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Radioactive Waste Management

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Abstract— **Nuclear power is the only large-scale energy-producing technology which takes full responsibility for all its wastes and fully costs this into the product. The amount of radioactive wastes is very small relative to wastes produced by fossil fuel electricity generation. Used nuclear fuel may be treated as a resource or simply as a waste. Nuclear wastes are neither particularly hazardous nor hard to manage relative to other toxic industrial wastes. Safe methods for the final disposal of high-level radioactive waste are technically proven; the international consensus is that this should be geological disposal.**

Index Terms— **Radioactive waste, industrial waste, geological disposal**

I. INTRODUCTION

All parts of the nuclear fuel cycle produce some radioactive waste (radwaste) and the relatively modest 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. At each stage of the fuel cycle there are proven technologies to dispose of the radioactive wastes safely. For low- and intermediate-level wastes these are mostly being implemented. For high-level wastes some countries await the accumulation of enough of it to warrant building geological repositories; others, such as the USA, have encountered political delays. Unlike other industrial wastes, the level of hazard of all nuclear waste - its radioactivity - diminishes with time. Each radionuclide contained in the waste 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 wastes decay into non-radioactive elements. The more radioactive an isotope is, the faster it decays.

The main objective in managing and disposing of radioactive (or other) waste is to protect people and the environment. This means isolating or diluting the waste so that the rate or concentration of any radionuclides returned to the biosphere is harmless. To achieve this, practically all wastes are contained and managed – some clearly need deep and permanent burial. From nuclear power generation, none is allowed to cause harmful pollution.

All toxic wastes need to be dealt with safely, not just radioactive wastes. In countries with nuclear power, radioactive wastes comprise less than 1% of total industrial toxic wastes (the balance of which remains hazardous indefinitely).

A. I. TYPES OF RADIOACTIVE WASTES

1) EXEMPT WASTE & 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. The waste is therefore disposed of with domestic refuse, although countries such as France are currently developing facilities to store VLLW in specifically designed VLLW disposal facilities.

1) A. Low-Level Waste

Low-level waste (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. It does not require shielding during handling and transport and is suitable for shallow land burial. To reduce its volume, it is often compacted or incinerated before disposal. It comprises some 90% of the volume but only 1% of the radioactivity of all radioactive waste.

2) B. Intermediate-Level Waste

Intermediate-level waste (ILW) contains higher amounts of radioactivity and some requires shielding. It 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 radwaste.

3) C. High-Level Waste

High-level waste (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. It is highly radioactive and hot, so requires cooling and shielding. It can be considered as the 'ash' from 'burning' uranium. HLW accounts for over 95% of the total radioactivity produced in the process of electricity generation. There are two distinct kinds of HLW:

- Used fuel itself.
- Separated waste from reprocessing the 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 no longer hazardous for people and the surrounding environment. If generally short-lived fission

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products can be separated from long-lived actinides, this distinction becomes important in management and disposal of HLW.

II. MINING AND MILLING

Traditional uranium mining generates fine sandy tailings, which contain virtually all the naturally occurring radioactive elements naturally found in uranium ore. These are collected in engineered tailings dams and finally covered with a layer of clay and rock to inhibit the leakage of radon gas and 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 wastes.

III. CONVERSION, ENRICHMENT, FUEL

Uranium oxide concentrate from mining, essentially 'yellowcake' (U3O8), is not significantly radioactive – barely more so than the granite used in buildings. It is refined then converted to uranium hexafluoride gas (UF6). 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 (UO2) for assembly as reactor fuel elements.

The main byproduct of enrichment is depleted uranium (DU), principally the U-238 isotope, which is stored either as UF6 or U3O8. About 1.2 million tonnes of DU is now stored. Some is used in applications where it’s extremely high density makes it valuable, such as the keels of yachts and military projectiles. It is also used (with reprocessed plutonium) for making mixed oxide fuel and to dilute highly-enriched uranium from dismantled weapons which are now being used for reactor fuel.

IV. ELECTRICITY GENERATION

In terms of radioactivity, high-level waste (HLW) is the major issue arising from the use of nuclear reactors to generate electricity. Highly radioactive fission products and also 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 utilized reprocessing to recycle material from used fuel, the fission products and minor actinides are separated from uranium and plutonium and treated as HLW (uranium and plutonium is then re-used as fuel in reactors). In countries where used fuel is not reprocessed, the used fuel itself is considered a waste and therefore classified as HLW.

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

V. HOW MUCH WASTE IS PRODUCED?

As already noted, the volume of nuclear waste produced by the nuclear industry is very small compared with other wastes generated. Each year, nuclear power generation facilities worldwide produce about 200,000 m^3 of low- and intermediate-level radioactive waste, and about 10,000 m^3 of high-level waste including used fuel designated as waste[1].

In the OECD countries, some 300 million tonnes of toxic wastes are produced each year, but conditioned radioactive wastes amount to only 81,000 m^3 per year.

In the UK, for example, the total amount of radioactive waste (including radioactive waste expected to arise from existing nuclear facilities) is about 4.7 million m^3, or around 5 million tonnes. A further 1 million m^3 has already been disposed. Of the UK's total radioactive waste, about 94% (*i.e.* about 4.4 million m^3) falls into the low-level radioactive waste (LLW) category. About 6% (290,000 m^3) is in the intermediate-level radioactive waste (ILW) category, and less than 0.1% (1000 m^3) is classed as high-level waste (HLW). Although the volume of HLW is relatively small, it contains about 95% of the total inventory of radioactivity.

A typical 1000 MWe light water reactor will generate (directly and indirectly) 200-350 m^3 low- and intermediate-level waste per year. It will also discharge about 20 m^3 (27 tonnes) of used fuel per year, which corresponds to a 75 m^3 disposal volume following encapsulation if it is treated as waste. Where that used fuel is reprocessed, only 3 m^3 of vitrified waste (glass) is produced, which is equivalent to a 28 m^3 disposal volume following placement in a disposal canister.

This compares with an average 400,000 tonnes of ash produced from a coal-fired plant of the same power capacity. Today, volume reduction techniques and abatement technologies as well as continuing good practice within the work force all contribute to continuing minimization of waste produced, a key principle of waste management policy in the nuclear industry. Whilst the volumes of nuclear wastes produced are very small, the most important issue for the nuclear industry is managing their toxic nature in a way that is environmentally sound and presents no hazard to both workers and the general public.

VI. MANAGING HLW FROM USED FUEL

Used fuel gives rise to HLW which may be either the used fuel itself in fuel rods, or the separated waste arising from reprocessing this. In either case, the amount is modest – as noted above, a typical reactor generates about 27 tonnes of spent fuel or 3 m^3 per year of vitrified waste. Both can be effectively and economically isolated, and have been handled and stored safely since nuclear power began.

Storage is mostly in ponds at reactor sites, or occasionally at a central site. See later section below.

If the used fuel is reprocessed, as is that from UK, French, Japanese and German reactors, HLW comprises highly-radioactive fission products and some transuranic elements with long-lived radioactivity. These are separated from the used fuel, enabling the uranium and plutonium to be recycled. Liquid HLW from reprocessing must be solidified. The HLW also generates a considerable amount of heat and requires cooling. It is vitrified into borosilicate (Pyrex) glass, encapsulated into heavy stainless steel cylinders about 1.3 meters high and stored for eventual disposal deep underground. This material has no conceivable future use and is unequivocally waste. The hulls and end-fittings of the reprocessed fuel assemblies are compacted, to reduce volume, and usually incorporated into cement prior to disposal as ILW. France has two commercial plants to vitrify HLW left over from reprocessing oxide fuel, and there are also plants in the UK and Belgium. The capacity of these Western

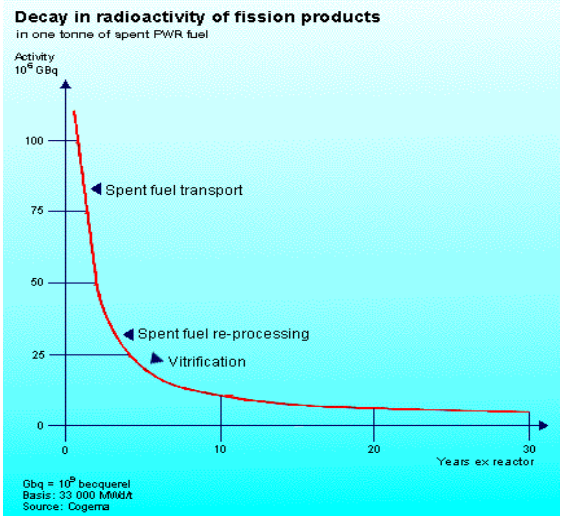
European plants is 2,500 canisters (1000 t) a year and some have been operating for three decades.

If used reactor fuel is not reprocessed, it will still contain all the highly radioactive isotopes, and then the entire fuel assembly 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.

Either way, after 40-50 years the heat and radioactivity have fallen to one thousandth of the level at removal. This provides a technical incentive to delay further action with HLW until the radioactivity has reduced to about 0.1% of its original level.

After storage for about 40 years the used fuel assemblies are ready for encapsulation or loading into casks ready for indefinite storage or permanent disposal underground.

Direct disposal of used fuel has been chosen by the USA and Sweden among others, although evolving concepts lean towards making it recoverable if future generations see it as a resource. This means allowing for a period of management and oversight before a repository is closed.



VII. RECYCLING 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 the U-238c. In total these account for some 96% of the original uranium and over half of the original energy content (ignoring U-238). Reprocessing, undertaken in Europe and Russia, separates this uranium and plutonium from the wastes so that they can be recycled for re-use in a nuclear reactor. Plutonium arising from reprocessing is recycled through a MOX fuel fabrication plant where it is mixed with depleted uranium oxide to make fresh fuel. European reactors currently use over 5 tonnes of plutonium a year in fresh MOX fuel.

Major commercial reprocessing plants operate in France, UK, and Russia with a capacity of some 5000 tonnes per year and cumulative civilian experience of 80,000 tonnes over 50 years. A new reprocessing plant with an 800 t/yr capacity at Rokkasho in Japan is undergoing commissioning. France and UK also undertake reprocessing for utilities in other countries, notably Japan, which has made over 140 shipments of used fuel to Europe since 1979. Until now most Japanese used fuel has been reprocessed in Europe, with the vitrified waste and the recovered uranium and plutonium (as MOX fuel) being returned to Japan to be used in fresh fuel. Russia also reprocesses some spent fuel from Soviet-designed reactors in other countries.

There are several proposed developments of reprocessing technologies.One technology under development would separate plutonium along with the minor actinides as one product. This however cannot be simply put into MOX fuel and recycled in conventional reactors; it requires fast neutron reactors which are as yet few and far between. On the other hand, it would make disposal of high-level wastes easier.

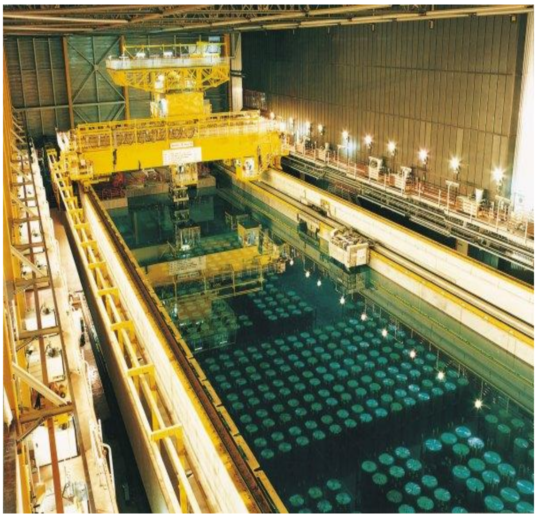


Fig:Storage pond for used fuel at the Thermal Oxide Reprocessing Plant at the UK's Sellafield site

VIII. STORAGE AND DISPOSAL OF USED FUEL AND OTHER HLW

There are about 270,000 tonnes of used fuel in storage, much of it at reactor sites. About 90% of this is in storage ponds (smaller versions of that illustrated above), the balance in dry storage. Much of the world's used fuel is stored thus, and some of it has been there for decades. Annual arisings of used fuel are about 12,000 tonnes, and 3,000 tonnes of this goes for reprocessing. Final disposal is not urgent in any logistical sense.

Storage ponds at reactors, and those at centralized facilities such as CLAB in Sweden, are 7-12 metres deep, to allow several metres of water over the used fuel comprising racked fuel assemblies typically about 4 m long and standing on end. 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 for the life of the reactor.

Some storage of fuel assemblies which have been cooling in ponds for at least five years is 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 about 80 fuel assemblies with inert gas. Casks/ MPCs may be used also for transporting 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, cooled by air convection, or they may be below grade, with just the tops showing. The modules are robust and provide full shielding.

A collection of casks or modules comprises an Independent Spent Fuel Storage Installation (ISFSI), which in the USA is licensed separately from any associated power plant, and is for interim storage only. About one quarter of US used fuel is stored thus.

For disposal, to ensure that no significant environmental releases occur over tens of thousands of years, 'multiple barrier' geological disposal is planned. This immobilizes the radioactive elements in HLW and some ILW and isolates them from the biosphere. The main barriers are:

- Immobilize waste in an insoluble matrix such as borosilicate glass or synthetic rock (fuel pellets are already a very stable ceramic: UO2).
- Seal it inside a corrosion-resistant container, such as stainless steel.
- Locate it deep underground in a stable rock structure.
- Surround containers with an impermeable backfill such as bentonite clay if the repository is wet.

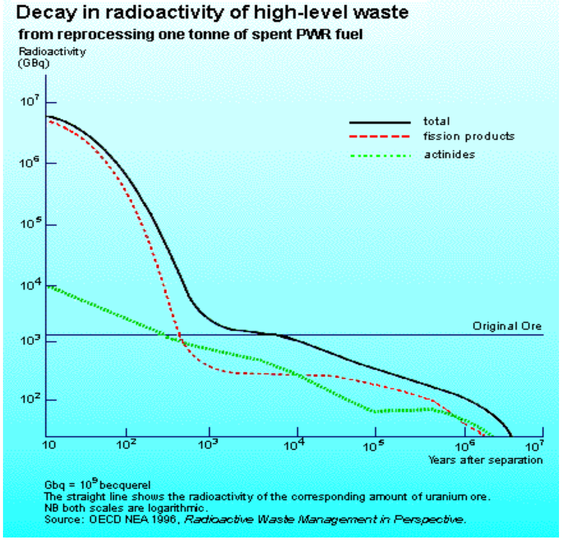
Fig: Loading silos with canisters containing vitrified HLW in the UK. Each disc on the floor covers a silo holding ten canisters

HLW from reprocessing must be solidified. France has two commercial plants to vitrify HLW left over from reprocessing oxide fuel, and there are also significant plants in the UK and Belgium. The capacity of these western European plants are2,500 canisters (1000 t) a year and some have been operating for three decades. By mid-2009, the UK Sellafieldvitrification plant had produced it 5000th canister of vitrified HLW, representing 3000 m^3 of liquor reduced to 750 m^3 of glass. The plant fills about 400 canisters per year.

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

To date there has been no practical need for final HLW repositories, as surface storage for 40-50 years is first required so that heat and radioactivity can decay to levels which make handling and storage easier.

The process of selecting appropriate deep geological repositories is now underway in several countries. Finland and Sweden are well advanced with plans for direct disposal of used fuel, since their parliaments decided to proceed on the basis that it was safe, using existing technology. Both countries have selected sites, in Sweden, after competition between two municipalities. The USA has opted for a final repository at Yucca Mountain in Nevada, though this is now stalled due to political decision.



Decay in radioactivity of high-level waste

from reprocessing one tonne of spent PWR fuel

Gbq = 10^9 becquerel

The straight line shows the radioactivity of the corresponding amount of uranium ore.

NB both scales are logarithmic.

Source: OECD NEA 1996, *Radioactive Waste Management in Perspective*.

A pending question is whether wastes should be emplaced so that they are 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 1,000 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.

France's 2006 waste law says that HLW disposal must be "reversible", which seems to refer to the management strategy. France, Switzerland, Canada, Japan and the USA require retrievability and that is policy also in most other countries, but this presupposes that 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 wastes are described in an Appendix to this paper and summarized in the following Table.

IX. WASTE MANAGEMENT FOR USED FUEL AND HLW FROM NUCLEAR POWER REACTORS

Country	**Policy**	**Facilities and progress towards final repositories**
Belgium	Reprocessing	• Central waste storage at Dessel • Underground laboratory established 1984 at Mol • Construction of repository to begin

Country	Policy	Facilities and progress towards final repositories
		about 2035
Canada	Direct disposal	• Nuclear Waste Management Organization set up 2002 • Deep geological repository confirmed as policy, retrievable • Repository site search from 2009, planned for use 2025
China	Reprocessing	• Central used fuel storage at LanZhou • Repository site selection to be completed by 2020 • Underground research laboratory from 2020, disposal from 2050
Finland	Direct disposal	• Program start 1983, two used fuel storages in operation • PosivaOy set up 1995 to implement deep geological disposal • Underground research laboratory Onkalo under construction • Repository planned from this, near Olkiluoto, open in 2020
France	Reprocessing	• Underground rock laboratories in clay and granite • Parliamentary confirmation in 2006 of deep geological disposal, containers to be retrievable and policy "reversible" • Bure clay deposit is likely repository site to be licensed 2015, operating 2025
Germany	Reprocessing but moving to direct disposal	• Repository planning started 1973 • Used fuel storage at Ahaus and Gorleben salt dome • Geological repository may be operational at Gorleben after 2025
India	Reprocessing	• Research on deep geological disposal for HLW
Japan	Reprocessing	• Underground laboratory at Mizunami in granite since 1996 • Used fuel and HLW storage facility at Rokkasho since 1995 • Used fuel storage under construction at Mutsu, start up 2013 • NUMO set up 2000, site selection for deep geological repository under

Country	Policy	Facilities and progress towards final repositories
		way to 2025, operation from 2035, retrievable
Russia	Reprocessing	• Underground laboratory in granite or gneiss in Krasnoyarsk region from 2015, may evolve into repository • Sites for final repository under investigation on Kola peninsula • Pool storage for used VVER-1000 fuel at Zheleznogorsk since 1985 • Dry storage for used RBMK and other fuel at Zheleznogorsk from 2012 • Various interim storage facilities in operation
South Korea	Direct disposal, maybe change	• Waste program confirmed 1998, KRWM seet up 2009 • Central interim storage planned from 2016
Spain	Direct disposal	• ENRESA established 1984, its plan accepted 1999 • Central interim storage at Villar de Canas from 2016 (volunteered location)
		• Research on deep geological disposal, decision after 2010
Sweden	Direct disposal	• Central used fuel storage facility – CLAB – in operation since 1985 • Underground research laboratory at Aspo for HLW repository • Osthammar site selected for repository (volunteered location)
Switzerland	Reprocessing	• Central interim storage for HLW and used fuel at ZZL Wurenlingen since 2001 • Smaller used fuel storage at Beznau • Underground research laboratory for high-level waste repository at Grimsel since 1983 • Deep repository by 2020, containers to be retrievable
United Kingdom	Reprocessing	• Low-level waste repository in operation since 1959 • HLW from reprocessing is vitrified and stored at Sellafield

Country	**Policy**	**Facilities and progress towards final repositories**
		• Repository location to be on basis of community agreement • New NDA subsidiary to progress geological disposal
USA	Direct disposal but reconsidering	• DoE responsible for used fuel from 1998, accumulated $32 billion waste fund • Considerable research and development on repository in welded tuffs at Yucca Mountain, Nevada • The 2002 Congress decision that geological repository be at Yucca Mountain was countered politically in 2009 • Central interim storage for used fuel now likely

X. WASTES FROM DECOMMISSIONING NUCLEAR PLANTS

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 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.

Generally, short-lived intermediate-level wastes (mainly from decommissioning reactors) are buried, while long-lived intermediate-level wastes (from fuel reprocessing) will be disposed of deep underground. Low-level wastes are disposed of in shallow burial sites.

XI. DISPOSAL OF OTHER RADIOACTIVE WASTES

Some low-level liquid wastes from reprocessing plants are discharged to the sea. These include 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, they have short half-lives, and the radioactivity in the emissions is diminished by delaying their release. Also the first two are chemically inert. 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.

The US Nuclear Regulatory Commission classifies low-level wastes into four categories based on radioactivity corresponding to management and disposal requirements: Class A waste has the lowest radioactivity level and decays to background level after about 100 years. It accounts for about 99% of the volume of LLW generated in the USA and includes slightly contaminated paper products, clothing, rags, mops, equipment and tools, as well as depleted uranium. Class B and C wastes include filters, resins, irradiated hardware with activation products, and longer-lived radioisotopes that decay after 300 and 500 years, respectively. Greater-than-Class C LLW has radionuclide concentration limits greater than those specified for Class C waste.

It is noteworthy that coal burning produces some 280 million tonnes of ash per year, most of it containing low levels of natural radionuclides. Some of this could be classified as LLW. It is simply buried.

XII. COSTS OF RADIOACTIVE WASTE MANAGEMENT

Financial provisions are made for managing all kinds of civilian radioactive waste. The cost of managing and disposing of nuclear power plant wastes 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 management and disposal of their wastes. So far some US$ 28 billion has been committed to the US waste fund by electricity consumers.

The actual arrangements for paying for waste management and decommissioning also 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[4]:

A. Provisions On The Balance Sheet

Sums to cover the anticipated costs 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.

B. Internal Fund

Payments are made over the life 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.

C. 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, others allow companies to borrow a percentage of the fund to reinvest in their business.

XIII. 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.

The study of such natural phenomena is important for any assessment of geologic repositories, and is the subject of several international research projects. However, it must be noted that the Oklo reactions proceeded because groundwater was present as a moderator in the 'enriched' and permeable uranium ore.

XIV. LEGACY WASTES

In addition to the routine wastes from current nuclear power generation there are other radioactive wastes referred to as 'legacy wastes'. These wastes exist in several countries which pioneered nuclear power and especially where power programmes were developed out of military programmes. These are sometimes voluminous and difficult, and arose in the course of those countries getting to a position where nuclear technology is a commercial proposition for power generation. They represent a liability which is not covered by current funding arrangements. In the UK, some £73 billion (undiscounted) is estimated to be involved in addressing these 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.

XV. REGULATION

The nuclear and radioactive waste management industries work to well-established safety standards for the management of radioactive waste. International and regional organizations such as the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD), the European Commission (EC) and the International Commission on Radiological Protection (ICRP) develop standards, guidelines and recommendations under a framework of co-operation to assist countries in establishing and maintaining national standards. National policies, legislation and regulations are all developed from these internationally agreed standards, guidelines and recommendations. Amongst others, these standards aim to ensure the protection of the public and the environment, both now and into the future.

International agreements in the form of conventions have also been established such as the *Joint Convention on Nuclear Safety and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*. The latter was adopted in 1997 by a diplomatic conference convened by the IAEA and came into force in June 2001 following the required number of ratifications.

Other international conventions and directives seek to provide for inter alia, the safe transportation of radioactive material, protection of the environment (including the marine environment) from radioactive waste, and the control of imports and exports of radioactive waste and transboundary movements.

XVI. INTERNATIONAL ATOMIC ENERGY AGENCY

The IAEA is the international organization that advises on the safe and peaceful uses of nuclear technology. It is an agency of the United Nations, based in Vienna, Austria founded in 1957 and it currently has 134 member states from countries with and without nuclear energy programmes. The IAEA develops safety standards, guidelines and recommendations and inter alia provides technical guidance to member states on radioactive waste principles. Member states use the standards and guidelines in developing their own legislation, regulatory documents and guidelines. It also verifies through a safeguards inspection programme compliance with the Nuclear Non-Proliferation Treaty (NPT).

The IAEA's Waste and Environmental Safety Section works to develop internationally agreed standards on the safety of radioactive waste. The Radioactive Waste Safety Standards Programme (RADWASS) provides guidance to member states to produce their own policies and regulations for the safe management of radioactive waste, including disposal.

In addition, the IAEA helps member states by providing technical assistance with services, equipment and training and by conducting radiological assessments.

XVII. NUCLEAR ENERGY AGENCY

The Nuclear Energy Agency of the OECD is based in Paris, France. It has a variety of waste management programmes involving its 28 member states. The organization aims to assist these states in developing safe waste disposal strategies and policies for spent nuclear fuel, HLW and waste from decommissioning nuclear facilities. It also works closely with the IAEA on nuclear safety standards and other technical activities.

XVIII. EUROPEAN COMMISSION

For several years, the European Commission (EC) has attempted to pass Directives aimed at ensuring a common approach to nuclear safety and radioactive waste management. The so-called 'Nuclear Package' of Directives on nuclear safety and waste management was a top-down approach which met with considerable opposition from several Member States and was revised on several occasions leading to the 2011 adoption of a scaled-back version.8

In July 2011 the European Union adopted a directive for the disposal of used nuclear fuel and radioactive wastes* which requires member countries to develop national waste management plans for European Commission review by 2015. The plans must include firm timetables for the construction of disposal facilities, descriptions of needed implementation activities, cost assessments, and financing schemes. Safety standards promulgated by the IAEA will become legally binding within the EU-wide policy framework.

* Proposal for a Council Directive on the management of spent fuel and radioactive waste, COM(2010) 618 final.

The agreement allows two or more member nations to develop joint disposal facilities and allows transport of used fuel and radioactive wastes within the EU. Exports outside the EU will only be possible to countries that already have a repository in operation that meets IAEA standards. For overseas reprocessing, ultimate wastes must be returned to the originating EU country. The directive acknowledges that no country currently operates such a repository and projects that a minimum of 40 years would be required to develop one. The shipment of used fuel and radioactive wastes to African, Pacific and Caribbean countries and to Antarctica is explicitly banned. Plans are expected to use a step-by-step approach to geologic disposal based on the voluntary involvement of potential host communities. Two routes are acknowledged: one to dispose of used nuclear fuel as waste; the other to reprocess the fuel and recycle the uranium and plutonium while disposing of the remainder as waste.The directive is expected to become effective in August 2011, and national governments, which retain ultimate responsibility for wastes, will have two years to bring their nuclear waste legislation into line with it. There are 143 nuclear energy facilities generating used fuel in 14 of the EU’s 27 member nations. The remaining nations possess radioactive waste requiring disposal that has been produced by research, medicine and industry.

XIX. INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

The International Commission on Radiological Protection (ICRP) is an independent registered charity that issues recommendations for protection against all sources of radiation. The IAEA interprets these recommendations into international safety standards and guidelines for radiological protection. National regulators may also adopt the recommendations by the ICRP for their own radiation protection standards.

In March 2007, the ICRP approved its new fundamental Recommendations on radiological protection (ICRP Publication 103)11, replacing the Commission’s previous Recommendations from 1990. Amongst others, the new recommendations include for the first time an approach for developing a framework to demonstrate radiological protection of the environment.

XX. FURTHER INFORMATION APPENDICES

Appendix 1: Treatment and Conditioning of Nuclear Wastes
Appendix 2: Storage and Disposal Options
Appendix 3: National Policies
Appendix 4: National Funding
Appendix 5: Environmental and Ethical Aspects of Radioactive Waste Management

XXI. NOTES

a. A radionuclide is a radioactive isotope of a particular element. Different isotopes of a given element have different numbers of neutrons, but the same number of protons; hence, isotopes of the same element share atomic numbers but not mass numbers.

b. Uranium and plutonium are members of the actinide group, which comprises the 15 successive chemical elements from actinium on the periodic table. The so-called 'minor actinides' are the actinides present in used nuclear fuel other than uranium and plutonium.

c. Used fuel from light water reactors contains approximately:
95.6% uranium (less than 1% of which is U-235)
2.9% stable fission products
0.9% plutonium
0.3% caesium& strontium (fission products)
0.1% iodine and technetium (fission products)
0.1% other long-lived fission products
0.1% minor actinides (americium, curium, neptunium)

Increasingly, reactors are using fuel enriched to over 4% U-235 and burning it longer, to end up with less than 0.5% U-235 in the used fuel. This provides less incentive to reprocess.

d. See the home page of the IAEA's Division of Radiation, Transport and Waste Safety (www-ns.iaea.org/home/rtws.asp) for further information.

e. See the radioactive waste management section of the NEA's website (www.nea.fr/html/rwm) for further information.

f. See the International Commssion on Radiological Protection's website (www.icrp.org) for further information.

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