TOPIC IV: RADIOACTIVE WASTE MANAGEMENT - FUNDAMENTALS

Content: Sources, measures, health effects, nuclear power plants and fuel production, waste generation from nuclear power plants, disposal options

Source for graphic above: www.keprtv.com

ABSTRACT

This module introduces the concept of radioactive waste and its management. It will also briefly focus on nuclear power plants in India.

IITM-EWRE

Solid and Hazardous Waste Management

Radioactivity

Radioactive decay occurs in an unstable atomic nucleus – i.e., an atomic nucleus that does not have enough binding energy to hold the nucleus together due to an excess of either protons or neutrons. There are three types of radioactive decay:

- Alpha decay: An alpha particle is identical to a helium nucleus, being made up of two protons and two neutrons. It initially escapes from the nucleus of the parent atom by quantum mechanical processes and is further repelled from it by electromagnetism, as both the alpha particle and nucleus are positively charged.
- Beta decay: Beta decay itself comes in two kinds – β^+ and β^-. β^- emission occurs by the transformation of one of the neutrons into a proton, an electron and an antineutrino. β^+ decay is similar, but involves a proton changing into a neutron, a positron and a neutrino.
- Gamma decay: After a nucleus undergoes alpha or beta decay, it is often left in an excited state with excess energy. An atomic nucleus loses energy by emitting a gamma ray. Gamma radiation is the most penetrating of the three.

Sources of radiation

Radiation is present all around us. UNSCEAR (United States Scientific Committee on the Effects of Atomic Radiation) suggests that the annual dose of radiation, averaged over the population of the Earth, is around 2.8 mSv in total. (*Sv* is the unit Sievert – it is a measure of health effect of low levels of radiation on the human body). Cosmic rays reaching the earth from outer space are high energy positively charged radiation. Gamma rays from the Earth and radon decay products in the air all contribute to radiation too. The Earth itself is radioactive and all materials in the Earth's crust contain radionuclides. Our bodies also naturally contain some radioactive materials: Carbon-14, Potassium-40 and Polonium-210. People living at considerable altitude may receive annual doses several times higher than those living at sea level. Some protons with lower energies come from the sun and are emitted in bursts during solar flares – this is more prevalent near the equator. X-rays, fallout from testing of nuclear weapons in the atmosphere, discharges of radioactive waste from nuclear fuel industry also contribute to background radiation.

Worldwide natural exposures to radiation would be expected to result in an effective dose to the majority of people in the range of 1-10 mSv per year, with a central value of 2.4 mSv per year. Sizeable population groups are also exposed to annual doses of 20-30 mSv in some areas. Individuals might be exposed to doses several times higher than this, due to exceptionally high background radiation (where mineral sands or radioactive ore bodies occur close to the surface). For example, the population of the city of Ramsar in northern Iran is exposed to doses as high as 260 mSv per year (Ghiassi-nejad et al., 2002).

Radioactive nuclear waste is produced from industrial, scientific and medical processes. The largest quantities of nuclear waste (in terms of radioactivity and volume) are generated by commercial nuclear power reactors industries manufacturing nuclear weapons, followed by mining and refining of uranium and thorium to support these activities. In both commercial and military sectors, some of the radioactive waste is mixed with other hazardous substances (e.g. organic solvents). The major problem we face with respect to nuclear waste is that it will be radioactive for many hundreds of years, and its isolation and disposal must be planned in such a way that future generations are not affected.

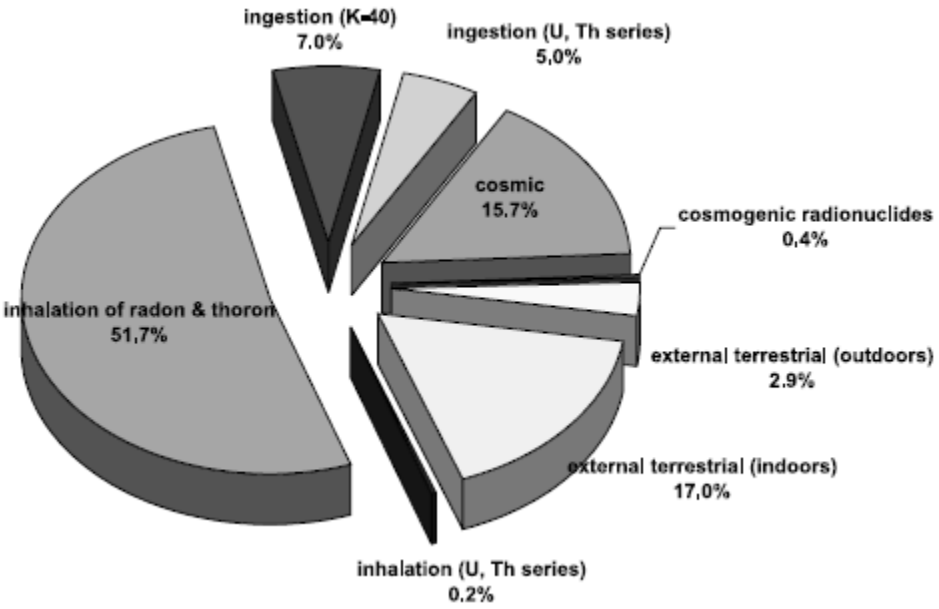

Fig. 1: Individual source proportions of worldwide average exposure to natural radiation of 2.4 mSv per year
Source: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2000 Report

Measures of radioactivity: Half-life

Radioactive decay rate is measured in terms of half-life. The half-life of a radioactive isotope is the time after which, on average, half the original material will have decayed. For example, uranium and plutonium are weakly radioactive but have very long half-lives – in the case of ^{238}U, around 4.5 billion years. ^{131}I has a half-life of about 8 days.

Radioactivity is measured in Becquerel (Bq) units.

$1\ Bq = 1\ disintegration\ per\ second$

$1\ Curie = 3.7 * 10^{10}\ Bq\ (3.7 * 10^{10}\ disintegrations\ per\ second)$

Radioactive decay is described as an exponential decay process. Consider the case of A decaying into B. The number of decay events $-dN$ expected to occur in a small time interval of dt is proportional to the number of atoms present N.

$A \rightarrow B$

$$-\frac{\mathrm{d}N}{\mathrm{d}t} \propto N$$

Different nuclides decay at different rates, so each has its own decay constant λ.

$$-\frac{dN}{dt} = \lambda N$$

The solution to this first order differential equation is:

$$N(t) = N_o e^{-\lambda t}$$

Where N_o is the value of N at *t=0*.

If the number of non-decayed A nuclei is: $N_A = N_{Ao} e^{-\lambda t}$,

Then the number of nuclei of B, i.e., the number of decayed A nuclei will be:

$$N_B = N_{Ao} - N_A = N_{Ao}\left(1 - e^{-\lambda t}\right)$$

To calculate half-life: $N(t) = \frac{N_o}{2}$ and $t=t_{1/2}$

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

Average lifetime of radioactive isotope $\tau = \frac{1}{\lambda}$

Example 1: C-14 is a radioactive isotope of carbon, with a half-life of 5730 years. Find the decay constant λ for C-14.

Solution:

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{5730\ yr * 365\frac{days}{yr} * 24\frac{hr}{day} * 3600\frac{s}{hr}} = 3.84 * 10^{-12}\ s^{-1}$$

Example 2: Co-60 has a half-life of 5.27 years. Find the average life time of each Co-60 atom.

Solution:

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{5.27\ yr} = 0.13\ yr^{-1}$$

Average lifetime $\tau = \frac{1}{\lambda} = \frac{1}{0.13} = 7.7\ yr$

Example 3: The half-life of I-131 is 8.1 days. How long will it take for three-fourths of the sample to decay?

Solution:

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{8.1} = 0.0856\ day^{-1}$$

For three-fourths of the sample to decay:

$$N = \frac{3}{4}N_o$$

$$0.75N_o = N_o e^{-\lambda t}$$

$$\ln 0.75 = -0.288 = -0.0856 * t_{0.75}$$

$$t_{0.75} = 3.36\ days$$

Example 4: After 500 years, a sample of Ra-226 has decayed to 80.4% of its original mass. Find the half-life of this radium isotope.

Solution:

$0.804N_o = N_o e^{-500\lambda}$ since $N = 0.804N_o$ after 500 years

$$\ln 0.804 = -0.218 = -500 * \lambda$$

$\lambda = 4.36 * 10^{-4}\ yr^{-1}$ and therefore $t_{1/2} = \frac{0.693}{4.36*10^{-4}\ yr^{-1}} = 1589.45\ yrs$

Fuel production in nuclear power plants

The first stage is mining for uranium ore.

- Uranium ore mined
- Uranium ore is crushed in a mill
- Crushed ore is ground with water to produce slurry
- Slurry is leached with H_2SO_4 to dissolve uranium oxides leaving behind rock and other dirt
- Liquid with uranium is filtered and dried to produce uranium oxide concentrate (U_3O_8) – bright yellow in colour (or brown colour after drying at high temperatures)
- Uranium oxide concentrate is only mildly radioactive

The second stage is enrichment of the ore.

- Increase amount of U-235 present from 0.7% to 3.5-5%
- Mostly done by centrifuging
- After conversion to U-235, there is little use for the remaining U-238 (“depleted uranium”)

The third stage is the fuel fabrication.

The fuel fabrication process is described in the figure below:

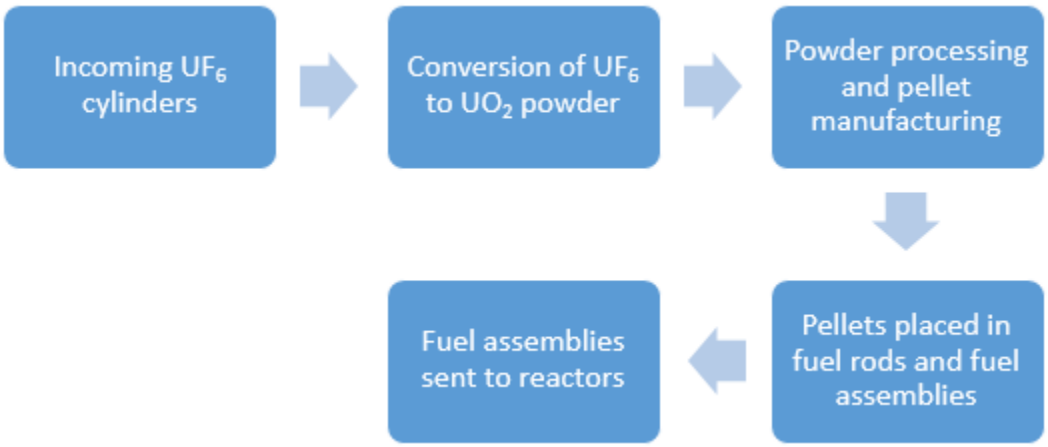

Fig. 2: Fuel fabrication process
Source: www.world-nuclear.org *Nuclear Fuel Fabrication*

In nuclear power plants, the fuel fabrication process usually occurs in these three steps:

1. Producing pure uranium dioxide from uranium ores (UF_6 or UO_3)
2. Manufacturing uranium pellets (accurate shape and sizing – 1 cm in length)
3. Producing the framework for the fuel assembly (using zirconium alloy mainly, 4 metres in length)

Power production in nuclear plants

Energy released from the fission of uranium atoms is utilized in boiling water to make steam, which in turn drives turbine generators. Several hundred fuel assemblies are required to make up the core of the reactor. The control over the process depends on the presence of a moderator and coolant. The moderator slows down the neutrons produced during fission of uranium nuclei, which aids in prolonging the fission reaction. The coolant is present to remove excess heat from the system, and control the temperature as there is some heat generated from radioactive decay even after operations are stopped.

Thorium fuel cycle – Nuclear power production in India

Thorium is more abundant than uranium in the earth's crust. In India, nuclear power is produced using thorium as fuel. One of the disadvantages of using thorium as nuclear fuel is that it contains no natural fissile isotopes – generally, U^{233} or U^{235} is added to achieve critical mass (for the reaction to take place). Also, the residual U^{233} has a very long half-life, which makes its disposal significant.

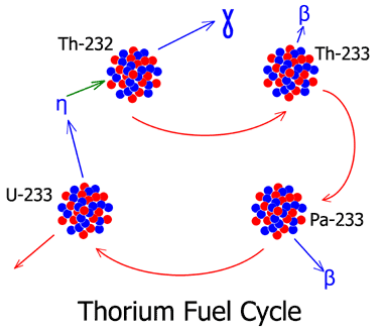

Fig. 3: Thorium fuel cycle (used for nuclear power generation in India)
Source: Nuclear Technology Basics www.neurovoresnetworknews.blogspot.in

Fast Breeder Test Reactor (FBTR) in Kalpakkam

This reactor was constructed by IGCAR and BARC, and is designed to produce 40 MW of thermal power and 13.2 MW of electrical power. The fuel is a mix of plutonium carbide and uranium carbide (found indigenously) and the coolant used in liquid sodium. Some of the residual uranium is placed in the core to aid in further reactions. Fast breeder reactors are called so as they breed more fuel than they consume.

Exposure pathways

Like with other hazardous chemicals, exposure to radioactive material occurs through different means: inhalation, ingestion and direct exposure – with different effects for each of these exposures.

Inhalation

- Occurs when people breathe in radioactive materials
- Sources: contaminated dust, smoke, gaseous nuclides

Ingestion

- Occurs when radioactive materials are swallowed
  - Drinking contaminated radioactive ground water
  - Farming on land with contaminated soil
  - Use of contaminated water for irrigation
  - Consumption of fish from contaminated waters
  - Bathing or swimming in contaminated waters
- Ingested radionuclides expose entire digestive system – can be absorbed by kidneys and other organs, as well as bones

Direct Exposure

- Depends on duration the person is exposed to radiation, distance from source, presence of shielding (for instance, gamma rays can travel long distances and penetrate through the human body)

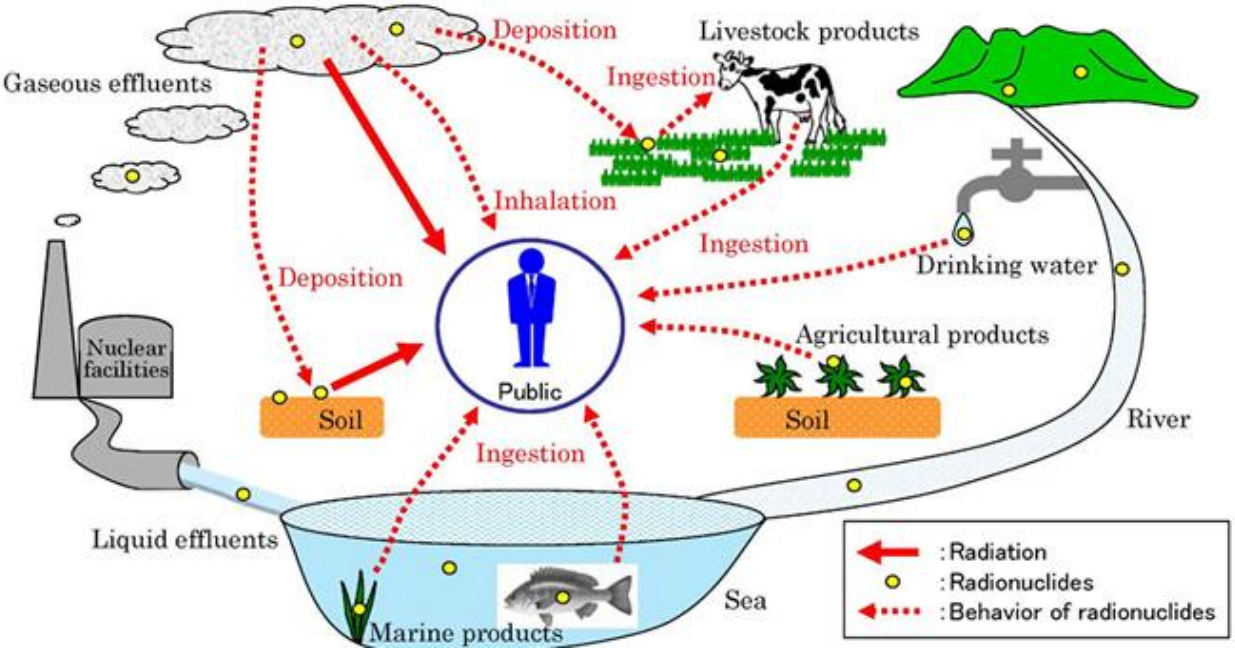

Fig. 4: Radiation exposure pathways
Source: Radiation Safety and Control|Japan www.jaea.go.jp

Health effects of radioactivity

Cancer is considered to be the primary health effect from radiation exposure (evidence from observation). Radiation can damage processes happening at the cellular or molecular level, permitting the uncontrolled growth of cells which leads to cancer. Radiation can also cause changes in DNA (mutations) of exposed populations. These are chronic side-effects. Non-cancerous side effects can manifest burns and "radiation sickness" – which can cause premature aging and even death. If the dose is fatal, death can occur within two months. The symptoms of radiation sickness include nausea, weakness, hair loss, skin burns, diminished organ function.

Radiation dose is measured in *rem*. *Rem* is a unit of radiation dosage, such as from X-rays, applied to humans. It is the dosage in *rads* that will cause the same amount of biological injury as one rad of X-rays or gamma rays. *Rad* is the unit of absorbed dose of ionizing radiation and is equal to the amount of radiation that releases an energy of 100 ergs per grams of matter.

Table 1: Estimated threshold exposures for various non-cancerous side effects

Exposure (rem)	Health Effect	Time to Onset (Without Treatment)
5-10	Changes in blood chemistry	
50	Nausea	Hours
55	Fatigue	
70	Vomitting	
75	Hair loss	2-3 weeks
90	Diarrhea	
100	Hemorrhage	
400	Possible death	Within 2 months
1000	Destruction of intestinal lining, internal bleeding and death	1-2 weeks
2000	Damage to central nervous system, loss of consciousness and death	Minutes/ hours to days

Source: USEPA|Radiation Protection www.epa.gov

Estimating risk from radioactive exposure

Existing data and mathematical calculations are used to estimate quantitatively the risk posed by radioactive materials on exposed populations.

Characteristics of a radionuclide that are important in estimating risk:

- Energy of the radiation emitted
- Half-life of radioactive nuclide
- Biological half-life (rate at which body digests and eliminates the radionuclide)
- Type of cancer that the radionuclide tends to cause

There is much uncertainty involved in estimating risk from exposure to ionizing radiation. There are many challenges such as: developing exposure history, determine which effects are caused by background radiation and which effects due to specific incidents of radiation dosing, determining if radiation exposure causes a particular health effect (by observing different groups of people).

$$Health\ risk\ (R) from\ an\ event = [Probability\ of\ event\ occurring\ (P) * Dose\ that\ would\ result\ from\ event * Probability\ of\ death\ per\ unit\ dose]$$

Radiation protection quantities

- Activity (A): The amount of a radionuclide can be expressed in terms of activity, which is the average number of spontaneous nuclear transformations (decays or disintegrations) taking place per unit time. The unit used is Becquerel (Bq), which is equivalent to one transformation per second.
- Absorbed dose (D): It is the energy imparted by incident ionizing radiation per unit mass. The unit of absorbed energy is Gray (Gy), which is equivalent to one joule per kg.
- Equivalent dose (H): The absorbed dose delivered by a specific type of radiation over a tissue or organ, multiplied by a weighting factor for the type of radiation which reflects the effectiveness of different types of radiation in inducing health effects (alpha radiation having a much higher weighting factor than beta and gamma radiation). The unit used is Sievert (Sv).
- Effective dose (E): The sum of tissue equivalent doses, each multiplied by the appropriate tissue weighting factor which reflects the different sensitivities of different organs and tissues to the induction of stochastic effects of radiation. The highest weighting factors include those for the gonads, bone marrow, lung and stomach, and lowest for skin and bone surface. The unit is Sv.
- Annual effective dose limits (taken from IAEA Basic Safety Standards, 1996):
    - Occupational – averaged over five consecutive years: 20 mSv
    - Occupational – in any single year: 50 mSv
    - Members of the public: 1 mSv

Managing radioactive waste

Mining, nuclear power generation, various processes in industry, defence, medicine and scientific research all produce radioactive discharge – which can be in solid, liquid or gaseous form. The level of radioactivity can also vary.

Usually, efforts to control environmental impacts of wastes have centered on limiting atmospheric and liquid discharges, and to ensure that solid wastes are routed to appropriate landfills or burial sites. These efforts are collectively termed "concentrate and contain". Only recently have standards begun to consider less obvious risks, such as stochastic risks (where the probability of harm rather than severity is governed by exposure), direct risks to future generations, and risks of genetic consequences.

Concerns of countries which generate nuclear power:

- Defining what comprises adequate protection now and in the future
- Developing deep geological disposal solutions for long-lived wastes that offer protection
- Carrying out evaluations of future behaviour of disposal systems that can be accepted with sufficient confidence

A deep geological repository consists of the following:

- The repository: Underground openings for access and waste placement, and the Engineered Barrier System (EBS) – comprising the waste itself and components placed around the waste
- The geosphere: Rock formations in which the repository in constructed, and those surrounding and overlying the host rock formation up to the ground surface
- The biosphere: The near-surface and surface natural environment in which people carry out their everyday activities

It can help to take some suggestions from nature. Direct indications of how radioactive wastes might behave over very long periods of time can be found in natural geological systems such as uranium ore deposits.

Some site-selection guidelines are given below:

- Geological setting should be amenable to characterization, should have geometrical, geomechanical, geochemical and hydrogeological characteristics that inhibit radionuclide transport and allow safe repository construction, operation and closure
- Host rock and repository containment system should not be adversely affected by future dynamic processes of climate change, seismic and volcanic activity, etc.
- Hydrogeological environment should tend to restrict groundwater flow and support waste isolation
- Physicochemical and geochemical characteristics should limit radionuclide releases to the environment
- Surface and underground characteristics should allow optimized infrastructure design in accordance with mining rules
- Site should be located such that waste transport to it does not give rise to unacceptable radiation or environmental impacts
- Land use and ownership in the area of the site should be considered in connection to possible future development and regional planning
- Overall societal impact of developing a repository at the chosen site must be acceptable

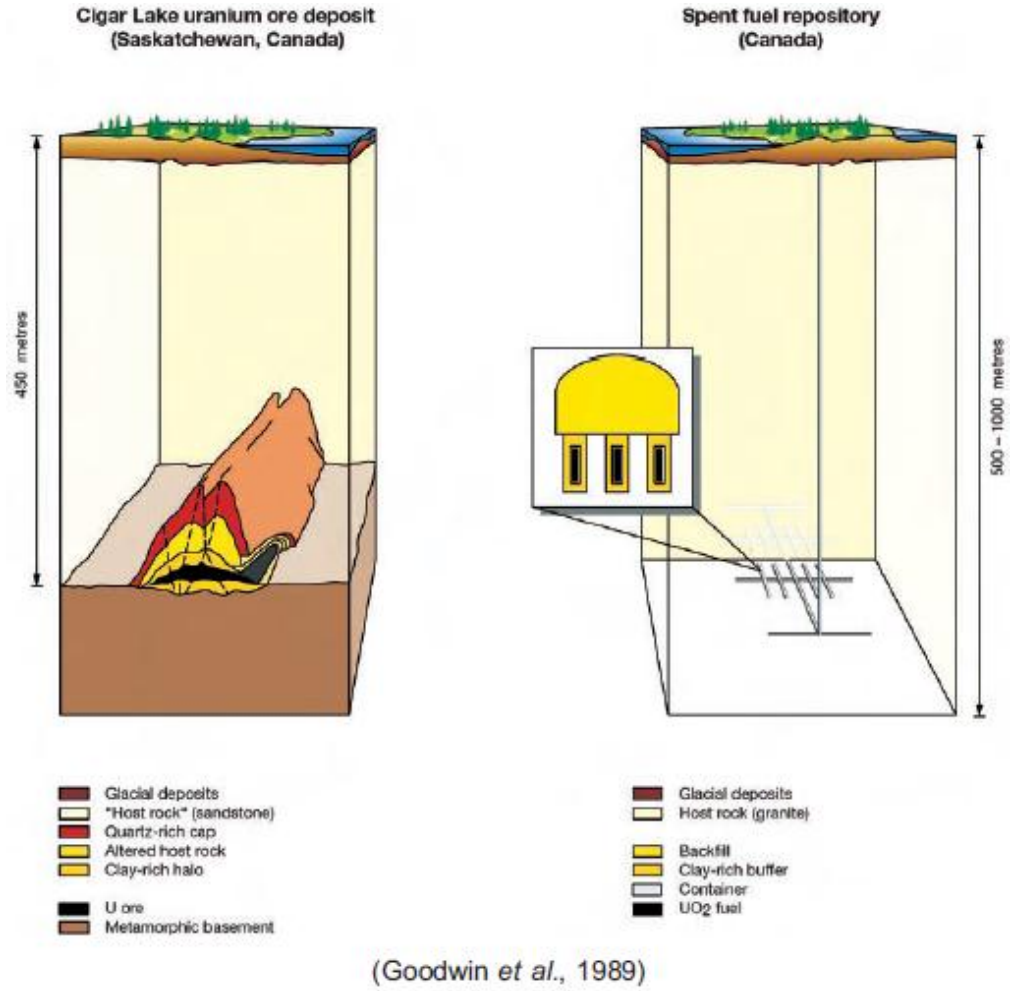

Fig. 5: Comparing deep geological repository with natural ore deposits (Goodwin et al., 1989)

Types of radioactive waste

There are six general categories:

- Exempt waste and very low level radioactive waste
  - Consists mainly of demolished material (concrete, plaster, bricks, metal, valves, piping) produced during dismantling operations at nuclear industrial sites, some waste from chemical and food processing industries
  - Disposed along with domestic waste
- High-level radioactive waste
  - Sources: reprocessing of spent nuclear fuel including liquid waste directly produced and solid material derived from the liquid waste that contains fission products in sufficient concentrations, used fuel itself
  - Short-lived and long-lived radionuclides (wastes from operation of nuclear facilities, materials from production and dismantling of nuclear weapons, construction materials from decommissioned reactors and nuclear plants)
  - Plutonium and americium – elements of concern
- Low-level radioactive waste
  - This is made up of isotopes having shorter half-lives. Radioactivity level is low.
  - Sources: laboratory research, industrial activities, medicine, contaminated protective clothing
  - Does not require shielding during handling and transport
  - Suitable for shallow land burial
  - Storing the waste for a period of 10-50 years will allow most of the radioactive isotopes to decay
- Uranium mill waste from mining and milling industries
  - Fine sandy uranium tailings generated during uranium milling
- Transuranic radioactive waste from manufacture of nuclear weapons
- Naturally occurring radioactive material

Storage and disposal of High Level Waste (HLW)

Used fuel gives rise to HLW – which contains recoverable elements such as uranium and plutonium. If used reactor fuel is not reprocessed, it will still contain highly radioactive isotopes, and in that case, the entire fuel assembly is treated as HLW for direct disposal. The waste generates a lot of heat and requires cooling before disposal. After storage for about 40-50 years, the radioactivity of the used fuel would have fallen. The fuel assemblies are then ready for encapsulation or loading into casks and made ready for permanent disposal underground. HLW from reprocessing must be solidified. In order to ensure that no significant releases occur in the future, a "multiple barrier" geological disposal is necessary. The main barriers are:

- Immobilize waste in an insoluble matrix such as borosilicate glass or synthetic rock
- Seal it inside a corrosion-resistant container – such as stainless steel
- Locate it deep underground in a stable rock structure
- Surround containers with impermeable backfill such as bentonite clay if the repository is wet

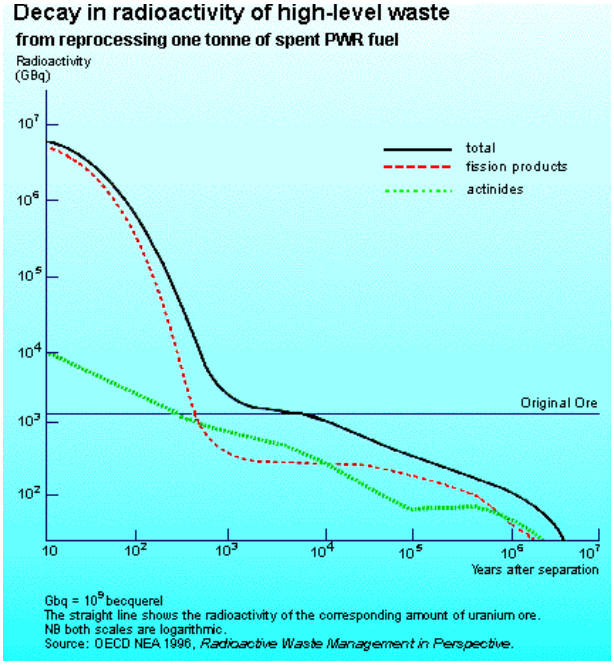

Fig. 6: Decay in radioactivity of HLW with time
Source: www.huntingtonnews.net

Disposal of other radioactive waste

Some Low Level Waste (LLW) from reprocessing plants is discharged to the sea. These include radionuclides which are distinctive, notably technetium-99 (sometimes used as a tracer in environmental studies). Such discharges must be regulated and controlled, and the maximum dose anyone receives from these discharges is a small fraction of natural background radiation. Nuclear power stations and reprocessing plants release small quantities of radioactive gases (e.g. krypton-85 and xenon-133) and trace amounts of iodine-131 into the atmosphere. However, they have short half-lives and do not have large impacts. The US Nuclear Regulatory Commission classifies LLW into four categories based on radioactivity

- Class A
  - Lowest radioactivity level, decays to background level after ~100 years
  - Includes contaminated paper, clothing, rags, mops, equipment, tools
- Classes B and C
  - Decay after 300 and 500 years, respectively

    - Includes filter, resins, irradiated hardware
- Greater than class C
    - Greater radionuclide concentration than classes above

In summary, some of the available means of disposal for radioactive waste are:

- Deep geological repositories
- Ocean dumping
- Seabed burial
- Sub-seabed disposal: These sites are away from deep-sea trenches, mid-oceanic ridges or formation zones where geological activities are high.
- Subductive waste disposal method: Subduction is a process where one tectonic plate slides beneath another and is eventually reabsorbed into the mantle. The subductive waste disposal method forms a high-level radioactive waste repository in a subducting plate, so that the waste will be carried beneath the Earth's crust.
- Transforming radioactive waste to stable non-radioactive waste

Approaches to radioactive waste handling:

- Delay and decay: If the concentrations of radioactive elements are mostly short-lived, they can be released in small amounts over long periods of time.
- Dilute and disperse: This is useful in minimizing the hazard posed to the environment.
- Concentrate and contain: For HLW, radioactive material that has a long half-life, and so on; it is important to make sure that the waste is contained to a space marked for the purpose.

Nuclear power in India

Nuclear power for civil use is well established in India. For instance, the most recently commissioned Koodankulam Nuclear Power Project (KKNPP) in Tamil Nadu is expected start commercial production before September 2014.

Fig. 7: First unit at KKNPP
Source: www.thehindu.com

The Nuclear Power Corporation of India Ltd. (NPCIL) is responsible for design, construction, commissioning and operation of thermal nuclear power plants. India's operating nuclear power reactors are:

Table 2: Operating nuclear power plants in India

Reactor	State	Net MW	Commercial operation
Tarapur 1&2	Maharashtra	150	1969
Kaiga 1&2	Karnataka	202	1999-2000
Kaiga 3&4	Karnataka	202	2007-2012
Kakrapar 1&2	Gujarat	202	1993-95
Madras 1&2	Tamil Nadu	202	1984-86
Narora 1&2	Uttar Pradesh	202	1991-92
Rajasthan 1	Rajasthan	90	1973
Rajasthan 2	Rajasthan	187	1981
Rajasthan 3&4	Rajasthan	202	1999-2000
Rajasthan 5&6	Rajasthan	202	2010
Tarapur 3&4	Maharashtra	490	2005-06
Koodankulam 1	Tamil Nadu	917	2014

Source: World Nuclear Association www.world-nuclear.org

Several nuclear power projects are in the pipeline, in order to combat the growing need to electricity in the country. Radioactive waste management has been an integral part of the entire fuel cycle in India. Low-level radioactive waste and intermediate-level waste arise from operations of reactors and fuel reprocessing facilities. The low-level radioactive waste liquid is retained as sludge after chemical treatment, resulting in decontamination factors ranging from 10 to 1000. Solid radioactive waste is compacted, bailed or incinerated depending upon the nature of the waste. Solar evaporation of liquid waste, reverse osmosis and immobilization using cement matrix are adopted depending on the form of waste. Underground engineered trenches in near-surface disposal facilities are utilized for disposal of solid waste; these disposal sites are

under continuous surveillance and monitoring. High efficiency particulate air (HEPA) filters are used to minimize air-borne radioactivity. Over the past four decades, radioactive waste management facilities have been set up at Trombay, Tarapore, Rawatbhata, Kalpakkam, Narora, Kakrapara, Hyderabad and Jaduguda. Multiple barrier approach is followed in handling solid waste.

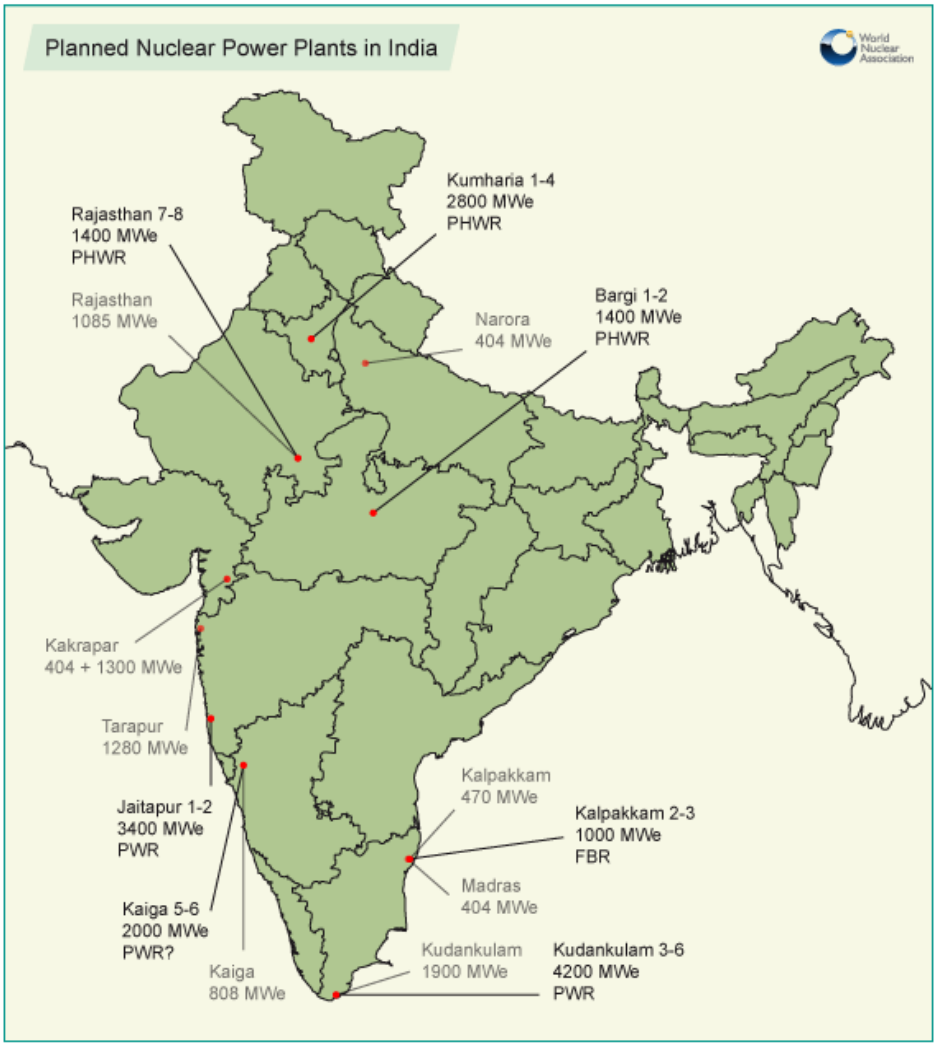

Fig. 8: Planned nuclear power projects in India
Source: World Nuclear Association www.world-nuclear.org

Radioactive wastes from nuclear reactors and reprocessing plants are treated and stored on site. Waste Immobilization Plants (WIPs) are in operation at Tarapur and Trombay, and a vitrification plant was commissioned by BARC at Kalpakkam in 2013 for reprocessing used fuel from the Madras plants. The WIPs use borosilicate glass for disposal of radioactive waste. Research on final disposal of HLW is going on at BARC.

Online resources:

- USEPA – Radiation Protection
  - http://www.epa.gov/radiation/index.html
- World Nuclear Association →Information Library → Nuclear Fuel Cycle → Nuclear Wastes → Radioactive Waste Management
  - http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Nuclear-Wastes/Radioactive-Waste-Management/#
- World Nuclear Association → Information Library → Country Profiles → Countries G-N → India
  - http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/India/

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