EU Sustainable Finance Taxonomy – Radioactive Waste Management Review

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EU Sustainable Taxonomy: Radioactive Waste Management Review

Section 1: Introduction

Introduction: Purpose of Report

This report presents an overview of radioactive waste management strategies, showing how they have developed, how safe practices are ensured, and where they differ from strategies associated with other forms of energy production.

Introduction

Nuclear energy forms a significant part of the global electricity generation mix, providing roughly 26% of all electricity produced in Europe in 2018. The remainder was made up by renewable sources including wind and solar (28%), and the combustion of fossil fuels, such as gas and coal (46%). As climate change and scarcity of resources become greater concerns, there is an ever-growing requirement to reduce the energy sector's dependency on fossil fuel combustion, and to look to alternative sources of energy with much smaller environmental footprints.

In order to make substantial changes to a country's energy mix, the implications associated with adopting revised energy policies and making use of alternative sources must be considered, particularly with regards to other outputs associated with energy production, namely: raw materials, manufacturing, decommissioning and waste management.

The purpose of this report is to undertake a literary review into the last of these with a specific focus on nuclear energy and the production and management of radioactive wastes, and to present the findings on how this compares to other forms of power generation, particularly with regards to waste quantities and types, recycling, storage and disposal.

In general, waste production across all sectors, including energy, is a growing concern. All forms of industry produce a variety of waste streams, which can include hazardous or toxic materials requiring appropriate management. Even the production of radioactive waste, often thought to be unique to the nuclear industry, is a significant output from fossil fuel production and use, when burning coal at a coal-fired power station or in the oil and gas industry, for example.

However, in the nuclear industry, operators are legally required to take full ownership of the wastes generated during operation and maintenance, and must bear the costs associated with its long-term management, storage and disposal. In the UK it is a legal requirement for new nuclear build project developers to define and seek Government approval for funding arrangements to cover waste management and decommissioning activities prior to starting construction, to ensure that sufficient funding is generated and reserved during the operational phase. The cost of operation must also take into account front-end activities associated with fuel production and purchase. However, the expenditure associated with fuel purchase is a fraction of the overall plant cost.

Whilst, there is a financial driver for operators to reduce waste generation, the nuclear industry is also leading the way in reducing risk to people and the environment, through a culture of continuous improvement driven by internal and external regulation. The nature of the waste streams produced, along with the perceived risk, has ultimately led to the implementation of tighter controls when compared with other industries, to ensure that risks to the public and environment are negligible. The Environmental Permitting (England and Wales) Regulations 2016 (EPR) set the requirement for Operators to reduce radiation levels and environmental impact resulting from disposal and management of radioactive waste to As Low As Reasonably Achievable (ALARA) levels. In the UK, this is implemented via the application of the Best Available Technique (BAT) methodology, which is a permit requirement where operators must demonstrate environmental optimisation (minimisation of potential impact) through BAT.

This is in contrast to numerous other forms of power generation, where the waste products generated during operation or following decommissioning are often not subject to the same level of scrutiny or audit. Waste from other industries can often be diverted to landfill, with no long-term disposal or reprocessing strategy in place, and the potential to cause long-term, adverse effects on the environment.

Furthermore, the total volumes of waste generated by Nuclear Power Plants (NPP) are less than the waste streams produced from coal-fired power generation (IAEA), solar (IRENA) and wind power (Wind turbine blade waste in 2050, by Liu, Pu; Barlow, Claire Y, 2017), for example. A culture of continuous improvement ensures that this is being reduced further with NPP design, operating arrangements and R&D into improved waste management techniques. Each of these contributes to an increase in the quantity of materials that can be reclaimed and recycled, even when used in highly radioactive and contaminated areas.

The first generation of NPPs started operation during the 1950s and radioactive materials have been generated and safely stored from that time. Since then, continuous investment in reactor technology and in the safe management of the radioactive waste generated has contributed to substantial reductions in waste volumes and significant improvements in best practice for safe waste management. These improvements have been driven by a number of factors including: learning from experience of early NPP operation; technological and design improvements; knowledge sharing through numerous international platforms, such as the World Association of Nuclear Operators (WANO); collaboration between governments and countries; regulatory influence; and learning from accidents or events that have occurred during operation or decommissioning activities.

This experience collated over several decades of operation presents many examples highlighting the nuclear industry's ability and drive to learn and subsequently enact change to its culture and processes, often setting the bar far above the standards adopted by other industries. Furthermore, research and development (R&D) strives to complement the high standards set though exploring and developing solutions to improve storage and processing options.

Introduction: Radioactivity Overview

Radiation occurs from a number of different sources; however, it is the potential for dose to people and radioactive release to the environment that represents the impact of that radioactivity.

Radiation and Radioactivity

Radiation is the emission and transmission of energy from electromagnetic waves (such as visible light, radio waves, microwaves, x-rays, or cosmic rays emitted by the sun) or from particles such as atoms.

There are many types of radiation with a wide range of energy levels. Electromagnetic waves or particles with sufficiently high energy to directly or indirectly knock electrons out from an atom or molecule, producing ions (atoms with a positive or negative charge), are referred to as "ionising radiation".

While most atoms are stable, the atoms of some elements found in nature or produced artificially are slightly unstable and, to achieve greater stability, they emit energy in the form of ionising radiation. Such atoms are referred to as being radioactive, and the process of emitting this radiation is known as radioactive decay. Each instance of radioactive decay is measured as one Becquerel (Bq), and this unit is used as the measure of radioactivity.

When ionising radiation is absorbed by the human body, the amount received is referred to 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 to better convey the small quantities of radiation typically absorbed in everyday life and in industry. For example:

- The legal upper dose limit in the UK for any person working at an NPP is 20 mSv; and
- The legal upper dose limit for any member of the public in the UK due to NPP operation is 1 mSv.

Yet, in reality, the doses absorbed by anyone due to NPP operation are far below the legal limits as shown in the adjacent chart.

Background Radiation

Background radiation is the same as any other form of radiation, only it comes from sources associated with everyday life, such as food, the ground or cosmic radiation from the outer space. For example, small amounts of naturally occurring potassium-40 are present in bananas, coffee and brazil nuts, and this undergoes a form of radioactive decay known as beta decay.

A Radioactive Dose Chart is presented in the image opposite and highlights the different sources of radiation a person may be exposed to, namely: natural sources, medical procedures (the greatest contributors) and from industry. For example, 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 NPP worker over the course of one year.

Radiation Dose Chart

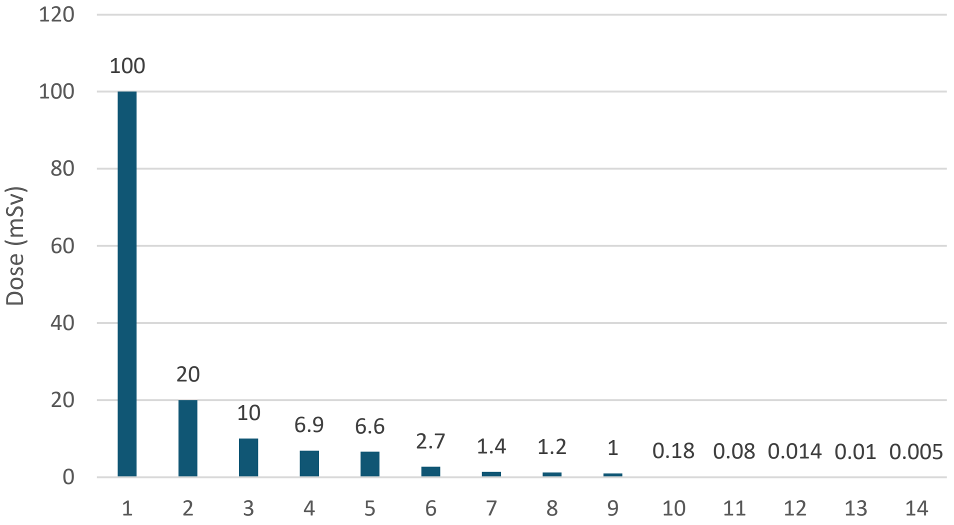


Chart Ref.	Example of Background Radiation Source	Dose (mSv)
1	Lowest level linked to an increased risk of developing cancer	100
2	Legal upper dose limit for NPP workers	20
3	CT scan of the whole spine	10
4	Average annual radon dose to people in Cornwall, UK	6.9
5	CT scan on chest	6.6
6	UK average annual radiation dose	2.7
7	CT scan of the head	1.4
8	UK annual average Radon dose	1.2
9	Legal upper dose limit for the public due to NPP operation	1.0
10	NPP worker average annual occupational exposure (2010)	0.18
11	Transatlantic flight	0.08
12	Chest x-ray	0.014
13	Eating 100g of brazil nuts	0.01
14	Dental x-ray	0.005

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

Introduction: Nuclear Power Technology Overview

Nuclear reactor technology has evolved from the first commercial NPP at Calder Hall, UK in 1956, to the modern PWRs, such as EPRs, that are being constructed today.

Nuclear Fission

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-235, 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-235 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. Many of these lighter elements are also radioactive and by a similar process generate heat by radioactive decay.
- 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.

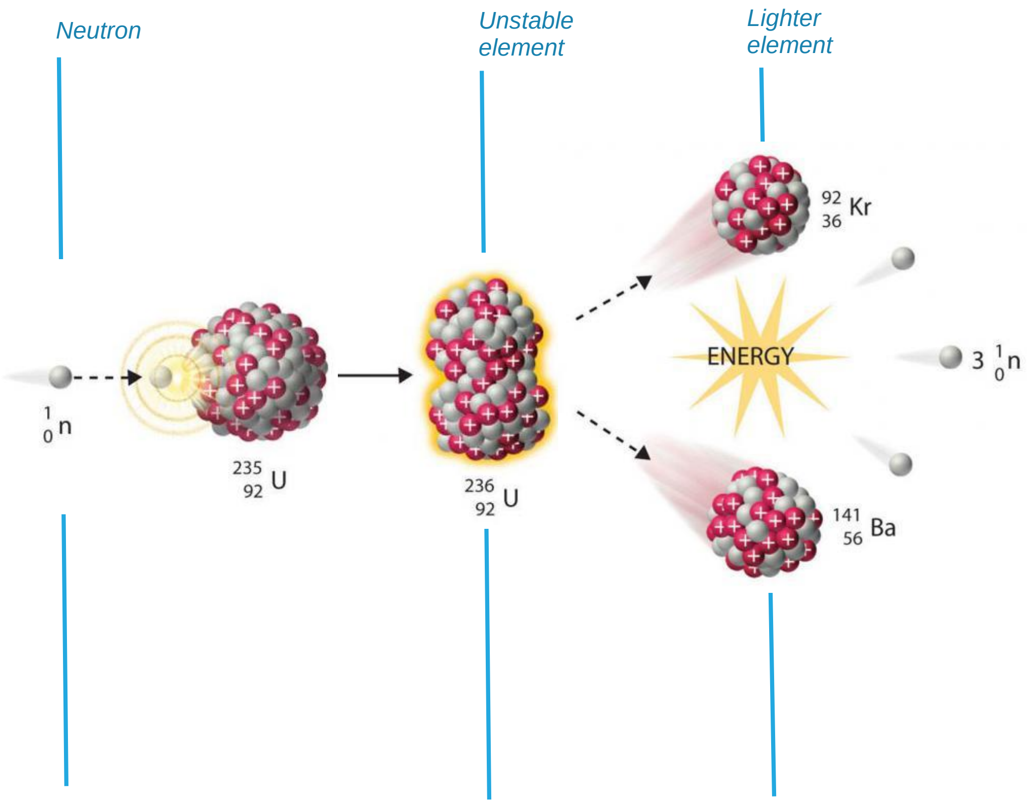
Nuclear Power Plants Overview

Drivers supporting the use of nuclear power are as follows:

- During operation, there are no greenhouse gases, particulates or NO_x emissions produced.
- Modern NPPs 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”).
- NPPs can remain operational for long periods of time, with modern designs aiming to generate electricity for between 60 and 100 years.
- Uranium is an abundant element, presenting high fuel security.
- The nuclear industry is the most stringently regulated form of power generation, and the risks presented to the public and environment are extremely low.
- Operation of an NPP requires specialist skills, which are exportable.

The following slides provide overviews of nuclear reactor designs currently in operation in the UK.

Example of nuclear fission chain reaction



Source: European Union Science Hub

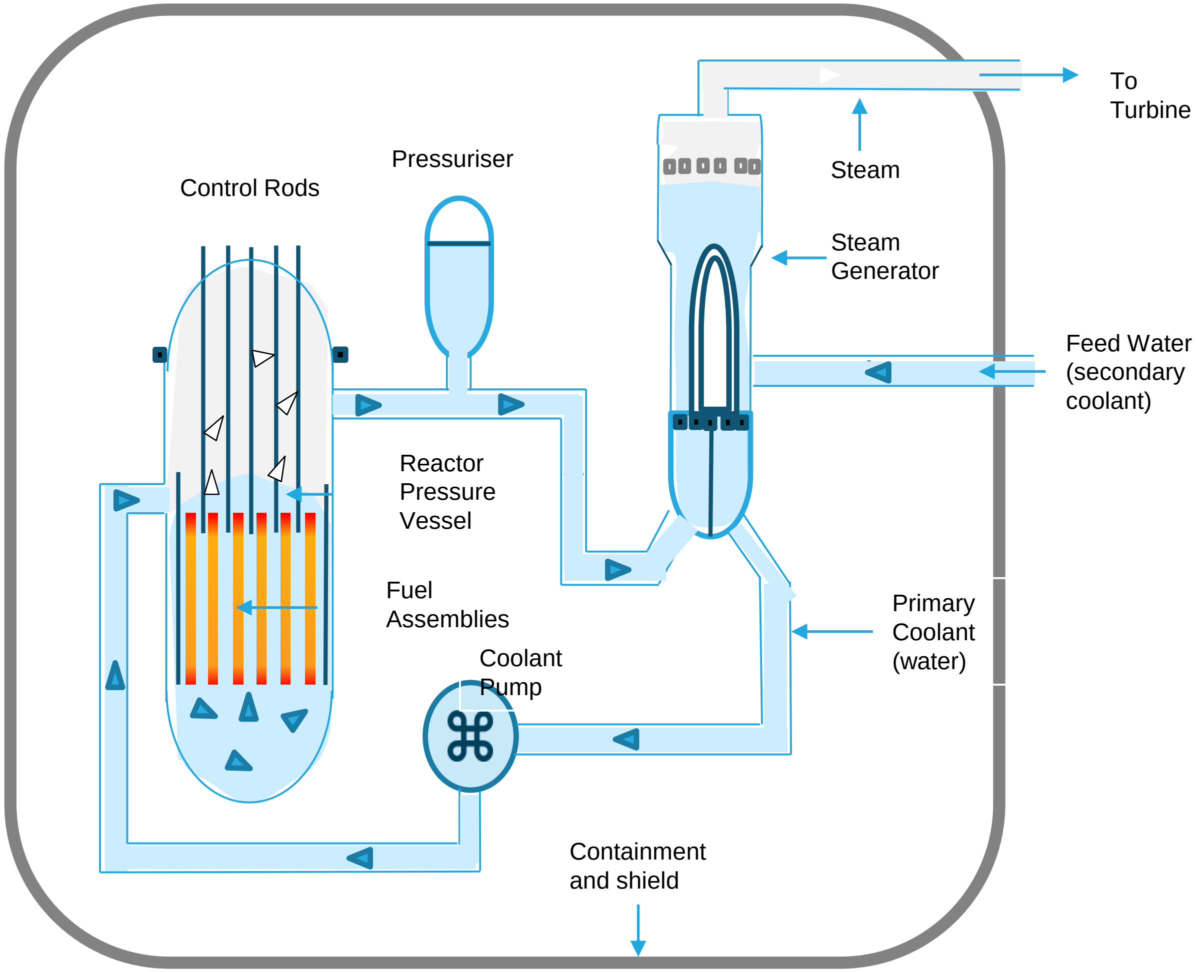
Introduction: Pressurised Water Reactor (PWR) Technology Overview

Nuclear fission produces heat that is transferred to a pressurised water circuit. This passes through steam generators and transfers this heat to a secondary water circuit, turning it into steam that drives a turbine, producing electricity.

PWR Reactor Schematic

Most NPPs 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.



Introduction: Advanced Gas-cooled Reactor (AGR) Technology

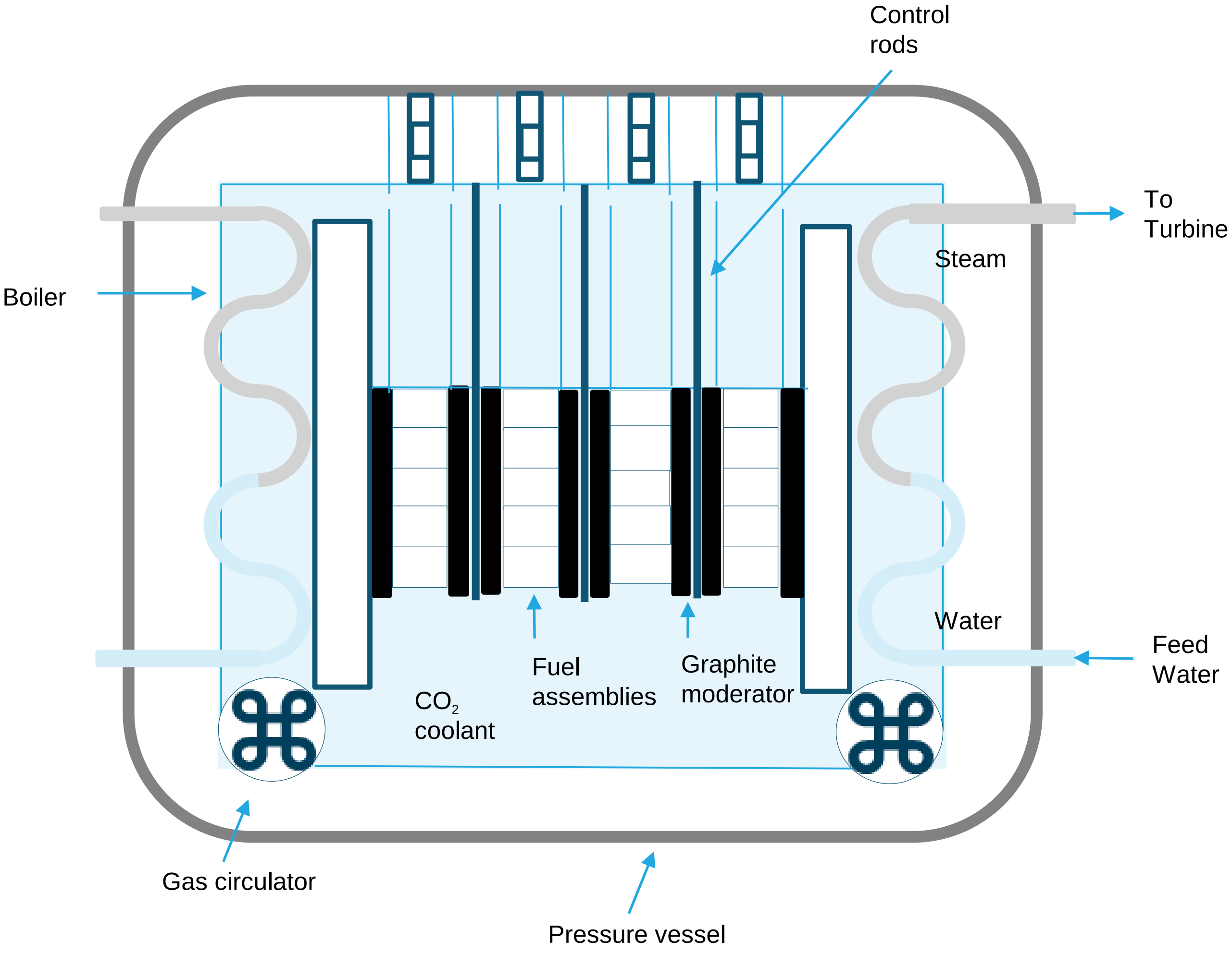
Electricity is generated in an AGR NPP through a sustained nuclear reaction heating pressurised gas circulated over the fuel assemblies. This heat is transferred to a secondary, closed-loop containing water to produce steam.

AGR Design Overview

In the UK, an alternative type of reactor is also in operation, known as an Advanced Gas-Cooled Reactor (AGR). The process for heat production and transfer is largely the same as in a PWR. However, this design uses CO_2 as the primary coolant and graphite bricks as the moderator. The key features and differences are listed below

- **Fuel Assemblies** are of a different design, but still contain Uranium, the element which undergoes fission to produce heat.
- **Control Rods** are, again, of a different design to those used in PWRs, but they still control and limit the reactivity by absorbing neutrons, and the further they are inserted, the further the reactivity and heat produced drops.
- **The Primary Coolant** is CO_2 instead of water, and this absorbs heat from the fuel, and transfers it to water contained within boiler tubes. The gas circulators encourage flow and improve heat transfer.
- **The Moderator** is made of graphite, as no water is present in the reactor core. However, it performs the same moderating function as water does in a PWR and slows neutrons down to the correct speed.
- The **Reactor Pressure Vessel** houses the reactor core, the CO_2 coolant and the heat transfer sections of the boilers.
- Instead of steam generators, AGRs use **Boilers.** Sections of these are located inside the **Reactor Pressure Vessel**, which absorb heat from the CO_2 coolant, turning **Feed Water** into steam that is used to turn a **Turbine**.
- As with a PWR, the **Turbine** is connected to a **Generator**, which produces electricity.

AGR Reactor Schematic



Legislation & Regulation: UK Nuclear Power

Decommissioned, generating or future civil nuclear power stations are all subject to stringent safety and environmental regulations

UK Nuclear Power

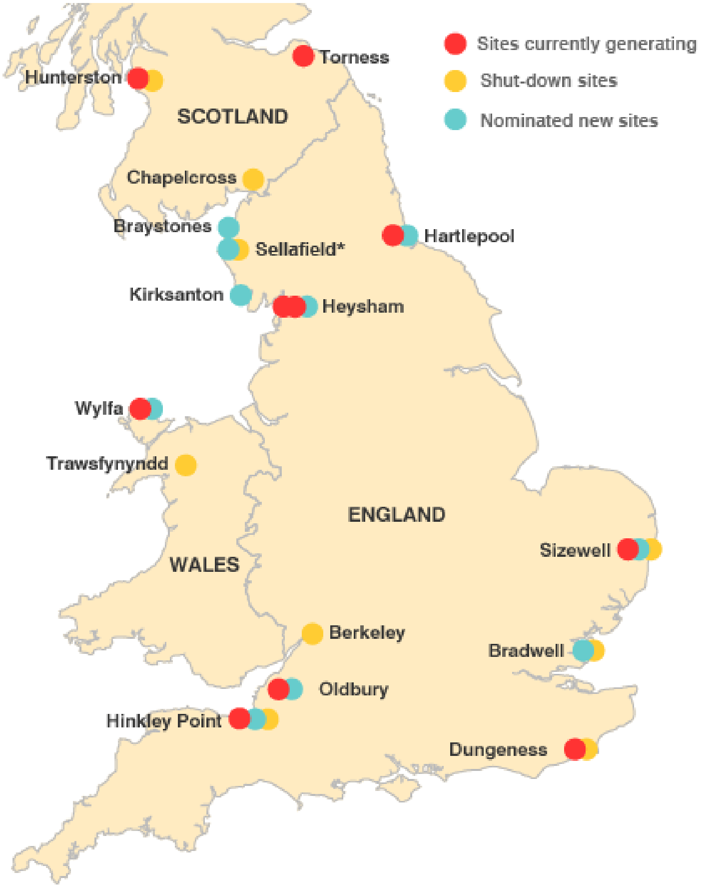
Since 1956, nuclear power has played an important role in producing low-carbon power for the UK grid. The adjacent image highlights that there are currently:

- Decommissioning (non-operational): 11 Generation-I gas-cooled reactor (Magnox) sites;
- Operational: 7 twin-reactor AGRs and 1 single-reactor PWR (Generation-II); and
- Several nominated/suitable sites for future nuclear new build construction.

Each of these is subject to extremely strict safety and environmental regulations. Each site must comply with regulatory requirements that apply to the site's lifecycle stage. The table below provides example considerations for sites undergoing decommissioning, and for those currently generating, or being constructed. The mechanisms for achieving regulatory compliance along with greater detail on the requirements and process, are discussed in the next section and throughout the report.

Site	Stage	Aim	Outline of Requirements
Berkeley	Decommission and waste retrieval	Process legacy waste streams from past operational practices in line with current requirements.	Legacy waste retrieval, segregation and packaging. Containment of all radioactivity (no operational discharge). Safe and secure on-site interim storage of waste retrieved. Demonstration to the regulators that risk to people and the environment is ALARA at all times.
Sizewell B	Operational	Continuously improve NPP operation in line with evolving legislation, to minimise current and future impact.	Waste minimisation, correct sentencing and record keeping. Process discharges justified and below regulatory limits. On-site interim storage of spent fuel. Demonstration to the regulators that the risk to people and the environment is ALARA at all times. Demonstration of continuous learning and improvement.
Hinkley Point C	Design and Construction	Design and construct NPP to minimise operational and post-generating impacts, ensuring all waste streams are segregated and sentenced appropriately.	Proof that waste minimisation, correct sentencing and record keeping will be achieved and present an improvement over previous sites (such as those listed above). Proof that process discharges will be below regulatory requirements and justified, and present an improvement over previous sites (again, such as those listed above). Proof that safe and secure on-site interim storage of spent fuel and radioactive waste can be achieved for as long as is required. Demonstration to the regulators that risk to people and the environment is, and will continue to be, ALARA.

UK Civil Nuclear Sites



Source: HM Government

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EU Sustainable Taxonomy: Radioactive Waste Management Review

Section 2: Legislation & Regulation

Legislation & Regulation: Overview

Stringent legislation and regulation drives best practice within the industry. The requirements associated with the management of radioactive waste ensure the risks to people and the environment are negligible.

Overview and Principles

Governments ensure that the types and volumes of waste generated by NPPs, as well as from other activities involving radioactive material, are highly regulated and closely controlled. This helps to drive safe procedures and standards for the management, transport and storage of radioactive waste. Through striving for continuous improvement and adopting lessons learnt, policy makers have implemented increasingly strict regulations and worked to determine the best long-term disposal method for radioactive waste.

In general, the main principles that govern decisions by regulators and government bodies are driven by considering a number of different influencing factors: from the general public's opinion, international communities, UK strategy and industry itself (amongst others). The main factors that influence regulations and legislation in the UK are given as an example in the diagram below, with the associated documentation and bodies involved indicated. This is a similar approach taken by most governments in countries with a commercial nuclear power industry.

A key part of regulation is not only the legislation describing the overarching objectives, but that policies are set to enable the delivery of these objectives and implement desirable management practices that are both safe for the public and economically viable. These methods of implementation vary between countries as well as how they are applied to different industries. The regulatory control of radioactive waste management involves a number of elements and bodies associated with their delivery. These elements generally start with the recognition of the need for regulatory control and development of a policy for its implementation. In its simplest form, regulation originally focused on the protection against ionising radiation, which includes radioactive waste management. However, the role of regulators has expanded in recent years, with many regulators of many countries looking at the broader environmental, internal, social and economic objectives. This has led to international standards and guidelines for the disposal site selection criteria and waste management practices. For most countries, radioactive waste management and its regulation is controlled by the central government, who will be advised by various departments and independent advisory bodies.

International Community	EU Directives			International Standards and Guidance e.g. IAEA, Nuclear Energy Agency (NEA), European Atomic Energy Community (Euratom), International Commission on Radiological Protection (ICRP) and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)	
UK Policy	UK & Devolved Government Policy – Energy Act 2008				
	Policy for the long term management of solid LLW in the UK~2007	Implementing Geological Disposal working with communities 2018	Scotland's Higher Activity Waste (HAW) Policy 2011	Welsh Government Geological Disposal: Working with Communities 2019	Committee on Radioactive Waste Management (CoRWM) Independent scrutiny of government policy
UK Strategy	Strategy for the management of solid LLW from the nuclear industry - 2016	UK Strategy for Radioactive Discharges, 2017 disposal working with communities '18	Nuclear Decommissioning Authority (NDA) Strategy - 2016	Implementation Strategy for Scotland's Policy on HAW - 2016	Ministry of Defence (MOD) Nuclear Liabilities Management Strategy – 2011
Local Government	Local Authorities Development Plans planning Applications		Nuclear Legacy Advisory Forum (NuLEAF) Scottish Councils of Radioactive Substances (SCORS)		NDA site stakeholder groups, local liaison groups
Radioactive Waste Producers	Decommissioning and Waste Management Plans & Funding Arrangements Integrated Waste Strategies		Radioactive Waste Management Cases Environmental Optimisation Cases Best Available Techniques (BAT) Cases		Disposability Assessment
Regulators	Environmental Agency Scottish Environmental Protection Agency Natural Resources Wales		Nuclear Safety Office for Nuclear Regulation (ONR)		Permits and authorisation Letters of Compliance
	Guidance on requirements for authorisations of Near-Surface and Geological Disposal			Joint regulatory guidance on radioactive waste management	

Source: HM Government – Radioactive Waste Strategy 2019

Legislation & Regulation: The UK Regulator

In the UK, the regulator sets licence conditions as a goal setting approach, putting the onus on those in the industry to demonstrate their arrangements for assuring nuclear safety are suitable and sufficient, allowing for future innovation.

UK Regulatory Environment Overview

In the UK, the legal framework is derived from the Nuclear Installation Act 1965, the Health and Safety at Work Act 1974 (HSWA), the Energy Act 2013 and the Ionising Radiations Regulations 2017 (IRR17). Subject to approval, each NPP is granted a Nuclear Site Licence (NSL) issued under the Nuclear Installation Act 1965. The NSL consists of 36 standardised Licence Conditions that set out the arrangements by which the Licensee shall conduct its business activities to ensure nuclear safety. These are highlighted in the table opposite and enforced by the Office for Nuclear Regulation (ONR).

The ONR enforces strict Safety Assessment Principles (SAP) against which UK operators are assessed. Licensees must demonstrate compliance with these strict requirements under each of the Licence Conditions, which are designed to ensure that NPP construction, operation and decommissioning is all undertaken safely and does not put human health or the environment at risk. The key focus is on risk reduction and, if the operator cannot demonstrate compliance and that risk has been reduced to ALARA levels, then permission to operate will be withheld.

The ONR practices an “enabling regulation” approach and the goal setting nature of UK nuclear regulation, which places the onus on the Licensee to demonstrate that their arrangements for assuring nuclear safety are suitable and sufficient. The ONR then carries out inspections and assessments to judge whether licensees are operating with risk reduced to ALARP, based on the demonstration that any further safety measures, would be grossly disproportionate to the results achieved. This kind of interaction aims to facilitate the mature, transparent and collaborative relationship between NPP operators and the regulator. There is also a drive to share lessons learned in an open way and co-operate with international regulators on issues relating to common areas such as safety, security and how radioactive waste is managed, including associated areas of research.

As a result of this stringent and collaborative approach, the risks associated with nuclear power, at any point of the lifecycle, are extremely low. For example, the European Atomic Energy Community (Euratom) and the Ionising Radiation Regulations 2017 (UK) 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); the limits of exposure are 20 mSv for radiation workers and 1 mSv for members of the public per year (bottom table). However, typical dose rates for workers on an NPP site are far below levels seen for other common sources, such as background radiation and certain medical procedures. A more detailed comparison of doses from various sources is provided later in this section.

The 36 UK Licence Conditions

1	Interpretation	19	Construction or installation of new plant
2	Marking of the site boundary	20	Modification to design of plant under construction
3	Control of property transactions	21	Commissioning
4	Restrictions on nuclear matter on the site	22	Modification or experiment on existing plant
5	Consignment of nuclear matter	23	Operating rules
6	Documents, records, authorities and certificates	24	Operating instructions
7	Incidents on the site	25	Operational records
8	Warning Notices	26	Control and supervision of operations
9	Instructions to persons on the site	27	Safety mechanisms, devices and circuits
10	Training	28	Examination, inspection, maintenance and testing
11	Emergency Arrangements	29	Duty to carry out tests, inspections and examinations
12	Duly authorised and other suitably qualified and experienced persons	30	Periodic shutdown
13	Nuclear safety committee	31	Shutdown of specified operations
14	Safety documentation	32	Accumulation of radioactive waste
15	Periodic review	33	Disposal of radioactive waste
16	Site plans, designs and specifications	34	Leakage and escape of radioactive material and radioactive waste
17	Management systems	35	Decommissioning
18	Radiological protection	36	Organisational capability

Source: ONR

Summary of Dose Limits for the Public

Dose Limit	Dose limit for the skin	Dose limit for lens of the eye	Single site constraint	Single source constraint	Investigation level	Potentially ‘of no regulatory concern’
1 mSv/y	50 mSv/y average over 1 cm³	15 mSv/y	0.5 mSv/y	0.3 mSv/y (max)	30% of GDC or 0.1 mSv/y	≤ 0.01 mSv/y

Note: Generalised Derived Constraints (GDC) are constraints placed on radiological discharges from NPPs.

Source: EA, SEPA, Northern Ireland Environment Agency, Health Protection Agency and Food Standards Agency

Legislation & Regulation: Environmental Permitting

All NPPs must demonstrate the implementation of BAT in their management of radioactive waste. In the UK, this is a legal requirement for all industries including NPPs to secure their operating permits.

Environmental Permitting

Whilst there is a financial driver for operators to reduce waste production, the nuclear industry places environmental and public risk reduction as the overriding priorities, through a mixture of strict internal and external regulation. The nature of the waste streams produced, along with the perceived risk, has ultimately led to the implementation of tighter controls when compared with other industries, to ensure the risks to the public and environment are negligible.

The Environmental Permitting Regulations set the requirement for operators to reduce radiation levels from disposal and management of radioactive waste to ALARA levels. In the UK, this is implemented via the application of Best Available Techniques (BAT), which is a permit requirement where operators must demonstrate environmental optimisation through the application of BAT before they can commence construction or continue existing activities, such as operation or decommissioning.

BAT Requirements

Demonstration of BAT is legal requirement in the UK for any form of industrial installation that could have an impact on the environment through emissions release or discharging of waste, for example. In line with the Oslo-Paris (OSPAR) convention, the UK government adopts the following definition for the demonstration of BAT:

> *The term "best available techniques" means the latest stage of development (state of the art) of processes, of facilities or of methods of operation which indicate the practical suitability of a particular measure for limiting discharges, emissions and waste. In determining whether a set of processes, facilities and methods of operation constitute the best available techniques in general or individual cases, special consideration shall be given to:*
>
> - *comparable processes, facilities or methods of operation which have recently been successfully tried out;*
> - *technological advances and changes in scientific knowledge and understanding;*
> - *the economic feasibility of such techniques;*
> - *time limits for installation in both new and existing plants;*
> - *the nature and volume of the discharges and emissions concerned.*

There is a legal requirement when designing an NPP for the operator to demonstrate environmental optimisation from the outset, throughout the entire life cycle of the plant including decommissioning and waste disposal activities. This includes preventing the generation of radioactive waste and, where this is not possible, minimising generation and enabling the opportunity for materials re-use and recycling, ultimately reducing the amount required to be disposed of. A key factor here is to ensure waste streams are kept separate. LLW requires less processing and is less of a burden in terms of the space occupied during storage, manpower and cost. As such, preventing waste streams from becoming mixed ensures that LLW streams are not unnecessarily directed through ILW processing routes. With this in mind, modern NPP design ensures that, through optimised process and system design, waste is appropriately segregated, and thorough and accurate records are maintained to ensure the minimum impact is realised.

Prior to construction, NPP operators must present substantial levels of justification that the necessary steps have been taken. This includes proof that BAT has been applied and that the operator will strive for continuous improvement as technology evolves and lessons are shared.

Demonstration of BAT

Each NPP requires a documented BAT assessment, that must be approved by the respective environmental agency (EA, SEPA or NRW) to demonstrate that they are complying with legal requirements for the minimisation and management of waste streams and discharges from an NPP. The BAT assessment must comprise the following:

- Clear identification all operating and future waste stream types;
- Accurate assessment of waste stream quantities, along with the demonstration that these have been minimised in line with environmental requirements;
- The identification of disposal routes for all possible waste streams;
- An assessment of all potential environmental impacts during the NPP lifecycle; and
- Clear Examination, Inspection, Maintenance and Testing (EIMT) plans to ensure systems and equipment are maintained in line with requirements, to ensure functionality and reduce disposal requirements.

The ultimate purpose is to demonstrate that the potential risk to humans and the environment has been reduced ALARA. Not only must this be done prior to being given a permit to begin construction and then operation, but the BAT assessment must remain under review. The industry is under a process of continuous improvement and, as such, must continue to demonstrate environmental optimisation in line with the earlier definition. That is to say, the incorporation of recent successful processes, and technological and scientific advances must be considered going forward, even after the permit has been granted.

Legislation & Regulation: Industry Learning, Collaboration and Improvement

Multiple platforms and organisational bodies exist to enable worldwide collaboration and the sharing of operational experience, to continuously improve safety and reduce the potential impact.

Industry Collaboration

Beyond stringent and collaborative regulation, multiple organisations exist to create a platform for the sharing of knowledge and experience. A key and common focus for the nuclear industry around the world, is to strive for improved safety and reducing the potential impact on the environment, whilst enabling the production of low-carbon electricity.

A selection of organisations that exist and actively improve the nuclear industry through knowledge sharing, legislation development and distribution of best practice is provided below.

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 promotes the sharing and development of operational experience and scientific knowledge for the purposes of driving advances in technology and operational safety. The IAEA undertakes and promotes research and development within the nuclear industry to improve understanding and drive improvements to operational processes, design and safety.

Furthermore, the IAEA produces its own Basis Safety Standards (BSS), derived from a global understanding of radiation and the nuclear industry, and these are used to inform international legislation, such as the UK’s Ionising Radiation Regulations 2017 (IRR17).

Under the IAEA, The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management is the first legal instrument to address the issue of spent fuel and radioactive waste management safety on a global scale. It does so by establishing fundamental safety principles and creating a similar “peer review” process to the Convention on Nuclear Safety. The Convention applies to spent fuel resulting from the operation of civilian nuclear reactors and to radioactive waste resulting from civilian applications. It also applies to spent fuel and radioactive waste from military or defence programmes if such materials are transferred permanently to and managed within exclusively civilian programmes, or when declared as spent fuel or radioactive waste for the purpose of the Convention by the Contracting Party concerned. In addition, it covers planned and controlled releases into the environment of liquid or gaseous radioactive materials from regulated nuclear facilities.

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 working together to 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, who subsequently highlight areas of high performance and provide feedback on areas for improvement. This organisation enables NPP operators all over the world to share operational experience, driving continuous improvement through knowledge sharing and learning from experience.

The European Atomic Energy Community (Euratom)

Euratom aims to pursue nuclear research and training activities with an emphasis on continually improving nuclear safety, security and radiation protection, notably to contribute to the long-term decarbonisation of the energy system in a safe, efficient and secure way.

The Euratom Programme puts a strong emphasis on developing nuclear skills and competence. This will allow Europe to maintain world leadership in nuclear safety and waste management and to attain the highest level of protection from radiation. As with the IAEA, Euratom’s Basic Safety Standards Directive (BSSD) establishes uniform basic safety standards for the protection of individuals against the dangers arising from ionising radiation, excluding medical and background sources (EU). These standards are used to drive international legislation to ensure the operation of industries utilising ionising radiation can Do No Significant Harm.

WANO
GLOBAL LEADERSHIP IN **NUCLEAR SAFETY**

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Legislation & Regulation: Risk Reduction

Other sources of radiation far outweigh the radiation resulting from the operation of NPPs. For example the average annual radiation dose received by a typical NPP worker is comparable to undertaking two transatlantic flights.

Comparison of radiation sources

In the UK, Licence Conditions on waste minimisation and containment are enforced by the ONR and must be followed to be granted an operating licence. High levels of safety are achieved on a risk-minimisation basis, where the risk to the public must be reduced to ALARA levels.

On this basis, the radiation levels due to NPP operation are far lower in comparison to other sources of radiation, such as radon emitted from the ground, increased cosmic radiation exposure on long-haul flights, and even naturally-occurring radioisotopes in some types of food.

A study undertaken in 1990, on the sources of radiation to which people in the Nordic regions are exposed, revealed NPP operation to be the lowest source of radiation (0.02%), with radon being the greatest source (totalling 66.36%), and even radiation produced from peat and coal-fired powerplant operation being greater (0.08% – labelled as ‘energy production’ in the pie chart opposite).

These low levels are driven by the stringent national and international regulations employed, which ensure the risk presented to the public is negligible, and is considerably lower in comparison to other sources of radiation.

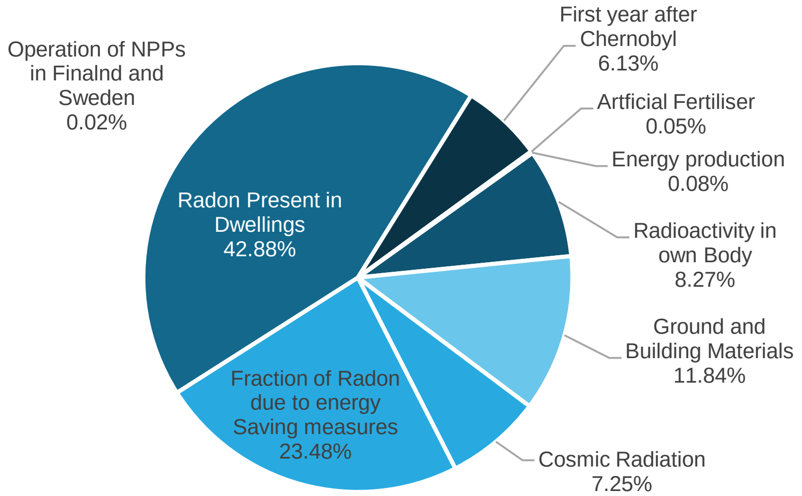
The adjacent table provides a comparison of typical radiation sources in the UK, highlighting that the average annual radiation dose received by a typical NPP worker (linked directly to working on an NPP) is comparable to undertaking roughly two transatlantic flights.

Natural background radiation typically comprises radon emitted from the ground and cosmic rays from outer space. These sources are primarily responsible for the average annual dose received by a member of the public, which is further increased by long-haul flights and medical scans, resulting in a potential total far greater than the legal limit for public exposure from an NPP (1 mSv).

Ultimately, these studies highlight the negligible levels of radiation to which the public are exposed due to the lifecycle of an NPP, including its decommissioning and management of waste. The stringent regulations and highly-controlled processes, in combination with hugely conservative design margins (in container shielding and durability, for example) ensure that the risk to the public and environment posed by the processing and storage of radioactive waste is negligible when compared to the other multiple sources of background radiation, including those originating from other forms of power generation.

The next section of this report discusses the sources and types of radioactive waste produced by the sector, and how continuous improvement has been applied since commercial operations began.

Comparison of radiation doses in the Nordics by source



Source: International Atomic Energy Agency (IAEA)

Radiations doses by sources

Source of Exposure	Dose (mSv)
Annual exposure limit for nuclear industry employees	20
CT scan of the whole spine	10
Average annual radon dose to people in Cornwall, UK	6.9
CT scan on chest	6.6
USA average annual radiation dose	6.2
UK average annual radiation dose	2.7
CT scan of the head	1.4
UK annual av. Radon dose	1.2
NPP worker average annual occupational exposure (2010)	0.18
Transatlantic flight	0.08
Chest x-ray	0.014
Eating 100g of Brazil nuts	0.01
Dental x-ray	0.005

Source: UK government

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EU Sustainable Taxonomy: Radioactive Waste Management Review

Section 3: Radioactive Waste

Waste Generation: Radioactive Waste Streams

Varying amounts of radioactive waste are generated at each stage of the nuclear fuel cycle, as highlighted below. These are appropriately regulated, managed and disposed of to ensure public safety and reduce the environmental impact.

Overview of Waste Stream and Nuclear fuel cycle

Radioactive waste is any material that is either radioactive itself or is contaminated by radioactivity, for which no further use is envisaged. This is produced by multiple industries outside of nuclear power, including the oil and gas sector, coal-fired power stations, and from medical applications. The Environment Agency (EA), adopts the following definition for determining what falls into this category:

> *Any substance or article which is waste, and which satisfies Section 1A of the Radioactive Substances Act 1993 or Paragraph 3.(1), Schedule 23 of the Environmental Permitting (England and Wales) Regulations 2016.*

Radioactive substances are widely used or produced by hospitals, universities and industry for a variety of reasons, such as patient diagnosis and treatment, in manufacturing processes, oil and gas processes, as well as energy production. However, nuclear power is the only large-scale energy-producing technology that takes full responsibility for all its waste and fully costs this into the product (World Nuclear Association).

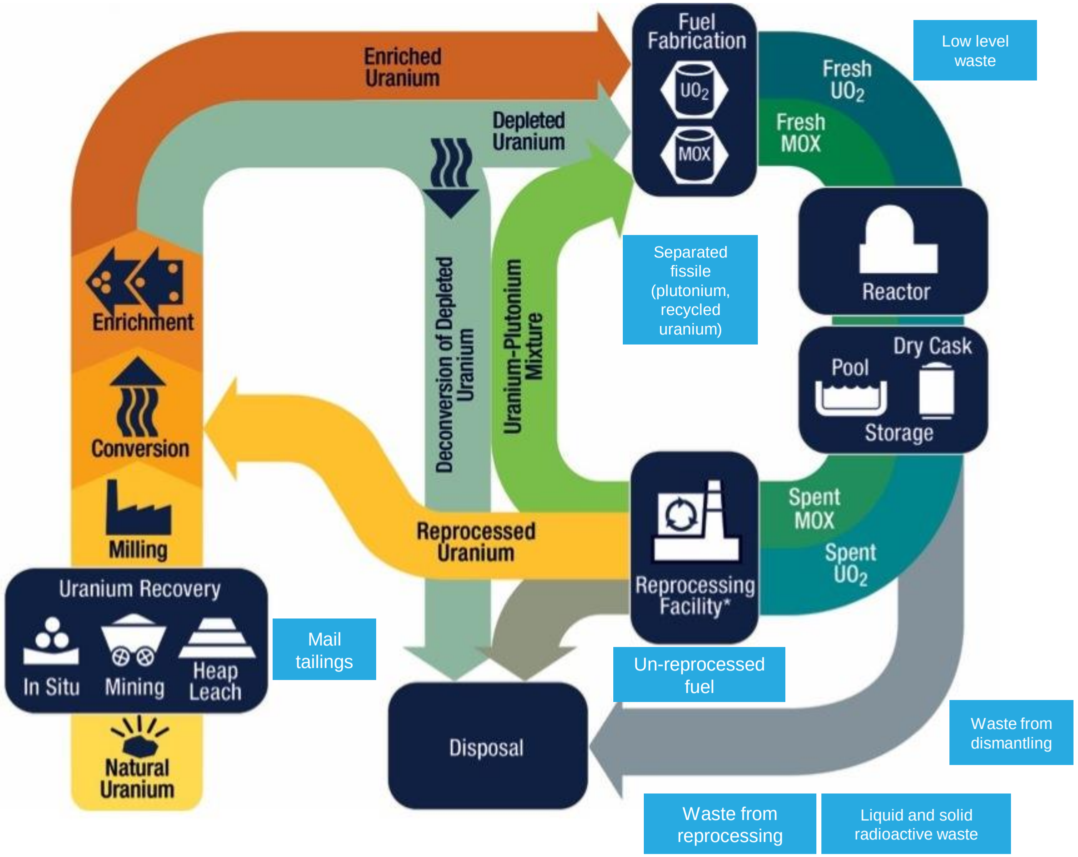
A simplified overview of the fuel cycle, including the main waste streams and options for final storage currently employed, is highlighted in the flow chart opposite. This process is largely driven by reactor design and legislation in countries with NPPs installed. This is described in more detail later in the report.

Waste streams

Radioactive waste is a type of waste containing radioactive material; it can be a by-product of nuclear power generation or other industrial processes such as the combustion of coal, mining or from oil and gas production. In the UK, radioactive waste is regulated by the Office for Nuclear Regulation (ONR) and the EA in England, Scottish Environment protection Agency (SEPA) and Natural Resources Wales (NRW), in order to protect humans and the environment.

Not all radioactive waste presents a risk to the environment or human health. For example, for streams categorised as Very Low Level Waste (VLLW), the radiation emitted is significantly lower than the levels of background radiation (discussed earlier), and can therefore be disposed of or recycled through conventional means (i.e. no shielding or protection is required) in accordance with allowable limits. Waste with the greatest levels of radiation is categorised as High Level Waste (HLW), which can result from the activation of components close to nuclear fuel during operation, or from the processing of spent uranium fuel. HLW has the greatest potential to impact the environment and public health and is managed according to specific, tightly-controlled processes. Each category of waste is discussed further on the next page.

Nuclear fuel cycle



Source: Nuclear Regulatory Commission from US. License: CC BY 2.0

Waste Generation: Classification of Waste in the Nuclear Energy Industry

Radioactive Waste is separated into five distinct categories, each with its own dedicated disposal route. These are defined by regulation and are broadly based on the level of radioactivity and the heat generated by the waste.

Classifications of Radioactive Waste

Out of Scope

Some level of radioactivity is always naturally present in the environment. As such, certain wastes with an activity threshold below the Out of Scope values in the Environmental Permitting Regime are not classified as radioactive by law and are exempt from regulation. If this lower limit were not defined then almost everything in everyday life and, therefore, all waste produced would be classified as radioactive waste.

Very Low Level Waste (VLLW) – Exemption Provision

Sites that produce VLLW can dispose of the waste with regular household or industrial waste at permitted facilities, in accordance with permitted limits. The major components of VLLW are building rubble, soil and steel. These arise from the dismantling and demolition of NPP facilities. Waste categorised as VLLW poses no radiological risk to the public or environment as the radioactivity of the materials is significantly less than natural background radiation levels.

Low Level Waste (LLW)

LLW contains relatively low levels of radioactivity, but exceeds the limits defined for VLLW. Most LLW comes from the operation and decommissioning of nuclear facilities, and includes items such as scrap metal, paper and plastics. Some smaller amounts of LLW also come from hospitals and universities. About 69% of all radioactive waste worldwide (by volume) is in the LLW category. Some LLW is managed as Intermediate Level Waste (ILW). This may be because it is too difficult to separate from ILW or does not meet the Waste Acceptance Criteria for current LLW disposal facilities due to specific properties, such as its chemical composition.

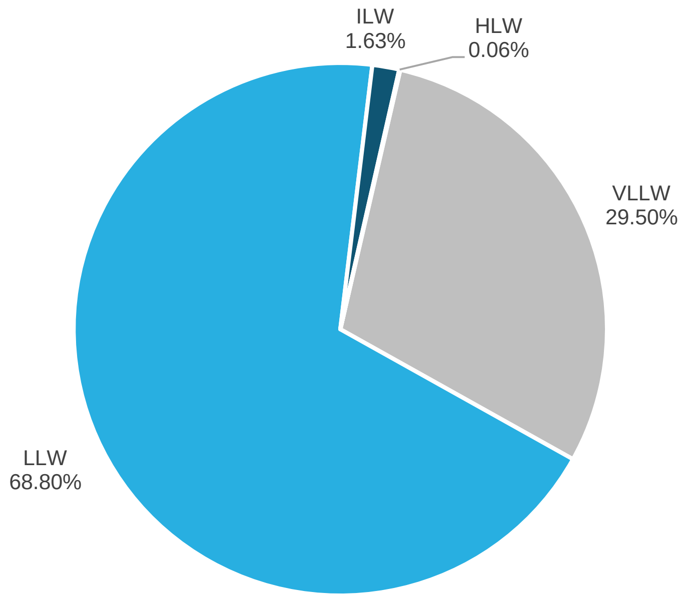
Intermediate Level Waste (ILW)

ILW exceeds the upper boundaries for Low Level Waste (see Low Level Waste above) but does not generate a significant amount of heat. About 6% of all radioactive wastes (by volume) are in the ILW category. The major components of ILW are nuclear reactor components, graphite from reactor cores and sludges from the treatment of radioactive liquid effluents.

High Level Waste (HLW)

The radioactivity levels associated with HLW result in heat generation that is significant enough to require management through passive cooling. The design of waste storage or disposal facilities must take this into consideration. Less than 1% of all radioactive wastes (by volume) are in the HLW category. Most HLW is produced as a by-product from reprocessing spent fuel (which is not classified as a waste stream – this is discussed later in the report) from nuclear reactors, and typically occurs in liquid form. The process of 'vitrification' immobilises the liquid HLW by trapping it in a stable borosilicate glass matrix. This solid product is easier to manage and store.

Worldwide Radioactive Waste Inventory by Category



Type	Volume (m3)	Percentage (%)
VLLW	10,262,000	29.50%
LLW	23,930,000	68.80%
ILW	567,000	1.63%
HLW	22,000	0.06%
Total	**34,781,000**	**100%**

Source: International Atomic Energy Agency (IAEA)

Waste Generation: Classification of Waste in the Nuclear Energy Industry

The production of radioactive waste started before the construction of civil NPPs. Large quantities of legacy waste can be attributed to early and prototype reactor designs and military activities.

Radioactive Waste Streams

There are multiple sources of radioactive waste in the UK and across the world. However, the primary sources relate to early reactor designs and military applications. Prior to large-scale adoption of nuclear power, and the ability to implement lessons learned, the extent of waste production, the need for segregation and record keeping, and the required processing routes were largely unknown. As such, significant improvements were implemented during the design of Generation-II reactors (AGRs and PWRs in the UK), which, in combination with developed guidelines and legislation, saw the implementation of dedicated processing routes and on-site storage. The table below provides an outline of the key sources of radioactive waste in the UK. The next page provides a timeline of reactor design showing significant improvements in the quantities of waste produced when compared to the amount of energy produced.

Source	Example Site	Example Waste Descriptions	Management process	Track record / industry reference
Military activity	Vulcan	• LLW – Metals, plastics, organic materials • ILW – Activated submarine reactor components (stainless steel), organic resins • HLW – Small proportion of activated steel reactor components	• Management techniques were not known or were inefficient	• Forms a large part of Sellafield legacy • From an experimental period so very little track record to learn from • Poor recording of waste presents difficulties with understanding waste composition
Research	Dounreay	• LLW – Metals, plastics, organic materials • ILW – Activated reactor components (stainless steel), organic resins • HLW – Small proportion of activated steel reactor components	• Originally underground vault storage and immobilisation. Now being recovered for on-site interim storage	• Sub-standard record keeping, with quantities and types only being approximated • Very little or no waste segregation • Exposure to water and humidity, causing degradation, presenting further handling, treatment and packaging challenges • Substantial recovery and accounting effort subsequently required
Gen-I Magnox reactors	Berkeley	• LLW – Graphite, vault gravel • ILW - Reactor core and fuel element graphite, stainless steel, magnesium and zirconium components, filters and ‘sludges’, • HLW – Fuel fragments and small quantities of activated steel	• Originally underground vault storage and immobilisation. Now being recovered for on-site interim storage	• Sub-standard record keeping, with quantities and types only being approximated • Very little or no waste segregation • Exposure to water and humidity, causing degradation, presenting further handling, treatment and packaging challenges • Substantial recovery and accounting effort subsequently required
Gen-II (current) reactors	Torness	• LLW – Consumables such as packing, paper, plastics • ILW – Core graphite, steel fuel assembly functional components (e.g. reflectors, shielding) • HLW – Small amount of activated reactor components	• Temporary on-site storage followed by transport to Sellafield for waste streams and fuel	• Waste streams are more manageable • Strict segregation of waste types ensures ease of record keeping and clear understanding of management requirements • Past and future waste quantities are well defined • Techniques for storage and transport are widely used internationally and are well understood
	Sizewell B	• LLW - Filters • ILW - Stainless steel reactor components • HLW - Small amount of activated reactor components	• On-site interim storage followed by a time extension or direct transfer to a long-term solution	
Future new nuclear	Hinkley Point C Sizewell C	• LLW – Filters, contaminated consumables • ILW - Steel reactor components, sludges and resins • HLW - Small amount of activated reactor components	• On-site interim storage followed by a time extension or direct transfer to a long-term solution	• Waste reduced further through design • Waste types, quantities, management and storage strategies are defined well in advance of construction, based on several decades of learning

Waste Generation: Evolution of Nuclear Reactor Technology in the UK

The timeline below highlights, with the evolution of reactor technology, how the quantities of Low Level Waste and Intermediate Level Waste produced have been reduced.

Radioactive Waste Quantities

The vast majority of radioactive waste in the UK originates from early NPP designs (Gen-I), R&D (non-civil nuclear) and military applications. The timeline presented below provides an overview of how the quantities of waste produced per unit of energy have reduced dramatically as lessons learned have been implemented and understanding has improved. For example, when comparing an early Magnox reactor from the 1950s to a modern EPR, the quantities of waste have dropped by roughly 75%, yet the power produced over the life of the plant has increased by more than 10 times. These advances have been made through design improvements, reducing complexity and improving the potential for material recycling and re-use, and through strict waste management strategies.

Reactor Generation: Gen-I
Type: Magnox
Installation: 1956 – 1971
Shut down: 2003 – 2015
Capacity: 200 – 980 MWe

Reactor Generation: Gen-II
Type: AGR
Installation: 1976 – 1989
Shut down: 2023 – 2030
Capacity: 830 – 1240 MWe

Reactor Generation: Gen-II
Type: PWR
Installation: 1988
Shut down: 2035+
Capacity: 1250+ MWe

Reactor Generation: Gen-III
Type: EPR
Installation: 2025+
Shut down: 2085+
Capacity: 3200+ MWe

1950 1960 1970 1980 1990 2000 2010 2020 2030

Magnox

Type	Example quantities (m^3)	m^3/TWh
LLW	33,500	218.5
ILW	5,080	33.1

- Improved output for commercial use
- Unknowns regarding waste management
- Vault storage adopted

AGRs

Type	Example quantities (m^3)	m^3/TWh
LLW	18,700	48.5
ILW	3,290	8.5

- Much greater outputs
- Waste production significantly reduced through design
- Mature regulatory requirements

PWRs

Type	Example quantities (m^3)	m^3/TWh
LLW	22,400	40.9
ILW	866	1.58

- Waste streams reduced further through design
- Greater opportunity for recycling of reactor components

EPRs

Type	Example quantities (m^3)	m^3/TWh
LLW	8766	5.2
ILW	1200	0.7

- Greater safety
- Reactor power increased further
- Waste production decreased further

[1] HLW is formally the responsibility of the Nuclear Decommissioning Authority; does not form part of NPP inventory and cannot be explicitly quantified per NPP. However, improvements in fuel enrichment, design and strategy have led to greater optimisation in fuel use, resulting in greater outputs per tonne of Uranium used, which has a direct correlation on HLW waste production. As such, HLW production has also reduced with time.

Source: UK Radioactive Waste Inventory and GDA Assessment Report UK EPR-06

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Section 4: Radioactive Waste Management Strategies

Radioactive Waste Management Strategies: Waste Hierarchy

Multiple processing routes exist; however, reactor and NPP design and strategies are undertaken in accordance with the waste hierarchy – prioritising prevention and minimisation of radioactive waste over disposal.

Waste Hierarchy Overview

The waste hierarchy sets out the priorities and preferred approach for managing all waste types, including radioactive waste materials generated at each stage of the NPP lifecycle. This is illustrated in the adjacent diagram, which highlights the preference of prevention and minimisation of waste, as well as re-use and recycling, over disposal.

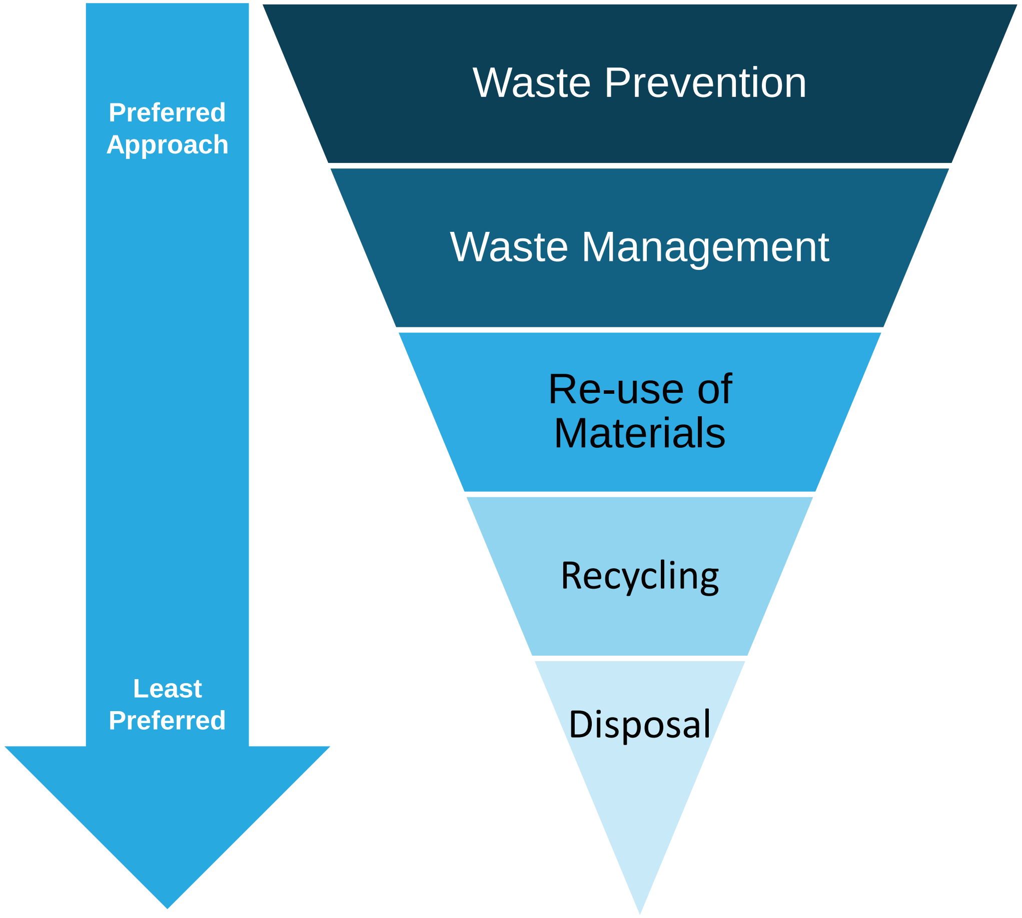
As shown, the order of preference for the implementation of a specific type of waste management strategy is: (1) Prevention; (2) Management (or Minimisation); (3) Re-Use; (4) Recycling and (5) Disposal, with safety remaining as the overriding priority for all waste processing routes.

With this waste hierarchy in mind, management of radioactive waste can be enacted through a number of ways, namely: design, planning and preparation; waste treatment; packaging; storage and disposal. Broadly speaking, the nuclear industry's management strategies for how radioactive waste is managed can be separated into the following main categories:

- *Prevention strategies* – These are developed during the concept and detailed design phases to remove unnecessary processes and reduce excess materials prior to construction.
- *Minimisation strategies* – These include accurate classification of waste and record keeping, sorting, reducing volumes and decontamination.
- *Re-use –* This is enabled through optimised design, effective decontamination, and well-designed processes to enable materials and components that come into contact with radioactivity to be used more than once.
- *Recycling* – The proportion of materials that can be reclaimed is increasing, even activated components, such as steel reactor components, can be safely recycled following treatment.
- *Disposal strategies* – These comprise above-ground, near-surface and deep geological disposal – multiple long-term options currently, and will continue to, exist.
- *R&D potential future solutions* – The aim of reducing the half-life (accelerating radioactive decay) of specific radionuclides (known as transmutation) is under investigation, along with continued investigation into improved reactor design to further reduce the amount of material used or contaminated in the first place.

Examples of how each of these strategies are applied in the nuclear industry are given on the following pages. These highlight where strategies have led to improvements in radioactive waste management and what future strategies, currently in R&D, may be implemented going forward.

Radioactive Waste Hierarchy



Source: Nuclear Decommissioning Authority (NDA)

Radioactive Waste Management Strategies: Prevention and Minimisation Strategies

Strategies for prevention of radwaste throughout the nuclear fuel cycle are considered and come from the inherent design of the entire system. Minimisation strategies are implemented to reduce the overall volume sent to disposal repositories.

Prevention Strategies

The total volume of waste produced during the operation of a NPP has been dramatically reduced through the evolution of design in each new generation of NPP. This is highlighted in the introductory section of this report. Wherever reasonably practicable, NPP designers and operators aim to eliminate waste before it arises, while reducing the amount of waste they produce, where this is not possible. This is a regulatory requirement, known as BAT and, in the UK, is enforced by the relevant environmental regulatory body (EA, SEPA or NRW).

Through improving the design of the entire system, based on lessons learnt through early operation of NPPs and through continued investment and R&D, many of the waste materials observed during the operation of the first Magnox reactors for example, have been completely removed from the process, allowing the total quantities of materials classed as radioactive waste to be reduced. For example, the use of heavy reflectors in the EPR design, which reflect and absorb neutrons around the core, significantly reduces the activation of other parts of the plant and the generation of radioactive waste.

Minimisation strategies

Once the overall design of the NPP is complete, other strategies can be utilised during the operation of an NPP to minimise the total volumes of waste sent for disposal. An overview of some of the strategies that are currently implemented by the nuclear industry is given below:

- *Volume Reduction* – this ensures efficient use of limited space in storage and disposal facilities and is a fundamental requirement. This can be done through compaction or incineration of solid wastes, to reduce air pockets, or by evaporation of excess fluids, to reduce the volume of non-radioactive substances being sent to disposal.
- *Waste Segregation* – materials or even parts of the same waste stream can be separated more effectively into the different radioactivity classifications. This allows the small amounts of waste showing higher levels of radioactivity to be sent to disposal, while separating out materials that may be suitable for re-use or recycling.
- *Minimising exposure of equipment to radiation* – through design (such as the heavy reflector described earlier) and operational optimisation the total volume of irradiated waste can be reduced or sentenced to a lower category.
- *Planning of decommissioning operations* – it is important to control and optimise the resources required. This is becoming more of a focus in the UK as the ageing NPP fleet reaches the end of their operating life. A number of Magnox NPPs are currently being decommissioned and many of the lessons learnt here are being applied to future decommissioning activities.

Waste type	Suitable waste management strategy
LLW	Low Level Waste Repository (LLWR) • Since 1959, there have been sites in areas such as Cumbria where waste is grouted in metal containers before being stacked in concrete-lined, engineered vaults. These are capped when the containers fill up the vaults. • Metal recycling – separates radioactive contaminates and send small volume of these LLWR • Incineration – reduces the volume by c.90%, leaving only ash and filter dust. • Direct disposal. • Alternative disposal – sent to normal landfill or recycling facilities (exemption provision/VLLW only).
ILW	Near-surface, Interim Storage or GDF • Super-compacting is the process of volume reduction, to increase the density of the ILW and enable more efficient use of the available area. • Immobilisation of waste can be utilised to improve shielding associated with higher radioactivity levels, and to further improve container durability. Some containers, such as the GNS 'yellow box' can achieve shielding and longevity requirements without immobilisation. • Interim Storage is often utilised as an initial step, lasting up to 150 years, prior to final disposal; however, this does remain as a long-term above-ground solution. • Long-term management – deep, non-deep or near surface disposal can be adopted post-interim storage, but may not be essential.
HLW	Interim Storage or GDF • The by-products from reprocessing spent fuel are classified as HLW. • Vitrification – this takes place at Sellafield, Cumbria. Liquid HLW is mixed with crushed gels in a furnace then poured into a stainless steel canister, trapping the waste in a stable solid for long-term storage or disposal. • Long-term management – as with ILW, deep or near surface disposal, can be adopted post-interim storage, but is not essential.

Source: World Nuclear Association

Radioactive Waste Management Strategies: Re-use and Recycling

Material re-use and recycling helps reduce the total volumes of waste sent to repositories, reducing costs and the associated burden. For example both waste metal and storage containers can be recycled or reused.

Equipment Re-use

Re-using or recycling radioactive waste can help to reduce the total volume of waste going to the final disposal facility. Application of the waste hierarchy encourages NPPs to divert LLW away form LLW Repositories, such as the one in Cumbria, which in turn can increase their operational life, by reducing the burden placed upon them.

There are opportunities for waste producers to re-use equipment and materials that become irradiated but may still be useful elsewhere, either directly or after refurbishment. An example of re-using irradiated materials is in the use of spent fuel flasks. These are robust, shielded containers used for transporting spent fuel elements from the majority of UK NPPs to Sellafield for reprocessing. Once the spent fuel is removed, flasks are decontaminated, inspected and prepared for transport. The adjacent image (top) shows the spent fuel transport flask design used in the UK.

Recycling

Some metals can also be recycled. This is done for metals with low levels of surface radioactivity. The waste is cut into pieces and placed into containers. Prior to recycling, the surface of the metal is removed by shot blasting, leaving clean material beneath where the radioactivity has not penetrated. Alternatively, metal can also be melted and the radioactive contaminants removed, leaving only a small volume of waste for direct disposal to an authorised LLW facility.

In March 2012, when undergoing this process, one-third of the 310-tonne boilers were removed from Berkeley NPP (UK) and transported to Sweden for decontamination and recycling.

Swedish recycling specialist Studsvik bought the boilers to dismantle, smelt and recycle, releasing a large proportion of the metal for re-use in the market. Up to 90% of the metal was recycled (c.4,185 tonnes – World Nuclear News). This was carried out at the Studsvik Industrial site outside Nyköping, which is currently owned and operated by Cyclife Sweden AB.

By removing and recycling the boilers in this way, rather than treating them as radioactive waste for disposal, the volume of waste and the space taken up by legacy waste from decommissioned NPPs can be drastically reduced.

Magnox Spent Fuel Transport Flask

Source: London Science Museum

Berkeley NPP Boiler

Source: Magnox

Radioactive Waste Management Strategies: Re-use and Recycling – Examples (2/2)

The metal within old PWR steam generators can be recycled by separating out the LLW components and only returning the higher radioactive contents back to the repository, allowing a reduction of c.90% in waste materials.

Ringhals, Sweden – Steam Generator

As described earlier in this report, the steam generators in a PWR form part of the primary and secondary loops and are therefore exposed to water that has passed directly over irradiated fuel assemblies. This causes activation of certain surfaces within the steam generator, turning them radioactive.

When Vattenfall's Ringhals 4 PWR NPP in Sweden replaced three of their steam generators during an uprating and life extension project, they were able to recycle a large proportion of metal from the decommissioned components, reducing the total amount of waste requiring storage in a repository.

The steam generators weighed roughly 300 tonnes each and would require up to $400m^3$ of storage space. It is usually expensive and complicated to scrap all the steam generators components in repositories due to their size. As such, they were transported to Studsvik's special recycling facility (now the Cyclife facility).

The process at Studsvik's facility allows a reduced volume to be disposed of, reducing waste and associated costs. A high-level overview of the process is provided in the adjacent diagram (bottom) and summarised below:

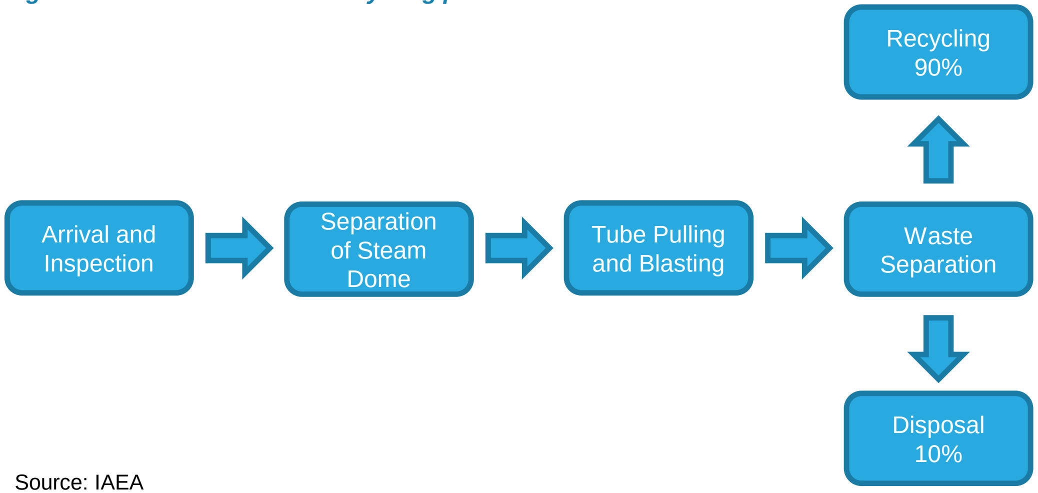
1. Upon arrival, the steam generator is inspected.
2. The steam generator is then segmented and the steam dome removed.
3. The radioactive tube bundle is then decontaminated and either compacted or melted, depending on the type of material and radioactive content.
4. The steel shell and other low-level radioactive components are melted to be recycled and are suitable to be sold on the market.
5. The completed tube bundle and ingots that are classified as radioactive waste were then returned to Vattenfall. This includes residual waste such as crushed slag, sorted material, cuttings, blasting residues, and dust from the ventilation filters.

This process reduces the total material and the volume of disposal space required of the steam generator returned to a repository by c.90%.

Image of the Steam Generator at the Ringhals NPP, Vattenfall

Source: World Nuclear News

High-Level Steam Generator recycling process



Arrival and Inspection

Separation of Steam Dome

Tube Pulling and Blasting

Waste Separation

Recycling 90%

Disposal 10%

Source: IAEA

Radioactive Waste Management Strategies: R&D – Reprocessing

Spent nuclear fuel can potentially be reprocessed to extract the remaining fissile materials to be recycled as fresh fuel for NPPs, thereby turning the materials from this waste stream into a resource for future use.

Reprocessing of spent nuclear fuel overview

As described earlier, spent fuel is not considered as a radioactive waste stream, on the basis that it can continue to be utilised following reprocessing. Spent fuel can be disposed of as HLW; however, intermediate and long-term storage is adopted to ensure options for reprocessing and reuse remain available. Nuclear reprocessing is the chemical separation of fission products and unused uranium from spent nuclear fuel. The materials usually available for reprocessing, along with their management requirements, are highlighted in the table opposite.

Spent nuclear fuel can be reprocessed to extract the remaining fissile materials to be recycled as fresh fuel for NPPs. This, reduces the volume of HLW sent to disposal, turning a potential waste stream into a resource and improving the overall sustainability of Nuclear Energy. This mostly focuses on three areas:

- Conversion of fertile U-238 to fissile plutonium.
- Reprocessing for new fast neutron reactors which burn all uranium and plutonium without separation from one another.
- Plutonium recycled into Mixed-Oxide (MO_X) fuel.

Being able to recycle spent fuel in one of these ways has a number of benefits:

- It makes fuel use more efficient;
- It reduces the volume of HLW sent to disposal facilities; and
- The radioactivity of the waste from the reprocessing is much lower.

Reprocessing is relatively expensive, compared to mining natural uranium deposits (as done in the traditional nuclear fuel cycle) and may not always be economically viable. However, spent nuclear fuel can be safely stored for long periods of time, above ground until reprocessing becomes viable or is implemented through legislation.

Reprocessing is carefully controlled because it chemically separates plutonium that can be used directly in the manufacture of nuclear weapons. Currently the countries where there are fully functional reprocessing plants are Russia, Japan, France and the UK. The world's commercial reprocessing capacity is highlighted in the table opposite (bottom) according to the WNA.

Summary of waste product from nuclear fission

Waste Material	Management Requirements
Plutonium, minor actinides, reprocessed uranium	Fission in fast, fusion, or subcritical reactors
Reprocessed uranium, cladding, filters	Interim and long-term storage
Long-lived fission and activation products	Nuclear transmutation or long-term storage
Medium-lived fission products	Interim or long-term storage as HLW
Useful radionuclides and noble metals	Industrial and medical uses

World Commercial reprocessing capacity

Type of spent fuel	Reprocessing facility	Facility capacity (tonnes per year)
LWR fuel	France, LA Hague	1,700
	UK, Sellafield (THORP)	600
	Russia, Ozersk (Maak)	400
	Japan (Rokkasho)	800
	Total LWR spent fuel	**3,500**
Other nuclear fuels	UK, Sellafield (Magnox)	1,500
	India (PHWR, 4 plants)	350
	Japan, Tokai MOX	40
	Total other spent fuel	**1,870**
Total capacity for civil nuclear reprocessing		**5,370**

Source: World Nuclear Association

Radioactive Waste Management Strategies: Disposal Strategies – Overview

Disposal strategies are implemented after all other methods higher in the waste hierarchy are considered. Depending on the classification of waste the disposal strategy involves either: NSSF, ISSF or GDFs.

Disposal Strategies Overview

The disposal strategy for a given radioactive waste stream is mostly driven by government policy, which dictates how certain materials – such as waste from spent nuclear fuel in NPPs, fuel reprocessing plants, hospitals, research facilities, academic use and other commercial or industrial uses – are categorised as waste. Regulations establish minimum acceptable performance criteria for licensees managing wastes, while providing for flexibility in the technological approach.

All radioactive material has a half-life, which is the time taken for half of its atoms to decay and lose half of its radioactivity. As previously discussed, radioactive waste is typically classified as either LLW, ILW or HLW and this is primarily based on the waste's level of radioactivity and the heat it generates. The broad levels of radioactivity in alpha, beta and gamma emissions for each of these classifications are given in the table below, which will dictate the most appropriate disposal method. This is also driven by International and European agreements, such as the Joint Convention on Radioactive Waste Management and the European Atomic Energy Community (Euratom) framework, which ensure that members across the world conform to the responsible and safe management of spent fuel and radioactive waste.

There are several disposal methods available to the nuclear industry for each waste stream that include varying degrees of proposed storage duration and location. These include:

- *Near Surface Storage Facilities (**NSSF**)*
- *Interim Storage Facilities (**ISF**)*
- *Geological Disposal Facilities (**GDF**)*

Each of these are discussed in more detail on the following pages.

Waste Classification

Waste Classification Category	Alpha radioactivity (GBq / t)	Beta – Gamma radioactivity (GBq / t)	Heat Generation (kW / m³)	Examples	Requirements
LLW	< 4	< 12	0	Paper, rags, tools, closing, filters etc.	Disposal in NSSF, minimal shielding required during handling or transportation
ILW	> 4	> 12	< 2	Metals, chemical sludges, metal fuel cladding, contaminants from decommissioning	Requires shielding
HLW	> 4	> 12	> 2	Fission products, transuranic elements, separated waste from reprocessing used fuel	Requires cooling and shielding.

Source: NDA and World Nuclear Association

Radioactive Waste Management Strategies: Disposal Strategies – Near Surface Storage Facilities

NSSFs are usually the preferred disposal method for LLW and possibly some ILW with short half-lives. The depth of a facility will usually depend on the nature of waste placed there, the facility design & local environmental conditions.

Near Surface Storage Facilities

Near Surface Storage Facilities (NSSF) are regulated, designated disposal sites where solid, or solidified, radioactive waste is placed. The depth of a facility will usually depend on the nature of the waste that will be placed there, the facility design and the local environmental conditions, that will serve to ensure safe and secure containment of radioactive material.

The aim of an NSSF is to manage the radioactive waste and isolate it from the environment, this may include concentrating the waste to reduce its volume and mass, and then containing it. The general strategy for containment and isolation is to utilise a series of complementary barriers separating the waste from the environment.

A near-surface disposal route has been implemented in a number of countries for LLW including: Czech Republic, France, Japan, the Netherlands, Spain, UK, and USA, as well as for certain ILW waste streams in Finland and Sweden. There are essentially two types of NSSF:

- *Those at ground levels* – waste containers are placed in constructed vaults, which are backfilled and capped with an impermeable membrane and topsoil when full. These facilities may incorporate some form of drainage and possibly a gas venting system, if required.
- *Those in caverns below ground level* – an underground excavation of caverns, which can be tens of metres below the surface, and are accessed through a drift. These are actually forms of non-deep geological disposal, which is covered in greater detail on the next page.

Examples of these two types of NSSF are highlighted opposite, along with the countries in which they have been adopted.

Benefits of an NSSF

NSSFs allow for the waste to be more easily managed, controlled and accessed if needed at a future date for possible re-use or repurposing, while isolating the waste from the environment and other surrounding human activities, to ensure the potential risks are suitably low.

Disadvantages of an NSSF

These facilities may be affected by long-term climate change (such as glaciation). However, this effect is taken into account during conception, and the appropriate measures are taken to ensure safety is not compromised. This type of facility is restricted in what it can stored, and is typically permitted for LLW and short-lived ILW with half-lives of up to 30 years. As such, alternative means are adopted for other forms of ILW. Continuous monitoring is undertaken to ensure that any potential changes to waste package condition or the surroundings are identified, so that the appropriate action can be taken. Waste can also be retrieved and transferred to another type of facility if required.

NSSF near Drigg, Cumbria

Source: NDA

Storage Facilities Adopted Worldwide

Country	Examples of above ground NSSF	Operator
UK	LLW Repository at Drigg in Cumbria	UK Nuclear Waste Management (Studsvik UK, Serco, and Areva) on behalf of the NDA
Spain	El Cabril LLW and ILW disposal facility	ENRESA.
France	Centre de l'Aube	Andra
USA	Five LLW disposal facilities: Texas, South Carolina; Utah; Tennessee; and Washington	Waste Control Specialists; Energy Solutions; American Ecology Corporation
Russia	Ozersk, Tomsk, Novouralsk, Sosnovy Bor	NO RAO.
South Korea	Wolseong	KRORAD
Japan	LLW Disposal Centre at Rokkasho-Mura	Japan Nuclear Fuel Limited

Country	Examples caverns below ground NSSF	Operator
Sweden	SFR final repository for short-lived radwaste at Forsmark (depth c.50m under the seabed)	Swedish Nuclear Fuel and Waste Management Company (SKB).
Finland	Underground repository at Olkiluoto and at Loviisa for LLW and ILW (depth c. 100m)	Operational since 1992 and 1997, respectively

Source: World Nuclear Association

Radioactive Waste Management Strategies: Disposal Strategies – Geological Disposal Facility

The Geological Disposal Facility has emerged as the preferred final disposal method for Higher Activity Wastes. However, some countries are choosing ongoing management of near-surface facilities as a permanent solution.

Geological Disposal Facility

As some classifications of waste remain radioactive for long durations (hundreds or thousands of years), final disposal options have been identified, which do not rely heavily on future generations and ensure waste resides in a stable environment. This has led to the design of deep and non-deep Geological Disposal Facilities (GDF) in underground repositories. The concept utilises multiple barriers, both engineered and natural (such as the surrounding rock and materials) to isolate the various waste streams. Repository locations with limited ground water present are selected to minimise the possibility of mobilisation of radioactive particles. The general layout of a deep GDF is highlighted in the image opposite.

Geological disposal at various depths is a selected long-term option for nuclear waste management in several countries, including (but not limited to) Argentina, Belgium, Canada, Czech Republic, Finland, France, Japan, the Netherlands, Russia, Sweden, Switzerland, the UK, and the USA.

There are different types of GDFs currently being explored, constructed or in operation, including:

- *Non-deep facilities -* c.50 - 100m below the ground;
- *Mined repositories* – excavating c.500m - 1000m below the surface; and
- *Deep boreholes* – boreholes c.3000m deep, backfilled with materials such as bentonite.

The first purpose-built deep geological repository that is currently licensed for disposal operations is the Waste Isolation Pilot Plant (WIPP) in the USA. However Sweden and Finland have non-deep facilities that have been operated safely for over 20 years. A number of other countries have advanced plans and are carrying out site selection, such as the UK and Canada, with Finland in an advanced stage of construction for its c.400m deep repository.

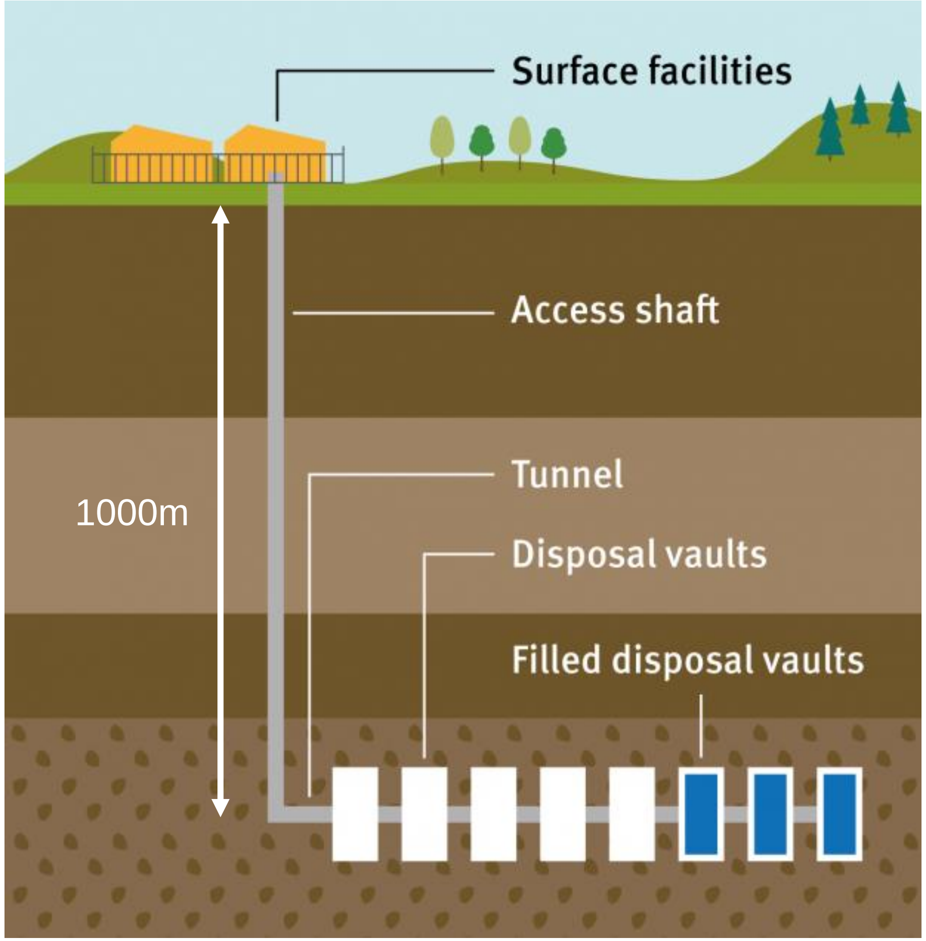
GDF Characteristics

There are a number of benefits specific to a GDF, which include:

- They require no or very little ongoing maintenance;
- They are isolated from human activities such as terrorism or war;
- They are protected from natural processes such as climate change;
- This is a long-term solution with no defined life span, the cost is spread over a long duration of time, with no requirement (but there remains the option) to undertake ongoing maintenance; and
- Multiple suitable locations, with the required geological conditions, already exist.

Whilst the design requirements are known and understood, the availability of a GDF will not be required for some time. Above-ground interim storage solutions provide safe and secure storage for as long as required, as explained on the next page.

High-Level Geological Disposal Facility Outline



Source: Environment Agency

Radioactive Waste Management Strategies: Disposal Strategies – Interim Storage Facilities

Existing waste package designs (such as those produced by Holtec and GNS) allow for safe storage and transportation of various waste streams for upwards of 100 years. Beyond this, waste can be repackaged if necessary, to extend this further.

Interim Storage Facilities

The current design of Interim Storage Facilities (ISF) adopted in the UK makes use of above-ground facilities to house shielded radioactive waste containers. The approach taken for the UK's Magnox sites that are currently undergoing decommissioning, such as Berkeley NPP, is to retrieve, process and package ILW into Ductile Cast-Iron Containers. There are various types of containers available depending on requirements and the specifics of the waste stream to be packaged; however, they all adopt the following traits:

- Thick-walled and shielded, to reduce external radiation to negligible levels;
- High-integrity, long-life seals ensure contamination is unable to escape; and
- Robust design ensures, in the unlikely event of a drop or collision, the contents remain secure, and the public and environment are not placed at risk.

Prior to storage, each waste stream can also be immobilised using a variety of techniques. For example, LLW or ILW can be mixed with polymers or concreting substances to prevent waste movement, provide additional shielding and to extend package design life. For similar reasons, HLW undergoes vitrification, the process of immobilising the waste in a stable borosilicate glass matrix.

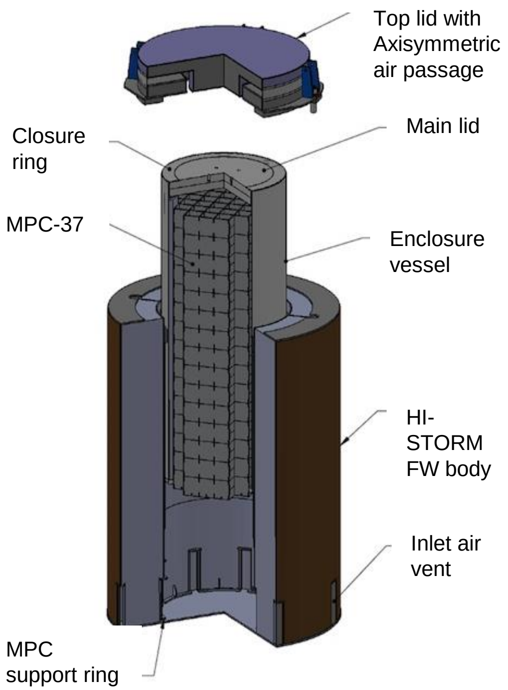
Interim storage also exists for spent fuel assemblies. The package design differs from that described above as spent fuel continues to produce heat following removal from the reactor. As such, container designs, such as Holtec's HI-STORM (adjacent image) incorporate features to enable continuous passive cooling through convection. Furthermore, high levels of shielding are achieved through a mixture of steel and concrete, to ensure those in the vicinity are not exposed to radiation. Finally, an extremely robust design ensures spent fuel assemblies remain safely stored under all foreseeable hazard scenarios such as flood, fire and even aircraft impact.

Whilst referred to as 'interim storage', the minimum design life exceeds 100 years. Over the course of this duration, package condition is monitored to understand whether or not degradation is taking place. As the design life is approached, if degradation is seen then the processes exist today to enable repackaging of waste and recycling of the disused containers. If not, then the storage licence can be extended, subject to regulatory approval. It has been initially estimated that repackaging may be required roughly every 100 - 150 years. However, this process can be undertaken as often and as many times as necessary. Therefore, it is not dependent on the availability of a GDF, and is considered to be a viable and safe long-term, above-ground solution. Furthermore, HLW radioactivity decreases rapidly over time. For example, after 180 years of storage, the radioactivity of HLW reduces to less than 2% of its original value (UK NDA).

As such, HLW is being safely managed at its most hazardous today (and has been for many years) in interim storage facilities around the world.

As stated earlier, spent fuel is not a waste product. However, this has been highlighted to show that the option for safe, above-ground interim storage exists, even for the most radioactive materials without putting the public or environment at risk. Above-ground storage can be implemented for long periods of time, ensuring spent fuel remains accessible for when it is ready to be re-used.

Spent Fuel Dry Casks



Source: www.holtecinternational.com

Radioactive Waste Management Strategies: Future R&D

Transmutation of spent nuclear fuel can change elements in sub-critical fuel assemblies and be encouraged to undergo additional nuclear fission reactions in fast reactors, potentially turning spent fuel in repositories into a resource.

Research and Development

Beyond the numerous options available for safe, long-term storage of all radioactive waste streams and spent fuel, research and development of existing and alternative solutions continues to be undertaken.

Materials Development

R&D into material suitability is a key area for ensuring current and future waste streams can be packaged and stored for long durations of time. Materials use in the nuclear industry is highly-regulated, and only those pre-approved by the relevant authority may be used for specific applications (such as reactor components, transport packages or storage containers). This ensures there are no undesirable consequences resulting from material selection, such as premature corrosion or dangerous reactions. To that end, a significant amount of research is undertaken into materials development, to ensure the list of suitable candidates continues to grow and those which are unsuitable are identified.

For example, in May 2020, the US Department of Energy (DoE) announced the addition of a new metal alloy (617) to the approved list of materials for use in advanced high-temperature NPP design (World Nuclear News). This is the first material in 30 years, following USD $15 million of investment, that has been added to the American Society of Mechanical Engineers (ASME) boiler and pressure vessel code, which is adopted worldwide for NPP design. This level of scrutiny is undertaken to ensure materials adopted are suitable, not only for high-temperature applications, but also for improving plant life, even under highly radioactive conditions.

Transmutation of Spent Fuel and Fission Products

Another activity that continues to be explored, is the process of transmutation. Nuclear transmutation is the process of converting one element or isotope into a different element through particle (usually neutron) bombardment.

By undertaking neutron bombardment of certain radioactive isotopes, the absorption of a neutron into the nucleus can encourage radioactive decay earlier than would otherwise be observed were the material left to decay according to its own natural half-life.

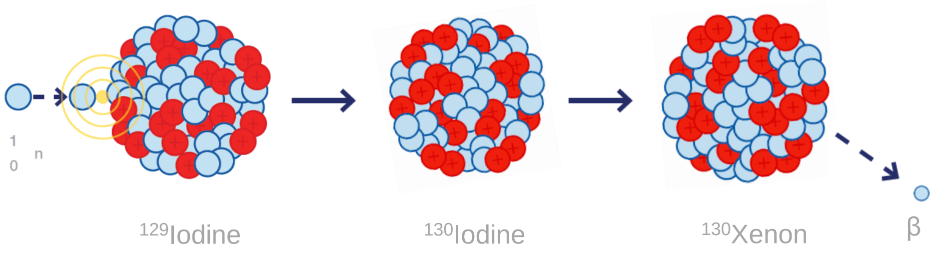
Transmutation has the potential to reduce the half-life of specific long-lived radioisotopes. However, this process is under development and is dependent on a number of factors, such as:

- The requirement to separate out particular elements, to ensure the correct material is targeted; and
- The availability of significant and expensive resources to undertake transmutation.

Where the process of transmutation is more developed is through the re-use of spent nuclear fuel in Fast Neutron Reactors (FNR). The specific composition of nuclear fuel is tightly controlled and well-defined. As such, transmutation of radioactive products from spent nuclear fuel – such as isotopes of Plutonium (Pu-239) that form about 1% by weight of used nuclear fuel in LWRs (World Nuclear Association) – can be achieved through irradiation with fast neutrons in an FNR. Radionuclides such as Pu-239 can undergo nuclear fission, producing a spectrum of other shorter-lived radioactive and non-radioactive fission products. Furthermore, long-lived fission products originally generated can also be converted into short-lived radioisotopes by fast neutrons.

The result of this is that spent nuclear fuel from LWRs (i.e. such as PWRs) can be, and is, reused for energy production and encouraged to undergo additional nuclear fission in Generation IV FNRs. This may improve how radioactive waste is managed as it can reduce the proportion of long-lived isotopes contained in fuel assemblies that will eventually be designated for long-term storage, effectively reducing the average half-life of the radioactive waste.

Neutron Capture Transmutation



Source: US Department of Energy

Radioactive Waste Management: Lessons Learned

There is evidence of the nuclear industry learning lessons from events, especially from those that have drawn public attention, and driving improvements of how radioactive waste is managed safely and efficiently.

UK Contamination Events leading to improved Radwaste management

Since the start of the civil nuclear power industry in the 1950s there has been a learning curve to the industry's understanding and approach to managing radioactive waste. This has come from the UK undertaking a number of firsts when it comes to decommissioning and to the implementation of innovative storage techniques for spent fuel, as well as radioactive waste products. Certain events in the UK, and globally, have illuminated areas in radioactive waste management where improvements had to be made to ensure the continued safety of the public and the environment. This in turn has driven policy which sets specific requirements and safety regulation for how different types of waste are managed.

Together, these events have highlighted several key themes that future management strategies look to focus on to ensure continual improvement as the industry learns. These are highlighted opposite. Some of the key events that have driven changes in the industry include:

- *Dounreay Silo* – from 1955, the Dounreay site was the UK's centre of fast reactor research during the height of the cold war, when the need for nuclear independence was at its greatest and there was an urgent requirement for rapid development in this sector. As part of the radioactive waste management plan, an existing 65-metre access shaft was lined with concrete and converted into a storage solution for various waste streams, including sodium and potassium experimental reactor coolants. The unforeseen ingress of groundwater resulted in the release of radioactive material into the environment, necessitating thorough clean-up and monitoring operations in the local area. This presents an important example of experience gained from the R&D and military sectors, highlighting the need for strict materials selection and segregation, and thorough record keeping on the types and volumes of waste being disposed of to prevent potential unwanted interactions. As an experimental research reactor site, the experiences at Dounreay took place at a time when significant external pressures existed, and the nuclear R&D community was still in the learning phase. Advances in understanding led to improvements in culture and methods, which were directly applied to the civil nuclear sector to ensure such events could not (and did not) happen at commercial nuclear sites.
- *Berkeley NPP decommissioning* – this was the first Magnox site to undergo defueling and decommissioning. The original method for waste disposal was permanent storage in underground vaults present on site, which would eventually be backfilled with concrete. However, there were subsequent discoveries into concrete porosity and the possibility for radionuclides to leach out beyond the vault limits and into the environment. As such, waste retrieval, processing and storage is currently underway, to prevent this eventuality, resolving the issue. Lessons learnt during this process have been applied to future sites. The methodologies adopted for waste record keeping and storage at Magnox sites has led to significant improvements in the monitoring of the waste streams during the operation of nuclear power plants, to ensure all radioactive waste is accounted for and processed in accordance with today's strict legislation.

Events such as these took place when the industry was in its infancy and the learning from these has contributed to plant design and safety culture improvements on nuclear licenced sites. The benefits of nuclear power had been realised, with the ability to extract large quantities of energy from relatively small quantities of fuel (especially when compared to coal and gas). However, a clear understanding of the by-products associated with generation was still being developed. These learning experiences have resulted in a more developed framework and strict controls on waste management to ensure the associated risks are ALARA. Specifically, these two examples highlight the importance of waste segregation and containment. Vault storage is still adopted today, but only as a temporary measure during a plant's operational life, and with strict controls on the waste stream selection and its management.

While undesirable, incidents provide valuable learning to better inform the whole industry on implementing the necessary barriers when managing radioactive waste. Lessons learnt are shared amongst the industry, through multiple channels enabling a culture of continuous improvement. The World Association of Nuclear Operators (WANO), Institute of Nuclear Power Operators (INPO), and International Atomic Energy Agency (IAEA) are all examples of organisations, platforms and resources actively contributing to improved levels of safety across the world. Furthermore, strong and productive relationships between regulators ensure improvements in safety are distributed and implemented.

Example themes of focus for future Radwaste management strategies

Thorough and accurate record keeping

Strict separation of waste streams

Preventing the transport of radionuclides

Material selection

Reduction of waste quantities through design

Resilience to transport accidents

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EU Sustainable Taxonomy: Radioactive Waste Management Review

Section 5: Comparisons to other forms of Power Generation

Waste Generation: Comparison of waste between energy sources

While presenting specific challenges; waste quantities are significantly less in comparison to several other forms of power generation. The volumes of waste are highlighted in this slide.

Volumes of Waste

Each form of power generation has its own specific challenges; however, putting aside the waste quantities, radioactive waste is the only waste stream stringently regulated to ensure the risk to people and the environment is appropriately managed. Furthermore, the quantities of waste produced each year by the nuclear industry are significantly lower when compared to other power generating assets, such as coal-fired stations. This section provides a direct comparison of volumes of waste production across coal, wind, solar and nuclear power generation.

Coal

In addition to the significant CO_2 emissions, it is estimated that coal-fired plants produce approximately 300 million tonnes of fly ash each year during electricity generation (IAEA). Since this IAEA estimate, coal use has approximately doubled, along with fly ash production. Due to the content of the fuel, coal ash also contains radioactive isotopes, which result in radiation levels exceeding those recommended by the International Atomic Energy Agency (IAEA) for general waste disposal. It should be noted that this estimate only conservatively covers fly ash production. It does not include multiple other waste streams, including those associated with plant decommissioning.

Wind Turbines

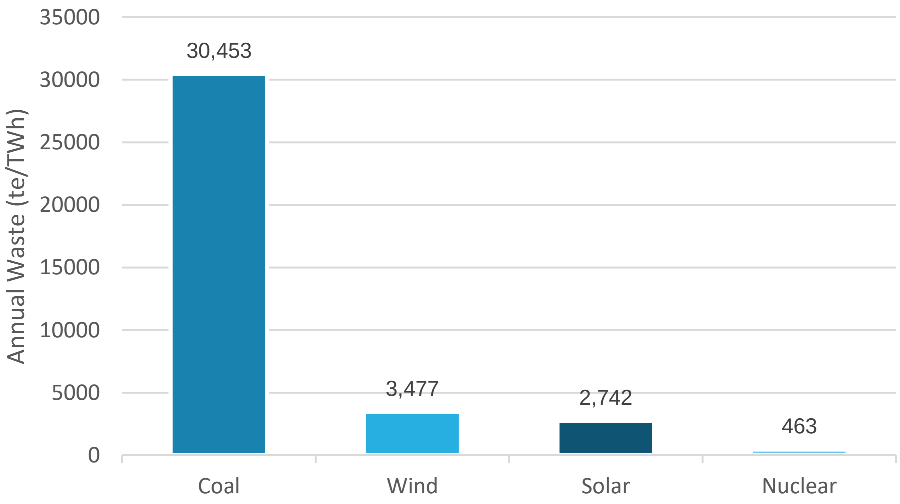
Whilst recycling methods are improving, wind turbines typically last for 20 – 25 years. As a result, large quantities of composite material must be processed and disposed of following wind turbine decommissioning. As renewables form a greater part of the energy mix, the amount of composite (containing high proportions of plastic) waste increases. It is estimated that up to 2.9 million tonnes of waste will be produced from wind turbines each year (Wind turbine blade waste in 2050, by Liu, Pu; Barlow, Claire Y, 2017). It is noted that, whilst difficult to process, composites do not present the same level of toxicity seen with the wastes associated with nuclear, coal or solar power generation. However, plastic production, use and disposal are becoming growing concerns, are heavily reliant on the oil and gas industry, and composite recycling capacity is still very limited.

Solar – Photovoltaic Cells

The presence of plastics, lead, cadmium and antimony create difficulties when looking to recycle Photovoltaic (PV) cell solar panels. As a result, a large quantity of this waste, containing toxic heavy metals is not disposed of correctly. If placed uncontained in land-fill, these toxic heavy metals can be drawn out and can contaminate the surrounding land and ground water

Based on the projected growth of solar panel use from 2016 to 2050 (IRENA projections), there may be up to 78 million tonnes of PV waste by 2050, equating to roughly 2.3 million tonnes per year. As with wind turbines, the challenge presented is associated with the ability to reclaim, recycle and repurpose the complex array of materials from PV cells.

Indicative Waste Production per TWh, for Nuclear, Renewables and Coal



Source: World Nuclear Association – based on 2017 energy outputs

Estimated annual Waste Production, for Nuclear, Renewables and Coal

Source	Waste Generation (te / year)	Note
Coal	300,000,000	Fly Ash
Wind	2,900,000	Composite blade waste
Solar	2,286,765	Solar panels containing toxic material
Nuclear	1,159,367	VLLW, LLW, ILW and HLW.

1. Coal: 300 million tonnes is a previous global estimate sourced from IAEA. Coal-fired energy production has roughly doubled since. As such the value provided is an under-estimate.
2. Wind: turbine blade waste based on industry assumptions
3. Solar: Based on projections from the International Renewable Energy Agency (IRENA) up to 2050
4. Nuclear: Divides the total global radioactive waste inventory by 50 years of generation, and assumes a density of 2 tonnes/m^3
5. In 2017, nuclear power contributed almost twice as much to the global energy mix as solar and wind combined: c.10% compared to c.6.6% for renewables (International Energy Agency).

Source: World Nuclear Association, IAEA, IRENA, and Liu, Pu; Barlow, Claire Y.

Waste Generation: Comparison of waste between energy sources

Furthermore, land usage per MW of nuclear power is favourable, or comparable, to other sources. This is a key factor for countries with limited land mass available for power generation and a growing demand for electricity.

Resource Efficiency and Land Usage

Further to waste generation, each form of power generation has its own specific impact on the planet, that varies from land use, to impacts on wildlife and the environment. Land use can be adopted as a suitable measure of plant energy density, but in reality is of greater concern to countries where available land is scarce and should be prioritised for other industries. However, in order to highlight that all forms of power generation must address their respective environmental impacts, this section provides a high-level view of the concerns that each must tackle.

Land Use

Another consideration that should be taken into account for power generation is land use. This is mostly driven by the energy density of a type of power generation technology.

A 2017 study into efficient land use by Strata in the US estimated that the area of land required for nuclear energy is comparable to that of coal or gas, as a result of the high energy density associated with nuclear fission. The efficiency of each of the major forms of power generation is highlighted in the graph opposite, showing the number of acres required for each MWe of capacity. This suggests that, along with generating a relatively small volume of waste, NPPs occupy significantly less land than that required for key types of renewables, where onshore wind farms and solar PV farms require large areas of space to generate the same amount of power.

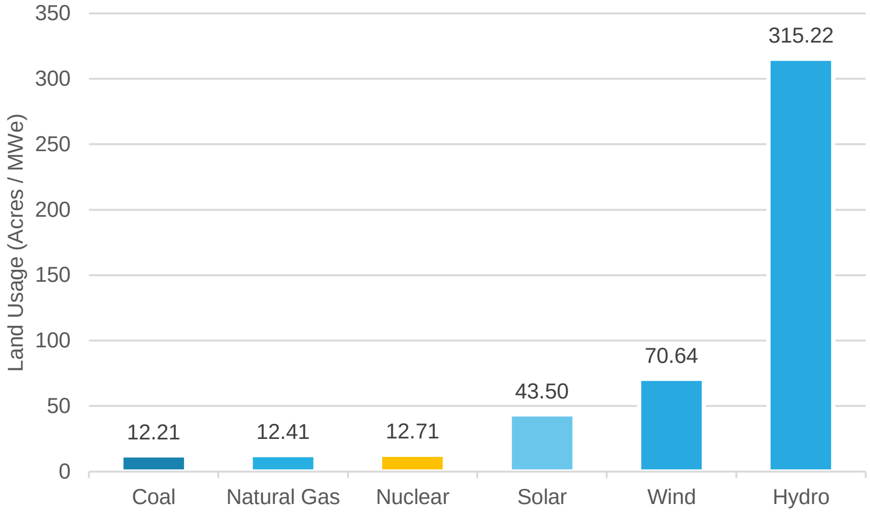
It is noted here that wind turbines are typically placed offshore, which makes the impact on land minimal, something that cannot realistically be achieved for other sources (with some minor exceptions). The graph opposite represents the land usage by onshore wind.

Environmental Considerations

As stated, each form of power generation has its own specific effect on the environment. For example, a 2013 study undertaken by the United States union of concerned scientists highlighted the significant number of potential impacts associated with large-scale hydropower construction and use. In addition to the substantial areas of land required, the need to divert, restrict and store water flows can have a significant impact on water oxygen levels, fish migration and population.

As stated previously waste and discharges from NPPs are strictly controlled to reduce their impact on the environment – operators are held entirely responsible for their waste products. In the UK, a large number of operating and decommissioned NPPs are located on Sites of Special Scientific Interest (SSSI), designated as such due to the presence of particular species or geological conditions. Industry operators in these conservation areas must ensure that SSSIs are not adversely affected by their presence, and the responsibility is placed upon them to ensure their upkeep and conservation. On that basis, NPP operators in the UK allocate funding to ensure this is the case.

Land usage from main waste stream for major forms of power generation.



Source: Strata Research, US

UK Onshore Windfarm

Source: UK Government

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EU Sustainable Taxonomy: Radioactive Waste Management Review

→ Section 6: Conclusions

Conclusions

Radioactive waste is managed safely and securely with multiple strategies available for long-term storage and disposal.

Conclusions

Each form of power generation is subject to its own difficulties and constraints, which must be balanced with resource availability, energy demand, environmental impact and cost. The current view of the EU acknowledges the role of nuclear power in reducing global CO_2 emissions, but does raise concerns over the ability of the industry to manage the waste streams produced.

The purpose of this report has been to collate the findings of a literary review into radioactive waste production and management, and how this compares to other forms of power generation, particularly with regards to waste quantities, types and emissions. The findings demonstrate that, not only does nuclear power contribute significantly to the reduction in greenhouse gas emissions, but that it is also the only form of power generation that takes full responsibility for the management of all waste produced. The findings and conclusions are summarised below.

Waste Quantity

On average, the quantities of waste produced by the nuclear industry are significantly less when compared with several other forms of power generation. In addition, the nuclear industry is the only form of power generation that takes full responsibility for the management of the waste produced, allowing the public and environmental impact to be clearly understood and tracked. Coal-fired stations produce by far the largest quantity of waste, which must be managed and either disposed of or distributed for use in other industries such as construction (which presents its own hazards). Wind turbine blades and Solar PVs present a growing problem, which has drawn greater attention as the energy mix draws more heavily on renewable sources, and millions of tonnes of waste are placed in land-fill once decommissioned.

Safety

Despite the hazardous nature of radioactive waste, the level of regulation and the safety culture adopted in the nuclear industry in general ensures the public and environment remain protected against all eventualities. The nuclear industry in general has an excellent track record in safety, with very few incidents. Once packaged, radioactive waste is essentially benign. Package design and process security ensure that radiation doses are negligible and the contents are securely contained and cannot be accessed, even following a serious event (such as flooding or even an aircraft impact). Radioactive waste storage and disposal has no effect on public safety.

Resources

Due to the energy density associated with an NPP, resource use (such as land), is significantly reduced, when compared to other forms of power generation. Solar, onshore wind and hydropower require much greater areas of land in order to achieve comparable outputs. When compared to coal-fired stations and gas-fired stations, nuclear power presents a comparable energy density, but does not suffer from the same levels of fuel scarcity. Natural uranium is an abundant resource, the same cannot be said for coal and gas.

Furthermore, solar PVs rely on the reliable mining and processing of rare heavy metals, and will be affected by material scarcity and resource availability. Wind turbine blades, on the other hand, are composite materials, utilising carbon fibre in a polymer resin, and are therefore heavily dependent on the oil and gas industry.

Renewable sources of energy play an important role in energy production; however, key considerations, potentially affecting the environment, can often be overlooked. For example, several studies have been undertaken into hydropower, concluding that appreciable negative impacts can be seen on rivers and habitats within the vicinity and downstream of hydropower stations.

Waste Disposal

Finally, while radioactive waste is hazardous, the requirements associated with owning and operating an NPP have ensured that multiple safe, dedicated disposal routes have been identified, and are either available, or can be made available in the coming years. This is in contrast to other forms of waste, for which the disposal or reprocessing is not comprehensively regulated, and land-fill remains a chosen option for the mixture of polymers and even toxic materials.

There currently exist several suitable long-term solutions for processing, packaging and storing radioactive waste. Whilst a GDF does not currently exist within the UK or Europe, it is not necessarily required, and is just one of multiple options, such as ISFs and NSSFs, that can be used in combination or independently. As such, safe and secure long-term solutions for radioactive waste disposal currently exist, and have done for some time.