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THE SAFE MANAGEMENT OF HAZARDS IN THE NUCLEAR INDUSTRY

Nuclear Power Plant Hazards Review

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GLOSSARY OF TERMS

Definitions

Definitions

Active Systems	Systems that must be operated (whether automatically or manually) to fulfil their role – for example, a fan would be an active cooling system
Backup Equipment	Equipment that can fulfil a role or function in case the main (primary) equipment fail
Control Rods	Steel-alloy rods that are designed to absorb neutrons and reduce reactor criticality, slowing or stopping the fission chain reaction
Conventional Hazard	A hazard that can exist on any industrial site
Criticality	When nuclear fission becomes self-sustaining
Diversity	The selection of backup equipment that can perform a function in a different way to the primary equipment that would normally carry out that function
Dropped Load	An object such as a piece of equipment dropped from a crane
Elimination	Designing out a hazard to ensure it can never occur
Fuel Cladding	A metal alloy housing the Uranium fuel pellets and containing fission products – this is a primary containment barrier
Hold Down	Prevention of the fission reaction from restarting following shutdown
Light/Daughter Nuclei	The resulting atoms following fission – also known as ‘fission products’
Mitigation	Reducing or minimising the overall effects of an event
Moderator	A material or substance that slows neutrons down to the optimum speed to enable fission – in a gas-cooled reactor, this is graphite, in a pressurised water reactor, this is the coolant (boronated water)
Natural/Background Radiation	Radiation from space or naturally occurring sources such as food and drink and rocks in the ground – unrelated to industry or medicine
Nuclear Fission	Radiation from space or naturally occurring sources such as food and drink and rocks in the ground – unrelated to industry or medicine

Passive Systems	Systems that fulfil a role with no intervention – for example, gas-cooled reactor fuel channels are designed to allow natural convection of the CO_2 coolant, so heat is removed with no operation required
Primary Circuit/Loop	The coolant that is heated directly by the fuel in the reactor
Primary Equipment	Equipment that fulfils a role or function under normal operation
Prevention	Stopping an event from occurring, by incorporating design features
Protection	Measures such as shielding to ensure hazards cannot affect personnel or the public
Radiological Hazard	A hazard that can result in a direct radiation dose and/or the release of radioactivity
Redundancy	The provision of duplicate equipment within the design of primary or backup systems so that these systems can tolerate equipment failure and still function
Risk	Probability multiplied by consequence
Secondary Circuit	Water that is turned into steam by heat transfer from the primary circuit coolant.
Segregation	Backup equipment that is protected or distanced from primary equipment
Seismic Event	An earthquake
Shutdown	Halting the nuclear fission chain reaction
Uranium	The primary source of fuel in the nuclear industry

Summary

Summary

Over the course of several decades, the nuclear industry has been proven to not only be one of the safest forms of power generation, but also one of the safest industries for both operators and the public.

Nuclear Power

- Nuclear fission is the process of splitting Uranium atoms to produce energy.
- This energy heats water, producing steam, which drives a turbine to produce electricity.
- This process has been achieved in several ways by many countries for power generation since the 1950s.
- The process uses small amounts of fuel and produces no harmful CO_2, NO_X or particulate emissions.
- Nuclear power plants provide a stable and reliable electricity supply to the national grid (sometimes referred to as the 'base load').
- Nuclear power plants have many processes in common with other industries and forms of power generation, such as waste and water treatment, steam production, chemical use and electricity transmission.
- Nuclear fuel is radioactive and must be managed with care to maintain control, cooling and containment.

Safety

- To ensure nuclear power plants can operate safely, important equipment always has one or more backup on standby.
- In the event an important backup fails, alternative equipment can achieve the same job but in a different way.
- Important safety functions are monitored and controlled automatically so they do not require human input.
- Nuclear fuel is transported and stored in containers so robust they can survive drops onto concrete, intense fires and even a collision with a train.
- Even if all protection measures are lost, nuclear operators and the emergency services plan for and regularly practice emergency procedures
- If the regulator is not convinced that operators have done everything in their power to minimise risk, then permission to operate will not be granted.

Hazards

- As with many industries and sectors, nuclear power plant operation presents multiple hazards including those which are of a conventional, chemical and radiological nature.
- The nuclear industry takes a uniquely stringent approach to managing risk to protect people and the environment. All hazards, regardless of type, are managed to a level that ensures they can Do No Significant Harm.
- The nuclear industry has developed extremely high standards to ensure that radiation is contained and presents no risk to human health.
- Stringent legislation, alongside a drive for continuous improvement, ensures the amount of radiation a person might receive from a nuclear power plant is far less than normal background levels.
- The probability of some events occurring on a nuclear power plant is less than 1 in every 10 million years, which is less likely than being struck by lightning.
- This strong safety culture feeds into all aspects of power plant operation, resulting in nuclear power being statistically one of the safest industries to work in.

Continuous Improvement

- The uncompromising standpoint on safety extends to all operations on site, including machinery operation, construction, inspections or general site activities, regardless of whether there is radiation present.
- As such, the nuclear industry has one of the best health and safety track records of any industry – working in construction, agriculture, oil and gas or even driving all present much greater levels of risk.
- Even so, the industry is always learning from experience and improving – modern nuclear reactors must always present improvements over past iterations.
- In the UK, the regulations are the strictest in world, and these drive continuous improvement in the sector – simply meeting targets is not enough, and the industry must prove it has done all it can to ensure operational safety.
- Beyond regulations, the nuclear industry is self-motivated to drive for leading standards – multiple organisations provide a global platform for operators to openly share knowledge, operational experience and learning.
- If learning is not used, and improvement not seen, then operation is not permitted.

Introduction

INTRODUCTION

Nuclear Power

in this report, the typical risks present on a Nuclear Power Plant (NPP) and how these are managed safely are considered.

Introduction

Two of the key pillars that support the use of civil nuclear power are its ability to generate continuous baseload electricity, and its low carbon qualities. In 2018, roughly 26% of the energy demand of the member states of the European Union (EU) was met by nuclear power. Furthermore, as shown in the adjacent graph (bottom), reviews into the total CO_2 emissions across the life of a nuclear power plant have concluded its total contribution to be amongst the lowest from any form of power generation.

However, it is also universally accepted that nuclear power is unique in the energy sector, due to the need to consider and effectively manage nuclear safety. As such, the design, construction and operation of a nuclear power plant is based on conservative decision making as part of a strong safety culture.

When considering the occurrence of hazards, nuclear power is highly regulated. Safety and environmental protection remain the overriding priorities, and operators are required to thoroughly demonstrate to the independent nuclear regulator that plant operation will not impact either of these.

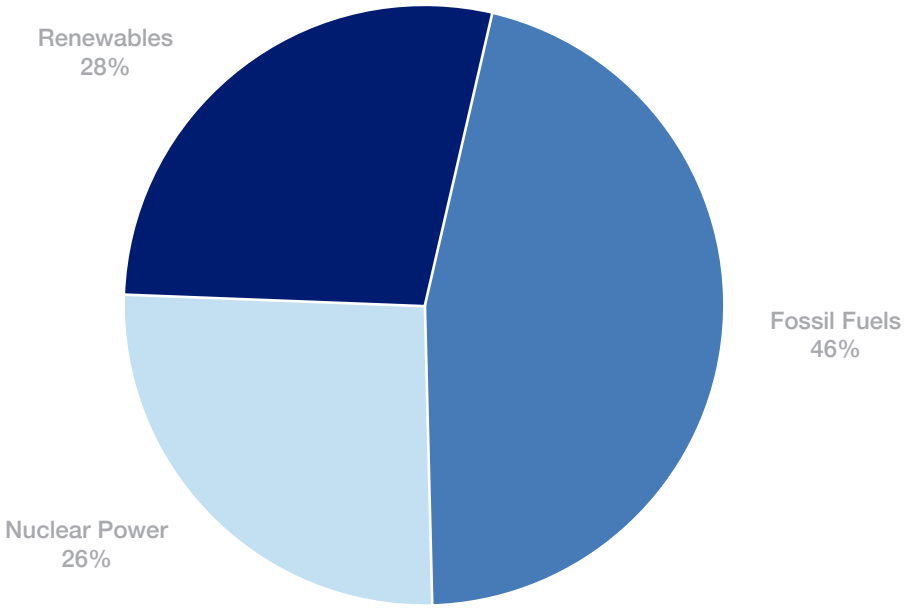
Furthermore, beyond strict regulations, countries and nuclear power plant operators actively collaborate through multiple existing platforms and organisations, such as the International Atomic Energy Agency (IAEA), to share experience and to work towards the common goal in driving continuous improvements in safety and regulation.

Ultimately, all potential hazards present on a nuclear power plant, regardless of the type or source, are regulated and controlled in line with strict national and international legislation, which is developed in line with strong underlying scientific evidence and continuous sharing of knowledge and experience. Comprehensive regulation and oversight ensure compliance at all times and that plant construction, operation, decommissioning and waste management activities can **Do No Significant Harm.**

With this in mind, the following sections provide:

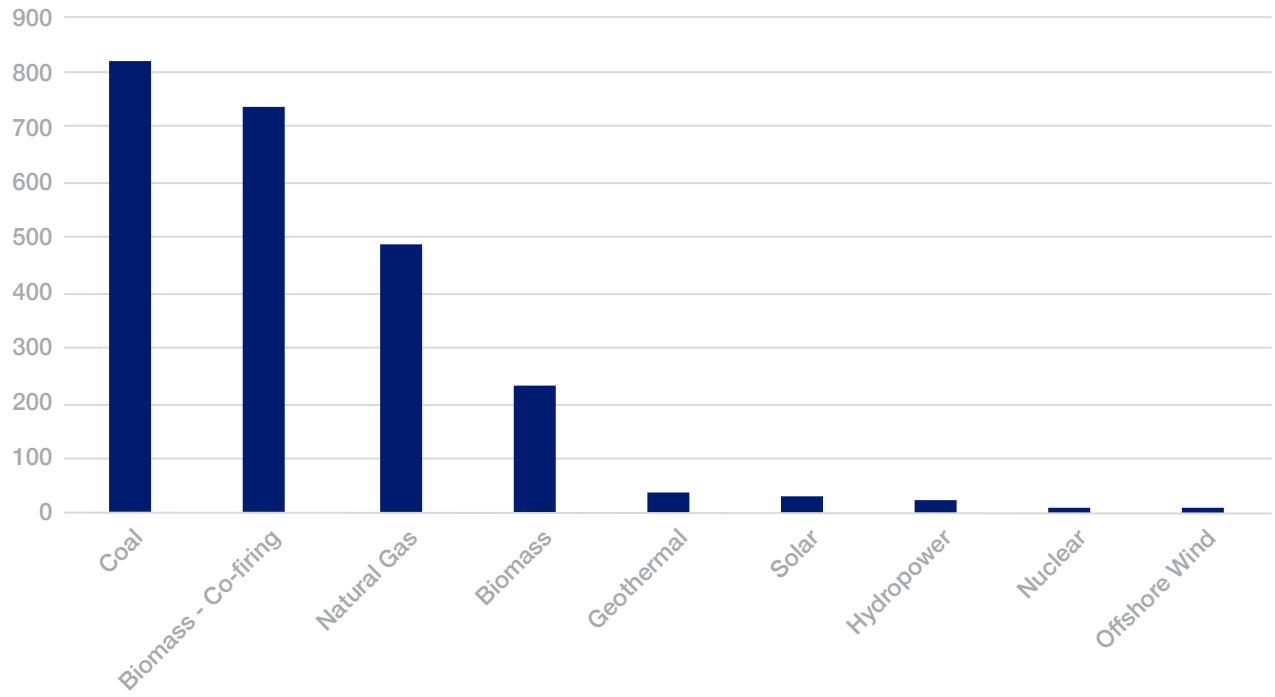
- A general overview of reactor technology and how nuclear fission is safely utilised for power generation;
- An insight into the risk reduction methods used by the nuclear industry to ensure nuclear power plant design, operation and maintenance are suitably robust;
- Examples of faults and hazards typically associated with nuclear power plant operation, and how the associated risks are managed; and
- How the approach to risk management and associated results compare to other industries.

Split of energy generation forms in the European Union



Source: World Nuclear Association (WNA)

CO_2 Emissions by Generation Type



Source: Intergovernmental Panel on Climate Change (IPCC – 2014 Study)

INTRODUCTION

Nuclear Power Overview

The utilisation of nuclear fission enables low-carbon, stable power generation, requiring much smaller quantities of fuel and environmental resources than conventional power stations using fossil fuels.

Nuclear Fission Reaction Overview

Nuclear power plants are similar to other types of power plant in that they generate heat from fuel to create steam that rotates a turbine, which is connected to a generator and is used to generate electricity. However, the primary difference is in the type of fuel used: Uranium.

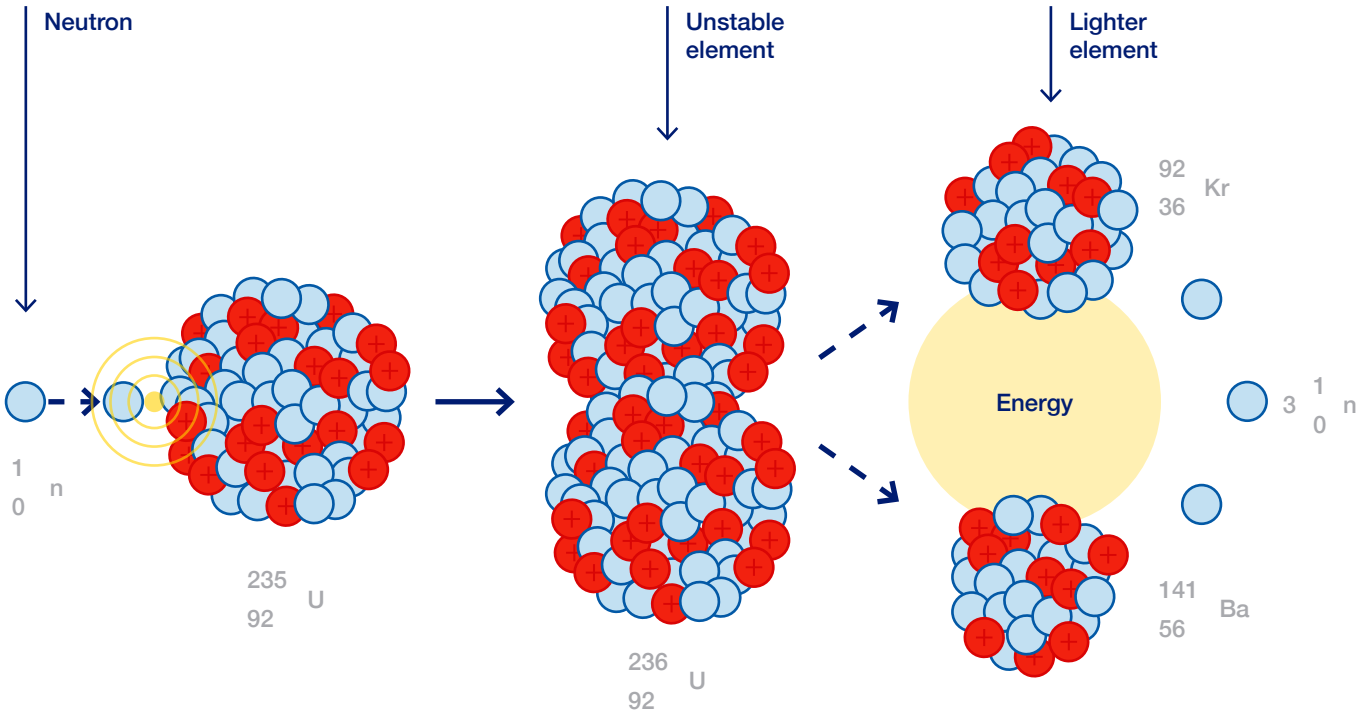
Nuclear fission reactors all follow the same basic principle for power generation. This is shown in the adjacent image and comprises the following high-level steps:

- Atoms of Uranium, the primary fuel present in the core of a nuclear reactor, can fission (split) when low energy (slow) neutrons collide with them.
- The fission process releases more neutrons, which once moderated (slowed down) can then collide with other Uranium atoms, causing them to split, releasing further neutrons. Carefully controlled, this can produce a chain reaction.
- The fission process releases large amounts of energy, in the form of kinetic energy of the lighter elements and neutrons. As these slow down and interact with materials in the fuel this energy is converted into heat.
- The heat produced is transferred to the reactor coolant (which is normally CO_2 or water, depending on the reactor design), which is circulated through the core in a closed loop. The reactor coolant, also known as the ‘primary loop’ circulates and either directly turns to steam and drives a turbine, or transfers its heat to water contained within a ‘secondary loop’, which is then turned to steam and used to drive a turbine.
- The spinning turbine drives a generator, which feeds electricity to the grid, and the cooled steam is collected, condensed and recirculated.

As a result of this process:

- There are no harmful greenhouse gases, particulates or Nitrogen Oxides (NO_x) emissions produced; and
- Modern nuclear power plants can run continuously at full power for 18 months before they require refuelling, ensuring a stable and reliable supply of electricity for the grid (often referred to as “base load”).

Diagram of a Typical Nuclear Fission Reaction



Source: European Union Science Hub

INTRODUCTION

Nuclear Power Overview

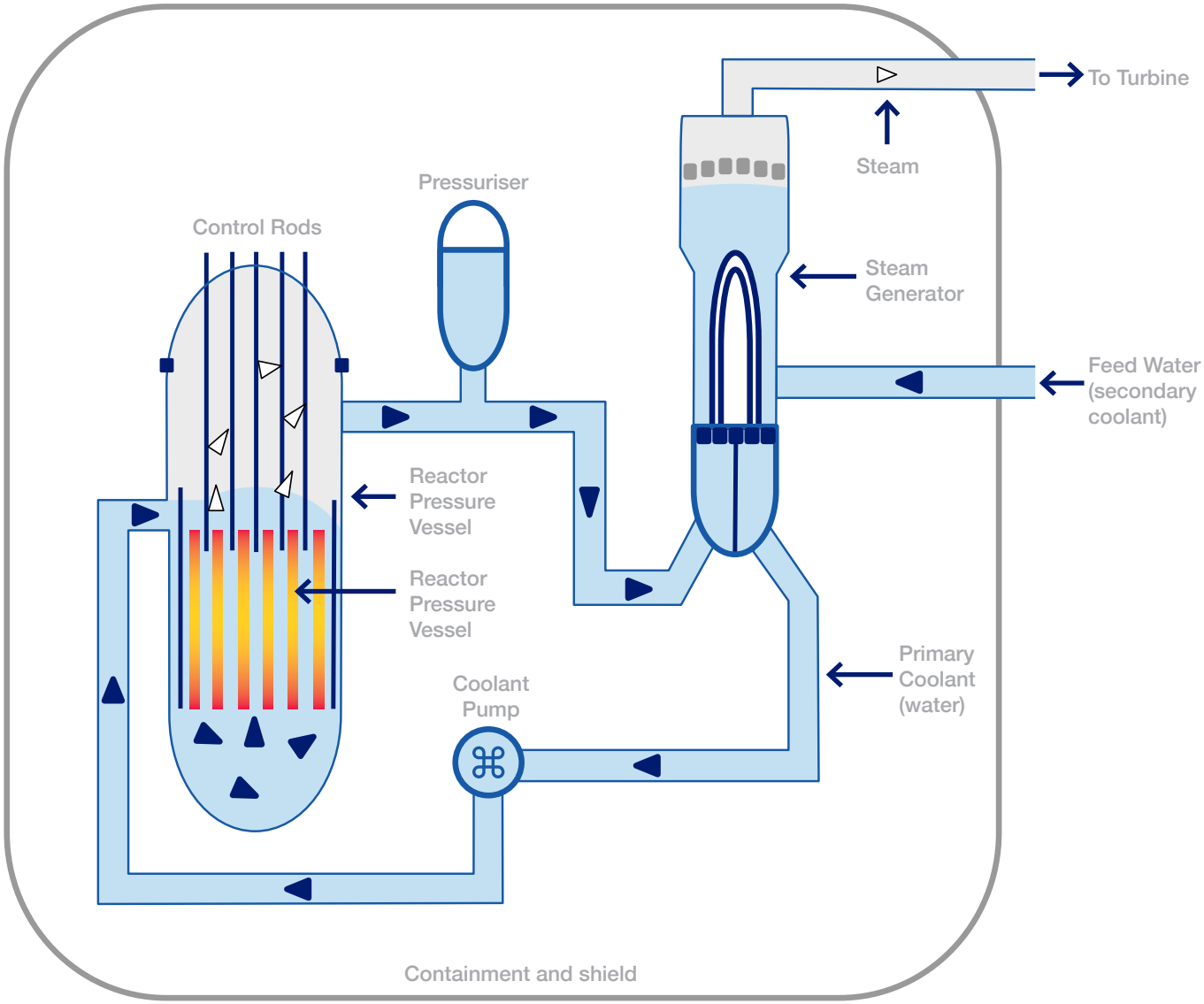
There are many proven reactor technologies used worldwide; those using pressurised water as the coolant and moderator are the most common.

PWR Reactor Schematic

Most nuclear power plants use water to remove heat from the core. In a Pressurised Water Reactor (PWR – the most common reactor type globally), heat is removed via pressurised water in a closed loop called the "Primary Circuit", pumps direct water through a reactor vessel containing the nuclear fuel that is generating heat. The water carries the heat to steam generators in which water from a second closed loop, the "Secondary Circuit" is heated to create steam. The steam is then used to turn a turbine and generate large amounts of energy in the same way as in a conventional power station. The adjacent schematic provides an outline of a nuclear reactor operation, with definitions of key components provided below.

- Fuel Assemblies contain Uranium, the element which undergoes fission to produce heat.
- Control Rods are designed to control and limit the reactivity by absorbing neutrons – the further they are inserted, the further the reactivity and heat produced drops.
- The Primary Coolant (water) absorbs the heat, and transfers it to a heat exchanger, known as a Steam Generator.
- In a PWR, the Primary Coolant is also the Moderator, which slows neutrons down to the correct speed to be captured by the Uranium atoms.
- The Reactor Pressure Vessel contains the Fuel Assemblies and allows the flow of Primary Coolant to cool the fuel.
- The Pressuriser is used to regulate the Primary Circuit pressure, increasing it if it drops, or reducing it if it goes too high.
- Steam Generators are heat exchangers, where heat is transferred from the Primary Coolant to the Secondary Coolant loop turning Feed Water into steam, which drives a turbine.
- The Turbine is connected to a Generator, which produces electricity.
- The steam produced is also used for other processes on site, making more efficient use of the heat produced by the reactor.
- At the end of the process, the steam is condensed back into water and recirculated, where the process begins again.

Diagram of a Typical Nuclear Fission Reaction



Source: European Union Science Hub

Risk Management

RISK MANAGEMENT

Health and Safety Record

The definition of a hazard is ‘anything that can cause harm’. As such, all aspects of everyday life, including all work-related activities, present potential hazards.

Hazards - Overview

The UK Health and Safety Executive (HSE) defines a hazard as:

> *‘…anything that may cause harm; these can be hazards to physical health such as chemicals, electricity, working from ladders, an open drawer or to mental health – if, for example the common causes of work-related mental ill health e.g. demands, control and support for individuals are not properly managed in the workplace’.*

On this basis, every form of industry, whether it is site or office-based, presents some form of hazard to people or the environment.

The key objective is to ensure that all potential hazards are managed and controlled appropriately, to ensure that they can Do No Significant Harm.

Examples of Typical Hazards

Slips, trips and falls in the office due to untidy cables, spilt drinks or unmarked stairwells.

Biological hazards, present in hospitals due to contaminated materials such as gloves, cloths, masks and syringes.

Electrical hazards, presented by electrical appliances, plug sockets in the home or car batteries.

Fire hazards seen at petrol stations or even in the home due to the presence of flammable materials such as wood, fabric and paper, and ignition sources, including the electrical hazards listed above.

Explosion hazards such as a gas leak in the home.

RISK MANAGEMENT

Health and Safety Record

Reflecting the high value the nuclear industry places on safety, the sector sets itself the goal of achieving zero harm across all aspects of generation. As a result, the industry consistently achieves world-leading health and safety standards.

Risk Management in the Nuclear Industry

The nuclear industry takes a unique approach to managing the risks associated with its operations. Furthermore, the stringent domestic and international regulations in place for nuclear power plant operation, and the methodologies used for managing nuclear and radiological risk, positively impact the approach taken for more conventional hazards. This results in industry-leading health and safety figures.

There are a number of organisations across the world such as the IAEA, Institute of Nuclear Operators (INPO) and World Association of Nuclear Operators (WANO), that facilitate the sharing of knowledge, best practice and lessons learnt through the nuclear technology life cycle. This includes design, construction, licensing, commissioning, operation, maintenance and decommissioning of nuclear power plants (as well as other nuclear technology-based systems).

Through these organisations, operators are able to access and share information and lessons learned from nuclear power plant operations, helping to set best practice guidelines, avoid repeat events and to proactively provide advice and guidance to other operators. Open access to this type of information places safety ahead of commercial considerations and, through peer review activities conducted through these organisations, there is a shared emphasis on improving safety standards and the safety culture across the nuclear sector globally.

Through a combination of these factors, the risks associated with nuclear power plant operation have been driven to extremely low levels, ensuring that the world can continue to benefit from the safe use of nuclear power.

The adjacent table provides some examples of the probability of a fatality associated with some of the risks of everyday life. In the UK, the regulator requires all nuclear power plant operators to ensure the greatest risks associated with operation, namely those that might result in a public fatality, are reduced below the probability of being struck by lightning.

Examples of Fatality Probabilities

Source	Probability per annum[1]
Risk of death from five hours of rock climbing every weekend	1 in 100
Risk of death due to work in high-risk groups within relatively risky industries, such as mining	1 in 1000
General risk of death in a traffic accident	1 in 10,000
Risk of death in an accident in the very safest parts of industry (such as service industries)	1 in 100,000
General risk of death in a fire or explosion from gas at home	1 in 1 million
Risk of death by being struck by lightning	1 in 10 million
Risk of wide-spread radiation release from nuclear power plant failure (but may not result in fatality)	Less than 1 in 10 million

[1]Probability per annum is the chance of a particular event occurring within the space of one year. This could also be equated to the number of years required to for an event to occur. For example, a probability of 1 in 1 million per annum would also equal an event occurring once in the space of 1 million years.

Source: Tolerability of Risk from Nuclear Power Plants and Office for Nuclear Regulation (ONR)

RISK MANAGEMENT

Safety Barriers

Stringent regulations enforce the use of a wide range of measures to ensure nuclear power plant operation is safe.

Risk Reduction

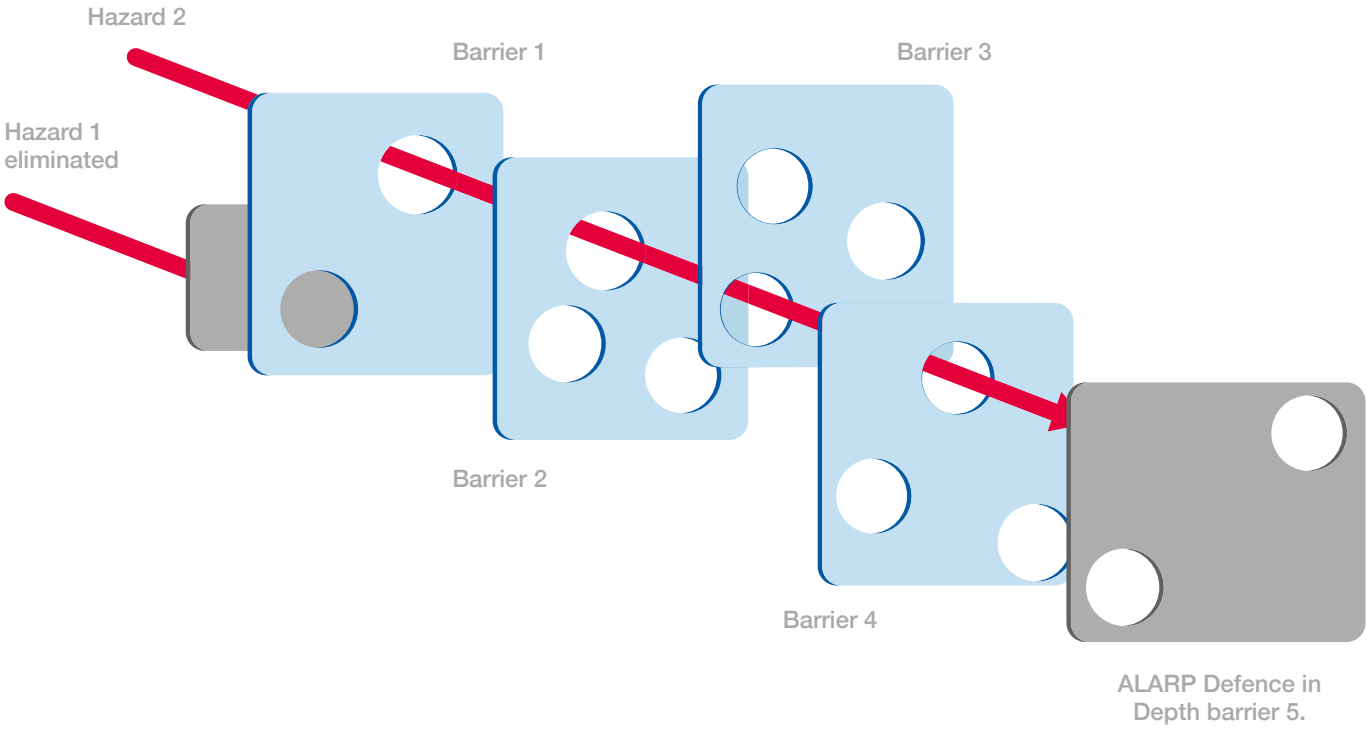
For every potential hazard, the types and amount of protection required are chosen according to the hazard type and its potential impact. The greater the hazard, the more protection will be applied and included in the design. For example, if a hazard can affect the health of the public, a wide variety of protection is specified to ensure this will not happen. On the other hand, if the hazard can only have a financial impact, then very few layers of protection will be adopted. Each safety measure is sometimes referred to as a "Barrier". This can also be likened to the "Swiss Cheese" model used across multiple industries (such as aviation and process safety), whereby a greater number of barriers is employed to reduce the probability of the "holes aligning", lowering the risk. Some key methodologies adopted in the nuclear industry are as follows:

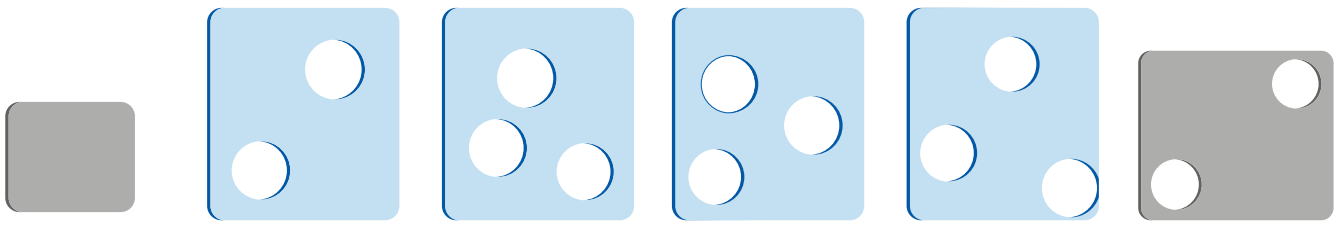
- **Hazard Elimination:** The nuclear industry adopts a strict hierarchy which requires that, where possible, the potential for certain events is removed from the design altogether, or the design prevents the hazard from occurring.
- **Equipment backup:** Important equipment will always have a backup that can fulfil the same duty. This backup may be made by another manufacturer ("diversity") and located on another part of the site ("segregation"). This way, it will not be affected by the same issues.
- **ALARA:** In reducing risk to As Low As Reasonably Achievable (ALARA), the operator must prove to the regulator that, not only have the safety requirements been met, but that if more "barriers" can be added, then it will be investigated and adopted. This is known as "Defence in Depth". In the UK, the principle of reducing risk to As Low As Reasonably Practicable (ALARP) is applied to all hazards on a nuclear power plant.

In the UK, the regulator and operator take a collaborative approach to nuclear safety by ensuring the methodologies listed above are used to their full potential.

- The regulators and independent bodies undertake regular site visits and inspections to ensure the barriers in place are maintained and functioning correctly.
- Nuclear power plant operators draw on, and contribute to, domestic and international experience to better understand how safety can be improved.
- Improved understanding over the course of several decades has resulted in improved designs that eliminate some hazards altogether.

The “Swiss Cheese” model





Plant design means this hazard cannot occur

Plant is operated within safe operating parameters

Primary equipment fitted with redundancy

Diverse and segregated backup equipment

Engineered design features and on site actions mitigate event consequences

Emergency procedures reduce risk to people/ environment

RISK MANAGEMENT

Hazard Types

The nuclear industry presents its own specific risks, for which a unique level of protection is afforded. However, nuclear power plants also present conventional hazards seen in numerous other industries.

Nuclear Power Plant Hazards Overview

The only unique element to a Nuclear Power Plant is the nuclear hazard associated with the use of nuclear fuel. This is controlled in line with domestic and international legislation through the Euratom Nuclear Safety Directive. This legally binding directive draws on specialist knowledge from the European Nuclear Safety Regulators Group and Euratom Scientific Expert Group to maintain and promote the continuous improvement of nuclear safety.

Other conventional and radiological hazards are common across a number of technologies and sectors. The safety standards across these sectors are defined by common EU Directives, such as the Basic Safety Standards Directive (BSSD), which includes the protection against radiation.

In addition to managing the nuclear hazard associated with nuclear fission, numerous other hazards exist on nuclear power plants such as chemical storage and use, and the presence of hazardous environments.

For example:

- Chemicals are stored and used on site to ensure high quality water supplies are available at all times.
- Similarly, vehicle and crane operation is required for lifting and transporting large pieces of equipment.
- Pressurised steam circuits and electrical equipment form an essential part of power plant operation, without which electricity production would not be possible.

Each of these are also present on a coal-fired or gas-fired power station and across industry in general. Some further examples are provided on the adjacent page.

In the following sections, examples of typical hazards on a nuclear power plant, and the barriers in place to prevent or protect against the consequences, are provided in greater detail.

Example Hazard Sources

Nuclear

– Nuclear fuel

Radiation

– Radiography equipment (x-rays) for assessing components such as pipework, to ensure they are in good condition
– Other radiation sources such as radioactive waste

Chemicals and Gases

– Ammonia for water pH control
– Boric acid for effective reactor operation
– Acidic and alkaline solutions for fuel pond water cleaning
– CO_2 for reactor operation and fire suppression
– Nitrogen for backup reactor shutdown
– Fuels, oils and lubricants for machinery operation
– Hydrogen used for efficient generator operation

Conventional Mechanical and Electrical Hazards

– Electricity due to the requirement for medium and high-voltage equipment, such as transformers and switchboards.
– Vehicle (such as forklift trucks) movements on site
– Fire due to the presence of flammable materials, such as lubricants
– Projectiles from high-pressure circuits and rotating equipment
– Steam for the purposes of power generation
– Dropped loads and collisions from crane operation
– Slips, trips and falls
– High noise and vibration levels
– Asphyxiation and drowning due to storage of gases and presence of water

Radiation

RADIATION

Overview

Strict legislation ensures that all nuclear power plant operators must adhere to extremely low radiation dose limits, far below those typically resulting from common sources such as background radiation or even some types of food.

Legal Dose Limits

Radioactivity is the measure of radioactive decay of an element. Unstable naturally occurring atoms, such as Uranium-235, Carbon-14 and Potassium-40 undergo random radioactive decay and emit radiation.

This radiation carries energy and when this is absorbed by the human body it is known as the radiation dose. Radiation dose is measured in sieverts (Sv); however, this is a large unit, and millisieverts (mSv) or microsieverts (μSv), one-thousandth or one-millionth of a Sievert, respectively, are used in accordance with Euratom Directives.

The European Atomic Energy Community (Euratom) and the UK's domestic regulations (such as the Ionising Radiation Regulations 2017) provide strict radiation dose limits for both the public and operators, which must be adhered to by all operators (Basic Safety Standards Directive, 2013/59/Euratom and IRR17). In general, these limits are:

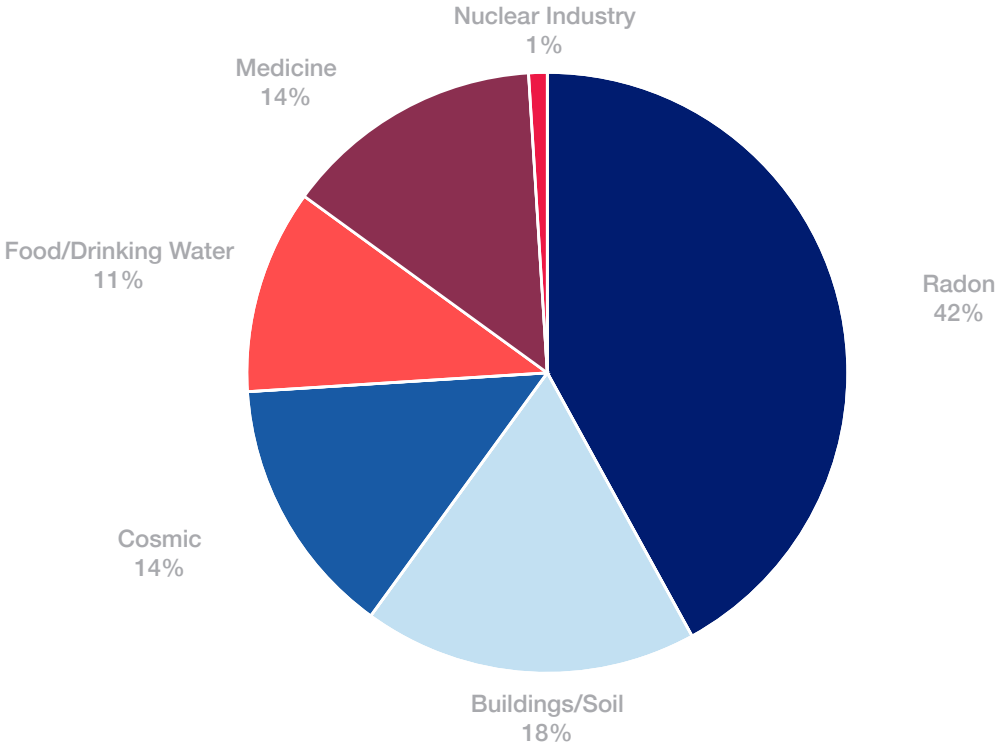
– 20 mSv per year for personnel working on a nuclear power plant; and
– 1 mSv per year for members of the public.

Such requirements apply equally to all aspects of the nuclear industry including construction, electricity generation, decommissioning, and management of spent fuel and waste.

These limits are extremely low. For example, 1 mSv per year is actually less than the average dose absorbed by the public in the UK due to natural background radiation (UK Government). In fact, because of these strict limits, nuclear power plant operation contributes roughly 1% of the total amount of background radiation in the UK. This is far less than other natural sources of radiation, such as outer space and the ground, certain foods and even other means of power generation, such as the burning of coal in conventional power stations[1].

[1] Numerous studies have shown that the radiation released to the environment by burning coal in a coal-fired power station is far greater than that released from a similar-sized operating nuclear power plant. The findings, outlining the presence of radioactive material in coal, have been collated by numerous organisations, such as the International Atomic Energy Agency, US Environmental Protection Agency and Oak Ridge National Laboratory, amongst others.

Primary Sources of Background Radiation



Source: World Nuclear Association

Source	Reason
Buildings/Soil	Construction materials can often comprise materials, such as fly ash, with low levels of naturally occurring radiation present
Cosmic	Radiation from outer space
Food/Drinking Water	Foods such as coffee, brazil nuts and bananas contain naturally-occurring potassium-40, which is radioactive
Medicine	Procedures such as X-rays and CAT scans all result in a radiation dose being absorbed by the patient
Nuclear Industry	Small quantities of radioactive material are discharged in compliance with strict environmental legislation
Radon	Radon gas is a naturally occurring element that is emitted from certain rock types in the ground

RADIATION

Overview

Radiation occurs from a number of different sources; however, it is the dose uptake level in people and the environment that represents the impact of that radioactivity.

Sources of Radiation

The legal limits enforced are upper values which must not be exceeded. In the UK, operators are required to reduce radiation dose to “As Low as Reasonably Practicable”, a legal term that means they must have in place measures that ensure that radiation doses received are low.

In reality, the average dose received by workers or a member of the public due to nuclear power plant operation is therefore far less than the legal limits. The typical nuclear power plant worker only receives 0.18 mSv per year (UK Government), which is much lower than typical sources of background radiation, and less than one-hundredth of the 20 mSv legal limit.

As described earlier, there are many sources of naturally occurring radiation in the environment. Foods containing naturally occurring, radioactive potassium-40 (such as brazil nuts, coffee, bananas and low sodium salt), outer space, and even the ground are all sources of radiation to which the public is exposed.

To put the radiation dose received by the typical nuclear power plant worker in a year into context:

- Eating 100g of Brazil nuts results in a radioactive dose of 0.01 mSv (10 μSv), or 1/18th of the dose received by a typical nuclear power plant worker over the course of one year;
- After just two transatlantic flights someone would receive a comparable radiation dose to another individual working full-time on a nuclear power plant;
- For someone living in Cornwall in the UK, the total dose absorbed due to background radiation (due to high levels of naturallyoccurring radon gas emitted from the ground) is 38 times greater than the average full-time nuclear power plant worker; and
- For a member of the public living near to the Hinkley Point C nuclear power plant that is currently being constructed, the annual dose is predicted to be approximately 2 μSv per year, which is less than the amount of radiation received by drinking a cup of coffee every 5 days (Radiological hazard of coffee to humans: a comparative study of Arabian and Turkish coffees, W. R. Alharbi and Zain M. Alamoudi).

Source: HM Government and Oxford Martin Restatements, 'The Health Effects of Low-Level Ionizing Radiation'

RADIATION RELEASE

Overview

The potential for a release of radiological material drives the legislation and regulation measures in place, which are the strictest of any industry.

Overview

Radiological hazards are events with the potential to cause harm due to exposure to sources of ionising radiation, and are not unique to the nuclear industry. The food industry, hospitals, Universities and engineering all make use of radiation sources for various reasons, such as medical procedures, sterilisation or inspection activities.

Designers and operators must review and plan for a wide range of possibilities including equipment failure, human error and large-scale hazards such as earthquakes, to ensure that activities can Do No Significant Harm.

Within the nuclear industry, a prominent example is in the design of containers used for transporting fuel assemblies. In 1984, in order to test the robustness of the UK's fuel container design, a standard example containing simulated fuel was placed onto a disused railway line, and a 239-ton diesel locomotive was crashed directly into it at roughly 100 mph. The container emerged with very little damage. The test, known as 'Operation Smash Hit', was shown live on the BBC 6 o'clock news and presented a compelling argument for how safe the transport of nuclear fuel is, and how seriously the nuclear industry takes its responsibility to ensure nuclear safety is maintained under all scenarios.

Nuclear hazards are a subset of radiological hazards and are unique to the nuclear industry. Whilst multiple other industries make use of, or produce, radioactive materials, the potential for an uncontrolled nuclear fission reaction, due to the use of Uranium fuel, is specific to a nuclear power plant. Perhaps the most famous nuclear hazard example is the sequence of events that occurred in Chernobyl, where a flawed reactor design, coupled with inadequately-trained personnel and an extreme hierarchical system of command, created a chain of events that led to loss of fuel criticality control, overheating of the fuel and then loss of containment.

The hazards that could result in a radiological release are each stringently regulated in accordance with national and international legislation as outlined on the next page.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RADIATION RELEASE

Regulation

International and domestic regulations governing the requirement to reduce radiological risk in the UK are enforced by the Office for Nuclear Regulation. These strict regulations, along with international learning and collaboration, are the key driver behind the nuclear industry's leading health and safety record.

Legislation

International Atomic Energy Agency (IAEA)

- The IAEA is an organisational body whose purpose is to promote the safe and peaceful use of atomic energy. This collaborative organisation enables the sharing and development of operational experience and scientific knowledge for the purposes of driving advances in technology and operational safety.
- The IAEA's Basis Safety Standards (BSS) are used to inform international legislation, such as the UK's IRR17.

European Atomic Energy Community (Euratom)

- The Euratom BSSD establishes uniform basic safety standards for the protection of individuals against the dangers arising from ionising radiation (excluding medical and background sources - EU).
- As with the IAEA's BSSs, these standards are used to drive international legislation to ensure operations in industries utilising ionising radiation can Do No Significant Harm.

Ionising Radiation Regulations 2017 (IRR17)

- IRR17 requires employers to keep exposure to ionising radiations ALARP. This legislation defines the specified dose limits for those working on a nuclear power plant. Restriction of exposure should be achieved first by means of engineering control and design features.
- IRR oversight is provided by the HSE, who work in conjunction with the UK's regulator, the ONR, ensuring that specific dose limits are complied with. The ONR ensures radiation doses to workers and the public are extremely low.

Environmental Permitting Regulations

- Protect the environment so that statutory and government policy environmental targets and outcomes are achieved.
- Requires all operators to ensure that any discharges of radioactive or non-radioactive materials and disposals of wastes apply the principles of environmental optimisation (including ALARA) and pose no harm to human health or the environment.
- Encourage regulators to promote best practice in the operation of facilities and continue to implement European legislation fully.

Regulation

Office for Nuclear Regulation (ONR)

- The ONR publishes Safety Assessment Principles against which UK operators are assessed to determine if their future or existing nuclear power plant complies with requirements. The key focus is on risk reduction and, as described earlier, if the nuclear power plant operator cannot demonstrate compliance and that risks have been reduced to ALARP, then the regulator is able to withhold permission to operate.
- In the UK, it is not sufficient for operators to meet set targets. Where practicable, targets must be exceeded and risks reduced to ALARP. As such, further specialist support is provided in the form of Technical Assessment Guides. These provide regulators with specialist advice on nuclear power plant risk reduction, enabling operators and the regulator to work towards a common goal.

Environmental Protection Agencies:

- Enforce laws and regulations that aim to protect human health and the environment.
- Authorise and control the disposal of radioactive waste into the air, water and land.
- Regulate nuclear sites under the Environmental Permitting Regulations (in England and Wales) or the Radioactive Substances Act (in Scotland).
- Issue consents for non-radioactive environmental activities.

Knowledge Sharing and Improvement

World Association of Nuclear Operators (WANO)

- WANO is a non-regulatory, non-profit organisation that exists to maximise the safety and reliability of nuclear power plants worldwide by enabling plant operators to jointly assess, benchmark and improve performance through mutual support, exchange of information, and emulation of best practices.
- Whilst they are a non-regulatory body, nuclear operators do undergo WANO inspections, that subsequently highlight areas of high performance and provide feedback on areas for improvement.
- This organisation enables nuclear power plant operators all over the world to share operational experience, driving continuous improvement through knowledge sharing and learning from experience.

Euratom and IAEA

- In addition to producing legislation, Euratom and IAEA fund and pursue nuclear research and training for the purposes of continually improving nuclear safety.
- Both organisations place a strong emphasis on developing nuclear skills and competence. Each encourages and enables the sharing of knowledge and experience to enable a drive for improvements in safety worldwide.

RADIATION RELEASE

Example Hazard

There are multiple, diverse ways to shut down nuclear reactors. One of the most serious hazards considered within the design is a major seismic event. The following example shows how the primary safety functions of reactor shutdown, hold down and long-term cooling of the fuel is achieved in such an event.

Earthquake – Sequence of Events

Taking one of the existing UK Advanced Gas-Cooled Reactor (AGR) nuclear power plants, which utilises a solid graphite core, the adjacent example outlines how multiple barriers are adopted to ensure the reactor can be safely shut down under the most extreme scenarios.

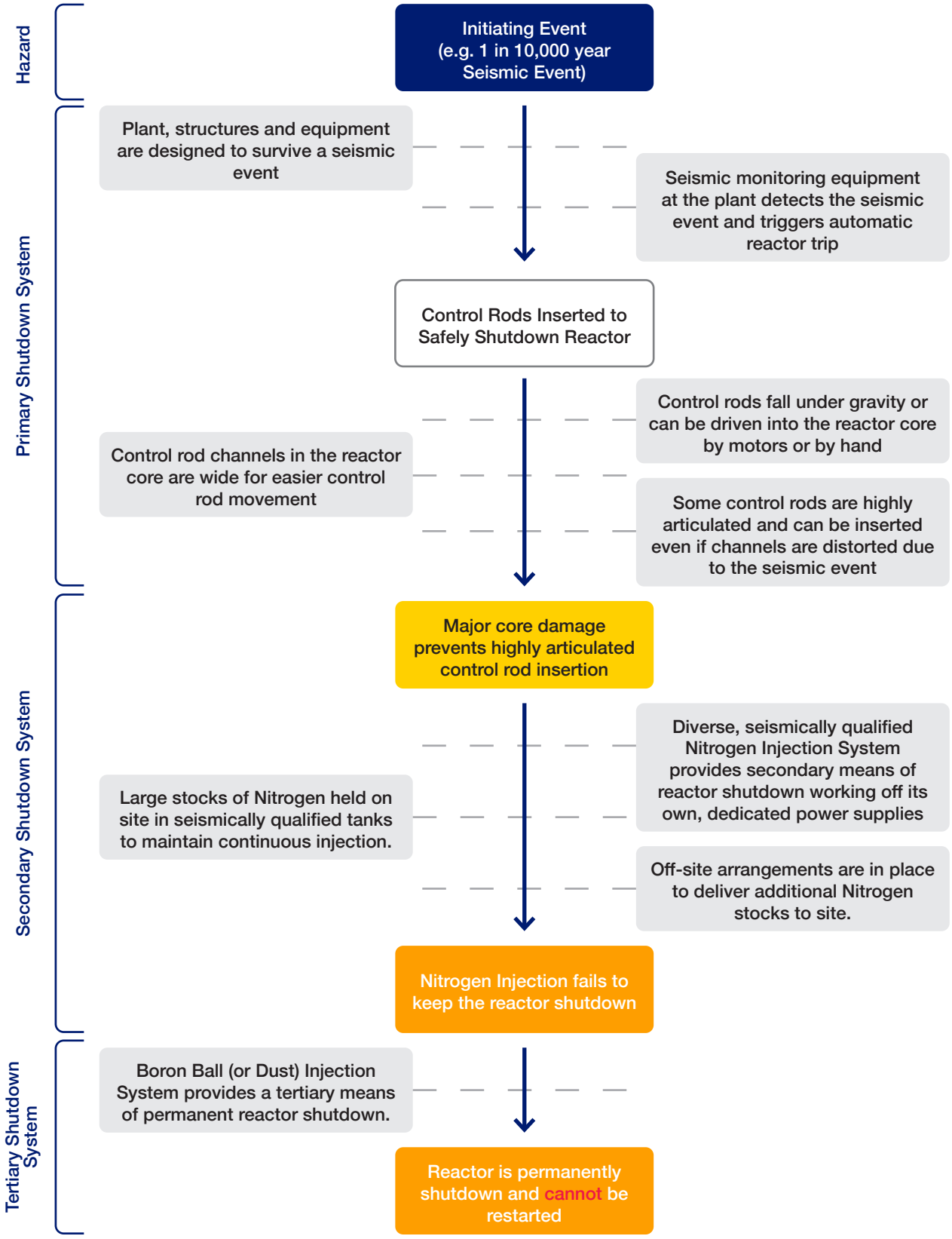
Radiological Risk

By utilising the wide range of measures available, nuclear power plant designers and operators are able to reduce the probability of a hazard occurring to less than 1 in 1 million years, 1 in 10 million years, or even further. Where a risk to operators or the public is presented, a single line of protection is deemed to be insufficient, and backups, in multiple forms are specified. Another key part of reducing risk is through the use of automatic systems. During nuclear power plant operation, there is actually very little manual intervention required, and equipment performing a safety role is designed to continuously monitor and adjust automatically. With all these considerations in place, operators are then required to continuously assess whether more can be done to reduce risk, and protect people and the environment.

Furthermore, a well-established platform exists for operators worldwide to share their experience to ensure others can benefit from the lessons learned. This has created a culture of continuous learning and improvement. This drive to improve is reinforced by the regulators, who adopt the same mentality, with a view of improving safety through consistently reviewing and developing legislation, further driving up the already high standards seen in the industry.

As a result, the nuclear industry has been proven to be an extremely safe form of power generation, and this approach to nuclear safety is used across all aspects of plant operation. Regardless of whether radioactivity is the primary risk or not, the drive for zero harm has resulted in industry-leading health and safety standards for all types of risk.

In the next section, the conventional risks associated with a nuclear power plant operation, which are seen across multiple industries, are discussed.


Hazard
Primary Shutdown System
Secondary Shutdown System
Tertiary Shutdown System
Initiating Event (e.g. 1 in 10,000 year Seismic Event)
Plant, structures and equipment are designed to survive a seismic event
Seismic monitoring equipment at the plant detects the seismic event and triggers automatic reactor trip
Control Rods Inserted to Safely Shutdown Reactor
Control rod channels in the reactor core are wide for easier control rod movement
Control rods fall under gravity or can be driven into the reactor core by motors or by hand
Some control rods are highly articulated and can be inserted even if channels are distorted due to the seismic event
Major core damage prevents highly articulated control rod insertion
Large stocks of Nitrogen held on site in seismically qualified tanks to maintain continuous injection.
Diverse, seismically qualified Nitrogen Injection System provides secondary means of reactor shutdown working off its own, dedicated power supplies
Off-site arrangements are in place to deliver additional Nitrogen stocks to site.
Nitrogen Injection fails to keep the reactor shutdown
Boron Ball (or Dust) Injection System provides a tertiary means of permanent reactor shutdown.
Reactor is permanently shutdown and cannot be restarted

Chemical and Gas Release

Control

In order to store and use chemicals and harmful substances, all industries, including nuclear power plants, must conform with domestic and international legislation.

Legislation

An on-site chemical release would have the potential to cause serious injury or death on site if they are toxic, corrosive, or generally hazardous to health. Some chemicals can also affect the environment through the contamination of land and water. As such, numerous protection measures are still employed.

As with many sites utilising hazardous chemicals, nuclear power plants can fall under the Control of Major Accident Hazards Regulations 2015 (COMAH) due to the requirement to store large quantities of chemicals for operational purposes. The purpose is to prevent and mitigate the effects of major accidents involving dangerous substances which can cause serious damage/harm to people and/or the environment. COMAH treats risks to the environment as seriously as those to people (UK HSE). As with radiological and nuclear risks, compliance with COMAH is stringently regulated by the ONR and relevant environment agency.

Further to this, the storage and use of chemicals is regulated by the HSE through the Control of Substances Hazardous to Health Regulations 2002 (COSHH). Compliance with COSHH is a legal requirement.

All companies and businesses which utilise substances on the COSHH register, including nuclear power plant operators, are required to demonstrate, in advance of operation, that the required measures can and will be put in place to ensure the risk to workers is suitably low. If the appropriate controls are not in place, operators are not suitably trained or informed, a continuous process of review is not undertaken, or unauthorised use is not prevented, then nuclear power plant operation will not be permitted.

The overall purpose is to manage the potential hazards such that they can **Do No Significant Harm**.

The subsequent pages provide some examples of chemicals stored on a nuclear power plant, along with the relevant risks and protection measures in place.

COSHH Principles of Good Control Practice

Minimise Emission, Release and Spread	Design and operate processes and activities to minimise emission, release and spread of substances hazardous to health.
Consider Routes of Exposure	Take into account all relevant routes of exposure – inhalation, skin and ingestion – when developing control measures.
Choose Control Measures Proportionate to the Risk	The more severe the potential health effect and the greater the likelihood of it occurring, the stricter the measures required to control exposure.
Effective Control Options	Choose the most effective and reliable control options that minimise the escape and spread of substances hazardous to health.
Personal Protective Equipment (PPE)	Where adequate control of exposure cannot be achieved by other means, provide, in combination with other control measures, suitable PPE.
Review the Effectiveness of Controls	Check and review regularly all elements of control measures for their continuing effectiveness.
Provide Information and Training	Inform and train all employees on the hazards and risks from substances with which they work, and the use of control measures developed to minimise the risks.
New Measures, New Risks	Ensure that the introduction of measures to control exposure does not increase the overall risk to health and safety.

Source: HSE

Use

As with numerous other industries, the nuclear industry uses a large variety of gaseous, liquid and solid chemicals and products for operational and maintenance requirements, some of which are harmful. As such, the potential for the release of hazardous material exists and must be controlled under COSHH.

Overview

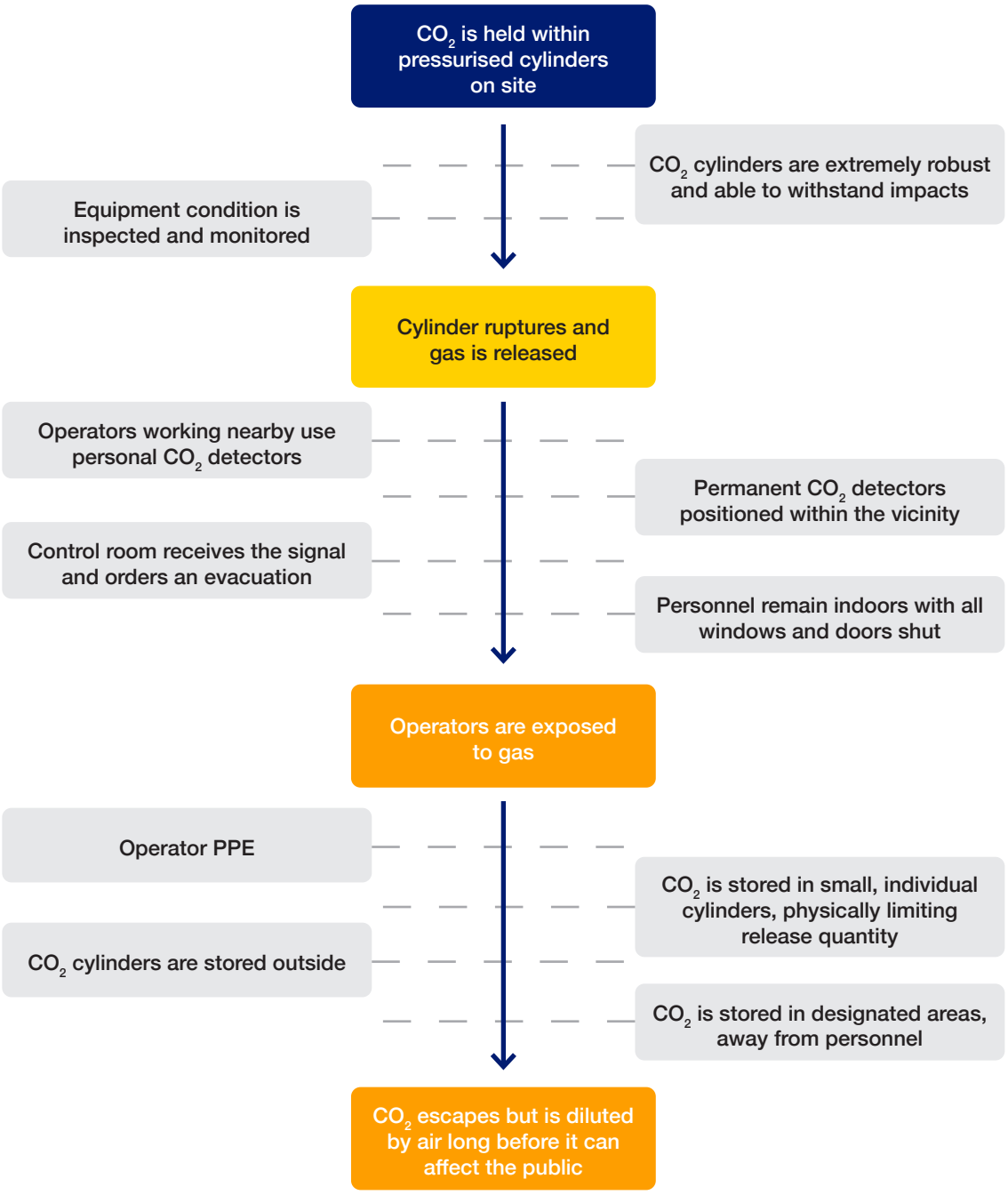
In order to support power generation at a nuclear power plant, the site must maintain reserves of chemicals and gases which are required to fulfil specific roles. These may be associated with operational safety, plant longevity, reducing environmental impact, or a combination of these. The following is a non-exhaustive list of examples:

- **Toxic substances such as Hydrazine (N_2H_4) or Ammonia (NH_4)** – corrosion inhibitors and pH control for high-quality, demineralised water supplies used in power generation processes.
- **Corrosive substances such as Sulphuric Acid (H_2SO_4) or Sodium Hydroxide (NaOH)** – used to enable water demineralisation.
- **Asphyxiant gases such as Carbon Dioxide (CO_2) or Nitrogen (N_2)** – used for gas-cooled reactor operation and for fire suppression.
- **Explosive gases such as Hydrogen (H_2)** – used in alternators (connected to the turbine) to improve efficiency.
- **Flammable and carcinogenic oils, fuels and lubricants** – used for lubrication and for backup diesel generator operation.

Taking CO_2 release as an example, the adjacent image provides an example of the measures in place to comply with COSHH regulations and protect people and the environment.

The nuclear industry's approach to risk assessment does not change when the risk in question is not radiological. The operator's responsibility to ensure all risks on site are reduced to As Low As Reasonably Achievable, means multiple measures are in place to ensure personnel are protected against all considered hazards, regardless of the source.

In the next section, conventional mechanical and physical hazards, such as dropped loads and fire, are discussed. As with the previous section, the types of risks and their potential consequences are discussed, along with the barriers in place to prevent harm and further damage.


CO_2 is held within pressurised cylinders on site
CO_2 cylinders are extremely robust and able to withstand impacts
Equipment condition is inspected and monitored
Cylinder ruptures and gas is released
Operators working nearby use personal CO_2 detectors
Permanent CO_2 detectors positioned within the vicinity
Control room receives the signal and orders an evacuation
Personnel remain indoors with all windows and doors shut
Operators are exposed to gas
Operator PPE
CO_2 is stored in small, individual cylinders, physically limiting release quantity
CO_2 cylinders are stored outside
CO_2 is stored in designated areas, away from personnel
CO_2 escapes but is diluted by air long before it can affect the public

Conventional Hazards

CONVENTIONAL HAZARDS

Overview

The majority of conventional hazards present on a nuclear power plant are common with other forms of industry. These include fire, dropped loads and electric shock.

Overview

In addition to chemical and radiological hazards, numerous conventional risks exist on nuclear power plants, that are common with many other forms of industry. These may be associated with fire, dropped loads, electric shock, or vehicle movements, and each of these would also be present on a coal-fired or gas power station.

Typically, the consequences associated with a conventional hazard could be injury or loss of life. However, on a nuclear site, there is the potential for the impact to spread beyond this. For instance, in the event of a fire, individuals within the vicinity are at risk, but if the fire continues to spread, it may impact important equipment, responsible for maintaining nuclear safety. This link between conventional and radiological safety applies to numerous hazards. Therefore, the same level of rigour that is applied for ensuring nuclear safety, is used for these conventional hazards. As a result, the risk to personnel on site is reduced when compared to other forms of power generation and industries.

This section looks at how the nuclear industry considers these conventional hazards and highlights the protective measures and strategies implemented to ensure the safety of the plant, operators, the public and the environment during operation of a nuclear power plant.

Control

Numerous sets of regulations exist to ensure that sufficient measures are in place to protect workers from all conceivable hazards arising from operations in all industries, including the nuclear industry.

Regulations

There is a wide range of conventional hazards that can occur on industrial facilities and, as such, there are several sets of regulations enforced by domestic and international legislation to ensure that operations undertaken do not present unnecessary risks to workers. Legislation for ensuring the safety of workers includes:

- The Health and Safety at Work (HSW) Act 1974
- Provision and Use of Work Equipment (PUWER) 1998
- Lifting Operations and Lifting Equipment Regulations (LOLER) 1998
- Pressure Systems Safety Regulations (PSSR) 2000
- The Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002
- The Electricity at Work Regulations 1989 (under the HSW Act)
- The Confined Space Regulations 1997
- The Personal Protective Equipment (PPE) Regulations 2002

The next pages provide a high-level overview of a selection of these legislative acts, along with some of the key requirements placed on operators across all sectors. The common themes across each of these are that operators must ensure all equipment is safe and suitable for use, workers are appropriately trained and approval for continued use is provided by the necessary authority.

As with chemical hazards (which are managed through COSHH), compliance with these regulations is a regulatory requirement, without which nuclear power plant operation would not be permitted.

Conventional Hazard Regulations

Provision and Use of Work Equipment (PUWER)	– PUWER requires that equipment provided for use at work is suitable and safe for use, maintained in a safe condition and inspected to ensure it is correctly installed and does not subsequently deteriorate – Only people who have received adequate instruction and training are permitted to use equipment under this category – Suitable health and safety measures, such as protective devices and controls are in place. These will normally include emergency stop devices, adequate means of isolation from sources of energy, clearly visible markings and warning devices – Use is in accordance with specific requirements, for mobile work equipment and power presses
Lifting Operations and Lifting Equipment Regulations (LOLER)	– These place duties on people and companies who own, operate or have control over lifting equipment. This includes all businesses and organisations whose employees use lifting equipment, whether owned by them or not. All lifting operations involving lifting equipment must be properly planned by a competent person, appropriately supervised and carried out in a safe manner. – LOLER also requires that all equipment used for lifting is fit for purpose, appropriate for the task, suitably marked and, in many cases, subject to statutory periodic 'thorough examination'. Records must be kept of all thorough examinations and any defects found must be reported to both the person responsible for the equipment and the relevant enforcing authority

Pressure Systems Safety Regulations (PSSR)	– The aim of PSSR is to prevent serious injury from the hazard of stored energy, as a result of the failure of a pressure system or one of its component parts – Before using any qualifying pressure equipment (new or otherwise), a written scheme of examination must be in place, and an examination undertaken – Only authorised, competent persons are permitted to operate systems which fall under PSSR regulations
The Dangerous Substances and Explosive Atmospheres Regulations (DSEAR)	– Determine what dangerous substances are in the workplace and the associated risks – Identify and apply measures to either remove those risks or control them – prepare plans and procedures to deal with accidents, incidents and emergencies – Ensure employees are properly informed and trained – Identify and classify areas of the workplace where explosive atmospheres may occur and avoid ignition sources
The Confined Spaces Regulations 1997	– Determine the risks and hazards associated with the area, such as gas or fire – Undertake all work outside of the confined space if at all possible – If this cannot be done, undertake a comprehensive risk assessment and define a safe system of work with clear instructions and adequate emergency arrangements, such as evacuation, prior to entry

Source: HSE

Fire

Fire is a key risk to both personnel and nuclear safety. As such, the nuclear industry adopts a stringent and conservative approach to ensure the risks are significantly reduced.

Fire

The risk of fire on a nuclear power plant, although present on most conventional power plants, can ultimately result in a much more severe impact due to the potential for it to affect important equipment, which may threaten nuclear safety.

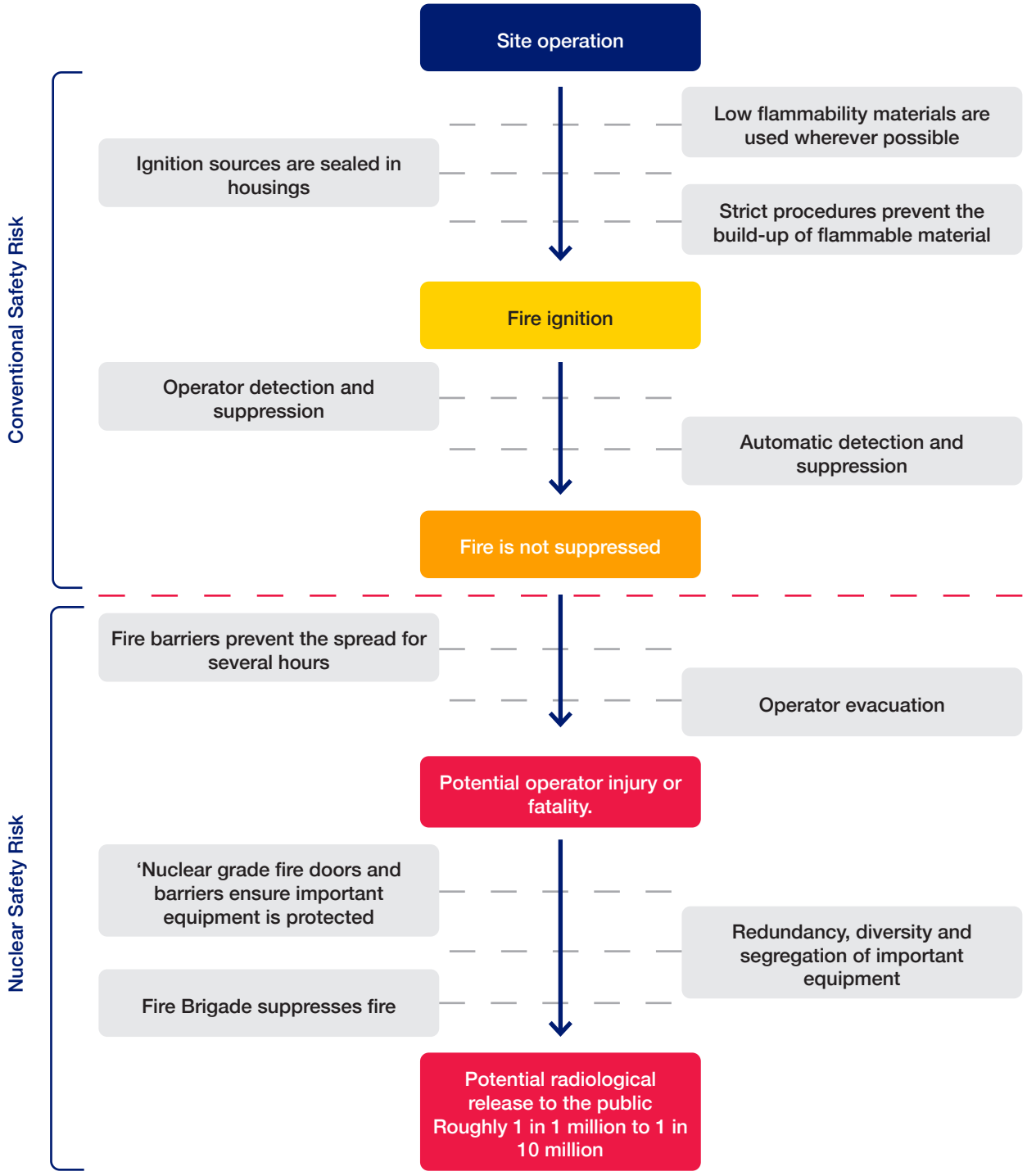
The defence in depth principle, adopted during nuclear power plant design and operation, incorporates three main objectives:

1. **To prevent fires from starting** (e.g. by control of ignition sources and minimisation of combustible materials on site).
2. **To quickly detect and extinguish fires**, reducing the overall damage to the nuclear power plant and risk to personnel – this can be done through manual or automatic means.
3. **To prevent the spread of fire** that has not been extinguished (i.e. containment), minimising the overall effect on equipment and ensuring the safety of personnel.

The robust measures required to demonstrate nuclear safety also have a positive impact on the protection of plant workers from fire. For example, 'Nuclear Significant Fire Doors' are adopted on nuclear power plants that are either locked or are alarmed if they are opened for access and not closed quickly. Such doors can withstand the most severe fires for long durations of time (far in excess of the time required to shut down a reactor and evacuate personnel). These are used in order to maintain nuclear safety, but also directly protect personnel.

As a result, the number of protective measures against the propagation of fire is generally higher than on conventional power plants or other large industrial sites. This is illustrated in the adjacent diagram.

Defence in Depth – Fire Hazards



CONVENTIONAL HAZARDS

Heavy lifting

Crane operation presents both conventional and radiological risks on a nuclear power plant. Multiple layers of redundancy are built in to ensure safety is maintained at all times.

Introduction

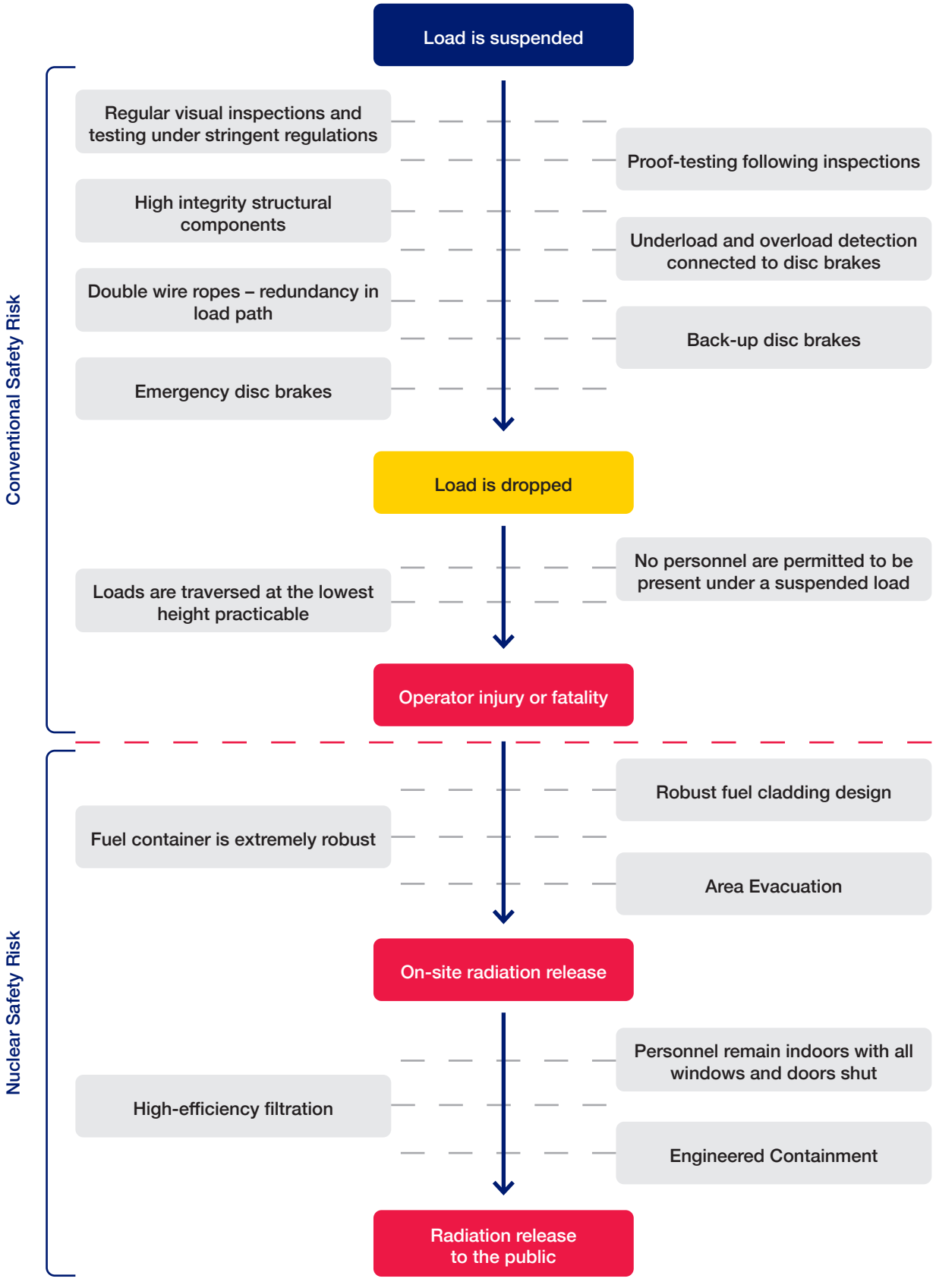
Lifting of heavy equipment is often required on a nuclear site, for example when undertaking turbine maintenance. The primary events of concern associated with using lifting equipment include:

- Dropping loads with the potential to injure personnel or damage equipment;
- Skewing of the crane beam during travel, causing the crane to become stuck and the load becoming suspended; and
- Collisions with structures or equipment, which could result in harm to personnel or damage to important equipment.

Dropped loads or collisions have the potential to affect nuclear safety. The nuclear industry takes a uniquely stringent approach to crane design to ensure these events do not occur. To implement this, multiple layers of protection are put in place, such as:

- **Regular and thorough inspections –** this is a legal requirement in line with LOLER regulations and, without this, the equipment in question cannot be used.
- **Proof-testing**, which proves that the equipment can undertake lifts greater than would be required under normal operation.
- **Load path redundancy**: dual wire ropes, each capable of individually supporting the maximum load;
- **High factors of safety**: the crane will be able to lift much more than is required of it;
- **Primary, backup and emergency brakes:** to halt movement and/or lifting in the event of a fault;
- **Primary and backup limit switches:** to detect when motion is beyond allowable limits;
- **Reduced speed operation:** in the event of a collision, the impact forces are reduced;
- **No personnel may be present under a suspended load,** preventing the possibility for operator injury during lifting operations; and
- Loads are traversed at the l**owest practicable height** until raising is required.

These are just some examples of the measures taken for nuclear crane design, which all have a positive effect on conventional safety. An example fault sequence, highlighting the barriers and protection measures in place, is provided overleaf.


Load is suspended
Regular visual inspections and testing under stringent regulations
Proof-testing following inspections
High integrity structural components
Underload and overload detection connected to disc brakes
Double wire ropes – redundancy in load path
Back-up disc brakes
Emergency disc brakes
Load is dropped
Loads are traversed at the lowest height practicable
No personnel are permitted to be present under a suspended load
Operator injury or fatality
Conventional Safety Risk
Fuel container is extremely robust
Robust fuel cladding design
Area Evacuation
On-site radiation release
High-efficiency filtration
Personnel remain indoors with all windows and doors shut
Engineered Containment
Radiation release to the public
Nuclear Safety Risk

Conclusion

Conclusion

The nuclear industry adopts a culture of continuous improvement as well as sharing of best practice and lessons learned. Compliance with strict domestic and international legislation ensures nuclear is the safest form of power generation.

Since 1956, nuclear power has played an important role in producing low-carbon power for the UK grid. The nuclear industry is subject to extremely strict safety and environmental domestic and international regulations that ensure hazards can Do No Significant Harm.

All forms of industry, including nuclear, present the potential for hazards to occur. In the commercial sector, the requirement to maintain nuclear safety is unique to the operation of a nuclear power plant. However, all hazards present on a nuclear power plant are regulated in line with strict, well-developed national and international legislation.

Conventional hazards, such as crane and vehicle operation, the potential for fire or explosion, the use of chemicals and gases, electrical hazards and mechanical hazards are all present on coal and gas-fired stations, in manufacturing and in many other industries. Numerous other sectors also present radiological hazards, through the use or production of radioactive material. The key difference between each of these and the nuclear industry is in the approach to managing and reducing risk.

Along with the collaborative learning culture, a drive for continuous improvement and a strong scientific underpinning, compliance with stringent legislation and regulation ensures that operators must prove they have done everything they can to reduce risk, and that site operation can Do No Significant Harm.

This results in an operating environment that presents extremely low levels of risk, regardless of the hazard in question. As such, over the course of several decades, the nuclear industry has demonstrated that it is not only one of the safest forms of power generation, but also one of the safest industries for both operators and the public.

This brochure has been developed by Arup on behalf of EDF