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Chapter 4

International practice in high-level nuclear waste management

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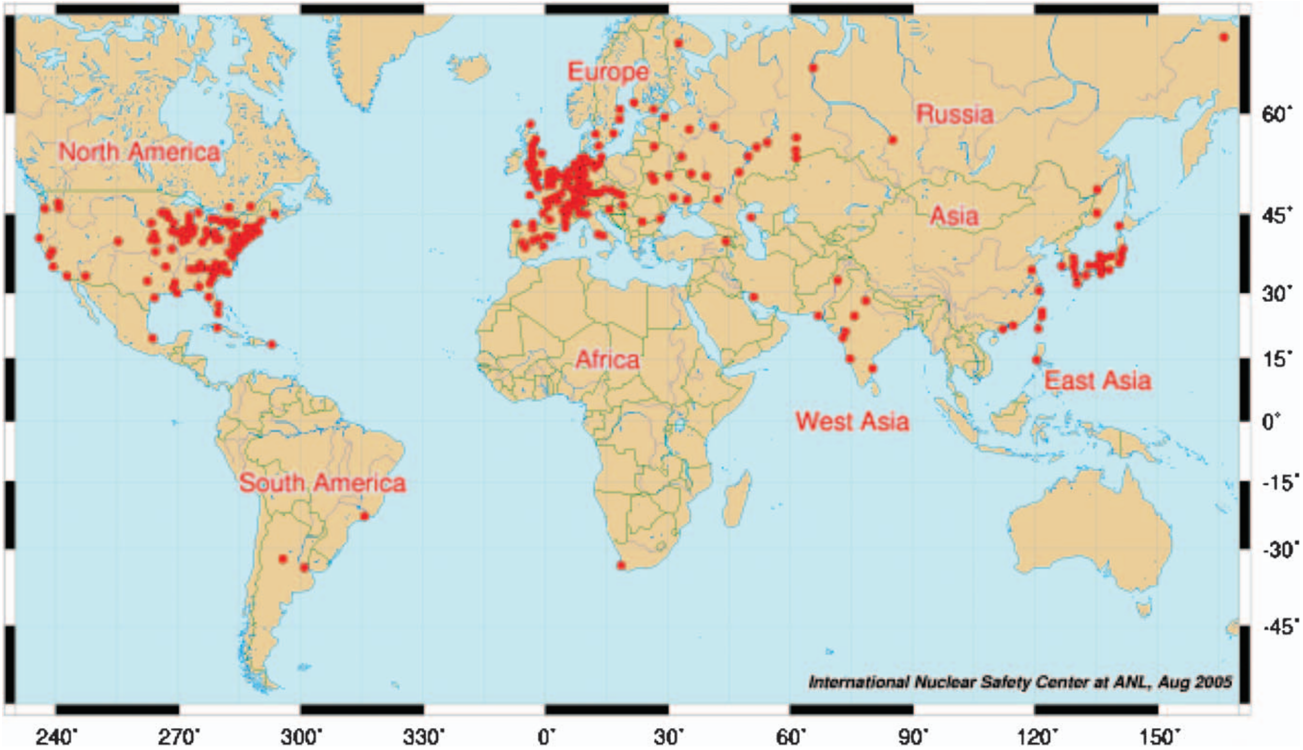
Abstract

Over the past five decades a huge quantity of high-level nuclear (radioactive) waste has accumulated worldwide in 30 countries. Despite the fact that high-level waste presents serious hazard to human health and the environment, not a single facility for disposal of high-level waste exits anywhere in the world. This paper presents a discussion of the utilization of nuclear energy on a global basis as well as the current practice of temporary storage and planned management of high-level waste. Progress made by Finland, Sweden, and the U.S.A. in finalizing permanent deep geological repositories is reviewed. Details of the Yucca Mountain Project, U.S.A., the Olkiluoto site in Finland, and Oskarshamn and Östhammar sites in Sweden are presented in the paper. Status of plans for permanent disposal of high-level waste by other countries is summarized. The recently proposed concept of shared regional/international deep geological repository is reviewed.

4.1. Introduction

Ever since the discovery of nuclear fission and development of technology to unleash the tremendous energy locked up in the nucleus of certain radioactive elements, many countries opted to use nuclear energy to meet their power needs. For about 60 years huge quantity of fissionable materials has been used for electric power generation and making atomic/nuclear bombs. One outcome of this technological innovation has been generation of a large quantity of very dangerous waste that requires careful handling, storage, transportation, and disposal.

According to the International Atomic Energy Agency (IAEA, 2007) as of April 18, 2007, 436 nuclear power plants were in operation worldwide, generating about 368.9 GWe of electric power (Figs. 4.1a, 4.1b). These power plants provide 16% of world electricity and produce 10,500



International Nuclear Safety Center at ANL, Aug 2005

Figure 4.1a. Location of operating nuclear power plants in the world (Adapted from: International Nuclear Safety Center, Argonne National Laboratory, 2005).

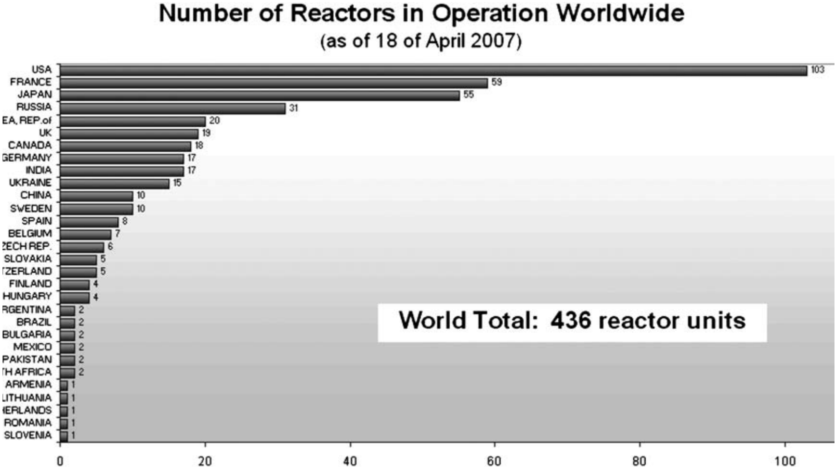


Figure 4.1b. Number of nuclear power plants worldwide as of April 18, 2007 (Adapted from: IAEA, 2007).

tonnes (metric) of high-level nuclear waste (HLW) every year. This paper presents an overview of the global status of management of HLW generated only in the civilian sector as information on use of nuclear materials in military programs of various countries is classified and is generally not available.

After the April 26, 1986 Chernobyl tragedy, interest in using nuclear energy for electricity plummeted and the nuclear industry remained in a state of dormancy for nearly 20 years. It is only in recent years that it has revived, and quite a few countries are moving ahead with construction of new nuclear power plants. As of November 2005, 30 new power plants were under construction in Argentina, Bulgaria, China, Finland, India, Iran, Japan, S. Korea, Pakistan, Romania, Russia, and Ukraine (IAEA, 2007) (Fig. 4.2) with 79% of them being located in Asian countries (IAEA, 2007). In addition to meeting the exploding energy need, another reason for the come back is the concern for global warming and adoption of the Kyoto Protocol by nearly 150 countries. Besides eliminating output of CO_2, nuclear power plants have several other advantages that might be the reason for its revival (Table 4.1).

A large volume of information on civilian use of nuclear energy is available in published books, articles, and reports, and also at websites maintained by many agencies, notably the IAEA (http://www.iaea.org/), World Nuclear Association (http://www.world-nuclear.org/), Nuclear Energy Institute (http://www.nei.org/), and the U.S. Department of Energy (http://www.eia.doe.gov/). Detailed technical information on the

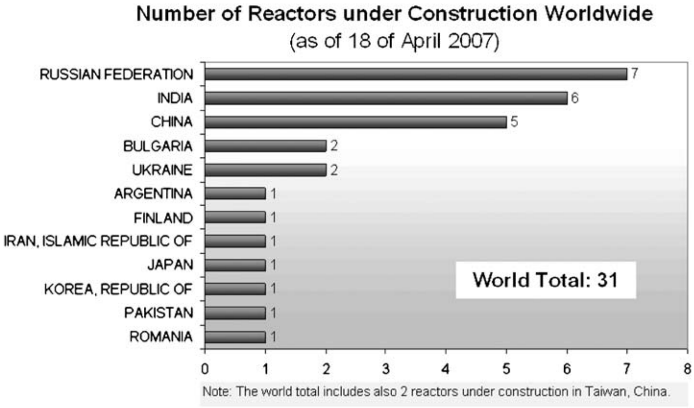


Figure 4.2. Nuclear power plants under construction, April 2007 (Adapted from: IAEA, 2007).

Table 4.1. Economic and environmental comparison for nuclear and coal-fired power plants (Data from International Atomic Energy Agency, World Energy Organization, and other)

Items	Nuclear power plant*	Coal-fired power plant*
Electricity cost per kWh (current)	\$0.02 (IAEA, 2004)	\$0.07–0.09
Projected cost after 2% rise in fuel cost	\$0.04–0.08 (200–400% increase)	\$0.42–0.63 (600–700% increase)
Capital cost	\$1500–2000 kW^{-1}	\$1250–1775 kW^{-1}
Construction time	Very long: several years to decade	< few years
Carbon emission	2–6 $g\,kW^{-1}\,h^{-1}$ (same as wind and solar)	20–60 $g\,kW^{-1}\,h^{-1}$
Waste generated/year	30 tonnes of HLW and 300 m^3 of LLW	300,000 tonnes of fly ash
Geographic distribution of fuel	Relatively widespread (U.S; Australia and Canada: > 50% of all uranium mined in 2003)	Concentrated in three countries (U.S; Russia and China account for 58% of world's reserve)
Land requirements	1–4 km^2	20–50 km^2 (solar); 50–150 km^2 (wind)
Environmental contamination	None—no harmful metal or gas released; compact waste sequestered at safe locations	Widespread—As, Hg, SO_x, NO_x, CO_2 disperse over large areas
Environmental issues	Does not contribute to acid rain or global warming	Major contributor to acid rain and global warming
Fuel transport	Concentrated energy form does not require extensive transportation system	Requires extensive transportation lines

*1000 MW installed capacity.

proposed deep geological repositories in the United States, Finland, and Sweden are available at http://www.ocrwm.doe.gov/, http://www.posiva.fi/englanti/, and http://www.skb.se/default____8563.aspx respectively.

The paper addresses the current status of management of high-level waste on a global basis. It does not include discussion of intermediate and low-level wastes because these are being managed in an acceptable manner in many countries and, unlike the HLW, their disposal is not a major concern.

4.2. Definition and classification

4.2.1. Definition

Nuclear or radioactive waste is a special kind of waste containing radioactive materials that emit harmful ionizing radiation along with attendant heat.

4.2.2. Classification

A number of classification schemes are in use internationally. Almost all of them essentially group the nuclear waste into three major categories

1. High-level nuclear wastes (HLW): includes solid, liquid, and gases and possess the following characteristics:
   - are highly radioactive;
   - come from nuclear power plants, defense research facilities, spent fuel reprocessing, and weapons production plants;
   - some have very long half-life, e.g. ^{239}Pu with a half-life of 24,000 years; and
   - continuously give off heat and radiation as they decay: therefore, need to be cooled and contained.

   HLW includes: (i) Spent nuclear fuel (SNF) which are fuel assemblies, about 4 m long and weighing about 410 kg, containing nearly 200 fuel rods that are removed from nuclear power plants every 4–6 years and (ii) wastes produced at military nuclear research facilities and weapons production plants. HLW from military facilities are mostly in liquid form and stored in tanks. Nuclear vessels generate HLW in the form of SNFs (Bodansky, 1996).
2. Transuranic waste (TRU): Comes mainly from reprocessing of spent nuclear fuel and fabrication of nuclear weapons. It consists of clothing, tools, rags, debris, soil and sludge, residues, and other disposable

Table 4.2. U.S. DOE's classification of nuclear waste (Modified from USNAS, 2003)

Category	Radioactivity level in liquid waste	Radiation dose on surface of solid waste package
HLW	$\geq 1\,\mathrm{Ci\,l^{-1}}$	$\geq 1\,\mathrm{rad\,h^{-1}}$
ILW	$1\text{–}10^{-5}\,\mathrm{Ci\,l^{-1}}$	$1\text{–}>300\ \mathrm{mrad\,h^{-1}}$
MLW	—	$300\text{–}30\,\mathrm{mrad\,h^{-1}}$
LLW	$<10^{-5}\,\mathrm{Ci\,l^{-1}}$	$<30\,\mathrm{mrad\,h^{-1}}$

items (tarpaulins, plastic sheeting) contaminated with radioactive elements. These elements have atomic number greater than that of uranium, i.e. >92 and include Pu (94), Am (95), Cm (96), and Np (93)—man-made elements that are created during nuclear reactor operations. In the U.S.A. TRU waste is being disposed off at the WIPP site in New Mexico since March, 1999 in openings excavated in 600-m thick salt beds of the Permian age (250–290 Ma) Salado Formation at a depth of 654 m.

The IAEA subdivides TRU wastes into intermediate-level waste (ILW) and medium-level waste (MLW).

3. Low-level nuclear waste (LLW): Could be in solid, liquid, or gas form and is characterized by short half-life and low level of radiation.

The U.S. Department of Energy also categorizes nuclear waste into four categories based on its radioactivity levels and radiation dose (Table 4.2).

4.3. Scope of the problem

Nuclear fission was discovered in 1939 and the first successful chain reaction took place in a research reactor that was built in 1942 at the University of Chicago as part of the *Manhattan Project*. Electricity was first generated in a nuclear reactor at the National Reactor Testing Station in Idaho in December, 1951. The first commercial production of electricity from a nuclear reactor occurred in June, 1954 when the town of Obninsk near Moscow in the former USSR was connected to an electric power grid, providing 5000 kW of electricity to residences and businesses. For nearly 50 years since nuclear power has been used in the civilian sector, a huge quantity of high-level waste has accumulated. This waste, in the form of spent fuel assemblies, referred to as SNF rods, is much more radioactive than fresh fuel rods. The SNF assemblies have been sitting at temporary storage at nuclear power plant sites and military weapons facilities for half-a-century.

Spent nuclear fuel rods give off intense radiation and heat. They are kept under steel-lined concrete pools where water is force-circulated to allow it to cool off. With time, SNF radiation drops to levels much lower than newly discharged SNF. When the SNF undergoes sufficient cooling, it may be transported to a reprocessing plant to recover Pu or it may be stored at "dry storage" sites awaiting ultimate disposal in a geological repository.

In the U.S. alone, a total of 47,000 tonnes of high-level waste had accumulated by 2003. By 2005 the quantity was estimated to be over 52,000 tonnes; and by the year 2035 this amount will increase to an estimated 105,000 tonnes (USDOE, 2005). These figures do not include HLW placed in temporary storage at military weapons facilities.

Globally, as of December 2004, about 270,000 tonnes of HLW were in temporary storage, mainly at reactor sites across the world. The World Nuclear Association (2007) estimates that on an annual basis, 12,000 tonnes of HLW is generated, of which 3000 tonnes are reprocessed, leaving 9000 tonnes for disposal.

4.4. Management of high-level nuclear waste

High-level nuclear waste is being stored at temporary locations at 440 nuclear power plants (NPP) in 30 countries across the world. While eight countries reprocess the spent fuel rods to recover Pu and U to produce mixed-oxide (MOX) fuel, others have opted for direct disposal of the HLW (Table 4.3).

It is worth noting that as of May, 2007, not a single permanent disposal facility for HLW existed *anywhere* in the world. However, Sweden and Finland have received approvals from their governments to construct the deep geological repositories, planned to begin accepting waste in 2017 and 2020, respectively. In the U.S., the Yucca Mountain Site in Nevada was designated as the HLW repository by the President in 2002.

4.4.1. Geological and environmental considerations for locating HLW repository

A geological repository for safe disposal of HLW should, at a minimum, meet the following basic criteria:

- minimal or no possibility of exposure to the environment for 1000 s of years;
- stable geologic environment: no significant erosion, or possibility of major earthquakes, or volcanic activities; and
- fail-safe mechanisms for handling and transportation of HLW.

Table 4.3. Status of HLW management in various countries (Adapted from World Nuclear Association, April, 2007)

Country	Policy	Facilities and progress towards HLW repositories
Belgium	Reprocessing	Investigations underway at underground laboratory. Construction of repository to begin about 2035
Canada	Direct disposal	Underground repository laboratory established. Repository planned in crystalline rocks at 500–1000 m depth for use in 2025
China	Reprocessing	Feasibility studies planned for 2010–2020; repository operations after 2040
Finland	Direct disposal	Site near Olkiluoto selected for deep repository for spent fuel; construction commences 2010; waste emplacement planned for 2020
France	Reprocessing	Site selection studies underway for deep repository for commissioning 2020. Sites in clay and granite being studied
Germany	Reprocessing and direct disposal	Spent fuel storage at Ahaus and Gorleben. Sate dome at Gorleban studied from 1986 to 1999. Plans for HLW repository put on hold
India	Reprocessing	Research on deep geological disposal for HLW underway
Japan	Reprocessing	Nuclear waste Management Organization established in October 2002. Construction of repository in granite or sedimentary rock planned for the 2030 s
Russia	Reprocessing	Sites for final disposal in salt, granite, clay and/or basalt under early stage of investigation
South Korea	Direct disposal	Investigating deep HLW repository sites
Spain	Direct disposal	Preliminary design developed from studies at three candidate sites in clay, granite and salt. Final decision not until 2010
Sweden	Direct disposal	Site selection for repository in two volunteered locations in granitic rock completed; waste emplacement planned to begin in 2017
Switzerland	Reprocessing	Investigations being conducted at underground research laboratory for HLW repository. Also considering shared HLW repository
United Kingdom	Reprocessing	HLW is vitrified and stored at Sellafiled. Underground HLW repository planned; date for construction not determined
USA	Direct disposal	2002 decision to proceed with geological repository at Yucca Mountain; waste emplacement planned for 2010 (pending licensing)

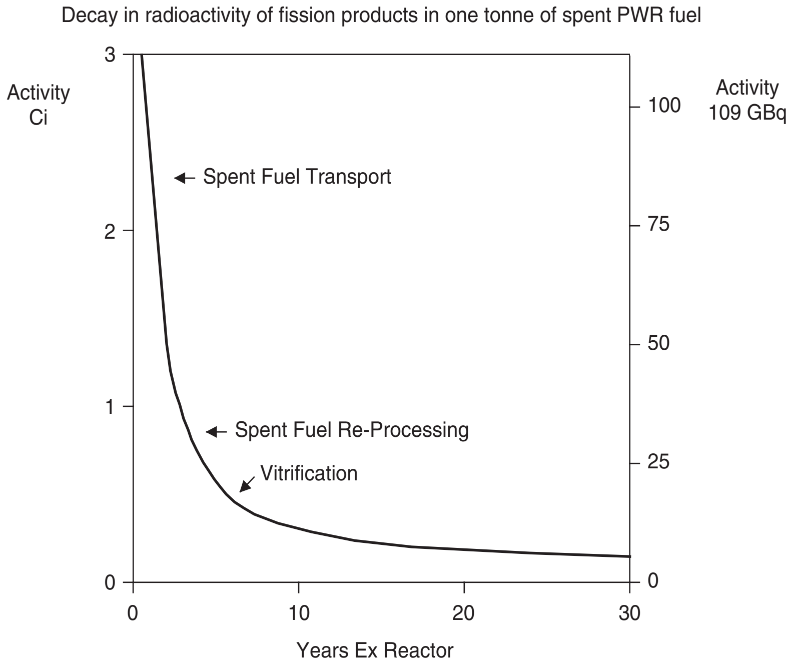
The IAEA (1995) has developed a set of guidelines to ensure protection of human health and the environment. These include

- *Protection of human health and the environment*. HLW should be managed in such a way as to ensure an acceptable level of protection for human health and the environment.
- *Protection beyond national borders*. HLW management should include consideration of possible effects on human health and the environment beyond national borders.
- *Protection of future generations*. HLW should be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today; no undue burdens should be placed on future generations.
- *National legal framework*. HLW should be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.
- *Control of radioactive waste generation*. Waste minimization techniques should be given due consideration to assure minimization of the volume of waste generated.
- *Safety of facilities*. The safety of facilities for radioactive waste management should be appropriately assured during their lifetime.

It is generally believed that allowing the SNF to sit at temporary storage sites under water is a good practice—provided its safety is assured—as it allows for significant reduction of radioactivity and heat content. Figure 4.3 shows that 1 tonne of SNF undergoes rapid loss of heat and radioactivity such that in about 30 years it loses 90% of its original radioactivity. Sweden allows the SNFs to be kept under water for up to 40 years after which the reduced levels of heat and radiation would make permanent disposal much safer. Most other countries, such as Belgium, Japan, U.K., and others, vitrify the solid HLW and plan to store their waste at temporary locations for periods ranging from 30 to 50 years.

4.4.2. Permanent disposal of HLW

Three countries, Finland, Sweden, and the United States, have been actively pursuing plans for construction of deep geological repositories for many years. In May 2001, Finland achieved the distinction of being the first country to approve plans to build a repository near Olkiluoto with construction beginning in 2011 and waste emplacement planned for 2020 (Posiva, 2003). Sweden also received a favorable referendum from the citizens in the municipalities of Oskarshamn and



Decay in radioactivity of fission products in one tonne of spent PWR fuel

GBq = 109 Becquerel
Basis : 33,000 MWd/t
Source : Cogema

Figure 4.3. Reduction of radioactivity in SNF (Adapted from World Nuclear Association, April, 2007).

Östhammar where detailed site investigations have been conducted since 2001 with the goal of emplacing HLW in 2017 (Thegerström, 2004). In July 2002, the U.S. government approved a repository site at Yucca Mountain, but the license for its construction has not been submitted as of this writing. Worldwide, 20 more repositories are planned by the year 2030 (IAEA, 2007). Detailed research and feasibility studies at underground locations are in progress in Belgium, Canada, Switzerland, and the U.K.

4.4.3. Rock types being considered

All three main classes of rocks, igneous, sedimentary and metamorphic, are being investigated for disposal of HLW. Table 4.4 is a summary of the various rock types along with their gross mechanical properties that are being investigated for underground geological repository.

Table 4.4. Rock types being investigated for HLW repository (IAEA, 2003)

Rock type	Country	Mechanical property/limitation
Granite	Canada, China, Finland, Sweden, Switzerland	High strength, no lining required/fractures may allow groundwater movement causing radionuclide transport by advection and/or diffusion
Claystone, shale	France, Switzerland, Belgium	Low to medium strength, lining required. High porosity, negligible permeability unless fractured, may develop high pore water pressure/Radionuclides transport by diffusion
Salt domes	Germany	Plastic/no pores; no lining required, self sealing fractures/no transport of radionuclides
Volcanic tuff	U.S.A	Medium strength above groundwater table: pores and fractures unsaturated. Light lining at some places/some radionuclide transport possible with percolating water

4.4.4. Regional HLW repository

Recently, the idea of shared repositories for disposal of HLW has been proposed that has received favorable reaction from IAEA and some European countries. The concept is that for small countries situated in a particular geographic region, such as eastern Europe, it would be more economical and expedient to agree upon constructing a geological repository in one of the countries in the region where each participating country can send its HLW. This concept is especially attractive to countries with unfavorable geologic conditions who will greatly benefit from such regional repository. McCombie and Boutellier (2004) have argued in favor of such international collaboration, emphasizing the following advantages:

- ensuring common standards for safety, handling, and disposal;
- affordability by economically disadvantaged countries and possibility of fair compensation if the international repository is located in such country;
- ethical and political benefit of shared responsibility; and
- better security from potential terrorist activities.

A strong argument in favor of a shared international repository in Europe, according to McCombie and Boutellier (2004), is that the U.S.A.—a single country with a far greater area than the combined area of HLW-generating countries in Europe—is having serious problems in finalizing its first HLW repository; the problems would be far more complex and time consuming for the 17 eastern and western European countries if each decides to build its own repository.

4.5. HLW disposal in various countries

This section presents an overview of the current status of efforts being made by various countries for disposal of HLW. Detailed information is included for the Yucca Mountain project and a summarized discussion is provided for Sweden and Finland. Status of HLW disposal in other countries is summarized at the end of this section.

4.5.1. U.S.A.

The United States has 104 operating nuclear power plants that provide 20% of its electricity. The proposed site for disposal of HLW is located at Yucca Mountain in Nye County in the State of Nevada, 100 miles NW of Las Vegas (Fig. 4.4a, 4.4b). After spending over 20 years in intense scientific and engineering investigations and $6.6 billion, President Bush, on July 23, 2002, approved the site for a deep geological repository. If the Nuclear Regulatory Commission grants a license to the U.S. Department

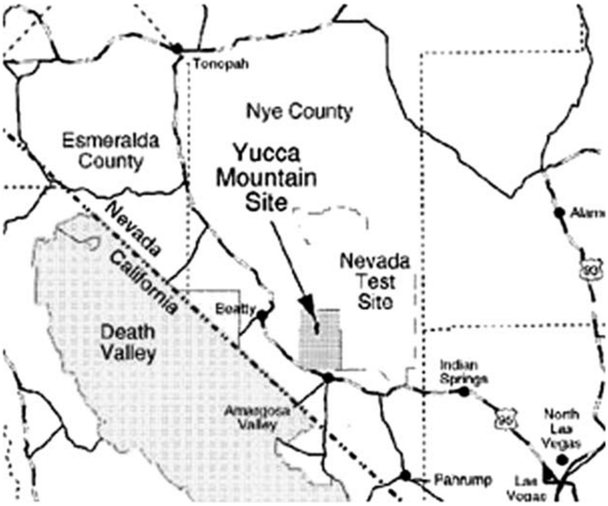


Figure 4.4a. Location map of the proposed Yucca Mountain repository site (Adapted from: USDOE, 2004).

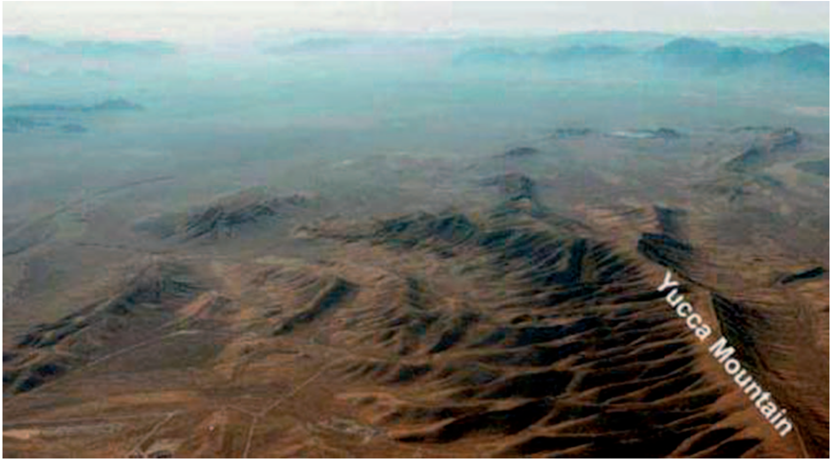


Figure 4.4b. Photograph of the Yucca Mountain in Nevada (Adapted from: USDOE, 2004).

of Energy, which would construct and operate the repository, the Yucca Mountain site is expected to begin receiving HLW in 2010. About 2,725 tonnes of HLW will be placed in the repository each year. By 2041, the emplacement of 70,000 tonnes of HLW will be complete; site closure operations would begin in 2110, and the program would end in 2119.

- The Yucca Mountain site has the following favorable conditions (USDOE, 2002):
- Land owned by the federal government; no one lives within 22 km of the site.
- The area has a very dry climate—receiving a combined average of about 19.1 cm of precipitation per year. Approximately 95% of this either runs off, evaporates, or is taken up by the desert vegetation, with about 1 cm of infiltration. The dry climate is an important factor because water is the primary way by which radionuclides could move from a repository.
- The groundwater table is very deep, about 610 m. If a repository is built at Yucca Mountain, it would be located about 366 m below the surface and nearly 234 m above the groundwater table. So, any water that does not run off or evaporate at the surface would have to move down nearly 366 m before reaching the repository and then another 308 m before it reached the groundwater table.
- Insignificant to very low rate of erosion, 0.1–0.5 cm per thousand years in the Yucca Mountain area.

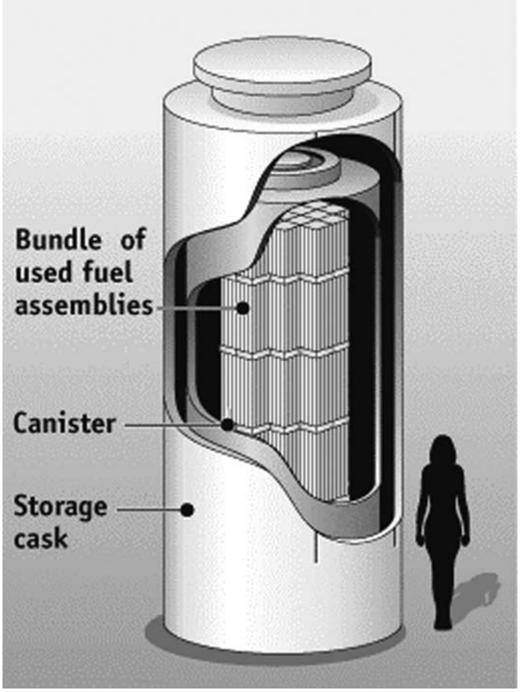


Figure 4.5. Multiple engineering barriers (Adapted from: USDOE, 2004).

The Yucca Mountain repository is being designed on the principle of multiple barriers. It is expected that a combination of suitable geologic medium and engineered barriers will prevent uncontrolled release of radionuclides into the environment. The first level of containment will come from the zircalloy metal cladding that encloses pellets in the fuel rod. Spent fuel assemblies will then be placed in a specially designed canister from which all water and air will be removed. After filling the canister with an inert gas, it will be welded shut (Fig. 4.5) and placed in a metal barrel (“cask”) to prepare it for dry storage or transportation.

Figure 4.6 shows the essential features of the proposed repository at the Yucca Mountain. According to current plans, HLW will be shipped to the site by road and rail and stored at an above-ground facility. Waste emplacement is projected to begin in 2010 and the repository will become full in 2041. After 70 years of post-closure monitoring the site will be finally closed in 2119. The total cost of the project from its beginning in 1981 until 2119 is estimated at $49.3 billion in constant 2000 U.S. dollars (USDOE, 2002).

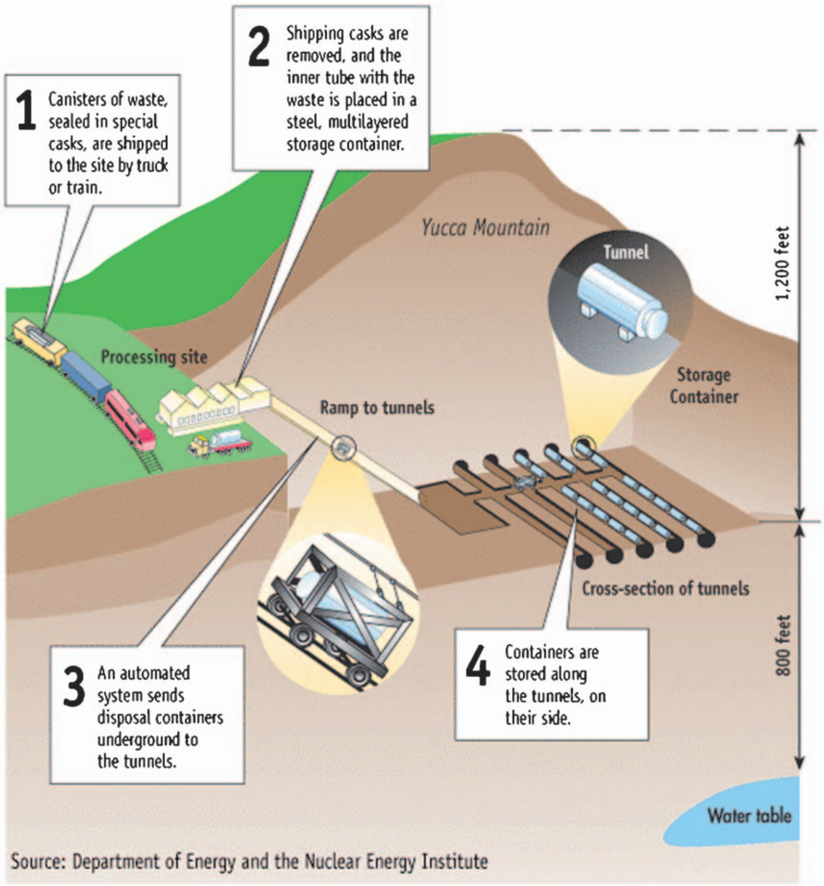


Figure 4.6. Layout of the proposed Yucca Mountain HLW repository (Adapted from: USDOE, 2004).

4.5.2. Sweden

Sweden currently has 11 operating nuclear power reactors that collectively meet 47% of the country's electric power need. Sweden's HLW management policy is based on the following three-step process (SKB, 2005a):

(1) The SNF rods are allowed to cool for one year at the nuclear power plant.
(2) The waste is then packaged and the casks are sent to Sweden's Central Interim Storage Facility, known as CLAB, to Oskarshamn in southeast

Sweden where pools are built in an underground rock cavern to shield the radiation. Thirty years of cooling will result in substantial lowering of temperature and 90% reduction of radioactivity (SKB, 2005b).
(3) Finally, the waste will be transferred to the deep geological repository in 2017.

Sweden is actively engaged in site investigations to build a deep geological repository that will isolate the HLW for 100,000 years. It also utilizes the concept of multiple engineered barriers. Spent fuel rods will be placed in a cast iron–copper canister. The canister will be entombed in a layer of bentonite before being deposited in the repository to be constructed in granitic rocks.

After preliminary site screening studies, conducted in eight municipalities between 1993 and 2000, two candidate sites were selected for further studies—in the municipalities of Östhammar and Oskarshamn. Detailed investigations commenced in 2002 and by July 2005, Forsmark in the former and Simpevarp and Laxemar in the latter were selected as potential repository locations.

The proposed repository will be located at a depth of 500 m (Fig. 4.7). The bedrock at potential sites is Precambrian-fractured granite, garnodiorite and diorite. Detailed investigations to characterize the hydrogeology of fractured granitic rocks, thermal effects from heat emanating from the SNF, along with data analyses and system modeling studies are underway. The contractor, Svensk Kärnbränslehantering AB (SKB) is planning to submit the permitting application in 2008 and expects to have the deep repository ready for waste emplacement in 2017.

4.5.3. Finland

Finland has four nuclear power plants that provide 33% of electric power and generate 70 tonnes of SNF each year. Finland's is a model case study in the sense that it illustrates the importance of thorough planning, public involvement, and political will of the government. Finland began planning for permanent disposal of HLW as early as the 1970s when its first two nuclear power plants were still under construction. Pursuant to its Nuclear Energy Act, the Finnish government in 1993 set the target date of 2010 for construction of the deep geological repository with the goal of opening it for waste emplacement by 2020. Finland aggressively moved ahead with site selection, detailed characterization, and environmental impact studies and selected a site for the deep geological repository on the island of Olkiluoto in Eurajoki municipality, in the southwestern part of the country (Fig. 4.8a). Selection of the Olkiluoto

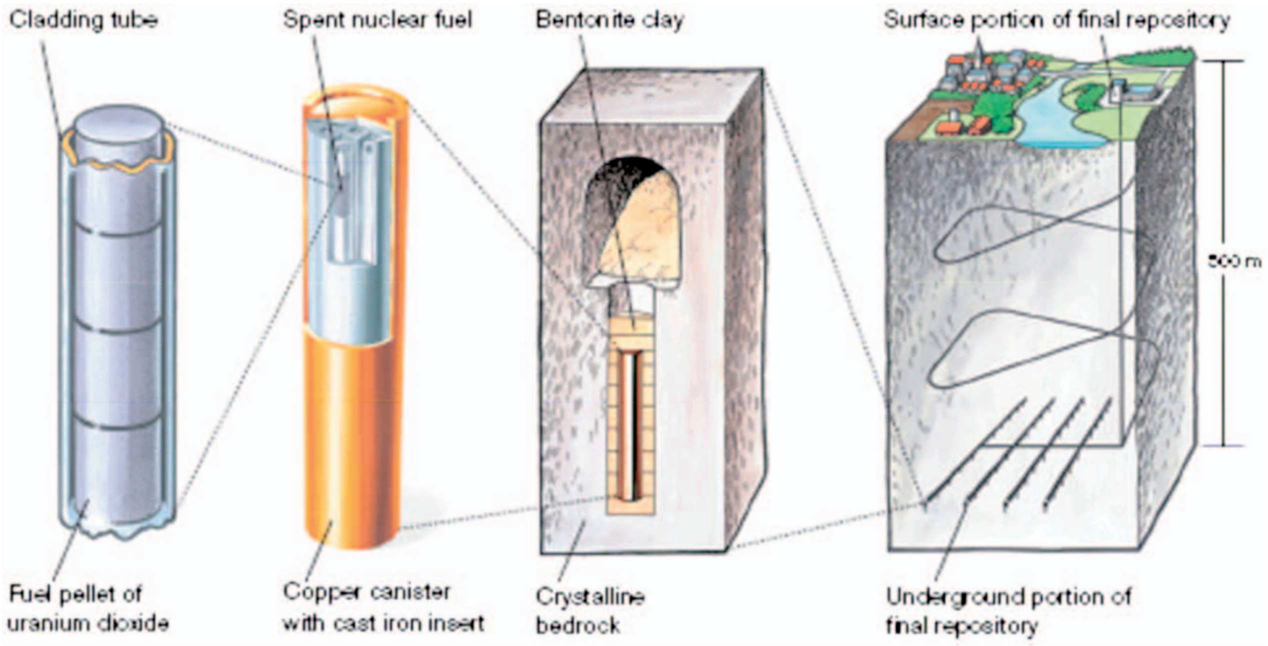


Figure 4.7. Multiple barrier approach and layout of the proposed HLW repository, Sweden (Adapted from: SKB, 2005a).

Figure 4.8a. Location map of the Olkiluoto site in the Eurajoki Municipality (Adapted from: Posiva. Oy, 2003).

site was based on: geological suitability, acceptance by local population, environmental considerations, and technical feasibility. Finland's example is instructive because it placed great importance on public acceptance and took steps to settle this critical issue in the very beginning. The public was involved in the decision-making process and the deep geological repository site was selected after the respective municipal council had voted in favor of the location. This is a most desirable approach as it saves later delays due to potential legal and political reasons.

The geological repository will be at 500 m depth in granitic rock (Fig. 4.8b) and is designed to receive 6,500 tonnes of SNF that will have accumulated by the 30–40 life of the existing nuclear power plants. Total cost, including construction, waste packaging, shipment, and final disposal of 6,500 tonnes of SNF is estimated at €845 million at December 2002 price level (1.14 billion at 2007 exchange rate).

Finland has collaborated with Sweden in the design of the copper canister for packaging spent fuel assemblies. Using the multiple barrier approach, fuel assemblies (after 30–40 years of cooling in pools) will be

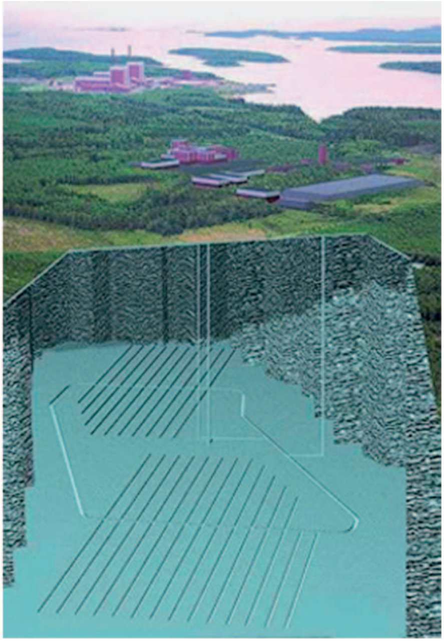


Figure 4.8b. Conceptual layout of the proposed Olkiluoto repository, Finland (Adapted from: Posiva. Oy, 2003).

placed in a canister made of cast iron with a copper overpack layer, each holding between 9 and 12 fuel assemblies and weighing 16–21 tonnes. The canister will be transported to the repository site where it will be placed in the excavated rock, surrounded by bentonite before being backfilled by concrete or a similar material. These barriers, combined with 500-m deep disposal environment, would assure that the waste will remain isolated for a very long period of time and pose no danger to humans and/or the environment.

4.5.4. HLW disposal in other countries

The status of management of HLW in other countries ranges widely from very preliminary ideas of deep geological repositories to advanced research and testing being carried out in underground geological locations. Table 4.3 also includes a summary of the HLW management efforts in these countries.

4.6. Summary and conclusions

After two decades of inactivity in construction of new nuclear power plants, there is resurgence in nuclear industry and currently 31 nuclear power plants are under construction worldwide, mostly in Asia. With the passage of the Kyoto Treaty to combat greenhouse effect, many countries are leaning toward nuclear power plants to meet their future energy needs because of the distinct advantage of nuclear power plants in eliminating production of CO_2.

Ever since the coming-on-line of the first commercial nuclear power plant in Russia in 1954, a very large volume of extremely hazardous waste has accumulated in 30 countries where nuclear power plants and/or spent fuel reprocessing facilities are in operation. The concerning fact is that despite more than five decades of utilization of nuclear energy, there is not a single facility anywhere in the world for permanent disposal of HLW. Storage at temporary locations is not desirable from many considerations, including safety and security issues.

Three countries, Finland, Sweden, and the United States, have made impressive progress in their plans to construct deep geological repositories with planned dates for emplacement of HLW set at 2020, 2017, and 2010, respectively. Worldwide 20 more repositories are planned by the year 2030.

The IAEA, along with some other countries, is supporting the new concept of regional and international repositories that will be based on scientific, technical, economic, and security considerations. It is likely that some small European countries, sharing borders with each other within distances of 300–500 km, may seriously consider joining each other to construct a deep geological repository.

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REFERENCES

Bodansky, D., 1996. Nuclear Energy: Principles, Practices, and Prospects. American Institute of Physics Press, Woodbury, NY, p. 123, 125.

International Atomic Energy Agency (IAEA), 1995. The Principles of Radioactive Waste Management, Safety Series 111-F, Vienna, p. 24 Available at: http://www-pub.iaea.org/MTCD/Publications/PDF/Pub989e_scr.pdf Accessed November 24, 2005.

International Atomic Energy Agency (IAEA), 2003. Scientific and Technical Basis for Geological Disposal of Radioactive Wastes. Technical Report Series No. 413, Vienna, p. 80.

International Atomic Energy Agency (IAEA), 2004. Nuclear Power's Changing Future (Press Release). Available at http://www.iaea.org/NewsCenter/PressReleases/2004/prn200405.html Accessed November 27, 2005.

International Atomic Energy Agency (IAEA), 2007. Nuclear Power Plant Information (PRIS Database). Available at: http://www.iaea.org/programmes/a2 Accessed May 13, 2007.

International Nuclear Safety Center, Argonne National Laboratory, 2005. Maps of Nuclear Power Reactor: World Map. Available at http://www.insc.anl.gov/pwrmaps/map/world_map.php. Accessed May 13, 2007.

McCombie, C., Boutellier C., 2004. Problems of an international repository for radioactive waste: political and legal aspects of international repositories. Available at: http://www.arius-world.org/pages/pdfs_pub/INLA-paper%2027-09-04.pdf Accessed July 7, 2005.

Posiva, O., 2003. Into Olkiluoto Bedrock—Final Disposal of Spent Nuclear Fuel in Finland. Available at: http://www.posiva.fi/esitteet/Bedrock_201102.pdf Accessed November 16, 2005.

SKB, 2005a. Encapsulation Plant and Final Repository for Spent Nuclear Fuel. Available at: http://www.skb.se/upload/publications/pdf/Ebso_InakapslTryckE.pdf Accessed November 27, 2005.

SKB, 2005b. Activities 2004. Available at: http://www.skb.se/upload/publications/pdf/SKB_ENGVerksam_2004.11.5.pdf Accessed July 15, 2005.

Thegerström, C., 2004. Down to Earth and Below: Sweden's Plans for Nuclear Waste. IAEA Bull 46(1), 36–38.

U.S. Department of Energy (USDOE), 2004. Information Digest, U.S. Nuclear Regulatory Commission, NUREG-1350, vol. 16, p. 151 Available at: http://www.nrc.gov/waste/hlw-disposal/photo-loc.html Accessed July 15, 2005.

U.S. Department of Energy (USDOE), Office of Civilian Radioactive Waste Management, Yucca Mountain Project: Now Much Nuclear Waste is in the United States? Available at: http://www.ocrwm.doe.gov/ymp/about/howmuch.shtml Accessed July 1, 2005.

U.S. Department of Energy (USDOE), Office of Civilian Radioactive Waste Management, 2002. Science and Engineering Report: Technical Information Supporting Site Recommendation Consideration, Revision 1. Report No. DOE/RW-0539-1, unpaginated. Available at: http://www.ocrwm.doe.gov/documents/ser_b/index.htm Accessed November 27, 2005.

U.S. National Academy of Sciences (USNAS), 2003. End Points for Spent Nuclear Fuel and High-Level Radioactive Waste in Russia and the United States. National Academy Press, Washington, D.C, p. 137.

World Energy Organization, Proved Coal Reserve at 1999 end. Available at: www.worldenery.org/wec-geis/publications/reports/ser/coal/coal.asp Accessed November 1, 2005.

World Nuclear Association, April, 2007. Waste Management in the Nuclear Fuel Cycle. Available at: http://www.world-nuclear.org/info/inf04.htm Accessed May 13, 2007.