WORLD NUCLEAR ASSOCIATION

NUCLEAR FUEL CYCLE

Radioactive Waste Management

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> 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.
>
> The amount of waste generated by nuclear power is very small relative to other thermal electricity generation technologies.
>
> Used nuclear fuel may be treated as a resource or simply as waste.
>
> Nuclear waste is neither particularly hazardous nor hard to manage relative to other toxic industrial waste.
>
> Safe methods for the final disposal of high-level radioactive waste are technically proven; the international consensus is that geological disposal is the best option.

Like all industries, the generation of electricity produces waste. Whatever fuel is used, the waste produced in generating electricity must be managed in ways that safeguard human health and minimize the impact on the environment.

For radioactive waste, this means isolating or diluting it such that the rate or concentration of any radionuclides returned to the biosphere is harmless. To achieve this, practically all radioactive waste is contained and managed, with some clearly needing deep and permanent burial. From nuclear power generation, unlike all other forms of thermal electricity generation, all waste is regulated

– none is allowed to cause pollution.

Nuclear power is characterized by the very large amount of energy produced from a very small amount of fuel, and the amount of waste produced during this process is also relatively small. However, much of the waste produced is radioactive and therefore must be carefully managed as hazardous material. All parts of the nuclear fuel cycle produce some radioactive waste and the cost of managing and disposing of this is part of the electricity cost (*i.e.* it is internalized and paid for by the electricity consumers).

All toxic waste needs be dealt with safely – not just radioactive waste – and in countries with nuclear power, radioactive waste comprises a very small proportion of total industrial hazardous waste generated.

Radioactive waste is not unique to the nuclear fuel cycle. Radioactive materials are used extensively in medicine, agriculture, research, manufacturing, non-destructive testing, and minerals exploration. Unlike other hazardous industrial materials the level of hazard of all radioactive waste – its radioactivity – diminishes with time.

Types of radioactive waste

Radioactive waste includes any material that is either intrinsically radioactive, or has been contaminated by radioactivity, and that is deemed to have no further use. Government policy dictates whether certain materials – such as used nuclear fuel and plutonium – are categorized as waste.

Every radionuclide has a half-life – the time taken for half of its atoms to decay, and thus for it to lose half of its radioactivity. Radionuclides with long half-lives tend to be alpha and beta emitters – making their handling easier – while those with short half-lives tend to emit the more penetrating gamma rays. Eventually all radioactive waste decays into non-radioactive elements. The more radioactive an isotope is, the faster it decays. Radioactive waste is typically classified as either low-level (LLW), intermediate-level (ILW), or high-level (HLW), dependent, primarily, on its level of radioactivity.

Low-level waste

Low-level waste (LLW) has a radioactive content not exceeding four giga-becquerels per tonne (GBq/t) of alpha activity or 12 GBq/t beta-gamma activity. LLW does not require shielding during handling and transport, and is suitable for disposal in near surface facilities.

LLW is generated from hospitals and industry, as well as the nuclear fuel cycle. It comprises paper, rags, tools, clothing, filters, etc., which contain small amounts of mostly short-lived radioactivity. To reduce its volume, LLW is often compacted or incinerated before disposal. LLW comprises some 90% of the volume but only 1% of the radioactivity of all radioactive waste.

Intermediate-level waste

Intermediate-level waste (ILW) is more radioactive than LLW, but the heat it generates (<2 kW/m^3) is not sufficient to be taken into account in the design or selection of storage and disposal facilities. Due to its higher levels of radioactivity, ILW requires some shielding.

ILW typically comprises resins, chemical sludges, and metal fuel cladding, as well as contaminated materials from reactor decommissioning. Smaller items and any non-solids may be solidified in concrete or bitumen for disposal. It makes up some 7% of the volume and has 4% of the radioactivity of all radioactive waste.

High-level waste

High-level waste (HLW) is sufficiently radioactive for its decay heat (>2kW/m^3) to increase its temperature, and the temperature of its surroundings, significantly. As a result, HLW requires cooling and shielding.

HLW arises from the 'burning' of uranium fuel in a nuclear reactor. HLW contains the fission products and transuranic elements generated in the reactor core. HLW accounts for just 3% of the volume, but 95% of the total radioactivity of produced waste. There are two distinct kinds of HLW:

- Used fuel that has been designated as waste.
- Separated waste from reprocessing of used fuel.

HLW has both long-lived and short-lived components, depending on the length of time it will take for the radioactivity of particular radionuclides to decrease to levels that are considered nonhazardous for people and the surrounding environment. If generally short-lived fission products can be separated from long-lived actinides, this distinction becomes important in management and disposal of HLW.

HLW is the focus of significant attention regarding nuclear power, and is managed accordingly.

Very low-level waste

Exempt waste and very low-level waste (VLLW) contains radioactive materials at a level which is not considered harmful to people or the surrounding environment. It consists mainly of demolished material (such as concrete, plaster, bricks, metal, valves, piping, etc.) produced during rehabilitation or dismantling operations on nuclear industrial sites. Other industries, such as food processing, chemical, steel, etc., also produce VLLW as a result of the concentration of natural radioactivity present in certain minerals used in their manufacturing processes (see also information page on Naturally-Occurring Radioactive Materials). The waste is therefore disposed of with domestic refuse, although countries such as France are currently developing specifically designed VLLW disposal facilities.

Where and when is waste produced?

(See also information page on The Nuclear Fuel Cycle.)

Radioactive waste is produced at all stages of the nuclear fuel cycle – the process of producing electricity from nuclear materials. The fuel cycle involves the mining and milling of uranium ore, its processing and fabrication into nuclear fuel, its use in the reactor, its reprocessing (if conducted), the treatment of the used fuel taken from the reactor, and finally, disposal of the waste. Whilst waste is produced during mining and milling and fuel fabrication, the majority (in terms of radioactivity) comes from the actual 'burning' of uranium to produce electricity. Where the used fuel is reprocessed, the amount of waste is reduced materially.

Mining through to fuel fabrication

Traditional uranium mining generates fine sandy tailings, which contain virtually all the naturally occurring radioactive elements found in uranium ore. The tailings are collected in engineered dams and finally covered with a layer of clay and rock to inhibit the leakage of radon gas, and to ensure long-term stability. In the short term, the tailings material is often covered with water. After a few months, the tailings material contains about 75% of the radioactivity of the original ore. Strictly speaking these are not classified as radioactive waste.

Uranium oxide concentrate from mining, essentially 'yellowcake' (U_3O_8), is not significantly radioactive – barely more so than the granite used in buildings. It is refined then converted to uranium hexafluoride (UF_6) gas. As a gas, it undergoes enrichment to increase the U-235 content from 0.7% to about 3.5%. It is then turned into a hard ceramic oxide (UO_2) for assembly as reactor fuel elements.

The main by-product of enrichment is depleted uranium (DU), principally the U-238 isotope, which is stored either as UF_6 or U_3O_8. Some DU is used in applications where its extremely high density makes it valuable, such as for the keels of yachts and military projectiles. It is also used (with reprocessed plutonium) for making mixed oxide (MOX) fuel and to dilute highly-enriched uranium from dismantled weapons, which can then be used for reactor fuel (see pages on Uranium and Depleted Uranium and Military Warheads as a Source of Nuclear Fuel).

Electricity generation

In terms of radioactivity, the major source arising from the use of nuclear reactors to generate electricity comes from the material classified as HLW. Highly radioactive fission products and transuranic elements are produced from uranium and plutonium during reactor operations, and are contained within the used fuel. Where countries have adopted a closed cycle and reprocess used fuel, the fission products and minor actinides are separated from uranium and plutonium and treated as HLW (see below). In countries where used fuel is not reprocessed, the used fuel itself is considered a waste and therefore classified as HLW.

LLW and ILW is produced as a result of general operations, such as the cleaning of reactor cooling systems and fuel storage ponds, and the decontamination of equipment, filters, and metal components that have become radioactive as a result of their use in or near the reactor.

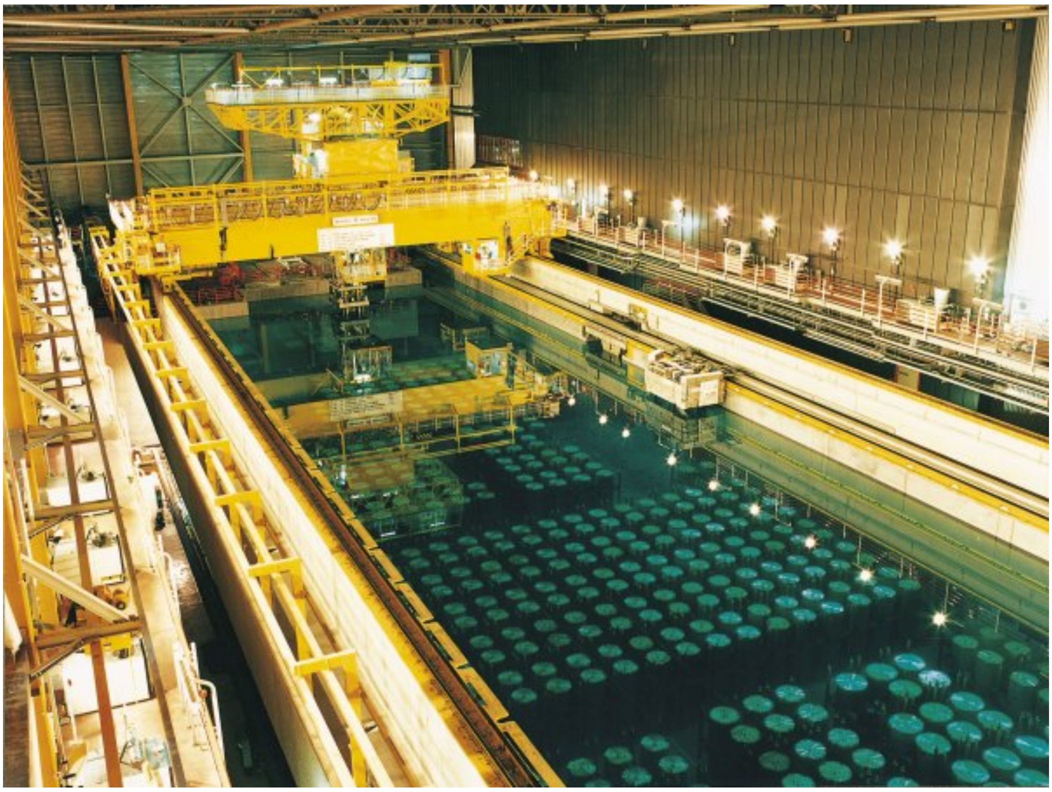
Reprocessing of used fuel

Any used fuel will still contain some of the original U-235 as well as various plutonium isotopes which have been formed inside the reactor core, and U-238. In total these account for some 96% of the original uranium and over half of the original energy content (ignoring U-238). Used nuclear fuel has long been reprocessed to extract fissile materials for recycling and to reduce the volume of HLW (see also information page on Processing of Used Nuclear Fuel). Several European countries, as well as Russia, China, and Japan have policies to reprocess used nuclear fuel.

Reprocessing allows for a significant amount of plutonium to be recovered from used fuel, which is then mixed with depleted uranium oxide in a MOX fabrication plant to make fresh fuel. This process allows some 25-30% more energy to be extracted from the original uranium ore, and significantly reduces the volume of HLW (by about 85%). The IAEA estimates that of the 390,000 metric tonnes of heavy metal (MTHM) produced since the advent of civil nuclear power production, 127,000 MTHM has been reprocessed.[1] In addition, the remaining HLW is significantly less radioactive – decaying to the same level as the original ore within 9000 years (vs. 300,000 years). (See also information pages on Mixed Oxide Fuel and Processing of Used Nuclear Fuel.)

Commercial reprocessing plants currently operate in France and Russia. Another is being commissioned in Japan, and China plans to construct one too. France undertakes reprocessing for utilities in other countries, and a lot of Japan's fuel has been reprocessed there, with both waste and recycled plutonium in MOX fuel being returned to Japan. (See also information pages on Japanese Waste and MOX Shipments From Europe.)

The main historical and current process is Purex, a hydrometallurgical process. The main prospective ones are electrometallurgical – often called pyroprocessing since it happens to be hot. With it, all actinide anions (notably uranium and plutonium) are recovered together. Whilst not yet operational, these technologies will result in waste that only needs 300 years to reach the same level of radioactivity as the originally mined ore.



Storage pond for used fuel at the Thermal Oxide Reprocessing Plant (Thorp) at the UK's Sellafield site (Sellafield Ltd).

Decommissioning nuclear plants

(See also information page on Decommissioning Nuclear Facilities.)

In the case of nuclear reactors, about 99% of the radioactivity is associated with the fuel. Apart from any surface contamination of plant, the remaining radioactivity comes from 'activation products' such as steel components which have long been exposed to neutron irradiation. Their atoms are changed into different isotopes such as iron-55, cobalt-60, nickel-63, and carbon-14. The first two are highly radioactive, emitting gamma rays, but with correspondingly short half-lives so that after 50 years from final shutdown their hazard is much diminished. Some caesium-137 may also be found in decommissioning wastes.

Some scrap material from decommissioning may be recycled, but for uses outside the industry very low clearance levels are applied, so most is buried and some is recycled within the industry.

Legacy waste

In addition to the routine waste from current nuclear power generation there is other radioactive waste referred to as 'legacy waste'. This waste exists in several countries that pioneered nuclear power and especially where power programs were developed out of military programs. It is sometimes voluminous and difficult to manage, and arose in the course of those countries getting to a position where nuclear technology is a commercial proposition for power generation. It represents a liability which is not covered by current funding arrangements. In the UK, some £164 billion (undiscounted) is estimated to be involved in addressing this waste – principally from Magnox and some early AGR developments – and about 30% of the total is attributable to military programmes. In the USA, Russia, and France the liabilities are also considerable.

Non-nuclear power waste

In recent years, in both the radiological protection and radioactive waste management communities, there has been increased attention on how to effectively manage non-power related nuclear waste. All countries, including those that do not have nuclear power plants, have to manage radioactive waste generated by activities unrelated to the production of nuclear energy, including: national laboratory and university research activities; used and lost industrial gauges and radiography sources; and nuclear medicine activities at hospitals. Although much of this waste is not long-lived, the variety of the sources makes any general assessment of physical or radiological characteristics difficult. The relatively source-specific nature of the waste poses questions and challenges for its management at a national level.

Treatment and conditioning

(See also information page on Treatment and Conditioning of Nuclear Waste)

Treatment involves operations intended to change waste streams' characteristics to improve safety or economy. Treatment techniques may involve compaction to reduce volume, filtration or ion exchange to remove radionuclide content, or precipitation to induce changes in composition.

Conditioning is undertaken to change waste into a form that is suitable for safe handling, transportation, storage, and disposal. This step typically involves the immobilisation of waste in containers. Liquid LLW and ILW are typically solidified in cement, whilst HLW is calcined/dried then vitrified in a glass matrix. Immobilized waste will be placed in a container suitable for its characteristics.

Storage and disposal

(See also information page on Storage and Disposal of Radioactive Waste.)

Storage of waste may take place at any stage during the management process. Storage involves maintaining the waste in a manner such that it is retrievable, whilst ensuring it is isolated from the external environment. Waste may be stored to make the next stage of management easier (for example, by allowing its natural radioactivity to decay). Storage facilities are commonly onsite at the power plant, but may be also be separate from the facility where it was produced.

Disposal of waste takes place when there is no further foreseeable use for it, and in the case of HLW, when radioactivity has decayed to relatively low levels after about 40-50 years.

LLW and short-lived ILW

Most LLW and short-lived ILW are typically sent to land-based disposal immediately following packaging. This means that for the majority (>90% by volume) of all of the waste types, a satisfactory disposal means has been developed and is being implemented around the world.

Near-surface disposal facilities are currently in operation in many countries, including:

> UK – LLW Repository at Drigg in Cumbria operated by UK Nuclear Waste Management (a consortium led by Washington Group International with Studsvik UK, Serco, and Areva) on behalf of the Nuclear Decommissioning Authority.
>
> Spain – El Cabril LLW and ILW disposal facility operated by ENRESA.
>
> France – Centre de l'Aube and Morvilliers operated by ANDRA.
>
> Sweden – SFR at Forsmark operated by SKB.
>
> Finland – Olkiluoto and Loviisa, operated by TVO and Fortum.
>
> Russia – Ozersk, Tomsk, Novouralsk, Sosnovy Bor, operated by

NO RAO.

South Korea – Wolseong, operated by KORAD.

Japan – LLW Disposal Center at Rokkasho-Mura operated by Japan Nuclear Fuel Limited.

USA – five LLW disposal facilities: Texas Compact facility near the New Mexico border, operated by Waste Control Specialists; Barnwell, South Carolina; Clive, Utah; Oak Ridge, Tennessee – all operated by Energy Solutions; and Richland, Washington – operated by American Ecology Corporation.

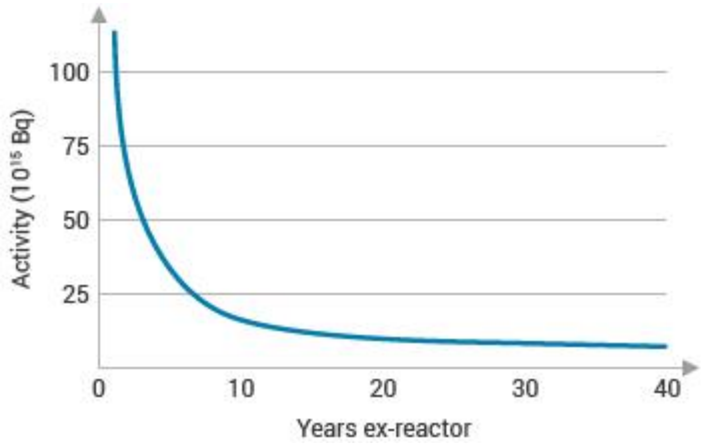
Some low-level liquid waste from reprocessing plants is discharged to the sea. This includes radionuclides which are distinctive, notably technetium-99 (sometimes used as a tracer in environmental studies), and this can be discerned many hundred kilometres away. However, such discharges are regulated and controlled, and the maximum radiation dose anyone receives from them is a small fraction of natural background radiation.

Nuclear power stations and reprocessing plants release small quantities of radioactive gases (e.g. krypton-85 and xenon-133) and trace amounts of iodine-131 to the atmosphere. However, krypton-85 and xenon-133 are chemically inert, all three gases have short half-lives, and the radioactivity in the emissions is diminished by delaying their release. The net effect is too small to warrant consideration in any life-cycle analysis. A little tritium is also produced but regulators do not consider its release to be significant.

Long-lived ILW and HLW

The long timescales over which some ILW and HLW – including used fuel when considered a waste – remains radioactive has led to universal acceptance of the concept of deep geological disposal. Many other long-term waste management options have been investigated, but deep disposal in a mined repository is now the preferred option in most countries. The Waste Isolation Pilot Plant (WIPP) deep geological waste repository is in operation in the US for the disposal of transuranic waste – long-lived ILW from military sources, contaminated with plutonium.

To date there has been no practical need for final HLW repositories. As outlined above, used fuel may either by reprocessed or disposed of directly. Either way, there is a strong technical incentive to delay final disposal of HLW for about 40-50 years after removal, at which point the heat and radioactivity will have reduced by over 99%. Interim storage of used fuel is mostly in ponds associated with individual reactors, or in a common pool at multi-reactor sites, or occasionally at a central site. At present there is about 263,000 tonnes of used fuel in storage. Over two-thirds of this is in storage ponds, with an increasing proportion in dry storage.[1]



Illustrative decay in radioactivity of fission products – one tonne of spent PWR fuel.

Storage ponds at reactors, and those at centralized facilities such as CLAB in Sweden, are 7-12 metres deep to allow for several metres of water over the used fuel (assembled in racks typically about 4 metres long and standing on end). The multiple racks are made of metal with neutron absorbers incorporated. The circulating water both shields and cools the fuel. These pools are robust constructions made of thick reinforced concrete with steel liners. Ponds at reactors are often designed to hold all the used fuel produced over the planned operating lifetime of the reactor.

Water-filled storage pools at the Central Interim Storage Facility for Spent Nuclear Fuel (CLAB) facility in Sweden.

Some fuel that has cooled in ponds for at least five years is stored in dry casks or vaults with air circulation inside concrete shielding. One common system is for sealed steel casks or multi-purpose canisters (MPCs) each holding up to about 40 fuel assemblies with inert gas. Casks/MPCs may also be used for the transport and eventual disposal of the used fuel. For storage, each is enclosed in a ventilated storage module made of concrete and steel. These are commonly standing on the surface, about 6m high, and cooled by air convection, or they may be below grade, with just the tops showing. The modules are robust and provide full shielding. Each cask has up to 45 kW heat load.

If used reactor fuel is reprocessed, the resulting liquid HLW must be solidified. The HLW also generates a considerable amount of heat and requires cooling. It is vitrified into borosilicate (Pyrex) glass, sealed into heavy stainless steel cylinders about 1.3 metres high, and stored for eventual disposal deep underground. This material has no conceivable future use and is universally classified as waste. France has two commercial plants to vitrify HLW left over from reprocessing fuel, and there are also plants active in the UK and Belgium. The capacity of these Western European plants is 2500 canisters (1000 t) a year, and some have been operating for three decades. Sellafield, UK, has produced over 6000 canisters of vitrified HLW.

The Australian Synroc (synthetic rock) system is a more sophisticated way to immobilize such waste, and this process may eventually come into commercial use for civil waste (see information page on Synroc).

If used reactor fuel is not reprocessed, it will still contain all the highly radioactive isotopes. Spent fuel that is not reprocessed is treated as HLW for direct disposal. It too generates a lot of heat and requires cooling. However, since it largely consists of uranium (with a little plutonium), it represents a potentially valuable resource, and there is an increasing reluctance to dispose of it irretrievably.

For final disposal, to ensure that no significant environmental releases occur over tens of thousands of years, 'multiple barrier' geological disposal is planned. This technique will immobilize the radioactive elements in HLW and long-lived ILW, and isolate them from the biosphere. The multiple barriers are:

> Immobilisation of waste in an insoluble matrix such as borosilicate glass or synthetic rock (fuel pellets are already a very stable ceramic, UO_2).
>
> Contain waste sealed inside a corrosion-resistant container,

such as stainless steel.

Isolate waste from people and the environment, so eventually locate it deep underground in a stable rock structure.

Delay any significant migration of radionuclides from the repository, so surround containers with an impermeable backfill such as bentonite clay if the repository is wet.

Loading silos with canisters containing vitrified HLW in the UK. Each disc on the floor covers a silo holding ten canisters.

Due to the long-term nature of these management plans, sustainable options must have one or more pre-defined milestones where a decision could be taken on which option to proceed with.

A current question is whether waste should be emplaced so that it is readily retrievable from repositories. There are sound reasons for keeping such options open – in particular, it is possible that future generations might consider the buried waste to be a valuable resource. On the other hand, permanent closure might increase long-term security of the facility. After being buried for about 1000 years most of the radioactivity will have decayed. The amount of radioactivity then remaining would be similar to that of the naturally-occurring uranium ore from which it originated, though it would be more concentrated. In mined repositories, which represent the main concept being pursued, retrievability can be straightforward, but any deep borehole disposal is permanent.

France's 2006 waste law says that HLW disposal must be 'reversible', which was clarified in a 2015 amendment to mean guaranteeing long-term flexibility in disposal policy, while 'retrievable' referred to short-term practicality. France, Switzerland, Canada, Japan, and the USA require retrievability.[2] That policy is followed also in most other countries, though this presupposes that in the long-term, the repository would be sealed to satisfy safety requirements.

The measures or plans that various countries have in place to store, reprocess, and dispose of used fuel and waste are described in an appendix to this paper covering National Policies and Funding. Storage and disposal options are described more fully in the information paper on Storage and Disposal of Radioactive Waste.

Natural precedents for geological disposal

Nature has already proven that geological isolation is possible through several natural examples (or 'analogues'). The most significant case occurred almost 2 billion years ago at Oklo, in what is now Gabon in West Africa, where several spontaneous nuclear reactors operated within a rich vein of uranium ore. (At that time the concentration of U-235 in all natural uranium was about 3%.) These natural nuclear reactors continued for about 500,000 years before dying away. They produced all the radionuclides found in HLW, including over 5 tonnes of fission products and 1.5 tonnes of plutonium, all of which remained at the site and eventually decayed into non-radioactive elements.[3]

The study of such natural phenomena is important for any assessment of geologic repositories, and is the subject of several international research projects.

Funding waste management

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. Financial provisions are made for managing all kinds of civilian radioactive waste. The cost of managing and disposing of nuclear power plant waste typically represents about 5% of the total cost of the electricity generated.

Most nuclear utilities are required by governments to put aside a levy (e.g. 0.1 cents per kilowatt hour in the USA, 0.14 ¢/kWh in France) to provide for the management and disposal of their waste.

The actual arrangements for paying for waste management and decommissioning vary. The key objective is, however, always the same: to ensure that sufficient funds are available when they are needed. There are three main approaches:

> Provisions on the balance sheet. Sums to cover the anticipated cost of waste management and decommissioning are included on the generating company's balance sheet as a liability. As waste management and decommissioning work proceeds, the company has to ensure that it has sufficient investments and cashflow to meet the required payments.
>
> Internal fund. Payments are made over the operating lifetime of the nuclear facility into a special fund that is held and administered within the company. The rules for the management of the fund vary, but many countries allow the fund to be re-invested in the assets of the company, subject to adequate securities and investment returns.
>
> External fund. Payments are made into a fund that is held outside the company, often within government or administered by a group of independent trustees. Again, rules for the management of the fund vary. Some countries only allow the fund to be used for waste management and decommissioning purposes, whilst others allow companies to borrow a percentage of the fund to reinvest in their business.

How much waste is produced?

The volume of high-level radioactive waste (HLW) produced by the civil nuclear industry is small. The IAEA estimates that 392,000 tonnes of heavy metal (tHM) in the form of used fuel have been discharged since the first nuclear power plants commenced operation. Of this, the agency estimates that 127,000 tHM have been reprocessed. The IAEA estimates that the disposal volume[b] of the current solid HLW inventory is approximately 29,000 m^3.[1] For context, this is a volume roughly equivalent to a three metre tall building covering an area the size of a soccer pitch.

The amounts of ILW, LLW, and VLLW produced are greater in volume, but are much less radioactive (see above section on Types of radioactive waste). Given its lower inherent radioactivity, the majority of waste produced by nuclear power production and classified as LLW or VLLW has already been placed in disposal. The IAEA estimates that over 80% of all LLW and VLLW produced to date is in disposal.

Nuclear waste inventory (IAEA estimates, 2022)[1]

	Solid radioactive waste in storage (m^3)	Solid radioactive waste in disposal (m^3)	Proportion of waste type in disposal
VLLW	2,918,000	11,842,000	80%
LLW	1,471,000	18,499,000	92%
ILW	2,740,000	133,000	5%
HLW	29,000	0	0%

Note: all volumetric figures are provided as estimates based on operating and proposed final disposal solutions for different types of waste. Figures, published in January 2022, are estimates for end of 2016.

All hazardous waste requires careful management and disposal, not just radioactive waste. The amount of waste produced by the nuclear power industry is small relative to both other forms of electricity generation and general industrial activity. For example, in the UK – the world's oldest nuclear industry – the total amount of radioactive waste produced to date, and forecast to 2125, is about 4.9 million tonnes. After all waste has been packaged, it is estimated that the final volume would occupy a space similar to that of a large, modern soccer stadium. This compares with an annual generation of 200 million tonnes of conventional waste, of which 4.3 million tonnes is classified as hazardous. About 94% of radioactive waste in the UK is classified as LLW, about 6% is ILW, and less than 0.03% is classified as HLW.[4]

In over 50 years of civil nuclear power experience, the management and disposal of civil nuclear waste has not caused any serious health or environmental problems, nor posed any real risk to the general public. Alternatives for power generation are not without challenges, and their undesirable by-products are generally not well controlled.

To put the production and management of nuclear waste in context, it is important to consider the non-desirable by-products – most notably carbon dioxide emissions – of other large-scale commercial electricity generating technologies. In 2019, nuclear power plants supplied 2657 TWh of electricity, about 10% of the world's total consumption. Fossil fuels supplied about 63%, of which coal contributed the most (9914 TWh), followed by gas (6346TWh), and oil (747 TWh). If the about 10% of electricity supplied by nuclear power had been replaced by gas – by far the cleanest burning fossil fuel – an additional c. 1300 million tonnes of CO_2 would have been released into the atmosphere; the equivalent of putting an additional 250 million cars on the road.[6, c]

CO_2 emissions avoided through the use of nuclear power

	Lifecycle emissions (gCO_2eq/kWh)[5, a]	Estimated emissions to produce 2710 TWh electricity (million tonnes CO_2)	Potential emissions avoided through use of nuclear power (million tonnes CO_2)	Potential emissions avoided through use of nuclear (million cars equivalent)[6, c]
Nuclear power	12	32	NA	NA
Gas (CCS)	490	1300	1268	c. 250
Coal	820	2180	2148	c. 400

Note: Lifecycle emissions estimates from the IPCC. Estimate of average emissions per vehicle from the EPA.

In addition to producing very significant emissions of carbon, hydrocarbon industries also create significant amounts of radioactive waste. The radioactive material produced as a waste product from the oil and gas industry is referred to as 'technologically enhanced naturally occurring radioactive materials' (Tenorm). In oil and gas production, radium-226, radium-228, and lead-210 are deposited as scale in pipes and equipment in many parts of the world. Published data show radionuclide concentrations in scales up to 300,000 Bq/kg for Pb-210, 250,000 Bq/kg for Ra-226, and 100,000 Bq/kg for Ra-228. This level is 1000 times higher than the clearance level for recycled material (both steel and concrete) from the nuclear industry, where anything above 500 Bq/kg may not be cleared from regulatory control for recycling.[7]

The largest Tenorm waste stream is coal ash, with around 280 million tonnes arising globally each year, carrying uranium-238 and all its non-gaseous decay products, as well as thorium-232 and its progeny. This ash is usually just buried, or may be used as a constituent in building materials. As such, the same radionuclide, at the same concentration, may be sent to deep disposal if from the nuclear industry, or released for use in building materials if in the form of fly ash from the coal industry.[8]

Notes & references

References

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2. The 2006 Programme Act on the Sustainable Management of Radioactive Materials and Wastes, Assemblée nationale (2006)
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4. Radioactive Waste in the UK: A summary of the 2010 Inventory, Nuclear Decommissioning Authority (2010) [Back]
5. Technology-specific Cost and Performance Parameters, Intergovernmental Panel on Climate Change (2014) [Back]
6. Greenhouse Gas Emissions from a Typical Passenger Vehicle, United States Environmental Protection Agency (2014) [Back]
7. Technogically enhanced naturally occuring radioactive materials in the oil industry (TENORM), Nukleonika (2009) [Back]
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Notes

a. Lifecycle emissions data are IPCC's median estimates, and are inclusive of albedo effect. Gas data relate to combined cycle, and coal data relate to pulverized coal (PC). In reality, average lifecycle emissions for both gas and coal are likely to be higher. [Back]

b. Disposal volumes vary based on the chosen solution for waste disposal. In arriving at its estimate, the IAEA has made assumptions with respect to packaging and repository design for countries without confirmed disposal solutions based on the plans proposed by countries more advanced in the process. [Back]

c. The EPA estimates that the average road vehicle emits the equivalent of 4.7 tonnes of CO_2 per year. [Back]

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Appendices

Radioactive Waste Management Appendix 2: National Policies and Funding
Radioactive Waste Management Appendix 1: Synroc

Related information

Naturally-Occurring Radioactive Materials NORM
Military Warheads as a Source of Nuclear Fuel
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OUR ASSOCIATION

Our Mission

Leadership

Our Members

Vacancies

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REUSE OF WORLD NUCLEAR ASSOCIATION CONTENT