WORLD NUCLEAR ASSOCIATION

Storage and Disposal Options

Radioactive Waste Management Appendix 2

(Updated May 2015)

Most low-level radioactive waste (LLW) is typically sent to land-based disposal immediately following its packaging for long-term management. 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.

Concentrating on intermediate-level waste (ILW) and high-level waste (HLW), many long-term waste management options have been investigated worldwide which seek to provide publicly acceptable, safe and environmentally sound solutions to the management of radioactive waste. Some countries are at the preliminary stages of their investigations whilst others such as Finland and Sweden have made good progress in their investigations to select publicly acceptable sites for the future disposal of waste. In Carlsbad, New Mexico in the USA, the Waste Isolation Pilot Plant (WIPP) disposal facility for defence-related transuranic wastes is in operation, underground in a salt formation.

The following table sets out the commonly accepted disposal options. When considering these, it should be noted that the suitability of an option or idea can be dependent on the wasteform, volume and radioactivity of the waste. As such, waste management options and ideas described in this section are not all applicable to different types of waste.

Commonly-accepted disposal options

Option	Examples
Near-surface disposal at ground level, or in caverns below ground level (at depths of tens of metres)	• Implemented for LLW in many countries, including Czech Republic, Finland, France, Japan, Netherlands, Spain, Sweden, UK and USA. • Implemented in Finland and Sweden for LLW and short-lived ILW.
Deep geological disposal (at depths between 250m and 1000m for mined repositories, or 2000m to 5000m for boreholes)	• Most countries with high-level and long-lived radioactive waste have investigated deep geological disposal and it is official policy in various countries (variations also include multinational facilities). • Implemented in USA for defence-related ILW. • Preferred sites for HLW/spent fuel selected in France, Sweden, Finland and USA[a]. • Geological repository site selection

	process commenced in UK and Canada.

Additional ideas have also been considered and discounted in the past (see section on Other ideas for disposal below).

Near-surface disposal

The International Atomic Energy Agency (IAEA) definition[b] of this option is the disposal of waste, with or without engineered barriers, in:

- Near-surface disposal facilities at ground level. These facilities are on or below the surface where the protective covering is of the order of a few metres thick. Waste containers are placed in constructed vaults and when full the vaults are backfilled. Eventually they will be covered and capped with an impermeable membrane and topsoil. These facilities may incorporate some form of drainage and possibly a gas venting system.
- Near-surface disposal facilities in caverns below ground level. Unlike near-surface disposal at ground level where the excavations are conducted from the surface, shallow disposal requires underground excavation of caverns but the facility is at a depth of several tens of metres below the Earth's surface and accessed through a drift.

The term near-surface disposal replaces the terms 'shallow land' and 'ground disposal', but these older terms are still sometimes used when referring to this option.

These facilities will be affected by long-term climate changes (such as glaciation) and this effect must be taken into account when considering safety as such changes could cause disruption of these facilities. This type of facility is therefore typically used for LLW and ILW with a radionuclide content of short half-life (up to about 30 years).

Near-surface disposal facilities are currently in operation in:

- UK – Low Level Waste Repository at Drigg in Cumbria operated by UK Nuclear Waste Management Ltd (a consortium led by Washington Group International with Studsvik UK, Serco and Areva) on behalf of the Nuclear Decommissioning Authority.
- Spain – El Cabril low and intermediate level radioactive waste disposal facility operated by ENRESA.
- France – Centre de l'Aube operated by Andra.
- Japan – Low-Level Radioactive Waste Disposal Center at Rokkasho-Mura operated by Japan Nuclear Fuel Limited.
- USA – five low-level waste 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 EnergySolutions; and Richland, Washington – operated by American Ecology Corporation.

Near-surface disposal facilities in caverns below ground level are currently in operation in:

- Sweden – the SFR final repository for short-lived radioactive waste at Forsmark, where the depth of the facility is 50m under the Baltic seabed – operated by the Swedish Nuclear Fuel and Waste Management Company (SKB).[c]
- Finland – Olkiluoto and Loviisa power stations where the depth of the facilities are each at about 100 metres.[d]

Deep geological disposal

The long timescales over which some of the waste remains radioactive led to the idea of deep geological disposal in underground repositories in stable geological formations. Isolation is provided by a combination of engineered and natural barriers (rock, salt, clay) and no obligation to actively maintain the facility is passed on to future generations. This is often termed a multi-barrier concept, with the waste packaging, the engineered repository and the geology all providing barriers to prevent the radionuclides from reaching humans and the environment.

Mined repositories

The main concept is for a repository comprising mined tunnels or caverns into which packaged waste would be placed. In some cases (*e.g.* wet rock) the waste containers are then surrounded by a material such as cement or clay (usually bentonite) to provide another barrier (called buffer and/or backfill). The choice of waste container materials and design and buffer/backfill material varies depending on the type of waste to be contained and the nature of the host rock-type available.

Excavation of a deep underground repository using standard mining or civil engineering technology is limited to accessible locations (*e.g.* under land or nearshore), to rock units that are reasonably stable and without major groundwater flow, and to depths of between 250m and 1000m. At a depth greater than 1000m. The contents of the repository would be retrievable in the short term, and if desired, longer-term.

Deep geological disposal remains the preferred option for waste management of long-lived radioactive waste in several countries, including Argentina, Australia, Belgium, Czech Republic, Finland, Japan, Netherlands, Republic of Korea, Russia, Spain, Sweden, Switzerland and USA. Hence, there is much information available on different disposal concepts; a few examples are given here. The only purpose-built deep geological repository for long-lived ILW that is currently licensed for disposal operations is in the USA. Plans for disposal of spent fuel are well advanced in Finland, Sweden, France and the USA, though in the USA there has been a political setback. In Canada and the UK, deep disposal has been selected and the site selection process has commenced.

The Swedish proposed KBS-3 disposal concept[e] uses a copper container with a steel insert to contain the spent fuel. After placement in the repository about 500 metres deep in the bedrock, the container would be surrounded by a bentonite clay buffer to provide a very high level of containment of the radioactivity in the wastes over a very long time period. In June 2009, the Swedish Nuclear Fuel and Waste Management Company (SKB) announced its decision to locate the repository at Östhammar (Forsmark).

Finland's repository programme is also based on the KBS-3 concept. Spent nuclear fuel packed in copper canisters will be embedded in the Olkiluoto bedrock at a depth of around 400 metres. The country's nuclear waste management company, Posiva Oy, expects the repository to begin disposal operations in 2020.

The deposits of native (pure) copper in the world have proven that the copper also used in the final disposal container can remain unchanged inside the bedrock for extremely long periods, if the geochemical conditions are appropriate (reducing groundwaters). The findings of ancient copper tools, many thousands of years old, also demonstrate the long-term corrosion resistance of copper, making it a credible container material for long-term radioactive waste storage.

Deep boreholes

As well as mined repositories which have been the focus of international efforts so far, deep borehole disposal of high-level radioactive waste has been considered as an option for geological isolation for many years, including original evaluations by the US National Academy of Sciences in 1957 and more recent conceptual evaluations. In contrast to recent thinking on mined repositories, the contents would not be retrievable.

The concept consists of drilling a boreholes into crystalline basement rock to a depth of about 5000 metres, emplacing waste canisters containing used nuclear fuel or vitrified radioactive waste from reprocessing in the lower 2000 metres of the borehole, and sealing the upper 3000 metres of the borehole with materials such as bentonite, asphalt or concrete. The disposal zone of a single borehole could thus contain 400 steel canisters each 5 metres long and one-third to half a metre diameter. These might be emplaced in strings of 40 canisters. The waste containers would be separated from each other by a layer of bentonite or cement.

Boreholes can be readily drilled offshore (as described in the section below on sub seabed disposal) as well as onshore in host rocks both crystalline and sedimentary. This capability significantly expands the range of locations that can be considered for the disposal of radioactive waste.

Deep borehole concepts have been developed (but not implemented) in several countries, including Denmark, Sweden, Switzerland and USA for HLW and spent fuel. Compared with deep geological disposal in a mined underground repository, placement in deep boreholes is considered to be more expensive for large volumes of waste. This option was abandoned in countries such as Sweden, Finland and the USA. The borehole concept remains an attractive proposition for the disposal of smaller waste forms including sealed radioactive sources from medical and industrial applications.[o]

An October 2014 US Department of Energy report said: “Preliminary evaluations of deep borehole disposal indicate a high potential for robust isolation of the waste, and the concept could offer a pathway for earlier disposal of some wastes than might be possible in a mined repository.”

Disposal in clay, Europe

The Belgian disposal concept proposes that spent fuel and HLW is placed in high integrity steel containers and then emplaced in excavated tunnels within a ductile (self-sealing) clay[f]. The very low permeability of the clay leads to virtually no groundwater flow over long time periods. Waste would be backfilled with excavated clay or, alternatively, could be emplaced into unlined secondary tunnels where the clay would be allowed to creep into contact with the waste containers. Similar systems have been proposed in the Netherlands and, using less plastic clays, in France and Switzerland[g].

The French radioactive waste disposal agency Andra is designing a deep geological repository in clays at Bure in eastern France. This will be for disposal of vitrified high-level waste (HLW) and long-lived intermediate-level waste. The repository is designed to operate at up to 90ºC, which is likely to be reached about 20 years after emplacement. Andra expects to apply for a construction and operating licence in 2014.

Yucca Mountain, USA

At the end of 1987, the Nuclear Waste Policy Act was amended to designate Yucca Mountain, located in the remote Nevada desert, as the sole US national repository for spent fuel and high-level waste from nuclear power and military defence programmes. An application by the US Department of Energy (DoE) to construct the repository was submitted in June 2008.

The repository would exist 300 metres underground in an unsaturated layer of welded volcanic tuff rock. Waste would be stored in highly corrosion-resistant double-shelled metal containers, with the outer layer made of a highly corrosion-resistant metal alloy, and a structurally strong inner layer of stainless steel. Since the geological formation is essentially dry, it would not be backfilled but left open to some air circulation. Drip shields made of corrosion-resistant titanium would cover the waste containers to divert possible future water percolation and provide protection from possible falling rock or debris. Containment relies on the extremely low water table, which lies approximately 300 metres below the repository, and the long-term durability of the engineered barriers.

The project has experienced many delays since its inception and following the 2009 presidential election the Barack Obama administration decided to cancel it[h]. However, in June 2010, the Nuclear Regulatory Commission's Atomic Safety and Licensing Board (ASLB) rejected the DOE's motion to withdraw the licence application, and in August 2013 the federal Appeals Court ordered the NRC to resume its review of the

DOE's application for a licence to construct and operate the Yucca Mountain repository. The final volumes of the NRC's safety evaluation report were published early in 2015[i].

Disposal in layered salt strata or domes

Geological salt environments have a very low rate (perhaps even absence) of groundwater flow and feature gradual self-sealing of the excavations due to creep of the salt, which is plastic.

The Waste Isolation Pilot Plant (WIPP)[j] in New Mexico for defence transuranic wastes (long-lived ILW) has been operational since 1999. For this repository natural rock salt is excavated from a Permian layer several metres thick, between other types of rock, 650 metres below ground level. The wastes placed in these excavations contain large volumes of long-lived ILW, usually in steel drums. These are then placed on pallets and stowed in excavated rooms or caverns. The salt is plastic and will eventually seal the wastes and isolate them permanently. Containment of the radionuclides in the wasteform mostly relies on the almost complete absence of water flow in the salt. To July 2013, there had been 11,500 road shipments of wastes to WIPP from 12 DOE sites, and 87,500 cubic metres of ILW disposed[2].

Salt environments are also available in northern Germany and the Netherlands although these are salt domes rather than bedded formations. In Germany, the former salt mines at Asse and Morsleben have been used for LLW and ILW disposal though this has now been suspended. The decommissioning process is now being investigated to determine the method for backfilling and sealing the repository.[k]

Following an exhaustive site selection process the state government of Lower Saxony in 1977 declared the salt dome at Gorleben to be the location for a German national centre for disposal of radioactive wastes. It is now considered a possible site for geological disposal of high-level waste. The site could be available as a final repository from 2025, with a decision to be made about 2019. Some €1.5 billion was spent over 1979 to 2000 researching the site. Work then stopped due to political edict, but resumption of excavation was approved following a change of government in 2009.[l]

Nirex Phased Disposal Concept, UK

The UK's Nirex Phased Disposal Concept (or Phased Geological Disposal Concept) has been developed for relatively large volumes of ILW and LLW, usually cemented into stainless steel containers.[m] These containers would be emplaced into a repository in a host rock environment below the water table. The waste would be monitored and remain retrievable and the groundwater managed to prevent contact with the wastes, until such a time that the repository is sealed. When this happens, the waste will be surrounded (backfilled) by specially formulated cement and the repository allowed to resaturate. The cement would provide a long lasting alkaline environment that contributes to containment of the waste by preventing many radionuclides from dissolving in the groundwater. Similar cement-based schemes for ILW disposal have been proposed in France, Japan, Sweden and Switzerland.

Multinational repositories[n]

Not all countries are adequately equipped to store or dispose of their own radioactive waste. Some countries are limited in area, or have unfavourable geology and therefore siting a repository and demonstrating its safety could be challenging. Some smaller countries may not have the resources to take the proper measures on their own to assure adequate safety and security, or they may not have enough radioactive waste to make construction and operation of their own repositories economically feasible.

It has been suggested that there could be multinational or regional repositories located in a willing host country that would accept waste from several countries. They could include, for example use by others of a national repository operating within a host country, or a fully international facility owned by a private company operated by a consortium of nations or even an international organisation. However, for the time being, many countries would not accept nuclear waste from other countries under their national laws. National policies towards radioactive waste management are listed in *Waste Management in the Nuclear Fuel Cycle Appendix 3: National Policies* and the information page on International nuclear waste disposal concepts.

Interim waste storage

Specially designed interim surface or sub surface storage waste facilities are currently used in many countries to ensure the safe storage of radioactive waste pending the availability of a long-term disposal option. Interim storage facilities are generally used for intermediate-level waste (ILW) and high-level waste (HLW), including used nuclear fuel from reactors.

Storage ponds at reactors, and those at centralised 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 multiple racks are made of metal with neutron absorbers incorporated in it. 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. Each cask has up to 45 kW heat load.

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.

A sophisticated below-ground ISFSI is Holtec's Hi-Storm UMAX storage system, already deployed at two US nuclear power plant sites, and is proposed for a consolidated site in New Mexico. This stores used fuel in ventilated vertical steel and concrete Cavity Enclosure Containers 5 metres high below ground, with massive lids. The containers are set up in a 7.6m deep excavation and low-strength concrete grout is backfilled around them. The final half metre of fill is a reinforced concrete pad. Each container can store 37 PWR fuel assemblies.

Zwilag's ZZL in Switzerland and Ahaus and Gorleben in Germany are examples of operating interim long-term above-ground central interim dry storage for HLW. In the USA a site for this is proposed in Texas.

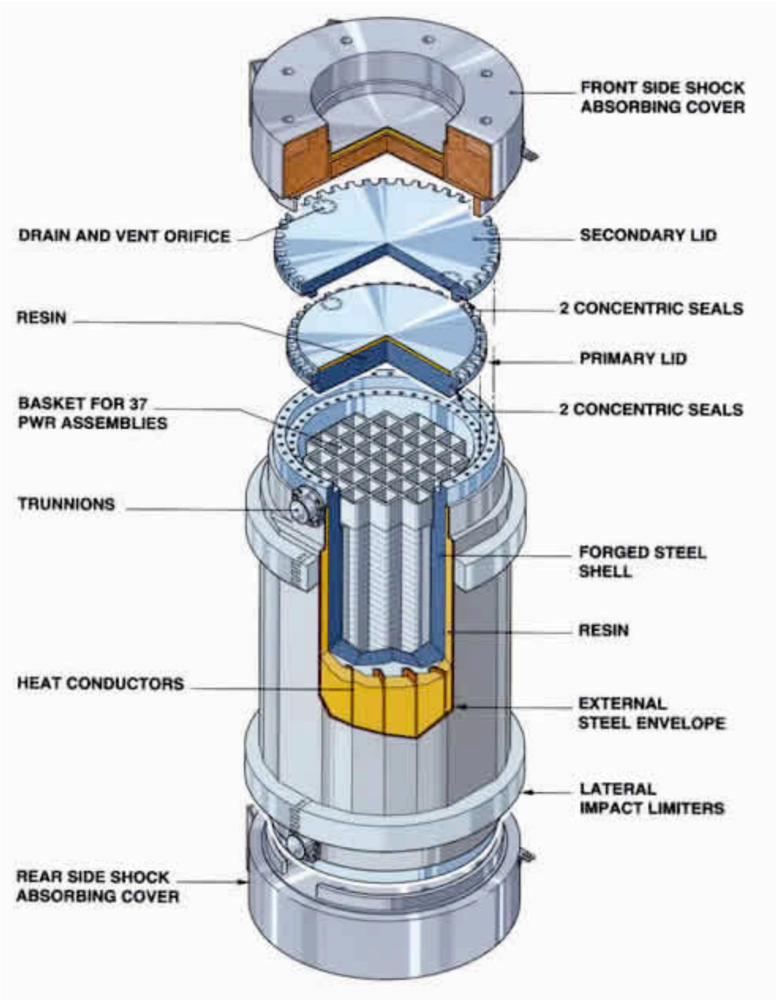
Some countries, including Australia, Belgium, Netherlands, Germany, Italy and Switzerland also place low-level waste (LLW) in interim storage, although most LLW is typically sent directly to land-based near-surface disposal facilities (see section above on Near-surface disposal).

Recognising that long-term management options, specifically for ILW and HLW, may require significant time to be achieved, interim storage arrangements may need to be extended beyond the time periods originally envisaged.

See also the section below on Long-term above ground storage.

Transport

The figure below illustrates a typical transport container used for used fuel. The multi-layer approach to containment is designed to ensure that the most penetrating forms of radiation cannot enter the outer environment.



Other ideas for disposal

Numerous options for long-term nuclear waste management have been considered in the past. The table below highlights a number of these.

Ideas	Examples
Long-term above ground storage	• Investigated in France, Netherlands, Switzerland, UK and USA. • Not currently planned to be implemented anywhere.
Disposal in outer space (proposed for wastes that are highly concentrated)	• Investigated by USA. • Investigations now abandoned due to cost and potential risks of launch failure.
Rock-melting (proposed for wastes that are heat-generating)	• Investigated by Russia, UK and USA. • Not implemented anywhere. • Laboratory studies performed in the UK.
Disposal at subduction zones	• Investigated by USA. • Not implemented anywhere. • Not permitted by international agreements.

Sea disposal	• Implemented by Belgium, France, Federal Republic of Germany, Italy, Japan, Netherlands, Russia, South Korea, Switzerland, UK and USA. • Not permitted by International agreements.
Sub seabed disposal	• Investigated by Sweden and UK (and organisations such as the OECD Nuclear Energy Agency). • Not implemented anywhere. • Not permitted by international agreements.
Disposal in ice sheets (proposed for wastes that are heat-generating)	• Investigated by USA. • Rejected by countries that have signed the Antarctic Treaty or committed to providing solutions within national boundaries.
Direct injection (only suitable for liquid wastes)	• Investigated by Russia and USA. • Implemented in Russia for 40 years and in USA (grouts). • Investigations abandoned in USA in favour of deep geological disposal of solid wastes.

Long-term above ground storage

Above ground storage is normally considered an interim measure for the management of radioactive waste (see section above on Interim waste storage). But it can be considered as effectively a disposal option. France investigated it for HLW within the framework of the 1991 law on research into radioactive waste management (Act No 91-1381 of 30 December 1991, also known as the 'Bataille Act' after the name of its proposer), but not as a means of final disposal. However, controlled surface storage over longer time periods (greater than a couple of hundred of years) has also been suggested as a long-term waste management option.

Long-term above ground storage involves specially constructed facilities at the earth's surface that would be neither backfilled nor permanently sealed. Hence, this option would allow monitoring and retrieval at any time without excessive expenditure.

Suggestions for long-term above ground storage broadly fall into two categories:

- Conventional stores of the type currently used for interim storage, which would require replacement and repackaging of waste every 200 years or so.
- Permanent stores that would be expected to remain intact for tens of thousands of years. These structures are often referred to as 'Monolith' stores or 'Mausoleums'.

The latter category of store is derived from the principle of 'guardianship', where future generations continue to monitor and supervise the waste.

Both suggestions would require information to be passed on to future generations, leading to the question of whether the stability of future societies could be ensured to the extent necessary to continue the required monitoring and supervision.

No country is currently planning to implement long-term (*i.e.* greater than a few hundred years) above ground storage. However, France is investigating long-term interim storage, but not necessarily above ground.

Long-term above ground storage has been considered as part of the range of management concepts in Switzerland by EKRA (Expert Group on Disposal Concepts for Radioactive Waste). The expert group (EKRA) observed that it was unclear what additional steps would be necessary to show how the long-term above ground storage concept could be brought to the state of development comparable with that of geological disposal and they recommended geological disposal as the preferred option.

Disposal in outer space

The objective of this option is to remove the radioactive waste from the Earth, for all time, by ejecting it into outer space. The waste would be packaged so that it would be likely to remain intact under most conceivable accident scenarios. A rocket or space shuttle would be used to launch the packaged waste into space. There are several ultimate destinations for the waste which have been considered, including directing it into the Sun.

The high cost means that such a method of waste disposal could only be appropriate for separated high-level waste (HLW) or spent fuel (*i.e.* long-lived highly radioactive material that is relatively small in volume). The question was investigated in the United States by NASA in the late 1970s and early 1980s. Because of the high cost of this option and the safety aspects associated with the risk of launch failure, this option was abandoned.

Today only radioisotope thermal generators (TRGs) containing a few kilograms of Pu-238 are launched by NASA (see information page on Nuclear Reactors for Space).

Rock melting

The deep rock melting option involves the melting of wastes in the adjacent rock. The idea is to either produce a stable, solid mass that incorporates the waste or encases the waste in a diluted form (*i.e.* dispersed throughout a large volume of rock) that cannot easily be leached and transported back to the surface. This technique has been mainly suggested for heat generating wastes such as vitrified HLW (see Waste Management in the Nuclear Fuel Cycle - Appendix 1: Treatment and Conditioning of Nuclear Wastes) and host rocks with suitable characteristics to reduce heat loss.

The HLW in liquid or solid form could be placed in an excavated cavity or a deep borehole. The heat generated by the wastes would then accumulate resulting in temperatures great enough to melt the surrounding rock and dissolve the radionuclides in a growing sphere of molten material. As the rock cools it would crystallise and incorporate the radionuclides in the rock matrix, thus dispersing the waste throughout a larger volume of rock. There are some variations of this option in which the heat-generating waste would be placed in containers and the rock around the container melted. Alternatively, if insufficient heat is generated the waste would be immobilised in the rock matrix by conventional or nuclear explosion.

Rock melting has not been implemented anywhere for radioactive waste. There have been no practical demonstrations of the feasibility of this option, apart from laboratory studies of rock melting. In the late 1970s and early 1980s, the rock melting option at depth was taken forward to the engineering design stage. This design involved a shaft or borehole which led to an excavated cavity at a depth of 2.5 kilometres. It was estimated, but not demonstrated, that the waste would be immobilised in a volume of rock 1000 times larger than the original volume of waste.

Another early proposal was the design of weighted, heat-resistant containers of heat generating wastes such that they would continue to melt the underlying rock, and allow them to move downwards to greater depths with the molten rock solidifying above it. This alternative resembles similar self-burial methods proposed for disposal of HLW in ice sheets (see section below on Disposal in ice sheets).

In the 1990s, there was renewed interest in this option, particularly for the disposal of limited volumes of specialised HLW, particularly plutonium, in Russia and in the UK. A scheme was proposed in which the waste content of the container, the container composition and the placement layout would be designed to preserve the container and prevent the wastes becoming incorporated in the molten rock. The host rock would be only partially melted and the container would not move to greater depths.

Russian scientists have proposed that HLW, particularly excess plutonium, could be placed in a deep shaft and immobilised by nuclear explosion. However, the major disturbance to the rock mass and groundwater by the use of nuclear explosions, as well as arms control considerations, has led to the general rejection of this option.

Disposal at a subduction zone

Subduction zones are areas where one denser section of the Earth's crust is moving towards and underneath another lighter section. The movement of one section of the Earth's crust below another is marked by an offshore trench, and earthquakes occur adjacent to the inclined contact between the two plates. The edge of the overriding plate is crumpled and uplifted to form a mountain chain parallel to the trench. Deep sea sediments may be scraped off the descending slab and incorporated into the adjacent mountains. As the oceanic plate descends into the hot mantle, parts of it may begin to melt. The magma thus formed migrates upwards, some of it reaching the surface as lava erupting from volcanic vents. The idea for this option would be to dispose of wastes in the trench region such that they would be drawn deep into the Earth.

Although subduction zones are present at a number of locations across the Earth's surface they are geographically very restricted. Not every waste-producing country would be able to consider disposal to deep-sea trenches, unless international solutions were sought. However, this option has not been implemented anywhere and, as it is a form of sea disposal, it is therefore not permitted by international agreements.

Disposal at sea

Disposal at sea involves radioactive waste being shipped out to sea and dropped into the sea in packaging designed to either: implode at depth, resulting in direct release and dispersion of radioactive material into the sea; or sink to the seabed intact. Over time the physical containment of containers would fail, and radionuclides would be dispersed and diluted in the sea. Further dilution would occur as the radionuclides migrated from the disposal site, carried by currents. The amount of radionuclides remaining in the sea water would be further reduced both by natural radioactive decay, and by the removal of radionuclides to seabed sediments by the process of sorption.

This method is not permitted by a number of international agreements.

The application of the sea disposal of LLW and ILW has evolved over time from being a disposal method that was actually implemented by a number of countries, to one that is now banned by international agreements. Countries that have at one time or another undertaken sea disposal using the above techniques include Belgium, France, Federal Republic of Germany, Italy, Netherlands, Sweden, Switzerland and the UK, as well as Japan, South Korea, and the USA. This option has not been implemented for HLW.

Sub seabed disposal

For the sub seabed disposal option radioactive waste containers would be buried in a suitable geological setting beneath the deep ocean floor. This option has been suggested for LLW, ILW and HLW. Variations of this option include:

- A repository located beneath the seabed. The repository would be accessed from land, a small uninhabited island or from an offshore structure.
- Burial of radioactive waste in deep ocean sediments.

Sub seabed disposal has not been implemented anywhere and is not permitted by international agreements.

The disposal of radioactive wastes in a repository constructed below the seabed has been considered by Sweden and the UK. In comparison to disposal in deep ocean sediments, if it were desirable the repository design concept could be developed so as to ensure that future retrieval of the waste remained possible. The monitoring of wastes in such a repository would also be less problematic than for other forms of sea disposal.

Burial of radioactive waste in deep ocean sediments could be made by two different techniques: penetrators or drilling placement. The burial depth of waste containers below the seabed can vary between the two methods. In the case of penetrators, waste containers could be placed about 50 metres into the sediments. Penetrators weighing a few tons would fall through the water, gaining enough momentum to embed themselves into the sediments. A key aspect of the disposal of waste to seabed sediments is that the waste is isolated from the seabed by a thickness of sediments. In 1986, some confidence in this process was obtained from experiments undertaken at a water depth of approximately 250 metres in the Mediterranean Sea. The experiments provided evidence that the entry paths created by penetrators were closed and filled with remoulded sediments of about the same density as the surrounding undisturbed sediments.

Wastes could also be placed using drilling equipment based on the techniques in use in the deep sea for about 30 years. By this method, stacks of packaged waste would be placed in holes drilled to a depth of 800 metres below the seabed, with the uppermost container about 300 metres below the seabed.

In the 1980s, the feasibility of the disposal of HLW in deep ocean sediments was investigated and reported by the Organisation for Economic Co-operation and Development. For this concept, radioactive waste would be packaged in corrosion-resistant containers or glass, which would be placed beneath at least 4000 metres of water in a stable deep seabed geology chosen both for its slow water flow and for its ability to retard the movement of radionuclides. Radionuclides that are transported through the geological media, to emerge at the bottom of the seawater volume, would then be subjected to the same processes of dilution, dispersion, diffusion and sorption that affect radioactive waste disposed of at sea (see section above on Disposal at sea). This method of disposal therefore provides additional containment of radionuclides when compared with the disposal of wastes directly to the seabed.

Disposal in ice sheets

For this option containers of heat-generating waste would be placed in stable ice sheets such as those found in Greenland and Antarctica. The containers would melt the surrounding ice and be drawn deep into the ice sheet, where the ice would refreeze above the wastes creating a thick barrier. Although disposal in ice sheets could be technically considered for all types of radioactive wastes, it has only been seriously investigated for HLW, where the heat generated by the wastes could be used to advantage to self-bury the wastes within the ice by melting.

The option of disposal in ice sheets has not been implemented anywhere. It has been rejected by countries that have signed the 1959 Antarctic Treaty or have committed to providing a solution to their radioactive waste management within their national boundaries. Since 1980 there has been no significant consideration of this option.

Direct injection

This approach involves the injection of liquid radioactive waste directly into a layer of rock deep underground that has been chosen because of its suitable characteristics to trap the waste (*i.e.* minimise any further movement following injection).

In order to achieve this there are two geological prerequisites. There must be a layer of rock (injection layer) with sufficient porosity to accommodate the waste and with sufficient permeability to allow easy injection (*i.e.* act like a sponge). Above and below the injection layer there must be impermeable layers that act as a natural seal. Additional benefits could be provided from geological features that limit horizontal or vertical migration. For example, injection into layers of rock containing natural brine groundwater. This is because the high density of brine (salt water) would reduce the potential for upward movement.

Direct injection could in principle be used on any type of radioactive waste provided that it could be transformed into a solution or slurry (very fine particles in water). Slurries containing a cement grout that would set as a solid when underground could also be used to help minimise movement of radioactive waste.

Direct injection has been implemented in Russia and the USA.

In 1957 extensive geological investigations started in Russia for suitable injection layers for radioactive waste. Three sites were found, all in sedimentary rocks. At Krasnoyarsk-26 and Tomsk-7 injection takes place into two porous sandstone beds capped by clays at depths up to 400 metres. Whereas at Dimitrovgrad injection has now stopped, but took place into a sandstone and limestone formations at a depth of 1400 metres. In total, some tens of millions of cubic metres of low-, intermediate- and high-level radioactive wastes have been injected in Russia.

In the USA, direct injection of about 7500 cubic metres of low-level radioactive wastes as cement slurries was undertaken during the 1970s at a depth of about 300 metres over a period of 10 years at the Oak Ridge National Laboratory, Tennessee. It was abandoned because of uncertainties over the migration of the grout in the surrounding fractured rocks (shales). In addition a scheme involving high-level waste injection into crystalline bedrock beneath the Savannah River Site in South Carolina was abandoned before it was implemented due to public concerns.

Tenorm

Radioactive material is produced as a waste product from the oil and gas industry and generally referred to as 'technologically enhanced naturally occurring radioactive materials' (Tenorm)[p]. 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[3] 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. However, scrap steel from gas plants may be recycled if it has less than 500,000 Bq/kg (0.5 MBq/kg) radioactivity (the exemption level)[q]. This level however is 1000 times higher than the clearance level for recycled material (both seel and concrete) from the nuclear industry, where anything above 500 Bq/kg may not be cleared from regulatory control for recycling.

The largest Tenorm waste stream is coal ash, with 280 million tonnes arising globally each year, and carrying uranium-238 and all its non-gaseous decay products, as well as thorium-232 and its progeny. This is usually just buried. However, the double standard means that the same radionuclide, at the same concentration, can either be sent to deep disposal (if from the nuclear industry) or released for use in building materials (if fly ash).

Further Information

Notes

a. In the USA, the Yucca Mountain site in Nevada has been chosen to site a deep geologic repository for disposal of high-level radioactive waste, but the project is beset by political interference. A licence application to construct the repository was submitted to the US Nuclear Regulatory Commission (NRC) by the US Department of Energy (DOE) on 3 June 2008. However, soon after entering office, the Barack Obama administration decided to cancel the project[1]. Later, in June 2010, the NRC's Atomic Safety and Licensing Board (ASLB) denied the DOE's motion to withdraw the licence application. The order by the ASLB noted the 1982 Nuclear Waste Policy Act (NWPA) "does not give the Secretary the discretion to substitute his policy for the one established by Congress in the NWPA." The ASLB concluded: "Unless Congress directs otherwise, DOE may not single-handedly derail the legislated decision-making process by withdrawing the Application. DOE's motion must therefore be denied." [Back]

b. See the Near Surface Disposal page in the Waste Technology Section of the IAEA website (www.iaea.org) for further information. [Back]

c. A brochure on SFR, the final repository for radioactive operational waste, is available from SKB. [Back]

d. Some information on the Finnish repositories for operating waste can be found in Nuclear Waste Management in Finland, Finnish Energy Industries (2007). [Back]

e. The Swedish repository programme is described in the SKB brochures Deep repository for spent nuclear fuel, SKB (2003) and Final repository for spent nuclear fuel (2008). More detailed technical information is in RD&D Programme 2007 - Programme for research, development and demonstration of methods for the management and disposal of nuclear waste, SKB Report TR-07-12 (2007). Information on the Finnish programme can be found in Nuclear Waste Management in Finland, Finnish Energy Industries (2007) and on the website of Posiva Oy (www.posiva.fi). [Back]

f. The SAFIR 2 report - which presented scientific and technical research on the possible final disposal of high-level and/or long-lived radioactive waste in deep clay layers. [Back]

g. The Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra) has proposed three siting regions for the high-level waste repository (see Announcement of potential siting regions for deep geological repositories, Nagra 06/11/2008). See the Nagra website (www.nagra.ch) for information on management of nuclear waste in Switzerland; in particular Opalinus Clay Project: Demonstration of feasibility of disposal ("Entsorgungsnachweis") for spent fuel, vitrified high-level waste and long-lived intermediate-level waste - Summary Overview, Nagra (December 2002). [Back]

h. The website of the Department of Energy's Office of Civilian Radioactive Waste Management (www.ocrwm.doe.gov) states: "The President has made clear that Yucca Mountain is not an option for waste storage." However, it appears that the Yucca Mountain project cannot be cancelled without the approval of Congress (see also Note a above). [Back]

i. See Note a above. [Back]

j. The website of the Waste Isolation Pilot Plant is at www.wipp.energy.gov [Back]

k. The website of the German Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS - see www.bfs.de) contains information on Morsleben. For Asse, see www.endlager-asse.de and www.asse-archiv.de. [Back]

l. The website of the German Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS - see www.bfs.de) contains information on Gorleben. [Back]

m. Nirex was incorporated into the Radioactive Waste Management Directorate of the UK's Nuclear Decommissioning Authority (NDA) in 2007 and no longer exists as a separate entity. The Nirex Phased Disposal Concept is outlined in the Introductory Leaflet What is the Nirex Phased Disposal Concept?, Nirex (2002). The NDA's strategy of research and development linked to the implementation of a geological disposal facility for higher activity radioactive wastes is given in The NDA's Research and Development Strategy to Underpin Geological Disposal of the United Kingdom's Higher-activity Radioactive Wastes, NDA

Report NDA/RWMD/011 (March 2009). [Back]

n. For more information on multinational repositories, see the International Nuclear Waste Disposal Concepts information page and the Association for Regional and International Underground Storage (Arius) website (www.arius-world.org). [Back]

o. See Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel (October 2014), and Disposal options for disused radioactive sources, International Atomic Energy Agency, Technical reports series, STI/DOC/010/436 (July 2005; ISBN: 9201003056). [Back]

p. In the UK, much of these wastes are exempt from the need for their disposal to be authorised under the UK's Radioactive Substances Act 1993 because of their low levels of radioactivity. However, some of the wastes are of higher activity and there are currently a limited number of disposal routes available. This includes re-injection back into the borehole (*i.e.* well-head), which is authorised by the UK's Environment Agency. [Back]

q. The main radionuclide in scrap from the oil and gas industry is radium-226, with a half-life of 1600 years as it decays to radon. [Back]

References

1. Obama dumps Yucca Mountain, World Nuclear News (27 February 2009); Yucca Mountain 'terminated', World Nuclear News (8 May 2009). [Back]

2. WIPP web site http://www.wipp.energy.gov [Back]

3. Malcolm B. Cooper, Naturally Occurring Radioactive Materials (NORM) in Australian Industries - Review of Current Inventories and Future Generation, ERS-006, A Report prepared for the Radiation Health and Safety Advisory Council (Revision of September 2005) [Back]

General sources

Geological Waste Disposal page in the Waste Technology Section of the IAEA website.

Fact Sheet Understanding the potential for volcanoes at Yucca Mountain, Office of Civilian Radioactive Waste Management, US Department of Energy

Deep Borehole Disposal of Nuclear Waste: Final Report, Sandia Report SAND2012-7789, Sept 2012

Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel, October 2014, US DOE

Related information pages

Waste Management in the Nuclear Fuel Cycle
International Nuclear Waste Disposal Concepts
