NUCLEAR WASTE MANAGEMENT

NUCLEAR WASTE MANAGEMENT

R Krishnan

Center for Study of Science, Technology and Policy
February, 2016

Center for Study of Science, Technology and Policy (CSTEP) is a private, not-for-profit (Section 25) Research Corporation registered in 2005.

Designing and Editing by CSTEP

This report should be cited as: R Krishnan,(2016). *Nuclear Waste Management*, (CSTEP-Report-2016-03).

February, 2016

Center for Study of Science, Technology and Policy

18, 10th Cross, Mayura Street,

Papanna Layout, Nagashettyhalli, RMV II Stage,

Bangalore-560094 Karnataka, INDIA

Tel.: +91 (80) 6690-2500

Fax: +91 (80) 2351-4269

Email: cpe@cstep.in

Website: www.cstep.in

Acknowledgements

The author thanks the interest and support given by Dr. VS Arunachalam, Chairman CSTEP in the preparation of the review. Thanks are due to Dr. LV Krishnan and Dr N Balasubramanian, Advisors, CSTEP for their critical review and comments to improve the contents of this report. Thanks are also due to Dr. Anshu Bharadwaj, Executive Director, CSTEP for permission to publish this review as a CSTEP report. Dr. Annapoorna Ravichander deserves special thanks for editing the manuscript. This report was prepared when the author was working at CSTEP during 2011-13 and he has updated the data as much as possible. The views expressed above are that of the author and do not necessarily reflect the views of CSTEP.

Executive Summary

Greenhouse gas emissions and global climate change are of great concern world over. Based on international agreements and as signatories of various protocols to reduce emission, several nations are trying to move away from coal-based thermal power stations. Renewable sources of energy such as solar and wind are attracting attention as alternatives. Denmark has recently claimed that 40% of its energy requirements are met by windmills. But, these are intermittent sources of energy and are not available when required, unless stored which pushes up the cost. In this context, nuclear energy merits serious consideration, in spite of a few natural and man-made accidents and disasters that have taken place. Based on these, design improvements have taken place and it is now possible to avoid foreseeable incidents. However, the general public is averse to accepting nuclear power as an alternative, because of lack of solution for effective management of high level radioactive wastes, particularly in the form of Spent Nuclear Fuel (SNF). This has become the 'Achilles heel' of nuclear power generation. While less populated countries may possibly get away with minimising nuclear power production gradually as is the case in Germany, heavily populated countries like India and China may find it difficult to manage with only intermittent resources of energy, unless some disruptive innovation in energy generation takes place.

It is in this context, that this report is written to enlighten the reader about the quantity of radioactive waste generated and how it is being managed and what are the courses of action required for effective containment and disposal. Section 1 gives a brief introduction to radioactive wastes.

Section 2 describes radioactive waste classification methodology. Out of the six categories of wastes, three merit considerable attention. In particular, High Level Waste (HLW) is the one which has eluded a solution for permanent disposal so far. Hence, this report mainly deals with HLW, particularly on storage of SNF. In the present day thinking of reuse and recycling of materials, SNF is not to be considered waste as it contains useful materials.

Section 3 enumerates the quantities of SNF generated globally and in a few major nuclear power producing countries such as USA, Canada, France, UK, Russia etc. It is also to be pointed out that countries like France, UK, Japan and India have opted for reprocessing SNF and as such the HLW wastes in storage in these countries would be less than that generated.

Methods suggested for preliminary, interim and permanent storage are many. A brief description of the various techniques proposed and utilised is given in Section 4. SNF removed annually from the reactor core is not only highly radioactive but thermally very hot. It needs to be stored in a pool of water for a few years so that its activity decays and temperature comes down. Then it could be stored in dry casks, which is cheaper than pool storage. It is agreed by several nuclear nations that the ultimate permanent storage of SNF is only in geological repositories. USA had gone ahead earlier on identifying the Yucca mountain site for this, but of late it has been shelved due to several considerations. However, Sweden and Finland have identified suitable locations for geo-disposal with public concurrence. This may lead other nations to follow suit, but countries which do not have large quantities of SNF may find it difficult to justify geological repositories from economic considerations. Reprocessing is an option to reduce waste volume apart from separating out

useful uranium and plutonium, but some countries, notably the USA, feel it is not an economic solution. However, France has shown that it is a viable option. But, if one wants to reduce the activity levels and volume of HLW, transmutation of fission products and plutonium would be a good option. Deep borehole disposal of unwanted fission products is certainly worth considering. In general, considering that effective containment has been achieved in temporary storage of solid HLW, there should not be a problem in extending the storing periods by many years, so that activity levels become less and volumes to be stored becomes manageable.

Economics has to be kept in view always, which is dealt with in Section 5. The cost of geological disposal is briefly pointed out. If one can store spent fuel for long time periods and allow the fission products to decay to a considerable extent, then the cost for geological disposal would come down. If it becomes necessary, it should be possible to retrieve the SNF at any stage for reprocessing.

The last Section pertains to Indian scenario with some suggestions for growth of nuclear power. It is not summarised here so that the readers may at least read this last section in full.

Glossary

Terminology	Description
Actinide	○ An element with atomic number between 89 and 103. Actinides are radioactive and typically have long half-lives ○ They are fissionable in a fast reactor ○ Minor actinides are americium, curium and neptunium.
Activation product	A radioactive isotope of an element which has been created by neutron bombardment
Activity	The number of disintegrations per unit time inside a radioactive source, expressed in Becquerels
Alpha particle	○ A positively-charged particle emitted from the nucleus of an atom during radioactive decay ○ Alpha particles are helium nuclei, with 2 protons and 2 neutrons
Becquerel	One Bq indicates a single disintegration per second. As this is a very small number, in practice one uses GBq or TBq
Beta particle	Beta particles are generally electrons (negatively charged) but may be positrons
Burn-up	Measure of thermal energy released by nuclear fuel relative to its mass, expressed as Giga-Watt days per ton of fuel (GWd/t)
Curie	1 curie is a non SI unit and is equal to 3.7×10^{10} decays per second
Decay	Disintegration of atomic nuclei resulting in the emission of alpha or beta particles (usually with gamma radiation)
Decommissioning	Removal of a facility (reactor) from service along with subsequent actions of safe storage, dismantling and making the site available for unrestricted use
Depleted uranium	Uranium having less than the natural 0.7% of U-235, the rest being U-238
Enriched uranium	Uranium in which the proportion of U-235 (to U-238) has been increased above the natural 0.7%
Fertile Material	A material that, while not itself fissionable by thermal neutrons, can be converted into a fissile material by neutron absorption
Fission products	'Daughter' nuclei resulting from fission of heavy elements such as uranium due to neutron bombardment
Gamma rays	High energy electro-magnetic radiation, similar to X-rays
Half-life	The period required for half of the atoms of a particular radioactive isotope to decay and become an isotope of another element

High-Level Wastes (HLW)	Extremely radioactive fission products and transuranic elements (usually other than plutonium) in used nuclear fuel
Intermediate-Level Waste (ILW)	Radioactive waste which requires shielding to protect people nearby, but not cooling
Isotope	variant of a particular chemical element that has the same number of protons in each atom but has different number of neutrons
Low-Level Waste (LLW)	Radioactive waste which can be handled safely without shielding
Mixed Oxide Fuel (MOX)	Reactor fuel which consists of both uranium and plutonium oxides
Radioactivity	The spontaneous decay of an unstable atomic nucleus, giving rise to emission of radiation
Radionuclide	A radioactive isotope of an element
Rems	Roentgen equivalent in man is an older CGS unit of radiation dose; It is equivalent to 0.01 Sievert, which is the current SI unit.
Reprocessing	Chemical treatment of used reactor fuel to separate uranium and plutonium and possibly transuranic elements from the small quantity of fission products, leaving a much reduced quantity of HLW
Spent nuclear fuel	Used fuel assemblies removed from a reactor, usually on a yearly basis
Tailings	Ground rock remaining after extraction of minerals from the ore
Transuranic element	A very heavy element with atomic number greater than 92 formed artificially by neutron capture and possibly subsequent beta decay
Vitrification	The incorporation of high-level waste in a glassy matrix

Table of Contents

List of Figures

List of Tables

1. Radioactive Waste

Waste is defined as material that is of no use to anyone anywhere and hence is usually disposed of. The manner in which it is to be disposed of requires some planning even when we are dealing with household garbage. When the waste material is associated with radioactivity, it is termed as 'radioactive waste' and needs special care in handling and disposal. Radioactive wastes are the leftovers from nuclear materials used for production of electricity, diagnosis and treatment of diseases etc. This waste may decay by emitting alpha, beta and gamma radiations. But, the decay process takes a long time. In nuclear power generation, radioactive waste starts from mining of uranium. Mill tailings from underground mines where uranium ore is extracted and processed could be considered as radioactive waste. There are other operations such as nuclear reactor fuel fabrication, reprocessing of spent nuclear fuel etc. which also lead to radioactive waste. When fuel containing natural uranium, enriched uranium or plutonium is used in a nuclear reactor to generate power, fission products produced during nuclear reactions are held inside the cladding (sheath) of the fuel. If reprocessing of Spent Nuclear Fuel (SNF) is not carried out, then SNF is treated as waste, even though it contains useful fissile materials such as plutonium and in some cases slightly enriched uranium. Even depleted uranium (with less than the 0.7% normal content of fissile isotope of uranium) in the fuel is of value. The composition of actinides (elements with atomic numbers from 89 to 103) in the SNF will be different for different fuels which may contain natural uranium, enriched uranium, mixed uranium-plutonium oxide etc. The actinides with their long half-lives pose a significant challenge in handling radioactive waste. It is also likely that some activation products are carried by the reactor coolant systems which are collected by the clean-up systems. Filters and resins used in the clean-up systems are also to be disposed of as nuclear waste. Apart from these, some Naturally Occurring Radioactive Materials (NORM), such as phosphate minerals, gold bearing rocks, coal, hydrocarbons etc. contain long lived radio-nuclides but in relatively low concentrations. In short, anything that gets contaminated and emits radiation is to be treated as radioactive waste and should be managed properly.

As of now, there is no permanent solution for the management of high level radioactive wastes even though considerable amount of such waste has accumulated in several countries and additional quantities are getting added annually. As a result, the public perception is that no country should continue operation of commercial nuclear power reactors, leave alone building new ones. In fact, the United States of America had stopped construction of nuclear reactors quite a while ago. After the Fukushima incident in Japan in 2004, the public opinion against operating the existing nuclear power reactors has hardened further. Germany has decided to phase out nuclear power production in the country by 2022. However, the fact is that wastes produced by the operation of nuclear reactors are very much less in quantity compared to that produced by other industrial sectors. The public also knows that interim storage facilities for radioactive wastes have operated well in several countries. After 40 years of storage, the activity reduces to about one thousandth of what it was when the SNF was removed from the reactor. It is now realised by the scientific community that the permanent disposal of high level radioactive waste requires not only suitable technology, but also acceptance at political and social levels. It is also to be realised that renewable energy resources such as solar or wind may not be adequate to meet the demand apart from the fact that these are intermittent sources of power and not available when required except when it is stored.

This report deals with the classification of radioactive wastes, quantities of wastes generated, methods of storage, possible technologies for management and disposal along with suggestions for growth of nuclear power. The only review from India that has been written earlier on nuclear waste is by KR Rao (1) The Department of Atomic Energy has also given some details about India's nuclear waste management programme (2). The International Atomic Energy Agency (IAEA) has issued several reports on classification of wastes, proposed methods of containment, and guidelines for protecting the environment and humanity.

2. Classification of Wastes

Radioactivity diminishes with time and if radioactive waste is stored for a sufficiently long time, it would no longer be a hazard. The radioactivity of HLWs decays in about 1,000 to 10,000 years to the level that is found in the mined uranium ore. The hazard due to waste depends on the type and extent of radiations emanating from them. Hence, radioactive wastes need to be classified.

Radioactive wastes are classified into six levels (Figure1), but generally the three levels that attract attention are: low-level, intermediate-level and high-level wastes, depending on their activity levels (3). The other categories called 'exempt waste'; 'very short lived waste' and 'very low-level waste' can be handled/disposed of easily.

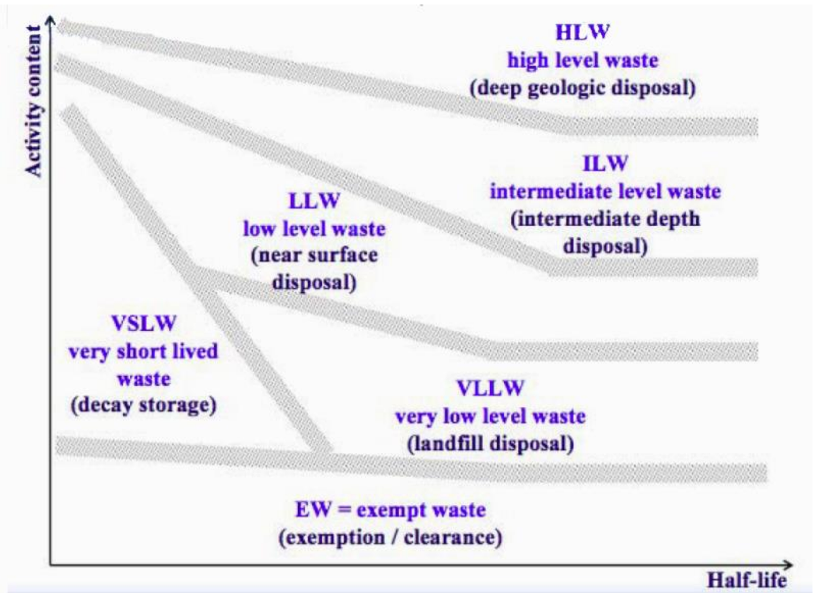


Figure 1: Conceptual Classification of Radioactive Wastes

Source: IAEA Safety Standards Classification of Radioactive Waste; GSG-1, 2009

2.1 Low-Level Waste

Low-Level Waste (LLW) arises from the beneficial uses of radioactive materials and consists of contaminated paper, rags, filters, clothing etc. These contain small amounts of short-lived radioactivity. The activity may be just above background levels found in nature. LLW is normally disposed of in shallow land burials. However, the volume of waste in this category is large and to reduce its volume, it is often compacted and incinerated. LLW occupies 90% by volume of nuclear wastes, but accounts for only 1% of total radioactivity.

2.2 Intermediate-Level Waste

Intermediate-Level Waste (ILW) typically comprises resins, chemical sludge; fuel clad etc. which arise from commercial nuclear power reactor operations. Reactor decommissioning also leads to some materials that fall under this category. These wastes are normally solidified in concrete or bitumen for disposal. This category of wastes takes up about 7% volume of all radioactive wastes and contains about 4 % of radioactivity.

2.3 High-Level Waste

HLW arises from the 'burning' of fissionable fuel like uranium and plutonium in a nuclear reactor. It consists of fission products and transuranic (TRU) elements (elements with atomic number greater than that of uranium) generated in a reactor core. It is highly radioactive and thermally hot; hence requires shielding for handling and cooling even for interim storage (Figure 2). SNF is highly radioactive and potentially very harmful. Standing near unshielded SNF could be fatal due to the high radiation levels. Ten years after removal of spent fuel from a reactor, the radiation dose 1 metre away from a typical spent fuel assembly exceeds 20,000 rems per hour. A dose of 5,000 rems is expected to cause death within one week (4).

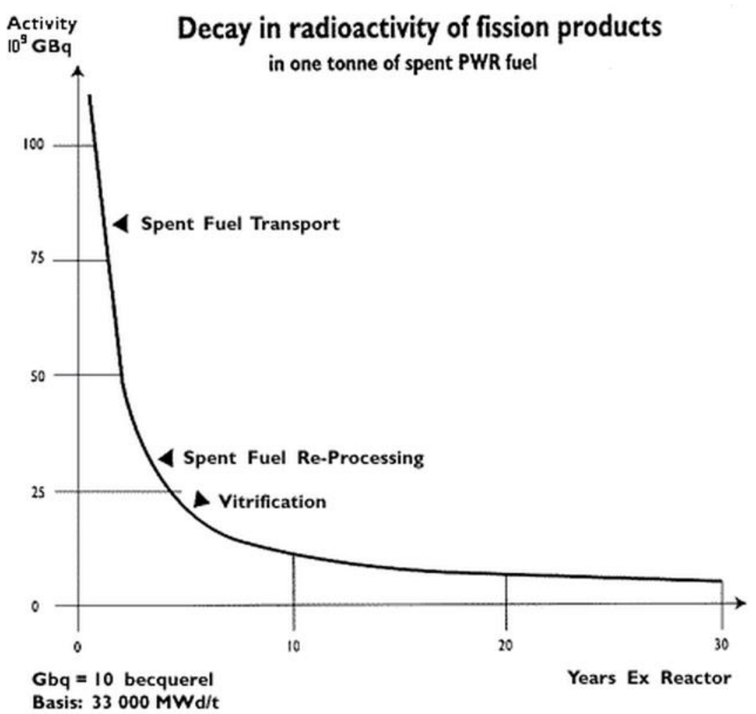


Figure 2: Decay in Radioactivity of Fission Products

Source: http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx

HLW accounts for over 95% of the total radioactivity of wastes, because of unburned uranium, actinide elements such as neptunium, plutonium, americium and curium, and fission products. It is known that over 200 radio-nuclides are produced in a reactor, but many of them have short half-lives and pose relatively less problems. SNF is classified as HLW.

Amongst the fission products generated when nuclear fuel is irradiated in a reactor, four are of special interest; strontium-90 (Sr-90), caesium-137 (Cs-137), iodine-129 (I-129) and technetium-99 (Tc-99). Sr-90 and Cs-137 release large amount of heat for the first 50 to 80 years after the fuel is removed from the reactor. I-129 and Tc-99 are very mobile isotopes that easily diffuse through geological formations. Removing them from the fission products would reduce the potential radiation dose to the biosphere, when geological disposal is resorted to. In addition, americium is a major long-term contributor of heat after the repository is closed, while neptunium is the major source of radiation to the biosphere. Removing both these elements would be beneficial for geological disposal.

How does SNF arise? When the nuclear fuel in the reactor core reaches the design irradiation level, it is removed and replaced with fresh fuel even though it contains significant amounts of fissile material. Normally, about one third of the fuel in an operating nuclear reactor is removed every year and replaced with fresh fuel. SNF is characterised by the amount of actinides present in it and is quantified in terms of Metric Tons of Heavy Metals (MTHM)* along with the activity associated at that point of time. SNF contains Tc-99 which has a half-life of 220,000 years and I-129 that has a half-life of 15.7 million years. SNF also contains TRUs like neptunium (Np-237) (half-life of 2 million years) and plutonium (Pu-239) (half-life of 24,100 years). Extraction of plutonium and uranium from SNF generates liquid HLW. It essentially consists of TRU isotopes, which are alpha emitters. Wastes containing more than 100 nanocuries/g and having half-lives greater than 20 years are classified as TRU wastes by US Department of Energy.

2.4 Half-Life and Hazardous Life

The half-life of a radioactive element is the time it takes to decrease its radioactivity to one-half of its original level. It decays either to a stable form or to another radioactive element in the 'decay chain'. After ten half-lives, one thousandth of the original active element will be left; after 20 half-lives, one millionth only will be there. The hazardous life of the waste generally extends over 10 to 20 half-lives. For instance, Pu-239 in the irradiated fuel has a hazardous life of a quarter million years. As it decays, uranium (U-235) is generated which has a half-life of 710,000 years. Thus, the hazard of SNF will continue for a million years or more.

** In this report, 'ton' only is used to specify metric tonne.*

3. Quantities of Spent Nuclear Fuel Generated

It is necessary to have an idea of the amount of HLW generated for effective management. Out of the 438 reactors in operation worldwide, there are 277 Pressurised Water Reactors (PWR), 80 Boiling Water Reactors (BWR), 49 Pressurised Heavy Water Reactors (PHWR), 15 graphite moderated reactors, 15 gas cooled reactors and 2 fast breeder reactors (5). The amount of spent fuel discharged depends on the type of reactor and the extent of 'burn-up' the fuel has undergone, i.e.; the extent of usage. Table 1 shows the approximate amount of SNF that would be discharged every year from a 1 GWe reactor (6). GWd/tHM is the amount of thermal energy released per ton of heavy metal.

Table 1: Annual Discharge of SNF from a 1 GWe Reactor Operating at 90% Capacity

Reactor type	Typical burn up (GWd/tHM)	Annual discharge of SNF (tons)
LWR	50	20
PHWR (CANDU)	7	140
RBMK (Graphite)	15	65

Source: fissilematerials.org/library/ipfm-spent-fuel-overview-june-2011.pdf

It can be seen that the CANDU PHWRs, which are mainly operating in Canada, India and South Korea discharge the maximum amount of SNF, compared to the other two reactor types, because of the low burn-up level of fuels in these reactors. At the same time it should also be mentioned that PHWR generates the least quantity of plutonium/ton of irradiated fuel.

The Net Enabled Waste Management Database (NEWMDB) provides data on solid radioactive waste (7). Additional information is also available from the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (8). SNF inventories in ten countries as of 2007 are shown in Table 2 (9).

Table 2: SNF Inventories in Ten Countries

Sl. No.	Country	SNF inventory (tons) as of end 2007
1	United States	61,000
2	Canada	38,400
3	Japan	19,000
4	France	13,500
5	Russia	13,000
6	South Korea	10,900
7	United Kingdom	5,850
8	Germany	5,850
9	Sweden	5,400
10	Finland	1,600

Source: www.gao.gov/assets/600/593745.pdf

World Information Service on Energy (WISE) has effectively summarised (Figure 3) the extent of wastes produced when 1 GWh/yr of electricity is generated (10).

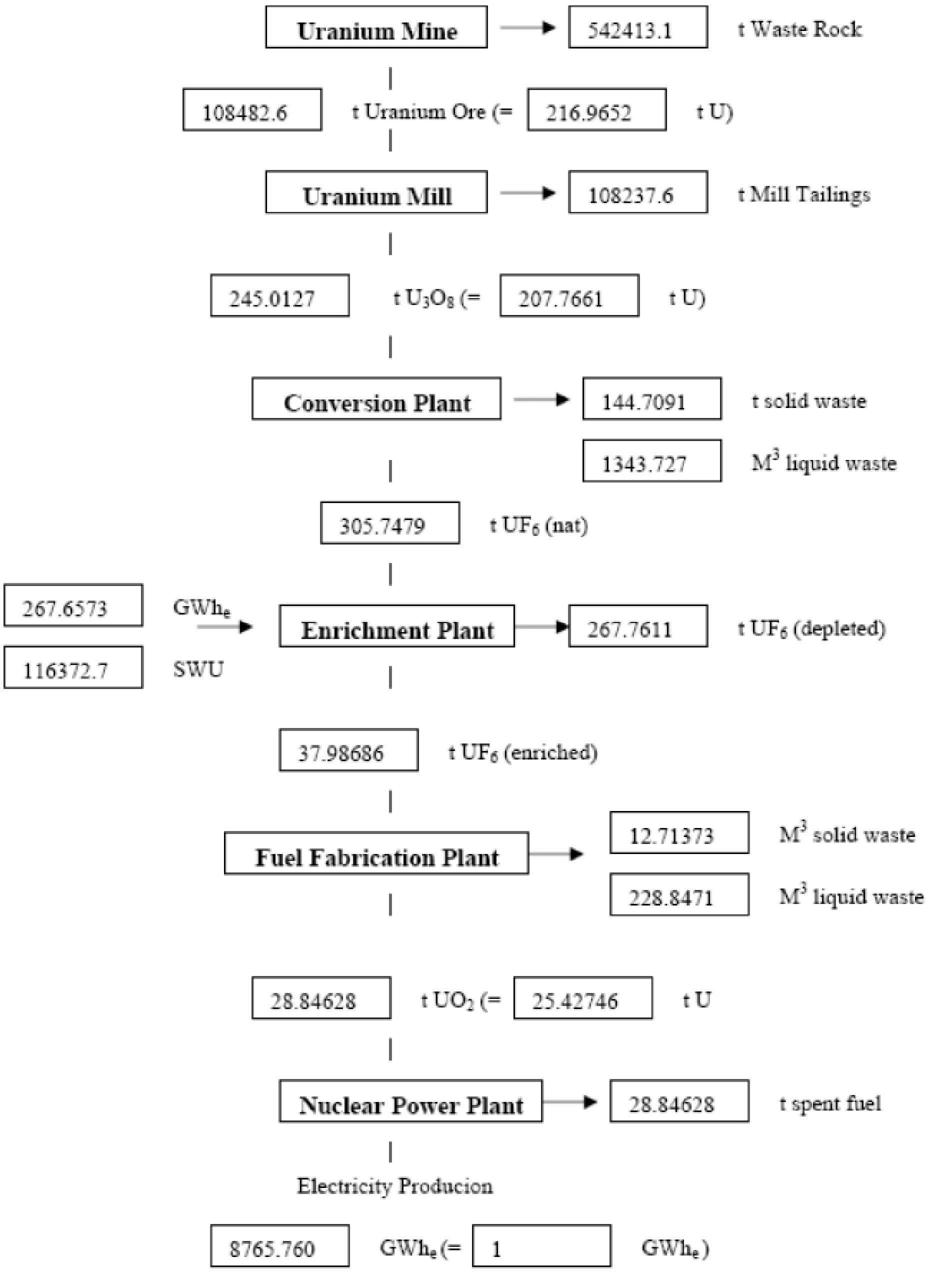


Figure 3: Nuclear Fuel Chain and Waste Production due to 1 GWh/Yr Electricity Generation

Source: http://www. Wise-uranium.org/nfp.html

As seen from Figure 3, a Light Water Reactor (LWR) of 1000 MWe capacity generates about 28 tons of SNF annually. This would correspond to about 75 m^3 of waste by volume with an initial activity of around 5.0 to 8.3 x 106 TBq. If the spent fuel were to be reprocessed, then only 3 m^3 of vitrified waste is left behind. But, the vitrified waste is to be placed in a canister for storage/disposal and thus the total waste volume goes up to about 28 m^3. Still, considerable reduction in volume of waste is achieved as a result of reprocessing.

As of end 2009, about 240,000 tons of SNF was in storage worldwide, mostly at reactor sites. While 90% of it was in storage pools the remaining was stored in dry casks. The annual generation of SNF is approximately 10,500 tons. Out of this, about 2,000 t is reprocessed

(11). The International Atomic Energy Agency (IAEA) estimates that the total SNF by 2020 would be about 445,000 tons (12).

3.1 Wastes Generated In USA

The US has 99 nuclear commercial power plants (98,639 MWe) in operation at present and many of them have been operating for several years. Some have already been decommissioned.
According to a Congressional Research Service (CRS) report (13), the US had accumulated about 62,683 tons of commercial SNF as of end 2009. Of this, 48,818 tons (78%) were in pools. 13,856 tons (22%) were stored in dry casks. In the US, the total amount of waste increases by 2,000 to 2,400 tons annually. Table 3 gives the amount of SNF generated along with the projected amount by the year 2020 (14).

Table 3: Projected Amounts of SNF in the USA

Year	Mass (t)
1995	32,200
2000	42,300
2010	61,800
2020	77,100

It was stated earlier that HLW generated is in relatively small volumes and masses. If all the SNF from the U.S. nuclear power plants in nearly 50 years of operation were stacked end-to-end, it would cover a football field to a depth of less than 10 yards (15). But, this may be misleading, because one cannot stack the fuel closely because of the heat generated by fission products. SNF contributes to a thermal load of about 2kW/m^3. Further, the football field has to be at a few hundred meters deep down.

Plutonium production has also led to large quantities of HLW. SNF was reprocessed for defence purposes at three sites: the Savannah River Site (SRS), the Idaho National Engineering Laboratory (INEL) and the Hanford Site. SNF was commercially reprocessed at West Valley, New York. Table 4 gives the volume of HLW along with associated activity in these sites (16).

At the Hanford site, 67 tons of Pu was produced from 97,000 tons of irradiated uranium fuel. This in turn has generated over 200,000 m3 of HLW, which is stored in 177 large underground tanks. Some of these tanks have been in service for over 60 years. Another 710,000 m^3 of solid radioactive waste is buried at this site (17).

Table 4: Volume of HLW Generated along with Activity Levels

Site	Volume (10^3 m^3)	Activity (MCi)
Hanford	233.5	339.9
Savannah River	126.5	502.2
Idaho National	11.2	49.3
West Valley	2.2	24.1
Total	373.4	915.5

Source: pbadupws.nrc.gov/docs/ML0834/ML083450160.pdf

At the Savannah River Site 130,000 m^3 of HLW is stored in 48 underground tanks. Efforts are under way to immobilise the sludge fraction of this waste in a borosilicate glass matrix. The Savannah River Site program of immobilising HLW went into production in 1996.

3.1.1 Decommissioning

In the US, reactors that were used to produce weapon grade plutonium were shut down between 1964 and 1971. The last Reactor 'N' was shut down in 1987. All these reactors (except B reactor) are entombed to allow radioactive materials to decay. There are another 10 decommissioned nuclear power reactors at 9 sites with no operations going on at present. According to a 2008 DOE report (18), approximately 2800 tons of SNF are stored at these nine sites. US Navy nuclear submarine reactor dry storage site contains sealed reactor sections of 114 US Navy submarines (as of 2008).

3.2 Canada

Canada has 19 operating reactors with an installed capacity of 13.5 GW. It has the maximum amount of SNF, as seen from Table 2. Every year Canada generates about 85,000 SNF bundles (1700 t) and in over 40 years of nuclear power generation, it has produced just over 2 million SNF bundles (40,000 t).

Table 5: Projected SNF Inventory in Canada

Site Name	Source Company Name	End of Reactor Operations	Nuclear Fuel Waste Inventory					
			To End of 2010		Projected to End of 2011		Project to the End of 2050	
			Number of fuel Bundles	Estimated volume (m^3)	Number of Fuel Bundles	Estimated Volume (m^3)	Number of Fuel Bundles	Estimated Volume (m^3)
POWER REACTORS								
Bruce-A	Ontario Power Generation	2034-2037	416,243	1,665	426,400	1,710	920600	3680
Bruce B	Ontario Power Generation	2042-2045	533079	2,132	556,000	2,220	1,314,000	5,260
Darlington	Ontario Power Generation	2050-2053	388,503	1,554	412,000	1,650	1,306,200	5,230
Pickering A and B	Ontario Power Generation	2017-2019	625,357	2,501	642,600	2,570	800,300	3,200
Gentilly-2	Hydro-Quebec	2039	107,237	473	122,200	490	235,000	940
Point Lepreau	NB Power	2037-2042	116,070	498	121,800	500	259,700	1,060
Subtotal Power Reactors			2,203,13	8,823	2,281,000	9,140	4,835,800	19,37

Source: Inventory of Radioactive Waste in Canada, LLRWMO-01613-041-10003

According to Canada's Nuclear Waste Management Organization (NWMO) for the existing reactor fleet, the total SNF inventory by 2050 would be over 19,000 m^3 (Table 5) (19). This high inventory is due to the fact that Canada operates CANDU reactors with low fuel burn-up.

3.3 Russia

Russia has a nuclear power generating capacity (24.65 GWe) with 34 reactors at ten sites: 18 VVERs (PWRs), 11 graphite-moderated, water-cooled RBMK-1000 reactors, four graphite-moderated, water-cooled EGP-6 reactors, and one BN-600 sodium-cooled fast breeder prototype reactor.

Ten of the VVER-1000s discharge annually about 210 tons of spent fuel (21t/GWe-yr) at a capacity factor of about 80 per cent (20). After 3 to 5 years of storage in cooling ponds adjacent to the reactors, the spent fuel is shipped to a central storage pool at the Mining and Chemical Combine (MCC) in Zheleznogorsk. The most recent VVER-1000 design incorporates some interim or final waste treatment and conditioning facilities. As of end 2009, the VVER-1000 reactors had discharged 5872 tons of SNF, of which about 5000 tons had been transported to the MCC (20). VVER-440 reactors discharge about 87 t of SNF annually.

The RBMK 1000 reactors discharge about 550 t of SNF annually, operating at 79% capacity factor. The SNF is stored at site in pools and as of end 2010 about 13,000 t of SNF was its inventory.

Russia continues the Soviet policy of taking the spent fuel back from reactors if it is of Russian origin and irradiated in Soviet or Russian-built reactors. Spent fuel from VVER-440 reactors in Finland, Hungary, Bulgaria and Slovakia was shipped to Mayak for reprocessing. SNF from the 400 MWe LWRs and BNR-600 are reprocessed at the RT-1 plant at Ozersk.

3.4 France

France has 58 nuclear power plants which generate eighty per cent of its electricity. As of end 2007, the total quantity of SNF in storage was 13,500 tons (20). This was mostly as spent low-enriched uranium fuel, about 1000 tons of MOX, 250 tons of fuel fabricated from reprocessed uranium, 100 tons of FBR fuel, 140 tons of naval reactor fuel etc. France discharges annually about 1,200 tons of spent fuel from its LWR fleet, including MOX fuel. The projected quantity of HLW by 2020 is 3679 m^3, while in 2030 it is likely to be around 5060 m^3 (21).

3.5 United Kingdom

The UK operates 16 reactors with an installed capacity of 9.4 GWe. The total volume of HLW generated in UK is about 1020 m^3 (2700 tons) (20). To reduce the volume of liquid HLW in storage tanks, they are conditioned and stored as glass blocks. All liquid wastes in Sellafield are to be converted to conditioned solids by 2023. Two thirds of HLW are already conditioned, while the remaining one third is yet to be conditioned.
Most of the UK's spent fuel from civil reactors has been reprocessed to separate plutonium and uranium. However, some spent fuel from existing Advanced Gas-cooled Reactor (AGR)

power stations and all the spent fuel from Sizewell B Pressurised Water Reactor (PWR) are not likely to be reprocessed.

3.6 Japan

As of the end of March 2010, the total amount of spent nuclear fuel stored at Japan's nuclear power plants was 13,150 tons. However, it has been sending SNF to UK and France for reprocessing. It has also built a reprocessing plant at Rokkasho to reprocess about 800 t of SNF annually (20). The storage pool at Rokkasho is full. Almost all of Japan's other spent fuel is stored in pools at the reactor sites with a small amount stored in casks at two sites. Construction of an interim dry cask storage facility was launched in Mutsu near the Rokkasho reprocessing plant but has been put on hold following the Fukushima earthquake. Japan has decided on deep geological disposal for its high level wastes and has committed that no waste will stay for more than 50 years in Aomori Prefecture, which hosts the Rokkasho Reprocessing Plant.

3.7 South Korea

The quantity of SNF generated by South Korea is about 10,900 t. At present, South Korea stores its spent fuel on-site at its four nuclear reactor sites. One of these sites, the Wolsong nuclear power plant, has four CANDU heavy-water reactors whose spent-fuel pools are full (20). Dry storage facilities have been built to accommodate the older spent fuel to make space in the pools for newly discharged spent fuel. South Korea's nuclear utility, Korea Hydro and Nuclear Power (KHNP) states that at the LWR sites, such dry storage is not politically possible even though the storage pools at these sites too will all fill up in the next decade or two. Attempts to establish off-site central spent fuel interim storage facilities have failed due to local opposition.

3.8 Germany

Germany is phasing-out its nuclear power generation and after 2022 there will be no nuclear power reactors. It is estimated that 10,300 tons of SNFs are likely to be generated till the shut-down of the last reactor Neckar-2 in 2022. This inventory will contain ~131 tons of plutonium, ~21 tons of minor actinides and 440 tons of fission products. Apart from this, about 215 tons of vitrified HLW will be present (20).

3.9 China

China is progressing at a good pace in establishing nuclear power stations (Table 6). The first stations were established in 1994. These were 900 MWe units. As of June 2013, there are 17 units operating with an installed capacity of 13.84 GWe (22). Only two of them are of CANDU type, while the rest are all PWRs. China expects to have an installed capacity of 50 – 60 GWe by 2020 and 80 – 120 GWe by 2030. The estimated quantity of SNF is shown in Table 7 (23). The PWRs are likely to reach a level of 200 GWe around 2040, when fast reactors are expected to take over the generating capacity.

Table 6: Commercial Operating Plants in China

Years	Province	Net capacity (each)	Type	Operator	Commercial operation
Daya Bay 1&2	GuangdongWh	944 MWe	PWR(French	CGN	1994
Qinshan Phase I	Zhejiang	298MWe	PWR(CNP-300)	CNNC	April 1994
Qinshan Phase II, 1-4	Zhejiang	610MWe	PWR(CNP-600)	CNNC	2002,2004,2010, 2012
Qinshan phase III, 1&2	Zhejiang	650MWe	PHWR (Candu 6)	CNNC	2002,2003
Ling Ao Phase I, 1&2	Guangdong	938MWe	PWR (French M310)	CGN	2002,2003
Tianwan 1&2	Jiangsu	990MWe	PWR(WER-1000)	CNNC	2007,2007
Ling Ao Phase II, 1&2	Guangdong	1020MWe	PWR(CPR-1000)	CGN	Sept 2010, Aug 2011
Ningde 1	Fujian	1020MWe	PWR(CPR-1000)	CGN	April 2013
Hongyanhe 1	Liaoning	1000MWe	PWR(CPR-1000)	CGN-CPI	June 2013
Total		13,842MWE			

Source: World Nuclear Association, Nuclear Power in China, Updated July 2013

Table 7: Estimate of Spent Nuclear Fuel in China

		2012	2020	2025	2035
High growth	B < reprocessing	1965	7921	14657	31744
	C > reprocessing	1955	7831	14407	27494
Low growth	B < reprocessing	1965	7372	12491	22583
	C > reprocessing	1955	7282	12241	18333
Reference	Low growth with < reprocessing	1965	7372	12510	27022

3.10 India

India has 20 operating reactors accounting for electricity generation of about 5,680 MWe. One Russian origin LWR of 1000 MWe capacity is in operation (included in the above); another one is to be commissioned soon. It has four PHWRs under construction with a capacity addition of 2,800 MWe, along with a PFBR of 500 MWe capacity as seen in Figure 4 (24). The amount of SNF generated over the years is not reported officially anywhere, but according to a nuclear waste management organisation report, India is likely to have 2750 ton SNF by 2000, which may go up to 15,150 t by 2020 (25). However, one can estimate this quantity based on the energy generated and supplied over the years (See Appendix 1). According to a CSTEP report (26), the total nuclear energy generated in India as of 2008 was 213,370 million kWh. Corresponding to this generation, the SNF would amount to about 3830 t. Nuclear energy generated during the period 2008 to 2015 is about 195,333 million units according to NPCIL annual reports in this period. This would have led to another 3510t of SNF. For the estimation of SNF by 2020, the two VVERs at Kudankulam and four PHWRs of 700 MWe capacity under construction at Kakrapar and Rawatbhata only are taken into account, when fast reactors are expected to take over nuclear power generation (Table 8).

Table 8: Projected Quantities of SNF Generation in India

Years	Power generated/ Installed Capacity	SNF(t) generated/likely to be generated	Total SNF (t)
Up to 2008	213 tWh	3,830	3,830
2008-15	195 tWh	3,510	7,340
2020	10.8 GWe	8,000	17,730

It is also known that India has reprocessing facilities and has utilised them to extract plutonium and as such the quantities of SNF in storage should be less than what is indicated in Table 8. India has an ambitious nuclear power program. It expects to have 27,500 MWe nuclear capacities by 2032. However, considering the delays in starting the projects, no attempt is made to estimate the possible generation of SNF beyond 2020.

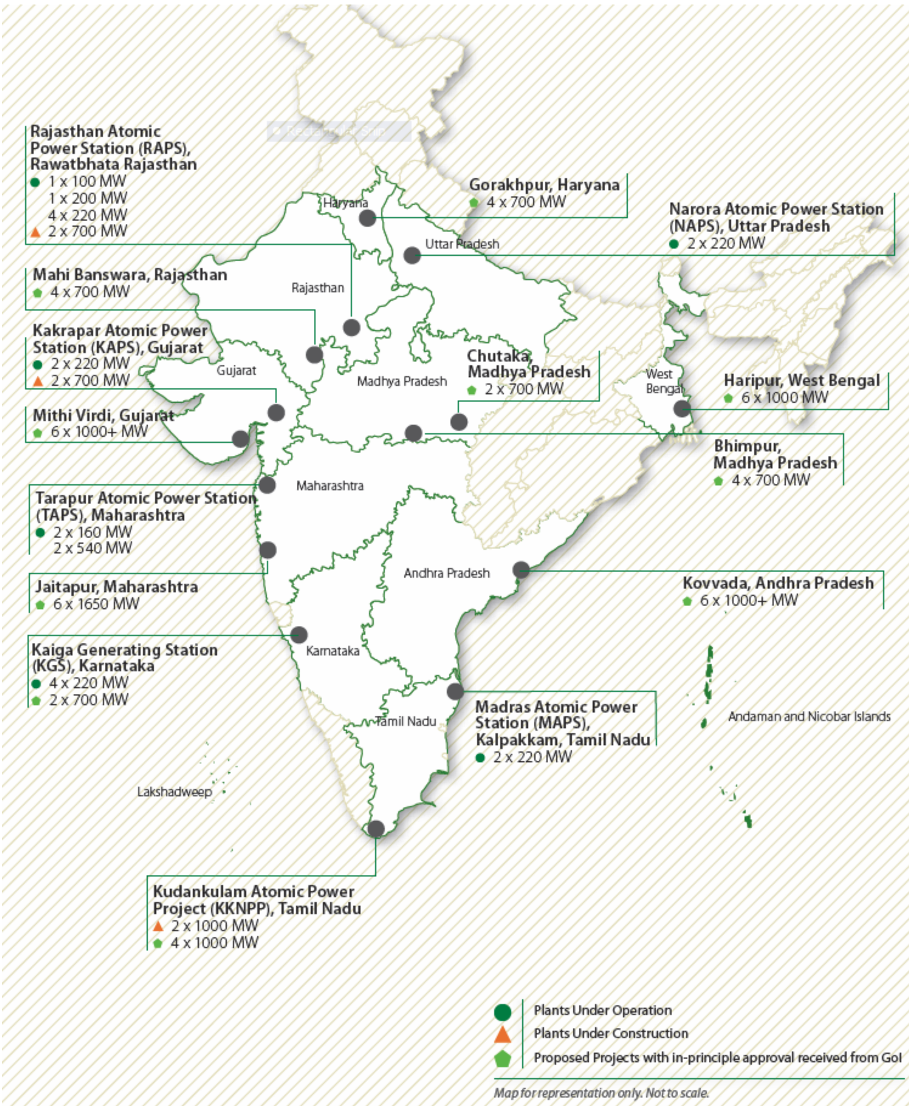


Figure 4: Nuclear Reactors in Operation, Under Construction and Proposed

Source: http://www.npcil.nic.in/main/AnnualReportDisplay.aspx

4. Storage and Disposal Techniques

The three general principles involved in disposal of radioactive wastes are:

1. Dilute and disperse
2. Delay and decay
3. Concentrate and confine

As stated earlier, HLW is highly active and thermally hot. It cannot be diluted or dispersed. But, its activity can be allowed to decay by appropriate storage for prolonged periods. However, it can be concentrated so that the storage volume becomes manageable for effective disposal. It has to be confined properly so that there is no leakage or dispersal into the environment or radiation hazard to living beings. If HLW can be kept in secure confinement for its activity to decay to a safe level, then the problem is solved. Several techniques for waste storage and disposal have been suggested and some are put into practice. We shall examine them in brief.

4.1 Activity Containment by Nature

We do learn many things from nature as seen in several disciplines. Has nature contained radioactivity? It appears so as seen in the sixteen repositories found in Oklo mine in Gabon, West Africa. About 1.7 billion years ago rich natural uranium deposits of this mine have produced nuclear fission over many years. Recent studies have shown that fission products have moved by as little as 3 to 10 metres over this long period of time (27). This was ascribed to better retention of fission products in the mineral uraninite. Reaction products were possibly less accessible to ground water attack. Another example of activity containment in nature pertains to Cigar Lake Mines in Canada. Here, uranium dioxide exists at 98% abundance level and the ore is protected from groundwater by a dome of clay. Even though the host rock is the highly permeable sandstone, clay buffer has protected the ore deposit for more than a billion years. It is at a depth of 430 metres and no chemical or radioactive signature is detected above ground (28).

The Alligator River ore body in Australia and that of Pocos de Caldas in Brazil are other examples that give us some insight for effective containment. Clay layer in the Loch Lomond bed in Scotland is known to have retarded diffusion of highly mobile elements for over 6000 years.

It appears that archaeologists may provide some clue for effective radioactive waste disposal. Glazed ceramic vases and figurines which are in various stages of decay have been unearthed in the Middle East. Based on studies of these, glasses with a higher proportion of alkaline components could be tried for radioactive containment. It should also be stated that the analogy is not perfect in the sense that radioactive waste contains boron, which is not a normal constituent of glasses. But, according to Russel Hand of University of Sheffield, even a partial similarity is valuable in the absence of long term data. Understanding nature is a sure way of improving our living standards.

4.2 Ocean Dumping

Contrary to nature that has been kind to the environment in containment of radioactivity, it is appalling to note that nuclear waste was handled rather indiscriminately by the weapon states.

UK is reported to have dumped radioactive waste amounting to ~35,000 TBq and the USA had dumped ~2900 TBq material in the Atlantic. Likewise, Pacific Ocean has been the recipient of active materials with ~900 TBq from the USSR and ~550 TBq from the USA. USSR had dumped ~750 TBq in the Sea of Japan (29, 30). During 1954 to 1969, the French reprocessing plant at La Hague discharged low-level waste directly into the English Channel. The Soviet Union secretly pumped waste containing 3 billion curies directly into the earth. Chernobyl accident which released approximately 50 million curies is dwarfed in comparison. The Mayak Nuclear Facility in Russia dumped nuclear waste into Lake Karachai which has ten times higher than the normal radiation levels. In 1993, Russia released the official Yablokov report detailing its history of dumping nuclear waste directly into the world's oceans.

It was soon realized by everyone concerned that such ocean dumping should stop forthwith and the United Nations Conference on the Human Environment drafted a treaty in London in 1972 prohibiting dumping of nuclear wastes into the sea (31). It entered into force on 30 August 1975 when 15 nations ratified the treaty. As of October 2001, there were 78 contracting parties to the Convention.

4.3 Pool Storage

This report mainly deals with HLW and thus storage of SNF becomes part of it. The core of a typical large PWR reactor consists of between 80 to 100 tons of enriched uranium (~3.5%) in multiple fuel assemblies. Each fuel assembly consists of 200-300 fuel rods roughly 3.5 m long. The total decay heat due to 1/3rd core is about 3.9 MW, 10 days after removal from the core of a Boiling Water Reactor (BWR) (32,33). Figure 5 shows a typical fuel storage pool at La Hague in France. Figure 6 shows how heat decays from a fuel bundle as a function of time with respect to a CANDU reactor as well as a PWR with slightly enriched uranium fuel and mixed oxide fuel (21). The heat liberated is the highest in the case of MOX fuel and this fact has to be kept in mind in pool storage of SNF.

The spent fuel pools are generally made of several feet thick reinforced concrete with steel liners. The normal depth of the pool is about 12-13 metres. This quantity of water is required to serve as shield against radiation as well as to cool the fuel bundle. Pool storage requires consistent satisfactory performance of multiple systems using pumps, piping etc. The size of the storage pool is usually arrived at depending on the amount of Sr-90 and Cs-137 present in the SNF. Isolating these two isotopes from the SNF would certainly bring down the activity level so that dry storage can be employed. If Sr-90 and Cs-137 were allowed to decay or "age" outside the repository for about 100 years, the repository volume would be considerably less. According to US DOE, after about 300 years, the material could even be disposed of as LLW. However, this would lead to storage of separated Cs and Sr but then the quantities to be handled are much less.

Figure 5: A Used Fuel Storage Pool at La Hague, France

Source: http://www.areva.com/EN/operations-1092/areva-la-hague-recycling-used-fuel.html

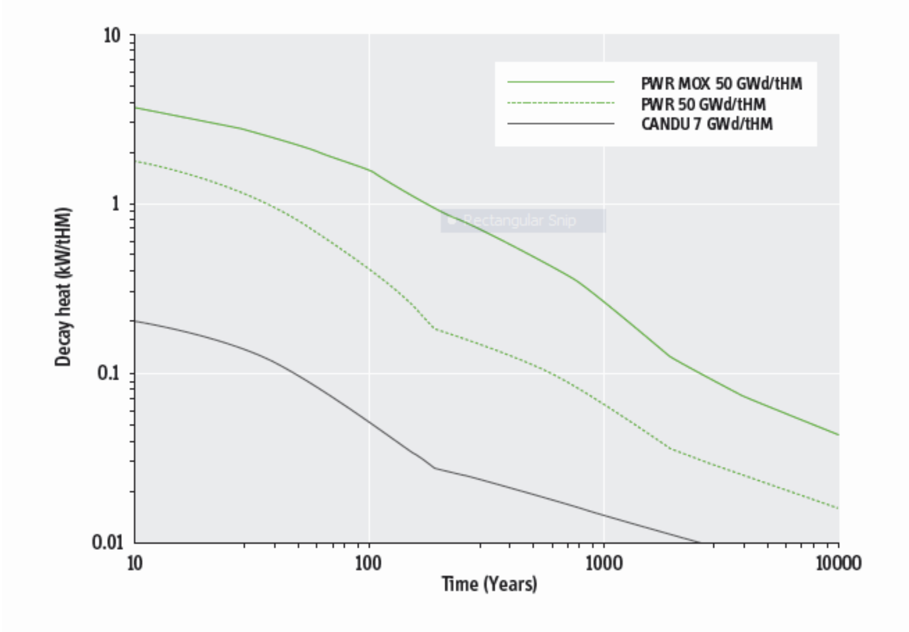


Figure 6: Decay Heat as a Function of Time from SNF

Source: IPFM- Managing Spent Fuel from Nuclear Power Reactors, www.fissilematerials.org, 2011; ISBN 978-0-9819275-9-6

The spent fuel from Russia's LWRs, along with the spent fuel of similar reactors in Ukraine and Bulgaria, is sent for storage to Zheleznogorsk in Siberia where a large storage pool was built in the 1980s. At present, the spent fuel from the Russian graphite-moderated, water-cooled RBMK reactors is stored at the reactor sites.

The present understanding is that SNF can be stored safely in pool followed by dry cask storage for at least 60 years beyond the licensed life of any reactor without significant environmental effects.

4.4 Dry Cask Storage

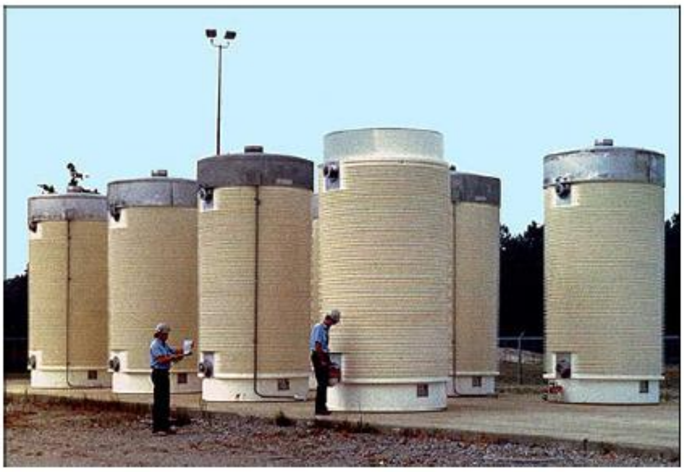
Pool storage at the reactor sites became inadequate to meet the rate of withdrawal of SNF from the reactor core. Hence, an alternate solution became necessary. It was thought that dry storage would be simpler, and safer as it avoids the problem arising out of loss of water and consequent overheating leading to fuel clad melting and releasing volatile fission products into the atmosphere. In addition, dry cask storage is more economical than pool storage. But, dry storage can be used only after the SNF has been out of the reactor for quite a few years so that the amount of heat released becomes manageable.

Figure 7 shows dry cask storage on a concrete pad with cutaway schematic of a cask. Details of some HLW containers used in the US are given in Table 10 (34). Each canister at the SRS can contain about 234 kCi which is much more than what is contained at INEL or Hanford.

Table 9: Details of HLW Canisters

	WVDP	SRS	HANFORD	INEL
Outer Dia. (cm)	61	61	68	NA
Height (cm)	300	300	457	NA
Material	304 L SS	304 L SS	304 L SS	304 L SS
Wall thickness	0.34 cm	0.95 cm	NA	NA
Wt. Canister (kg)	252	500	NA	NA
Glass/Ceramic (kg)	1900	1682	4200	2400
Activity/canister (Ci)	104,300	234,400	12,700	9,000
Decay heat/canister (W)	311	709	38	26

By 2010, 63 other "Independent Spent Fuel Storage Installations" were established in USA and were licensed to operate at 57 sites in 33 states. Over 1400 casks are stored in these facilities.



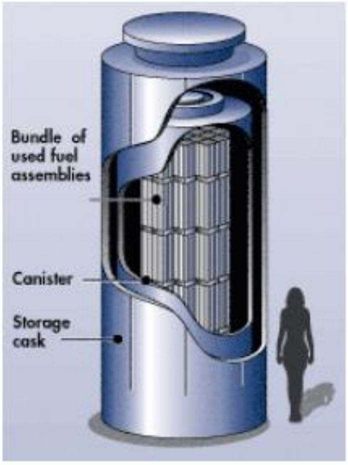


Figure 7: Dry Cask Storage on a Concrete Pad with Cutaway Schematic of a Cask

Source: http://www.climatewarmingcentral.com/nuclear_page.html
Source: http://www.nrc.gov/waste/spent-fuel-storage/diagram-typical-dry-cask-system.html

In the USSR, a very large dry cask storage facility is planned at Zheleznogorsk in Siberia. At present, the spent fuel from the Russian graphite-moderated, water-cooled RBMK reactors is stored at the reactor sites but the older spent fuel is to be shipped to Zheleznogorsk (20).

4.5 Centralised Interim Storage

As expected, pool storage facilities at the reactor sites were running out of space. Hence, setting up a centralised interim storage facility has been proposed as an integral part of the waste management programme. Long term storage of HLW above ground is advantageous because the material could be more easily observed and problems detected if any, could be managed. The decay of short-lived radio-nuclides will also significantly reduce the level of radioactivity. General Electric was licensed to operate a centralised storage facility in 1972, but that is also full at present. Centralised storage pending final storage will lead to additional cost. But a well-planned programme of interim storage will be very useful in final geological disposal. At the same time, the interim solution appears to have become a long term one, because the final disposal solution is not yet in sight. Thus, the public are averse to having any centralised interim storage facility in their vicinity.

Sweden has been sending their SNF to a Centralised Interim Storage Facility (CLAB) since 1985. The fuel will remain there for a minimum of 30 years before ultimate disposal in a geological repository (35).
The UK has decided that a robust programme of interim storage is necessary and is building up a facility for centralised storage. This facility is expected to hold waste for as long as it takes to identify and construct a geological disposal facility (36).

France is also for developing interim storage facilities. Under the Planning Act of 2006, they should create new storage facilities or modify existing facilities by 2015 for the storage of long-lived HLW and intermediate level wastes (37).

4.6 Reprocessing

To reduce the amount of waste and radiotoxicity, reprocessing of SNF is considered as an option, because Pu, U and other long-lived radio-nuclides could be converted to faster decaying fission products in special particle accelerators. France considers recycling as an economically viable approach and has already reprocessed about 22,000 t of SNF. There is also an inherent assumption that Cs-137 and Sr-90 would also be separated and stored in dry casks for a few hundred years to reduce their activity to normal ore levels.

However, an MIT study (38) shows that the extent of fission products in the once through fuel cycle is the same as that in a closed fuel cycle. But, the absence of long lived TRUs in the closed fuel cycle leads to faster cooling of waste. After 200 years, heat generated by the closed fuel cycle waste would be less by a factor of 18 than that of the once-through cycle (39). This would lead to a much smaller waste repository volume.

Another aspect to be kept in mind is that reprocessing would be of greater benefit for recently discharged used fuel than for fuel already in storage because the longer the used fuel is out of the reactor, the greater would be the build-up of Am at the cost of Pu. Hence, if Pu recovery from MOX fuel is being considered, reprocessing should be considered first for recently discharged used fuel.

The main emphasis in reprocessing is selective separation of minor actinides and interim storage till a decision regarding transmutation in the blankets of a fast reactor or in an

Accelerator Driven System such as DAIMEX-SANEX in France, TOGDA in Japan or TALSPEAK in the US. The other alternative is to carry out homogeneous recycling (GANEX in France, UREX+ in US, NEXT in Japan) in fast reactors. This is done by group actinide separation using an integrated fuel cycle (online fuel reprocessing and re-fabrication). Notwithstanding what is stated above, a geological repository is necessary for final disposal of unusable radioactive materials.

4.7 High Level Liquid Waste Storage

In the US, because of the nuclear weapons development programme, a few sites contain a large quantity of wastes. The Hanford site has 177 underground storage tanks built between 1943 and 1986 to store HLW. Out of these, 149 were single shelled stainless steel tanks while the 28 new ones were double-walled. These tanks were designed for a safe life of 20 years, but one started leaking within 6 years. By 1980s, 67 tanks developed leaks. It was estimated that 4 million litres of HLW (1 million curies) were released to the soil (40, 41). As of 2008, most of the liquid waste has been transferred to double-walled tanks.

The Savannah River Site has also a large inventory of HLW with approximately 126,300 m^3 of waste containing about 535 million Ci in underground, double-walled tanks (as of 1995) (42). Nine tanks were reported to have leaked into secondary confinements. One tank had overflowed even the secondary confinement.

The general conclusion that one can draw from the above incidents is that it is better to convert the liquid HLW as early as possible into solid waste so that there is less likelihood of any major leakages.

4.8 Vitrification

HLW of different compositions can be vitrified either in borosilicate or phosphate glass. In this process, radioactive elements are bound to nonradioactive glass-forming elements. Phosphate glass is better than borosilicate glass as the dissolution rate is lower, but it is not able to contain all radioactive products. Hence, phosphate storage may require more reprocessing efforts. It should be noted that plutonium does not bind with borosilicate glass and only trace quantities are loaded into it. This is probably an advantage from terrorism point of view.

The US Department of Energy is building a vitrification plant at the Hanford Site at a cost of approximately $12 billion. Construction began in 2001 and the plant is now scheduled to be operational in 2019, with vitrification of all the existing wastes to be completed by 2047. Savannah River Site tried to remove radio-nuclides before immobilisation in glass. This was in the form of an in-tank precipitation process for caesium removal, but surprisingly, large quantities of explosive benzene were produced. Hence, this was abandoned and SRS started a solvent extraction process that has a high selectivity for caesium.
France has commercial plants (total capacity 2,174 m^3) at La Hague to vitrify HLW left over from reprocessing oxide fuel. AREVA plans to expand their capacity to 3,648 m^3 with another expansion in 2022.

There are plants in UK and Belgium with production capacity of 2,500 canisters (1000t) a year. By mid-2009, the UK Sellafield vitrification plant had produced its 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.

It is gratifying to note that India has mastered the technology of vitrification of HLWs (43). One is not sure about the durability of the vitrified product. There may be phase separation and uncontrolled devitrification. In this context, it is worthwhile to mention the efforts of Neil Hyatt and his co-workers at University of Sheffield, UK, who claim to have developed a new way to vitrify radioactive wastes by heating them with glass forming chemicals at high temperatures. They have used Integrated Computational Materials Engineering approach (ICME) to select the best glass composition for a given type of waste suitable for safe, long term disposal.

4.9 Synroc Technology

The Australian Nuclear Science & Technology Organisation has carried out extensive research in radioactive waste disposal and has developed waste forms to treat radioactive wastes using hot-isostatic pressing (HIP) technique under the brand name SYNROC ANSTO (44). The minerals in SYNROC are hollandite ($BaAl_2Ti_6O_{16}$), zirconolite ($CaZrTi_2O_7$) and perovskite ($CaTiO_3$).The zirconolite and perovskite are hosts for the actinides. Strontium and barium are fixed in the perovskite. Caesium is fixed in the hollandite.

In December 2009, the US Department of Energy decided to use HIP technology to process and store 4400 m^3 of HLW at the Idaho National Laboratory. SYNROC has the advantage of incorporating wastes that cannot be handled by glasses. US DOE has been discussing with ANSTO for the cleaning up of Savannah River site and at Hanford. It should also be mentioned that pyrochlore-rich ceramic is quite efficient for immobilising uranium wastes without using neutron absorbers.

UK's National Nuclear Laboratory in association with ANSTO has used a composite Synroc-glass waste form for containing impure Pu stored at Sellafield. The glass-ceramic mix is subject to hot isostatic pressing. ANSTO and NNL have built and operated a demonstration plant there. The process will result in substantial cost savings to the UK government and can be applied to other actinide - notably plutonium - waste streams.

Another significant work pertains to considerable reductions in waste volume for the partitioning/conditioning strategy by immobilising the heat generating radio-nuclides such as Cs-137, Sr-90 and Cm-244 in Synroc–C, while the remaining waste can be immobilised in glass. Cm may be of importance when treating MOX fuels.

4.10 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 tons of fission products and 1.5 tons of plutonium, all of which remained at the site and eventually decayed into non-radioactive elements. Studying these natural phenomena would lead to a proper evaluation of geological repositories.

The US National Academy of Sciences way back in 1957 proposed geological waste disposal to effectively isolate waste from the biosphere for thousands of years. For this, HLW is to be encapsulated in a tight canister that would not disintegrate during its expected lifetime. In addition, the canisters are backfilled with appropriate materials that would limit water movement and thereby waste movement should the canisters break down.

A wide range of rock types (e.g., volcanic, granitic, shale, clay, salt), different repository designs and emplacement methods and different waste packaging and engineering barrier designs were arrived at. Investigations also revealed that 'reducing' as opposed to 'oxidising' conditions in the repository will decrease the solubility and mobility of TRUs in the geological environment.

The deposits of native copper in the world have proven that the copper used in the final disposal container can remain unchanged inside the bedrock for extremely long periods, if the geochemical conditions are appropriate (reducing ground waters). 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. SKB therefore designed a cask covered with a 5-cm thick shell of copper that it believed would not corrode for a million years and proposed to surround it with a thick layer of bentonite clay.

Out of 39 countries having HWL, 25 have opted for geological disposal. Finland's government is the first to approve construction of a deep underground repository at Olkiluoto, an island off Finland's west coast, which will start storing waste from about 2023. It will pack up to 6,500 tons of clay packed uranium in copper canisters that would be placed in a network of tunnels cut out of granite bedrock 400 metres underground. Finnish authorities estimate to seal this repository by 2120, when its radiation levels will be harmless.

In contrast to Finland choosing granite-based repository, Sweden has chosen their site containing shale located at Forsmark. This site is expected to be operational by 2023. Germany which has buried its low and medium level wastes in underground domes of salt, is considering its possible use for storing HLW also.

The Disposal Subcommittee of the Blue Ribbon Commission in USA also concluded that geologic disposal in a mined repository is the most promising and technically accepted option available for safely isolating high-level nuclear wastes for very long periods of time (45).

Canada has felt that safety must be viewed from both technical and social perspectives. The Nuclear Waste Management Organisation (NWMO) has used an 'adaptive phased management' approach after extensive public consultation (46). A few localities have come forward to explore the possibility. The earliest date for commencement of construction is 2035.

France's geological storage is handled by the Centre industrial de stockage géologique (Cigéo), which would hold all such wastes to be generated through 2052 by the operation of the current fleet of 58 reactors, and the future ones and also the defence wastes. The total volume has been estimated at around 100,000 m^3. The disposal facilities are to be developed on the basis of the 500 m deep geological laboratory in clay formation. The French radioactive waste disposal agency, Andra is designing a deep geological repository in clays at Bure in eastern France. The repository is designed to operate up to about 90C, which is likely to be reached in about 20 years after emplacement.

Geological salt environments have a very low rate of groundwater flow and in addition it gradually self-seals the excavations due to creep of the salt. The Waste Immobilisation Pilot Project (WIPP) in New Mexico for defence TRU wastes has been in operation from 1999. For this repository, natural rock salt is excavated from a Permian layer several metres thick, 650 metres below ground level. Till October 2010, 71,000 cubic metres of ILW has been disposed (47). However, in February 2015, a container with ILW appears to have ruptured and has released moderate levels of radioactivity into the repository and also into the environment. This plant may not reopen for at least 18 months. This incident is ascribed to human error. The project 'Support Action: Pilot Initiative for European Regional Repositories' (SAPIERR) involves European countries interested in a shared solution for deep geological disposal of HLW (48).

However, geological waste disposal program is fraught with legal challenges and public reluctance to accept this option. It is now realised that the help of social scientists is essential to communicate effectively with the public. The public opinion is geological disposal is a dirty option to get radioactive waste out of sight and out of mind.

4.11 Deep Borehole Sealing

Deep borehole concepts have been developed in several countries, including Denmark, Sweden, Switzerland and USA. But, no one has implemented it so far. An excellent review of this technology has been written by Sapiie and Driscol (49). The basic consideration is that water from such deep, old and stable rock would not communicate with the biosphere. In this option, solid packaged wastes would be placed in deep boreholes drilled to depths of a few km, about 2 to 5 km, with diameters typically less than 1 metre. The waste containers have to be separated from each other by a layer of bentonite or cement. The borehole is not to be completely filled with wastes. The top would be sealed with materials such as bentonite, asphalt or concrete. The heat generated by the wastes would lead to temperatures high enough to melt the surrounding rock and dissolve the radio-nuclides in a growing sphere of molten material. As the rock cools it would crystallise and incorporate the radio-nuclides in the rock matrix, thus dispersing the waste in a larger volume of rock.

Current concepts suggest that each borehole could contain up to 200 t of SNF. Sandia laboratory has estimated that a borehole with 150 t of SNF would correspond to a peak dose of 1x10-10 mrem/y, more than a billion times below the current regulatory limits (50).

In the US, borehole disposal was thought about in the 1970s but no trials have been conducted. It is estimated that about 800 boreholes can take care of existing stockpile and the SNF coming out of current reactors till 2050. In fact, deep borehole technique may be more easily adopted for short lived wastes arising out of GEN IV reactors.

4.12 Ocean Bed Disposal

The deep sea floor is one of the most stable and predictable geological formations and hence could be an alternative solution to deep geological disposal of HLW. Packaged HLW could be embedded in the sediment using suitable techniques and could be left for 500 to 1000 years. But, it is not yet proved to be an acceptable solution. The NEA/OECD in 1988 showed that sub-seabed burial of HLW was technically feasible (51). But, the long-term safety assessment requires further studies.

4.13 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. In the 1980s, the feasibility of the disposal of HLW in deep ocean sediments was investigated and reported by the OECD. Radioactive wastes 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 radio-nuclides (52). This method of disposal therefore provides additional containment of radio-nuclides when compared with the disposal of wastes directly to the seabed.

4.14 Transmutation

Partitioning and transmutation are actually an extension of an efficient closed nuclear fuel cycle. This method is based on placing the waste containing uranium, plutonium, thorium and fission products in an accelerator and bombarding it with high energy spallation neutrons so that the active materials get transmuted into stable products with shorter half-lives. The main advantage is that fission stops once the accelerator is switched off. However, one does not know at present what the final transmutation products will be and in what proportions. This process could also generate more energy than it consumes. The heat generated by splitting the waste nuclei can be used to generate electricity and as such this process may turn out to be quite attractive and economically viable since minor actinides also become additional fissile fuel. It is to be noted that the transmuted less hazardous waste is still to be stored.

Experts feel that a fast breeder reactor could use the fuel till all the plutonium and minor actinides are burnt up. The fast breeder reactor Phenix was used to test burning fuel assemblies containing high concentration of minor actinides. The Indian option of using the thorium fuel cycle would produce short-lived fission products and less minor actinides. Ultimately, one may have to think of multiple recycling of SNF to afford energy security for nations with huge populations like India and China.

Low Energy Nuclear Reaction is attracting the attention of researchers worldwide as an alternate source of clean energy. It appears to be useful in shortening the half-lives of radioactive materials by increasing their rate of emissions. The US Navy has been granted a patent for this process (53).

5. Economics

A geological repository for SNF or HLW would cost billions of dollars to build and operate. The US Department of Energy has estimated the cost for disposal of 77,000 t of SNF (likely to be generated by 2020) would be of the order of tens of billions dollars. The unit storage cost for liquid HLW at Hanford ranges between \$2.8 to \$4.5/yr/gal in 1994 dollars. The SRS has a large HLW inventory, with approximately 32 million gallons in underground, double-shelled tanks. The unit cost of operation of the HLW tank farms at SRS was estimated at \$5.5/yr/gal HLW in 1994 dollars (54). While the US costs are rather high, Finnish costs are the lowest.

Canadian NWMO has estimated that the geological disposal of 3.6 million spent fuel bundles (72,000 t) would cost about US \$ 25 billion, including the cost of a centralised interim SNF storage facility (55,56). This cost is inclusive of interim spent fuel storage in a centralised underground facility. If this were to be excluded for comparison with US costs, then the present value is estimated at 6.1 billion (in 2004 Canadian Dollars). If the spent fuel remained at reactor sites prior to deep repository disposal, this figure would be \$ 5.1 billion. Diverse international cost estimates have been published for spent fuel disposal and a broad consistency was found. The unit cost of disposal of SNF ranges from 80,000 to 1,200,000 €/t with the most common values from 300 000 to 600 000 €/t (Figure 6) (57).

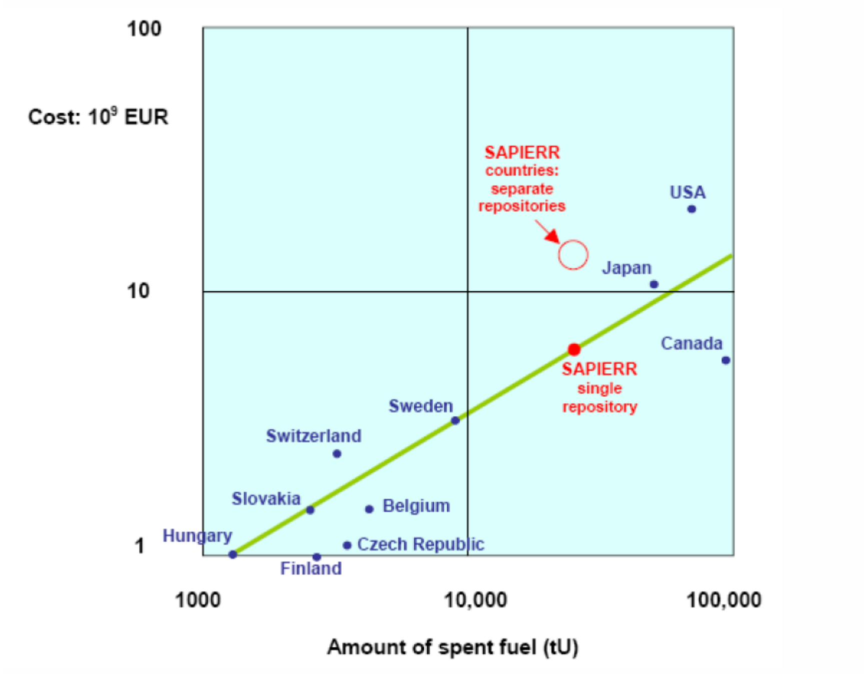


Figure 8: Deep Repository Costs as function of SNF Quantities

Source: ftp://ftp.cordis.europa.eu/pub/fp6-euratom/docs/sapierr-projrep_en.pdf

The spent fuel management and disposal costs are estimated to be about 10% of the total costs involved in producing electricity from a nuclear power plant. Thus, although the absolute costs of waste management are high, because waste volumes produced are small, they do not render the nuclear fuel cycle uneconomic (58). International studies have shown that the costs of disposal would be of the order of 1 cent per kWh and would not adversely affect the case for nuclear power.

6. Indian Scenario

The Department of Atomic Energy is examining a multi-barrier approach to dispose solid HLW. As is done everywhere, one needs to have engineered barriers along with good natural geological characteristics.

DAE has already established the first vitrification facility at Tarapur for immobilisation of waste generated from PHWR. The second vitrification facility has been commissioned at Trombay to manage HLW generated during reprocessing of SNF from the research reactors. A Waste Immobilisation Plant has been set up at Kalpakkam for HLW generated during reprocessing of irradiated fuel from PHWR and Fast Breeder Reactor (FBR).

Near Surface Disposal Facilities (NSDF) in widely different geo-hydrological conditions have been constructed and operated by the Department of Atomic Energy. Over the years, considerable expertise has generated in refining and improving the design and construction of these NSDFs. A system of multiple barriers employed in these NSDFs ensures isolation and release of radio-nuclides below permissible limits to the environment. Reinforced concrete trenches used are in sound condition even after an operational period of three to four decades. DAE has predicted a minimum service life of about 240 years based on modelling studies.

DAE has also carried out in-situ underground experiments for assessment of the rock mass response to thermal load from disposed waste. This experiment was carried out in an abandoned section of Kolar gold mine.

Geologically, India is endowed with a number of suitable rocks for geological repository. A few areas in NW and Central India having good quality granites have been investigated as possible locations. Preliminary studies indicate that bentonite deposits of Barmer Basin in Rajasthan are suitable candidates. One of these zones has been investigated in detail to narrow down an area of about 4 km^2 as suitable candidate site.

Decommissioned reactor sites could be possible locations for geological disposal of high level radioactive wastes, given suitable geophysical conditions. These sites are already contaminated and any remedial action may take not only enormous time but would also cost a lot. India is one of the very few countries to have opted for reprocessing spent fuel. This is not only necessary to make use of thorium reserves in the country, but would considerably reduce the heat load and activity levels, if minor actinides are removed along with plutonium and uranium. The heat load and activity levels should be brought down as much as possible, before wastes can be confined to a geological repository. Thus, India should formulate a robust 'away from reactor site' long-term pool storage, to be followed by dry cask storage. It should continue reprocessing and remove the troublesome isotopes, along with plutonium and uranium. One can adopt transmutation of technetium and iodine. Minor actinides would provide power while undergoing transmutation.

In the present global context of sustainable and green energy requirements renewable energy resources like solar, wind, tidal, geothermal etc. has attracted a lot of attention. India is not lagging behind in this direction. However, if one looks for alternate green energy sources available throughout the day, nuclear power takes the top spot. Today, world over nuclear power plants generate one-sixth of the total electricity supply. It is true that isolated incidents/accidents in some nuclear power stations have occurred; some attributable to human error while some others were due to natural calamities as at Fukushima. HLW storage is still to be mastered, but both Finnish and Swedish experiences in this area have given a great impetus to the nuclear power generation. Solving technological problems alone is not sufficient. Permanent high level waste disposal can happen only if it is consent based and transparent, in the sense that the public are made aware of the implications of the disposal action. The public should be able to feel confident that the facilities are meeting the rigorous safety and environmental standards. It is but natural that we return to mother earth what we have extracted from her, instead of thinking of exotic solution of disposing of waste in space.

China has projected construction of PWRs up to a capacity of 200 GWe after which it would switch to fast breeder reactors, which is essentially to bring down the amount nuclear waste to be managed. India is well ahead in the Fast Breeder programme and this would certainly increase the fuel burn-up. Possibly, it may require better fuel clad material to withstand the higher levels of irradiation. The Indo-US nuclear agreement was expected to initiate activities to set up more LWR reactors, which again would increase the fuel burn-up. That leaves us to sensitise our public about energy security, greenhouse gas emissions, radiation hazards, radioactive waste management, containment, disposal etc. As is practised elsewhere, India should also seek the assistance of social scientists and local non-governmental organisations in the above activities.

In this context, it is necessary to bring it to the attention of readers about recent developments in nuclear technology taking place elsewhere (59).A few manufacturers are developing compact fast reactors for spent fuel consumption, the leading example being General Electric-Hitachi S-Prism reactor. In this reactor, a recycling unit is integrated such that it takes the spent nuclear fuel to remove the fission products and puts the rejuvenated fuel back into the reactor. Extensive work has been carried out at Oak Ridge National Laboratory on molten salt reactors to consume plutonium and other long lived radioisotopes almost completely. High temperature nuclear reactors can provide zero-carbon heat for the industries. Adequate governmental funding and international consortium approach is necessary to commercially materialise these technologies within a reasonable timeframe. Finally, it should be possible to develop next generation breeder reactors such that the nuclear waste contains only intensely radioactive fission products that would decay in a few centuries.

7. References

1. K R Rao, 'Radioactive waste: The problem and its management, Current Science, 81, 1354 (2001).

2. BARC Highlights Report on Nuclear Fuel Cycle.2011, Chapter 17. Waste Management: Disposal of Radioactive Waste. www.barc.gov.in/publications/eb/golden/nfc/toc/Chapter17.pdf

3. IAEA Safety Standards Classification of Radioactive Waste; GSG-1, 2009.

www-pub.iaea.org/MTCD/publications/PDF/Pub1419_web.pdf

4. Radioactive Waste: Production, Storage, Disposal (NUREG/BR-0216, Revision 2)

5. Nuclear Power Reactors in the World - International Atomic Energy, 2015.

www.pub.iaea.org/IAEA Books

6. Spent Fuel from Nuclear Power Reactors - International

fissilematerials.org/library/ipfm-spent-fuel-overview-june-2011.pdf

7. The IAEA Net Enabled Waste Management Database- DISTEC 2004, Accessible on: http://www-newmdb.iaea.org/reports.asp

8. International Atomic Energy Agency, Joint Convention on the

Safety of Spent Fuel Management and on the Safety of Radioactive Waste

Management, IAEA International Law Series No. 1, IAEA, Vienna (2009)

Accessed on: http://www-ns.iaea.org/conventions/waste-jointconvention.html

9. GAO-12-797, Spent Nuclear Fuel: Accumulating

www.gao.gov/assets/600/593745.pdf

10. World Information Service on Energy (WISE) Uranium Project, home page: http://www. Wise-uranium.org/nfp.html.

11. Storage and disposal of spent fuel and high level radioactive waste, IAEA; gc50inf-3-att5_en.pdf

12. IAEA-Management of spent fuel from nuclear power reactors, IAEA Doc.STI/Pub/1295 (2007)

13. Congressional Research Report- www.crs.gov.RL 33461

14. Department of Energy, Integrated Data Base Report 1994: US

Spent Nuclear Fuel and Radioactive Waste Inventories, Projections and Characteristics, DOE/RW-0006, Revision 11, (1995)

15. NRC: Radioactive Waste: Production, Storage, Disposal

www.nrc.gov/reading-rm/doc-collections/nuregs/brochures/br0216/

16. Nuclear Waste Disposal- The Technical Challenges, K D Crowley, Physics Today, June 1997

17. DOE/RW-0596, Report to Congress on the Demonstration of ... - NRC

pbadupws.nrc.gov/docs/ML0834/ML083450160.pdf

18. Department of Energy.gov/sites/prod/files/EA-1889-FEA and FONSI-2012.pdf

19. Inventory of Radioactive Waste in Canada, LLRWMO-01613-041-10003;

CC3-1/2012

20. International Panel on Fissile Materials, Managing Spent Fuel from Nuclear Power Reactors; World Nuclear Association, "Country Briefings: Nuclear Power in Canada", http://www.world-nuclear.org;

21. IPFM- Managing Spent Fuel from Nuclear Power Reactors, www.fissilematerials.org, 2011; ISBN 978-0-9819275-9-6

22. World Nuclear Association, Nuclear Power in China, Updated July 2013

23. China's Nuclear Energy Development and Spent Fuel Management; nautilus.org › NAPSNet › Special Reports 2012

24. NPCIL Annual reports

25. A comparative overview of approaches to management of spent nuclear fuel and high level wastes in different countries, Charles McCombie & Bengt Tvieten, Nuclear waste Management organization, January 2004

26. Anshu Bharadwaj, L V Krishnan, S Rajgopal, Nuclear Power in India: The Road Ahead, CSTEP Report

27. Andrew Alden, The Oklo Natural Nuclear Reactor - Geology - About.com

28. Cameco - Mining - Cigar Lakewww.cameco.com/mining/cigar lake/

29. en.wikipedia.org/wiki/Ocean disposal of radioactive waste

30. IAEA TECDOC-1105 "Inventory of radioactive waste disposals at sea", 1999

31. Intergovernmental Conference on the Convention on the Dumping of Wastes at Sea, 13 November 1972, London

32. Spent Fuel Pool Storage - Nuclear Information and Resource Service

www.nirs.org/reactorwatch/security/nasrptsfp5.pdf

32. ORNL/TM-2011/290

33. S M Folga et al.; Argonne National Laboratory, ANL/EAD/TM-17 (1996); www.osti.gov/scitech/biblio/544722

34. Recent leaks from Hanford high level nuclear waste tanks, John R Brodeur, Energy Sciences and engineering, Kennewick, WA, 2006

35. Storage of spent nuclear fuel in Sweden

www.polsoz.fu-berlin.de/polwiss/forschung/.../ffu/.../Swahn-2014.pdf

36. Committee on Radioactive Waste Management, Interim Storage of Higher Activity Wastes and the Management of Spent Fuels, Plutonium and Uranium, CoRWM Doc 2500, March 2009.

37. National Policies: Radioactive Waste Management

www.world-nuclear.org/.../nuclear.../nuclear-wastes/.../radioactive-waste-...

38. Nuclear Fuel Cycle Study - MIT

web.mit.edu/ceepr/www/.../MIT%20Future_of_Nuclear_Fuel_Cycle.pdf

39. www.oecd-nea.org/ndd/pubs/2006/5990-advanced-nfc-rwm.pdf

40. www.ecy.wa.gov/programs/nwp/sections/tankwaste/closure/pages/tank_leak_FAQ.html

41. www.rt.com/usa/192300-hanford-nuclear-waste-leak/

42. www.srs.gov/general/news/factsheets/srs.pdf

43. Glass Matrices for Vitrification of Radioactive Waste – an Update on R & D Efforts, Kanwar Raj and C. P. Kaushik, International Seminar on Science and Technology of Glass Materials (ISSTGM-2009) IOP Conf. Series: Materials Science and Engineering 2 (2009) 012002 doi:10.1088/1757-899X/2/1/01200)

44. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Nuclear-Wastes/Synroc/

45. The Workings of an Ancient Nuclear Reactor – Scientific…

www.scientificamerican.com/article/ancient-nuclear-reactor/

46. www.nwmo.ca/.../Canadas...Adaptive-Phased-Management..

47. Waste Isolation Pilot Plant | Department of Energy

energy.gov/em/waste-isolation-pilot-plant

48. SAPIERR – Idea of European Regional Repositories ... - Arius

www.arius-world.org/.../IAEA_Safety_Conference-Tokyo-October.pdf

49. Sapiie, B., and M. J. Driscol, 2009; A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Waste. MIT Nuclear Fuel Cycle (NFC) Technology and Policy Program, MIT-NFC-TR-109

50. Brady, Patrick V. et al.; Deep Borehole Disposal of High-Level Radioactive Waste. Sandia Report, SAND 2009-4401

51. www.OECD-NEA.org/rwm/reports/1999/progress.pdf

52. Burial of radioactive waste under the seabed, CD Hollister & S Nadis, Scientific American, January 1998

53. System and Method for Generating Particles – US8419919 B1

54. Radioactive Wastes and The Savannah River Site Robert Alvarez on risks of SRS nuclear waste, 2013

55. www.cbc.ca/.../canada/storing-nuclear-waste-a-24-billion-problem-1.794, 2009

56. Nuclear Waste Management in Canada - Princeton University

www.princeton.edu/.../Canada-NuclearWasteManagement-EnergyPolicy, MV Ramana - 2013

57. ftp://ftp.cordis.europa.eu/pub/fp6-euratom/docs/sapierr-projrep_en.pdf

58 World Nuclear Association, Radioactive Wastes: Myths and Realities, Updated Oct. 2012

59. Nuclear Energy: Radical reactors, Nature 492, 25-29, 2012.

8. Appendix I

1. Mass of SNF generated is almost equal to the mass of fresh fuel loaded into the reactor. Thus,

$M = Q/B_d = Pe.\ CF.\ 365/\eta_{th}.\ B_d$

where, Q = thermal output of the reactor,

M = mass of discharged SNF in tHM

P_e = Installed capacity in GWe

CF = Capacity factor

η_{th} = thermal efficiency (GWe/GWth)

B_d = average burn-up in GWd_{th}/tHM

The expression shown above can be used to arrive at the amount of SNF. For CANDU type reactors, thermal efficiency is about 0.31 and average burn-up is about 7 GWd/tHM. This still needs capacity factor to be plugged in to estimate the value of SNF. In India, it is known that some reactors were operated at lower capacity factors because of lack of uranium. In the absence of reliable CF values over the years, it is difficult to arrive at the exact quantity of SNF generated.

2. Canada has estimated that for PHWR reactors, the average SNF generated is 18 t/TWh of power generated at a thermal efficiency of 0.31. Thus, from the extent of nuclear energy generated in India, (amounting to 408 TWh), the total amount of SNF generated would be about 7,340 t as of 2015.

Center for Study of Science, Technology and Policy

#18, 10th Cross, Mayura Street, Papanna layout

Nagashettyhalli, RMV II Stage, Bangalore-560094

Karnataka, India

www.cstep.in