Chapter 5

MANAGEMENT OF RADIOACTIVE WASTE

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5.1 INTRODUCTION

During normal operation, nuclear power plants generate two types of waste. High level waste consists primarily of used or spent fuel if a once-through fuel cycle is used, or the left-over materials from reprocessing if a recycling fuel cycle is used. It contains the fission products and the transuranic elements generated by multiple neutron captures. Low level wastes include contaminated equipment, maintenances materials, filters, and ion exchange resins used to purify water for the reactor cooling system. The low level waste is disposed of with other low level waste generated from nuclear medicine applications in hospitals, biological research and industrial applications of radioisotopes.

Less than one percent of the original energy of the mined uranium ore is used after the first discharge of the fuel from a nuclear power plant. This fuel still contains a substantial amount of available energy. This suggests that recycling of the fuel is the advisable long term alternative to the current once-through fuel cycle. In addition, the amount and volume of the waste would be significantly reduced. With the once-through fuel cycle, the Yucca Mountain repository would be filled within two years of its opening. Recycling of the fuel would significantly extend its capacity and usage for many years.

Figure 1. Yucca Mountain civilian nuclear fuel repository.

Figure 2. Yucca Mountain nuclear fuel repository entrance.

Because of their high energy density, nuclear power plants generate relatively small amounts of waste. A 1,000 MWe coal power plant uses 10,000 metric tonnes/day of coal, an oil fired power plant uses 44,000 barrels/day, but a nuclear power plant uses just 10 lbs of U^{235}/day. Such a 1,000 MWe nuclear power plant generates no more than 2-3 m^3/year of high level waste compared with 1,000 metric tonnes/day of ash from a coal power plant of the same power, in addition to its SO_x, NO_x, CO_x, mercury and even radioactive emissions that, because of their large volumes, are disposed of through the process of dilution in the environment.

In the USA spent nuclear from civilian power reactors is stored at 66 sites in 39 states awaiting eventual disposal in a permanent repository.

A proposition was set up to control waste management in the USA in that repositories must be proven to be absolutely and perfectly safe for an arbitrary span of 10,000 years. This conveniently ignores the physical fact that the source of the waste, uranium is itself radioactive in nature with a half life in the billions, not just 10,000 thousand years.

In September 2008, the USA Environmental Protection Agency, EPA revised its standard of a waste repository that for the first 10,000 years possible future residents should not be exposed to more than 15 mrem/year of effective dose, to the effect that from year 10,001 to one million years the effective dose should not exceed 100 mrem/year. According to the EPA, the new standard "will protect public health and the environment for 1 million years." This assumes an ability to predict into the future on the scale of geological ages.

The average American is exposed to 350 mrem/year from sources that range from the human body, food, dwellings, the natural environment and medical x rays. This is 350 / 15 = 23.3 times the EPA's standard. Bananas contain the naturally occurring radioactive isotope K^{40}. Eating 1-2 bananas per day adds the equivalent of a chest x-ray per year. The human body also contains radioactive C^{14} as part of the natural environment.

Ten thousand years is about twice mankind's recorded civilization's history. Within a few hundred, not thousand years, humanity would have redefined itself, speciating new kinds of Homo Sapiens spreading into space and the rest of the universe or would be back to the stone age; if incapable of establishing substitutes for its present fossil sources of energy and having used up its resources and destroyed its environment. In this situation, radioactivity dug out in the form of uranium from some spot on Earth then buried elsewhere in the form of fission products and minor actinides would be the least of its problems. Human civilization started about 10,000 years ago and it must survive other more serious challenges other than the buried waste such as climate change, astral invaders, disease epidemics and population growth.

Canada's more realistic and intelligent solution is to store waste away for 175 years or seven human generations rather than the USA's unrealistic 10,000 years. Over this period new options will come along together with new generations of safer, smaller, smarter and more economical reactors. Regardless, compared with the billions of tons of carbon dioxide causing global environmental change, digging out radiation in one form, then burying it in another form, and the enormous difference in consequences, makes nuclear power the more sensible option.

5.2 WASTE GENERATION

Society in modern time generates waste materials which need to be disposed of in nature without disturbing the ecological equilibrium. Some wastes do not have yet an effective disposal

technique. Most plastic products do not degrade, float on the surface of the oceans and are deposited on distant shores in a layer that would characterize the "plastics age' to some future anthropologists. Mercury, cadmium and arsenic do not decay. Piles of scrap steel, glass, cars, and airplanes rust out at desert junkyards. Many wastes are disposed off through dilution in the environment such as car and fossil power plant exhaust, sewage and waste water. People end up breathing and drinking these diluted discharges including noxious gases and aerosols.

As an example, the nine countries of the European Union alone are producing 1.8 billion metric tonnes of waste per year. This includes 1 billion tonnes of agricultural wastes, 300 million tonnes of sewage waste and waste water, 200 million tonnes of consumer waste, half of which is household waste and the rest scrap metal, old tires and waste oil. The mining industry waste and ash and clinker from coal combustion amount to 200 million tonnes of waste. Industrial waste amounts to 150 million tonnes of which 40 million tonnes are often toxic chemical wastes. This amount of generated waste is growing at a rate of two to three percent per year and poses a serious pollution problem, particularly when the contaminants do not decay.

5.3 POWER GENERATION WASTE

Power generation is associated with substantial waste generation. A typical 1,000 MWe coal fired power plant over its 30 years lifetime uses 60 million tonnes of coal and produces about 15 million tonnes of ash and millions of tonnes of gaseous effluents including the SO_x, NO_x and CO_x gaseous oxides of sulfur, nitrogen and carbon. The ash alone would generate a heap one square kilometer in area and 15 meters high. This ash contains toxic heavy metals including nondegradable cadmium and mercury, and even uranium with its decay products of radon and radium.

In comparison, a 1,000 MWe nuclear power plant and its associated fuel cycle would generate about 2 cubic meters of solidified high level waste and 23,000 cubic meters of low level solid waste, per year. These wastes are not diluted into the environment and remain under control at their special waste repositories. Small amounts of low level radiation are released under controlled conditions from nuclear power plants. This may include tritium resulting from tertiary fission leaking through the condenser tubing to a cooling lake or through the ventilation stack. This released radiation is minimal compared with the natural radiation background. For instance, the radiation exposure to people living in the vicinity of a nuclear power plant due to its radioactive releases is usually less than 5 percent of their exposure to radiation arising from the natural radiation background.

Because of the high energy density of nuclear fuel compared with other fuels, relatively small amounts of wastes are produced per unit of energy produced. The total high level waste generated by one person's energy consumption in a 70 years lifetime would amount to about 210 grams or 0.5 pound in solid form.

If coal is used the annual wastes generated from coal burning are compared to those from a nuclear fuel cycle with reprocessing to satisfy the energy needs for a family of four are shown in Table 1.

Table 1. Comparison of waste generated from coal and nuclear energy for a family of four.

Source	Waste volume [ft^3/year]
Coal burning	

Ash	3.2
Calcium sulfite from scrubber	1.3
Total	4.5
Nuclear Reprocessing	
High level waste	0.0001
Plutonium contaminated waste	0.0020
Total	0.0021

After 300 years the "radioactive hazard measure" or "biological hazard potential" in units of ingestion toxicity per unit of energy produced as [m^3 H_2O / (GWe.year)] through radioactive decay of the fission products wastes is less than for the original uranium ore from which it was extracted.

From a different perspective, our use of fossil fuels represents dissipation in a few hundred years of an accumulation made by nature through the process of photosynthesis over millions of years, while negatively affecting the Earth's climate through global warming and the greenhouse effect. Fossil fuels are the basis of a multiple chemical products such as fertilizers and transportation fuels, whereas uranium can only be used to produce energy. It seems that the storage of radioactive wastes in a few selected and safe sites is the appropriate stewardship option and care of the needs of future life and human generations on Earth.

5.4 PRODUCTS OF THE FISSION PROCESS

In other forms of energy production such as fossil fuels large volumes of wastes are produced in the form of ash and flue gases. The volume of these wastes is so large that they cannot be contained, and the only alternative for their disposal is through dilution of the gases in the atmosphere, and the disposal of solid wastes in landfills or use for road construction.

Nuclear power systems, in contrast are closed systems that contain the fission products in the spent fuel without dilution in the atmosphere. The wastes from nuclear power production never become diluted and spread over large land areas. The nuclear fuel automatically contains the fission products, since these products cannot move more than a millimeter and have to stay within the fuel.

Other than containment, another characteristic of nuclear fuel is its high energy density, and consequently its generation of small amounts of fission products compared with other energy sources. This makes it possible to ultimately dispose of these small amounts of fission products in geological formations where the original fuel was mined from in the first place. The fuel rods contain initially a mixture of the uranium isotopes U^{238} and small amount of U^{235} and a smaller amount of U^{234}. The spent fuel contains primarily U^{238} and U^{235} that have not fissionned, the fission products of those U^{235} nuclei that have fissionned, and a small amount of transuranics such as Pu^{239} and Np^{237} resulting from neutrons capture in U^{238}.

The amount of fission products produced from a nuclear power plant can be calculated as follows. For a reactor operating at a power of P thermal megawatts MWth, and assuming a recoverable energy per fission event of 190 [MeV/fission], ignoring the unrecoverable 10 MeV of energy carried out by the antineutrinos, one can write for the fission rate:

$$\frac{dF}{dt} = P\,[MWth]\ .10^6[\frac{Watt}{MWth}][\frac{(Joules/sec)}{Watt}].\frac{1}{190}[\frac{fission}{MeV}].\frac{1}{1.6\ x\ 10^{-13}}[\frac{MeV}{Joule}].86,400[\frac{sec}{day}]$$

$$= 2.84 \times 10^{21}\ P\,[\frac{fissions}{day}] \tag{1}$$

Using Avogadro's law we can express the number of fissions N in g grams of U^{235}:

$$N = \frac{g\ A_v}{M} \tag{2}$$

where A_v is Avogadro's number,

M is the molecular weight of U^{235} = 235 amu,

g is the mass in grams,

we can convert the fission rate into the "burnup rate" where:

$$burnup\ rate= \frac{dF}{dt}.\frac{g}{N}$$

$$= 2.84 \times 10^{21}\ P[\frac{fissions}{day}].\frac{M}{A_v}\ [\frac{gm}{fissions}]$$

$$= 2.84 \times 10^{21}\ P\frac{235}{0.6x10^{24}} \tag{3}$$

$$= 1.112\ P\,[\frac{gm}{day}]$$

EXAMPLE

Let us consider a nuclear power plant having a typical power of 1,000 MW(e) operating around the clock without interruption at a capacity factor CF of unity for a whole year. The thermal produced by this plant if its thermal efficiency is 1/3 becomes:

$$P[MWth] = \frac{P[MWe]}{\eta_{th}}.CF$$

$$= \frac{1,000}{1/3}.1 \tag{4}$$

$$= 3,000[MWth]$$

Thus, a reactor operating at a power of 1,000 MWe or 3,000 MWth, will have a U^{235} burnup rate of about:

$$burnup\ rate = 1.112P$$
$$= 1.112 \times 3,000 \qquad\qquad (5)$$
$$= 3,336\ [\frac{gm}{day}]$$

This means that such a plant produces just 3.3 kgs/day of fission products, or 3.3 x 365 = 1,204 kgs/yr. This small amount of about 1 metric ton of fission products generated per year is approximately equal to the weight of a compact car. This is the amount to be stored if fuel is recycled like in Europe and Japan. If the fuel is stored whole without reprocessing like in the once-through fuel cycle in the USA, the amount becomes ten times this amount. A typical 1,000 MWe nuclear power plant produces about 30 metric tonnes of spent fuel per year.

This small amount of waste generated by a nuclear power plant is characteristic of nuclear processes with their high energy density, where 1 pound of uranium the size of a golf ball has the same energy potential as nearly 30,000,000 pounds of coal which is about 25 railroad cars full of coal. This interesting fact can be glanced from Table 2 showing the annual fuel requirements of a 1,000 MWe plant operating at 75 percent of capacity.

Table 2. Annual fuel requirements of a 1,000 MWe power plant operating at 75 percent capacity.

Fuel	Amount
Uranium	30 metric tonnes
Coal	2.1 million metric tonnes
Residual fuel oil	10 million barrels
Natural gas	64 billion cubic feet
Solar cells	25,000 acres
Municipal waste	6.2 million metric tonnes

The composition of spent fuel in terms of the main fission products and transuranics is shown in Table 3. The fission products are primarily beta and gamma emitters, whereas the transuranics are primarily alpha particle emitters.

If the fuel is reprocessed, 1,000 kgs of spent uranium fuel yields 5,000 liters of high level liquid waste. Upon evaporation this can be reduced to 1,100 liters which can be initially stored in stainless steel tanks. Upon settlement, 380 liters or 100 gallons are left as solid waste that can be further isolated through drying and calcinations or vitrification in a glass matrix.

A 1,000 MWe electric plant would produce 5-7 metric tonnes of solidified high level wastes corresponding to 1.8-2.5 cubic meters per year. This can be isolated in 10-12 vitrified solid canisters each of a volume of 0.2 m^3.

Table 3. Composition of spent nuclear fuel in terms of fission products and transuranics.

Radioactive species	Half life (years)	Radiation type
Main fission products		
Strontium^{90}	28	β
Technetium^{99}	2.1×10^5	β
Cesium^{137}	30	β,γ

Main transuranics		
Pu^{238}	89	α. SF
Pu^{239}	2.4x10^4	α, SF
Pu^{240}	6.6x10^3	α, n, SF
Am^{241}	460	α, SF
Am^{243}	8.0x10^3	α
Curium^{244}	18	α, n, SF

5.5 FATE OF THE FISSION PRODUCTS AND TRANSURANICS

The decay of the fission products is shown in Fig. 3 in terms of activity per unit of energy produced in [Curies / (Gwe.year)]. In less than a thousand years these relatively small amounts decay back to the same level of activity as the original uranium ore from which they have been obtained in the first place. The transuranics take longer to decay depending on the different fuel cycles used:
1. The once-through cycle light water reactors (LWRs) cycle adopted by the USA leads to the highest level of residual activity.
2. The LWR cycle with reprocessing and uranium and plutonium recycle adopted by the European countries and Japan leads to a lower level of residual activity than the once-through fuel cycle and is associated with a more efficient use of the nuclear fuel resource.
3. The future implementation of the liquid metal fast breeder reactor (LMFBR) or adoption of the Th^{232}-U^{233} fuel cycle would lead to a lower residual activity and the best usage of the fuel resource.

Even the transuranics decay to the form from which they were initially generated. For instance a not so well known fact is that Pu^{239} which is produced by neutron capture in U^{238}:

$$_0n^1 + {}_{92}U^{238} \rightarrow {}_{92}U^{239}$$
$$_{92}U^{239} \rightarrow {}_{-1}e^0 + {}_{93}Np^{239} \qquad (6)$$
$$_{93}Np^{239} \rightarrow {}_{-1}e^0 + {}_{94}Pu^{239}$$

is an alpha emitter, which decays over time to none other than the other isotope of Uranium^{235} according to the reaction:

$$_{94}Pu^{239} \rightarrow {}_2He^4 + {}_{92}U^{235} \qquad (7)$$

By adding Eqns. 6 and 7, we obtain the very little known fact that nuclear reactors convert the uranium isotope U^{238} into the isotope U^{235}, releasing two electrons and a helium nucleus as well as usable energy in the process:
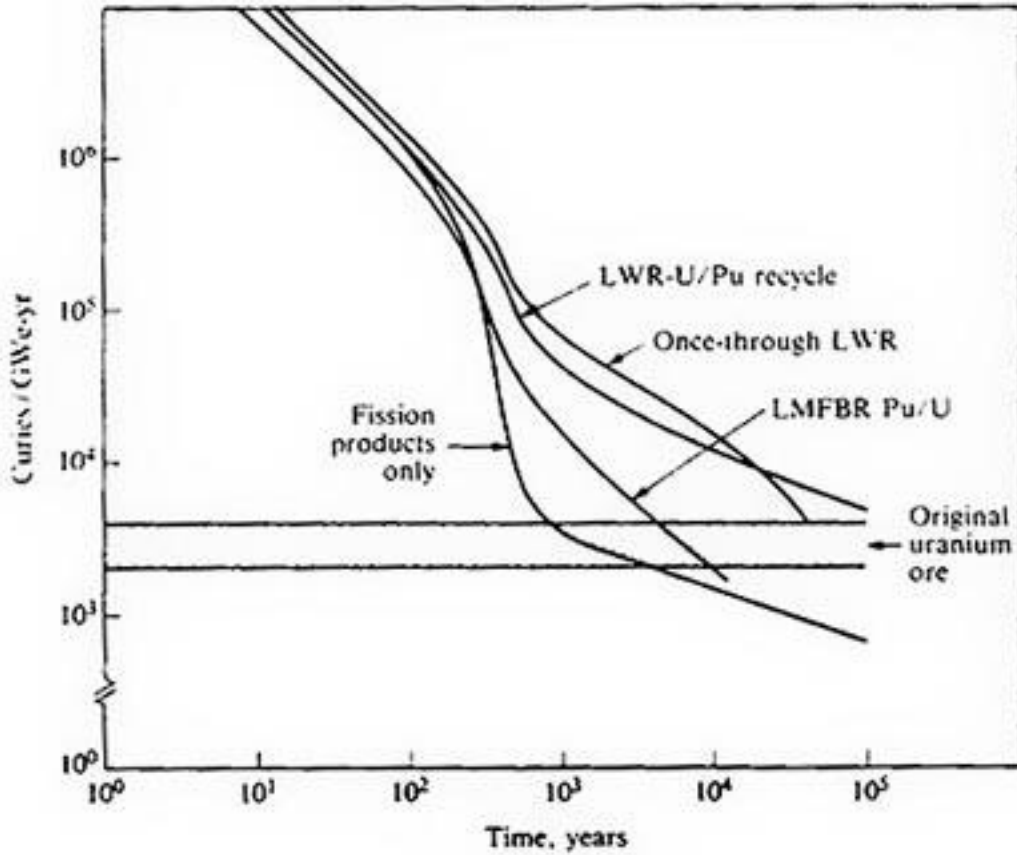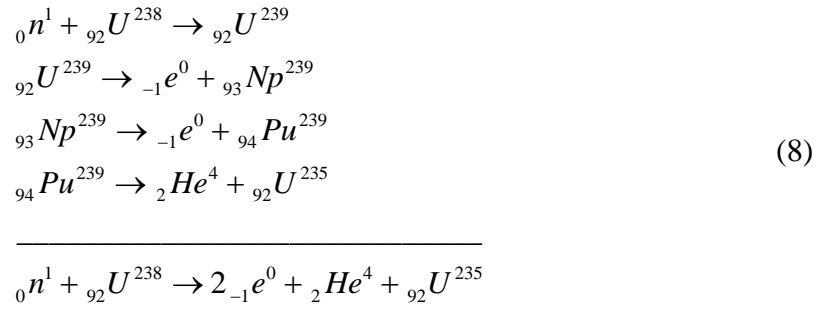
$$_0n^1 + {}_{92}U^{238} \rightarrow {}_{92}U^{239}$$

$$_{92}U^{239} \rightarrow {}_{-1}e^0 + {}_{93}Np^{239}$$

$$_{93}Np^{239} \rightarrow {}_{-1}e^0 + {}_{94}Pu^{239} \tag{8}$$

$$_{94}Pu^{239} \rightarrow {}_{2}He^4 + {}_{92}U^{235}$$

$$\overline{\qquad\qquad\qquad\qquad\qquad\qquad}$$

$$_0n^1 + {}_{92}U^{238} \rightarrow 2\,_{-1}e^0 + {}_{2}He^4 + {}_{92}U^{235}$$

Figure 3. Fission products and transuranics decay in different nuclear fuel cycles.
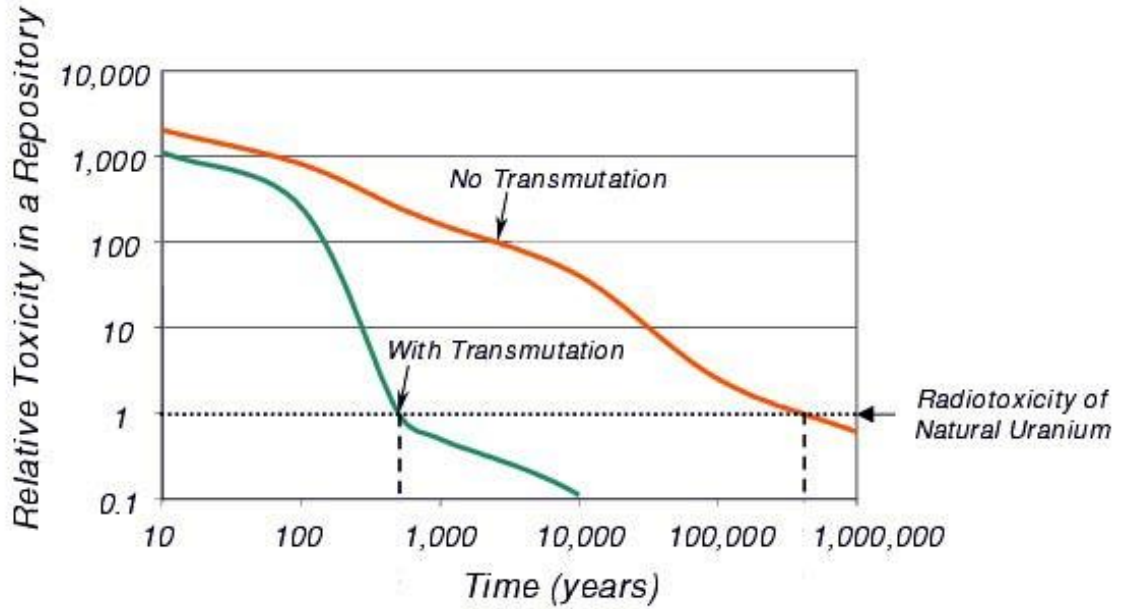
Figure 4. Decay of power production waste as a function of time.

The U^{239}, Np^{239} and Pu^{239} isotopes are nothing but catalysts, since they take part in the process but do not appear as final products in the overall reaction.

Thus the nuclear fuel is extracted from a geological formation as U^{238} and is returned back for long term geological disposal, in the form of U^{235} that is close to what was extracted from the ground as U^{238} in the first place.

5.6 RADIATION EXPOSURE

The protection of the public against potential radiation exposure is the overriding concern in radioactive waste disposal. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was established in 1955 as a result of international concern about the effects of fallout from atmospheric testing of nuclear explosions. It studies and disseminates information on observed levels of ionizing radiation and radioactivity whether natural or man made in the environment and on the effects of this radiation on man and his surroundings. According to the UNSCEAR: "Surface and deep burial of solid wastes carried out under control at suitable sites is expected to give rise to no significant public exposure."

TERRESTRIAL   INTERNAL   COSMIC   NATURAL SOURCES

THERAPY

DIAGNOSIS   RADIOLOGY

NUCLEAR MEDICINE

FALL-OUT

WASTE DISPOSAL

NUCLEAR POWER PRODUCTION [1 kW(s) PER PERSON]

OCCUPATIONAL

OTHER OCCUPATIONAL EXPOSURES

CONSUMER GOODS &c

0   20   40   60   80   100   120
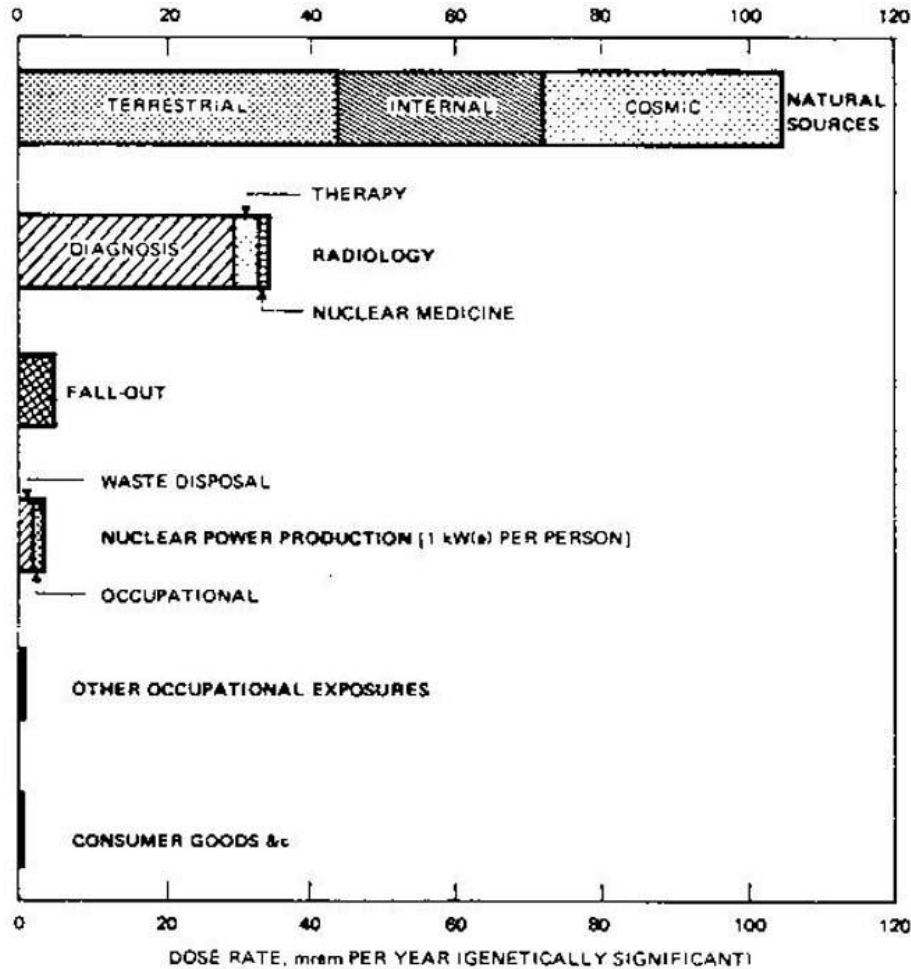
DOSE RATE, mrem PER YEAR (GENETICALLY SIGNIFICANT)

Figure 5. Per capita yearly effective dose from different sources of radiation. Source: IAEA.

At the request of USA's President Jimmy Carter in 1977, 66 countries and 5 international organizations participated in an international evaluation of the technical and analytical aspects of the nuclear fuel cycle. One of the eight working groups concerned itself with waste management and disposal problem in a study that lasted two years. The International Nuclear Cycle Evaluation (INFCE) concluded that: "Employing technology as assumed, the radioactive wastes from any of the fuel cycles studied can be managed and disposed of with a high degree of safety and without undue risk to man or the environment. Figure 5 shows that in fact the contribution of the exposure from radioactive waste is itself a small fraction of the exposure due to natural radiation sources.

5.7 CLASSIFICATION OF NUCLEAR WASTE

Radioactive wastes are generally classified into four major categories:

1.   **High level waste**:

Consists of spent nuclear reactor fuel, and waste from fuel reprocessing plants containing the bulk of the fission products. The main isotopes of concern here are Sr^{90} and Cs^{137} with a half

life of about 30 years. They also contain Zr^{93}, I^{129} and Cs^{135} with half lives larger than a million years. Cesium^{137} decays into Ba^{137} and Sr^{90} decays into Y^{90} and then with a half life of 64 hours into Zr^{90}.

2.   **Transuranic (TRU) waste**:

This is in the USA Department of Energy and Department of Defense generated waste. It contains isotopes of plutonium such as Pu^{239} with a half life of about 24,000 years, with a specific activity concentration larger than 10^{-9} [Ci/gm].

3.   **Low Level Radioactive Waste (LLRW):**

Contains a specific activity concentration of less than 10^{-9} [Ci/gm] of TRU nuclides or materials that are free of TRUs but still radioactive. Based on the national average, three classes of LLRW are identified:
Class A: 97% of total.
Class B: 2% of total.
Class C:1% of total.

4.   **Uranium and Thorium Mine and Mill Tailings**:

These are residues from thorium and uranium mining and milling. These contain primarily the isotope Radon^{222} of 3.8 days half life, a member of the U^{238} decay chain. They also contain the isotope Pb^{210} with a half life of 19.4 years. When disposed of, these wastes must be covered with at least 3 m of earth.

Table 4. Long lived radionuclides used to classify radioactive wastes.

Radionuclide	Activity density concentration [Curies/m^3]
Carbon^{14}	8
Carbon^{14} in activated metal	80
Nickel^{59} in activated metal	220
Niobium^{94} in activated metal	0.2
Technetium^{99}	3
Iodine^{129}	0.08
Alpha emitting transuranic nuclides with T_1 years	100

The Code of Federal Regulations (CFR) classifies LLRW waste according to its content in long-lived radionuclides such as shown in Table 4.
The following four classes of waste are defined by the CFR:

1.   **Class A wastes**:

Includes materials containing nuclides with an activity demsity concentrations less than 0.1 [Ci/m^3] in Table IV. These must be segregated from other classes at the disposal site.

2.   **Class B wastes**:

Are these wastes that meet requirements to ensure *stability* after disposal.

3.   **Class C wastes**:

Includes materials containing nuclides with an activity density concentrations more than 0.1 [Ci/m^3] in Table 4. These require stability plus measures at the disposal facility against inadvertent intrusion.

4.   Waste that is not acceptable for near-surface disposal.

5.8 WASTE MANAGEMENT PRINCIPLES

Tree general principles govern the process of management of radioactive wastes:

1. **Dilute and disperse**:

Applies to wastes to environment in effluents containing radionuclides in amounts below the authorized radiological limits. These have been set by the International Commission for Radiological Protection (ICRP).

2. **Delay and decay:**

Applies to those wastes which contain only short-lived radionuclides.

3. **Concentrate and confine**:

Used for those wastes which contain significant amounts of long-lived radionuclides.

The management of low and medium level wastes is now a routine industrial operation. They are disposed of in shallow ground and rock cavity repositories.

In the case of high level wastes there exists a great deal of experience in storing and handling them. This started in the USA during World War II as part of the nuclear weapons and defense program. The USA weapons program generated 0.2 million cubic meters in equivalent solidified volume of high level waste or 700 times more than the 300 cubic meters from commercial nuclear power plants. Civilian reactor waste in the USA reached just 10 percent of volume of the military waste by 2000. To place the matter in perspective a typical 1,000 MWe nuclear power plant produces just 30 metric tonnes of spent fuel per year.

By reprocessing this fuel, high level waste is separated and concentrated, reducing the amounts to be disposed of. In fact, the technology for storage of high level waste both liquid and solid is available and demonstrated. In France the vitrification process of high level waste from a 1,000 MWe nuclear power plant produces just 2 cubic meters of high level waste per year. In addition it is a better use of resources, since the unburned fuel in the fuel elements in the form of

fissile nuclides is used instead of being disposed of. Moreover, the transuranics formed are also separated to be burnt producing energy instead of being stored for a long period of time. These can be reloaded as fuel to reactors with a fast neutron spectrum to produce energy and be transmuted to shorter lived fission products, in the process saving significantly on the waste volume.

A single large reprocessing plant could service from 30 to 50 commercial nuclear power plants of 1,000 MWe each. There exists two large commercial reprocessing plants in the world, one at Sellafield , UK, and another at La Hague, France.

In France, all the high level waste produced between the years 1974 and 2000, with 20 nuclear power plants in operation in 1980, in solid form make up no more than the volume of a standard Olympic size swimming pool.

Figure 6. PWR fuel assembly.
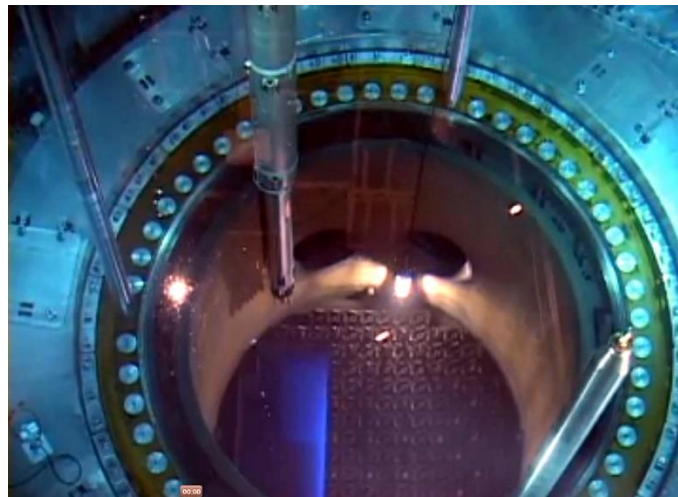
Figure 7. Refueling the Callaway PWR reactor core. Source: Ameren.
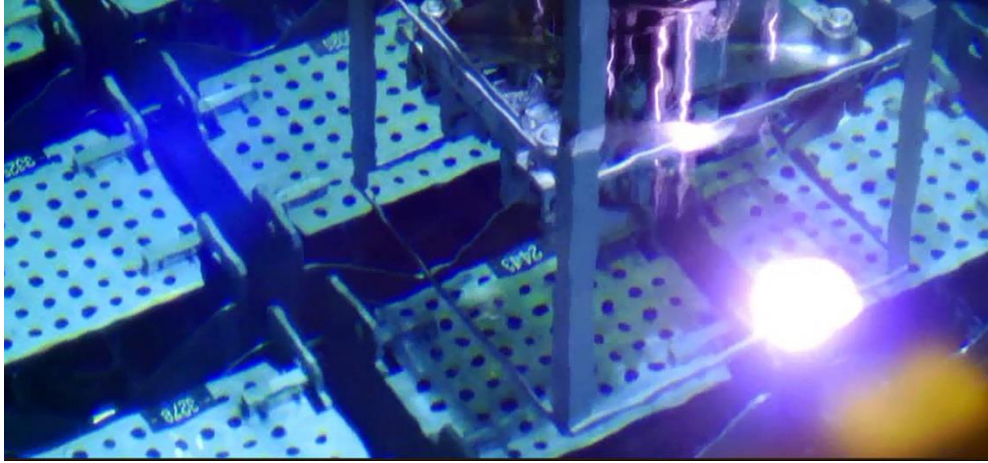
Figure 8. Spent fuel in fuel storage pool.

Figure 9. Fuel element storage if fuel storage pool.
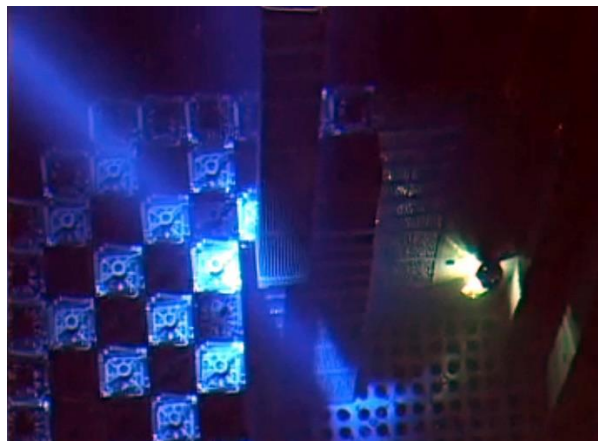
Figure 10. Fuel element storage in Callaway plant fuel pool. Source: Ameren.
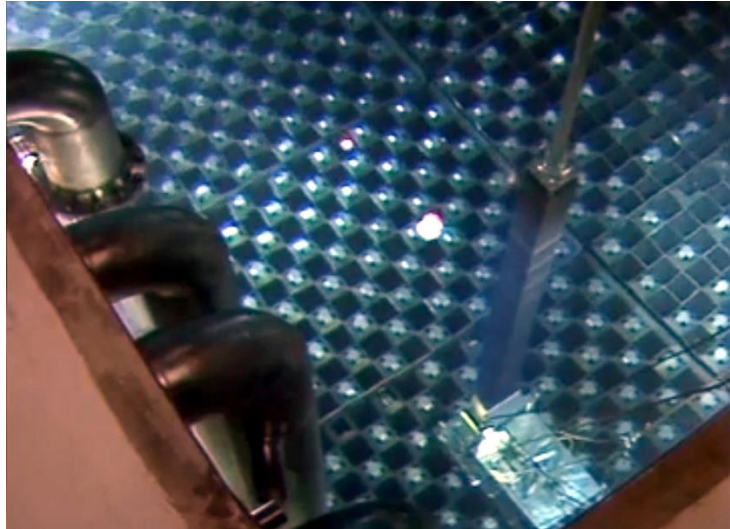
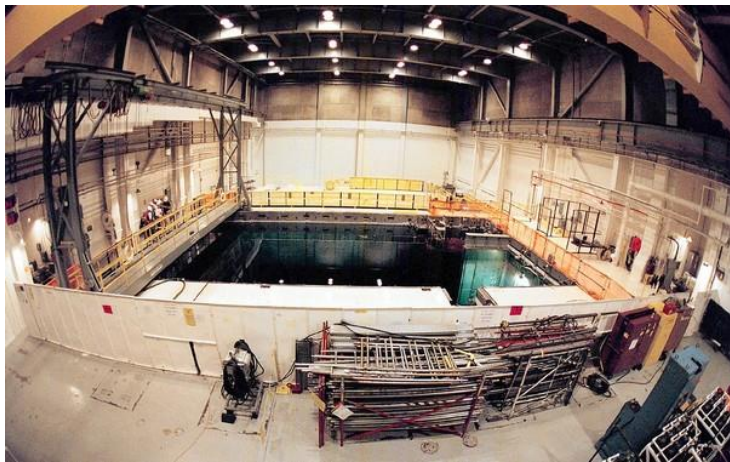Figure 11. Fuel element in water storage pool.

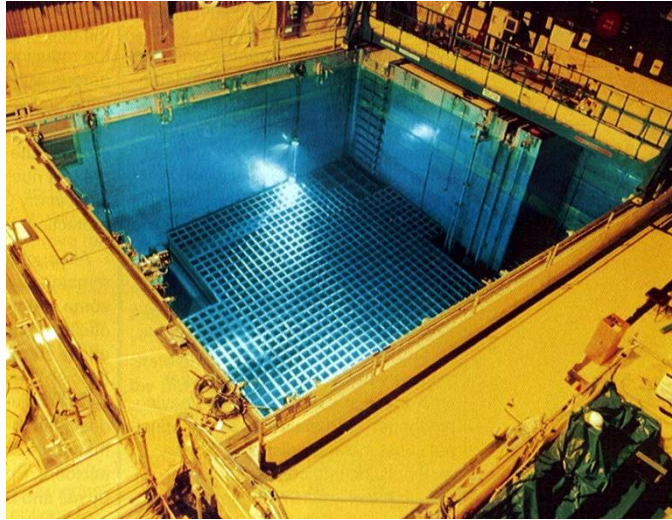Figure 12. Fuel storage pool of Zion plant. Source: Chicago Tribune.

Figure 13. Spent fuel water storage pool at a reactor facility.

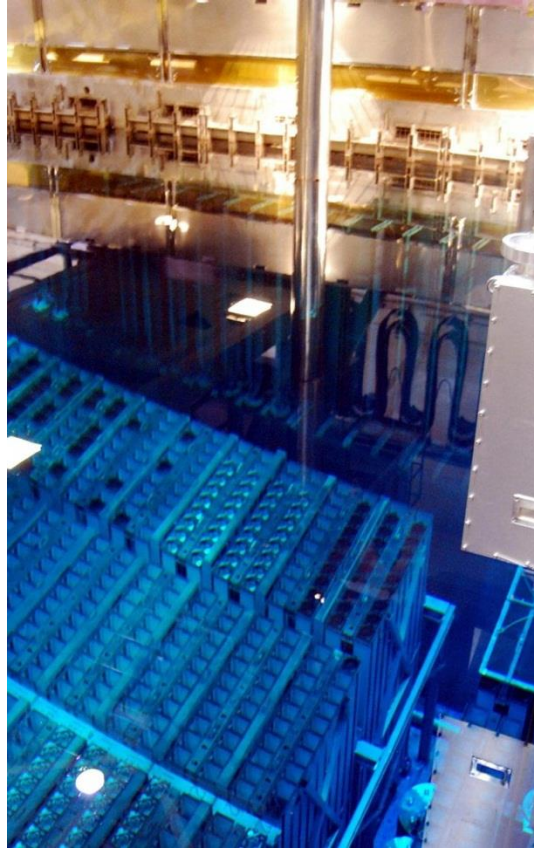Figure 14. Fuel storage pool at reactor compound, France.
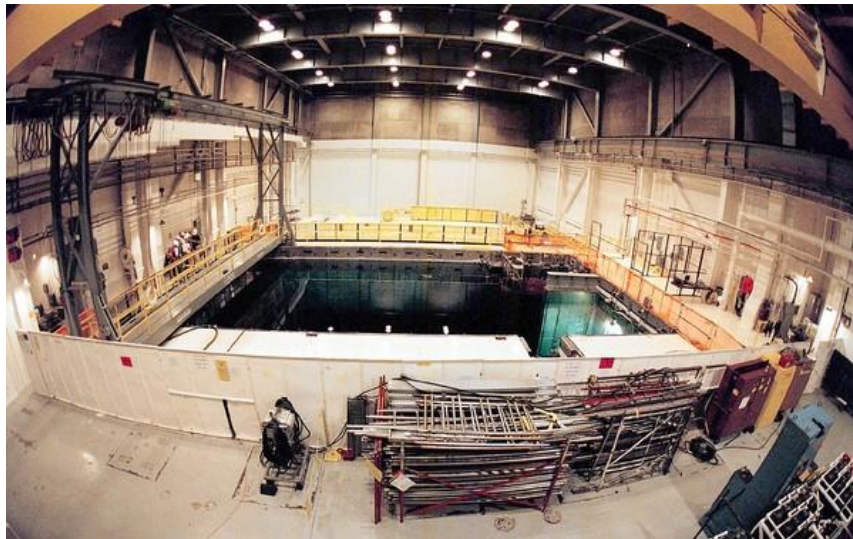
Figure 15. Cooling equipment and insertion of fuel assembly into the fuel rack.

Figure 16. Fuel storage pool at the Zion plant, Illinois, USA.

5.9 SPENT FUEL

Most of the highly spent fuel at nuclear power plants after usage in the USA is stored in specially designed water pools at the reactor sites. They are left there temporarily to allow their radioactivity to appreciably decay before being shipped out for either recycling in many nations or for permanent disposal like in the USA, where it is expected to be shipped whence to a high-level Federal facility is available for permanent disposal. Such a fuel storage pool at a reactor site is shown in Fig. 16.

At nuclear power reactor sites around the USA, 40,000 tons of spent fuel are placed in fuel storage pools cooling off its radioactive emissions, awaiting permanent disposal. The fuel is positioned within racks containing Boral which is an aluminum alloy with interspersed boron carbide (B_4C) particles. This ensures that the fuel in the pool, even with the presence of water will not reach a critical condition.

Whereas the reactors themselves are surrounded by protective containment structures of 4 feet thick reinforced concrete, the storage pools are enclosed by corrugated metal structures. It has been surmised that an accidental drainage of the water in the pools, by natural or man-made events, could lead to melting of the stored fuel with a subsequent fire that could release the radioactive fission products in the fuel. This release of radioactivity could contaminate, in a worst-case scenario, about 188 square miles, as reported by a 1997 study by Brookhaven National Laboratory. Reactor sites were not envisioned in the first place as permanent fuel storage sites, so this should be regarded as just a temporary measure.

5.10 DISPOSAL OF WASTES

While the front end of the nuclear fuel cycle is mining of uranium from geological formations, the back end is the permanent storage of these wastes in geological formations. The following storage options have been considered at one time or the other in different countries around the globe:

1. Storage in geological formations such as:
    a) Salt beds
    b) Limestone
    c) Granite
    d) Shale
    e) Volcanic tuff.
2. Seabed geological disposal
3. Polar ice sheet disposal
4. Extraterrestrial disposal:
    a) Very high Earth orbit
    b) Solar orbit
    c) Solar impact
    d) Escape from solar system.

Economical and safety considerations have favored so far in the USA the terrestrial disposal in volcanic tuff at the Yucca mountain site in the USA.
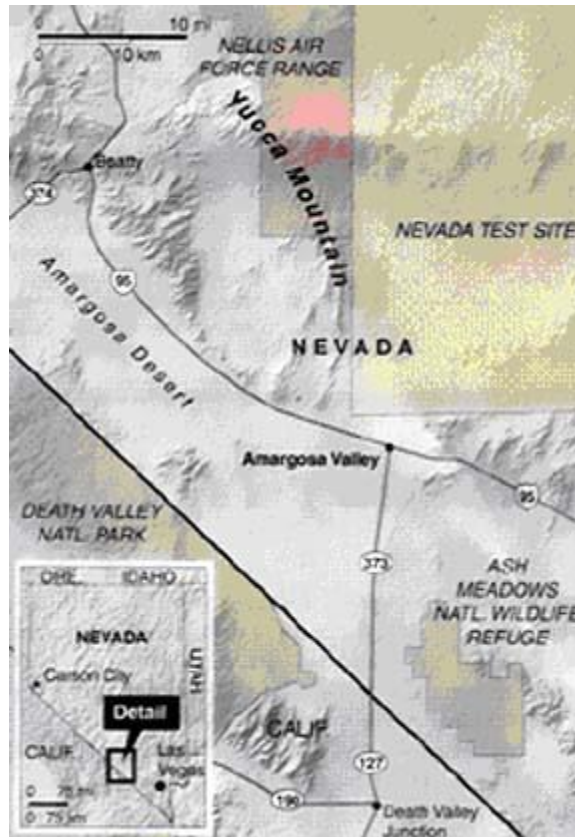
Figure 17. Location of the Nuclear Waste disposal site at Yucca Mountain, Nevada.

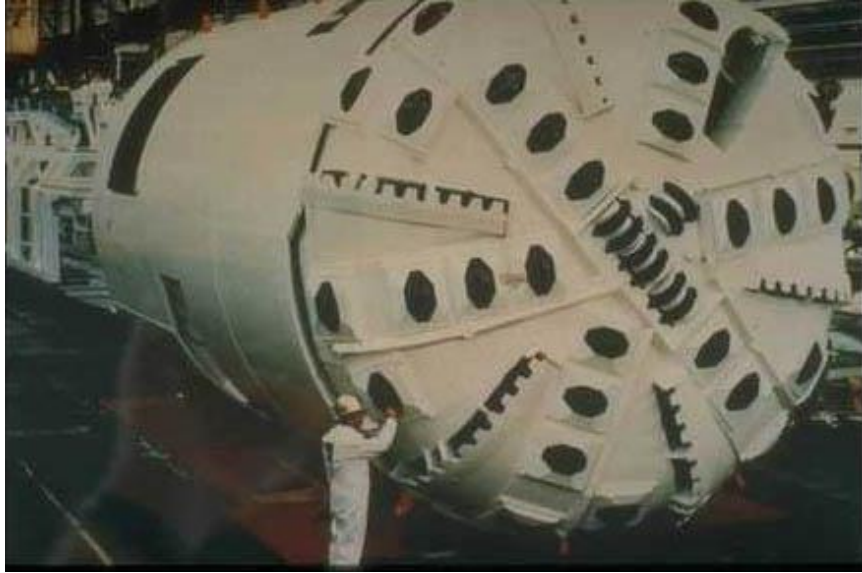Figure 18. Entrance of the Nuclear Waste disposal site at Yucca Mountain, Nevada.

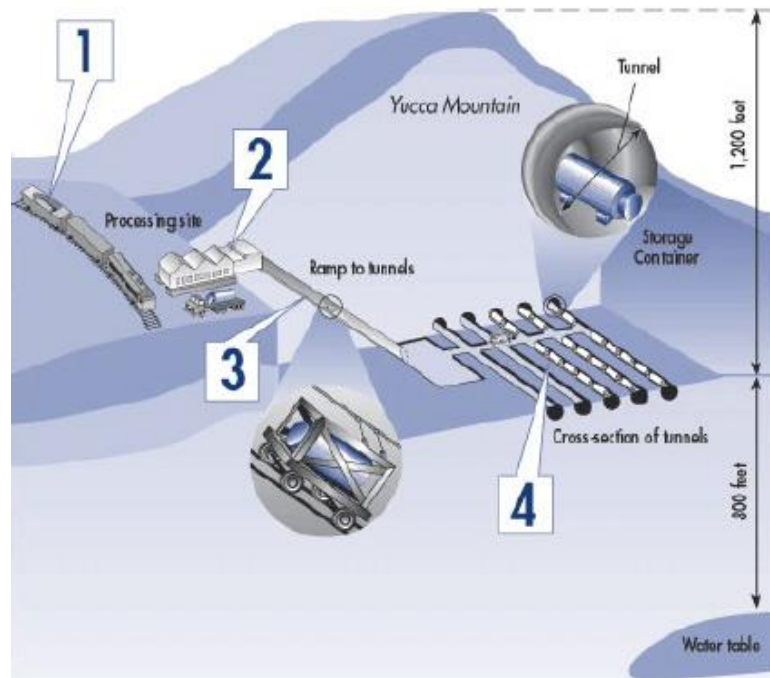Figure 19. Tunnel boring machine at the Yucca Mountain disposal site.

Figure 20. Storage scheme in the Yucca mountain storage facility. 1: Canisters of waste sealed in special casks are shipped to the site by truck or train. 2: Shipping casks are removed and the inner tube with the waste is placed in a steel multilayered container. 3: An automated system sends storage containers underground to the tunnels. 4: Containers are stored along the tunnels, either on their side as shown here, or standing upright in holes. Source: Nuclear Regulatory Commission, NRC.

5.11 YUCCA MOUNTAIN DISPOSAL SITE

A common-sense alternative has been scientifically and technically studied for many years at an expense of 7 billion dollars. A study completed in May of 2001 concluded that nuclear fuel could be safely stored at the barren Yucca Mountain in the Mojave desert, shown in Figs. 17 and 18, about 80 miles northwest of Las Vegas, in the Nevada desert. The spent fuel would be safely stored there 1,400 feet under the 4,950 feet high mountain in volcanic tuff deposits. Over a period of ten thousand years the radioactivity in the fuel would be reduced to the same level as the uranium ore that was mined to manufacture the fuel in the first place.

The USA secretary of energy declared the site as "scientifically sound and suitable" as a repository for spent reactor fuel stored at commercial reactors sites in 31 states and also for nuclear waste generated from the government's nuclear weapons program.

Numerous state governors, labor, business and policy groups support the use of the site. On the other hand, the State of Nevada politicians fought the project and sued the USA's department of energy challenging its criteria for choosing the site. Some anti-nuclear groups also fought the project because they see it as a way to block nuclear power.

The USA energy secretary, in notifying the governor of Nevada of the decision cited "sound science and compelling national interest," as well as growing concerns about the storage of nuclear materials at the distributed reactor sites that need to be consolidated at a central site.

The 11,000 containers at the proposed Yucca Mountain nuclear waste storage facility require 33 million pounds of molybdenum for corrosion resistance. The inner container would be made of Type 316L stainless steel with 2.2 percent Mo, and nickel-base Alloy 22 with 13.5 percent Mo for the outer container.

Based on political considerations, President Barack Obama's administration withdrew funding for the project and set up a "Blue Ribbon Panel" to study the alternatives at the request of Senator Reed from the state of Nevada.

5.12 LOW LEVEL RADIOACTIVE WASTE (LLRW)

Low Level Radioactive Waste (LLRW} is material which has been contaminated by or contains short-lived radio nuclides or longer-lived radio nuclides in relatively low concentrations. In the USA, LLRW is defined by law by what it is not. It is not supposed to be:

1. Spent fuel from nuclear reactors,
2. High-Level waste,
3. Transuranic waste,
4. Uranium or thorium mill tailings,
5. Naturally Occurring Radioactive Material (NORM).

Many societal activities could generate LLRW. These include:

1. Nuclear power plant operations,
2. Diagnostic and nuclear medicine applications,
3. Industrial processes and activities,
4. Academic institutions and research,
5. Governmental applications,
6. State agencies with radioactive material,

7. Military installations.

The distribution by volume and by activity of LLRW generated by these sources is shown in Table 5.

Three operating LLRW facilities exist in the USA:

1. The USA Ecology Facility in Richland, Washington.
2. The Envirocare Facility in Clive, Utah.
3. The Chem-Nuclear Facility in Barnwell, South Carolina.

The disposal of LLRW can be done either in engineered trenches below ground level as in Fig. 21, or in above surface facilities as shown in Fig. 22.
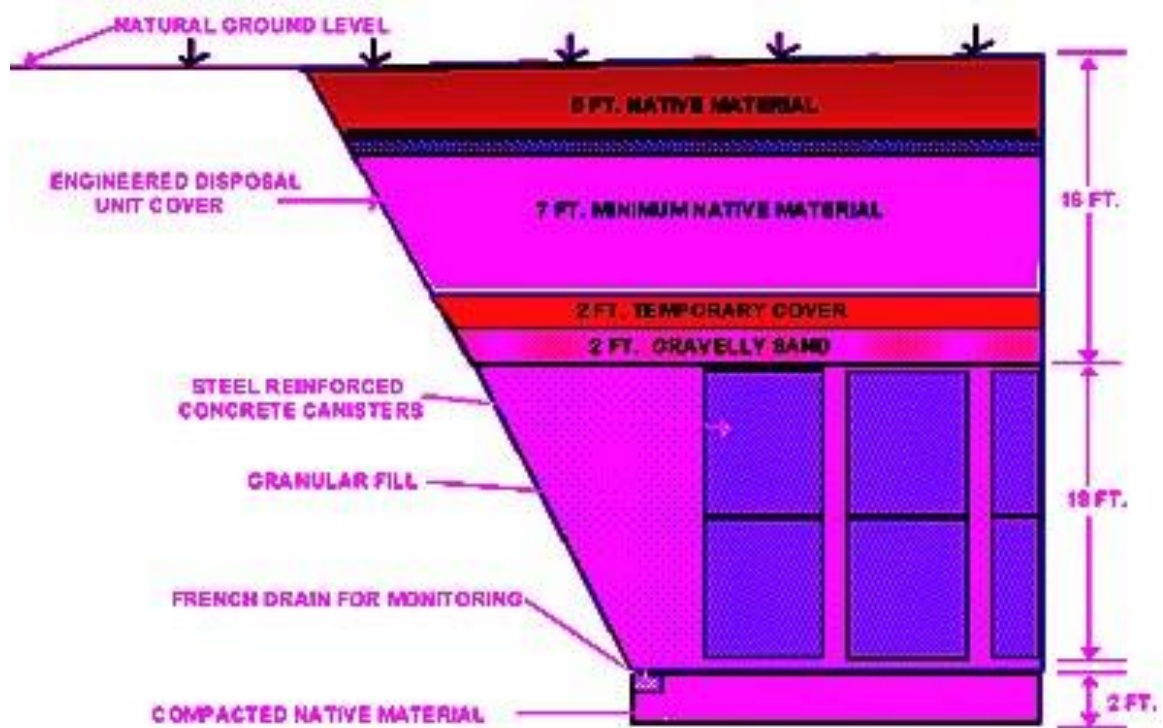

Figure 21. LLRW Engineered disposal unit design.

Figure 22. Above ground level assured isolation conceptual design.

Table 5. Distribution by volume and activity of operational LLRW generation.

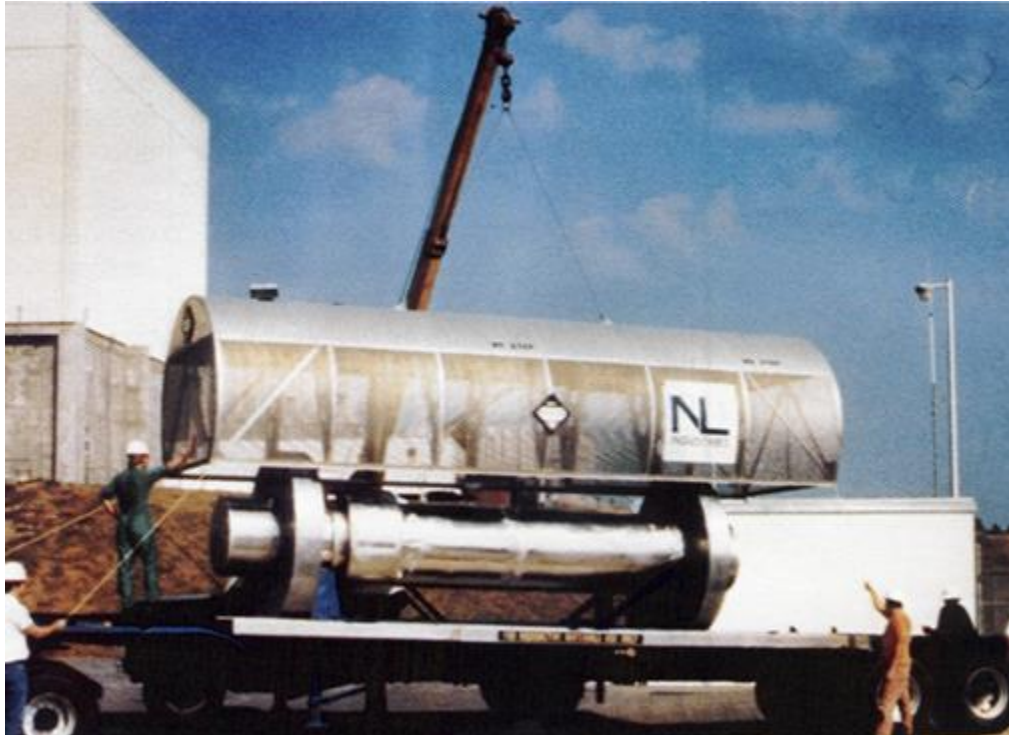| Source	Volume (percent)	Activity (percent)
Industry	60	22
Utilities	22	69
Military	5	8
Medical	11	<1
Academic	2	2
Total	100	100

Figure 23. Spent fuel transportation canister.

5.13 TRANSPORTATION

The transportation of the fuel to the disposal facilities is carried out in specially designed canisters which have been designed and tested to withstand fires, collisions, drops and a multitude of possible accidents.

5.14 EXPERIENCE WITH RADIOACTIVE WASTE

Knowledge about transuranic waste storage has already been accumulated in the handling of the wastes generated by the USA Department Of Energy in its nuclear weapons program are stored in a salt dome formation at the Carlsbad, New Mexico, Waste Isolation Plant WIPP.
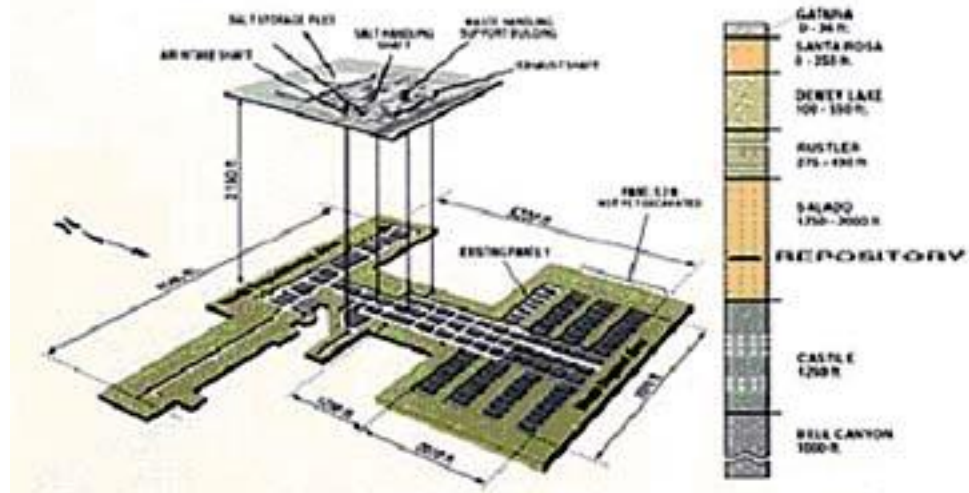
Figure 24. Storage scheme in the Carlsbad, New Mexico Waste Isolation Plant WIPP transuranic waste salt repository.

Figure 25. The Asse salt mine in Germany in operation since 1967 at 750 meters depth.

Figure 26. Gorleben salt dome disposal site, Germany. Source: Der Spiegel.

Figure 27. Pre-Cambrian irretrievable waste disposal, Canada.

The Asse salt mine in the Federal republic of Germany, which is 750 meters deep has been used since 1967 as an experimental facility for the development of methods and techniques for the safe disposal of low and medium level wastes with long lived radio nuclides. Salt formations are extremely stable. The Asse salt formations have remained undisturbed for over 100 million years and likely to continue to exist for the time required for the radioactive wastes to decay.

Glass is favored in France as a material for the solidification of high level wastes which combine well with the standard ingredients used in glass making. Vitrified waste glasses like Pyrex are very stable with good resistance to heat, chemical action, radiation as well as mechanical stress. Even in flowing warm water at a temperature of 40 degrees Celsius, it would take 100 years to dissolve away just 1 millimeter of the surface of the glass. The vitrified waste would still by then be sealed in corrosion resistant stainless steel containers.

Since ground water is likely to be saline, it is proposed that 10 cms of lead and 6 mm of titanium would be added as an extra cladding on the outside. The solution rate of titanium in flowing saline water at ambient temperature is 0.0013 mm per year. Thus, although the temperature is likely to be around 60 degrees Celsius, dropping to the ambient level in about 100 years, the titanium layer is likely to last at least 4,000 years. It is known that Roman lead articles survived in the salty water of the Mediterranean Sea with little loss so that the 10 cms lead clad should last longer still.
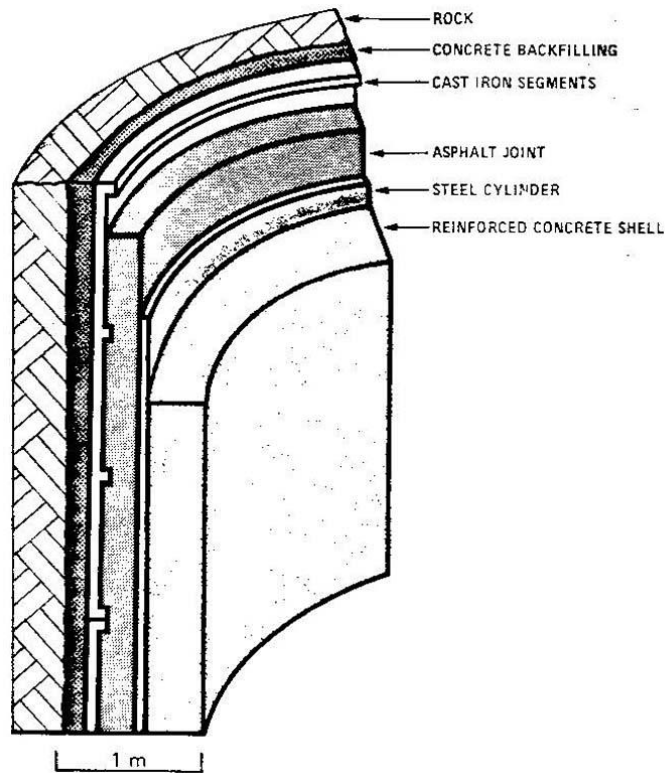
Figure 28. Waste container design.

Those waste containers would be initially stored over the first 30-50 years in water ponds or air cooled storage at the reprocessing plant. After the heat output would have declined appreciably the containers could be loaded into boreholes in rock formations where natural cooling would be sufficient to dissipate the heat generation.

The repositories would be excavated in deep geological formations hundreds of meters below ground level, and well below the water table.

Figure 29. Cut away of a waste container containing vitrified high level waste at the Marcoule plant, France.
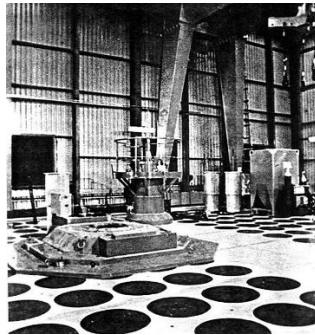

Figure 30. Storage wells for vitrified waste containers at the Marcoule plant in France.
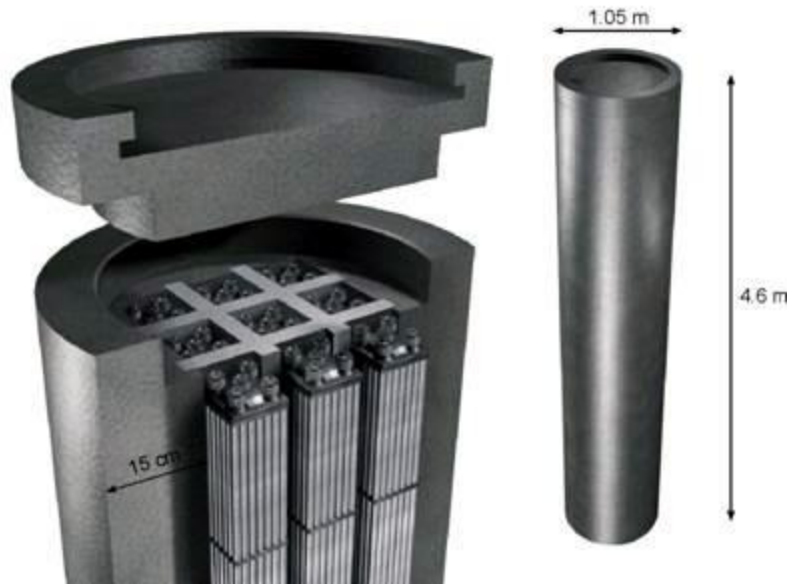
Figure 31. Swiss design of a canister for storage of BWR reactor spent fuel elements.
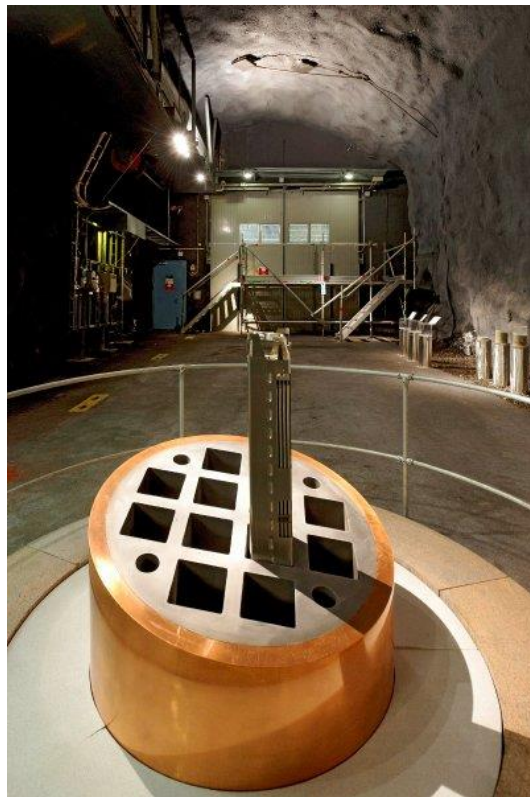

Figure 32. Swedish design of fuel storage canister with full retrievability. A massive iron cylinder with hollow spaces for the spent fuel elements is clad by a layer of copper 2 in (5 cm) in thickness. It would be lowered into a drilled hole that is filled with bentonite clay. Photo: Maurice Weiss.

In addition to the waste glass and its container other engineered barriers can be added to assure waste containment for more than an admittedly arbitrary chosen period of 1,000 years, even in the presence of corrosive ground water. Synthetic rock or synrock has been also suggested as an alternative disposal matrix. Once the containers are emplaced in the repositories, the access tunnels will be filled with rocks and sealed, effectively preventing movement of the radionuclides to the human environment. The engineered barriers and the natural geological barriers combine to return to the Earth what was earlier mined from it.

5.15 SUBSURFACE PLANAR VITRIFICATION

In subsurface waste vitrification, two solid graphite electrodes about 30 feet in length are inserted into the ground in proximity to a waste containing shaft. Four megawatts of power are delivered to these electrodes. A four foot tall sheet of graphite flake is pressure injected between the electrodes providing a current path. When current is passed between the electrodes for seven to ten days at a temperature of 1,700 degrees C, any waste and its surrounding is melted into a glass composition.

Figure 33. Subsurface vitrification using graphite electrodes.

The waste containing shaft is capped with a containment hood preventing the electrodes from moving once the melting process is started, and captures any radioactive fumes to a filtering system. When the electrical current is stopped, the resulting gel cools into a solid glass, encasing any waste for a long period of time. The glassy material would eventually be dug out and disposed of at the Carlsbad, New Mexico government waste disposal site. This technique has been developed for use at the Hanford Nuclear reservation in the state of Washington.

5.16 RADIATION PROTECTION STANDARD FOR YUCCA MOUNTAIN, DELAY AND AVOIDANCE

On June 6, 2001, the USA Environmental Protection Agency (EPA) announced the radiation protection standards to be used for Yucca Mountain, Nevada, the site of proposed high-level nuclear storage.

The final public health and environmental protection standards for Yucca Mountain was set at 0.015 cSv or rem per capita per year and 0.004 cSv or rem for groundwater. This is also referred to as the 15 mrem standard.

This represented the end of a struggle between the EPA and the Nuclear Regulatory Commission (NRC), which had recommended an overall limit of 0.025 cSv or rem per capita per year and no groundwater standard.

Energy Secretary Spencer Abraham, at the time, who had favored the NRC proposal, said on June 6, 2001, that the EPA standards were "tough and challenging" but that "we believe we can meet the requirements."

The nuclear industry, represented by the Nuclear Industry Institute filed two separate federal court lawsuits. One was filed in USA District Court and the other in the USA Court of Appeals for the District of Columbia Circuit, challenging the EPA standard. Stating that the industry "is extremely disappointed," the trade association said that the lower limits "will cost taxpayers and electricity consumers billions of additional dollars to license and build the Yucca Mountain repository without making the facility any safer."

In September 2008, the EPA revised its standard of a waste repository that for the first 10,000 years, possible future residents should not be exposed to more than 15 mrem/year of effective dose, to the requirement that from year 10,001 to one million years the dose equivalent should not exceed 100 mrem/year. According to the EPA, the new standard "will protect public health and the environment for 1 million years."

To express the strictness of the EPA so called 15-millirem per capita per year standard, the EPA stated that the standard means that a person living eleven miles from the Yucca Mountain site, the distance to which the standard applies, will absorb less radiation annually than a person receives from two round-trip transcontinental flights in the USA. The EPA also stated that background radiation exposes the average American to 360 millirems of radiation annually, while three chest x-rays lead to a total dose equivalent of about 18 millirems.

There is no way to prove that Yucca Mountain can meet the standards established by the EPA. Any models or simulations can be questioned and can provide the grounds for controversy. Arguing and delaying are ways to mine the tremendous amounts of money associated with the project.

The real answer to the problem is to recognize that radiation is a natural part of the natural environment and that humans have evolved the ability to cope with small amounts without health risk.

The level at which no risk can be found is roughly 10 cSv or rem over a short period of time. This is fully $10 / (15 \times 10^{-3}) = 666$ times the EPA unrealizable standard of 15 mrem. At significantly higher lifetime exposures demonstrated by many population studies in areas of high natural background radiation, the health risk is very low compared to that from other environmental influences.

The Yucca Mountain project is based on legislation dating back to 1982, and cannot be stopped by presidential fiat. The USA Department of Energy submitted an application to the Nuclear Regulatory Commission in September 2008 to license Yucca Mountain. This process is expected to last 3-4 years and includes passing judgment on the one million-year safety standard. The facility is expected to open in 2020 at the earliest, more than 20 years behind schedule to store 70,000 tons of spent nuclear fuel; a blink of an eye on the geological time scale.

5.17 ACCELERATOR-DRIVEN ENERGY AMPLIFIER TRANSMUTATION

The favored option is to store the treated and vitrified waste in deep geological repositories. Accelerator driven transmutation is a possible alternative.

The basic concept is to place the radioactive material in an accelerator and transmute it up into much more stable products, with shorter half lives using a beam of high energy subatomic particles such as protons.

The waste would still need to be stored, but would be less hazardous. The process of transmutation would eliminate other biologically toxic chemical products that exist in normal nuclear waste.

The process could also generate more energy than is used to drive it. The heat generated by splitting the waste nuclei can be used to generate electricity, a part of which being used to run the accelerator and the rest fed into the electrical grid.

A fail-safe mechanism is that when the particle beam is turned off, the reaction stops. This is characterized as an energy amplifier; an idea existing since the 1990s.

France has a program of research looking into accelerator transmutation. There are also initiatives in the USA, Russia, Switzerland, Italy and Japan. The difficulty is that we still do not know exactly what the final transmutation products will be, and in what proportions.

Experts argue that while transmutation is a feasible future technology, there are several other options available too. A fast breeder reactor would reuse the nuclear fuel over and over again until all the plutonium the minor actinides are burned up. Another option is to use the thorium fuel cycle which produces primarily short-lived fission products and less minor actinides.

5.18 DYSFUNCTIONAL STATUS OF NUCLEAR WASTE MANAGEMENT IN THE USA

Despite a commitment in 1982 by the USA government to provide storage of nuclear waste, 65,000 metric tonnes, the size of a 20-ft high football field, are stored at 65 reactor sites awaiting final disposal. The commitment to dispose of the waste has become another USA government unfunded liability, composed of a $25 billion ratepayer fund and $16 billion or more in estimated legal judgments to compensate the electrical utilities for their storage expenses. The costs of the ultimate disposal project are expected to rise, with no plan in sight to replace the cancelled waste disposal project at the Nevada's Yucca Mountain site [8].

The USA Department of Energy (USDOE) in 2008 estimated that constructing the Yucca Mountain facility and then transferring waste to it would cost $83 billion in 2007 dollars, most of it over a six-decade span, on top of the $13.5 billion already spent. If the plan is dead and the government has to find a new site, the ultimate cost of disposal will rise. Beyond the disposal costs, taxpayers are also potentially liable for damages suffered by the public from a nuclear accident, including those stemming from the spent fuel stored at commercial power plant sites. Under a 1950s law, plant operators currently must carry $375 million of liability insurance for each reactor, after which an industry insurance plan would take over, covering damages up to $12 billion. Any personal injury or property damages in excess of that would be borne by the Federal Government similar to major calamities such as floods, earthquake or hurricanes.
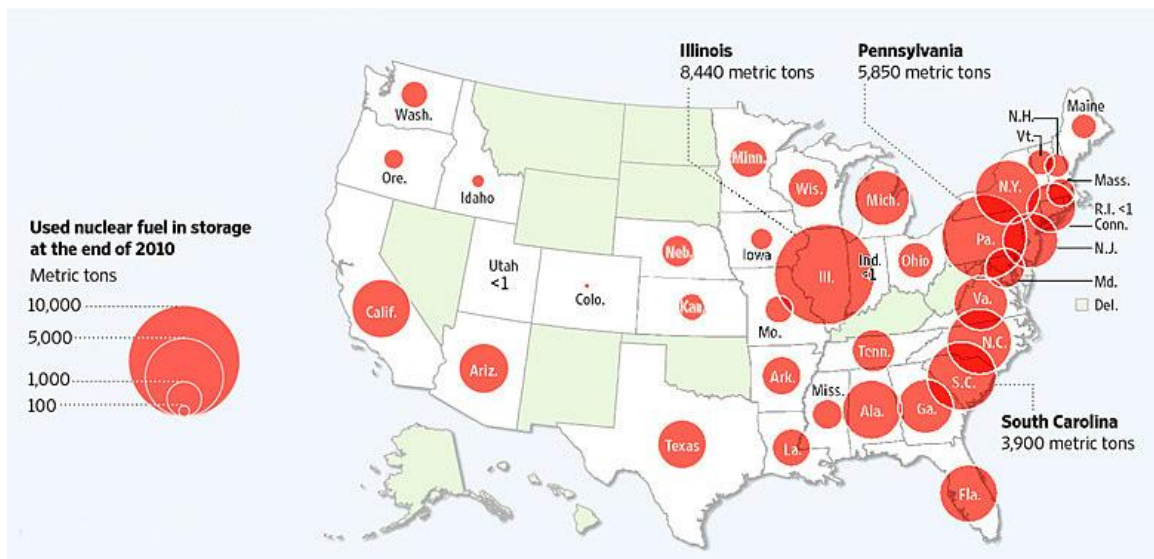

Figure 34. Weight and location of stored nuclear waste in the USA, 2010. Source: NEI.

A report issued on July 29, 2011 by the Blue Ribbon Commission on America's Nuclear Future, said the USA nuclear-waste disposal program had "all but broken down" and suggested a series of fixes. One recommendation was an overhaul of what it called the "dysfunctional Nuclear Waste Fund arrangement." The panel was formed in 2010 by President Barack Obama, after the administration's decision to withdraw funding from the Yucca Mountain project. The panel included former elected officials from both major parties, along with academic experts and representatives of industry and labor. One of the panel's proposals was to cut the annual fees collected from utilities to match the level of federal spending on the program. Uncollected funds would go into utility-run trust funds, to be tapped when needed for the waste project. That would put the project onto sounder fiscal footing, but would add to the near-term federal deficit because some of the utility fees would not be counted as current revenue. The panel report suggested: "the bill will come due at some point," because the government is contractually bound to remove the spent fuel.

President Barack Obama administration has requested no funding for the disposal program in its fiscal 2012 budget. The lack of assured long-term funding is a critical flaw in the capital project. Over the years it exposed the Yucca Mountain plan to political meddling and budget cuts that added delays and contributed to its demise. The project's funding arrangement is fundamentally broken, and overhauling it essential.

When the federal government took responsibility for nuclear-waste disposal under a "polluter pays doctrine," a 1982 law required nuclear utilities to shoulder the cost through an annual fee paid to the federal government. The fee was deposited in a newly-created Nuclear Waste Fund that the USDOE could tap to fund the storage project. The fee comes from nuclear-electricity customers as a surcharge of 1/10th of a cent per kW.hr of energy, amounts to about $750 million per year. Counting past expenditures and interest earned, the fund's balance is about $25 billion as of 2011. However, this cash does not really exist. Through the Balanced Budget and Emergency Deficit Control Act of 1985, Congress and successive administrations have changed the plan so that the fees paid by utilities essentially are treated like taxes and go into the government's general coffers. Congress has spent it on other pet projects. The $25 billion now amounts to a federal IOU that will have to be repaid. The nuclear-waste program was required to compete with other programs for annual appropriations from Congress. Spending on the program is counted against the deficit, instead of the self-funding intended in the original law.

Since the government failed to start taking spent fuel as promised beginning in 1998, the electrical utilities are suing the government to cover their additional storage costs. Federal officials have estimated it will cost $16.2 billion to pay legal judgments owed to the utilities by 2020, assuming that the USA is able to start taking waste from utilities starting then, and $500 million a year after that. In addition, a group of state regulators and the Nuclear Energy Institute, a trade organization, are suing the Department of Energy, seeking to suspend collection of the annual fees utilities pay into the waste fund.

The need to safely dispose of the nuclear waste at the 65 sites, including 9 where now-shutdown reactors, has taken on new urgency after the March 11, 2011 Fukushima earthquake and tsunami station blackout accident in Japan. The plant operator had to take emergency measures to keep the pools of spent fuel stored at the site from being drained and releasing radiation from the accident.

Figure 35. Dry fuel storage cask.

Figure 36. Schematic of dry fuel storage silo. Source Ameren.

Figure 37. Dry fuel storage silos.

Figure 38. Outdoor dry storage silos at nuclear power plants sites. Source: Ameren.

5.19 DISCUSSION

Nuclear Power has been compared with Gulliver in the land of Lilliput, tied down by thousands of threads and ropes stifling its motion and progress into the future. In a thermal neutron reactor less than 2 percent of the actinides are actually fissioned. The dispensed fuel still has an energy value of one terawatt-day/metallic ton. This energy is only accessible with fast neutron or breeder reactors. Recycling of nuclear waste reduces its volume by 97 percent. In the end it is safe to handle in about 300 years and there is no need to invoke the process of forecasting a million years into the future or even 10,000 years.

More than 1.7 billion years ago 15 nuclear reactors operated in nature for over a period of 100,000 years at the Oklo site in the Gabon Republic in West Africa. Plutonium as a transuranic element was produced in the reactive zones. This plutonium did not move away from the reaction zones and decayed slowly into U^{235}. The same happened to the fission products in that they remained at the reactions sites and did not leach away. This natural phenomenon should allay the concern about the ability of storing nuclear wastes in suitable underground formations.

The virtue of using solids like glass or synthetic rock (synrock) for holding materials for long periods of time is obvious from the occurrence of fossilized insects in perfect preservation in amber for millions of years. Frozen mammoths have been discovered in glaciers preserved for over 30,000 years. The Egyptian, Mayan, and Aztec tombs and pyramids have stood the test of time. Ancient objects made out of glass still remain in perfect condition today dating back 3,000 to 4,000 years from the early known civilizations.

As expressed by A. Gauvenet from Le Commissariat à L'Energie Atomique (CEA) in France: "The advantage of going to depths of hundreds of meters is that in inactive parts of the Earth's crust the geological structures and materials remain stable for millions of years. It is therefore already possible to guarantee that we are not bequeathing to future generations a higher radioactivity than that which our Earth contains naturally."

EXERCISES

1. Calculate the amount of uranium as a mixture of U^{235} and U^{238} used by a 1,000 MWe nuclear power plant in a year period if its enrichment is 5 percent in U^{235} per weight, the thermal efficiency is 1/3, and the operating capacity factor of the plant is 0.75.

2. Calculate the amount of fuel in the form of UO_2 at a density of about 10.1 [gm/cm^3] used by the same power plant in the last problem.

3. The uranium fuel requirement for a fission reactor operating at a capacity factor of 75 percent is 30 metric tonnes. The U^{235} burnup rate is given by: burnup rate= 1.112 P $[\dfrac{gm}{day}]$

Estimate the ratio of the weight of the fuel to be disposed of in the case of the once through fuel cycle, to the weight of the fission products in a fuel cycle with fuel recycling for a 1,000 MWe nuclear reactor operating at an overall thermal efficiency of 1/3.

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