividing the actual stack height by a factor of 2. As there is currently no detailed design for an FPP for electricity generation, the plant layout and the relative heights of the discharge stack and surroundings buildings is unknown; hence, it is not possible to accurately model building wake effects. Therefore, for the purposes of these calculations, it is assumed that no building wake effects occur. The release heights considered were ground level, 5 m, 10 m, 20 m and 30 m.

All calculations assume that all the other base case parameters, i.e. DF2 weather conditions, a release of 1 g of tritium in HTO form or 1 g of activated dust, a nominal release duration of one hour and an adult breathing rate of 1.2 m^3/hr remain the same.

6.5.1.3 Results

Figure 6.4 illustrates the early dose (mSv) received by an adult as function of distance from the source for a range of release heights under DF2 conditions. On each of the plots the distances of 200 m and 1 km are highlighted to reflect a nominal person located at the site boundary and in the surrounding area.



(a) HTO (b) Dust

Figure 6.4: Early dose for 1 g release under DF2 conditions for a range of release heights for a) HTO and b) dust

For HTO releases, Figure 6.4a shows that increasing the release height results in a lower dose received (i.e. a release from a height of 30 m will result in a lower dose than a release from a height of 20 m at all distances considered). This is most notable as the release height is increased above 10 m, as there is a sharp reduction in dose to the exposed person at all distances up to around 500 m. In the case of activated dust, Figure 6.4b shows a similar trend to the HTO release, but at around 6 km from the source the dose to the exposed person increases with increasing release heights relative to the reference case.

These results are explained primarily due to the reduced vertical mixing that takes place in DF2 conditions: the plume undergoes little dilution and so, as the release height is increased, less of the plume is mixed and brought down to ground level, resulting in a smaller dose to any exposed persons near the source. In the case of HTO, this effect is less pronounced as distance from the source increases, as the plume has travelled further downwind and so has undergone further dilution and is eventually brought to the ground. In the case of dust, as distance increases beyond 6 km the trend seems to reverse, i.e. the 20 m and 30 m release heights result in a larger dose compared to the release heights closer to the ground. There are two primary reasons for this: 1) at these distances the plumes that were released from the elevated heights have travelled a sufficient distance in order to

be brought down to ground level, increasing the dose received and; 2) the increased deposition that occurs close to the source from near-ground releases results in a plume of much lower concentration travelling downwind. Hence, at a distance of around 6 km the plumes from near-ground releases have a lower concentration than plumes from elevated releases that have been brought to the ground. This results in the lower dose received from near ground-level releases.

From these results, it is clear that the release height is important. A ground level (building) release will always dominate the dose received at distances out to around 6 km from the site of the accident. Release via a stack height of 30 m can reduce the dose at 200 m by several orders of magnitude and the dose at 1 km by an order of magnitude compared with the base case.

6.5.2 Dust Particle Size

6.5.2.1 Overview

Developing a source term for activated dust in an FPP is problematic as the dust inventory depends on a multitude of factors. Estimates of dust production rates depend upon the material type, location, plasma pulse length and disruption frequency [73]. In the RPrS it is assumed that the dust particles are all spherical with a diameter of one micron; however, in reality this is not the case. Sharpe *et al.* participated in a study in which they compared collected dust from a number of research devices including the Tokamak Fusion Test Reactor (TFTR) at Princeton, Alcator C-Mod at MIT, JET at Culham, ASDEX-Upgrade at the Max Planck Institute and the NOVA laser facility at the Lawrence Livermore National Laboratory [73]. Collection took place during periods of schedule maintenance, when the vacuum chamber is vented, and personnel can access the plasma chamber. They found that whilst most dust particles found in present fusion devices do generally exhibit a roughly spherical surface-to-volume ratio, the diameter of the particles span a range of values (see Figure 6.5). The size distribution shown in Figure 6.5 was obtained with dust collected at the lower divertor region of ASDEX-Upgrade. The figure shows measured size frequency data together with a fitted lognormal distribution [73]. Sharpe *et al.* also compared average dust sizes from different regions of the various fusion devices and found that the average particle size for this data is 2.8 $\pm$ 2.4 μm [73]. However, due to the lognormal nature of the size distribution, it is expected that dust found in fusion machines will typically range from 0.5 to 10 μm in diameter [73]. They concluded

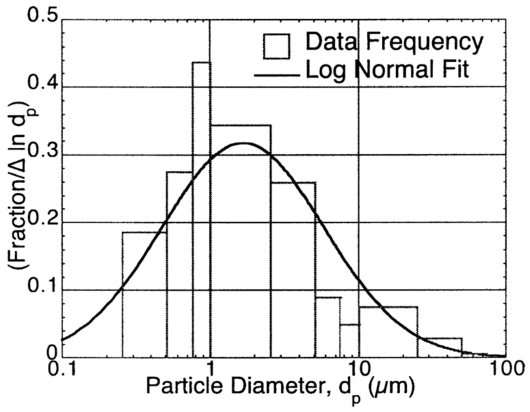


Figure 6.5: Typical count-based size distribution of dust from a fusion device. Source: [73]

that the similarity in the dust size distributions for the various devices suggests similar processes are involved in their production, mainly via condensation of material eroded during plasma-surface interactions [73].

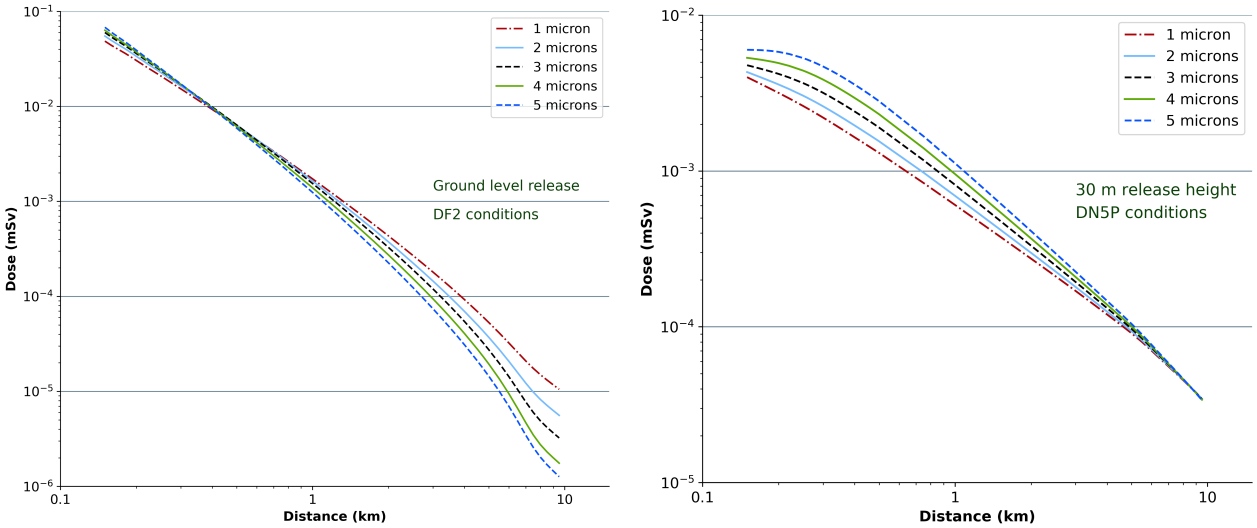
6.5.2.2 Release Characteristics

In order to investigate the effect of particle size on radiological dose, the model was used to simulate a 1 g release of dust particles of the following sizes: 1, 2, 3, 4 and 5 μm. These sizes were chosen as they cover a significant range of the particle sizes expected in an FPP (see Figure 6.5) and any trends between sizes should be discernible.

Given that dust particles have potential release pathways at ground level and via the stack, both ground level and elevated releases (30 m) were considered. For both release heights, worst-case weather conditions were assumed: for ground level releases DF2 conditions were assumed (to allow comparison with the reference case); for elevated releases DN5P conditions were assumed. All calculations assume a nominal release duration of one hour and an adult breathing rate of 1.2 m^3/hr.

6.5.2.3 Results

As shown in Figure 6.6b, for elevated releases as the size of the dust particles increases the dose received also increases up to a distance of around 8 km. This seems to be a product of the increased deposition that occurs as the particle size increases, contributing to the overall dose (note this trend was seen in both cases where wet and dry deposition were accounted for and dry deposition



(a) Ground level release – DF2

(b) Elevated (30 m) release – DN5P

Figure 6.6: Early dose for 1 g of activated dust released for a range of particle sizes for a) ground level release under DF2 conditions and b) elevated (30 m) release under DN5P conditions

only). As a comparison, an elevated release of 1 g of dust particles of diameter 1 µm under DN5P conditions results in a dose of 3.17E-03 mSv at 200 m and 6.05E-04 mSv at 1 km; whilst a release of particles of diameter 5 µm under the same conditions results in a dose of 5.82E-03 mSv at 200 m and 1.12E-03 mSv at 1 km – an increase of nearly 85% at both distances. Note that at a distance beyond 8 km there seems to be no distinction between the doses due to the various particle sizes.

The effect of particle size on dose is more complex for ground level releases under DF2 conditions. Figure 6.6a shows that whilst the dose received up to a distance of around 400 m shows the same trend as for elevated releases (dose increases as particle size increases), the size of this increase was significantly lower than in the elevated case. On top of this, beyond this distance the trend is reversed, i.e. dose decreases as particle size increases. This can again be explained by the increased deposition that occurs due to the larger particles: in the ground level case, the increased deposition of large particles that occurs close to the source results in a plume of significantly lower concentration travelling downwind, hence a reduction in dose received.

In the RPrS it is assumed that all dust particle releases are 1 µm in diameter; however, the results of this analysis suggest that, at least for an elevated release, a range of particle sizes should be

taken into account in any comprehensive safety analysis. Whilst the effect of particle size on dose seems modest for a ground level release, for an elevated release under DN5P conditions particles of diameter 5 μm result in a dose almost twice as large as particles of diameter 1 μm (up to a distance of around 1 km). As particles of this size are expected to be produced in an FPP, any robust safety case will either need to provide confidence that this assumption is incorrect and any particles produced are 1 μm in diameter (or close to), or it will need to take into account dust particles of different sizes.

6.5.3 Release Times

6.5.3.1 Overview

Varying the length of the release time may have an effect on the dose received. All accident scenarios considered in the RPrS have a release time of one hour; however, it is possible for accident scenarios to have different release times. One such factor that can influence release time is the rate of thermal outgassing of tritium from hot surfaces, which appears to be highly dependent on factors such as temperature and humidity [208].

6.5.3.2 Release Characteristics

In order to establish any effects of release time on dose, the following release times were considered: 1 minute, 1 hour, 2 hours and 5 hours. These choices were considered sufficient to cover a range of potential scenarios, from an almost instantaneous release of the inventory to a prolonged release that may either go unnoticed by operators or take a considerable length of time to rectify. As radionuclides in an FPP are expected to have multiple release pathways, both ground level and elevated (30 m) releases were considered.

All calculations assume DF2 weather conditions, a release of 1 g of tritium (in HTO form) or 1 g of activated dust, and an adult breathing rate of 1.2 m^3/hr. It is worth noting that in a real-world scenario there would be changes in wind direction and velocity over time, which could result in a reduction of the maximum dose received; however, for the purposes of this sensitivity study, it was assumed that the meteorological conditions are held constant throughout the modelling period.

6.5.3.3 Results

For all of the release times considered, there was no significant difference in dose received at all distances. This was the case for elevated releases and ground level releases for both HTO and activated dust. The consequence of this analysis is that FPP designers and operators must ensure that limiting the overall quantity of radionuclides released to the atmosphere is a priority, as reducing the rate of release has no significant effect on dose received (assuming the overall inventory released is the same). However, slowing the rate of release is beneficial if emergency countermeasures are implemented, as members of the public that are evacuated early from the surrounding area will be exposed to lower quantities of radioactive material.

6.5.4 Weather Conditions

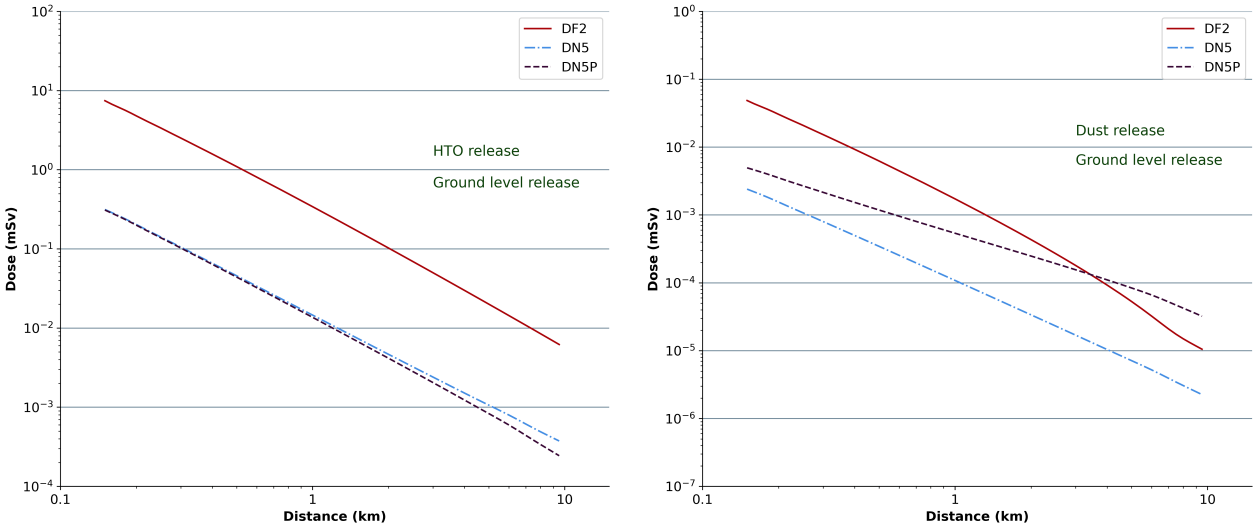
6.5.4.1 Overview

The weather conditions at the time of release play a pivotal role in determining how a plume of radionuclides are transported through the atmosphere (see Section 6.1.2). The transportation of the plume is likely to have an effect on the dose received by any exposed persons; as a result, the effect of weather conditions was investigated as part of the sensitivity study.

6.5.4.2 Release Characteristics

Consistent with the validation process in Section 6.3.2, the following weather conditions were considered: DF2 (reference case), DN5 and DN5P. These choices were considered sufficient to cover a range of potential scenarios and include a range of meteorological phenomena (e.g. wet deposition). Note, as radionuclides in an FPP are expected to have multiple release pathways, both ground level and elevated (30 m) releases are considered.

All calculations assume a release of 1 g of tritium (in HTO form) or activated dust and an adult breathing rate of 1.2 m^3/hr (base case assumptions).



(a) HTO (b) Dust

Figure 6.7: Early dose for 1 g ground level release for a range of meteorological conditions for a) HTO and b) dust

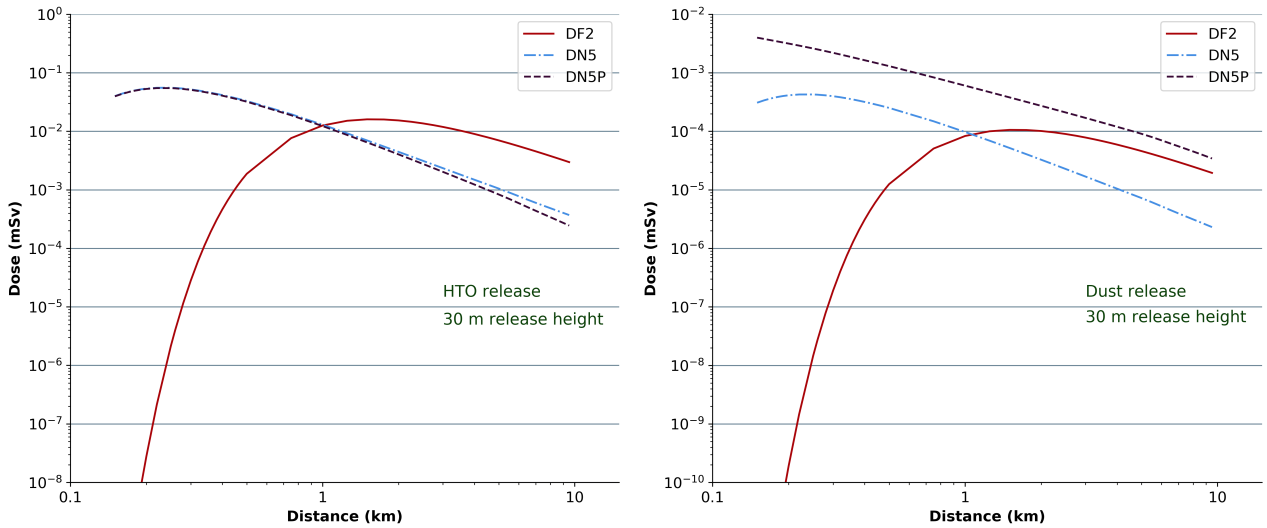
6.5.4.3 Results

Ground Level Releases

For HTO releases, Figure 6.7a shows that DF2 conditions result in the maximum dose received at all distances considered; DN5 and DN5P conditions result in largely similar doses at all distances, with DN5 conditions resulting in a slightly increased dose at distances greater than 1 km. In the case of activated dust, Figure 6.7b shows that up to around 3 km, DF2 conditions result in the maximum dose to any exposed persons. At distances beyond this, DN5P conditions result in the maximum dose. These results can similarly be explained by the reduced vertical mixing that takes place in DF2 conditions: once the plume is released from ground level, it undergoes little dilution upon reaching any exposed persons and therefore results in a larger dose. In the cases of DN5 and DN5P conditions the increased vertical mixing acts to raise the plume up into the atmosphere, resulting in increased dilution and a lower dose to any exposed persons. In the case of activated dust, beyond a distance of 3 km DN5P conditions result in a larger dose than DF2. This may be due to the increased deposition that occurs close to the source in DF2 conditions, resulting in a plume of lower concentration travelling downwind, hence a lower dose to any exposed persons.

It is clear from these figures that when considering worst-case weather conditions for ground level releases of radionuclides (e.g. conditions that will lead to a maximum dose close to the plant), DF2 conditions will need to be assumed. For HTO and activated dust (up to a distance of around 3 km), DF2 conditions result in the largest dose to any exposed persons, consistent with the findings of the RPrS [80]. It is worth noting that the early doses calculated in the model at a distance of 200 m considering a ground level 1 g release of both HTO and activated dust under DN5 and DN5P conditions are around $1/10^{th}$ of the values reported in the RPrS (see Section 6.3.2). At this stage it is unclear which predicted values are closer to the true value, due to the number of assumptions made and lack of experimental data to validate to.

Elevated Releases



(a) HTO (b) Dust

Figure 6.8: Early dose for 1 g elevated (30 m) release for a range of meteorological conditions for a) HTO and b) dust

As shown in Figure 6.8, elevated releases tend to exhibit the opposite effect to ground level releases, i.e. for elevated releases, DF2 conditions result in the lowest dose close to the plant whereas DN5P conditions tend to result in the maximum dose close the plant. This again is primarily explained by the reduced vertical mixing that takes place under DF2 conditions: if the plume is released from a large height under DF2 conditions, the plume will travel a significant distance downwind before it is brought to the ground, resulting in an extremely low dose close to the plant and an increasing

dose up to a distance of around 1.5 km. Conversely, in DN5 and DN5P conditions, the increased vertical mixing acts to bring the plume to the ground much closer to the release point, resulting in a much larger dose. In the case of dust, DN5P conditions results in a larger dose compared with DN5 as a result of the wet deposition that occurs in the DN5P case and is absent in the DN5 case - the increased quantities of dust on the ground contributes significantly to the early dose received. It is clear from these figures that when considering worst-case conditions for elevated releases, DN5/DN5P conditions will need to be assumed for HTO and DN5P conditions will need to be assumed for dust, consistent with the findings in the RPrS [80].

6.6 Hazard Potential

The above analysis shows that for a release of 1 g of tritium (in HTO form) and 1 g of activated dust under the most conservative weather and release height conditions, the radiation exposure to a worker at a distance of 200 m would be just under 5 mSv, with the major proportion of the dose coming from tritium. At 1 km a member of the public would receive a dose of around 0.34 mSv, with the major proportion of the dose again coming from tritium. The risk of harm is dependent upon the probability of occurrence x consequence and hence in the absence of a detailed design (from which the probability could be determined) the acceptability of these levels of exposure cannot be determined. Note, in any safety analysis, if the dose received was larger at distances other than the ones considered here, those doses would be taken into account. However, for these sensitivity studies, it was considered sufficient to compare the doses at 200 m, 500 m and 1 km.

Moreover, FPPs are expected to contain inventories much larger than the 1 g considered here (e.g. recent estimates of inventories expected at DEMO are up to 4.7 kg for tritium and up to 689 kg/year for dust [209]). Hence, it is possible that severe beyond design-basis accidents could have greater releases of radioactive material and hence the potential for larger doses to the public.

In the absence of a detailed design, one way to scope the hazard potential was to consider the size of the release that would be needed to trigger emergency preparedness countermeasures such as sheltering and evacuation. The sizes of these releases were then compared with likely FPP inventories to see if such releases were feasible or not.

6.6.1 Emergency Preparedness Countermeasures

In the case of nuclear fission, countries that have nuclear power programmes are required by international conventions to have emergency preparedness arrangements to mitigate the consequences in the event of a nuclear accident. These requirements are usually delivered through national legislation, although this varies between countries [210]. In the UK, the HSWA [171] requires employers to protect both their employees and the public from work activities. Specific regulations are used to set out requirements and place specific responsibilities on duty holders. REPPIR 2019 [175] relates to radiation emergencies and defines a radiation emergency as an event that is likely to result in a member of the public receiving an effective dose in excess of 1 mSv in the period of one year immediately following the event (note this is a reduction of the 5 mSv limit previously specified in REPPIR 2001 [211]). These regulations require emergency plans to make use of countermeasures to limit radiation exposure.

The UK emergency countermeasures use "Emergency Reference Levels" (ERLs) published by Public Health England [212], which are based on the whole body dose expected to be averted if the countermeasure is deployed following a radiation emergency (see Table 6.5).

	Dose equivalent level (mSv)	
Countermeasure	**Lower**	**Upper**
Sheltering	3	30
Evacuation	30	300

Table 6.5: UK Emergency Reference Levels (ERLs). Source: [212]

The dose levels in Table 6.5 are based on approximations and are not intended to be strict trigger values for implementing the countermeasure. Evacuation and the related panic may cause significant harm to people and so authorities may not evacuate without strong supporting evidence. However, for the purposes of this study the lower dose levels were used as a reference point for each countermeasure, i.e. the dose level that requires the countermeasure to be implemented.

6.6.2 Hazard Analysis

The validated ADMS-STAR model was used to investigate the quantities of tritium (in the form of HTO) and activated dust that need to be released in order to trigger the sheltering and evacuation lower ERL countermeasures. The aim of this work was to put the release quantities into context with a view to establishing the feasibility of such releases and identify important design features that could influence the release quantities. A matrix of calculations was used to investigate the impact of release height, particle size and weather conditions on the HTO and activated dust quantities.

6.6.2.1 Impact of Release Height

For these calculations a release period of 1 hour and particle size of 1 μm was assumed. Table 6.6 shows the quantities of tritium (in the form of HTO) and activated dust that would need to be released to trigger the 3 mSv lower sheltering ERL for a range of release heights. Table 6.7 shows the quantities needed to trigger the 30 mSv lower evacuation ERL. In both tables the worst-case weather conditions have been used in the model calculations for each release height (i.e. conditions that require the least amount of material to be released to trigger the ERL). This is to put into perspective the release quantities that could feasibly be released at each height and result in the triggering of sheltering or evacuation protocols.

The general trend shown in the tables is that as release height is increased, the quantity of material needed to be released in order to hit the ERL increases.

		Quantity released to reach 3 mSv dose limit			
Release height	**Inventory**	**At 200 m**	**At 500 m**	**At 1 km**	**Weather**
Ground release	HTO	0.6 g	3 g	9 g	DF2
	Dust	98 g	481 g	1.7 kg	DF2
5 m	HTO	1 g	3 g	9 g	DF2
	Dust	169 g	487 g	1.5 kg	DF2
10 m	HTO	3 g	9 g	24 g	DF2
	Dust	549 g	1.4 kg	3.8 kg	DF2
20 m	HTO	25 g	73 g	211 g	DN5
	Dust	831 g	2.2 kg	5.0 kg	DN5P
30 m	HTO	56 g	91 g	231 g	DN5
	Dust	946 g	2.3 kg	5.0 kg	DN5P

Table 6.6: Inventory release quantities (against release height) required to trigger sheltering

		Quantity released to reach 30 mSv dose limit			
Release height	**Inventory**	**At 200 m**	**At 500 m**	**At 1 km**	**Weather**
Ground release	HTO	6 g	27 g	88 g	DF2
	Dust	984 g	4.8 kg	17.3 kg	DF2
5 m	HTO	12 g	33 g	91 g	DF2
	Dust	1.7 kg	4.9 kg	14.9 kg	DF2
10 m	HTO	35 g	89 g	239 g	DF2
	Dust	5.5 kg	14.2 kg	37.9 kg	DF2
20 m	HTO	250 g	729 g	2.1 kg	DN5
	Dust	8.3 kg	22.4 kg	49.9 kg	DN5P
30 m	HTO	556 g	906 g	2.3 kg	DN5
	Dust	9.5 kg	22.9 kg	49.6 kg	DN5P

Table 6.7: Inventory release quantities (against release height) required to trigger evacuation

6.6.2.2 Impact of Particle Size

For these calculations a release period of 1 hour was again assumed. Two release heights were adopted to investigate the effect of particle size on release quantities; for both release heights worst-case weather conditions were assumed. Table 6.8 shows the quantities of dust needed to be released to trigger the 30 mSv lower evacuation ERL.

		Quantity released to reach 30 mSv dose limit		
Release type	**Particle size (μm)**	**At 200 m**	**At 500 m**	**At 1 km**
Ground release	1	984 g	4.8 kg	17.3 kg
DF2	2	890 g	4.7 kg	18.3 kg
	3	833 g	4.7 kg	19.5 kg
	4	804 g	4.9 kg	21.6 kg
	5	767 g	5.1 kg	24.2 kg
Elevated (30 m)	1	9.5 kg	22.9 kg	49.6 kg
DN5P	2	8.4 kg	19.4 kg	43.3 kg
	3	7.1 kg	15.8 kg	36.8 kg
	4	6.1 kg	13.0 kg	31.4 kg
	5	5.2 kg	10.7 kg	26.8 kg

Table 6.8: Inventory release quantities (against particle size) required to trigger evacuation

For elevated releases, as the particle size increases the quantity of material needed to be released to hit the 30 mSv lower evacuation ERL decreases. For ground level releases, at a distance of 200 m this same trend is shown, i.e. as the particle size increases the quantity of material needed to trigger the ERL decreases. However, at both 500 m and 1 km as the particle size increases the quantity of material needed to be released to trigger the ERL increases: a product of the increased deposition of these larger particles close to the plant.

6.7 Discussion

The key question is: Do FPPs have inventories of radioactive material that, if released in a severe beyond design-basis accident, could trigger emergency preparedness countermeasures such as sheltering and evacuation? The above analysis is an attempt to answer this question. Using the ADMS-STAR model, Tables 6.6, 6.7 and 6.8 show the source term releases required to trigger the sheltering and evacuation ERLs. The size of the release inventory is evaluated at different distances

from the source and for two release scenarios, i.e. a ground level (building) release and an elevated release.

For people living at a distance of 1 km from the plant, Table 6.6 shows that, providing the release pathways are entirely via an elevated 30 m stack (not taking into account building wake effects), it would require a release of 231 g of HTO or 5 kg of dust to consider implementing sheltering. The situation is more acute for an accident that results in a ground level release, in which only 9 g of HTO or 1.7 kg of dust is required to trigger the sheltering ERL at a distance of 1 km. In the case of evacuation, Table 6.7 shows that for an elevated (30 m) release, 2.3 kg of HTO or nearly 50 kg of dust would need to be released to trigger the ERL. Again, the situation is more acute for a ground level release where only 88 g of HTO or 17.3 kg of dust would need to escape.

From Table 6.8 it can be seen that for elevated releases at a distance of 1 km, as the particle size increases the quantity of material needed to be released to trigger the 30 mSv lower evacuation ERL decreases. For ground level releases the opposite is observed: at a distance of 1 km as the particle size increases the quantity of dust needed to trigger evacuation also increases. Nevertheless, when looking at risk to populations situated at least 1 km away, it would take a significant 26.8 kg of dust for an elevated release and 17.3 kg of dust for a ground level release to trigger the lower evacuation ERL, conservatively assuming the most pessimistic case for each release height.

The results for exposed workers at a distance of 200 m are of interest as the most pessimistic ground release case requires a release of only 767 g of dust for a worker to receive a 30 mSv dose, which is in excess of the 20 mSv annual limit. Given that, in the event of air or water ingress into the VV due to an accident there is potentially hundreds of kilograms of dust transferred to the drain and suppression tanks, a release this small is conceivable.

The results for HTO releases show that there is a large margin between the amount of tritium in the plasma and the release needed to trigger either sheltering or evacuation. However, there are other sources of tritium that can potentially be released in an accident scenario (such as in the breeder blankets and in the plasma facing walls). The release of the tritium in the plasma will be instantaneous, but the release from these other sources will take time to release, allowing operators to take remedial actions to prevent any longer-term uncontrolled releases. However, there is the

potential for up to 1 kg of tritium in the VV and hence if a severe beyond design-basis accident resulted in an uncontrolled release of radioactive material there is the potential to trigger the ERLs. In the case of dust, again there is the potential for dust inventories to exceed that required to trigger the ERLs, but it is possible to control the inventory by the design of the plasma facing materials and operational maintenance to reduce build-up.

The answer to the question above is yes, clearly there are inventories of radioactive materials in an FPP that, if released in a severe accident, would trigger the sheltering and evacuation ERLs.

The results of this work pose a number of challenges to FPP designers with respect to how releases of HTO and activated dust are controlled. The first challenge (option 1) is to ensure that the likelihood of accidents that can result in the significant release of HTO or dust from the vacuum vessel (VV) is suitably low to ensure the risks to both workers and the public are as low as reasonably practicable (ALARP/ALARA). The second challenge (option 2) is to ensure that if a significant release from the VV does occur, the design of the plant ensures the radionuclides are released via a high stack rather than leakage through walls. The third challenge (option 3) is that if neither of these options can be delivered, a robust, air-tight confinement building will need to be deployed to prevent an uncontrolled radioactive release.

To satisfy option 1, designers must ensure that scenarios in which the integrity of the primary confinement barrier is significantly challenged have an extremely low frequency of occurrence. Ref [213] highlights the potential accident scenarios in which the integrity of the VV is challenged including failure of the magnet systems, electromagnetic loading on the VV walls, and hydrogen and dust explosions, amongst others. These scenarios could result in a loss of confinement and an escape of the radioactive inventory. Failure of a PFC can also result in coolant from the blanket or divertor spilling into the VV, which will generally be followed by water or air ingress into the VV. This in turn will cause a pressure increase in the VV which, coupled with the hot components present, could provide a driving force to propel the radioactive inventories out of the vessel. To mitigate this, it is expected that an FPP will have a vacuum vessel pressure suppression system (VVPSS) that will act to reduce the potential to over-pressurise the VV and enable the inventories of tritium and dust to be transferred to drain and suppression tanks (ITER is currently expected to be the first fusion

machine to test this concept).

Ref [213] also highlights the need to investigate the scenario in which the VVPSS fails to activate following a rupture (and is therefore unavailable) to determine if there would be catastrophic failure of the VV and resultant uncontrolled release of radioactive material. What also needs to be substantiated is the capability of the VVPSS to transfer the inventories of tritium and dust to the drain tanks and ensure no leakage occurs. In the ITER RPrS there is assumed to be almost 1 kg of tritium and hundreds of kilograms of dust in the VV that is available for transfer to the drain tanks in the event of water ingress into the VV (note in the absence of a detailed design for an FPP, the assumptions made at ITER are a useful guide) [80]. If 1% of this inventory managed to escape to the environment at ground level, the 30 mSv evacuation ERL would be triggered at a distance of 200 m from the release (assuming worst-case conditions). If 10% of the inventory escaped via the stack (elevated release), the lower evacuation ERL would be triggered.

It is therefore essential for an FPP design to be substantiated and have a robust safety case, especially in relation to events that could challenge the integrity of the VV. It is also essential for the safety case to investigate the scenarios in which the VVPSS system fails to activate, and to investigate the capability and reliability of the VVPSS system to ensure that the radionuclide inventories mobilised within the VV are captured and transferred to the drain and suppression tanks, and that any potential leaks are accounted for and are within an acceptable range.

In the case of option 2, if there exists any scenario in which a significant quantity of tritium or dust leaks out of the VV at ground level, and the probability of occurrence is not so low to bring the scenario into the acceptable risk region, there would need to be some kind of detritiation system in place in every room adjacent to the plasma chamber (such a system is planned for ITER). This system would ensure that any escaped tritium and dust is captured and released to the environment from a high stack, significantly reducing the radiological consequences of a release. Again, there would need to be a robust safety case to show that the detritiation systems in the rooms surrounding the VV will perform their required functions. Given the relatively small fraction of the HTO inventory that would be needed to be released at ground level in order to trigger the 30 mSv lower evacuation ERL, these systems would be safety critical and require stricter regulatory focus.

If neither option 1 nor option 2 can be satisfied, then designers may have to consider option 3: the addition of a robust confinement structure to reduce the radiological consequences of any potential release. Whilst the majority of design-basis and beyond design-basis accidents identified in the RPrS do not require a mitigation solution as drastic as this, there are some scenarios that may justify the need for a confinement structure, and these therefore need further study. The scenario in which a failure of the VV causes significant air ingress resulting in a combined hydrogen and dust explosion was considered to be a beyond design-basis event in the RPrS and was found to result in a dose of 0.33 mSv at 200 m and 0.20 mSv at 2.5 km from the plant [80]. Radiation doses at this level would not result in the need to evacuate people in the surrounding areas. However, given the potentially larger size and added complexity of commercial FPPs, the consequences of a hydrogen/dust explosion could be more severe than that shown in the ITER analysis. As avoiding ignition sources is not a practical solution (the ignition energy for a hydrogen explosion is 0.02 mJ meaning an explosion can spark on any hot surface), mitigation tactics for future FPPs are currently being explored which include igniters within the VV, rapid injections of inert gas to reduce the rate of pressure increase, or avoiding beryllium as a plasma-facing material [32]. Given that such explosions have the potential to compromise the integrity of the VV, coupled with the relatively small radioactive inventories that need to be released to trigger the evacuation ERL at a distance of 200 m (6 g of HTO or 984 g of dust), these mitigation systems may also need to be substantiated as they are potentially safety critical systems. Further work is needed to establish the likelihood and severity of hydrogen/dust explosions to determine the radiological consequences for the surrounding public. Until it can be shown that the likelihood of these events is suitably low, or that any releases are orders of magnitude lower than the releases in Table 6.7, a robust confinement structure cannot be ruled out.

This work has shown that FPPs contain radioactive inventories that if released in the event of a severe accident may require off-site countermeasures to protect the public. As such, the design of an FPP will require detailed engineering substantiation and appropriate safety cases to demonstrate to the public that the risks to their health and safety have been reduced so far as is reasonably practicable. This will certainly necessitate robust regulatory oversight.

Part V

Part V - Analysis - FPP Regulation

Chapter 7

Mapping Regulatory Options for Fusion Power in the UK

When considering what is an appropriate regulatory system, it is important to remember that regulation should be based on the hazard potential (the unmitigated risk to the public) and not the mitigated risk. Hence, it is important to understand what can happen if things go wrong and what measures are needed to mitigate the risk. The work in Chapter 6 therefore demonstrated the need for FPPs to be subject to robust regulatory oversight. This chapter maps out the regulatory options for FPPs within the UK legal system, taking into account the hazard potential of FPPs and the international approach to fusion regulation explored in earlier chapters.

7.1 Background

Chapter 5 explored the current arrangements for regulating fusion facilities. It showed that there are no agreed approaches as to how FPPs should be regulated. In contrast there is extensive guidance on how civil nuclear installations associated with nuclear fission should be regulated. For countries that have a civil nuclear industry, their regulatory frameworks are built to accommodate fission-based technologies. The fundamental principle behind these frameworks is that a technology that has the potential to cause significant harm should come under regulatory control to ensure a user, usually a licensee, must seek permission from a regulatory body before constructing, commissioning or operating said technology. In order to obtain permission, the licensee must prove that the technology is safe. This "permissioning principle" is fundamental to fission-based regulatory frameworks due to the significant hazard potential of NPPs.

It is generally recognised that if the hazards associated with an industrial activity are low, then specific permission from the regulatory body may not be required. From the work performed in this project, it is clear that the hazard potential of FPPs is significantly lower than for NPPs and that a significant number of the safety issues associated with NPPs do not apply to FPPs. The key question to answer is: Is the hazard potential of FPPs sufficiently low as to not require regulatory body permission to design, construct, commission, operate or decommission? The answer to this question is not straightforward as different countries and organisations have differing views on the hazard potential of an FPP. However, any regulatory regime for FPPs will depend not only on the actual hazard potential but also on the perceived hazard potential given that FPPs are powered by a thermonuclear reaction.

The aim of this chapter is to explore the regulatory options available for fusion power in the UK, discuss the main features of each option and comment on the implications for FPP deployment. Chapter 8 will make a judgment on the most appropriate option and Chapter 9 will set out an appropriate framework for the regulation of fusion power in the UK.

Currently, there are no FPPs under construction or operating anywhere in the world; hence, there is no direct experience of regulatory approaches. However, there are a number of fusion research facilities in many countries, the largest being ITER (France) and JET (UK), and these have been regulated in a variety of ways ranging from the use of NPP regulation (ITER) to the use of normal occupational health and safety/environmental regulation (JET). To determine the main regulatory options for FPPs, the current literature surrounding fusion safety and regulation was examined (see Chapters 4 and 5), and an effort was made to attend any conferences focusing on fusion safety and regulation in order to gauge the views of those within the fusion industry; conversations were also held with industry experts within fusion safety and nuclear regulation. Drawing on these and the approaches taken internationally, there appears to be four main regulatory options that are worth considering, namely:

(1) Regulation using a licensing regime similar to that applied to NPPs

(2) Regulation using a licensing regime similar to that applied to lower hazard potential nuclear fuel cycle (including radioactive waste management) facilities

(3) Regulation using an occupational health and safety and environmental permitting approach similar to that applied to non-nuclear radiation facilities

(4) Regulation using a nuclear site licensing regime that is proportional to the hazard potential of FPPs

These options span a range of scenarios based on the perceived hazard potential of FPPs. If FPPs are perceived to have a high hazard potential (i.e. as high as NPPs), then as they are based on a nuclear process, it is reasonable to suggest that they are licensed in a similar manner to NPPs (Option 1). If FPPs are perceived to have a slightly lower hazard potential than NPPs, but albeit still a high hazard potential, then it is reasonable to suggest that they are licensed in a similar manner to nuclear fuel cycle facilities, such as radioactive waste management facilities (Option 2). If FPPs are perceived to have a low hazard potential, then it seems reasonable to suggest that they are not licensed and are regulated primarily via occupational health and safety and environmental permitting, similar to non-nuclear radiation facilities (Option 3). Finally, if FPPs are perceived to have a lower hazard potential than nuclear fuel cycle facilities, but a higher hazard potential than non-nuclear radiation facilities, it seems reasonable to suggest that they are licensed under the current nuclear site licensing regime, but that it is applied in a manner that is proportionate to the hazard potential of FPPs (Option 4).

Each of these options is explored in the following sections.

7.2 Option 1 – Regulatory Approach Similar to that Applied to NPPs

This section explores the implications of applying the existing nuclear site licensing approach that is used for NPPs to FPPs, despite the fact FPPs have a much lower hazard potential. The key pieces of legislation associated with nuclear site licensing are discussed.

7.2.1 Background to the Regulation of NPPs in the UK

The current national and international regulatory landscapes have been shaped by the special characteristics associated with NPPs. These include the high energy density locked in the atom, the

potential for criticality and associated exponential increases in power levels, the radioactive decay of fission products in the core that require cooling long after the fission process has been terminated, the large standing inventory of radioactive materials in the core and the production of radioactive waste [214]. These characteristics mean there has to be exceptional levels of control of the fission process, the ability to remove heat, and of the radioactive inventories present on site. These characteristics led the public and politicians to demand stringent controls and very high levels of protection. The international community, led by IAEA, responded to these demands and implemented a comprehensive international framework for nuclear safety and security that national governments could use to develop their own national laws and regulations to control the safety and security of NPPs during the design, construction, commissioning, operation and decommissioning stages.

Despite various countries having different legal systems and regulatory structures, there is generally a consistency of approach to the regulation of NPPs. The IAEA *Handbook on Nuclear Law* [215] sets out the general principles of nuclear law. Safety and security rightfully feature highly in these principles, but another important principle is that of "permissioning". The permissioning principle states that, due to the special characteristics of NPPs and their potential to cause harm, there must be some form of regulatory control that ensures the operator a) must seek permission from a competent authority before using the facility and b) cannot use the facility until it has been shown to be safe. This "permission" is usually granted via a "licence" (granted by a government or by a regulatory authority) which provides the public and politicians with confidence that the technology is being adequately controlled and that the health and safety of workers and the public is protected. This licensing feature, seen in many regulatory frameworks for NPPs around the world, generally places duties on the licensee/operator to ensure the facility is designed, constructed, commissioned, operated and decommissioned to provide appropriate levels of public protection.

As detailed in Chapter 5, the regulatory framework for NPPs in the UK revolves around three primary pieces of legislation: the *Health and Safety at Work etc. Act 1974* (HSWA) [171], the *Energy Act 2013* (EnA) [172] and the *Nuclear Installations Act 1965* (NIA) [167]. The roles and requirements of these Acts are discussed below. In the UK, no person can construct or operate a nuclear installation that is prescribed under the NIA without a licence and the licence is for a specific site. The following illustrates how these acts are applied in relation to the regulation of NPPs.

7.2.2 The UK Legal Framework

7.2.2.1 The Health and Safety at Work etc. Act 1974 (HSWA)

As detailed in Section 5.5.5.1, the HSWA requires that all employers, including those in the nuclear industry, implement measures to look after the health and safety of their employees and the public. It also introduces the concept of reducing risks to as low as reasonably practicable (ALARP). If FPPs are to be licensed in a similar manner to NPPs, there is nothing in the HSWA itself that would prohibit this or would place unduly onerous burdens on the operator/licensee. The Act is generally enforced by the Health and Safety Executive (HSE), but on a nuclear licensed site it is enforced by the Office for Nuclear Regulation (ONR). The requirements of the HSWA will be applicable to FPPs constructed and operated in the UK. Under the HSWA there are specific regulations that are concerned with nuclear related activities and these would apply to FPPs due to the presence of ionising radiation. These regulations are the IRRs [174] and REPPIR [175].

7.2.2.2 The Ionising Radiations Regulations 2017 (IRRs)

The IRRs ensure there is a system of authorisation for work with ionising radiation with a three-tier, risk-based system of regulatory control: notification, registration and consent. For the activities posing the lowest risk, employers are only required to notify the regulatory authority (HSE) before carrying out the work. For medium-risk activities involving ionising radiation (such as x-ray devices), employers must register with HSE before carrying out the work, whereas for activities posing the highest risk (such as operating an accelerator), employers must obtain consent from HSE before carrying out any work. It is worth noting, however, that for an NPP on a nuclear licensed site, none of these steps needs authorisation from HSE because ONR is the regulator and because control over these activities is governed by the conditions attached to the nuclear site licence. If an FPP was being regulated in the same way as an NPP, the same approach to the IRRs would be adopted with ONR as the regulator.

7.2.2.3 The Radiation (Emergency Preparedness and Public Information) Regulations 2019 (REPPIR)

REPPIR establishes a framework of preparedness measures to ensure that arrangements are in place to protect surrounding populations should a "radiation emergency" take place [175]. In the Regulations, a "radiation emergency" is defined as a "non-routine situation or event arising from work with ionising radiation that necessitates prompt action to mitigate the serious consequences... of a hazard resulting from that situation or event" [175]. These Regulations require emergency plans to make use of countermeasures to limit radiation exposure, which generally involve sheltering or evacuation of surrounding populations. REPPIR applies to NPPs for off-site emergency planning; hence, it will apply to FPPs if there is the potential for an off-site release of radioactivity that requires countermeasures to protect the public. In Schedule 1 Part 1 of REPPIR, the threshold activity for tritium stored is 1×10^{14} Bq ($\sim$0.3 g) [175]. As the first commercial FPPs will have higher inventories of stored tritium than this, it is expected that REPPIR will apply.

7.2.2.4 The Nuclear Installations Act 1965 (NIA)

As detailed in Section 5.5.5.5, the NIA sets out the requirement that "no person may use a site for the purpose of installing or operating any nuclear reactor... unless a licence to do so has been granted... by the appropriate authority" [167]. The NIA specifically allows ONR to attach conditions, known as licence conditions (LCs), that it considers "necessary or desirable in the interests of safety" [167]. These powers enable ONR to have regulatory control over every stage of the life cycle of the facility, including the "design, siting, construction, installation, operation, modification, and maintenance" of NPPs [167].

7.2.3 Nuclear Site Licensing and Licence Conditions

As discussed above, an NPP in the UK cannot be constructed or operated without a nuclear site licence. To obtain a licence, an applicant must be a corporate body that has the capacity and capability to be the *Controlling Mind* and an *Intelligent Customer*. Hence, onerous requirements are placed on an NPP nuclear site licensee. A nuclear site licence for an NPP will have 36 LCs - these are a mixture of prescriptive and goal setting conditions. The prescriptive conditions tend to relate

to specific legal requirements such as "marking of the site boundary" or displaying "warning notices" [216]. The goal setting conditions (which make up around two-thirds of the LCs) require the licensee to make and implement adequate arrangements to deliver specific safety related activities, such as construction, commissioning or maintenance. The UK licensing regime for NPPs is flexible but it is intrusive into the licensee's business. The driver behind this level of regulatory oversight is the hazard potential of an NPP.

Due to the hazard potential of NPPs (presence of fissile fuel and volatile fission products, significant decay heat in fuel following shutdown, potential for criticality with positive power and void coefficients, requirement for emergency core cooling systems and potential for significant off-site releases), the engineering substantiation and defence in depth requirements are comprehensive and rigorous. A safety case for an NPP would be expected to take into account the plant's response to a range of fault initiating events and both internal and external hazards such as fire, flooding, earthquakes, extreme temperatures and aircraft impact. The design would be expected to provide multiple independent protection systems and other barriers to detect the fault or abnormal event, prevent damage, or mitigate the consequences of a release of radioactive materials. For example, most NPPs are seismically qualified to ensure that all safety important components remain operational in the event of an earthquake. All modern NPPs in the UK also require comprehensive defence in depth for such things as reactor protection systems and emergency core cooling systems for decay heat removal [217]. These safety measures add significant cost and complexity; however, they are required because of the potentially catastrophic consequences of an uncontrolled release of radioactive material from an NPP as illustrated by the accidents at Chernobyl and Fukushima[1] (current release estimates of 1E+19 Bq and 9.4E+17 Bq, respectively). Whilst these strict regulatory measures may seem onerous, they are considered to be proportionate to the NPP hazard potential and necessary to ensure the safety of workers and the public and the protection of the environment. They also reassure the public that the technology is being adequately controlled.

[1]However, it should be noted that the NREFS papers [218] published in 2017 judged the government responses to these accidents of mass relocation of populations as grossly disproportionate to the actual risk present

7.2.4 Permissioning

As detailed in Section 5.5.5.6, permissioning is a key part of the regulation of NPPs in the UK as it enables ONR to apply regulatory control to various stages of the licensing process. Permissioning starts with the granting of the licence. A regulatory schedule to identify all the necessary regulatory hold points is often developed through discussion between ONR and the licensee. Depending on the type of permissioning, the licensee generally cannot move past a pre-defined "hold point" without the permission of ONR. To obtain permission from ONR, the licensee is required to produce safety documentation to demonstrate that the activity for which permission to proceed is being requested can be safely carried out and will deliver the required levels of safety. The continuous dialogue between licensee and regulator ensures that at each important stage of the facility's life cycle safety is demonstrated. Permissioning requires the regulator to have legal powers and ONR can make use of primary powers, derived powers and enhanced implementation monitoring and control (EIM&C). These can be used in isolation or in combination with one another to establish the necessary regulatory control [182].

7.2.4.1 Primary Powers

ONR has seven primary powers [182], i.e. the power to:

- **Grant** a licence
- **Consent** to a specific activity such as the start-up of a reactor
- Agree (**Agreement**) to a specific activity such as a major modification
- **Direct** the licensee to take a particular course of action such as shut down a reactor
- Approve (**Approval**) a specific activity such as the "freezing" of a set of arrangements
- Specify (**Specification**) the licensee to undertake a specific course of action
- Notify (**Notification**) the licensee of an ONR decision

These powers are explicit either in the NIA or in the wording of LCs and are therefore legally binding. The first three powers listed above are the 'permissioning' powers. All the powers enable ONR to control the licensee's activities in the interest of safety and are intrusive and potentially restrictive.

This level of control is considered appropriate given the hazard potential of an NPP but may be inappropriate for controlling low hazard potential activities [219].

7.2.4.2 Derived Powers

In the NPP licensing approach, the licensee is required to make and implement arrangements under numerous LCs and, through these arrangements, the licensee can agree hold points with ONR (in a regulatory schedule as discussed above) and if necessary opt to provide administrative 'powers' to ONR to grant ONR the ability to permission selected activities on the licensed site [182]. The licensee's arrangements made under LCs are legal documents and failure to comply with the arrangements is regarded as a breach of the law. The application of these derived powers is more flexible than primary powers. These derived powers can combine with the primary powers to develop effective regulatory schedules to ensure the effective regulation of such things as the design, construction and commissioning of new facilities on a nuclear licensed site. The permissioning of activities on a licensed site is generally achieved through ONR issuing licence instruments (LIs) [182].

7.2.4.3 Enhanced Implementation Monitoring & Control (EIM&C)

In addition to primary and derived powers, the permissioning of activities on a licensed site can also be done through EIM&C. This is generally opted for when either a) an LI is deemed disproportionate to control lower safety significant proposals or b) an LI has been issued to initially permission an activity, but the ONR inspector determines that it should also be subject to EIM&C to ensure that the licensee's arrangements are controlling its implementation [182]. This process is generally achieved by the licensee defining regulatory hold points which are then agreed to by ONR. EIM&C is generally used to permission activities which are of lower safety significance and use of an LI would be considered disproportionate.

7.2.5 Summary of Main Features and Implications for FPPs

The key features of an NPP licensing regime are that no one is allowed to construct or operate an NPP without obtaining a licence, the licensee is responsible for safety, permission from a competent and independent regulator is required in advance of undertaking major activities that may affect safety (i.e. construction, commissioning and operation), safety documentation must be provided

before obtaining permission to undertake a major safety related activity, and the regulator has appropriate enforcement powers if safety case requirements are not complied with. The extent to which licensees of NPPs meet these obligations is significant.

NPP nuclear site licensees must ensure through the safety case that there is considerable engineering substantiation of the design and that there are sufficient defence in depth measures to prevent or mitigate the consequences of an unplanned catastrophic release of radioactive material. Examples of this include protection measures against a wide range of fault conditions such as LOCAs and internal and external hazards (e.g. earthquakes and aircraft impact). Robust and comprehensive safety documentation is also produced at every important stage of the facility's life cycle (making up a safety case) to demonstrate to the licensee and to ONR that the facility is safe. ONR makes use of a variety of permissioning powers (that are often restrictive) to ensure that it establishes the necessary regulatory control over the licensee's activities. All of these requirements are onerous and add substantial complexity, costs and lead times to major NPP projects. However, the impact can be minimised by effective and efficient regulation. The UK's goal setting approach provides the flexibility for the licensee to produce the safety case and other operational arrangements to match the hazard potential of the NPP.

Adopting a regulatory approach similar to that applied to NPPs would mean FPP licensees having to meet the same obligations as licensees of NPPs. However, it is clear that the hazard potential of FPPs is significantly lower than for NPPs, primarily due to their respective inventories and the energetic driving mechanisms in fault situations. FPPs and NPPs have an almost completely different set of safety issues and accident scenarios. An FPP has no volatile fission products produced in the fuel, no significant decay heat within the fuel or plasma that would require emergency core cooling systems to remove decay heat (note in an FPP there is expected to be modest decay heat within activated structures; however, this decay heat is small when compared with an NPP and will not require emergency cooling), no potential for positive power or void coefficients and no potential for catastrophic off-site releases.

Chapter 4 highlighted the safety issues for FPPs, and Chapter 6 investigated the doses received by exposed populations in the case of an unplanned release of radioactive material from an FPP. It

is clear from both these chapters that whilst FPPs do have radioactive inventories that have the potential to be released in accident conditions, any release of radioactive material would result in significantly reduced consequences compared with the potential catastrophic release from an NPP. It is also not clear at this stage to what extent FPPs require protection against external hazards such as earthquakes and aircraft impact. If the radiological consequences of these events are insignificant, it would be disproportionate for ONR to demand protection measures against them. Further, FPPs have numerous safety issues that are entirely unique to FPPs (e.g. electromagnetic discharges, loss of plasma control, hydrogen/dust explosions etc.). Licensing in line with NPPs would mean that the regulatory oversight and FPP safety case would need to be apply the same rigorous defence in depth and engineering substantiation to these fusion-specific accident scenarios.

In terms of public perception, regulating FPPs in a similar way to NPPs would also send the message to the public and politicians that FPPs and NPPs have a similar hazard potential. It follows that licensing FPPs in line with that applied to NPPs would be substantially disproportionate to the hazard potential present. Whether in a primarily prescriptive framework (such as that found in the U.S.) or a more goal setting framework (the UK) the outcome is the same. The increased design complexity, engineering substantiation, defence in depth, management controls, regulatory costs and lead times that licensing FPPs in line with that for NPPs would undoubtedly present would be disproportionate and hence cannot be justified given the hazard potential of FPPs.

7.3 Option 2 – Regulatory Approach Similar to that for Nuclear Fuel Cycle (Including Radioactive Waste Management) Facilities

This section explores the implication of applying the existing nuclear site licensing approach that is used for the less hazardous nuclear fuel cycle facilities to FPPs, despite the fact FPPs have a much lower hazard potential than some of these facilities. The key pieces of legislation associated with nuclear site licensing are discussed.

7.3.1 Background to the Regulation of Fuel Cycle Facilities in the UK

The regulation of nuclear fuel cycle (including radioactive waste management) facilities varies, but in general the regulatory approach is not as onerous as that for NPPs due to the lower hazard potential of these facilities. The levels of protection required for fuel cycle facilities therefore takes into account the hazard potential and the consequences of failure. As an example, a nuclear fuel manufacturing facility would not be expected to have the same regulatory requirements and oversight as a reprocessing facility handling spent fuel with large fission product inventories. These distinct facilities would also have significantly different arrangements in place to deliver safety, due to the safety issues unique to each. Fuel cycle fabrication and enrichment facilities are primarily concerned with the safety issues that arise from storing, producing or managing unirradiated fissile materials (such as preventing criticality and the diversion of special nuclear material), whereas reprocessing and waste management facilities can have higher hazard potentials from the reprocessing of spent nuclear fuel and the subsequent treatment and storage of large quantities of fission products.

7.3.2 The UK Legal Framework

In the UK, fuel cycle facilities are prescribed activities under the NIA and, as such, are regulated under the same licensing framework as that for NPPs. Licensees of these facilities are therefore subject to the same suite of legislation and regulation as licensees of NPPs. These include the HSWA and its corresponding regulations (IRRs, REPPIR, etc.), the EnA, and the NIA and its associated nuclear site licensing framework. ONR has the same regulatory powers for fuel cycle facilities as they have for NPPs. Hence, ONR has the authority to permission selected activities and define regulatory hold points through a combination of primary powers, derived powers and EIM&C.

7.3.3 Licensing and Licence Conditions

In the UK, fuel cycle facilities are regulated under the same goal setting framework as NPPs. ONR applies a standard set of LCs to all nuclear licensed sites; as such, licences for fuel cycle facilities have the same 36 LCs attached. The licensee is ultimately responsible for safety and the licensee can make and implement its own arrangements to comply with the requirements of the licence and its attached LCs [181]. The licensee has the ability to produce arrangements that reflect the

hazard potential of the facility. Fuel cycle facilities do not have the same hazard potential as NPPs; hence, the level of regulatory oversight is not as onerous. The level of regulatory inspections is again proportionate to the hazard potential of the facility. It should be recognised that fuel cycle facilities usually contain large quantities of radioactive materials, they are often multifunctional and can contain multiple plants with integrated dependencies on one another. Fuel cycle facilities can also have radioactive material storage plants which cannot be shut down in the same way as an NPP.

The safety documentation and therefore the engineering substantiation and defence in depth is usually less rigorous at fuel cycle facilities compared with NPPs. Robust safety cases must still be developed; however, as it is up to the licensee to produce arrangements that reflect the hazard potential of the facility, licensees of fuel cycle facilities will focus on safety issues that are specific to these kinds of facilities, such as preventing criticality, restricting contamination and ventilation issues involving harmful fission products and the chemicals involved with reprocessing, guarding against diversion of fissile material and protecting the health of workers on-site. Fuel cycle facilities will also have various protection measures and defence in depth to mitigate the effects of internal and external hazards, including in some cases seismic protection and aircraft impact protection. Most countries operating fuel cycle facilities adopt a deterministic approach to seismic assessment and, if the radioactive inventory released or the adverse health effects from loss of containment are considered too great, the plant will be seismically qualified to a reference earthquake.

7.3.4 Permissioning

Permissioning is also a key part of the regulation of fuel cycle facilities in the UK, as it enables ONR to apply regulatory control to various stages of the licensing process. ONR can again make use of primary powers, derived powers and EIM&C to establish the necessary regulatory control (see Section 7.2.4) [182]. The licensee can agree 'hold points' with ONR and if necessary opt to provide administrative 'powers' to ONR to grant ONR the ability to permission selected activities on the licensed site [182].

7.3.5 Summary of Main Features and Implications for FPPs

In the UK, the key features of the regulatory regime for fuel cycle facilities are essentially the same as for an NPP regulatory regime. No one is allowed to construct or operate a facility without obtaining a licence, the licensee is responsible for safety, permission from a regulator is required in advance of undertaking major activities that may affect safety, safety documentation must be provided before obtaining permission to undertake a major safety related activity and the regulator has appropriate enforcement powers if safety case requirements are not complied with. The main difference is the extent to which the obligations within these features are met is reduced in the case of fuel cycle facilities when compared to NPPs, due to the reduced hazard potential. The levels of engineering substantiation, defence in depth measures and safety documentation are reduced for fuel cycle facilities (e.g., fuel cycle facilities will generally have a much less onerous maintenance schedule and fewer site inspectors per site), commensurate with the reduced hazard potential and limited safety issues associated with these facilities. The safety documentation and protection measures at these facilities are focused on the hazards that are unique to these facilities, i.e. preventing criticality and the diversion of special nuclear material, and the safety issues that arise from reprocessing of spent fuel and the subsequent treatment and storage of large inventories of fission products. For example, in radioactive waste repositories there is a greater focus on engineered safety features rather than control of operations, as engineered safety features play a larger role in delivering safety than administrative controls in these kinds of facilities [220]. However, the radiological consequences of an unplanned release of radioactive material at fuel cycle facilities can still be significant (due to the inventories present). Hence, the level of protection measures at fuel cycle facilities is still high (an example of this is that most modern fuel cycle facilities in the UK are seismically qualified).

Adopting a regulatory approach similar to that applied to fuel cycle facilities would mean licensees of FPPs would be subject to nuclear site licensing with the same level of regulatory oversight as licensees of fuel cycle facilities. On the one hand, it could be argued that this approach provides an example of proportionate regulation in which regulatory permissions are still required for certain activities, but the regulatory requirements reflect the hazard potential of the facility. However, FPPs have a significantly lower hazard potential than some fuel cycle facilities. FPPs have no mechanism

in which criticality of fissile fuel can occur, no treatment of spent fuel and subsequent storage of large inventories of harmful fission products, and no fissile material that could potentially be diverted (unless the blankets in an FPP were deliberately used to breed fissile material). It is also not clear at this stage to what extent FPPs require protection against external hazards, e.g. seismic protection. Licensing FPPs in line with fuel cycle facilities would also mean that the regulatory oversight and FPP safety case would need to apply the same rigorous defence in depth and engineering substantiation to these fusion-specific accident scenarios.

Regulating in this manner would also send the message to the public that FPPs have a similar hazard potential to fuel cycle facilities. It follows that regulating FPPs in a similar manner to fuel cycle facilities, whilst less onerous than regulating in line with NPPs, would still be disproportionate based on the hazard potential present. Whether in a primarily prescriptive framework (such as that found in the U.S.) or a more goal setting framework (the UK) the outcome is the same. The increased design complexity, engineering substantiation, defence in depth, regulatory controls and lead times that licensing FPPs in line with that used for fuel cycle facilities would be seen as disproportionate and hence it would not be justified given the hazard potential of FPPs.

7.4 Option 3 - Regulatory Approach Similar to that for Non-Nuclear Radiation Facilities

This section explores the implication of applying the industrial health and safety and environmental protection regulatory approach that is applied to non-nuclear radiation facilities to FPPs. The key pieces of legislation are discussed along with the regulatory powers and controls.

7.4.1 Background to the Regulation of Non-Nuclear Radiation Facilities

It has been argued by some in the fusion industry [143], [169] that, because of their low hazard potential, FPPs should be regulated in line with non-nuclear radiation facilities such as accelerators or cyclotrons. In the U.S., some [143] advocate the idea of treating FPPs as low risk facilities that should be regulated under 10 CFR Part 30 regulations (see Chapter 5). In the UK, others [169]

advocate the idea of regulating FPPs in a similar manner to how experimental fusion reactors such as JET are regulated. It was determined early in JET's development that fusion research was out of the scope of the NIA; hence, JET was not subject to regulation by HM NII. However, JET was located on a UKAEA site and under the control of UKAEA. UKAEA was exempt from licensing, but it was subject to a Ministerial Direction to provide an equivalent safety regime to that of licensed nuclear facilities. Currently, the primary day-to-day regulatory oversight for the operations at JET are by HSE, under the general provisions of implementing the HSWA, and EA, that is primarily concerned with releases of effluents into the environment and radioactive waste.

7.4.2 The UK Legal Framework

The main legislation covering non-nuclear radiation facilities such as accelerators and cyclotrons are the HSWA and its corresponding regulations (IRRs, REPPIR, etc.) and the *Environmental Permitting (England and Wales) Regulations 2016* (EPR).

7.4.2.1 The Health and Safety at Work etc. Act 1974 (HSWA)

As outlined in Section 7.2.2.1, the HSE-enforced HSWA applies to all industries and employers and obligates employers to implement measures to protect the health and safety of their employees and the public. It also specifies that risks should be reduced so far as is reasonably practicable to protect both workers and the public. Whilst the HSWA will apply to FPPs if they are to be regulated in line with non-nuclear radiation facilities, the obligations put upon the licensee to deliver safety are overly general and not nuclear or even radiation specific. Therefore, the control of radiation safety will be via the application of the radiation-related regulations (IRRs).

7.4.2.2 The Ionising Radiations Regulations 2017 (IRRs)

The IRRs apply to any employer intending to carry out work with ionising radiation (known as "radiation employers") ranging from hospitals and dentists using x-ray machines to research laboratories using particle accelerators. The IRRs require that duty holders involved in the "production, processing, handling, disposal... of radioactive substances" take appropriate measures to "restrict so far as is reasonably practicable the extent to which its employees and other persons are exposed to ionising radiation" [174]. This is achieved through a combination of measures. Regulation 8

compels the duty holder to perform a radiation risk assessment before commencing any new activity involving work with ionising radiation [174]. Although "commencing a new activity" is not explicitly defined, the wording of the Regulations suggest that it refers to the point of commencing working with radioactive materials or facilities that can generate ionising radiation. The risk assessment is to identify the measures the employer needs to take to restrict the exposure of any persons [174]. The employer is not permitted to carry out any work with ionising radiation unless it has made an assessment to demonstrate that a) all hazards that can cause a radiation accident have been identified and b) the magnitude of the risks to employees and other persons have been evaluated [174]. Regulation 9 obliges employers to restrict the exposure to ionising radiation through means of "engineering controls, design features and by the provision and use of safety features and warning devices" and "provide such systems of work as will, so far as is reasonably practicable, restrict the exposure to ionising radiation of employees and other persons" [174]. Regulations 10 and 11 stipulate that employers must provide suitable personal protective equipment (PPE) for employees and ensure that all engineering controls, design features and safety features are all properly maintained and that thorough examinations of such controls and features are carried out at suitable intervals [174]. Following this, Regulations 12 and 13 ensure that any doses received by any exposed persons do not exceed the dose limits specified in the attached Schedules and that, where the risk assessment has shown that a radiation accident is "reasonably foreseeable", the employer must "prepare a contingency plan designed to secure... the health and safety of persons who may be affected" [174].

The IRRs also ensure there is a system of authorisation for work with ionising radiation with a three-tier, risk-based system of regulatory control: notification, registration and consent. Regulation 7 relates to consent, the highest-risk tier, and stipulates that all employers carrying out a practice listed in regulation 7(1) require consent from the HSE before carrying out such work. "Carrying out a practice" in this sense means either the point of "production, processing, handling, disposal, use, storage, holding or transport of radioactive substances; or the operation of any electrical equipment emitting ionising radiation and containing components operating at a potential difference of more than 5 kV" [174]. Fusion power is not currently listed as a practice under regulation 7(1), but as accelerators are listed one would assume if FPPs are to be regulated under the same framework they may either be added as a listed practice at a later date or come under "practices discharging

significant amounts of radioactive material with airborne or liquid effluent into the environment" [174].

7.4.2.3 The Radiation (Emergency Preparedness and Public Information) Regulations 2019 (REPPIR)

As demonstrated in Section 7.2.2.3, as FPPs will have higher inventories of stored tritium than the threshold amount defined in Schedule 1 of Part 1 of REPPIR (∼0.3 g), the Regulations are expected to apply to radiation emergencies at FPPs [175]. REPPIR defines a radiation emergency as an event that is likely to result in a member of the public receiving an effective dose of 1 mSv in the period of one year immediately following the event (note this is a reduction of the 5 mSv limit previously specified in REPPIR 2001 [211]). These Regulations require emergency plans to make use of countermeasures to limit radiation exposure, usually in the form of sheltering or evacuation of local populations.

7.4.2.4 The Construction (Design and Management) Regulations 2015 (CDM Regulations)

Another statute that comes under the remit of the HSE implementing the HSWA is the *Construction (Design and Management) Regulations 2015* (CDM Regulations) [176]. These Regulations define various roles (Designer, Client, Principal Contractor, Contractor, CDM Co-ordinator) and the role of each member of the supply chain within a particular project. The CDM Regulations places various obligations on the duty holder and principal designers and contractors including ensuring the duty holder must make "suitable arrangements for managing a project, including the allocation of sufficient time and other resources" [176]. The duty holder must ensure that all construction work is carried out without risks to the health or safety of any person affected by the project, so far as is reasonably practicable. The duty holder must also ensure that before construction phase begins, a "construction phase plan" is drawn up by the principal contractor and that the principal designers prepares a "health and safety file for the project" [176]. The Regulations then ensure that the designers and contractors have the skills, knowledge and experience to fulfil the role they are appointed to undertake, and then obligate the principal contractor and principal designer to ensure that the health and safety of workers and the public is protected during all stages of the project.

7.4.2.5 The Environmental Permitting (England and Wales) Regulations 2016 (EPR)

The *Environmental Permitting (England and Wales) Regulations 2016* (EPR) will apply to FPPs [173]. Schedule 23 of the EPR, known as the *Radioactive Substances Regulations* (RSR), is primarily concerned with the storage of radioactive material and the disposal of radioactive waste into the environment. When drafted, the EPR essentially transposed numerous EU Directives into domestic law, with the RPR primarily concerned with the Basic Safety Standards Directive (96/29/Euratom) which applies to "all practices which involve a risk from ionising radiation emanating from an artificial source or from a natural radiation source in cases where natural radionuclides have been processed in view of their radioactive, fissile, or fertile properties" [173]. Note the EPR effectively repealed the *Radioactive Substances Act 1993* [179] in England and Wales.

Regulation 8 of the EPR lists the types of "regulated facility" that require an environment permit and it seems likely that FPPs will fall under regulation 8(1)(a) "an installation" [173]. Regulation 12 then stipulates that a person must not "operate a regulated facility" unless "authorised by an environmental permit" [173]. Whether FPPs will fall under the remit of the EPR depends upon the definition of radioactive materials and wastes within the Regulations (Schedule 23, Part 2, paragraphs 3 to 10) [173]. As both tritium and activated dust isotopes are explicitly defined in Table 2 of Schedule 23, there is no question that operators of FPPs will need to apply for an environmental permit under the RSR [173]. Note environmental permits are granted by EA and are granted to individuals (the operator of the facility); this is in contrast to the nuclear site licence in the NIA which can only be granted to a corporate body.

In order to receive the permit, operators must demonstrate to EA that the optimisation principle is met (Schedule 23, Part 4, paragraph 1), which ensures that all exposures to ionising radiation of any member of the public resulting from the disposal of radioactive waste are kept ALARA and that the sum of the doses resulting from the exposure of any member of the public to ionising radiation does not exceed the specified dose limits [173]. The dose limits set in the Regulations are 0.3 mSv per year from any single source and 0.5 mSv per year from the discharges from any single site; note these doses are for routine discharges only and don't take into account doses from accidental releases of radioactive material. EA will then set discharge limits set out in permit conditions that

are well below the levels at which the dose limits and constraints would be exceeded, based on a prospective dose estimation [221]. In addition, the operator must demonstrate that they have used "Best Available Techniques (BAT) in relation to waste management and other matters which could have an impact on radiation doses to members of the public" (such as routine discharges) [173], [221].

7.4.3 Permissioning

The regulations under the HSWA and the EPR do not have the same level of permissioning as that given by the wording of the NIA and LCs for a facility on a nuclear licensed site. The permissioning principle invoked by ONR can be applied at various stages of the facility's life cycle, from design through commissioning and operation, granting ONR considerable control to ensure at every major point of the life cycle that the health and safety of workers and the public is protected. Regulation 7 in the IRRs, however, ensures employers cannot "carry out a specified practice unless... granted a consent to carry out the practice by the appropriate authority" [174]. This would result in duty holders not having to apply for regulatory consent until the *point of use*, by which time the design has been finalised and the construction is more than likely at an advanced stage. For the EPR, there is nothing in the EPR to stop an operator from commencing construction before an environmental permit has been issued (but it should be noted that planning requirements are a separate issue) [222]. It is not hard to envisage scenarios in which duty holders are nearing completion of construction and apply for regulatory consent, only to find a significant safety or environmental issue that could have been rectified at minimal cost at the design stage but would at this point in the programme require significant modifications at considerable cost and potential programme delays. Considering the nascent nature of this industry, this scenario best be avoided. Effective and efficient regulation often requires an open dialogue between regulator and duty holder, so that the duty holder is aware of what is required at each stage (usually in the form of a regulatory schedule for licensed nuclear facilities) and can implement measures prior to these stages to give the best chance of obtaining approval. Neglecting the concept of regulatory approval at the design stage runs the risk that the constructed facility may not be fit for purpose and, as discussed above, require modification before the required approval could be granted with the potential for delays and increased costs.

7.4.4 Summary of Main Features and Implications for FPPs

The main features of regulating non-nuclear radiation facilities are: the duty holder must ensure the protection of workers and the public (general occupational health and safety); the duty holder cannot commence work with ionising radiation before obtaining consent from HSE; the duty holder cannot commence work with ionising radiation before commencing a risk assessment and demonstrating that all hazards that can cause a radiation accident have been identified and the magnitude of the risks to employees and the public have been evaluated; the duty holder must restrict the exposure to ionising radiation through means of engineering controls, design features and safety features; that specified dose limits are not exceeded; the duty holder may not operate a facility without obtaining an environment permit and; to obtain a permit the duty holder must demonstrate to the environmental regulator that the exposures to ionising radiation to any member of the public are kept ALARA. Given that there is no nuclear site licence granted in this case, there are no LCs that need to be adhered to by the duty holder; however, conditions are attached to environmental permits. The levels of engineering substantiation, defence in depth measures and safety documentation are significantly reduced in this case when compared with fuel cycle facilities and NPPs (e.g. NPP designers must employ 'nuclear' design codes which include significantly more onerous requirements than standard [non-nuclear] codes). The levels of permissioning are also reduced and regulators have less powers when compared with ONR regulating nuclear installations. The reasoning behind this is that non-nuclear radiation facilities have a significantly lower hazard potential in relation to public harm than fuel cycle facilities and NPPs.

Adopting a similar regulatory approach to that applied to non-nuclear radiation facilities would mean that there would be less regulatory control over the design and construction of FPPs. It would also result in fewer permissioning steps. This could increase regulatory uncertainty given the late stage of permissioning, i.e. at the point of use rather than at the commencement of construction. Regulatory uncertainty is not good for investors, owners and operators. Permissioning major safety related activities against a well defined regulatory schedule is key to delivering good safety but is also good business. As is the need for robust safety case documentation to give the public and politicians confidence that the technology is being adequately controlled and is safe. Safety case

documentation for non-nuclear radiation facilities is unlikely to be as comprehensive as a nuclear facility safety case and hence the true risk posed by the design and operation of an FPP is unlikely to be substantiated to the same level of certainty. Unlike a non-nuclear accelerator, FPPs will have mobile radioactive materials that can be released into the atmosphere in the event of an accident. Hence, the application of this non-nuclear radiation facility approach is questionable. As shown in Chapters 4 and 6, the radioactive materials in an FPP can, if released under severe accident scenarios, cause off-site releases that may result in countermeasures being implemented. Therefore, adopting the same regulatory approach for FPPs as that applied to non-nuclear radiation facilities could put the public at unnecessary risk.

7.4.4.1 Limitations of Regulating via IRRs

If FPPs are to be regulated in line with non-nuclear radiation facilities, the regulatory authority implementing the IRRs will be HSE, an agency with no direct experience of regulating any type of power plant utilising nuclear energy that contains a significant radiological hazard. It has been argued that HSE has regulated JET, currently the largest operational experimental fusion facility in the world, for the last forty years with no substantial safety concerns for workers or the surrounding public. However, it is not clear what role HSE played in regulating the design, construction and commissioning of JET.

It is also naive to compare an experimental facility like JET, designed to operate on a pulsed basis with an extremely small amount of radioactive material present, to a full scale FPP with a primary heat source, multiple breeder blankets, significant inventories of tritium and activated dust (and potentially ACPs) and considerable stored magnetic energies. The hazard potential of an FPP is likely to be much larger than any experimental fusion facility, primarily due to their respective inventories. The work performed in Chapter 6 showed that if even 1% of the expected dust inventory in an FPP escaped to the environment at ground level, there is the potential to trigger evacuation of the surrounding population. It seems unlikely that any experimental facilities, including JET, will have to contend with hazard potentials of this degree. As discussed above, the permissioning elements associated with the IRRs are limited and regulatory interventions at a late stage in a project carry unnecessary risk.

7.4.4.2 Limitations of Regulating via REPPIR and CDM Regulations

Whilst REPPIR will apply to FPPs, the issue is has the regulator (HSE) the experience of assessing the adequacy of off-site emergency planning, something that ONR does on a regular basis. The CDM Regulations will also apply to FPPs. These regulations give the regulator (HSE) no remit to control the design, construction, component manufacture or inactive commissioning of an FPP to ensure the safety of the public once the FPP goes into operation. The CDM Regulations give HSE some powers to ensure that the design and construction of the facility is suitably managed, and that appropriate contractors and designers are hired and that they are suitably qualified for the role, but it gives HSE no significant powers to control the actual design of an FPP to ensure that all radiological hazards have been accounted for and will be mitigated appropriately. The regulations also have no mechanism for implementing permissioning requirements which, as shown above, are essential prerequisites for the effective and efficient regulation of nuclear facilities.

7.4.4.3 Limitations of Regulating via EPR

In relation to environmental regulation, the first problem with treating FPPs as non-nuclear radiation facilities and applying the EPR comes from when consent from the regulator is required. There is nothing in the EPR to stop an operator from commencing construction before an environmental permit has been issued [222]. Now, where proposals involve substantial expenditure or contain complex or novel features, operators should usually make an application when they have drawn up full designs but before any construction work commences [222]. This is primarily to avoid any expensive delays or re-work. However, there is significant difference between what is usual practice and what is compulsory in the Regulations. If there is no explicit requirement for the design of FPPs to be approved by the regulator, there runs the risk that a prospective operator may move ahead with construction under the assumption that the design will be approved, only to be informed further down the line that significant modifications are needed, incurring additional costs and lead times.

Given the current nature of the fusion industry and the number of smaller private ventures attempting FPP concepts, as discussed above, this scenario best be avoided. It is worth noting that EA are currently in the process of developing "staged regulation" for the regulation of a geological disposal

facility (GDF) [221]. The main idea is that at each stage of the development of a GDF (surface investigation, underground operation phases, etc.) there will be an updated safety case produced with its own unique hazards and safety analysis, each requiring a revised environmental permit. This will in effect create makeshift regulatory hold points, resulting in the licensee/operator not able to move past this point until regulatory approval has been obtained and the revised permit has been issued (similar to the permissioning principle implemented by ONR in the LCs). As a GDF will be regulated by ONR, there will potentially be overlaps between EA and ONR permissioning activities. At this point, however, it remains unclear as to whether this "staged regulation" will apply to FPPs. If so, it begs the question are the environmental regulators trying to mirror the nuclear licensing regime where staged permissioning has been successfully implemented for over 35 years?

Another problem with using environmental regulation to regulate an FPP is again *who* the regulator will be. EA is responsible for granting the permits; hence, it will be EA inspecting the designs of the facility and setting the discharge limits. At this stage, it is questionable if EA has the knowledge base and technical capabilities to regulate the safety of the design, construction, commissioning and operation of an FPP. As detailed earlier, the experience gained in regulating JET will prove extremely useful, but the hazard potential of an experimental fusion facility is significantly lower than the hazard potential of a commercial FPP. Whilst EA will no doubt be highly competent in regulating the radioactive discharges from FPPs, it remains to be seen how it plans to upskill an entire workforce to regulate a technology with which they have very limited experience, an experience that for the most part remains with ONR.

7.4.4.4 Public and Political Expectations

It should be remembered that fusion is a thermonuclear process that will attract public and political interest. For the regulation of FPPs to be efficient and effective, one would presume there would be a regulatory requirement for the design of the facility to be assessed against safety requirements and controlled via regulatory approval before construction of the facility begins. As things stand, if FPPs are to be regulated in-line with non-nuclear radiation facilities there is nothing in the current regulatory framework that stipulates this. If, as expected, the public and politicians will want assurance that the technology is being adequately controlled, they will need assurance that the risks

to the health and safety of both workers and the public from the operation of FPPs are acceptably low. To demonstrate that the risks from such a complex machine are low requires not only the operating organisation to develop a substantial safety case (as shown in the case of ITER) but also a recognised independent safety regulator with experience of assessing complex safety cases. Neither of the regulators involved in the regulation of non-nuclear radiation facilities, HSE or EA, currently have the expertise to undertake this task.

7.5 Option 4 - Regulatory Approach that is Proportionate to the Hazard Potential of FPPs (Proportionate Regulation)

This section explores the option of applying a proportionate nuclear site licensing approach to the regulation of FPPs.

7.5.1 Background to Proportionate Regulation

The use of fusion energy to generate power in an FPP is a novel technology. Whilst it has been demonstrated that the hazard potential of FPPs is considerably less than NPPs, the hazard potential is not trivial and to ensure that the risks to both workers and the public are ALARP and within regulatory requirements there will need to be engineered systems with appropriate defence in depth. Hence, to provide assurance that the engineering will do its job some form of regulation is needed. The option discussed here is to develop and adopt a licensing regime for FPPs that reflects the FPP hazard potential - proportionate regulation. For this regime to be effective and efficient it must be stringent enough to provide the public and politicians with the confidence that the technology is being adequately controlled, that FPPs will be safe and the risks to the public are acceptably low. At the same time, the regulatory regime must not put unnecessary obstacles (or financial burdens) in the way of FPP innovation or development, or to the delivery and deployment of an FPP programme [214].

Having a regulatory approach that provides investors, owners and operators with certainty in relation to regulatory requirements is vital to the delivery of both safety and business goals. The UK's nuclear

site licensing regime has demonstrated that it is capable of providing both the flexibility to regulate a wide variety of nuclear installations and the required regulatory certainty. The UK, the U.S. and Canada have demonstrated that is it possible to develop and implement nuclear regulatory approaches that are proportionate to the hazard (see Chapter 5).

7.5.2 The UK Regulatory Framework for Nuclear Installations

At present the NIA only applies to fission-based activities, but it would be relatively straightforward to prescribe FPPs as a nuclear installation to ensure the Act includes fusion. This would enable the UK's highly efficient and effective nuclear site licensing to be applied to FPPs. If this change was made, FPPs, as with NPPs, would be subject to the general duties of the HSWA, the IRRs, REPPIR and environmental permitting. One big advantage would be that for nuclear safety, security, safeguards and industrial health and safety there would be a single regulator, the well-respected ONR. Minimising regulatory interfaces and overlapping responsibilities adds to regulatory effectiveness. As is currently the case, environmental permitting would be regulated by the environmental regulators, EA/NRW/SEPA, under the current Memorandum of Understanding arrangements.

7.5.3 Elements of a Proportionate Regulatory Regime for FPPs

The key goal of a proportionate approach to regulation is to ensure that the licensing regime provides suitable control over the licensee's activities without placing undue burdens on the licensee and hence FPP vendors/designers. The nuclear site licensing regime provides regulatory certainty, but the regulatory requirements must be designed in a way that they are proportionate to the hazard potential. Hence, the nuclear safety, security and safeguards performance requirements (Standards and Guidance) for FPPs need not be the same as those for NPPs. A new set of requirements, such as those developed by IAEA for NPPs, could be developed for FPPs. Also, in the case of the UK nuclear site licensing approach, the set of conditions attached to the licence need not be the same as those currently applied to NPP or fuel cycle facility licences. The UK's nuclear site licensing regime also enables the nature of the arrangements made under the LCs to be different and designed by the licensee to reflect the lower hazard potential and the reduced consequences should things go wrong.

In a proportionate licensing regime, a new set of LCs could be developed (in consultation with industry) to reflect what is important to the management of safety and, where appropriate, security

in the context of fusion. These LCs would be goal setting and require the licensee to make and implement the arrangements that would be necessary to deliver the goals (similar to the approach used for NPP licensing). In this way the range of LCs would focus on the things that are important to safety, the management of radioactive waste and, where appropriate, security. This approach would allow the licensee to develop arrangements and safety documentation that are proportionate to the hazard.

The successful deployment of fusion power will require public acceptance and in order to gain this, the public will need to be reassured that the technology is being properly managed to ensure worker and public safety and the protection of the environment. Effective regulation is key to gaining public acceptance. The fundamentals of effective nuclear safety regulation can be considered to be:

- no one is allowed to construct or operate a nuclear facility without obtaining a licence
- a licensee must be a fit and proper organisation with the necessary financial and technical resources
- the licensee is responsible for safety
- permission from a competent and independent regulator is required in advance of undertaking major activities that affect safety (such as commencement of construction, commissioning or operation)
- permission to undertake a major safety related activity is based on the adequacy of safety documentation (safety cases) submitted by the licensee
- the regulator has appropriate enforcement powers including the power to halt activities if safety case requirements are not complied with
- appropriate penalties are available for non-compliance

At first glance there is no reason why these fundamentals of effective nuclear safety regulation should not apply to the regulation of FPPs within a proportionate framework. What will differ in the case of FPPs when compared with NPPs is the extent to which the obligations within these fundamentals are met (e.g. less onerous safety requirements and documentation for FPPs commensurate with the reduced hazard potential).

The FPP nuclear site licensing framework will also need to accommodate the hazards and safety issues that are specific to FPPs and are not considered in the current nuclear regulatory regime, e.g. issues associated with breeder blankets, large stored magnetic energies, inventories of tritium and dust, etc. Chapter 9 will explore the development of a proportionate nuclear site licensing regulatory framework for FPPs and how the above (and potentially other) fundamentals for effective nuclear safety regulation can be implemented within the UK setting.

7.5.4 Permissioning

In a proportionate regulatory regime, permissioning is a vital tool that will provide both effective control over safety related activities and regulatory certainty to investors, owners and operators so that they are aware of what is required at each important stage of the life cycle of the facility. Once the licensee has been granted permission to move past a stage, the licensee (and owners and investors) will be confident that the regulator is satisfied with the design and safety of the facility. Permissioning is also crucial in terms of gaining the confidence of the public and the politicians who will want assurances from the nuclear safety regulator that the facility is being adequately controlled and the technology is safe. A robust permissioning system also grants the regulator appropriate enforcement powers to ensure that the licensee/duty holder is complying with any requirements put upon them. This is critical as the public will want assurances that the regulator has sufficient powers to control activities in order to maintain safety and to shut activities down if something goes wrong.

7.5.5 Summary of Main Features and Implications for FPPs

The main features of a proportionate nuclear site licensing regime for FPPs are similar to those for NPPs: no one is allowed to construct or operate an FPP without obtaining a licence, the licensee is responsible for safety, permission from the nuclear safety regulator is required in advance of undertaking major activities that may affect safety, safety documentation must be provided before obtaining permission to undertake a major safety related activity, safety standards reflect the hazard potential of the facility, safety documentation requirements reflect the hazard potential of the activity being proposed and the regulator has appropriate enforcement powers if safety case requirements are not complied with. The main difference between a proportionate nuclear site licensing regime for FPPs and that for NPPs is the less onerous safety requirements and hence safety documentation and

the extent of regulatory oversight. An example of this is external hazard protection measures such as seismic protection or aircraft impact protection - these would only be a regulatory requirement if the radiological consequences of such an event were shown to be intolerable.

In the UK, the regulator, ONR, would still be able to make use of a variety of permissioning powers to ensure that it established the necessary levels of regulatory control over the licensee's activities. However, given the lower hazard potential the use of these powers would be expected to be less intrusive and restrictive than the use of these powers on NPP or certain nuclear fuel cycle licensed sites. There is precedent for this: when NII licensed low hazard potential nuclear research reactor sites, the amount of regulatory oversight resources allocated to these sites was much lower than other more hazardous sites. Effective regulatory oversight is essential to providing the public and politicians with the assurance that the FPP programme is being managed appropriately and the risks to health and safety are acceptably low, whilst allowing the licensee more freedom to develop designs and engineering features with a lower hazard technology.

Developing a proportionate, goal setting nuclear site licensing regulatory framework for FPPs allows licensees the freedom to develop their designs and their own arrangements for managing safety that reflect the hazard potential of FPPs. Also, the adoption of a proportionate nuclear site licensing regime will provide the public and politicians with the confidence that this nuclear-based technology is being appropriately regulated on their behalf, and it gives investors, owners and licensees the confidence that the regulatory pathway is clear. The adoption of a nuclear site licensing approach in the UK will ensure that FPPs are safe and secure, construction will not be permitted to commence until ONR is satisfied with the safety case and that the licensee has the necessary arrangements in place to control construction, and subsequent commissioning and operation will be subject to ONR permissioning. A licensing approach also ensures that the likelihood of major disruptions during construction will be minimised and hence costly delays will be avoided.

The challenges with this approach include convincing the fusion industry that regulation via a licensing regime is a positive solution and the current lack of design standards for FPPs.

Chapter 8

Analysing Regulatory Options for Fusion Power in the UK

This chapter analyses the regulatory options for FPPs mapped out in the previous chapter in order to determine the most appropriate option.

8.1 Background

From the work done in this study and elsewhere, it is clear that FPPs have the potential to release radioactive materials into the environment under certain accident scenarios and therefore should be regulated in order to assure the public that the technology is safe and that the public and the environment are protected. It is equally clear that the hazard potential of an FPP is orders of magnitude below that of an NPP. Given this, it has been argued that it would be unreasonable for FPPs to be subject to the extremely strict regulatory framework that (rightly) exists for NPPs [214]. The key question therefore is: What type of regulation is appropriate for FPPs?

Chapter 5 showed that at present there are no internationally agreed approaches as to how FPPs should be regulated. Options range from the strict NPP approach to treating FPPs as non-nuclear radiation facilities subject only to occupational health and safety/environmental permitting legislation. The range of regulatory options available for FPPs within the UK legal framework was mapped out in Chapter 7.

In Chapter 7, four main options were considered:

(1) Regulation using a licensing regime similar to that applied to NPPs

(2) Regulation using a licensing regime similar to that applied to nuclear fuel cycle (including radioactive waste management) facilities

(3) Regulation using occupational health and safety and environmental permitting legislation similar to that applied to non-nuclear radiation facilities

(4) Regulation using a licensing regime that is proportionate to the hazard potential of FPPs

Each regulatory option was explored, and the applicable legislation/regulations were examined in order to gauge the implications for FPPs.

8.2 Criteria to Evaluate Regulatory Framework

To evaluate which of the options is the most appropriate, a selection of criteria have been developed. These criteria were drawn out of conversations with members of the fusion industry and have each been discussed at the increasing number of conferences held within the fusion industry focusing on the question of how FPPs should be regulated. The criteria are intended to reflect the factors that need to be considered when judging what is necessary to provide an effective and efficient regulatory system that is proportionate to the hazard potential of the facility being regulated. The criteria were developed by taking account of:

- IAEA guidance on the key characteristics of a regulatory body as set out in the IAEA *Handbook on Nuclear Law* [215] and *General Safety Requirements No. GSR 1 (Rev 1)* [223]
- the need for proportionality as set out in the IAEA 'graded approach'
- the need for regulation to be effective and efficient
- the benefits of having industry specific regulation
- the benefits of having regulatory certainty
- the need for public and political confidence in the safety and security of technology
- the need to comply with international safety, security and safeguards obligations

On the basis of the above, 10 criteria were developed and are given below:

(1) **Independence** - The regulator must be independent of the industry being regulated and independent of those in government that sponsor the industry being regulated.

(2) **Proportionality** - The regulatory burdens on the operator (and designers) are proportionate to the hazard potential of the facility being regulated. Regulatory control via permissioning hold points should be balanced against the consequences of failure. The higher the consequence the greater the regulatory control/intervention. Safety case substantiation should be commensurate with the hazard potential of the facility being regulated.

(3) **Effectiveness** - Regulation must be effective and efficient in order to minimise regulatory burdens associated with both programme delays and direct regulatory costs. For example, ONR regulates nuclear safety, security, safeguards, transport of nuclear and radioactive materials, and industrial health and safety on nuclear licensed sites.

(4) **Regulatory Certainty** - The demands from regulation need to be transparent and predictable. Regulatory certainty requires regulatory oversight of the whole cycle from 'cradle to grave'. Investors, owners and operators need to have confidence that when they commit to a build programme there will not be unexpected regulatory demands.

(5) **Technical Competence** - Regulators must have the engineering, scientific and technical resources to be capable of assessing the adequacy of the operator's safety, security and other regulatory documentation in order to permission activities.

(6) **Ring-Fenced Resources** - Regulators must have sufficient human and financial resources. These should be ring-fenced and allocated to the regulation of the industry to which the regulations apply.

(7) **Industry Focus** - The regulatory framework should enable regulators to be focused on the sector to be regulated in order to understand the technology and the industry. Generalised regulatory systems applied to a variety of industries tend to be ineffective in hazardous industries.

(8) **Public Confidence** - The regulatory framework must assure the public that the hazard and hence the risk to them is being managed properly by the organisation operating the facility.

Public confidence comes from knowing the regulator is independent, competent and has the necessary powers to control activities including the power to halt operations.

(9) **Political Confidence** - The regulatory framework must give the politicians confidence that technology needed to deliver national goals, such as security of supply and climate change goals, can be relied on. Politicians also need to be assured that major accidents with the potential to derail the delivery of these goals will be prevented not only to prevent undue risk to the public but also to minimise the cost to the treasury of any accident recovery and clean-up costs.

(10) **International Obligations** - The UK has certain obligations under international treaties and conventions. The regulatory framework should ensure that the regulation is consistent with these obligations.

8.3 Analysis of Regulatory Options

Each option has been evaluated against these principles. A scoring scheme has been applied using a scale of 1-5 as follows:

1) meets none of the requirements set out in the criteria

2) meets a few requirements set out in the criteria

3) meets some of the requirements set out in the criteria

4) meets most but not all of the requirements set out in the criteria

5) meets all of the requirements set out in the criteria

In the following analysis, the options have been evaluated against the requirements for safety, security and safeguards as there is already a regulatory framework covering the discharge of radioactive materials from facilities. The scores for each option will then be summed and the overall scores compared to make a judgement on which option is most appropriate. Clearly, there will be some variability in the scoring and readers may judge that certain options warrant a different score than

what is given below. For each criterion, an attempt has been made to map the reasoning behind each given score; however, as stated above, there is some subjectivity in this approach and different readers may come to different conclusions.

8.3.1 Analysis of Option 1 - NPP Approach

Option 1 involved licensing FPPs in a similar manner to NPPs under a strict and onerous regulatory framework. The regulation of NPPs provides regulatory oversight from cradle to grave via a nuclear site licensing regime. Licensees require permission from ONR in order to undertake such things as construction, commissioning, operation, reactor restart following statutory outages, major modifications or organisational change. To obtain permission, licensees must produce appropriate safety documentation and cannot proceed without the permission of ONR. All people who undertake safety related activities in an NPP must be suitably qualified and experienced. Licensees must be the "Controlling Mind" for NPP operations and the "Intelligent Customer" for services they buy in from other organisations. Nuclear site licenses have 36 attached conditions (LCs) which are primarily goal setting and envelope all the requirements to effectively manage nuclear safety. NPPs are also regulated by ONR for security and non-proliferation safeguards and each NPP has to have a security plan and is protected by the Civil Nuclear Constabulary (an armed protection force). EA/NRW/SEPA regulate routine environmental discharges from NPPs. Under Option 1, licensees of FPPs would be required to carry out any obligations with respect to safety, security, safeguards or environmental protection to the same extent as licensees of NPPs (e.g. similar levels of engineering substantiation, defence in depth, safety documentation, etc.).

The analysis of the regulation of FPPs via an NPP approach is shown below in relation to the 10 regulatory principles.

8.3.1.1 Independence

"The regulator must be independent of the industry being regulated and independent of those in government that sponsor the industry being regulated."

Under Option 1, the nuclear regulator ONR would take responsibility for the regulation of safety, security and safeguards at FPPs. ONR - previously NII - has successfully regulated nuclear installa-

tions in the UK since its inception and is entirely independent of the nuclear industry and of those in government that sponsor the nuclear industry. **Score 5**.

8.3.1.2 Proportionality

"The regulatory burdens on the operator (and designers) are proportionate to the hazard potential of the facility being regulated. Regulatory control via permissioning hold points should be balanced against the consequences of failure. The higher the consequence the greater the regulatory control/intervention. Safety case substantiation should be commensurate with the hazard potential of the facility being regulated."

Licensing FPPs in a similar manner to that applied to NPPs would result in regulatory burdens and safety design measures that would be grossly disproportionate to the hazard potential of FPPs. Despite the goal setting nature of the UK's nuclear regulatory framework and the ability for licensees to develop their own arrangements for managing safety, licensees of NPPs are expected to provide significant levels of safety documentation, engineering substantiation and defence in depth measures. NPPs must also be able to cope with a comprehensive range of internal and external hazards such as fire, extreme floods, earthquakes and aircraft impact. These measures are taken due to the considerable hazard potential of NPPs and the catastrophic consequences of a severe accident followed by a release of radioactive material. These measures are onerous, time-consuming and add significant complexity and cost, but they are considered proportionate to the hazard potential of an NPP.

Under this approach, licensees of FPPs would be expected to implement these measures to the same extent as licensees of NPPs. Operators and designers would be expected to provide similar levels of safety documentation, engineering substantiation and defence in depth measures, and FPPs would need to be built to withstand a similar list of internal and external hazards. These measures would provide high levels of safety; however, they are grossly disproportionate to the hazard potential of FPPs. The special characteristics associated with NPPs have shaped the current nuclear licensing regime. The regime is driven by the potential radioactive source term and the inherent characteristics associated with NPPs, such as the potential for criticality and associated exponential increases in power levels, the radioactive decay of fission products in the core that require constant cooling

and the production of radioactive waste that needs storing for hundreds of thousands of years (see Chapter 3). These characteristics do not apply to FPPs. Chapter 6 demonstrated that FPPs will have inventories of radioactive material that, if released under certain accident scenarios, could trigger emergency countermeasures. However, the release of material from an FPP would generally result in significantly reduced radiological consequences when compared to a release from an NPP. It is also not clear at this stage to what extent FPPs should be designed to protect against external hazards such as earthquakes and aircraft impact: if the radiological consequences are minor, it would be disproportionate for ONR to require licensees to protect against them. Moreover, this approach would require designers of FPPs to make use of 'nuclear' design codes for engineering design which could lead to more costly manufacturing.

Licensees of FPPs would also be subject to a similar number of strict permissioning hold points as licensees of NPPs, despite the significantly reduced hazard potential of FPPs compared with NPPs. To progress past these hold points, licensees/operators must provide significant levels of safety documentation illustrating the protection measures and defence in depth features present in the facility. More hold points means more regulatory burdens on the licensee; therefore, given the disparity in hazard potentials, demanding a similar number of permissioning hold points are in place for both NPPs and FPPs is markedly disproportionate to the hazard potential of FPPs. It follows that adopting an NPP approach, whilst delivering high levels of safety, would be significantly disproportionate to the hazard potential of FPPs, resulting in increased design complexity, engineering substantiation, defence in depth measures, regulatory costs and lead times. **Score 2**.

8.3.1.3 Effectiveness

"Regulation must be effective and efficient in order to minimise regulatory burdens associated with both programme delays and direct regulatory costs. For example, ONR regulates nuclear safety, security, safeguards, transport of nuclear and radioactive materials, and industrial health and safety on nuclear licensed sites."

Under Option 1, the nuclear regulator ONR would be responsible for regulating all aspects of FPPs except for routine discharges. Therefore, ONR would regulate nuclear safety, security, safeguards, transport of nuclear and radioactive materials, and industrial health and safety on nuclear licensed

sites for FPPs. This would increase effectiveness and efficiency as a single regulator is responsible for the entire process. However, licensing FPPs in a similar manner to that applied to NPPs would result in ONR allocating a similar number of resources for the regulation of an FPP as it would for the regulation of an NPP. For the regulation of NPPs, ONR must utilise a significant number of resources (such as time, manpower and cost) as the consequences of failure and hazard potential of an NPP are extremely high. Given the reduced hazard potential of FPPs, allocating a similar number of resources for the regulation of both NPPs and FPPs would be an inefficient and hence also an ineffective use of ONR's resources. **Score 2**.

8.3.1.4 Regulatory Certainty

"The demands from regulation need to be transparent and predictable. Regulatory certainty requires regulatory oversight of the whole cycle from cradle to grave. Investors, owners and operators need to have confidence that when they commit to a build programme there will not be unexpected regulatory demands."

Under the current nuclear regulatory framework, ONR regulates NPPs from the design stage through to decommissioning. This is achieved through the regulator and licensee agreeing a regulatory schedule so that at each stage, all parties are aware of what is required and there will not be unexpected regulatory demands. Licensing FPPs in a similar manner to that applied to NPPs would similarly mean that ONR regulates FPPs from the design stage through to decommissioning and that a regulatory schedule will be agreed to minimise the risk of project delays and to provide regulatory certainty to investors, owners and operators. **Score 5**.

8.3.1.5 Technical Competence

"Regulators must have the engineering, scientific and technical resources to be capable of assessing the adequacy of the operator's safety, security and other regulatory documentation in order to permission activities."

ONR (and the NII before it) is an established regulator that has successfully regulated civil nuclear installations in the UK for decades. Whilst Option 1 would require the upskilling of ONR's workforce to be able to regulate fusion technologies, it is expected that due to the operational experience it

has regulating nuclear installations, it has the engineering, scientific and technical resources to be capable of assessing the adequacy of an FPP operator's safety and security documentation in order to permission certain activities. **Score 4**.

8.3.1.6 Ring-Fenced Resources

"Regulators must have sufficient human and financial resources. These should be ring-fenced and allocated to the regulation of the industry to which the regulations apply."

Under Option 1, ONR would be responsible for regulating all aspects of FPPs (except for routine discharges) and would charge an FPP licensee for its regulatory activities. As regulating nuclear installations is ONR's core business, it is reasonable to assume that ONR would have sufficient human and financial resources to regulate FPPs and that these resources will be entirely allocated to the regulation of nuclear installations. **Score 5**.

8.3.1.7 Industry Focus

"The regulatory framework should enable regulators to be focused on the sector to be regulated in order to understand the technology and the industry. Generalised regulatory systems applied to a variety of industries tend to be ineffective in hazardous industries."

ONR is currently the only nuclear focused, bespoke regulator, with experience regulating all kinds of nuclear installations and activities including NPPs, fuel cycle facilities (including nuclear fuel manufacture facilities, uranium enrichment facilities, radioactive waste treatment and storage facilities), nuclear submarine refuelling and nuclear weapons production. Regulating nuclear installations is ONR's core business and it is entirely focused on the nuclear sector. It understands nuclear technologies and the nuclear industry. **Score 5**.

8.3.1.8 Public Confidence

"The regulatory framework must assure the public that the hazard and hence the risk to them is being managed properly by the organisation operating the facility. Public confidence comes from knowing the regulator is independent, competent and has the necessary powers to control activities including the power to halt operations."

It could be argued that licensing FPPs in a similar manner to NPPs would provide the public with confidence that the technology is being controlled with the same high level of regulatory oversight as that applied to NPPs. Under this approach, the public would know that the regulator is independent and competent (as ONR has experience successfully regulating nuclear installations in the UK) and that it has the necessary powers to control activities including the power to shut down the licensee's activities.

The counter to this point is that licensing FPPs in a similar manner to NPPs would send the wrong message to the public, i.e. "FPPs and NPPs have a similar hazard potential and should be treated similarly". As public acceptance is key to the successful deployment of fusion power, the distinction between the two technologies must be stressed. According to a 2013 report carried out by the UK Energy Research Centre, nuclear power is one of the nation's "least favoured energy sources" and "broadly similar proportions of people now support or oppose the use of nuclear power in Britain" [224]. From the report, two of the primary areas for concern are the storage of radioactive waste and accidents scenarios[1]. The work in this project has already demonstrated that the consequences of a release of radioactive material following an accident at an FPP are significantly reduced when compared with a release from an NPP. Licensing FPPs and NPPs in a similar manner could give rise to public concern based on a misguided perception of the hazard potential.

Overall, the regulation of FPPs by ONR applying a similar approach to that used for NPPs will give the public confidence that the technology is being adequately controlled by a competent regulator; however, it may raise public concern as the public will be sent the wrong message regarding the hazard potential. **Score 4**.

8.3.1.9 Political Confidence

"The regulatory framework must give the politicians confidence that technology needed to deliver national goals, such as security of supply and climate change goals, can be relied on. Politicians also need to be assured that major accidents with the potential to derail the delivery of these goals will be prevented not only to prevent undue risk to the public but also to minimise the cost to the treasury of any accident recovery and clean-up costs."

[1] However, this is not a universally held view and there remains public support for nuclear energy

Assessing political confidence is complicated due to the many factors at play. Politicians need to be assured that the fusion power programme will provide security of supply as well as contributing to the longer-term needs for low carbon energy. They also need to be assured that major accidents that result in a significant risk to the public and incur considerable accident recovery and clean-up costs can be prevented or reduced to a very low probability of occurrence. The effects and clean-up costs of nuclear accidents such as Chernobyl and Fukushima illustrated the consequences of major accidents at NPPs, with current estimates of costs at $235 billion and $202 billion, respectively [225], [226]. For NPPs, politicians have the confidence that the technology is being adequately controlled and the chances of a major accident are acceptably low due to the strict nuclear regulatory framework and the powers afforded to ONR to control licensees' activities. The work in this project has demonstrated that any major accident at an FPP would not result in the catastrophic consequences of a Chernobyl or Fukushima; however, a major accident could result in some release of radioactive materials and a disruption to the supply of electricity from FPPs. A scenario could occur in which a major accident at an FPP causes public outcry and as a political response all FPPs are shutdown. This would then hit security of supply and force the nation to increase its consumption of fossil fuels, potentially impacting future climate change targets (similar to what happened at Fukushima). It is reasonable to assume that politicians may opt for a stricter regulatory regime in order to prevent this type of scenario from occurring.

Politicians will have confidence in the high regulatory standards and oversight that are applied to NPPs; hence, extending these regulatory standards to FPPs would command political support. **Score 5**.

8.3.1.10 International Obligations

"The UK has certain obligations under international treaties and conventions. The regulatory framework should ensure that the regulation is consistent with these obligations."

Licensing FPPs in a similar manner to that applied to NPPs would result in fusion power coming under the remit of the NIA and FPPs being classed as nuclear installations [167]. As the current nuclear regulatory framework is consistent with the UK's nuclear safety obligations under international conventions, regulating FPPs under the same regime as that used for NPPs would ensure the UK

was in compliance with its nuclear safety obligations. At present fusion is not covered by the IAEA Nuclear Safety Convention or IAEA standards; however, there is interest within IAEA in bringing FPPs within its scope. **Score 5**.

Total score for Option 1 = 42/50

8.3.2 Analysis of Option 2 - Fuel Cycle (Including Radioactive Waste Management) Facilities Approach

Option 2 involved regulating FPPs in a similar manner to nuclear fuel cycle facilities. In the UK, this would again involve licensing FPPs under the NIA as a nuclear installation and licensees having to adhere to the same 36 LCs that are attached to every nuclear site licence. However, as the UK licensing regime is primarily goal setting, the licensee has the flexibility to tailor how it complies with the LCs. This way the required safety documentation and associated regulatory oversight can be tailored to reflect the hazard potential of the activity.

The analysis of the regulation of FPPs via a fuel cycle facility approach is shown below in relation to the 10 regulatory principles.

8.3.2.1 Independence

"The regulator must be independent of the industry being regulated and independent of those in government that sponsor the industry being regulated."

As in Option 1, ONR would regulate the whole life cycle of FPPs (whilst EA/NRW/SEPA would regulate routine discharges). The ONR is entirely independent of the nuclear industry and of those in government that sponsor the nuclear industry. **Score 5**.

8.3.2.2 Proportionality

"The regulatory burdens on the operator (and designers) are proportionate to the hazard potential of the facility being regulated. Regulatory control via permissioning hold points should be balanced against the consequences of failure. The higher the consequence the greater the regulatory control/intervention. Safety case substantiation should be commensurate with the hazard potential of the facility being regulated."

The regulatory framework for fuel cycle facilities is the same framework for NPPs; however, the goal setting nature of the licensing regime enables licensees to produce safety documentation that is proportionate to the hazard potential. Hence, the required safety features and associated engineering substantiation and defence in depth measures can be considerably less than those for NPPs.

Fuel cycle facilities must still be able to protect the public against a comprehensive range of internal and external hazards such as fire, extreme flooding, earthquakes and aircraft impact. The radiological consequences of a release of radioactive material from these facilities depends on the type of facility: for reprocessing facilities the consequences can still be significant, but less so for passively safe radioactive waste storage facilities. Hence, fuel cycle facilities have a range of regulatory oversight regimes relating to the number of permissioning hold points. The release of radioactive material from an FPP would generally result in reduced radiological consequences when compared to a release from a fuel cycle facility. Given the reduced hazard potential of FPPs compared with fuel cycle facilities, adopting the same requirements as fuel cycle facilities would be time-consuming and incur unnecessary complexity and costs.

It follows that adopting an approach similar to that applied to fuel cycle facilities, whilst less onerous than an NPP approach, would still be disproportionate due to the lower hazard potential of FPPs. **Score 3**.

8.3.2.3 Effectiveness

"Regulation must be effective and efficient in order to minimise regulatory burdens associated with both programme delays and direct regulatory costs. For example, ONR regulates nuclear safety, security, safeguards, transport of nuclear and radioactive materials, and industrial health and safety on nuclear licensed sites."

Under Option 2, ONR would be responsible for regulating all aspects of FPPs except for routine discharges. As in Option 1, the single regulator approach should increase both effectiveness and efficiency. However, licensing in a similar manner to that applied to fuel cycle facilities would result in ONR allocating similar regulatory resource levels to FPPs. Given the reduced hazard potential of FPPs, allocating a similar level of regulatory resources would not be optimal for both effectiveness and efficiency. **Score 3**.

8.3.2.4 Regulatory Certainty

"The demands from regulation need to be transparent and predictable. Regulatory certainty requires regulatory oversight of the whole cycle from cradle to grave. Investors, owners and operators need to have confidence that when they commit to a build programme there will not be unexpected regulatory demands."

Under Option 2, the NIA gives ONR the powers to regulate FPPs from the design stage through to decommissioning (with EA/NRW/SEPA regulating routine discharges). A regulatory schedule would be agreed between ONR and the licensee of the FPP to set out the regulatory points during construction, commissioning and operation, and the required safety documentation for each hold point. In this way the licensee/licence applicant and the associated investor and owner can have a clear understanding of what is required. This cradle to grave approach to regulation reduces project risk and provides regulatory certainty. **Score 5**.

8.3.2.5 Technical Competence

"Regulators must have the engineering, scientific and technical resources to be capable of assessing the adequacy of the operator's safety, security and other regulatory documentation in order to permission activities."

As in Option 1, it is expected that due to the operational experience ONR has regulating nuclear installations, it has the engineering, scientific and technical resources to be capable of assessing the adequacy of an FPP licensee's safety and security documentation in order to permission the licensee's activities. **Score 4**.

8.3.2.6 Ring-Fenced Resources

"Regulators must have sufficient human and financial resources. These should be ring-fenced and allocated to the regulation of the industry to which the regulations apply."

As in Option 1, FPPs would be regulated by ONR and classed as a type of nuclear installation in the NIA. As regulating nuclear installations is ONR's core business, it is reasonable to assume that it has sufficient human and financial resources to regulate FPPs and that these resources will be entirely allocated to the regulation of nuclear installations. **Score 5**.

8.3.2.7 Industry Focus

"The regulatory framework should enable regulators to be focused on the sector to be regulated in order to understand the technology and the industry. Generalised regulatory systems applied to a variety of industries tend to be ineffective in hazardous industries."

As detailed in Option 1, regulating nuclear installations is ONR's core business and it is entirely focused on the nuclear sector. It understands nuclear technologies and the nuclear industry. **Score 5**.

8.3.2.8 Public Confidence

"The regulatory framework must assure the public that the hazard and hence the risk to them is being managed properly by the organisation operating the facility. Public confidence comes from knowing the regulator is independent, competent and has the necessary powers to control activities including the power to halt operations."

It could be argued that licensing FPPs in a similar manner to that applied to fuel cycle facilities would provide the public with confidence that the technology would be controlled with a high level of regulatory oversight. Under this approach, the public would know that the regulator is independent and competent (as ONR has experience successfully regulating nuclear installations in the UK) and that it has the necessary powers to control activities including the power to shut down the licensee's activities. However, licensing FPPs in this manner could again send a wrong message, i.e. "FPPs need to be licensed in the same way as fuel cycle facilities and hence must have a similar hazard potential". This may again give rise to public concern based on a misguided perception of the hazard potential.

Overall, the regulation of FPPs by ONR applying a similar approach to that used for fuel cycle facilities will give the public confidence that the technology is being adequately controlled by a competent regulator; however, it may raise public concern as the public will be sent the wrong message regarding the hazard potential (albeit to a lesser extent than in Option 1). **Score 4**.

8.3.2.9 Political Confidence

"The regulatory framework must give the politicians confidence that technology needed to deliver national goals, such as security of supply and climate change goals, can be relied on. Politicians also need to be assured that major accidents with the potential to derail the delivery of these goals will be prevented not only to prevent undue risk to the public but also to minimise the cost to the treasury of any accident recovery and clean-up costs."

Politicians need to be assured that the fusion power programme will provide security of supply as well as contributing to the longer-term needs for low carbon energy. They also need to be assured that the likelihood of major accidents is sufficiently low. The current regulatory framework being applied to fuel cycle facilities implies there is political confidence in the approach.

Licensing FPPs in a similar manner to that applied to fuel cycle facilities would provide the politicians with the confidence that high regulatory standards and oversight are being applied to FPPs and the likelihood of major accidents would be minimised. **Score 5**.

8.3.2.10 International Obligations

"The UK has certain obligations under international treaties and conventions. The regulatory framework should ensure that the regulation is consistent with these obligations."

As in Option 1, licensing FPPs in a similar manner to that applied to fuel cycle facilities would result in FPPs coming under the remit of the NIA. As the current nuclear regulatory framework is consistent with the UK's nuclear safety obligations under international conventions, regulating FPPs under the same regime as that used for NPPs would ensure the UK was in compliance with its international obligations. **Score 5**.

Total score for Option 2 = 44/50

8.3.3 Analysis of Option 3 - Non-Nuclear Radiation Facilities Approach

This option considers the scenario in which FPPs are not treated as nuclear installations under the NIA but are instead regulated under occupational health and safety/environmental permitting

legislation. In the UK, the main legislation covering the regulation of non-nuclear radiation facilities such as accelerators and cyclotrons is the HSWA [171] and its supporting regulations – the IRRs [174], REPPIR [175], etc. - and the EPR [173].

The analysis of the regulation of FPPs using an occupational health and safety/environmental permitting approach is discussed below in relation to the 10 regulatory principles.

8.3.3.1 Independence

"The regulator must be independent of the industry being regulated and independent of those in government that sponsor the industry being regulated."

Under Option 3, the regulation of FPPs would come under the remit of HSE, implementing the HSWA, and EA/NRW/SEPA, primarily concerned with routine effluents into the environment. Each of these organisations is entirely independent of the nuclear industry and of those in government that sponsor the nuclear industry. **Score 5**.

8.3.3.2 Proportionality

"The regulatory burdens on the operator (and designers) are proportionate to the hazard potential of the facility being regulated. Regulatory control via permissioning hold points should be balanced against the consequences of failure. The higher the consequence the greater the regulatory control/intervention. Safety case substantiation should be commensurate with the hazard potential of the facility being regulated."

Under Option 3, FPPs would not be subject to a nuclear licensing regime. Instead, designers/operators would be responsible for complying with the requirements of the HSWA (and its relevant regulations) and the EPR. The key question is: Would the regulation of an FPP using these pieces of legislation as enforced by HSE and EA/SEPA/NRW be proportionate to the hazard potential? An examination of the regulatory powers contained within the legislation suggests that there are limitations with respect to having an ability to adequately control the design, construction, manufacture, commissioning and operation of an FPP.

An example of this is the ambiguous wording of the IRRs which suggests that duty holders would not have to apply for regulatory consent until the *point of use*. This would mean that there could

be no regulatory assessment of the design of an FPP until it was ready to commence commissioning with deuterium. If the design was deficient, it could mean either expensive backfitting of additional safety features, which could be expensive, or a reverse ALARP application would be made which could result in the acceptance of a less than optimal safety case. The CDM Regulations provide some regulatory oversight over construction to ensure that the health and safety of workers and the public is protected during construction; however, these are more general requirements and are not nuclear or even radiation specific. Likewise, in the EPR there is nothing to stop an operator from commencing construction before an environmental permit has been issued [222]. These deficiencies appear to violate IAEA's well-respected permissioning principle.

Regulating under the HSWA and EPR would therefore provide limited permissioning powers to the regulators to control design, construction and commissioning. This is in contrast to the cradle to grave regulatory oversight provided by the nuclear site licensing regime. A full scale FPP is a complex facility with a nuclear driven primary heat source, primary and secondary cooling requirements, multiple breeder blankets, significant inventories of tritium and activated dust, and large stored magnetic energies, with a potential for the off-site release of radioactive materials in accident conditions. Given this, a regulatory system using only HSWA and environmental permitting legislation would appear to be disproportionately lax. Regulating FPPs under normal occupational health and safety/environmental permitting legislation would result in limited protection measures and arrangements for managing the safety of FPPs. **Score 2**.

8.3.3.3 Effectiveness

"Regulation must be effective and efficient in order to minimise regulatory burdens associated with both programme delays and direct regulatory costs. For example, ONR regulates nuclear safety, security, safeguards, transport of nuclear and radioactive materials, and industrial health and safety on nuclear licensed sites."

Under Options 1 and 2, ONR is responsible for regulating nuclear safety, security, safeguards, transport of nuclear and radioactive materials, and industrial health and safety on nuclear licensed sites. Under Option 3, the regulation of FPPs would be split between HSE, enforcing any HSWA requirements, and EA/NRW/SEPA, enforcing the EPR requirements. ONR would still be responsible for

regulating and enforcing the Nuclear Safeguards Act 2018 (NSA18) [138] because of the potential for dual use technologies and the potential to breed fissile material in breeder blankets. Both of these would require ONR oversight of the design, construction, commissioning and operation of an FPP. Also, if IAEA includes FPPs as nuclear installations (likely given that France, Canada and China already treat FPPs as nuclear facilities), ONR would be obliged to regulate nuclear security under the NISR [130] for both physical protection (sabotage) and cybersecurity. Given the numerous regulatory interfaces and jurisdictions, this option provides a significant potential for inefficiencies and a lack of regulatory effectiveness. **Score 2**.

8.3.3.4 Regulatory Certainty

"The demands from regulation need to be transparent and predictable. Regulatory certainty requires regulatory oversight of the whole cycle from cradle to grave. Investors, owners and operators need to have confidence that when they commit to a build programme there will not be unexpected regulatory demands."

Given the lack of regulatory powers to effectively control the design, construction and commissioning process, this approach is unlikely to provide investors, owners and operators with the certainty they are looking for as there will be a risk that unexpected regulatory demands may appear after the commitment to commence the project. As illustrated in Section 7.4.3, it is not hard to envisage scenarios in which duty holders are nearing completion of construction and are then informed that significant modifications will be required in order to obtain regulatory approval arising from late regulatory reviews, which could incur considerable cost and delays in the project. **Score 1**.

8.3.3.5 Technical Competence

"Regulators must have the engineering, scientific and technical resources to be capable of assessing the adequacy of the operator's safety, security and other regulatory documentation in order to permission activities."

Under Option 3, the regulation of FPPs would be split between HSE and EA/NRW/SEPA. Regulating the design, construction, commissioning and operation of an FPP would be novel for these regulators and, unlike ONR, it would not be their core business. It is questionable whether these

regulators would initially have the knowledge base and technical capabilities to regulate the safety of the design, construction, commissioning and operation of an FPP. Whilst HSE has regulated the occupational health and safety of JET for the last forty years, and EA has regulated radioactive waste discharges over the same period, the regulation of an experimental fusion facility is not the same as regulating the design, construction, commissioning and operation of a full scale FPP for electricity generation, primarily due to the inventories involved in each. However, it should be recognised that HSE and EA/NRW/SEPA would be capable of acquiring additional technical competence if this option is pursued. **Score 3**.

8.3.3.6 Ring-Fenced Resources

"Regulators must have sufficient human and financial resources. These should be ring-fenced and allocated to the regulation of the industry to which the regulations apply."

The regulation of FPPs is not the core business of either HSE or the environmental regulators; however, all have the powers to levy charges for their regulatory activities. The challenge would be if it could be guaranteed that the income from the charges would be ring-fenced with the respective organisations. Past history would suggest that this is not easy. For example, the inability to ring-fence NII's income in HSE led to the removal of NII from HSE and the creation of ONR. **Score 3**.

8.3.3.7 Industry Focus

"The regulatory framework should enable regulators to be focused on the sector to be regulated in order to understand the technology and the industry. Generalised regulatory systems applied to a variety of industries tend to be ineffective in hazardous industries."

As regulating FPPs is not the core business of HSE or the environmental regulators, it is unlikely that FPP regulation would feature highly at board level in these regulatory organisations. Given that FPPs are based on a nuclear process and, if inadequately designed and operated, can result in an off-site release of radioactive materials that would result in emergency countermeasures, having an industry focused regulator would have many advantages. Applying a generalised regulatory system such as that proposed under Option 3 is unlikely to provide the required regulatory focus. **Score 2**.

8.3.3.8 Public Confidence

"The regulatory framework must assure the public that the hazard and hence the risk to them is being managed properly by the organisation operating the facility. Public confidence comes from knowing the regulator is independent, competent and has the necessary powers to control activities including the power to halt operations."

Public confidence is hard gained but easily lost. ONR and its predecessor NII gained considerable public confidence because of its technical expertise and robust regulatory approach. As discussed above, fusion is a nuclear process and it is naive to assume that the public will not recognise this and expect it to be regulated by the UK's nuclear regulator. It is difficult to see the public accepting a generalised regulatory system for FPPs, particularly where the regulators have come under criticism for their regulatory approach [227]–[230]. The public will most likely want assurances that FPPs are being regulated by a technically competent regulator that understands and is focused on the technology. The regulatory approach proposed in this option is unlikely to deliver this. **Score 2**.

8.3.3.9 Political Confidence

"The regulatory framework must give the politicians confidence that technology needed to deliver national goals, such as security of supply and climate change goals, can be relied on. Politicians also need to be assured that major accidents with the potential to derail the delivery of these goals will be prevented not only to prevent undue risk to the public but also to minimise the cost to the treasury of any accident recovery and clean-up costs."

As discussed above, political confidence in the regulatory system is driven by the ability of the regulatory system to prevent accidents that have the potential to both cause public concern and have high clean-up costs. In addition, politicians will want to be assured that any new energy technology for deployment in the UK to support security of supply and low carbon goals will have public support. Accidents that result in the release of radioactive materials have the potential to undermine public confidence; hence, the effectiveness of the regulatory system is vital. The regulatory framework surrounding occupational health and safety/environmental permitting is clearly less stringent, less focused and less predictable than the nuclear licensing regime and this could be of concern to politicians. **Score 2**.

8.3.3.10 International Obligations

"The UK has certain obligations under international treaties and conventions. The regulatory framework should ensure that the regulation is consistent with these obligations."

The nuclear safety and security international obligations do not currently extend to FPPs, but there is active international debate around the inclusion of FPPs into IAEA's remit. If there is international consensus that FPPs are to be included, then the UK's regulatory approach will need to recognise this. Under the current nuclear licensing regime, nuclear installations are regulated by ONR and ONR directly reports to the Secretary of State for Business, Energy and Industrial Strategy (BEIS) for any nuclear incidents involving nuclear safety, security, safeguards and emergency preparedness[2]. Therefore, if FPPs are designated as nuclear installations, regulation by ONR would be consistent with international obligations.

If FPPs are not designated as nuclear installations, the main UK obligation would be with respect to safeguards. As discussed above, ONR has responsibility for safeguards, not HSE or the environmental regulators. If there were a breach of the UK's international safeguards obligations, then it would be the Secretary of State for BEIS that will have to answer for this in Parliament.

Option 3 presents a number of complications. If FPPs were designated as nuclear installations by IAEA (as is likely) and the UK opted to regulate FPPs via Option 3, the absence of a clear nuclear regulator could be problematic, especially as ONR is held in such high regard in IAEA. The reporting of breaches in the UK's obligations would also be problematic. The Secretary of State for BEIS is responsible for reporting breaches to IAEA; however, under Option 3 the regulation of FPPs would be split between HSE, reporting to the Secretary of State for Work and Pensions, and EA, reporting to the Secretary of State for Environment, Food and Rural Affairs for FPPs in England (or the NRW reporting to the Welsh Government in Wales or SEPA reporting to the Scottish Government in Scotland). As the breach could have resulted from deficiencies in design or operation, BEIS would not be able to seek assistance from ONR on nuclear safety or security, so new reporting arrangements would need to be developed between BEIS, DWP, DEFRA, and the Welsh

[2]Note ONR reports to the Department for Work and Pensions (DWP) for matters including finance, governance and non-nuclear health and safety

and Scottish governments. Even if FPPs were not regarded as nuclear installations, the UK would still have safeguards obligations and given that the breach could have resulted from deficiencies in design or operation, resolution could require complicated interactions between ONR, HSE and the appropriate environmental regulator. **Score 3**.

Total score for Option 3 = 25/50

8.3.4 Analysis of Option 4 - Proportionate Regulation Approach

This option is a proportionate nuclear site licensing approach for FPPs in which FPPs are regulated by ONR for nuclear safety, security, safeguards and industrial health and safety. The environmental regulators would be responsible for the regulation of routine radioactive discharges and the disposal of radioactive waste. It is proportionate to the extent that the nuclear site licensing requirements reflect the hazard potential of an FPP. In this approach FPPs would be prescribed as nuclear installations and therefore the NIA would include fusion-based activities; however, the LCs that can be attached to FPP nuclear site licences in the interests of safety and the management of radioactive waste may not necessarily be the same as those that are attached to nuclear site licences for NPPs or fuel cycle facilities. A new set of LCs could be developed, in consultation with industry, to ensure that all activities that contribute to the effective management of nuclear safety are regulated in a proportionate way. The general duties of the HSWA would apply as would the IRRs, REPPIR, CDM Regulations, etc., but these would be regulated by ONR. The EPR would also apply and be regulated by the environment regulators as is the case for current nuclear licensed sites.

The suitability of this option to regulate FPPs is discussed below in relation to the 10 regulatory principles.

8.3.4.1 Independence

"The regulator must be independent of the industry being regulated and independent of those in government that sponsor the industry being regulated."

Under Option 4, ONR would regulate the whole life cycle of FPPs (whilst EA/NRW/SEPA would regulate routine discharges). As stated previously, ONR is entirely independent of the nuclear industry and of those in government that sponsor the nuclear industry. **Score 5**.

8.3.4.2 Proportionality

"The regulatory burdens on the operator (and designers) are proportionate to the hazard potential of the facility being regulated. Regulatory control via permissioning hold points should be balanced against the consequences of failure. The higher the consequence the greater the regulatory control/intervention. Safety case substantiation should be commensurate with the hazard potential of the facility being regulated."

The UK's nuclear site licensing regime is primarily goal setting and hence it allows the licensee/licence applicant to develop LC arrangements that are proportionate to the hazard potential of the activity being regulated. This option would allow ONR, in consultation with the fusion industry, to develop a new set of LCs to ensure that all activities that contribute to the effective management of nuclear safety in an FPP are regulated in a proportionate way. Once the LCs have been agreed, the licensee/licence applicant would be free to develop compliance arrangements that reflect the hazard potential. It would be for the licensee/licence applicant to demonstrate to ONR that their arrangements were adequate. The fusion industry would also be free to develop an FPP-specific suite of design guidelines for nuclear safety, security, safeguards and environmental protection that are proportionate to the hazard potential. ONR would also be free to develop an FPP-specific set of assessment principles that covered nuclear safety, security and safeguards. Together the FPP "SAPs" and design guidelines would provide a proportionate and transparent regulatory framework.

This approach would also allow ONR and the licensee/licence applicant to agree a regulatory schedule to identify regulatory hold points and required levels of regulatory documentation that are again proportionate to the hazard potential of FPPs. **Score 5**.

8.3.4.3 Effectiveness

"Regulation must be effective and efficient in order to minimise regulatory burdens associated with both programme delays and direct regulatory costs. For example, ONR regulates nuclear safety, security, safeguards, transport of nuclear and radioactive materials, and industrial health and safety on nuclear licensed sites."

Under Option 4, ONR would be responsible for regulating all aspects of FPPs except for routine

discharges. This single regulator approach should ensure efficient and efficient regulation, minimise potential regulatory burdens associated with programme delays and reduce regulatory costs. In addition, ONR's resources allocated to the regulation of FPPs would be expected to be proportionate to the hazard potential. As the hazard potential of FPPs is significantly lower than that of NPPs, it is not unreasonable to assume that ONR would require fewer resources to both assess documentation submitted by the licensee/licence applicant and to undertake routine inspection activities. **Score 5**.

8.3.4.4 Regulatory Certainty

"The demands from regulation need to be transparent and predictable. Regulatory certainty requires regulatory oversight of the whole cycle from cradle to grave. Investors, owners and operators need to have confidence that when they commit to a build programme there will not be unexpected regulatory demands."

Similar to the current nuclear site licensing regime, Option 4 would enable ONR to regulate FPPs from the design stage through operation to decommissioning. This approach would enable ONR and the licensee/licence applicant to agree a regulatory schedule to identify regulatory hold points and the required regulatory documentation submission dates. This, together with ONR's approval of the licensee's/licence applicant's Pre-Construction Safety Report (required before construction can commence), should give confidence in the design and provide certainty that no unexpected regulatory demands will be made during construction or commissioning that could delay the project and increase costs. **Score 5**.

8.3.4.5 Technical Competence

"Regulators must have the engineering, scientific and technical resources to be capable of assessing the adequacy of the operator's safety, security and other regulatory documentation in order to permission activities."

As in Options 1 and 2, it is expected that due to the operational experience ONR has in regulating nuclear installations, it has the necessary engineering, scientific and technical resources to be capable of assessing the adequacy of an FPP operator's safety documentation in order to permission major activities. However, it is recognised that ONR may initially need to recruit additional staff with fusion technology expertise. **Score 4**.

8.3.4.6 Ring-Fenced Resources

"Regulators must have sufficient human and financial resources. These should be ring-fenced and allocated to the regulation of the industry to which the regulations apply."

Option 4 requires the NIA to include fusion power. Under the act ONR recovers its costs from the licensee and, as regulating nuclear installations is ONR's core business, it is expected that ONR will be able to ring-fence its income to ensure the provision of sufficient resources to regulate FPPs. **Score 5**.

8.3.4.7 Industry Focus

"The regulatory framework should enable regulators to be focused on the sector to be regulated in order to understand the technology and the industry. Generalised regulatory systems applied to a variety of industries tend to be ineffective in hazardous industries."

ONR has experience regulating all manner of nuclear installations and as the nuclear sector makes up ONR's core business, it is entirely focused on the sector and understands the industry. **Score 5**.

8.3.4.8 Public Confidence

"The regulatory framework must assure the public that the hazard and hence the risk to them is being managed properly by the organisation operating the facility. Public confidence comes from knowing the regulator is independent, competent and has the necessary powers to control activities including the power to halt operations."

Regulating FPPs under a nuclear licensing regime should provide the public with confidence that the technology is being properly controlled by a competent and independent nuclear regulator (ONR) and that the regulator has appropriate powers to control licensees' activities. Explaining the proportionate approach that is applied to FPPs should enable the public to understand that whilst FPPs are being regulated as nuclear installations, the hazard potential of FPPs is significantly lower than NPPs and that there is no likelihood of a catastrophic release of radioactivity from accidents at FPPs. **Score 5**.

8.3.4.9 Political Confidence

"The regulatory framework must give the politicians confidence that technology needed to deliver national goals, such as security of supply and climate change goals, can be relied on. Politicians also need to be assured that major accidents with the potential to derail the delivery of these goals will be prevented not only to prevent undue risk to the public but also to minimise the cost to the treasury of any accident recovery and clean-up costs."

As discussed above, political confidence in the regulatory system is driven by the ability of the regulatory system to prevent accidents that have the potential to both cause public concern and result in high clean-up costs. In addition, politicians will want to be assured that any new energy technology for deployment in the UK to support security of supply and low carbon goals will have public support. Option 4 provides the assurance of a nuclear site licensing regime that has stood the test of time in the UK that is administered by a well-respected and competent nuclear regulator. The adoption of a proportionate regulatory approach should also give politicians confidence that no undue regulatory burdens are being imposed on the fusion power industry. **Score 4**.

8.3.4.10 International Obligations

"The UK has certain obligations under international treaties and conventions. The regulatory framework should ensure that the regulation is consistent with these obligations."

Regulating FPPs under a proportionate nuclear site licensing regime with ONR as the regulator should enable the UK to comply with is international nuclear safety, security and safeguards obligations. Regulating FPPs under this approach would also be consistent with current and potential future obligations under international treaties and conventions. Having ONR as the sole regulator for nuclear safety, security and safeguards at FPPs clarifies reporting lines to the Secretary of State for BEIS and avoids the difficulties identified with Option 3. **Score 5**.

Total score for Option 4 = 48/50

8.3.5 Selecting an Appropriate Regulatory Framework

The above analysis is summarised in the following table.

Regulatory Approach	Independence	Proportionality	Effectiveness	Regulatory Certainty	Technical Competence	Ring-Fenced Resources	Industry Focus	Public Confidence	Political Confidence	International Obligations	Total
Option 1	5	2	2	5	4	5	5	4	5	5	**42**
Option 2	5	3	3	5	4	5	5	4	5	5	**44**
Option 3	5	2	2	1	3	3	2	2	2	3	**25**
Option 4	5	5	5	5	4	5	5	5	4	5	**48**

Table 8.1: Grading regulatory options against each criterion

It is clear that Option 4, a proportionate nuclear site licensing approach, scored the highest when assessed against the 10 regulatory principles. A proportionate nuclear site licensing regime will provide an effective and efficient approach to regulation. ONR is a well-respected and trusted nuclear regulator with a track record of good proportionate regulation and will give both the public and the politicians the confidence that FPPs are being properly regulated and that risks are under control. Option 4 also enables a cradle to grave approach to be developed for FPP regulation; hence, it provides regulatory certainty for investors owners and licensees/licence applicants.

A proportionate licensing framework also enables licensees/licence applicants to engage with ONR to develop an appropriate set of LCs that reflect the hazard potential of FPPs. The licensees/licence applicants are also free to develop LC compliance arrangements that are proportionate to the hazard potential. Option 4 also allows licensees/licence applicants to work with ONR to develop a proportionate regulatory schedule and it allows the UK to effectively and efficiently meet its international nuclear safety, security and safeguards obligations.

Options 1 and 2 (the regulation of FPPs using an NPP approach and fuel cycle facilities approach, respectively) scored highly in relation to many of the regulatory principles; however, these regulatory approaches, especially Option 1, would result in regulatory requirements and regulatory oversight that are disproportionate to the hazard potential of FPPs. They would result in overly burdensome, ineffective and inefficient regulation that could adversely affect the commercial viability of a useful

low-carbon energy technology.

Option 3, the regulation of FPPs as non-nuclear radiation facilities using conventional industrial health and safety/environmental permitting legislation, scored the lowest when tested against the 10 regulatory principles. The major weaknesses in allowing FPPs in the UK to be regulated by HSE and the environmental regulators were associated with regulatory effectiveness, regulatory certainty, industry focus, and public and political confidence. FPPs are complex power plants, fuelled by a radioactive material and with a nuclear driven primary heat source. FPPs are not accelerators, industrial neutron generators or research facilities; hence, the application of conventional industrial health and safety/environmental permitting legislation could be considered to be disproportionately lax.

FPPs are facilities that could be located near or within industrial centres or large populations; therefore, they require proper regulation. Some countries have decided to regulate FPPs in the same way as they regulate NPPs. The international nuclear community is actively engaged in thinking about fusion regulation and the UK has an ideal opportunity to play a leading role in the development of the regulatory approach to this new and emerging technology and promote a proportionate nuclear site licensing approach.

Chapter 9

Development of a Licensing Regime for FPPs in the UK

This chapter looks at the application of the UK's nuclear site licensing regime to FPPs and what changes will be needed to implement an FPP licensing regime.

9.1 Background

The analysis in Chapter 8 showed that the most appropriate regulatory framework for FPPs would be one based on a proportionate nuclear site licensing regime. This chapter sets out how a proportionate licensing regime for FPPs can be developed in the UK. This includes looking at what the key elements of a proportionate licensing regime should be, how these elements could be implemented, what legal options are available, which LCs could be attached to a nuclear site licence for FPPs and what permissioning powers should be granted to the regulator to control licensees' activities.

9.2 Key Elements of a Proportionate Licensing Regime for FPPs

The fundamentals of nuclear safety regulation were discussed in Section 7.5.3. The work in this thesis has shown there is no reason why these fundamentals should not apply to the regulation of FPPs within a proportionate framework. The key goal of a proportionate approach to regulation is to ensure that the licensing regime provides suitable control over licensees' activities without placing undue burdens on licensees, vendors or designers. A licensing regime provides regulatory certainty,

but the regulatory requirements must be designed in such a way that they are proportionate to the hazard potential. What will differ in the case of FPPs when compared with NPPs or nuclear fuel cycle facilities will be the safety, security and safeguards performance requirements (Standards and Guidance) for FPPs. A new set of requirements such as those developed for NPPs by IAEA could be developed for FPPs. Also, in the case of the UK's nuclear site licensing approach, the set of conditions attached to the licence need not be the same as those currently applied to NPPs or fuel cycle facility licences (as discussed in Section 7.5.3).

9.2.1 Fundamental Regulatory Principles for FPPs

To evaluate the application of a nuclear site licensing regime to FPPs, the following fundamental regulatory principles (RPs) have been used.

RP1 - There should be a clear legal framework for the licensing of FPPs

RP2 - The regulatory process should be clear and predictable

RP3 - There should be a technically competent and independent regulator for nuclear safety, security and safeguards

RP4 - The regulator should have the power to grant nuclear site licences

RP5 - The regulator should have the power to attach conditions to nuclear site licences in the interests of nuclear safety or security

RP6 - The regulator should have appropriate enforcement powers including the power to halt activities in the interests of nuclear safety, security or safeguards

RP7 - There should be appropriate penalties for non-compliance

RP8 - A nuclear site licence should be required to construct or operate an FPP

RP9 - Only a fit and proper organisation with the necessary financial and technical resources should obtain a nuclear site licence

RP10 - The licensee should be responsible for nuclear safety and security

RP11 - Permission from the nuclear regulator should be required in advance of undertaking major activities that could affect nuclear safety or security

RP12 - Permission to undertake a major nuclear safety or security related activity should depend upon adequate supporting documentation submitted by the licensee

RP13 - The rigour of supporting documentation should be proportionate to the hazard potential of the activity

The application of these fundamental principles and the reasons they are essential to a regulatory framework for FPPs are discussed below together with what actions would be necessary to implement each fundamental.

9.2.1.1 RP1 - There should be a clear legal framework for the licensing of FPPs

Currently, there is a clear legal framework for the licensing of nuclear installations. No person may construct or operate a nuclear installation without obtaining a nuclear site licence from the nuclear regulator (ONR). A licence may only be obtained by a corporate body and ONR will only grant a nuclear site licence once it is satisfied that the licence applicant has sufficient human and financial resources required to ensure the safe operation of the site. At the time of granting a nuclear site licence, ONR will attach 36 licence conditions (LCs) in the interests of nuclear safety or the management of radioactive waste. The licensee must adhere to all obligations within these conditions or face penalties for non-compliance. Permission from ONR is required before undertaking any major activity that may impact safety and ONR has appropriate enforcement powers including the power to halt licensees' activities. Having a transparent regulatory framework such as this clearly sets out the roles and responsibilities of all parties (licence applicant/licensee/operator/regulator) and allows little room for misinterpretation. When dealing with a nuclear technology such as those found in nuclear installations, it is paramount that these roles and responsibilities are clear so that the health and safety of workers and the public is protected. It also helps provide the public and politicians with confidence that the technology is being managed properly.

Given that FPPs are expected to have radioactive inventories that, if released under severe accident scenarios, could result in emergency countermeasures being implemented, it is critical that the licensing of FPPs also comes under a clear, comprehensible legal framework. This ensures that any person planning to construct an FPP or use fusion technologies is aware of their legal obligations and

that the health and safety of the public is protected. Having a clear legal framework for the licensing of FPPs will also help provide the public and politicians with confidence that fusion technologies are being managed appropriately. For nuclear installations, legislation and regulations are usually drawn out from IAEA guidelines and international requirements. It seems reasonable to suggest that IAEA should develop similar guidelines for the effective licensing of FPPs, to ensure that all nations planning to deploy an FPP programme have some commonalities in approach.

The UK's nuclear site licensing regime, operated in a proportionate way, would satisfy this principle.

9.2.1.2 RP2 - The regulatory process should be clear and predictable

It is crucial that the regulatory process for the licensing of FPPs is clear and predictable. As argued previously, investors, owners and operators need to have confidence that when they commit to a build programme there will not be unexpected regulatory demands. Ensuring there is regulatory oversight of the whole cycle from cradle to grave eliminates the risk that licensees will be close to completing construction and are then informed that major modifications will be required in order to obtain regulatory approval arising from a late regulatory review, which could incur significant cost and delay the project.

For nuclear installations, a regulatory schedule is agreed between the licensee and ONR so that all parties have a clear understanding of what is required at each stage. Given the nascent stage of the fusion industry and the need for regulation to be efficient and effective, it seems reasonable to suggest that this process is mirrored in the licensing of FPPs. The FPP licensee/licence applicant and ONR will need to agree to a regulatory schedule to identify regulatory hold points and the required regulatory documentation submission dates. This will not only provide regulatory certainty and ensure that there will not be unexpected regulatory demands, but it will also provide the public and politicians with confidence that the technology is being managed appropriately.

The UK's nuclear site licensing regime, operated in a proportionate way, would satisfy this principle.

9.2.1.3 RP3 - There should be a technically competent and independent regulator for nuclear safety, security and safeguards

FPPs are complex facilities with significant inventories of radioactive material that, if released under severe accident scenarios, could result in emergency countermeasures being triggered. In addition, they will require significant levels of engineering substantiation and defence in depth measures in order to ensure that significant releases of radioactive material are extremely unlikely. Due to this, it seems reasonable to suggest that the regulator of FPPs must have the engineering, scientific and technical resources to be capable of assessing the adequacy of the operator's safety or security documentation in order to permission activities. The public and politicians will want assurances that the technology is being properly controlled, and they will want a technically competent regulator to not only regulate the day to day activities of FPPs but also ensure that the licensee is competent and is capable of being the *Controlling Mind* of operations and an *Intelligent Customer* of services that it buys in.

As argued in Section 8.3, a single regulator regulating nuclear safety, security and safeguards ensures an efficient approach to regulation and avoids the deficiencies in approach that comes with different regulators each regulating separate functions. Due to its experience successfully regulating nuclear installations and the technical competence it has accrued, ONR is best placed to regulate nuclear safety, security and safeguards at FPPs to a high standard.

Giving ONR the responsibility for regulating FPPs (as detailed below) would satisfy this principle.

9.2.1.4 RP4 - The regulator should have the power to grant nuclear site licences

Currently, no person may construct or operate a nuclear installation without obtaining a licence, and only the independent nuclear regulator (ONR) has the power to grant nuclear site licences. This requirement that only ONR has the ability to grant licences is a fundamental part of the nuclear regulatory framework, as it provides a separation of responsibilities between the government (who are responsible for the advancement of nuclear energy) and the organisation responsible for granting licences. Without this, there is potential for conflicts of interest and scenarios where nuclear site licences may be granted in situations where the licence applicant has not demonstrated that the licence is justified.

For nuclear installations, this fundamental is enforced through the wording of the NIA which states "no person may use a site for the purpose of installing or operating any nuclear reactor... or any other installation of a prescribed kind, unless a licence to do so has been granted in respect of the site by the appropriate national authority" [167]. To implement this fundamental for fusion, FPPs would need to be prescribed as a type of licensable installation under the NIA (see Section 5.5). In the UK, this can be achieved by a government department drafting a statutory instrument (SI), a type of secondary legislation, which is then laid in Parliament and debated by ministers before being approved or rejected. Note most SIs are negative SIs which do not need active approval by parliament; these are usually signed by the minister before being laid in Parliament and will automatically come into effect as law after a fixed period (usually 40 days) unless either House stops them within this time.

Following this process would enable ONR to licence FPPs and hence this would satisfy this principle.

9.2.1.5 RP5 - The regulator should have the power to attach conditions to nuclear site licences in the interests of nuclear safety or security

The set of 36 licence conditions (LCs) currently attached to nuclear site licences are generally split into two functions: setting out specific legal requirements (i.e. marking the site boundary) and goal setting objectives that envelope all the activities needed to effectively manage nuclear safety and the management of radioactive waste. These LCs are essential to the nuclear licensing regime as they set out the goals to be delivered and the responsibilities the licensee must adhere to in order to safely manage the facility - any breach of the LCs is a breach of the law and the regulator has a range of enforcement powers at its disposal to deal with non-compliance including the power to halt operations and to provide evidence to the prosecuting authorities for criminal prosecutions. The LCs cover the design, construction, commissioning, operation and decommissioning of each facility on a nuclear licensed site, ensuring there is regulatory oversight over the entire life cycle (cradle to grave). This level of regulatory oversight is vital in providing the public and politicians with confidence that the technology is being properly controlled.

Given the hazard potential and radioactive materials associated with FPPs, it is vital that the regulator has the power to attach LCs to nuclear site licences for FPPs also. However, whereas

the current set of LCs for nuclear installations only covers nuclear safety and the management of radioactive waste, it seems reasonable to suggest that a new set of LCs developed for FPPs should cover nuclear security as well. This way, all of the licensee's obligations required to effectively manage the facility and mitigate any nuclear safety or security issues can be found in one place. It also allows for security measures to be built in at the design stage and allows an integrated approach to managing nuclear safety and security. The current regulatory framework for nuclear installations does not allow this as the NIA does not allow conditions to be attached in the interests of nuclear security. Regulation of nuclear security is currently covered by the NISR [130]. Incorporating nuclear safety and security features into a single set of LCs all regulated by ONR would lead to more efficient and effective regulation.

For nuclear installations, this fundamental is enforced through Section 4 of the NIA which states "the appropriate national authority must... attach to it such conditions... in the interests of safety" [167]. To allow the regulator to attach conditions to nuclear site licences for FPPs in the interests of safety only, all that would need to happen is an SI would need to pass in which FPPs are prescribed as licensable installations under the NIA (see RP4). To allow the regulator to attach conditions in the interests of nuclear security also, Section 4 of the NIA would need to be amended to allow conditions to be attached in the "interests of safety and security" [167]. In addition, the NISR would need to be amended to exclude all installations located on a nuclear licensed site (including FPPs), and parts of the EnA relating to nuclear security may also need to be amended.

If the above changes can be made, the NIA would enable ONR to deliver this principle.

9.2.1.6 RP6 - The regulator should have appropriate enforcement powers including the power to halt activities in the interests of nuclear safety, security or safeguards

An essential component of a licensing regime is that the regulator must have appropriate enforcement powers to hold the duty holder to account in the event of non-compliance with regulatory requirements, including the power to halt activities if any requirements are contravened. As argued previously, these powers are crucial in providing the public and politicians with confidence that the technology is being properly controlled. For nuclear installations, ONR can make use of a variety of powers including primary powers, derived powers and enhanced implementation monitoring and

control (EIM&C). These are granted either through the wording of the NIA or LCs attached to a nuclear site licence, or through the licensee granting ONR administrative 'powers' to permission selected activities on the licensed site [182].

As detailed in Section 7.2.4, the different types of powers that ONR has at its disposal for controlling the activities on nuclear licensed sites are used for activities with a range of hazard potentials. Primary powers are generally used for higher hazard potential activities such as the start-up of a reactor or a major design modification; as such, they are intrusive and potentially restrictive. Derived powers are more flexible and can combine with primary powers to control things like the design, construction and commissioning of new facilities on a nuclear licensed site. EIM&C is used to permission activities which are of lower safety significance and the use of derived powers would be considered disproportionate.

Given the radiological inventories expected in FPPs and their potential to trigger emergency countermeasures if released, it is reasonable to suggest that ONR has the full range of powers at its disposal to establish the necessary regulatory control. The power to grant a licence or consent to the start-up of a reactor are both types of primary powers. Under a proportionate licensing regime, ONR will require the ability to do both of these things, not only to ensure the risks to the health and safety of workers and the public are sufficiently low, but in order to assure the public and politicians that it has an appropriate level of regulatory control over licensees' activities. These features will be discussed further in Section 9.4.

For nuclear installations, primary powers are granted through the wording of the NIA or LCs attached to the nuclear site licence, and derived powers and EIM&C are generally granted through through the development of the licensee's arrangements and where appropriate a regulatory schedule between the licensee and ONR. For FPPs, in order for ONR to have the full range of enforcement powers at its disposal, the NIA will need to include fusion power (see RP4) which will allow LCs to be attached to nuclear site licences for FPPs and a regulatory schedule will need to be developed between the licensee and ONR that sets out the relevant permissioning hold points and the enforcement powers ONR will be granted to deal with non-compliance (see Section 9.4).

If the changes suggested for RP4 and RP5 could be made (see above), the NIA would enable ONR

to deliver this principle.

9.2.1.7 RP7 - There should be appropriate penalties for non-compliance

For nuclear installations, ONR enforcement can range from "advice by inspectors to warnings, letters, notices, use of powers under the licence conditions and other nuclear safety, security and safeguards legislation or prosecutions" [182]. Due to the high hazard potential of nuclear installations and the significant radiological consequences should something go wrong, it is crucial that ONR has appropriate penalties available for licensees that breach regulatory requirements. Penalties are in place to ensure that any persons who breach regulatory requirements are held to account [182]. For example, under the NIA any person who breaches an LC attached to a nuclear site licence is liable to "imprisonment for a term exceeding 2 years, or a fine, or both" [167]. This not only applies to primary powers; any arrangements made under the LCs are legally binding and failure to comply with the arrangements is regarded as a breach of the law.

If the changes suggested for RP4 and RP5 could be made (see above), the NIA would enable ONR to deliver this principle.

9.2.1.8 RP8 - A nuclear site licence should be required to construct or operate an FPP

As argued above, FPPs are facilities with radiological inventories that, if released under certain accident scenarios, could result in emergency countermeasures being implemented. Due to this, it seems reasonable to ensure that no one is allowed to construct or operate an FPP without first obtaining a licence. This allows the regulator to assess the safety (and possibly the security) of the design to ensure that risks to workers and the public have been reduced so far as is reasonably practicable and that construction, commissioning, operation and decommissioning can be controlled to ensure that throughout the entire life cycle risks are adequately controlled. This approach also ensures that the licence applicant has the capability to be the Controlling Mind and an Intelligent Customer when it is in control of the nuclear licensed site.

For nuclear installations, this fundamental principle is delivered through the wording of the NIA which states "no person may use a site for the purpose of installing or operating any nuclear reactor... or

any other installation of a prescribed kind unless a licence to do so has been granted is respect of the site by the appropriate national authority" [167].

If the changes suggested for RP4 and RP5 could be made (see above), the NIA would enable ONR to deliver this principle.

9.2.1.9 RP9 - Only a fit and proper organisation with the necessary financial and technical resources should obtain a nuclear site licence

As argued above, FPPs are complex facilities with significant radiological inventories and nuclear safety issues that require real time mitigation tactics and significant levels of protection and defence in depth (see Chapter 4). Given this, it seems reasonable to demand that only a fit and proper organisation, with appropriate levels of financial and technical resources, can be granted a nuclear site licence for an FPP. At this stage it is questionable whether licensees of FPPs should require the same level of technical and financial resources as licensees of NPPs. Licensees of NPPs are required to take out nuclear liability insurance to cover the costs associated with an accident, with a maximum liability for operations now at €1.2 billion (an increase from the previous level of €163 million) [231]. In the UK, the nuclear liability regime is set out in the NIA, implementing the international Paris Convention (Convention on Third Liability in the Field of Nuclear Energy of 1960) [232] and Brussels Convention (Brussels Supplementary Convention on Nuclear Third Party Liability of 1963) [233]. These measures are required due to the high hazard potential of NPPs.

Chapter 6 has demonstrated that FPPs have radioactive material that, if released under severe accident scenarios, may result in countermeasures being implemented. However, the radiological consequences of a release from an FPP are significantly reduced when compared to a release from an NPP. Any tritium or activated dust that is potentially released from an FPP disperses significantly as it moves away from the site, resulting in significantly reduced doses at large distances (e.g. beyond 8 km). It is unlikely that releases from FPPs could give rise to cross-boundary consequences; hence, it is unlikely that FPPs would be required to comply with the Paris or Brussels Conventions, meaning licensees of FPPs should not have to concern themselves with an international liability regime.

If the changes suggested for RP4 and RP5 could be made (see above), the NIA would enable ONR to deliver this principle.

9.2.1.10 RP10 - The licensee should be responsible for nuclear safety and security

Within the goal setting, proportionate nuclear site licensing regime being proposed here, it is key that the licensee has the freedom to develop arrangements for managing safety in a way that is proportionate to the hazard potential of an FPP. In the UK, the licensee has the responsibility for safety under the law and, as discussed previously, the goal setting regime allows the licensee to determine the areas that will impact safety and allows the licensee to develop its own solutions and arrangements for managing safety. The same argument can be made for managing nuclear security. Incorporating nuclear security into a proportionate nuclear site licensing regime allows security measures to be built in at the design stage and ensures the licensee's LC arrangements provide an integrated approach to the management of both nuclear safety and security. This should also increase regulatory efficiency as all of the licensee's obligations regarding nuclear safety and security are found in one place.

If the changes suggested for RP4 and RP5 could be made (see above), the NIA would enable ONR to deliver this principle.

9.2.1.11 RP11 - Permission from the nuclear regulator should be required in advance of undertaking major activities that could affect nuclear safety or security

Chapter 6 demonstrated that FPPs are expected to have inventories of radioactive material that, if released under severe accident scenarios, could result in emergency countermeasures being implemented. Given this, it seems reasonable to expect that permission from a competent and independent regulator would be required in advance of undertaking major activities that may affect safety or security, such as the commencement of construction, operation or modification of the facility. There are numerous examples of accidents being caused by failure to adequately control modification activities, such as the Flixborough chemical plant disaster in 1974: hasty equipment modification coupled with a major leak caused a massive fuel-air explosion, killing 28 people [234].

If the changes suggested for RP5 could be made (see above), the amended NIA would enable ONR to deliver this principle.

9.2.1.12 RP12 - Permission to undertake a major nuclear safety or security related activity should depend upon adequate supporting documentation submitted by the licensee

For nuclear installations, ONR will only grant permission for the licensee to undertake a major safety related activity if it is satisfied with the safety documentation submitted by the licensee prior to the activity in question. This safety documentation forms part of the safety case and must demonstrate that the activity being proposed will be carried out safely, that a full range of risks and hazards have been assessed and that suitable controls and safety measures are in place. Generally, the higher the hazard potential of the activity being proposed, the more robust the safety documentation submitted to ONR for approval will need to be. If the activity being proposed is low hazard potential and hence likely to have lower risk, the safety documentation can be less exhaustive. It seems reasonable to adopt a similar approach for permissioning activities on nuclear licensed sites for FPPs. ONR's Safety Assessment Principles (SAPs) and Technical Assessment Guides (TAGs) enable ONR inspectors to provide consistent assessment of a licensee's safety documentation. Whilst much of the content in these documents could be applicable to FPPs, it seems reasonable to expect that, should ONR be the regulator for FPPs, a distinct set of SAPs and TAGs will be developed for FPPs.

If the changes suggested for RP4 and RP5 could be made (see above), the NIA would enable ONR to deliver this principle.

9.2.1.13 RP13 - The rigour of supporting documentation should be proportionate to the hazard potential of the activity

As detailed above, permission to undertake a major safety or security related activity should only be granted if the regulator is satisfied with the adequacy of the documentation submitted by the licensee. In a proportionate licensing regime, it is essential that the rigour of this supporting documentation is proportionate to the hazard potential of the activity being proposed. For an activity that has a high hazard potential, there should be significant levels of documentation highlighting the identified hazards and protection measures in place to mitigate against them. For an activity that has a low hazard potential, the levels of documentation detailing the levels of engineering substantiation can be less robust. This way, the regulator and licensee are not wasting resources (time and cost) preparing

and reviewing considerable levels of supporting documentation for activities that pose minimal risk to workers and the public. Effective and efficient regulation requires both the regulator and licensee to identify which activities have a high hazard potential and which have a low hazard potential and to allocate resources accordingly.

As above, this principle could be achieved by the fusion industry producing a set of standards and guides for the design, construction, commissioning, operation and decommissioning of FPPs.

9.3 Required Amendments to UK Legislation

Implementing a licensing regime for FPPs in the UK only requires a few changes to current legislation. As discussed in Section 5.5 and above, ensuring FPPs come under the *Nuclear Installations Act 1965* (NIA) and therefore require a nuclear site licence to construct or operate does not require any amendments to the Act itself. However, ensuring FPPs come under safeguards obligations will require an amendment to the *Nuclear Safeguards Act 2018* (NSA18) and, if the regulation of nuclear security is to be covered by nuclear site licensing, both the NIA and the *Nuclear Industries Security Regulations 2003* (NISR) - and potentially parts of the EnA dealing with nuclear security - will need to be amended. The aim here is to explore the amendments to current UK legislation and who will be required to enforce the legislation.

9.3.1 Nuclear Installations Act 1965 (NIA)

The NIA [167] sets out the requirement that no person can install or operate a nuclear installation without a licence. The Act then establishes that the designated authority (ONR) can attach conditions (LCs) to a nuclear site licence in the interests of safety. The NIA therefore gives the regulator the powers to control the design, construction, commissioning, operation and decommissioning of each facility on a nuclear licensed site. Currently, the NIA doesn't apply to FPPs. However, as discussed in Section 5.5, it would be straightforward for a government department or minister to draft an SI that prescribed FPPs as a type of licensable installation under Part 1(3)(a) of the NIA. Once passed, this would ensure that FPPs would require a licence to construct or operate.

Whilst prescribing FPPs as a type of licensable installation under the NIA would not require an amendment to the Act itself, the Act currently grants the designated authority the power to attach

conditions "in the interests of safety" only. To allow the set of LCs developed for FPPs to cover nuclear safety and security, it is suggested that the Act is amended so that conditions can be attached "in the interests of safety and security" [167].

Making the above changes to the NIA and prescribing FPPs as licensable facilities will enable all of the duties and obligations within the NIA (and by extension the EnA) to apply to FPPs and ensure that a nuclear site licence would be required for the construction and operation of an FPP.

9.3.2 Nuclear Safeguards Act 2018 (NSA18)

The NSA18 [138] sets out certain domestic provisions on nuclear safeguards and, crucially, defines the types of facilities that are required to implement safeguards measures following the implementation of *The Nuclear Safeguards (EU Exit) Regulations 2019* [139] (these Regulations came into force on 31st December 2020). Currently, the NSA18 doesn't apply to FPPs as they are not classed as a "qualifying nuclear facility"; similarly, tritium is not classed as a "qualifying nuclear material" [138]. As argued in Section 4.9, given the inventories of tritium expected at FPPs and the fact that breeder blankets can be adapted to breed fissile material, it seems reasonable to amend the NSA18 so that safeguards obligations are also applied to "qualifying fusion facilities" and "qualifying fusion material" (e.g. tritium). This would ensure that the robust safeguards measures that are applied to nuclear fuel cycle facilities and NPPs are also applied to FPPs, such as granting regulatory inspectors access to the facility to ensure no fissile material is being produced and stringent accountancy measures over stockpiles of tritium to ensure none is being unlawfully diverted.

9.3.3 The Nuclear Industries Security Regulations 2003 (NISR)

The NISR sets out the requirement that a security plan must be drawn up for each facility on a nuclear licensed site and that arrangements are in place to ensure the physical protection of all nuclear material; however, it currently doesn't apply to FPPs as they are not situated on nuclear licensed sites and tritium is not classed as a nuclear material. If FPPs are prescribed as a type of nuclear installation under the NIA, then the NISR will by default apply to FPPs as they will be on nuclear licensed sites. However, if (as recommended above), the regulation of nuclear security is to be covered by nuclear site licensing, the NISR will need to be amended as to exclude facilities

located on nuclear licensed sites from its remit. This will allow all measures regarding nuclear safety and security to be covered by an integrated set of LCs attached to nuclear site licences which should allow for more effective and efficient regulation.

9.4 Cradle-to-Grave Regulatory Control via Permissioning

The work in this thesis has shown that FPPs have a hazard potential that warrants robust regulatory oversight. A key part of this involves ensuring that there is regulatory oversight over all stages of the life cycle of FPPs from the design stage to decommissioning - a cradle to grave approach. This not only provides assurances to the public and politicians that the health and safety of the public is protected at all times, but it also provides investors, owners and operators with certainty that there will not be unexpected regulatory demands further down the line.

Regulatory control is usually achieved through the use of permissioning hold points - stages of the project where work cannot progress until safety documentation (the safety case) has been submitted to the regulator and the regulator is satisfied that the licence applicant/licensee has the necessary arrangements in place to ensure the health and safety of workers and the public is protected. Given the reduced hazard potential of FPPs compared with NPPs, it is expected that the level of permissioning hold points and associated safety documentation would be lower for FPPs.

Whilst the actual level of permissioning hold points will depend significantly on the perceived hazard potential of FPPs, this section will explore what levels of permissioning may be appropriate in a proportionate licensing regime based on current understanding.

9.4.1 Design

There are two options here: a direct licensing route (discussed below) or a design certification approach. The latter would be appropriate if a fleet of FPPs based upon the same design was being proposed. Licensing FPPs under a proportionate regime provides investors, owners and operators with regulatory certainty and reduces the risk of project delays and cost overruns. A key component of this is ensuring the design of the facility has obtained regulatory approval before construction

commences. This minimises the risk that unexpected regulatory demands will arise further down the line, potentially incurring considerable cost and lead times. The first step in this process is the submission of a Preliminary Safety Report (PSR) which includes a description of the facility and its operation, a summary of the main hazards and the measures in place to control them. Note the PSR generally does not include a detailed design; this is submitted later. The main purpose of the PSR is to demonstrate the main safety principles and show that there are no major "showstoppers". If ONR is satisfied with the PSR, the licence applicant/licensee can proceed and produce a more detailed Pre-Construction Safety Report (PCSR). If the facility is on a new site, the licence applicant will need to submit its PCSR and other safety related documentation and apply for a nuclear site licence. Construction cannot commence until the licence has been granted. If the proposed FPP is on an existing nuclear licensed site, the licensee will need to submit its PCSR and ONR, when satisfied, will give Consent to commence construction. A regulatory schedule is generally agreed between the licensee/licence applicant and ONR to identify any necessary hold points during the construction and commissioning stages.

9.4.2 Licensing and Commencement of Construction

As argued above, in a proportionate licensing regime it is crucial that there is a permissioning hold point, either by the granting of a new site licence or providing a Consent on an existing nuclear licensed site, prior to the construction stage as it provides investors, owners and operators with regulatory certainty that no unexpected regulatory demands will be required further down the line, potentially adding substantial cost. Submitting a PCSR to ONR allows the licensee to demonstrate that the plant can be constructed with minimal risk of design change and minimal risk to the health and safety of workers and the public. As FPPs are expected to require an environmental permit, making the PCSR available to EA/NRW/SEPA will enable them to assess the design in relation to the minimisation of routine discharges and allow them to comment on the minimisation of radioactive waste that would require disposal.

9.4.3 Inactive Commissioning

At this stage, it is unclear whether a proportionate licensing regime for FPPs should include a permissioning hold point at the inactive commissioning stage. This stage is generally used to assess

the piping, electrical wiring, pressure testing, valves etc., and at this stage there should be no radioactive material on site. For NPPs, the hold point is in place so ONR can assess the licensee's inactive commissioning schedule. Given the reduced hazard potential of FPPs, it may be that these items can be tested through less onerous means (such as routine inspections) and a hold point prior to this stage is not justified given the hazard potential. Further work is needed in this area.

9.4.4 Active Commissioning

Active commissioning is important as it not only involves introducing bulk quantities of nuclear/ radioactive material (tritium) onto site for the first time, but it also involves testing the production of a D-T plasma. At this point, the licensee needs to demonstrate that it is ready to deal with radioactive materials and it has the necessary arrangements in place to ensure the trials can be carried out safely and the staff are suitably qualified and experienced persons and adequately trained to undertake their tasks. The licensee will also need to demonstrate that it has sufficient security measures in place to deter potential saboteurs and secure the inventories of tritium. The introduction of tritium at this stage may also require a discharge authorisation and hence an environmental permit. To progress past this hold point, the licensee will need to submit a Pre-Commissioning Safety Report (PCmSR) to ONR and will require an environmental permit from the environmental regulator.

The application of proportionate regulation would enable the licensee to agree with the regulator its arrangements for conducting the commissioning process, including the first introduction of tritium into the plasma. The D-T plasma not only introduces radioactive tritium into the plasma chamber, potentially exposing workers to radioactive material, but the fusion process produces neutrons with considerable energies which will potentially expose workers and the public to ionising radiation. Before granting a Consent to commence active commissioning, ONR will likely require the licensee to demonstrate it has sufficient control over the fusion process (e.g. plasma control and plasma shutdown procedures), as well as substantial protection measures and defence in depth to ensure the risk to the health and safety of workers and the public is acceptably low. These requirements will be covered in the PCmSR and the licensee's LC commissioning arrangements.

9.4.5 Routine Operation

As with an NPP, the commencement of routine operation for an FPP is an important regulatory milestone. Hence, an FPP licensee will require a Consent from ONR to commence routine operation for the first time. This stage represents the state that the plant will be in the majority of the time (barring shutdowns); as such, the majority of safety issues identified in Chapter 4 can occur during this stage. During this stage significant levels of tritium will be cycled through the plant and recycled, large amounts of neutrons with considerable energies will bombard the VV walls producing inventories of activated structural materials, and erosion of plasma facing components will produce substantial inventories of activated dust. The licensee will therefore need to demonstrate to ONR, through a Pre-Operations Safety Report (POSR), that it is sufficiently prepared to safely carry out operations at the plant. The POSR is a major document that underpins the safety of the operation of the plant. It is the basis of the operating rules and instructions that maintain the plant in its safe working state and is the foundation of the emergency operating procedures to be adopted in the event of an accident. The document should also demonstrate how any outstanding hazards/safety issues identified previously have been resolved. Before granting a licensee permission to commence operation, ONR will want the licensee to demonstrate that all of these items have been considered and that the licensee is prepared to deal with any issues that may arise.

9.4.6 Plant Outages and Major Modifications

To restart operations following a major plant shutdown at an NPP (either for safety reasons or statutory maintenance), the licensee must receive ONR's Consent that operations may resume. This is achieved through LC30 and is enforced through ONR invoking a primary power. For NPPs this level of regulatory oversight is justified: NPPs typically shutdown for refuelling and statutory maintenance between every 18 and 36 months of operation (depending on reactor type). For FPPs this level of regulatory oversight is probably not justified and restart procedures could form part of the licensee's operating procedures that are required under LC arrangements.

Plant shutdowns for maintenance such as breeder blanket replacement could be dealt with in a proportionate way under LC arrangements. The radioactive inventories in the VV and its surrounding components are likely to be reduced once the blanket has been replaced, as much of the tritium

and activated radioisotopes present in the old blanket will be transferred to the hot cells. Therefore, placing a permissioning hold point prior to a plant restart for these operations would not be proportionate. However, control over major modifications to an FPP, which if inadequately conceived or implemented could challenge the original safety case, would warrant a proportionate hold point. Again, the exact circumstances that would require ONR permissioning could be agreed between the licensee and ONR to ensure an appropriate proportionate level of regulation.

9.4.7 Periodic Safety Reviews

Licensees of NPPs must undertake periodic safety reviews at various points throughout the plant's life. These are comprehensive studies to evaluate the impact of changes in safety standards since the previous periodic safety review (usually 10 years) and to look ahead 10 years ahead to identify any life limiting features that could affect nuclear safety. This then allows the safety of the future operation of the facility to be evaluated. Periodic safety reviews are a vital component of managing safety at NPPs. As safety standards and operating practices are advancing all the time, it is essential that licensees of NPPs stay up to date with these to ensure the long-term safe operation of the facility. Periodic safety reviews are implemented through LC15 which requires the licensee to "make and implement adequate arrangements for the periodic and systematic review and reassessment of safety cases" [235]. For NPPs, if the periodic safety review is not completed on time the plant is shutdown; LC30 ensures that operations do not resume unless the licensee has received ONR's Consent.

Given that safety standards and operating practices are continually being updated, and FPPs are complex facilities with significant inventories of radioactive material, it would be proportionate for LC15 requirements to apply to FPPs (see below) and that licensees of FPPs be required to undertake periodic safety reviews. For FPPs, a proportionate approach could allow the licensee to evaluate the implications of the periodic safety review and only notify ONR if there were major safety related implications for continued operation. ONR would then determine if further regulatory action was necessary to control any required plant upgrades.

9.4.8 Plant Closure and Decommissioning

For NPPs, the licensee is required to have an arrangement to enable the safe decommissioning of the plant. NPPs are also required to take decommissioning into account at the design stage. Whilst detailed designs for FPPs are not yet available, it is expected that at the end of their life FPPs will have significant levels of intermediate level radioactive waste due to the tritium that has migrated into structural components and the neutron-induced activation that occurs in structural materials. For NPPs, ONR requires the licensee to produce a Pre-Decommissioning Safety Report (PDmSR). As the commencement of decommissioning is an important stage in the life cycle of an FPP, it would be proportionate to have a permissioning hold point prior to the decommissioning stage so that ONR is satisfied that the PDmSR demonstrates that decommissioning can be undertaken without increasing the risk to workers or the surrounding public. The extent of the safety justification in the PDmSR will depend upon the residual hazard potential at the end of life. It may be the case that designers of FPPs develop low activated materials and utilise restoring processes such that the hazard potential and radioactive inventories present at the time of decommissioning are low. If this was the case there would be no requirement for significant documentation or regulatory oversight of decommissioning activities.

9.5 FPP Licence Conditions

The UK's flexible nuclear site licensing regime allows regulatory control via a combination of primary powers, such as granting a licence for a nuclear facility and conditions attached to the licence. The application of the set of conditions that could be attached to an FPP nuclear site licence is discussed below. As argued in Section 7.5.3, LCs developed for FPPs need not be the same LCs that were developed for other nuclear installations. The aim of this section is to evaluate each of the LCs currently attached to nuclear site licences for nuclear installations and determine their applicability to FPPs.

9.5.1 Role of Licence Conditions

As detailed earlier, conditions that are attached to a nuclear site licence in the UK's nuclear site licensing regime are intended to envelop all the activities that are needed to effectively manage nuclear

safety and the management of radioactive waste. The set of 36 LCs that are currently attached to nuclear site licences can be grouped into either prescriptive conditions (which set out specific legal requirements) and goal setting conditions (which enable the licensee to develop its own arrangements to deliver the required goal). The LCs set out a licensee's duties and responsibilities; a breach of the obligations within the LCs is a breach of the law. The LCs cover the design, construction, commissioning, operation and decommissioning of the facility, ensuring there is regulatory oversight over the entire life cycle (cradle to grave). As argued in Section 9.2.1.5, whereas the current set of LCs for nuclear installations omits nuclear security, it seems practical to propose that the LCs attached to nuclear site licences for FPPs cover nuclear safety and security (and the management of radioactive waste). This way, all of the licensee's obligations required to effectively manage the facility and mitigate any nuclear safety or security issues can be built into an integrated management system.

9.5.2 Prescriptive Conditions

LC1 - Interpretation - LC1 is essentially a list of definitions for words and phrases referred to throughout the other LCs. This LC would be relevant for FPPs, and no part would need to be amended.

LC5 - Consignment of nuclear matter - LC5 states that the licensee may not "consign nuclear matter to any place... without the **consent** of ONR" [235]. Given that the radioactive inventories at an FPP contain tritium, activated dust and radioactive waste, there should be a record of where these materials are being consigned to for safety, security and safeguards reasons. It seems reasonable and proportionate to retain this LC for FPPs.

LC8 - Warning notices - LC8 requires the licensee to ensure that "suitable and sufficient notices" are displayed on site [235]. This LC would again be proportionate for FPPs, and no part would need to be amended.

LC9 - Instructions to persons on the site - LC9 states the licensee must ensure that "every person authorised to be on the site receives adequate instructions... as regards the risks and hazards associated with the plant and its operation..." [235]. Given the radioactive inventories and safety

issues associated with FPPs, this LC is again proportionate and no part would need to be amended.

LC13 - Nuclear safety committee - LC13 requires the licensee to establish a nuclear safety committee (NSC) to advise on "all matters required by or under these conditions" and safety matters on or off the site [235]. Given the radioactive inventories and safety issues associated with FPPs, it seems reasonable to suggest that licensees of FPPs should also establish a safety committee. This LC is again proportionate but if security was included in the licensing process, parts of the wording of this condition would need to be changed to give the NSC the responsibility for nuclear security as well.

LC16 - Site plans, designs and specifications - LC16 instructs the licensee to submit a plan of the site to ONR that includes the "location of the boundary of the licensed site and every building or plant on the site which may affect safety" [235]. Given the radioactive inventories and safety issues associated with FPPs, it would be proportionate to retain this LC for nuclear site licences for FPPs. However, minor changes would be needed to ensure the condition covers nuclear security activities.

LC18 - Radiological protection - LC18 instructs the licensee to make an "assessment of the average dose" to employees and members of the public and to notify ONR if the average effective doses exceed pre-defined levels [235]. It is questionable whether this LC would be necessary for FPPs as the intent is covered by the obligations within the IRRs, which licensees of FPPs will already be obligated to comply with. Under the IRRs, the duty holder must carry out radiation risk assessments and ensure employees and other persons are not exposed to ionising radiation to an extent that a pre-defined dose limit is exceeded in a calendar year (see Section 5.5.5.2). It could be argued that the inclusion of this LC is simply mirroring the obligations already found in the IRRs and would therefore be redundant. However, the LC was included following recommendations of the public inquiry into Sizewell B PWR and exclusion could give the impression that worker safety was of lesser importance. Hence, on balance the LC could be retained without impacting unduly on the licensee.

LC23 - Operating rules; LC24 - Operating instructions; LC25 - Operational records - These LCs instruct the licensee to "identify the conditions and limits necessary [for operation] in the interests of safety", to "ensure that all operations which may affect safety are carried out in accordance with written instructions" and to keep "adequate records... of the operation, inspection

and maintenance of any plant which may affect safety" [235]. Given the radioactive inventories and safety issues associated with FPPs, it seems reasonable to retain each of these LCs for nuclear site licences for FPPs. However, as argued earlier, if security was to be included in the licensing regime, this LC would need to be amended to include nuclear security. This way, licensees will be required to identify conditions and limits necessary for operation in the interests of safety and security and any operations which may affect safety and security will be carried out in accordance with written instructions.

LC26 - Control and supervision of operations - LC26 ensures that "no operations are carried out which may affect safety except under the control and supervision of suitably qualified and experienced persons" [235]. Given the radioactive inventories associated with FPPs, it would be proportionate to retain this LC for nuclear site licences for FPPs. As above, if security was to be included in the licensing regime, this LC could also be amended to cover operations which may affect nuclear security.

LC27 - Safety mechanisms, devices and circuits - LC27 ensures that "a plant is not operated, inspected, maintained or tested unless suitable and sufficient safety mechanisms, devices and circuits are properly connected and in good working order" [235]. Given the hazard potential of FPPs, it is again proportionate to retain this LC for nuclear site licences for FPPs. As above, if security was to be included in the licensing regime, this LC could also be amended to cover mechanisms associated with nuclear security.

LC29 - Duty to carry out tests, inspections and examinations - LC29 requires the licensee to carry out "tests, inspections and examinations [specified in LC28]" of all equipment and processes which "may affect safety" and wherever ONR may **specify** [235]. Given the radiological inventories and the risks and hazards expected at FPPs, it would be proportionate to retain this LC for a nuclear site licence for an FPP. As above, if security was to be included in the licensing regime, this LC could also be amended to cover equipment and processes which may affect nuclear security.

LC30 - Periodic shutdown - LC30 requires that, for the purposes of "examination, inspection, maintenance or testing", if a plant is required to be shut down in accordance with its maintenance schedule, it cannot be "started up again thereafter without the **consent** of ONR" [235]. This LC is

restrictive as it places a permissioning hold point prior to the restarting of a plant following shutdown that is required by the plant maintenance schedule and enforces this through invoking a primary power. For NPPs this level of regulatory oversight is justified due to the potentially catastrophic consequences of an uncontrolled release of radioactive material. As FPPs have a much lower hazard potential than FPPs, however, this level of regulatory oversight may not be justified for the restarting of an FPP following such shutdowns (see Section 9.4.6). This is an important condition, but to ensure proportionality guidance should be given to ONR inspectors in relation to the circumstances that would require ONR to Specify that a Consent is required to restart after a periodic shutdown.

LC31 - Shutdown of specified operations - LC31 requires that the licensee, if directed by ONR, must "shut down any plant, operation or process on the site" and cannot restart the plant, operation or process "without the **consent** of ONR" [235]. This LC is crucial in ensuring ONR has adequate control over the licensee's activities on a nuclear licensed site. If ONR directs a licensee to halt activities due to a risk to the health and safety of workers or the public, it is vital that the licensee does not then restart activities without ONR's Consent as this could be putting workers and the public at risk. Given the hazard potential of FPPs, it is essential that this LC is also applied to nuclear site licences for FPPs. In the context of public and political confidence that the technology is being adequately controlled, the retention of this LC is proportionate.

LC33 - Disposal of radioactive waste - LC33 requires the licensee to, if directed by ONR, "ensure that radioactive waste accumulated or stored on the site is disposed of as ONR may **specify** and in accordance with an environmental permit" [235]. Given that FPPs are expected to produce large quantities of intermediate level radioactive waste that will need to undergo recycling processes or be moved to long-term storage, it is again proportionate to retain this LC for nuclear site licences for FPPs to prevent the build up of radioactive waste on site when alternative disposal/storage routes are available.

LC34 - Leakage and escape of radioactive material and radioactive waste - LC34 requires the licensee to "ensure, so far as is reasonably practicable, that radioactive material and radioactive waste on the site is at all times adequately controlled or contained so that it cannot leak or otherwise escape from such control or containment" [235]. Given the radioactive inventories expected at FPPs,

it is proportionate to retain this LC for nuclear site licences for FPPs.

9.5.3 Goal Setting Licence Conditions

LC2 - Marking of the site boundary - LC2 instructs the licensee to "make and implement adequate arrangements to prevent unauthorised persons from entering the site" by marking "the boundaries of the site by fences or other appropriate means" [235]. This LC is to control access to a nuclear licensed site and ensure members of the public are aware that they are entering a nuclear site where certain legal obligations apply. Again, given the thermonuclear process driving FPPs and the inventories of radioactive material expected at FPPs, it is proportionate to retain this LC for nuclear site licences for FPPs. The arrangements that the licensee is required to make should be relatively straightforward in relation to fencing and control of access and should cover nuclear safety and security requirements.

LC3 - Control of property transactions - LC3 requires the licensee to control property transactions affecting any part of the site to ensure that the licensee remains in overall control of the site and that any new buildings or structures not owned by the licensee will not adversely affect safety. The inclusion of this LC seems relevant and proportionate to FPPs, and no part would need to be amended.

LC4 - Restrictions on nuclear matter on the site - LC4 stipulates that no nuclear matter should be brought onto the site unless in accordance with "adequate arrangements" made by the licensee [235]. LC4 states "for new installations, if ONR so **specifies**, the licensee shall ensure that no nuclear matter... is brought onto site for the first time without the **consent** of ONR" [235]. Bringing and storing nuclear matter (nuclear fuel in the case of an NPP, tritium for an FPP) on a site under controlled conditions is important for nuclear safety and security reasons. For a new nuclear site it is an important milestone: it marks the transition from a construction site to one where additional nuclear safety and security requirements come into force. The words "specifies" and "consent" are clear invocations of the primary powers that ONR has at its disposal. At this point, the licensee needs to demonstrate that it is prepared to deal with nuclear materials, and it has the necessary arrangements in place. Placing a permissioning hold point here seems both reasonable and proportionate for FPPs.

LC6 - Documents, records, authorities and certificates - LC6 requires the to licensee keep "adequate records to demonstrate compliance" with all LCs [235]. Keeping documents and records that are relevant to nuclear safety, security and safeguards is essential and hence retaining this LC is both reasonable and proportionate for FPPs.

LC7 - Incidents on the site - LC7 requires the licensee to ensure adequate arrangements are in place for the "notification, recording, investigation and reporting" of incidents on site [235]. This LC is again proportionate for FPPs, and no part would need to be amended.

LC10 - Training - LC10 requires the licensee to implement "adequate arrangements for suitable training for all those on site who have responsibility for any operations which may affect safety" [235]. Given the radioactive inventories and safety issues associated with FPPs, the inclusion of this LC is relevant and proportionate. However, if security was to be included in the licensing regime, the LC would need to be amended to incorporate training for any operations which may affect nuclear security .

LC11 - Emergency arrangements - LC11 requires the licensee to "make and implement adequate arrangements for dealing with any accident or emergency arising on the site and their effects" [235]. For nuclear installations, the obligations under LC11 are focused on accidents or emergencies that require an on-site or off-site response. For off-site emergencies, the licensee's arrangements go beyond REPPIR but are consistent when relevant to REPPIR [175]. Licensees of NPPs must produce comprehensive emergency plans and liaise with local authorities to map out a detailed emergency planning zone in which countermeasures can be applied to limit radiation exposure. These measures are taken due to the potentially catastrophic consequences of a release of radioactive material from an NPP and are controlled through ONR invoking the primary powers Approval and Specify. As argued in Section 7.2.2.3, it may be the case that FPP designers build in sufficient protection systems and reduce radioactive inventories to such an amount that an emergency planning zone is not required. However, emergency preparedness is to provide assurance that should things fail there are measures in place to mitigate the consequences whether for on-site or off-site events; therefore, retention of this LC is necessary and proportionate. For FPPs, the off-site consequences will be considerably less than for NPPs and hence the necessary arrangements would be expected to be

simpler.

LC12 - Duly authorised and other suitably qualified and experienced persons - LC12 requires the licensee to make arrangements to ensure that "only suitably qualified and experienced persons perform any duties which may affect the safety of operations..." [235]. Given the radioactive inventories and safety issues associated with FPPs, this LC is both relevant and proportionate. However, if security was to be included in the licensing regime, the LC would need to be amended to include nuclear security.

LC14 - Safety documentation - LC14 requires the licensee to "make and implement adequate arrangements for the production and assessment of safety cases consisting of documentation to justify safety during the design, construction, manufacture, commissioning, operation and decommissioning phases of the installation" [235]. Again, this LC is both reasonable and proportionate for FPPs. However, if security was to be included in the licensing regime, the wording of the LC would need to be amended to include nuclear security documentation.

LC15 - Periodic review - LC15 requires the licensee to perform "periodic and systematic reviews and reassessments of safety cases" [235]. As shown above, reviewing the adequacy of the safety case for an FPP at regular intervals is essential to reflect changes in standards and knowledge and to look forward to identify any life limiting effects. As such, the inclusion of this LC for FPPs is proportionate. As with other LCs above, if security was to be included in the licensing regime, this LC would need to be reworded to include nuclear security.

LC17 - Management systems - LC17 requires the licensee to "establish and implement management systems which give due priority to safety" [235]. Given the radioactive inventories and safety issues associated with FPPs, it is again relevant and proportionate to retain this LC for FPPs. As above, if security was to be included in the licensing regime, this LC would need to be amended to include nuclear security.

LC19 - Construction or installation of new plant - For NPPs, LC19 requires that the licensee has adequate control of its construction to ensure that it is built in accordance with the requirements set out in the PCSR. It enables a licensee to split construction into stages and, where ONR specifies,

the licensee cannot "proceed from one stage to the next of the construction or installation [of any new plant which may affect safety] without the **consent** of ONR" [235]. This LC allows ONR to place a permissioning hold point prior to the commencement of construction stage and the licensee cannot progress past this stage without ONR's Consent. Given the radioactive inventories and safety issues associated with FPPs, it is relevant and proportionate to retain this LC for FPPs. As above, if security was to be included in the licensing regime, this LC would need to be amended to include nuclear security.

LC20 - Modification to design of plant under construction - LC20 is there to control modifications made to the design of a plant that is under construction by requiring the licensee to have adequate arrangements to control design changes. The LC gives ONR the powers to permission design changes in the interests of safety and hence require the licensee to justify that the change will not adversely affect safety. This LC is again relevant and proportionate for FPPs; however, if security was to be included in the licensing regime, the LC would need to be amended to include modifications that could affect nuclear security.

LC21 - Commissioning - Similar to LC19, LC21 requires that, where ONR specifies, the licensee cannot "proceed from one [commissioning] stage to the next... without the **consent** of ONR" [235]. As FPPs will contain inventories of tritium which, if accidentally released, could result in countermeasures being implemented, it seems reasonable to place a permissioning hold point prior to the active commissioning stage (see Section 9.4). Therefore, this LC is again both relevant and proportionate for FPPs.

LC22 - Modification or experiment on existing plant - LC22 requires the licensee to "implement adequate arrangements to control any modification or experiment carried out on any part of the existing plant or processes which may affect safety" [235]. Where ONR specifies, the licensee cannot "proceed from one stage to the next of the modification or experiment without the **consent** of ONR" [235]. The control of modifications is vitally important to ensure effective safety management of hazardous installations; hence, the inclusion of this LC for FPPs is relevant and proportionate. As above, if security was to be included in the licensing regime, this LC would need to be amended to include modifications which may affect nuclear security.

LC28 - Examination, inspection, maintenance and testing - LC28 requires the licensee to "make and implement adequate arrangements for the regular and systematic examination, inspection, maintenance and testing of all plant which may affect safety" [235]. Given the radiological inventories expected in FPPs, it is relevant and proportionate to retain this LC for FPPs. As above, if security was to be included in the licensing regime, this LC would need to be amended to include nuclear security related plant and equipment.

LC32 - Accumulation of radioactive waste - LC32 requires the licensee to "make and implement adequate arrangements for minimising so far as is reasonably practicable the rate of production and total quantity of radioactive waste accumulated on the site" [235]. Given that FPPs are expected to produce large quantities of intermediate level waste that will need to undergo recycling processes or be moved to long-term storage (or both), this LC is relevant and proportionate for FPPs.

LC35 - Decommissioning - LC35 requires the licensee to "implement adequate arrangements for the decommissioning of any plant or process which may affect safety" [235]. Where ONR specifies, the licensee cannot "proceed from one [decommissioning] stage to the next... without the **consent** of ONR" [235]. As argued in Section 9.4, given the large quantities of intermediate level waste expected at the end of life of an FPP, it would be proportionate to have a permissioning hold point prior to the decommissioning stage so ONR is satisfied that the PDmSR demonstrates the health and safety of workers and the public is protected. It is therefore relevant and proportionate to retain this LC for FPPs; however, if security was to be included in the licensing regime, the wording of the LC would need to be amended to include nuclear security.

LC36 - Organisational capability - LC36 requires the licensee to "maintain adequate financial and human resources to ensure the safe operation of the licensed site" [235]. The key word is adequate and hence the licensee can make arrangements that are proportionate to the hazard potential. LC36 requires the licensee to make and implement arrangements for the control of organisational change and it gives ONR the power to "halt the change to its [the licensee's] organisational structure or resources... without the **consent** of ONR" [235]" [235]. Section 9.2.1.9 has argued the importance of ensuring the licensee is a fit and proper organisation and has appropriate financial and human resources to construct and operate an FPP safely. It also demonstrated that it is unlikely that

licensees of FPPs will require the same level of financial resources as licensees of NPPs, as the hazard potential of FPPs is much lower and licensees of FPPs will most likely not need to concern themselves with an international liability regime. However, control to prevent potentially damaging changes to financial resources or organisational structures that are needed to maintain safety is important and would be proportionate; hence, this LC should be retained for FPPs.

9.6 Proportionate Licensing

9.6.1 Conditions Attached to FPP Site Licences

As shown above, all of the LCs that are currently applied to nuclear site licences in the UK are considered appropriate for application to FPPs. Having the same set of LCs should help provide the public and politicians with confidence that FPPs are under appropriate control. However, a graded approach can be applied to the scope and application of the "adequate arrangements" that are required under the goal setting conditions.

Also, as many of the LCs give powers to the regulator (ONR) to control the licensee's activities, there is also the potential to provide a graded regulatory approach in relation to the range of circumstances in which ONR would use its regulatory powers via the use of Directions, Specifications, Consents, Agreements and Approvals. Guidance could be developed for ONR inspectors to set expectations and criteria for when powers are used that are proportionate to the hazard potential of FPPs. As discussed above, a new set of SAPs and TAGs could be produced for ONR inspectors to reinforce proportionality. Given the nascent stage of the fusion industry and the collective need for the deployment of FPPs to be as quick and as straightforward as possible, it is vital that regulatory intervention is only permitted at times when the hazard potential justifies it and that regulatory powers are used proportionately. This will allow designers and licensees the freedom to develop various designs and processes whilst also ensuring the health and safety of workers and the public is protected.

9.6.2 Safety and Security Documentation Requirements

Many of the current LCs give powers to the regulator to require the licensee to submit safety documentation prior to the activity for which the LC is associated can take place. It has already

been suggested above that FPPs should be subject to nuclear site licensing. If this is accepted, then nuclear safety or security documentation (and potentially a combination of the two) will need, when requested, to be submitted to ONR prior to any activity which may majorly affect nuclear safety or security. The purpose of this documentation will be to demonstrate the adequacy of the proposed engineering substantiation arguments and defence in depth measures. As argued previously, given the reduced hazard potential of FPPs when compared with NPPs, the extent of the engineering substantiation required can be reduced in the case of FPPs. A new set of Standards and Guidance will need to be developed for FPPs that reflect the reduced hazard potential. This is a key element of the "proportionate" component of a proportionate FPP site licensing regime., It allows for effective and efficient regulation where the amount of resources allocated to activities is proportionate to the hazard potential.

9.7 Other Approaches

Whilst this chapter has mapped out what a proportionate licensing framework for FPPs could look like in the UK with ONR as the regulator for nuclear safety, security and safeguards, other approaches should be considered in which there is a different (perhaps new) regulator for FPPs. There is some concern within the fusion industry that due to ONR's experience regulating fission-based installations, it may not be able to adjust appropriately to regulating a new technology and may be tempted to rely on fission-based approaches that are disproportionate to the hazard potential of FPPs. Whilst this criticism is perhaps overblown (ONR has experience regulating a wide range of facilities with varying hazard potentials from small research reactors to fuel cycle facilities to NPPs, and applies proportionate regulation to each depending on its hazard potential), it may be worthwhile to evaluate the benefits and drawbacks of developing a new, bespoke regulator for FPPs to avoid the potential drawbacks with relying on ONR. However, if a new regulator is developed, it begs the question why spend the time and resources developing and implementing a new regulator with a similar skill set to the highly regarded ONR?

Part VI

Part VI - Conclusion and Recommendations

Chapter 10

Conclusion and Recommendations

This project aimed to answer the question of how FPPs should be regulated in the areas of nuclear safety, security and safeguards. To answer this question, research was undertaken to identify and evaluate:

- the characteristics of FPPs and their supporting technologies
- the key nuclear safety, security and safeguards issues for FPPs
- the potential off-site release of radioactive materials in accident conditions to scope the hazard potential of FPPs
- international approaches to FPP regulation
- the current UK legal infrastructure for regulating hazardous industries
- the UK approach to licensing nuclear installations
- the UK options for regulating FPPs

This chapter draws together the key findings from the work performed in researching this thesis; it provides the answer to the question and makes recommendations for future work.

10.1 Key Findings from Nuclear Safety Issues for FPPs

In Chapter 4, a number of FPP safety issues were reviewed together with their impact on public safety. The key safety issues identified were:

- loss-of-coolant to breeder blanket and divertor
- loss-of-coolant to vacuum vessel
- loss of cooling during transfer of blanket sectors
- electromagnetic discharges
- production of WO_3
- hydrogen and dust explosion
- fire in the tokamak building
- fire in the tritium plant
- lack of component failure rate data

Whilst many of these safety issues were considered in the ITER RPrS and it was reported that none of them would result in significant off-site radiological consequences, in these scenarios it is assumed that many of the safety and protection systems (e.g. the detritiation systems) operate as intended (i.e. mitigated risk). When scoping the hazard potential, it is necessary to consider the radiological consequences without relying on safety and protection systems operating as intended (i.e. unmitigated risk). Moreover, the increased complexity and potentially increased size of commercial FPPs means that the consequences of these accident scenarios may be more severe and further work is needed to determine the consequences to workers and the public. Matters such as the production of chemically toxic WO_3 due to air ingress into the VV or the consequences of a loss of cooling during the transfer of blanket sectors were not taken into account in the ITER RPrS and further work is needed in these areas to determine the risk to workers and the public. The radiological consequences of external hazards such as earthquakes and aircraft impact should determine the levels of engineering measures in place to protect against them. If the consequences are tolerable, enhanced design requirements to protect against them would not be justified on safety grounds; however, they may be included for asset protection reasons.

The large gaps in component failure rate data is a significant issue for the robust safety analysis and engineering substantiation that will be needed for FPPs. This is especially true for the new fusion-specific systems that are being developed (e.g. plasma control systems and negative ion

neutral beam injectors). Without robust failure rate data, the probabilities of potential accidents will be based on engineering judgement rather than hard data. This will impact on the robustness of the design and of the necessary supporting safety cases. Without a detailed knowledge of how likely an accident is, the risk approach to safety becomes less robust and subject to uncertainty. The current development of a fusion-specific database is aiming to combat this potential weakness. The work at ITER aims to fill in many of the gaps but more work needs to be focused in this area. The production of a robust system and component failure rate database should be a main priority in the coming years to enable the early delivery of FPPs.

It is argued by some that FPPs have such a low hazard potential that they should be regulated in line with non-nuclear radiation facilities such as accelerators (see Section 7.4). However, the work reported in Chapter 4 has shown that FPPs will require substantial engineering systems and defence in depth measures in order to ensure that in the event of a potential accident scenario the radiological consequences to workers and the public remain at tolerable levels. It is clear that FPPs have challenging nuclear safety issues that need to be addressed in the design and operation of the facility. Many of the engineering systems will be safety critical and hence will require robust engineering that will need to be substantiated via a rigorous safety case.

10.2 Key Findings from Nuclear Security Issues for FPPs

Section 4.7 mapped out the key nuclear security issues that will need to be taken into account if FPPs are to be successfully deployed. The key security issues were:

- loss-of-coolant event (LOCE)
- direct attack on the vacuum vessel
- control of tritium / sabotage of tritium plant
- political consequences associated with terrorist occupation of an FPP

Given the security issues and the radioactive inventories expected at FPPs, it seems reasonable to suggest there will need to be some form of physical protection at FPPs in order to deter any potential saboteurs. The large inventories of tritium that will be stored and cycled through the tritium plant seem a likely target for any attackers: the tritium plant will likely be much more accessible than

the VV and a large release of the tritium inventory can result in significant off-site radiological consequences. As discussed, tritium can also be used to boost the effectiveness of nuclear weapons. It therefore seems reasonable to suggest that there should be significant security measures protecting the inventories of tritium from terrorists or other activists.

From the work reported in Section 4.7, it is clear that FPPs are not benign installations. Rather, they are complex facilities with large inventories of radioactive material that, if released by terrorists or other activists, can have a significantly harmful effect on the public. In order to assure the public and politicians that FPPs are secure and the health and safety of workers and the public is protected, it is expected that FPPs will require physical protection, advanced surveillance systems, restricted access, robust cybersecurity and personnel vetting (insider threat), amongst other security measures.

10.3 Key Findings from Nuclear Safeguards Issues for FPPs

Section 4.9 mapped out the key nuclear safeguards issues associated with FPPs. The key safeguards issues were:

- control over tritium inventories
- clandestine production of fissile material in an undeclared facility
- covert production of fissile material in a declared facility
- use of a declared facility in a breakout scenario

As discussed in Section 4.9, inventories of tritium are currently not controlled under any safeguards obligations. However, as highlighted above, inventories of tritium may be diverted to be used in nuclear weapons. If FPPs are to be successfully deployed, it therefore seems sensible to implement a safeguards regime around inventories of tritium to ensure that they are not diverted for malicious aims.

Safeguards measures also cover sensitive information and technologies, especially dual-use technologies. From the work reported in Section 4.9, it is clear that fusion technologies can be used to breed fissile materials and hence will require the application of robust safeguards measures. These

will likely include monitoring seals to ensure tampering has not occurred, ensuring all breeder blanket modules are inspected for fertile material and routine inspections to ensure no fissile material production is taking place will be necessary to ensure that the proliferation risks are kept low.

10.4 Key Findings from Mapping International Approaches to Fusion Regulation

Chapter 5 mapped out the international approaches to regulating FPPs and showed that there is currently no agreed view as to how FPPs should be regulated. A lack of IAEA guidance on the matter has contributed to nations adopting or proposing to adopt different approaches to regulating FPPs. Whilst it is expected that IAEA will publish guidance on how best to regulate FPPs in the near future, there is a risk that countries pressing ahead with FPP technologies may be locked in less than optimum regulatory solutions.

Countries such as France and Canada have already determined that FPPs will be regulated under the same framework as NPPs and other civil nuclear installations. FPPs are to be classed as BNIs and Class 1A nuclear facilities in France and Canada, respectively. These approaches may result in designers of FPPs having to include strict arrangements for managing safety that are considered appropriate for NPPs (considering the potentially catastrophic consequences of an accident resulting in a release of radioactive material), but are not proportionate given the significantly reduced hazard potential of FPPs. Whilst the regulatory frameworks for nuclear installations in France and Canada are primarily goal setting, there is the risk that regulating FPPs in a similar manner to NPPs will require designers of FPPs to take into account certain criteria when demonstrating the safety of FPPs, such as significant levels of defence in depth, diverse and redundant protection systems, and ensuring the facility is built to withstand earthquakes, floods, aircraft impact and other external hazards, despite the potential for the radiological consequences of such an event being low.

The U.S. has not finalised its approach to regulating FPPs, but the nuclear regulator NRC has been tasked with establishing a regulatory framework for FPPs by no later than December 2027. The UK has also not finalised its approach; however, the UK Government has recently published a paper outlining its proposals for the regulation of fusion energy [95], following engagement with

independent committees (RHC) and the fusion industry.

10.5 Key Findings from an Analysis of the Hazard Potential of FPPs

An important part of this project was to consider the hazard potential of FPPs to inform the development of an appropriate regulatory system. As previously stated, when considering what is an appropriate regulatory system it is important to remember that regulation should be based on the hazard potential (the unmitigated risk to the public) and not the mitigated risk. Chapter 6 showed that any actions that may be needed to protect the public in the event of an accident at an FPP depend upon the size of the radioactive source term, the nature of the release and the weather conditions at the time of the accident. The hazard potential, therefore, critically depends on the FPP design and the most realistic limiting radioactive source term. In the absence of a detailed design for an FPP, it was decided to use the size of a radioactive release required to trigger UK emergency reference levels (ERLs) for both public sheltering and evacuation as a means of evaluating the hazard potential.

The ADMS-STAR model was developed and validated to simulate accidental releases of HTO and activated dust from an FPP. A reference case scenario was then used to evaluate the radiological dose that any exposed persons would receive following a release of tritium (in the form of HTO) and activated dust. A sensitivity study was used to evaluate the impact of changing various parameters including the release height, dust particle size, release duration and weather conditions. Release height and weather conditions were found to be particularly important and ground level releases under DF2 conditions gave the most limiting results. Dust particle size was found to have a modest effect on ground level releases but slightly more of an effect on elevated releases. Release duration had very little impact on the results.

The analysis showed that a release from a 30 m stack (elevated release) would require a release of 231 g of HTO or 5 kg of dust to consider sheltering at 1 km from the plant and 2.3 kg of HTO or 49.6 kg of dust to consider evacuation. For a ground level release (leakage through walls, etc.), it would only require a release of 9 g of HTO or 1.7 kg of dust to trigger the lower sheltering ERL at

a distance of 1 km from the plant, and 88 g of HTO or 17.3 kg of dust to trigger the evacuation ERL.

Whist the actual source terms will depend upon the size and design of an FPP, the above figures can be compared with the ITER safety case maximum inventories of 1 kg of HTO and 1000 kg of dust. If these figures are representative for FPPs, it can be seen that for a high-level release the HTO source term (1 kg) has the potential to trigger sheltering (required 231 g) but not evacuation (required 2.3 kg), depending on what fraction of this inventory could be released in an accident scenario. In relation to dust the source term (1000 kg) has the potential to trigger both sheltering (required 5 kg) and evacuation (required 49.6 kg). For a ground-level release, however, the source term (1 kg HTO and 1000 kg dust) has the potential to trigger both sheltering (required 9 g HTO or 1.7 kg dust) and evacuation (required 88 g HTO or 17.3 kg dust) ERLs. Given the important contribution dust makes to the radiological consequences of a release, more work is needed to evaluate dust formation and build-up during operation to obtain a better understanding of the likely quantities of dust in the VV of an operating FPP. Experience gained during the initial operation of ITER will be valuable for this.

This work does not imply that FPPs are capable of releasing the identified quantities of radioactive materials; it simply shows that FPPs with similar source term characteristics will have the potential in an accident scenario where there is an uncontrolled release of radioactive materials to require off-site countermeasures to be taken. Whether the release of the identified quantities of radioactive materials is feasible or realistic will primarily depend upon the FPP design, but it will also depend on things such as the agreed maintenance schedules (where some of the radioactive inventories will be removed from the VV) and the outgassing rates of tritium from in-vessel components and walls. Build-up of dust will negatively impact the performance of an FPP (as it pollutes the plasma), so it is expected that there will be maintenance periods during which dust (and with that tritium co-deposited in dust particles) will be removed from the VV.

It is the release of the tritium that has been absorbed by the VV components and breeder blankets and the build up of dust that provides the main radiological source term. Hence, there is the opportunity for FPP designers to design out or minimise both the tritium and dust source terms. It

is also possible for designers to build in the necessary protection systems and containment systems with defence in depth to reduce the probability of an uncontrolled release so that risks are in the broadly acceptable zone. However, the level of engineering performance to achieve this will need to be justified in a robust safety case. The safety case will also require strong regulatory oversight to check the claims made.

10.6 Key Findings from Mapping Regulatory Options for Fusion Power in the UK

Having identified that FPPs have a hazard potential that requires design solutions and engineered protection systems, the type of regulatory approach that would be needed to give assurance to the public and politicians that FPPs will be designed and operated properly to ensure public safety was examined. The work reported in Chapter 5 demonstrated that there are no internationally agreed approaches as to how FPPs should be regulated. Four possible UK regulatory options were developed, as reported in Chapter 7.

Option 1 assumes FPPs are licensed in a similar manner to NPPs. This would involve FPPs coming under the remit of the *Nuclear Installations Act 1965* (NIA) and being subject to the 36 LCs that are attached to every nuclear site licence. Licensees of FPPs would be responsible for safety but would require permission from ONR to undertake things such as construction, commissioning, operation, reactor restart following outages, major modifications and decommissioning. To obtain permission, licensees would need to produce safety documentation to demonstrate the adequacy of the proposed engineering substantiation arguments and defence in depth measures. The design standards used in the design process would be expected to be similar to those used for NPPs. ONR would also be expected to apply the same regulatory oversight via its permissioning powers as it does for NPPs.

Licensing FPPs in this manner would result in licensees/designers of FPPs meeting all regulatory obligations to the same extent as licensees/designers of NPPs, despite the significantly reduced hazard potential of FPPs. FPPs have an almost completely distinct set of safety issues compared with NPPs, with no standing volatile fission product or actinide inventory in the core, no significant decay heat in the fuel, no positive power or void coefficients and no potential for catastrophic off-site

radioactive releases. However, this option would require licensees/designers to include arrangements for managing safety to a similar extent as licensees/designers of NPPs. This approach could also send the wrong message to the public regarding the hazard potential of FPPs. Licensing FPPs in a similar manner to NPPs would result in increased design complexity, engineering substantiation, defence in depth, regulatory costs and lead times that cannot be justified by the hazard potential.

Option 2 assumes FPPs are licensed in a similar manner to nuclear fuel cycle facilities with FPPs coming under the remit of the NIA and being subject to the 36 LCs that are attached to every nuclear site licence. In the UK, fuel cycle facilities are regulated using the same nuclear site licensing approach as NPPs. The main difference is the goal setting regime allows the licence applicant/licensee to determine the plant safety standards and operating procedures to reflect the hazard potential of the facility it wants to build and operate. Fuel cycle facilities have lower hazard potentials when compared with NPPs and hence safety safety cases can be easier to make and ONR's regulatory oversight requirements can be tailored to suit.

Licensing FPPs in this manner would result in licensees/designers of FPPs meeting all regulatory obligations to the same extent as licensees/designers of fuel cycle facilities. Whilst this would be to a lesser extent than in the case of NPPs, it would still be disproportionate given the hazard potential of FPPs. The safety issues associated with fuel cycle facilities are generally concerned with avoiding criticality, the treatment of spent fuel and subsequent storage of large inventories of harmful fission products and the potential diversion of fissile material. None of these safety issues applies to FPPs. This approach could again send the wrong message to the public regarding the hazard potential of FPPs (albeit to a lesser extent than Option 1). If FPPs were subject to the licensing requirements for large fuel cycle facilities such as reprocessing plants, the resultant increased design complexity, engineering substantiation, regulatory controls and lead times are not justified by the hazard potential of FPPs.

Option 3 assumes that FPPs would be regulated in a similar manner to non-nuclear radiation facilities under occupational health and safety/environmental permitting legislation. Under this approach, FPPs would be regulated by HSE, implementing the relevant provisions of the HSWA and its corresponding regulations (IRRs, REPPIR, etc.), and EA, implementing the EPR. The main

features of regulating non-nuclear radiation facilities are: the duty holder must ensure the protection of workers and the public; the duty holder may not commence work with ionising radiation prior to obtaining consent from HSE; a risk assessment must be carried out prior to carrying out work with ionising radiation; the duty holder must restrict exposure to ionising radiation through engineering controls, design features and safety features; the duty holder may not operate a facility without an environment permit; and to obtain a permit the duty holder must demonstrate to EA that any exposures to ionising radiation are kept ALARA. As there is no nuclear site licence granted in this case, the duty holder would not need to comply with any obligations within LCs. The levels of permissioning and enforcement powers available to the regulators are also reduced in this case compared with the nuclear licensing regime, due to the lower hazard potential of non-nuclear radiation facilities compared with NPPs and fuel cycle facilities. As reported in Section 7.4.4.3, EA are currently in the process of developing "staged regulation" for the regulation of a GDF which will create makeshift permissioning hold points at stages which may majorly affect safety, effectively duplicating some of ONR's processes from its nuclear site licensing regime. It is unclear at this stage whether this staged regulation approach will apply to FPPs, but if it is, it begs the question why try and duplicate certain processes when it is simpler and more effective to apply the nuclear site licensing regime that already exists? The duplication of ONR's existing regulatory processes cannot be regarded as better regulation.

If this staged regulation approach is not applied to FPPs, then regulating in this manner would result in limited regulatory control over the design and construction of FPPs. The limited permissioning powers and safety documentation required under this regime are potentially far too lax, considering that FPPs are power plants that contain a significant radiological hazard and have inventories of radioactive material that, if released under severe accident scenarios, can result in emergency countermeasures being implemented.

The effectiveness and efficiency of having HSE and EA/NRW/SEPA regulate FPPs is questionable: more regulatory interfaces can give operators more problems. In Option 3, ONR would still be responsible for regulating nuclear safeguards and potentially nuclear security, which would add to the regulatory interfaces and jurisdictions, providing opportunities for regulatory ineffectiveness and inefficiency. Given that regulating FPPs is not the core business of HSE or EA/NRW/SEPA, it is

arguable whether these organisations have the technical competence required to successfully regulate a large-scale FPP programme in the UK.

It is also questionable whether the obligations required by the HSWA, IRRs, REPPIR and EPR will be enough to provide the public and politicians with confidence that the technology is being managed appropriately and that the health and safety of workers and the public is protected. It is also hard to see the public accepting the UK's fusion power programme being regulated solely by HSE and EA, regulators who have experience regulating occupational health and safety and routine releases but have no experience regulating the safety of the design and operation of a full-scale power plant with a significant radiological hazard.

Option 4 assumes that FPPs would be regulated under a proportionate nuclear site licensing regime that covers nuclear safety (and potentially security) and is tailored to the hazard potential of FPPs (proportionate regulation). The use of a nuclear site licensing regime is a tried and trusted approach in the UK that achieves the level of regulatory certainty that will be required for FPPs. Nuclear site licensing is not unique to the UK; as shown in Chapter 5 many countries including the U.S., France and Canada have successfully implemented proportionate nuclear site licensing regimes[1]. Under Option 4, FPPs would need to be prescribed as installations requiring a nuclear site licence under the NIA and if security was to be included in the licensing regime, the NIA would need to be amended to cover safety and security. This would allow ONR to regulate the design, siting, construction, commissioning, operation and decommissioning of FPPs. The relevant provisions of the HSWA and its corresponding regulations (IRRs, REPPIR, etc.) would apply to FPPs; however, as with NPPs, it would be ONR that enforces these provisions, not HSE. The relevant provisions of the EPR would still be enforced by EA/NRW/SEPA. Whilst an FPP nuclear site licence would have a set of attached LCs, the licence applicant/licensee would be free to develop compliance arrangements that reflect the hazard potential associated with FPPs.

Under this approach, ONR would still have a variety of powers at its disposal to control licensees' activities and to ensure that a licensee does not progress past any stages that may affect safety without obtaining permission from ONR. However, as with the LCs, it may be determined that the

[1] Although the demand for ITER to include seismic and aircraft protection may be considered disproportionate to the hazard potential

stages in which permission from ONR is required are not the same stages in which permission is required for the development of an NPP or fuel cycle facility. It may be determined that certain stages (e.g. inactive commissioning) do not majorly affect safety and therefore do not require a permissioning hold point.

Developing a proportionate, goal setting licensing regime for FPPs would be straightforward for the UK as the current nuclear site licensing regime is flexible enough to accommodate the licensing of FPPs and it allows licensees to meet any obligations within LCs to an extent that is proportionate to the hazard potential. Similarly, the levels of safety documentation produced and engineering substantiation and defence in depth measures included will be proportionate to the hazard potential. Protection measures such as seismic protection or aircraft impact protection will only be a regulatory requirement if it is demonstrated that the unmitigated radiological consequences of such an event are unacceptable. A goal setting licensing framework will deliver high levels of nuclear safety and security (if licensing is extended to cover nuclear security), as the licensee will have the freedom to develop arrangements for managing nuclear safety and security that are wholly focused on the safety and security issues that are associated with FPPs. Ensuring ONR has a sufficient range of regulatory powers at its disposal to control licensees' activities will be key to providing the public and politicians with confidence that FPPs are being managed appropriately and that the risks to health and safety are acceptably low. A licensing regime will also provide regulatory certainty to investors, operators and licensees that there will be no unexpected regulatory requirements further down the line.

10.7 Key Findings from Analysing Regulatory Options for Fusion Power in the UK

Having identified and analysed the four main regulatory options, a process was developed to identify the most appropriate option. A set of 10 criteria considered necessary to providing an effective and efficient regulatory system was developed. Each regulatory option was evaluated against each criterion and ranked on a scale of 1-5, depending on the extent to which the option met the requirements within the criterion.

Regulatory Approach	Independence	Proportionality	Effectiveness	Regulatory Certainty	Technical Competence	Ring-Fenced Resources	Industry Focus	Public Confidence	Political Confidence	International Obligations	Total
Option 1	5	2	2	5	4	5	5	4	5	5	**42**
Option 2	5	3	3	5	4	5	5	4	5	5	**44**
Option 3	5	2	2	1	3	3	2	2	2	3	**25**
Option 4	5	5	5	5	4	5	5	5	4	5	**48**

Table 10.1: Grading regulatory options against each criterion (repeated from page 230)

From the analysis, it is clear that Option 4, a proportionate nuclear site licensing regime, scored the highest when ranked against the 10 principles of good regulation.

Option 1 (NPP approach) and Option 2 (fuel cycle facilities approach) scored highly against the 10 principles of good regulation; however, the main drawbacks with these options were the lack of proportionality that would result in a lack of regulatory effectiveness and efficiency.

As can be seen, Option 3, regulating FPPs via occupational health and safety/environmental permitting legislation, scored the lowest when assessed against the 10 principles of good regulation.

10.8 Key Findings from the Development of a Licensing Regime for FPPs in the UK

The work reported in Chapter 8 demonstrated the most appropriate regulatory framework for FPPs in the UK would be one based on a proportionate FPP site licensing regime. The next challenge, as reported in Chapter 9, was to determine how a proportionate licensing regime for FPPs could be developed in the UK. This included looking at what the key elements of the licensing regime should be, what amendments to legislation would be required, which LCs should be attached to an FPP site licence and what permissioning powers should be granted to the regulator.

To assist in the development of the regulatory approach, 13 regulatory principles (RPs) were identified

as being essential for a proportionate licensing regime for FPPs. These RPs include the need for a clear legal framework with a clear and predictable regulatory process; the regulator for nuclear safety, security and safeguards is independent and technically competent with appropriate enforcement powers to control licensees' activities; licensees should be responsible for nuclear safety and security; permission to undertake a major safety or security related activity can only be achieved through the submission of supporting documentation to the regulator; and said documentation should be proportionate to the hazard potential of the activity being proposed.

Required Legislative Changes

To implement an FPP site licensing regime based upon the 13 RPs, the primary pieces of legislation that would need to be amended are the *Nuclear Installations Act 1965* (NIA) [167], the *Nuclear Industries Security Regulations 2003* (NISR) [130] and the *Nuclear Safeguards Act 2018* (NSA18) [138]. Prescribing FPPs as a type of installation that will be subject to nuclear site licensing under Section 1(3)(a) of the NIA would ensure that a licence would be required to construct or operate an FPP and that the nuclear regulator ONR would be responsible for granting licences. Note this would not require an amendment to the NIA but could be achieved through the submission of an SI. It would also allow ONR to attach a set of LCs to FPP site licences. The 36 LCs in place currently are concerned with nuclear safety and the management of radioactive waste, with no mention of nuclear security. It is argued that FPP site licences could cover also cover nuclear security. To achieve this, the NIA would need to be amended so that LCs can be attached in the "interests of safety or security" [167] and the NISR would need to be amended to exclude nuclear installations. This would allow an integrated approach to delivering safety and security and would allow security measures to be developed at the design stage, rather than under the current system where administrative controls for delivering security are bolted on at a later stage.

Finally, amending the NSA18 to include fusion technologies and materials would grant IAEA inspectors access to FPPs to perform verification processes to ensure fissile material is not being produced and tritium is not being unlawfully diverted.

ONR Regulatory Oversight

The analysis of the regulatory options and the application of the RPs reported in this thesis has shown that an FPP site licensing regime operated by ONR as the principle regulator is the optimum solution for the regulation of FPPs. It is envisaged that the licensing of FPPs would easily fit into the current nuclear site licensing regime.

In the absence of a detailed design of an FPP, the level of permissioning hold points considered appropriate in a proportionate licensing regime based on current understanding of FPPs was explored. The design and construction stages will undoubtedly require hold points prior to them in order to provide investors, owners and operators with regulatory certainty that no unexpected regulatory demands will be required further down the line, potentially leading to considerable additional cost and project delays. It seems reasonable to require a PSR and PCSR be submitted to ONR for approval prior to granting a licence for a site or a Consent to commence construction on an existing nuclear licensed site. This would be the first main regulatory hold point, and it would enable ONR to confirm that the design of the facility was sound and that all relevant hazards have been identified and suitability mitigated for. In the proportionate regime envisaged, the fusion industry would be expected to develop appropriate nuclear safety and security standards that would be used in FPP design and substantiated in the relevant safety cases. For FPPs, permissioning of construction in a proportionate regime could also include inactive commissioning.

The second main regulatory hold point would be the active commissioning stage, i.e. the introduction of tritium on the site for the first time and commencement of testing the D-T plasma.

The third main regulatory hold point would be prior to the commencement of routine operations. At this stage, the licensee will need to submit the POSR to ONR for approval. Again, in the proportionate approach envisaged, the standards used in the POSR would be those developed by the fusion industry. As discussed previously, it would be expected that ONR would produce a new set of Safety Assessment Principles (SAPs) which would again be proportionate to the hazard potential of FPPs.

In a proportionate regulatory regime, permission from ONR for restart following routine plant shut-

down is not envisaged. However, ONR would retain the power to require permission if it so specified. Such situations could include a major statutory outage for inspection and maintenance, or following a major modification that if incorrectly designed or implemented could result in an uncontrolled release of radioactive material.

The fourth main regulatory hold point in the envisaged proportionate approach would be prior to the commencement of decommissioning. This would be to ensure that the licensee had effective plans to decommission and clean up the site. Again, the standards used in the PDmSR would be developed by the fusion industry. ONR would retain the power to direct the licensee to shut down operations in the interests of nuclear safety and security (if security was to be included in the licensing regime).

FPP Site Licence Conditions

It was determined that the current set of 36 LCs, which have been designed to cover all the activities that are needed to effectively manage nuclear safety, are relevant and proportionate for application to an FPP site. As discussed earlier, if licensing was extended to cover nuclear security, the wording in some of the LCs would need to be amended. This would enable the licensee to develop an integrated approach to the management of nuclear safety and security that would be proportionate to the hazard potential of FPPs, which should improve regulatory effectiveness and efficiency.

It is also vital that a graded approach is applied to the scope and application of the "adequate arrangements" that are required under many of the LCs. In the envisaged proportionate regulatory approach, the licensee would be free to develop its compliance arrangements to reflect the hazard potential of FPPs. A global approach to safety amongst the fusion industry and regulators, spear-headed by IAEA, would also be welcome to ensure that a consistent proportionate approach to safety is adopted internationally.

10.9 Overall Conclusion on an FPP Regulatory Regime for the UK

This project aimed to answer the question of how FPPs should be regulated in the areas of nuclear safety, security and safeguards. The nuclear safety, security and safeguards issues identified in this

study have demonstrated that FPPs are going to require effective regulatory oversight. However, as shown above, at a level less onerous than that found at NPPs or fuel cycle facilities. The work reported in this thesis has demonstrated that, once prescribed, FPPs can fit comfortably within the existing nuclear site licensing regime. This proportionate regime provides fusion licensees with the opportunity to develop LC arrangements that reflect the hazard potential of FPPs, and it enables the fusion industry to develop fusion-specific safety design guidelines.

Given the nascent stage of the fusion industry and the collective need for FPPs to deploy successfully, it is vital that there is only regulatory intervention when it is justified. However, the implementation of the proposal to incorporate FPPs into the nuclear site licensing regime operated by ONR should not be viewed by the fusion industry as an unwanted inconvenience that should be avoided at all costs. It should be viewed as an opportunity for the UK to take a leading role in helping not only the successful deployment of FPPs in the UK but also the international development of FPP regulatory principles and safety standards. It is essential not only to providing the public and politicians with confidence that the technology is being properly controlled, but also to provide the fusion industry with the regulatory certainty that it needs. Good safety means good business, and the inclusion of FPPs into the flexible and proportionate UK nuclear site licensing regime, as outlined in this study, should be seen as a positive way forward for the fusion industry.

10.10 Recommendations for Future Work

Whilst this thesis has attempted to map out the key nuclear safety, security and safeguards issues for FPPs and perform an analysis of the hazard potential of FPPs in order to determine the most appropriate regulatory framework, time and resource constraints mean there are clearly areas where further work is required. To ensure that future regulatory decisions concerning FPPs are taken using the best possible information, it is suggested that the fusion industry carries out further work in the following:

- better understand the mechanisms behind plasma disruptions
- better understand accident scenarios associated with the transfer of breeder blanket sectors
- develop a comprehensive component failure rate database for fusion-specific components

- better understand the conditions that could trigger a hydrogen and dust explosion and the consequences
- analyse the range of accidents that could lead to the production and release of WO_3
- better understand the nuclear security and safeguards issues to inform FPP design and operation
- better understand the modelling of radioactive source term release mechanisms
- better understand building wake effects on atmospheric releases of radioactive material
- develop more realistic meteorological conditions for dispersion calculations
- incorporate the long-term radiation effects from things such as ingestion or re-emission into the ADMS-STAR model
- better understand dust formation and build-up processes in order to determine a more accurate source term to use in safety analyses
- develop a more robust understanding of the hazard potential of FPPs
- develop design safety standards and requirements for FPPs
- develop a generic suite of LC compliance arrangements for FPPs

Finally, the regulators should develop a bespoke set of assessment principles to enable their inspectors to assess FPP safety cases.

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