DISPOSAL OF NUCLEAR WASTES AND REACTOR DECOMMISSIONING.

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Keywords

Wastes, nuclear wastes, spent fuel, fission nuclides, transuranium nuclides, deep geological disposal, military warheads, plutonium, vitrification, reactor decommissioning.

Contents

Glossary

AECL	Atomic Energy of Canada Limited
DOE	US Department of Energy, responsible for weapons sites.
DU	Depleted Uranium
EPA	U.S. Environmental Protection Agency
HEU	High Enriched Uranium
HLW	High Level Wastes
IAEA	International Atomic Energy Agency
LEU	Low Enriched Uranium
LILW	Low and Intermediate Level Waste
LNT	Linear, No Threshold Hypothesis of radiation risk
LWR	Light Water Reactor
MOX	Mixed Oxide Fuel
OECD/NEA	Organisation for Economic Co-operation and Development - Nuclear Energy Agency
TU	Trans-Uranium, nuclides above uranium in atomic number
USDOE	United States Department of Energy
USECO	United States Enrichment Corporation.

Summary

A brief introduction to wastes in general, including nuclear wastes, leads into a more detailed analysis of the processes at the back end of the nuclear cycle from spent fuel management, to fission waste stabilization and geological deep disposal. There is some consideration of bringing retired nuclear weapons plutonium into the nuclear cycle rather than treating it as waste, as had been initially suggested. The weapons-grade uranium-235 from retired weapons, was never considered as waste, as it is readily blended into existing reactor fuel. In the reactor cycle, the plutonium-239 is blended as MOX fuel for a once-through pass, which leaves the residual plutonium trapped in the spent fuel matrix and thus provides greater short-term security for these materials. The process of Geological emplacement of nuclear wastes is examined, and some of the various risks associated with the construction, operation, and following closure of the facility are evaluated and are broadly compared with the surface storage option. Finally, an overview of a reactor decommissioning process is outlined.

1. INTRODUCTION

Many of the issues associated with waste production of any kind, and their regulation and management, especially in terms of how they are believed to impact upon people and the environment, show how the most emotionally publicized and least understood social issues are usually the most poorly judged and therefore are the most frequently over-regulated and mismanaged.

The issue of wastes, especially of nuclear wastes and the costs forced upon their handling and management by over-estimating risks, is a case in point, where regulatory costs of managing most materials, including many that are radioactive at little more than natural background radiation, far outweigh the social benefits. The **perception** of the associated risk is typically thousands of times larger than the **actual and definable** social (or environmental) risk

2. WASTES IN SOCIETY

The common wastes found throughout society, and their approximate abundance, health concerns and effects, are shown in Table 1. They are placed in approximate order of their relative effects upon society - the worst first. This is also, very approximately, in inverse order to the degree of attention and of spending upon some of them.

Table 1. Common Social and Industrial Wastes Produced throughout the World, Estimated Relative Quantities and their Social and Environmental Impacts.

Waste Materials	**Tonnes per year**	**Fate**	**Locations**	**Present Impact**
Sewage, - assuming 1kg per person per day.	2 billion	Mostly Discharged directly into Water Supplies, and on to the Land Surface. Processed for fertilizer in some areas, or landfilled.	Population centers and Global.	Causes millions of deaths worldwide, and numerous diseases such as Cholera in poor societies. Counteracted by chlorination.
Animal farm wastes, solids and sludges.	Billions	Often a serious disposal problem, used as natural 'organic' fertilizer, burned, and used as cooking fuel in the third world.	Global and Local.	Food contamination and water pollution health risks, everywhere they are used. Counteracted by chlorination. Air pollution in homes from fuel use.
Refuse, - assuming 5 kg per person per day.	10 billion	Most is sent to uncontrolled landfill. Some to sanitary land-fill.	Population centers and local.	Causes thousands of deaths and numerous diseases in poor societies through improper controls.
Combustion wastes - gases.	30 billion	Atmospheric releases. Scrubbed gases become solid waste.	Global.	Implicated in thousands of deaths in all societies from air pollution.
Combustion wastes - solids.	500 million	Mostly controlled in surface land-fill.	Localized.	Groundwater pollution and related effects.
Chemical wastes, and fertilizer run-off.	Millions	Mostly controlled in selected and protected sites.	Localized.	Minor groundwater pollution.
Industrial wastes.	Millions	Mostly controlled in selected and protected sites.	Localized.	Minor groundwater pollution.
Mining Wastes - acidic wastes, toxic metals.	Billions	Surface disposal mostly in confined areas with the application of some controls in some regions.	Mine sites.	Localized groundwater pollution. Acid mine drainage.
Nuclear and other high radioactivity wastes - solids.*	40 Thousand	Totally retained, controlled and managed according to international standards.	Only in specific, licensed disposal sites.	Minor, if any, health impact, yet gives rise to significant political angst, and social misinformation.

* The operation of the 443 commercial nuclear plants in the world (2003) displaces, each year, the emission to the atmosphere of about 3 billion tonnes of carbon dioxide, about 30 million tonnes of sulfur dioxide and millions of tonnes of solid wastes and vaporized toxic metals including mercury, selenium and arsenic.

Risk managers are well aware that society in general, underestimates the common risks that kill people in large numbers, and overestimates the poorly known risks that don't. This leads to the inevitable consequences of over-spending upon the wrong issues, while neglecting the issues that should be better funded. Too often, the significance of risk is wrongly assumed to be proportional to the amount of publicity devoted to it, and that it can be determined by consensus, rather than by any scientifically defensible epidemiological determination. Radiation and radioactive wastes are such an issue.

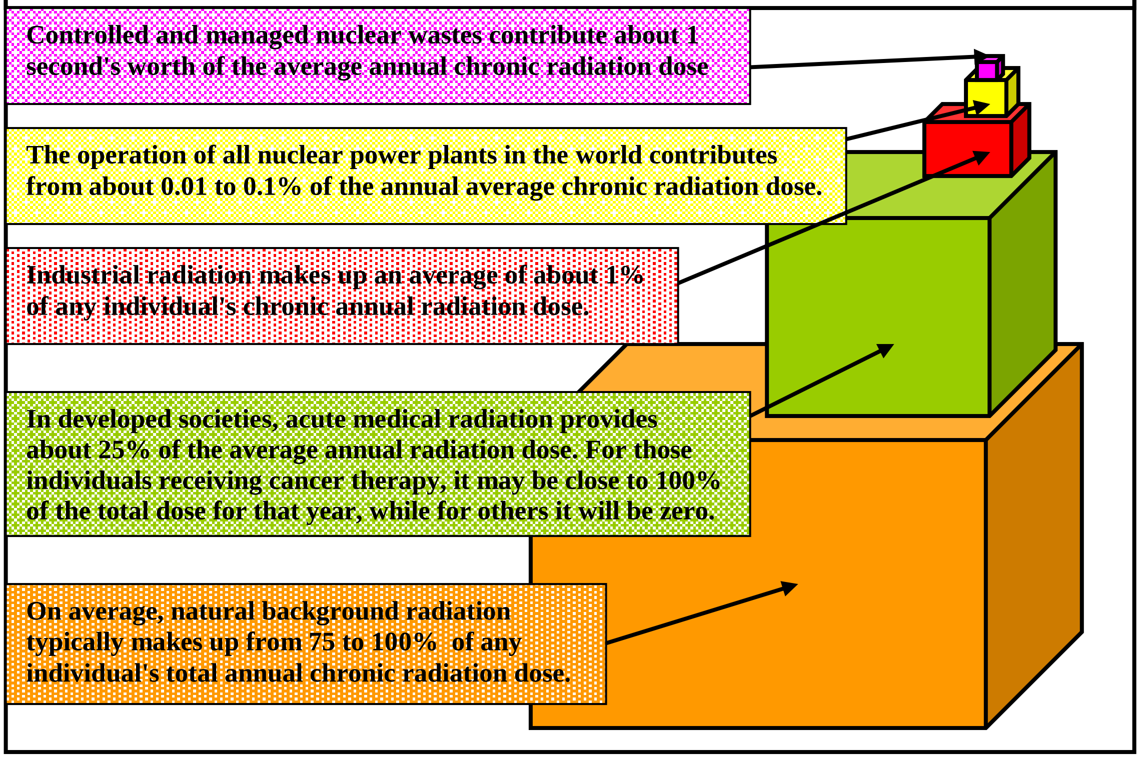
The small quantities of waste that are highly radioactive, and occur throughout society from medical, industrial and nuclear processes are controlled in such a way that the radioactivity is generally not detectable anywhere in society above background, and does not reach anyone that it shouldn't. The exceptions are those patients who are deliberately treated with radiation, and those workers concerned with its uses, placement, security and management, and who are protected by regulation and dose limits. Unlike any of the major fossil fuel energy production wastes, or the socially significant wastes shown in Table 1, nuclear wastes are 100 percent managed. We are also unavoidably surrounded by many uncontrolled natural materials that are both abundant and notably radioactive, as shown in Table 2, and often at relatively high levels.

Table 2. Major Contributions to Naturally Occurring Radioactivity - Natural Background - at the Surface of the Earth, all of Which Affect each of us, and all of Which are Unavoidable	
Radiation and Source	Magnitude
Cosmic Rays from the sun, especially during solar flares	About 100 000 cosmic ray neutrons and about 400 000 secondary cosmic rays hit each one of us, each hour. Billions of neutrinos pass through us without interacting, each hour. Frequent flyers and flight crew are more exposed from cosmic radiation, but not hazardously so. Cosmonauts receive the largest cosmic doses, especially from solar flares, and avoid the Van Allen radiation belt during their missions.
Radon in air (ubiquitous)	About 30 000 atoms of radon disintegrate in our lungs each hour.
Radon in water (ubiquitous)	Many well-waters, especially those from deep wells or in areas of elevated natural radiation, contain millions of becquerels of radon and its daughters per litre.
Potassium in foods. A small fraction of all potassium is K-40 which is radioactive	Potassium is essential to life. Bananas and other foods are a rich source of potassium and therefore of radiation. All mammalian (Human and cows) milk, blood and urine contain potassium.
Potassium and uranium in our bodies from diet	About 25 000 000 potassium-40 atoms, and about 7000 uranium atoms, radioactively decay in our bodies each hour. Without potassium, we die, and without potassium-40 many test animals also become moribund.
Potassium in agricultural and garden fertilizers	Potassium phosphates are radioactive because of K-40. The potassium is taken up by fruits and vegetables and becomes part of our diet.
Uranium-238, uranium-235 and their progeny in all foods	Many foods grown in areas of elevated natural radiation contain significant natural concentrations of uranium and thorium and their radioactive progeny. Brazil nuts are a source of radiation dose from the radium that they typically contain.
Radioactivity in Tobacco, Coffee, Nuts and Chocolate	Polonium-210 in tobacco leaf is a major source of alpha radiation dose to the mouths and trachea of smokers, especially in some Brazilian tobaccos.
Radiation from Soil and building materials (ubiquitous)	More than 200 000 000 gamma rays pass through us each hour from building materials, soil, and the rocks beneath us. Granite is often notably radioactive.
Natural radiation in coal ash and incineration wastes	Coal fly ash and bottom ash contain significant concentrations of natural uranium, thorium and their numerous radioactive progeny, as well as concentrations of potassium (K-40 is radioactive) in silicates.

Radiation exposures come from all foods, air, water and numerous life support materials and life-style choices (where one lives, elevation, frequent flyer, dental care, medical screening, health spa visits) from which one cannot easily be protected without loss of some quality of life. It is from these materials, choices and actions - usually totally ignored by society from a radiation point of view - that we get almost 100 percent of our lifetime radiation dose.

Some indications of the relative dose contributions from these various natural and man-made sources of radiation are shown in Figure 1. The estimated maximum dose that might be received by the exposed public from nuclear wastes, whether left where they are in storage at the surface, or deeply disposed, is about 1E-08 mSv a^{-1}. This dose is about 300 million times less than natural background radiation to which we are all exposed, and is approximately equivalent to a few second's worth of natural radiation in a year from all natural sources. However, it receives more emotional and political attention than almost any other source of radiation dose, or risk, and diverts social resources out of all proportion to its minuscule risks without achieving any improvement in the safety of society, as it poses no significant radiation risk to any member of the public, even as it is managed at the present.

Figure 1. Average Relative Contributions to a Typical Individual Annual Radiation Dose of about 5 millisieverts. Medical Cancer-Therapy Treatments may give the Individual Receiving those Treatments up to about 10 Thousand Millisieverts of Acute Whole Body Dose, to 100 Thousand Millisieverts of Targeted Acute Dose to the Cancer, or to Destroy a Thyroid Gland.



3. RADIOACTIVE WASTES

Many substances and wastes that are significantly radioactive are often ignored (fly ash, fertilizer, coal ash, wood ash, some drinking water supplies), as to try and control them in any significant way would impose much greater alternative risks and severe costs upon society, that would far exceed the extremely small benefit, if any, that would result.

Other sources of radioactive wastes from nuclear and medical operations, are stringently controlled. Only waste materials that are either highly radioactive (some medical and industrial wastes) and which occur in relatively large, but manageable quantities (spent fuel and other nuclear wastes), require careful controls and are usually addressed as radioactive wastes that require such control and management. Nuclear wastes, which may contain elevated levels of radioactivity, have been significantly produced only in the last 60 years. Some of them are shown in Table 3, along with some of the much higher activity materials used in medicine and industry.

Table 3. Typical Very Approximate Activity or Activity Ranges in Selected Industrial Wastes and Other Materials in Society

Industrial - Mostly Uncontrolled - Radioactive 'Waste'	**Activity (Bq kg^{-1} or as indicated)**
Most Metal Mining Wastes (U, Th and progeny)*	Background to 400 000
Coal Ash (K-40, U, Th and progeny)	200 to 25 000
Scale in oil/gas pipes (radium and progeny)	Background to 15 000 000
Oil/Gas sludges (radium and progeny)	Background to 40 000
Oil/Gas produced water (radium and progeny)	10 000 to 40 000
Water Treatment solids (Radium and radon progeny)	600 to 1 300 000
Phosphate processing solids (Uranium, thorium and K-40)	5 000 to 25 000
Geothermal solids (U, Th and progeny)	Background to 400 000
Nuclear Controlled 'Wastes'	
Depleted Uranium, DU (no ingrown progeny)	12 000 000
Spent Fuel (40 000 MWdays/tonne), after 6 years	2E13
LILW	100 000 to 1E9
Other Radioactive Materials and Devices	
Pitchblende or Uraninite (U and progeny)	160E6
Granite (U and Th, and progeny)	1000 to 5000
Wood ash (K-40, Sr-90, Cs-137)	Background to 1000
Tritium EXIT sign (H-3)**	7E10 Bq per sign
Radiography inspection device (Ir-192)**	About 1E12 Bq per device
Radiation Therapy Co-60 source**	Up to about 4E13 Bq per device
Hospital diagnostic radionuclides (numerous)**	1E6 to 1E10 Bq per source
Household smoke detector - americium-241	50 000 Bq per device
Typical granulated fertilizer (K-40)	5000
Typical adult human (K-40)	7000
Mammalian milk, blood and urine	50 (from K-40 alone)
Radon gas in most homes	3000 Bq m^{-3} to 30 000 Bq m^{-3}
Radon gas in many mines and some home basements	10 000 Bq m^{-3} to >1 000 000 Bq m^{-3}

*Progeny, are all of the radioactive daughters in the natural decay sequence.
** When these radionuclides age and lose much of their activity, or are discarded, they become controlled wastes.
The industrial radioactive waste is usually Technologically Enhanced Naturally Occurring Radioactive Materials or TE NORMs. The unit of radioactivity - the becquerel - is one radioactive disintegration per second. **Data are from the IAEA and other sources.**

Low-level radioactive wastes have been produced ever since humans began mining anything and at least almost 2000 years ago when the Romans used slave labor to mine tin from radioactive Cornish granites as well as in other mines throughout their empire.

Some of the most important and mostly 'controlled' radioactive wastes - controlled only in recent decades - and other materials that are not true wastes, are shown in Table 4.

Table 4. Major Sources of Radioactive Controlled and Other Wastes	
High Activity/Low-Volume Wastes	**Low Activity/High-Volume Wastes**
Controlled for reasons of high radioactivity or for strategic reasons,	The degree of control depends upon the jurisdiction, environmental regulations, potential for acidic and metallic pollution of groundwater and streams, rather than upon the minor radioactivity.
• **Nuclear Reactor Spent Fuel. *** • Fission Radionuclides from Re-Processed Spent Fuel. • Retired Medical Radiotherapy, and Industrial Irradiation Devices. • Military Reprocessing Wastes. • Maintenance Wastes From Nuclear Reactor Operations**. Type 1 - Less than 2 mSv/h (unshielded contact dose rate) Type 2 - Two to 125 mSv/h Type 3 - > 125 mSv/h	• Uranium Mine Tailings (pollution controls, acid mine drainage controls, and slowing radon gas leakage). • Thorium Mine Tailings (as above). • Some Base-Metal Mine Tailings (Uncontrolled, except for acid mine drainage in most areas). • **Depleted Uranium Stockpiles. *** Depleted uranium is of relatively low radioactivity. The extremely high potential value of depleted uranium, in terms of its energy content, ensures that it is controlled for possible future use, either to extract more uranium-235; for use to downblend weapons grade uranium-235 or plutonium-239; or for use in the future breeder reactor cycle.
* 'Wastes', only if not recycled. ** Different jurisdictions may use other dose-rate criteria for classification and control.	

3.1. Waste Classification and Waste Control

Radioactive wastes of any kind - mining, nuclear, medical or industrial - that may be required to be controlled, need to be classified in order to ensure that they are managed and controlled according to their contained radioactive materials, activity (Bq per kilogram), and half-life. An overall classification is shown in Table 5, with some indication of options and considerations for disposal outlined in Table 6.

Table 5. Broad Classification of Radioactive Wastes, Management Time Frame and Some Considered Disposal Options (Mostly from IAEA)					
Category	**Exempt and very Low Level Wastes**	**Low Level and Intermediate Level Wastes (LILW) - heat output less than about 2kW m^{-3}, and activity - ILW > 4000 Bq g^{-1}**		**High Level and Transuranium Wastes (HLW) (high radioactivity and >2kW m^{-3} heat output)**	
Half-Life	**Long or short half-lives**	**Short half-lives <30y**	**Long half-lives >30y**	**Short half-lives <30y**	**Long half-lives >30y**
Material	Uranium mine and other mine tailings. Some coal ash. Some wood ash. Phosphate fertilizer wastes.	Most nuclear maintenance wastes contaminated with fission nuclides. Some hospital and medical wastes.	Some nuclear maintenance wastes, and by-product wastes containing transuranium nuclides.	Separated fission products (Cs-137 and Sr-90 are the significant nuclides). Some retired medical, industrial and research devices.	Spent fuel, if not reprocessed. Retired military plutonium warheads, if not used as reactor Mixed Oxide (MOX) fuel. Defense wastes.
Management or Security Time Frame	Not required. Usually low radioactivity.	Typically less than 20 years, and half-life dependent.	Hundreds to thousands of years, based upon nuclides and half-lives.	Several hundred years, more or less, depending upon half-lives.	Thousands of years. Security of plutonium is the issue, rather than radiation, as widely publicized.
Disposal Options	No radiological restrictions, disposal as for other possibly-hazardous mine wastes.	Enclosed surface, or near-surface facility.	Near surface facility or intermediate-depth geological facility.	Geological disposal facility.	Surface Management with reprocessing, or Deep geological disposal facility.
Radionuclides with half-lives longer than 30 years are regarded as long-lived wastes; those with half-lives less than 30 years are considered short-lived. Intermediate Level Wastes, although containing significant radioactivity relative to low-level wastes, do not give rise to notable heating effects, as do High Level Wastes for the first few years. Jurisdictions usually specify their own criteria for definition and control.					

The most publicized, and the most significant of these wastes are those which arise in the operation of nuclear reactors, yet as can be seen from Figure 1, they contribute the least doses to anyone in society - either population doses or individual doses - while being the most publicized, feared, politically manipulated, controlled, and regulated.

Table 6. Summary of Nuclear Waste Categories and General Disposal Considerations

High Level Wastes (HLW, initially very intensely radioactive)

These consist of the small tonnage of spent fuel (if not reprocessed) discharged from the reactor each year, and the separated fission nuclides if it is reprocessed. Spent fuel contains all of the fission products (about 3 percent of the wastes) and un-fissioned actinides (about 97 percent). It has an initially high heat output, rapidly falling within a few years (5 to 10) to about 1 kW T^{-1} depending upon 'burn-up' of the fuel. It requires water cooling and water shielding for the first few years after discharge and may then be dry stored in concrete shielded structures or re-processed to recover the un-fissioned actinides and plutonium, to be re-used in the energy cycle.
This category may also include the vitrified and relatively short half-life fission radionuclides from spent fuel reprocessing in those countries where spent fuel is re-cycled.
The long-lived HLW including spent fuel and TU wastes, as well as the shorter-lived separated fission wastes are to be stored in deep geological formations, which are designed and required to generally maintain their integrity for several thousands of years.

Intermediate Level Wastes (ILW)

These consist of radioactive wastes whose radioactivity is intermediate between the low and high-level categories. They contain fission products but few or no actinides. Ion exchange resins used to purify reactor water may fall into this category or as High Level Wastes. In the US, nuclear waste is treated as either high level or low-level waste, without this intermediate category. Some of these longer-lived LILW wastes may be disposed of in deep geological repositories along with HLW, but much of it can be placed in relatively shallow burial, as it is relatively short-lived.

Low Level Wastes (LLW)

These are of relatively low radioactivity and consist mostly of compacted maintenance wastes (protective clothing, rags, cleaning materials, tools) and other large-bulk low-density short-lived wastes. Within a few years - typically no more than about 20 or 30, they are usually sufficiently decayed that some of these wastes may be re-assessed as non-radioactive materials and either recovered (tools), discarded into landfill operations or, if not adequately decayed to background levels of natural radiation, returned to surface storage for a brief time.

4. NUCLEAR WASTES

Nuclear Wastes are those significantly radioactive wastes originating in the operating cycles of a nuclear reactor. They include wastes of any kind containing fission, activation or transuranium nuclides, and include highly radioactive spent fuel; moderately high to medium radioactivity reactor operating wastes (process wastes - ion exchange resins and filters); and relatively low radioactivity maintenance wastes (discarded coveralls, protective clothing, cleaning materials).

Medical nuclides which may be produced in high purity materials introduced into the cores of certain reactors, are processed outside of the reactor operation by independently licensed industries at a separate location, and give rise to generally short-lived radioactive wastes that are dealt with by industry outside of the nuclear reactor cycle, while conforming to the same general precautionary and regulatory requirements.

Naval-vessel reactor wastes are not considered here, as they are usually administered separately, though the control and management requirements are almost the same.

There are four main sources of Nuclear Waste:

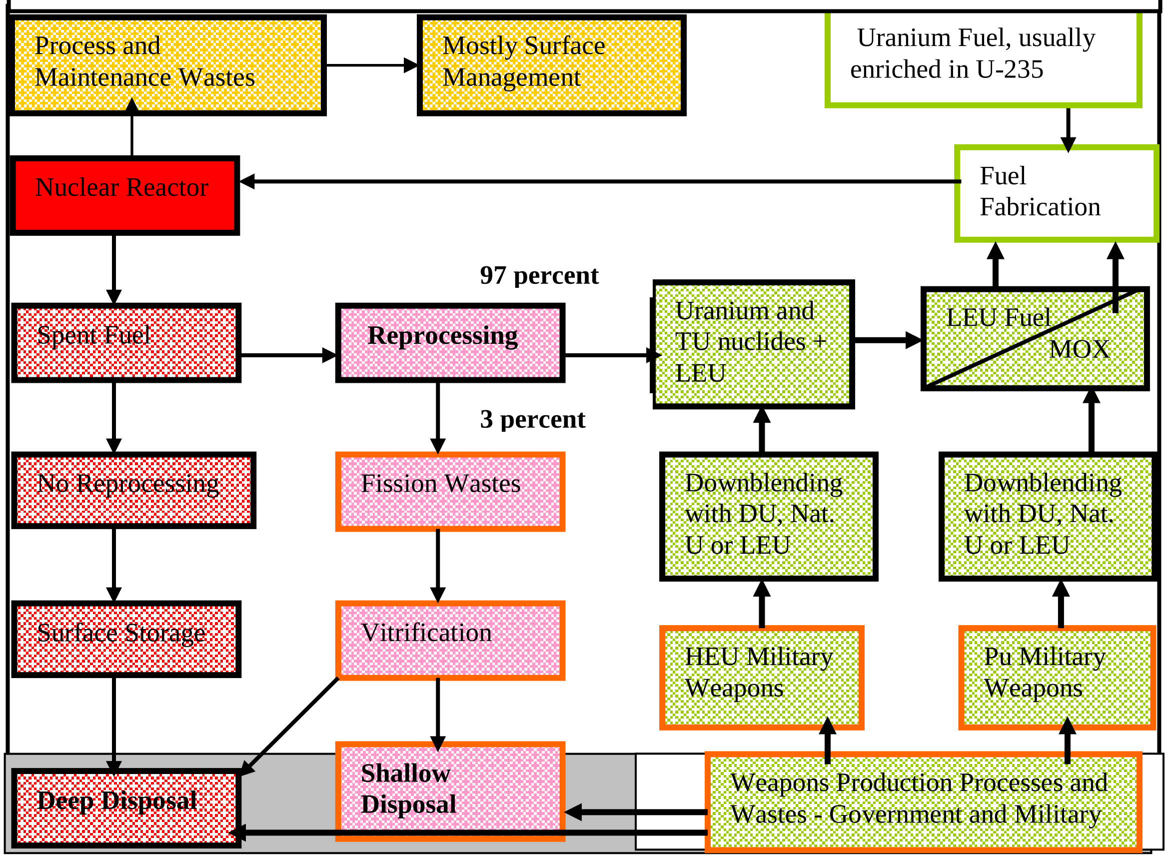
1. **Reactor maintenance and process wastes**. These usually contain minor fission and activation wastes and are mostly low and intermediate level wastes. Activation nuclides are usually more of a consideration during decommissioning than at any other time. These are described in more detail in Articles 3.6.3.3 and 3.6.3.5.
2. **Fission product wastes from spent fuel reprocessing**. These are the highly radioactive fission nuclides from which the 95 to 97 percent of unburned uranium fuel and transuranium nuclides have been removed in the fuel reprocessing cycle, for return into the reactor. The remaining 3 to 5 percent of fission nuclides are managed as short half-life, high level wastes.
3. **Military weapons production and reactor process wastes**. These include the relatively minor wastes from uranium-235 enrichment (ignoring the much greater quantities of uranium-238 - depleted uranium which is not waste, considering its immense energy value in a future breeder cycle). They also include the relatively large quantities of highly radioactive fission nuclide wastes from the reprocessing of the military reactor spent fuel in order to extract plutonium. As with naval reactor vessel wastes, these are usually separately administered by another branch of government, and are not expanded upon in the present discussion.
4. **Spent fuel - where it is not reprocessed** - should be regarded only as temporary waste, though it is of relatively high radioactivity in the short term. This spent fuel contains unburned recyclable uranium (low radioactivity), fission nuclides (high radioactivity), and recyclable transuranium nuclides (mostly low radioactivity). Spent enriched fuel can be, and eventually will likely be, re-processed to recover the unused uranium and the 95 percent or more of the energy that was not initially produced. Reprocessing takes place in many countries, though not at this time in the U.S. There is less economic incentive to reprocess spent natural (as opposed

to enriched) uranium fuel in the short term, but even this spent fuel becomes economically attractive with time and especially following the adoption of the breeder cycle in which the uranium-238 becomes a major source of energy.

These four groups are generally shown in Figure 2. The low radioactivity wastes from the 'front end' of the reactor cycle: mining, refining, conversion and enrichment, leading to the production of fuel and depleted uranium, are described in detail in Article 3.6.3.3.

Although the initial political considerations for the disposal of nuclear weapons were to treat them as waste, the safety and proliferation concerns, as well as the remaining immense quantities of useful and non-polluting energy in them, dictated that they be brought into the fuel cycle. After down-blending with depleted uranium (also regarded as 'waste' at one time) or natural uranium, and following a single pass through the reactor, these strategic materials can be progressively recycled until exhausted. If not recycled beyond this point, then they are securely held in the highly radioactive spent fuel matrix at low concentrations and do not represent a significant or credible proliferation threat in any democratic society.

Figure 2. General Uranium Fuel Cycle at the 'Back-end', and Waste Production and Disposal, including Fuel Reprocessing and Bringing Retired Nuclear Weapons into the Fuel Cycle.



Security of such wastes - especially those containing transuranium nuclides - non-reprocessed spent fuel, and transuranium wastes from weapons production - influences both the politics and regulations concerning how they are controlled and how they may be ultimately disposed of, and the time frame in which they are required to be managed.

The major considerations for any of them are that the general public at large, shall not be exposed to any of these materials - and they are not - and that those who work with these materials shall conform to required radiation protection regulations, training and safe work practices, and that their regulated dose limits shall not be exceeded during their work.

4.1 Reactor Maintenance and Process Wastes.

During reactor operation and maintenance, fission and activation nuclides can circulate outside of the reactor core and become trapped in piping, tubing, resins, filters and valves which may subsequently be accessed for cleaning, change-out and maintenance. These low and intermediate level wastes from such routine operations also include disposable work clothes and cleaning materials when the various contaminated systems are accessed. The contained fission nuclides (mostly zirconium-95) in these materials are of relatively short half-life. Management of such wastes is often required for no more than about 20 years before radioactive decay has significantly reduced their radioactivity so that they may be disposed of into normal, non-radioactive waste processes or recycled.

4.2 Fission Product Wastes from Spent Fuel Reprocessing.

If spent fuel is reprocessed, then the recovered uranium and transuranium nuclides are returned to the reactor cycle, and the fuel cladding and the separated fission wastes are managed and discarded as radioactive wastes. Because the typical half life of fission radionuclides is much less than 30 years as shown in Table 7, and they do not contain transuranium nuclides, these wastes do not require the same longer term security and proliferation considerations as for unprocessed spent fuel with its much longer-lived transuranium nuclides. More detail of fission nuclides is given in Article 3.6.3.5.

Table 7. Summary of all Fission Product Nuclides in Spent Fuel, immediately after Reactor Shutdown following Full-Power Operation.	
Fission-product Half-lives	**Number of Defined* Fission Nuclides**
Less than 24 hours	**438+**
1 day to 1 year	**42**
>1 year to 10 years	**4**
> 10 years	**12***
Stable fission isotopes	**101**
Total fission nuclides	**615**
+ Many fission nuclides have extremely short, and difficult-to-define half-lives. * The two most significant of these longer-lived fission nuclides are strontium-90 and cesium-137 with half-lives of 28.78 years and 30.07 years respectively.	

4.3 Military Weapons Production and Reactor Process Wastes

Nuclear weapons may be produced either by physically enriching uranium-235, or by producing plutonium-239 in a dedicated (military) reactor. In the case of reactor production of plutonium, the partially consumed fuel, discharged from these reactors after only a few weeks of operation, is reprocessed to strip out the plutonium. During this process, volumes of liquid and solid highly-radioactive wastes are produced, though with the relatively low burnup of fuel, there is much less fission activity in the discharged fuel and in the subsequent reprocessing wastes, than in the relatively high burnup fuel from present day commercial reactors.

In the U.S. most of this liquid re-processing waste is still being managed at the U.S. Department of Energy (USDOE) controlled sites - especially at the Hanford Nuclear Reservation in Washington State, which began operation in 1943. The Hanford operation was scheduled for closure starting in 1964, but was restarted in 1984 until 1989. Now, these closed military reactors and their sites are gradually being cleaned up. At this point in time, almost 15 years after these plutonium-production facilities were finally closed, the fission nuclides have mostly decayed and the stabilized fission and transuranium wastes are in process of being vitrified for disposal.

Wastes from Hanford and other defense sites, will be disposed of at Yucca Mountain when that facility is eventually constructed and becomes operational. However, there are concerns that the presently designed storage capacity of Yucca Mountain (77,000 tons; a quantity that is comparable to the output of mined ore from many commercial base metal mines on a daily basis), will be too small to accept un-reprocessed commercial reactor spent fuel as well as all of the vitrified fission and transuranium 'defense' wastes, beyond about 2035. It seems clear that the existing facility will need to be expanded - a simple engineering task, but requiring political approval - or what is even much more difficult in terms of political approval, an additional facility considered. One possible suggested compromise (February 2003) was to provide additional licensed storage space at the surface above the Yucca facility for the materials most easily and safely managed in this way. Although there has been some negative commentary about this, with allegations about future risks, it still represents secure, safe, controllable, monitored and managed storage.

Other waste isolation facilities already exist. In 1999 a deep geological disposal facility - WIPP: Waste Isolation Pilot Plant - was commissioned in New Mexico and began to receive military transuranium wastes from Los Alamos. The facility is contained in a geologically old salt formation, at a depth of 2150 feet (650 metres) below the surface. Most of this waste is of relatively low radioactivity as are most defense facility wastes today and, in the U.S. at least and for the present, is managed separately from the much higher radioactivity HLW wastes - but still of rapidly decreasing radioactivity - from commercial fission reactors.

These defense wastes are not further considered in this article.

4.3.1 Retired Military Warheads, Uranium/Plutonium

About 100 to 110 tons of plutonium-239, and about 500 to 550 tons of HEU from nuclear warheads are expected to be taken out of the weapons arsenals of each of the U.S. and the former U.S.S.R., and disposed of as 'nuclear waste' (an option for the plutonium that seems to have been abandoned as wasteful, and not providing the necessary security) or down-blended and refabricated into reactor fuel in the coming years. These quantities were augmented (May 2002) by agreement to further reduce the nuclear arsenal of both sides.

Uranium.

Surplus of weapons-grade highly enriched uranium (HEU) has led to an agreement between the U.S. and Russia (Megatons to Megawatts) for the HEU from Russian warheads and military stockpiles to be down-blended prior to delivery to the United States Enrichment Corporation (USECO) where it is fabricated into fuel and then used in commercial nuclear reactors. Under the 'swords for ploughshares' deal signed in 1994, the U.S. Government will purchase 500 tonnes of weapons-grade HEU over 20 years from Russia for US$ 11.9 billion ($23 000 kg^{-1}), which is about half the value of the electrical energy that can be recovered from the down-blended LEU uranium fuel in one pass through a PWR reactor (assuming 50,000 MWdays T^{-1}, and $40 MWh^{-1} for electricity).

Weapons-grade HEU contains over 90 percent U-235 while light water reactor fuel is usually enriched to only about 3 to 4 percent. To be used in most commercial nuclear reactors, military HEU must therefore be diluted about 1:25 by blending with depleted uranium (mostly U-238), natural uranium (0.7 percent U-235), or greater quantities of partially enriched uranium.

Since about 1995 to the present (2003), the equivalent of nearly 5600 Russian nuclear warheads, or some 141 tonnes of high-enriched uranium, were converted by down-blending with uranium-238 (DU). By 2013 the quantity is expected to reach 500 tonnes or more. In the U.S. in 2002, approximately half of the nuclear electricity was derived from down-blended uranium-235 from retired nuclear weapons from the former U.S.S.R.

Plutonium.

Disarmament will also give rise to some 150-200 tonnes of weapons-grade plutonium from the stockpiles of both countries. Initially, political expediency suggested that this should be earmarked for disposal in the U.S. by being vitrified with high-level wastes, thus treating the plutonium itself as waste. However, re-evaluation of both the unnecessary waste of a valuable resource that this represents, and the social and political risks, has suggested that the plutonium should be downblended with uranium oxide as a mixed oxide (MOX) fuel for burning in existing reactors using the once-through cycle, and at least partially recovering the immense quantities of energy contained in this extremely valuable material.

This has the advantage of bringing all plutonium into the very secure spent fuel management process, through which some of its energy is constructively used and - where re-processing beyond the 'once-through' cycle is not yet an option - of trapping the remaining un-consumed plutonium in a highly radioactive matrix, providing a high degree of security in the intermediate term. Long-term security can be achieved by reviving reprocessing in the U.S. or by allowing the U.S. reactor spent fuel to be re-processed in Europe - which is yet another politically difficult issue.

MOX fuel is currently being used in commercial reactors in Belgium, France, Germany, Japan, Switzerland, and the United Kingdom, with certain reactor operations in the U.S. seeking a license for such use. Russia also intends to use plutonium in the future as a fuel in both conventional and fast neutron reactors.

4.4 Spent Fuel Management

Spent fuel contains unused uranium (about 95 to 99 percent of the starting uranium), fission wastes (about 1 to 5 percent) and unused transuranium nuclides (about 1 percent or less) both produced and consumed in the fuel, as most transuranium nuclides have a high neutron capture cross section and can become fissile, or are fissile themselves. Discharged spent fuel is highly radioactive after being in the reactor core up to 24 months, and is managed at the reactor site initially in water filled spent fuel bays to provide heat removal and shielding. If the spent fuel is not reprocessed - which normally takes place after about 150 days following discharge - then it remains in the spent fuel bays for several years. After this, it may be transferred to dry fuel storage, also usually on the reactor site for safety, security and control purposes.

4.4.1 With reprocessing

With reprocessing, the uranium and transuranium nuclides which make up about 95 percent of the spent fuel volume are separated from the fission nuclides and returned to the reactor cycle where they are further consumed through the reactor cycle and continued reprocessing.

The separated low volume fission wastes from each fuel cycle (about 3 to 5 percent by volume) are mixed with fluxes and silicates and are fused (vitrified) into glass blocks, or are otherwise trapped in a stable matrix in preparation for permanent - but relatively short management-term - secure final disposal.

The reprocessing option for spent fuel, and implications for waste management are discussed in detail in Article 3.6.3.5.

4.4.2 Without reprocessing

Without reprocessing, the next eventual stage after about 50 years is for the entire volume of spent fuel to be consigned to a secure, deep geological repository. With time - no more than a few hundred years - the highly radioactive fission products have completely decayed, and the repository contains a low radioactivity uranium-plutonium ore body, representing either a valuable energy resource to future generations, or a security concern in the longer term from the nuclear proliferation point of view.

There are at least three main options for managing spent fuel that is not reprocessed:

1. Continue with the present management process of initial management in a water-filled spent fuel bay for up to about 10 years, with subsequent transferal to above ground dry storage for the following 50 to 100 years or longer. This option can continue almost indefinitely as the overall volumes are small, and as they gradually lose their radioactivity, can be stored in fewer, larger volume, shielded containers.
2. Return the spent fuel to the contracted fuel supplier, if possible, for disposal or reprocessing. In the case of a relatively small nuclear program and where fuel was purchased from a foreign supplier, the fuel contract can stipulate that spent fuel will be returned to the original supplier for management and disposal.
3. Proceed to deep geological 'permanent' disposal, once the volume of material requiring such disposal justifies this process, and a site is approved. This process is generally agreed by IAEA member states as being the most politically desirable, secure and socially-preferred ultimate option. It may also be required, as spelled out in the U.S. Nuclear Waste Policy Act (1982). However, the process is extremely costly, and in terms of cost-benefit considerations alone, without the political baggage, is difficult to justify.

In the last option there is still a further possibility that the emplaced spent fuel can be re-accessed if the politics or economics of re-processing and re-use, recognize that the contents of such a facility, after a relatively short period of decay, represent a highly cost-effective resource of low radioactivity, immense energy potential with minimum pollution, that can be safely exploited.

4.5 Waste Vitrification - Fission Waste Stabilization

Vitrification is the process of containing and stabilizing the small volume of highly-radioactive separated fission wastes (less than about 5 percent by volume of the original spent fuel) from the reprocessing cycle, into an inert and stable ceramic or borosilicate glass block form, for secure non-retrievable disposal. Other methods may include the use of concrete or other materials as a containing medium.

These blocks are relatively small in total volume - though of initially high radioactivity - and can be securely packaged or encased before being temporarily stored in monitored and shielded facilities until underground disposal (the generally accepted method) or concrete vault disposal is required.

As they contain only relatively short half-life fission radionuclides - as summarized in Table 7 - their management time frame is no more than about 300 years at most, and they do not constitute a nuclear proliferation issue, as they do not contain transuranium nuclides.

5. GEOLOGICAL DEEP DISPOSAL

Deep disposal of the small volumes of nuclear waste following spent fuel reprocessing has generally been the option of choice from a safety, scientific, and engineering point of view. However this option needed to be re-evaluated when it became clear that the political decision by the Carter administration in 1977 in the U.S., to abandon fuel reprocessing, could lead to an increase in waste disposal volumes by about a factor of 30. This forced the industry to shoulder considerably higher costs, much greater long-term safeguards, and required major development of new disposal space that had not previously been envisaged.

The longer term considerations also had to be expanded from a matter of about 500 years at most - as most fission nuclides are completely decayed prior to about 300 years - to consideration out to several thousands of years to allow for the decay of the relatively long lived plutonium-239 (half-life 24 000 years). This extended period of management is not because of the contained radioactivity, which is minor at this time, but because of the security aspect associated with plutonium. Proliferation risks in the longer term, because of unauthorized access to the repository, are the main concern.

Despite these major politically-created changes, geological disposal (of fission nuclides, transuranium wastes and possibly spent fuel) is believed to represent the most secure long-term method of dealing with nuclear wastes and safely removing them from society.

The deep disposal process was also briefly considered, but soon discarded, as a means of disposing of retired nuclear warheads, and is still being considered in some jurisdictions for non-reprocessed spent fuel. As the operational time frame for such a repository is still at least a decade or more away, the political fallout from any decision to dispose of spent fuel in this way, representing a massive waste of a valuable resource during a time of energy difficulties, may require that the issue be re-visited.

Such disposal also increases the likelihood that any such facility will need to be legally re-accessed to get at the relatively pure uranium and plutonium for future energy production, and also increases the likelihood that such a facility might become the target of nuclear proliferation efforts in the future by those also interested in trying to access plutonium in the - by then - low radioactive environment. There is an irony to all of this, in that through political efforts to reduce the perceived dangers of proliferation by forcing the U.S. nuclear industry to abandon reprocessing and recycling through the reactor, then-president Carter created a much larger proliferation risk for future generations. In addition, efforts to minimize reliance upon foreign sources of energy through the development of advanced and breeder reactors were setback by decades, also leading to much greater risk of both social instability and international conflict.

5.1 Development of the Concept and of a Disposal Facility

The development of the disposal concept, and defining the requirements for a deep disposal facility require an intimate knowledge of the materials that need to be disposed of, the environment into which they will be placed, and some knowledge of the human risks and their significance that may need to be addressed. It also requires detailed definition of the conventional chemistry of the materials requiring disposal; of the geological and groundwater chemistry of the environment in which they will be placed; and the internal repository characteristics, as well as geological external changes that are likely to be encountered with time.

Some of the concepts and engineering safeguards required, and which are used in deep storage applications, are shown in Table 8.

Table 8. Geological, Design, Engineering, Remedial and Temporal Barriers to Dissolution, Migration and Environmental Dispersal of Nuclides from a Repository.

Barriers	Specific Requirements
Conceptual and scientific	Minimal waste. Vitrification of fission wastes. Encapsulation and stabilization of wastes. Geologically stable rock formation (granite, tuff, salt). Low seismic activity. Minimal jointing. Minimal groundwater flow. Low population density. Minimal environmental impact.
Engineering design	Deep site burial, non-permeable - chemically inert - materials, eventual backfill and sealing, provisions for security and maintaining site integrity.
Regional, site surface, and site deep monitoring	Deep sited and surface detectors, borehole logging, air monitoring, groundwater analysis, groundwater flow patterns and volumes, meteorological monitoring, seismic monitoring, total environmental monitoring, International safeguards and surveillance. Financial rewards for those providing a site.
Remedial	Grouting and sealing of fracture zones, use of impermeable membranes, inflow only - no outflow, chemical modification of groundwater to reduce aggressiveness, water collection and monitoring, ion exchange cleanup.
Time	Radionuclide decay. Residual effects are those due to chemical, rather than radiological toxicity. Allowance must be made for retrieval of recyclable resources, re-processing and replacement of wastes.

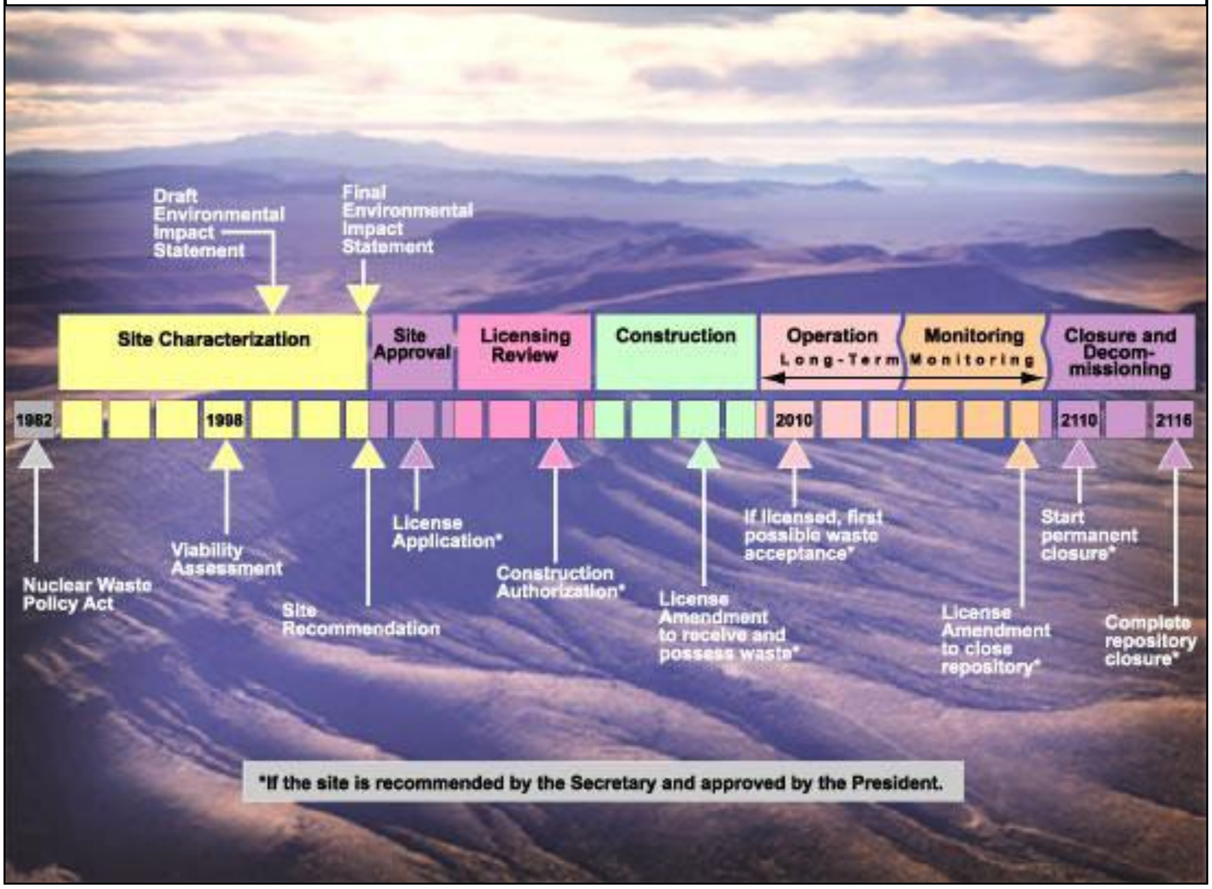
All of these conceptual and engineering requirements are brought together in the actual site selection process. The Yucca Mountain facility in the U.S. as shown in Figure 3, exemplifies the usual course of events, including political disagreement and obstruction, as well as other interventionist activities in de-railing or stalling the lengthy process through court challenges.

The present situation for Yucca is that, upon completion and closure of the facility, 90 percent of its volume (or about 70 000 tonnes of wastes) will be made up of spent fuel and fission wastes from commercial nuclear power facilities and 10 percent (about 7000 tonnes) will be defense wastes. Had reprocessing of spent fuel not been proscribed by the Carter administration, then the quantity of commercial High Level wastes requiring disposal today, from all of the commercial reactors in the U.S. would be no more than about 3000 tonnes, and Yucca would have been fully capable of containing all of the commercial and defense wastes for the foreseeable future without consideration of either expanding it, or of being forced to consider politically thorny alternatives and additions.

The general stages of site selection and the processes following from there, are shown in Table 9 and Figure 3, which summarize the approximate milestones and time schedule for most such disposal sites as well as, in part, to the Yucca Mountain facility.

Table 9. Typical Stages and Milestones in a Site Selection and Disposal Operation Process	
Stages	Milestones, some of which may be revisited.
Policy Formulation	Political recognition of need, and consideration of costs. Definition of the basic disposal criteria that must be addressed and met. Assumptions concerning future society and its risks that may influence these criteria. Public participation in the decision making process. Evaluation of rational options and selection of preferred option. Modifications, additions and political policy variances, and changing standards, such as for water quality guidelines.
Site Proposals and Site Evaluations	Scientifically defined criteria for site acceptability. Definition of suitable sites that meet these criteria. Narrowing of selections. Site recommendation (s). Public participation. Political approval, accommodation, and adjustments. Changing Criteria.
Site Selection(s)	Site conditional approval. Political approval and adjustments. Changing criteria.
Site Characterization	Natural background radiation measurements and site geological definition. Environmental impact assessment - short-term and long-term - of the site operation. Environmental Impact Statement. Site recommendation. Political approval and changes. Changing criteria.
Site Approval	License application. Licensing review. License approval. Changing standards and license conditions.
License Approval	Construction authorization. Changing construction requirements and approvals.
Site Construction	Ongoing site evaluation. Construction completed. License amended to allow receipt and possession of radioactive waste materials. Changing standards and approvals.
Operational Phase	Receipt of wastes. Inventory, classification, and record of placement. Progressive placement and backfilling as required. Changing standards.
Monitoring	Continuous monitoring as the facility receives and places materials. Consideration of remote passive monitoring requirements of selected placement zones. Continuous monitoring following completion of waste placement in the facility.
Closure and Decommissioning	Start permanent closure. Complete the repository closure.
Post closure	Active monitoring, giving way to passive monitoring of the facility at surface, in boreholes, and of groundwater (if any). Changing requirements and standards
Future security	Political requirements and consideration of rules for re-access

Figure 3. Overview of the Yucca Mountain Facility in Nevada in the U.S. with an approximate time-line for its Operation and Closure (from the US. DOE, NRC and EPA).



Geological disposal in comparable sites that have undergone some or all of these initial stages is already practiced in some countries (Finland, Sweden, U.K., Germany) for disposal of Low and Intermediate Level Wastes (LILW). Comparable facilities are also being identified and prepared for eventual disposal of High Level Wastes including spent fuel. However, other countries, for the moment, deal with LILW in either shallow burial or surface management facilities, and are considering deep disposal mostly for High Level wastes such as spent fuel (if not reprocessed), fission nuclides, and Transuranium Wastes.

Geological Deep Disposal is envisaged for all High Level Wastes (HLW) in those countries with relatively large nuclear programs. Other countries with smaller nuclear programs need to safely store their HL wastes until a re-processing or disposal process is decided either domestically or by contractual arrangement with another country. Some countries already adopt such supply contracts for fuel and spent fuel reprocessing or disposal, which relieves them of the need to conduct a relatively small scale and expensive operation, but necessitates that spent fuel is securely managed until it can be safely transported. Some jurisdictions (governments) are studying the feasibility of selling such a disposal service to those countries that would prefer that the issue be dealt with by others. An international consortium - ARIUS - Association for Regional and International Underground Storage, is looking at becoming such an international and regional manager of nuclear wastes in Europe at least. Russia is considering a similar role.

5.2 Description of a Typical Geological Disposal facility

Numerous pilot projects have been constructed which have demonstrated the feasibility of this general disposal concept.

Supportive data have also been obtained from the last century of mining activities at thousands of sites and from the study of numerous ore bodies - including Oklo, a natural uranium reactor that operated 1.8 billion years ago - their long term stabilities; and groundwater circulation and transport characteristics in a variety of climates and geological formations.

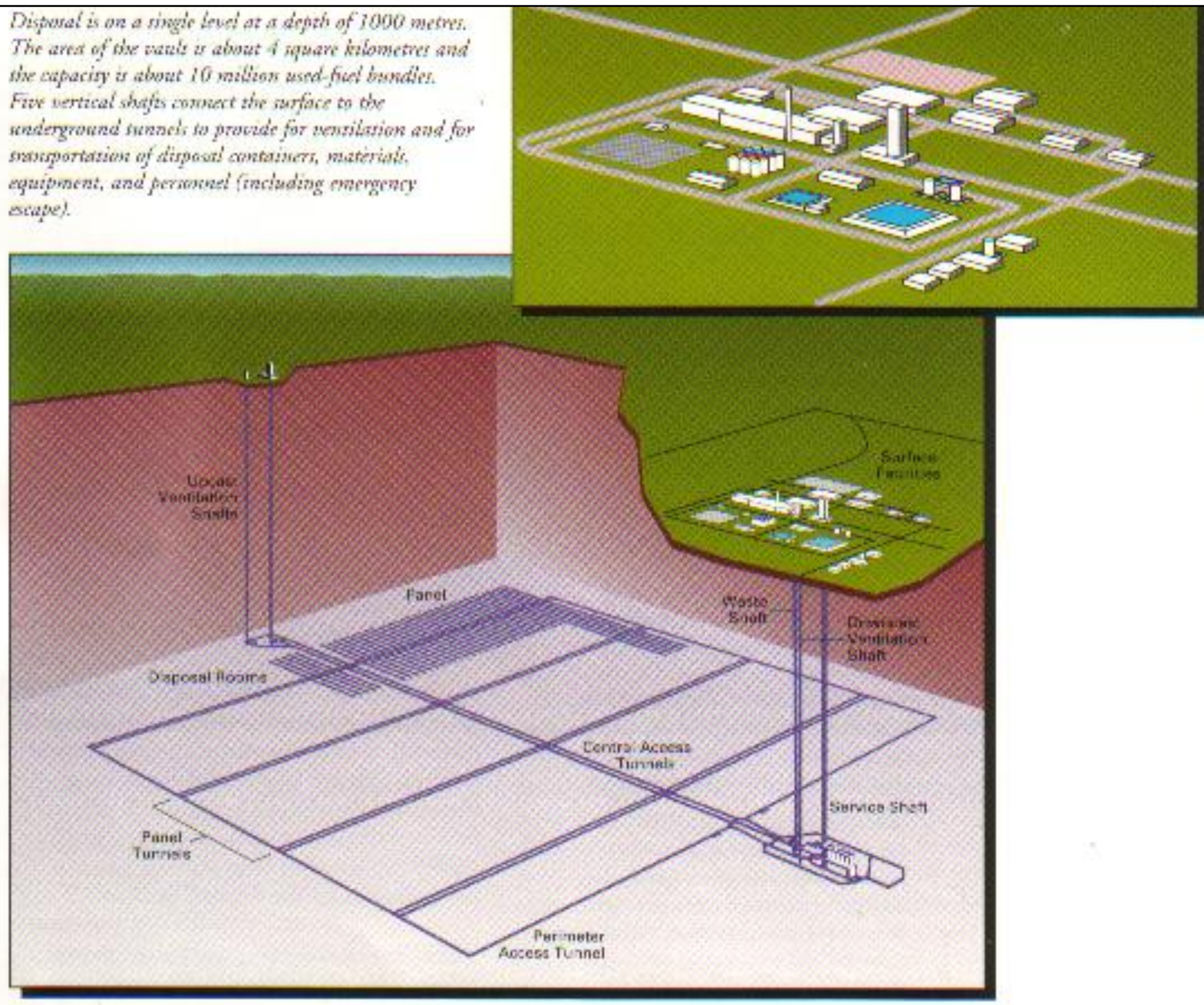
The disposal requirements can allow use of an existing mine site, or require that a specific disposal facility be constructed, as with the politically controversial Yucca Mountain project in Nevada in the U.S. Each country with a major nuclear program is likely to construct such facilities according to its own perceived requirements and safeguards. The general requirements are that it be deep in a stable rock formation with minimal or no water circulation, and it should be remote from human activities. Whereas a normal mine is constructed to take ore out of the ground without any such considerations, this one will be constructed to accept radioactive materials.

One deep facility concept - that of Atomic Energy of Canada Ltd (AECL) - is shown in Figures 4 and 5. In general details the facility is comparable to any mine or other deep disposal facility, and addresses many of the same requirements for mine safety, stability and control, but with special additional restrictive criteria (restricted groundwater penetration and circulation, few joints and fractures), and security requirements that will be much less onerous than those found in diamond mining operations today.

The external and surface signs of its operation will be that of a typical mine site but with none of the ore-processing facilities and with whatever level of security is mandated. There will be an all weather access road; electrical transmission lines; one or more entry and ventilation structures; security fences and structures; administration and maintenance offices; laboratories and buildings for vehicle and equipment maintenance; standby generator; special packing materials for backfilling, packaging and transfer operations; and an associated waste pile consisting of rock removed from underground, and safely disposed of at the surface. Some of this rock material will later be used as backfill when the repository is to be 'permanently' sealed, after some 50 years or more of monitoring.

Access to the underground facility may be by vertical or inclined shafts, or horizontal or inclined adits if the structure allows this. The underground structures will consist of a usually rectangular grid arrangement of access tunnels either leading to large storage chambers, or from which storage holes of a few cubic metres capacity are excavated to the sides or in the floor to receive packaged materials. Spacing and separation of contents will be to control temperature rise in the eventually sealed facility. What is disposed of, how, and where, will generally be a function of initial heat dispersal requirements. However, there is also the recognition that this heating effect can also serve to keep circulating groundwater out of the facility for a considerable time.

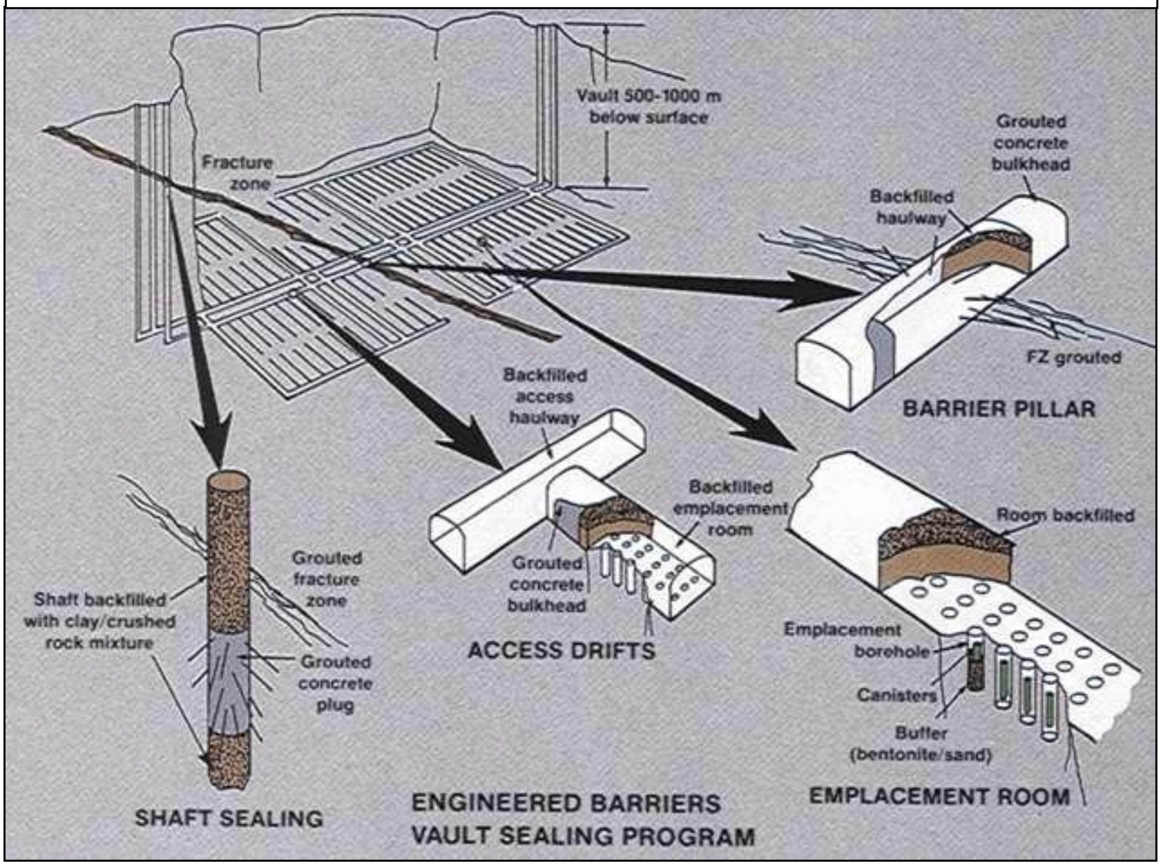
Figure 4. Schematic Overview of a Proposed Deep Disposal Facility Constructed in the Canadian Pre-Cambrian Shield (Atomic Energy of Canada Limited)



The concepts of 'permanence' (meaning also, inaccessible) and 'retrievability' have little meaning with respect to these structures, as they can never be made entirely inaccessible, and certainly they would never be engineered to be easily accessible either. Some disposal plans allow for the possibility that certain of the identified contents may be eventually retrieved by knowledgeable future generations if they contain spent fuel or

other potentially valuable materials. The way in which the structure is constructed, laid out, and filled, will need to take into account this possibility.
However, if the contents are fission nuclides, without spent fuel, there is no reason to either access the facility at some future time, nor to consider its security beyond even a few decades, as the radioactivity of the contents will rapidly become negligible.

Figure 5. Schematic of Possible Structure within a Disposal Facility, Showing Disposal Compartments and Possible Protective Schemes to Address Geological Fractures (AECL).



If the disposed material is non-re-processed spent fuel then the facility will eventually (after about 500 years) become radioactively and economically comparable to a very rich uranium ore body, but with plutonium. Possible catastrophic effects that might disrupt the facility: earthquakes, volcanic activity, glaciation, or meteorite impacts are no different from those that have affected natural uranium ore-bodies over the past history of the earth, and would have similar and negligible effects considering the depth of placement. Any such effect that might be large enough to affect the facility at a depth of one kilometre would have much more serious social and regional consequences at the surface, than would the relatively minor effects from breaching such a facility.

5.3 Summary Points of Prepared Nuclear Wastes, and Aspects of their Disposal

- Spent fuel that is not destined for reprocessing should **not** be consigned to deep disposal, as there will be a need to recover this resource in the future.
- Spent fuel that is not reprocessed remains radioactive at a very low level, only because of the original uranium (about 95 percent of the starting quantity, by weight) that remains in it.
- Spent fuel that is not reprocessed gradually becomes little different from uranium in a rich uranium ore body, but with significant plutonium content. Contrary to popular wisdom, plutonium is practically harmless outside of the body and is of relatively low radioactivity. The greatest threat with plutonium is its use in weapons. For this reason, such a deep repository is assumed to discourage and restrict unauthorized access to the repository to recover it for some use other than recycling it for commercial energy production.
- Vitrified high-level fission wastes, are low-volume radioactive insoluble solids that are both easily shielded and safely transported. They are typically much less radioactive than many medical radiation devices and materials which are safely shipped around the world, with millions of such medical shipments each year.
- As solids, and like other geological 'rocks', once buried and sealed with various engineered barriers including metal casing, impermeable clay and concrete and bitumen plugs and boundaries, spent fuel and other nuclear materials can neither leak nor migrate and they become similar to existing rock formations once emplaced underground.
- After about 500 years, the vitrified fission waste is essentially non-radioactive because of decay. Radioactively, it is harmless; chemically, it may contain harmful elements if they are taken into solution and brought to the surface to interact with the biosphere, but without monitoring or control.
- Presumed failure of the repository and leaching by water after several thousands of years when its radioactivity is little different from that of a natural uranium orebody, would be comparable in every way to the leaching of present-day uranium ore bodies; mostly undetectable, and inconsequential. Even Uranium ore-bodies near the surface are hard to find by sophisticated analytical techniques whose detection limits are billions of times more sensitive than conventional chemical analyses for typical pollutants.
- Dissolution of materials in a repository, by groundwater, after several thousand years would be on an atom by atom basis - as for most 'insoluble' vitreous rocks, and practically insignificant, though detectable to modern methods of analysis, looking at water in boreholes drilled into the facility.
- Anything detectable is remediable before it might reach humans, and is as easily corrected by simple chemical treatments, as 'hard' water from a household water supply.
- Migration of soluble trace materials in groundwater at depth, usually takes many thousands of years to move even a few metres. This groundwater may also never reach the surface, especially if it is a relatively dense brine as in salt formations often chosen for this reason as repository locations. If it did eventually reach the surface, the consequences of any trace quantities of long-lived and low

radioactivity radionuclides would likely not be detectable in the normal background of natural radium and radon daughters.

5.4 Risks of Emplacement.

The potential future radiation risk to **hypothetical** residents of the area from the completed and closed facility up to 10 000 years (long after all of the significant fission nuclides have completely decayed), is the only risk - as vanishingly small as that is - that seems to concern those examining this concept. However, it is not the only risk that should be considered. There are other, larger risks associated with all of the various stages leading up to permanent disposal that should also be examined. These are:

- Risks in building the permanent storage facility. Mining fatalities and accidents, and shaft-sinking fatalities and accidents at the time of construction, are significant to miners, and would undoubtedly exceed all future risks from the completed and closed facility to any segment of society.
- The risks involved in bringing radioactive rock-waste containing natural uranium, thorium, radium and radon gas to the surface as the facility is developed, and storing this material at the surface for decades until some of it might be replaced.
- The radon exposure risk (calculated) to workers from surface-placed materials and underground.
- Risks to workers transferring the 50-year old spent fuel into transportation flasks from the existing dry storage facilities.
- Occupational Risks to drivers from transporting radioactive spent fuel up to several thousand kilometres, in thousands of shipments, to the disposal site.
- Risks to drivers and the public from transportation accidents. Highway transportation accidents are a significant source of risk to all road users. The risk from radiation release in such accidents is almost non-existent.
- Risks to workers at the surface and underground during transfer and movement of fuel into the permanent storage facility and during the filling operation until completion and closure.
- The risks and costs of re-accessing and re-mining the uranium `waste' from a sealed facility at some distant time in the future.

A comparison of the various estimated approximate risks to workers and the public from the two rational options available is shown in Table 10. These options are:

1. **Continue with the existing process**. Leave the waste at the surface, as it is at present, in managed and secure storage, as shown in Figure 6. This can be either an interim option in preparation for shipment to permanent storage, or can be used to store spent fuel for a longer term as suggested in Figure 6, while keeping it available for possible future reprocessing. Figure 6, shows a CANDU surface temporary storage facility. The spent fuel in these silos is not as economically attractive for reprocessing as spent enriched fuel, though the possibility for reprocessing even natural spent fuel, remains an option in the future and is one reason why permanent

deep disposal may not take place for spent fuel, as it would soon need to be re-accessed.

2. **Consign all nuclear wastes to a deep disposal facility** (Figure 4), as at present envisaged for all such wastes.

Figure 6. A Typical Spent Fuel and Radioactive Waste, Surface-Storage Facility in Canada. The Cylindrical Concrete Canisters in the Background (100 of them) are sufficient to safely hold the approximately 1000 Tonnes of Spent Fuel from about 10 Years of Full Power Operation of a CANDU Reactor. The Site will accommodate 200 more such Canisters to securely contain all Spent Fuel from at least Thirty Years of Reactor Operation. The Concrete Structures in the Foreground hold relatively low activity Maintenance and Process Wastes. (Photo, Courtesy of NB Power).

The second option - deep disposal - may follow from the first - surface management, but not necessarily if it is clear that spent fuel will need to be re-accessed. The alternative possibilities are shown in Figure 7. Deep disposal is excessively expensive; achieves little or no reduction in actual risks, and may increase them; but it is a politically safe and acceptable option for all such wastes, even though it may be justified only for the small volume, reprocessed, fission nuclides.

Figure 7. Options, Management Stages, and Time Lines for Spent Fuel Management, Reprocessing, and Surface or Deep Underground Disposal.

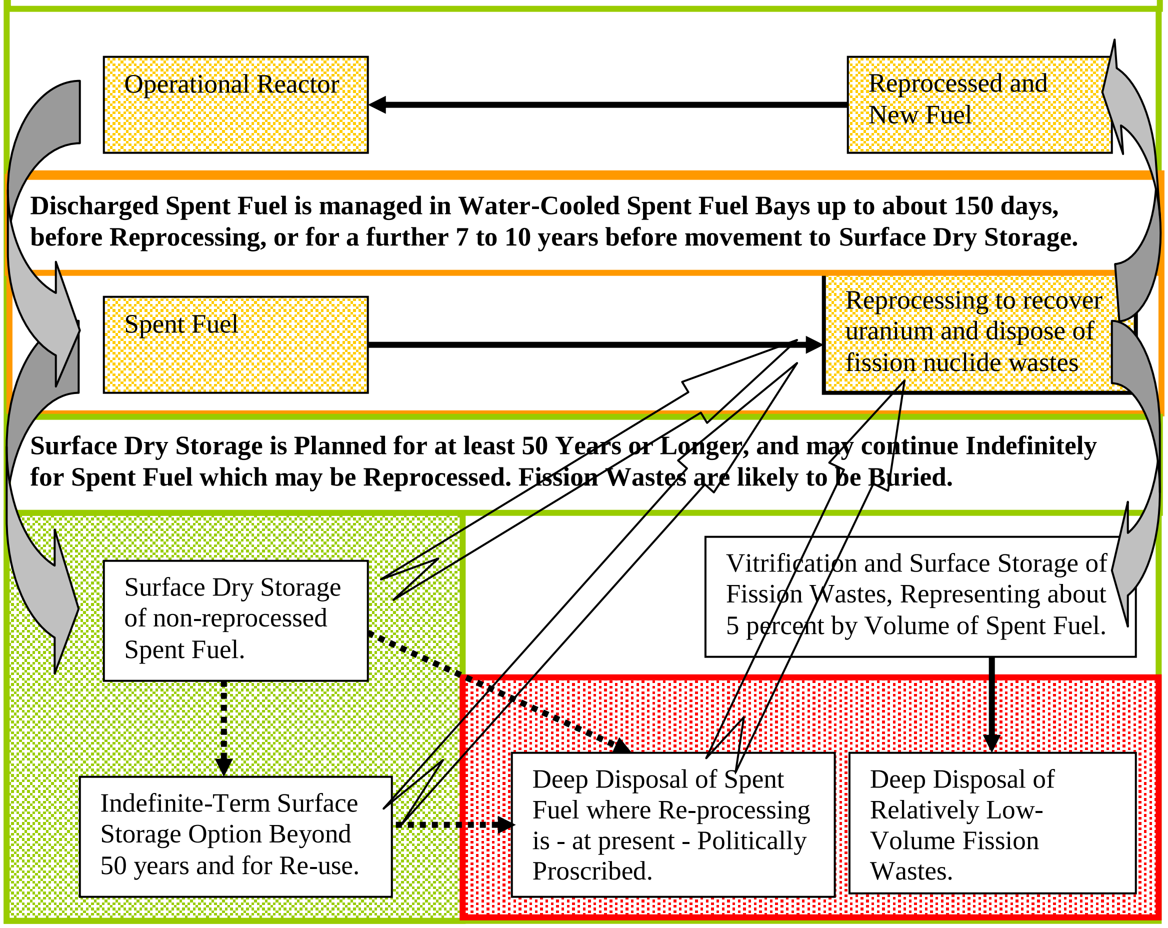


Table 10. Estimated Risks to the Public and Workers from Surface Storage, and Deep Geological Disposal of High Level, Transuranium Nuclear Wastes, Fission Wastes, and Spent Fuel.		
Storage and Management, or disposal options	**Public lifetime risk from chronic radiation exposure**.	**Worker risk, (calculated, in days of lost life expectancy (LLE)) from chronic radiation exposure, assuming 30 years of employment**
1. Surface Concrete Canisters	The general public is not significantly at risk from such a facility which is secure, controlled and managed, with round-the-clock surveillance, and to which they have no access.	Worker risks are low and controlled. Dose limits apply. Minor conventional risks (falls, etc) with a surface facility.
Radiation risks to public and workers	No likelihood of exposure. Risk is therefore close to zero.	14 days of LLE calculated (*), assuming the validity of the LNT hypothesis
Other risks	No exposure and no access, therefore risks are close to zero.	Conventional hazards: falls, etc.
Advantages	Secondary benefits through the social health of society by using a nuclear power source rather than fossil fuels for energy.	Employment
Total risk to individuals	**Essentially none.**	**Minuscule, and controlled by regulatory dose limits**
2. Geological Deep Disposal Facility	**Public risk from radiation and transportation accidents associated with the movement of waste to the facility and from radiation risks in the far future - post closure.**	**Worker risks from radiation and from conventional industrial hazards.**
Construction	Minimal public risk; some benefit through employment	About 400 days of LLE. Shaft sinking and mine work, are dangerous occupations
Radiation risks from removed granite	Local surface risks (minor) from radon leakage from waste rock.	Underground radon risks (calculated (*)), controlled by occupational dose limits
Transfer and transportation risks	Almost zero, to minor risk.	About 50 days of LLE. Conventional and Radiological Risks (*) to workers sending, transporting, and receiving the 'waste'.
Placement risks to workers	Mimimal. No public access.	Conventional mining risks. Radiological risks are controlled by radiation dose limits.
Public radiation risk to 500 years	Minimal from the secured and continuously decaying contents, shielded by 1 km of overburden. No access.	Minimal. No workers are involved.
Public radiation risk to 10 000 years	No access. Potential risks are continuously falling with time. By the time the facility may fail or leak, anytime after 500 years, the contents are little more radioactive than natural uranium	Minimal. No workers are involved.
Total risk to exposed individuals	**Minor risks during transportation and filling. Practically zero after completion.**	**Risks to workers during construction. Practically zero risk after completion unless re-access is required.**
* Calculated risk expressed in terms of Loss of Life Expectancy (LLE) assuming the validity of the LNT radiation risk hypothesis. This controversial and questionable assumption is likely to overestimate risks from chronic and low dose radiation exposures by at least a factor of 10.		

Comparing these risks, and assessing costs incurred relative to benefits achieved, indicates that either option involves extremely low related risks to the public or workers, which on any ranking of social risks is very close to the bottom of such a list. The least risk of the two considered to society in general over any time frame, and workers in particular, comes from leaving the material where most of it is at this time, in secure, monitored and managed, relatively low cost, dry storage concrete canisters on the surface. This avoids the risks of underground construction, transportation risks, and avoids the massive costs associated with permanent deep disposal and thus should be the most cost effective action. This is not, however, a politically acceptable conclusion at this time.

Objective assessment of costs and risks both incurred and avoided, suggests that more lives would be lost in conventional accidents during constructing, moving materials, and operating a deep disposal facility, than would be at risk from any cause, by leaving the nuclear waste, indefinitely, in its present managed storage where it will eventually be re-accessed for reprocessing after a few decades to perhaps 100 years. By the diversion (loss) of many billions of dollars from the economy in constructing a deep disposal facility, major loss of life is incurred by depriving other, more deserving, risk-reducing social programs of funding.

6. REACTOR DECOMMISSIONING

Reactor decommissioning could be considered only after the reactor has been completely de-fueled and possibly mothballed for some length of time to allow for the decay of the relatively short half-life activation and other nuclides.

Typically, fission nuclides are mostly trapped in the fuel matrix and are removed with the spent fuel, however, some fission nuclides escape from any fuel which develops pinhole leakage or which fails more significantly during use in the reactor, and these may circulate through the primary coolant systems to plate out or otherwise become trapped within those systems. These decay while work is undertaken on decommissioning the other, non-radiological parts of the facility. After some period of time, decided by balancing the radiological costs of dose, against cost constraints of not proceeding with dismantling that particular reactor, which could be from a few years to several decades, reactor decommissioning may proceed.

Some radioactive wastes are produced in the decommissioning phase of reactor retirement. They arise during reactor operation from neutron activation of trace elements in the metallic components, neutron activation of gases, such as air (containing nitrogen which is activated to carbon-14) and from fission nuclides that escaped the fuel and become trapped in systems outside of the reactor core.

Table 11. Main Activation Radioisotopes Produced by Neutron Activation of Reactor Components and other Materials Exposed to Neutrons.

Radio-isotope	Source and Reaction	Half-life
Nitrogen-17	Oxygen-17 (n,p)	4.17 seconds
Nitrogen-16	Oxygen-16 (n,p)	7.13 seconds
Oxygen-19	Oxygen-18 (n,)	26.9 seconds
Aluminum-28	Aluminum-27 (n,)	2.25 minutes
Argon-41	Argon-40 (n,)	1.83 hours
Manganese-56	Iron-56 (n,p)	2.58 hours
Copper-64	Copper-63 (n,)	12.70 hours
Sodium-24	Sodium-23 (n,)	14.95 hours
Tungsten-187	Tungsten-186 (n,)	23.9 hours
Phosphorus-32	Phosphorus-31 (n,)	14.28 days
Rubidium-86	Rubidium-85 (n,)	18.65 days
Chromium-51	Chromium-50 (n,)	27.7 days
Iron-59	Cobalt-59 (n,p)	44.51 days
Cobalt-58	Nickel-58 (n,p)	70.88 days
Tantalum-182	Tantalum-181 (n,)	114.43 days
Zinc-65	Zinc-64 (n,)	243.8 days
Sodium-22	Sodium-23 (n,2n)	2.60 years
Iron-55	Iron-54 (n,)	2.73 years
Cobalt-60	Cobalt-59 (n,)	5.27 years
Tritium (H-3)	Deuterium (n,)	12.33 years
Carbon-14	Nitrogen-14 (n,p)	5715 years

Most data updated from 'Radioactive Wastes', former U.S. Atomic Energy Commission publication in the series 'Understanding the Atom' and Chart of the Nuclides.

Generally these decommissioning wastes are free of most radionuclides of fairly short half-life, which have decayed, while others still remaining are those with a half-life longer than several months. They may include those shown in Table 11, beyond iron-59 in terms of half-life. Cobalt-60 - if present - is usually of most concern, as it can make up about 40 percent of the activation radionuclides. It has a relatively high-energy gamma emission of about 2.5 MeV on each decay. With a half-life of about 5 years it requires about 50 to 100 years for almost total decay, though decommissioning work can proceed at any stage, provided worker dose limits are not exceeded.

Reactor components are usually carefully selected and specified to be free of certain trace metal impurities if possible, to minimize the production of certain activation nuclides.

Many of the components, those with minimal activity, may be promptly recycled and re-used on the facility site in those areas where their radioactivity may already be less than materials in some reactor areas and applications. For release to off-site use, disposal, or recycling, however, the components must meet the defined regulatory criteria and present no hazard to the public.

Decommissioning is the process of taking the retired and de-fueled reactor, and most or all of its remaining structures out of service. It usually takes place in 3 stages over an interval of time to allow activated materials to radioactively decay to the point where they can be most safely removed and possibly recycled. Usually, the site may contain other operating units or is chosen as the location of a next-generation facility, in which case some of the retired components may be re-used or recycled into the new structure. The various stages are approximately outlined below. The actual processes, their timing and completion are the subject of planning decisions that are specific to the individual reactor or facility and the regulatory requirements of the jurisdiction in which it is located.

Stage 1. After reactor shutdown all fuel is promptly removed from the reactor and stored on site until it can be removed and safely transported to another secure site for re-processing or for transitional storage. All liquid systems are drained, with recovery and processing of the liquids to remove soluble isotopes into ion exchange resins for disposal as solids, before the fluids may be discharged. Usually, all systems and access points are sealed to ensure no exchange of airborne or leaking materials between the reactor components and the outside environment. The facility is monitored and kept under surveillance but with limited access to ensure that it remains in a secure and safe state.

Stage 2. At this stage possibly several years after stage 1, all equipment and buildings that are required to be dismantled are removed and stored according to their radioactive classification, or may be discarded or re-cycled. Others may be decontaminated and re-used for other purposes on the site. The reactor core and its associated shielding is left in a protected and monitored state.

Stage 3. If the remaining structures are not being re-used in some way then all of the former structures may be removed. All remaining materials and the general location are surveyed to ensure that residual radiation levels are not significantly different from the original natural background radiation in the general area. The site may then be considered safe and available for alternative and unrestricted use. After such decommissioning of the U.S. Shippingport Nuclear Reactor - the first operating land-based reactor in the U.S. - the site was declared safe for public use in 1987.

However, once a suitable site has been licensed for reactor operation, it is likely to continue to be used for that purpose as there is unlikely to be any decrease in energy requirements in society, nor any obvious alternative to nuclear energy that fits environmental requirements of minimal pollution, can meet all of society's human and industrial needs in an adequately safe manner, and can meet expanding energy requirements in the future without concerns of resource depletion and resulting energy shortages.

7. CONCLUSION

Nuclear wastes; their regulation, control, management and disposal, are among the most sensitive, politically-manipulated issues in all society. No matter what is believed likely to be the rational course of action in dealing with nuclear issues and wastes, or what has been politically decided, the intervention of new political ideologies can drastically change the way an issue is addressed and dealt with, almost overnight. This was best exemplified by the Carter administration decision in 1977 to ban reprocessing spent fuel, and thus to stall the development of advanced reactors. The subsequent effects upon the U.S. nuclear industry, as well as upon energy implications for succeeding decades and into the far future have been incalculable. The effects, because of greatly augmenting nuclear waste disposal volumes were, and are, all-too-obvious today. The associated waste of energy resources in times of energy crises, which have cycled with increasing regularity as conventional reserves and availability are progressively less assured, are beginning to be appreciated. The effects upon the social stability and energy future of parts of the world have yet to unfold, but are likely to be serious.

In any society that is concerned with achieving the greatest good for the greatest number, there should be an attempt made to identify, and rank all of the social risks that impact upon that society. Resources to address known risks, should be allocated to those items towards the top of the risk ranking, rather than to the bottom, where they will be wasted. However, most governments appear to ignore their own regulations when it comes to justifying their actions. They largely ignore rules which require justification and consideration of cost-benefit comparisons in their implementation of various social programs. This leads to misallocation of resources, to great social detriment and cost.

The purpose of cost benefit analysis is to ensure that any action considered in society will be rationally justified, and will obviously and definably confer more benefit to society than detriment, or more obviously, will result in fewer deaths than the alternatives.

Although it seems morally desirable and responsible to extrapolate and address potential human risks out to perhaps thousands of years in considering nuclear waste disposal, this is neither responsible, nor justified. There are current, present-day risks thousands of times more significant than nuclear wastes, to societal health, which we conveniently ignore, and on which a relatively modest increase in spending (preventive health care, immunization, disease prevention, sewage treatment) would dramatically improve human health and the quality of life for both present and future generations. The best way to protect future generations in any way is to provide as healthy a lifestyle as possible in present day society. We do this by **not** wasting scarce monetary resources on mostly emotional and low risk issues, or on hypothesizing about future risks - but by spending social resources where they will actually and definably do the most social good.

Comparison of the effects (costs and benefits) of different uses of social resources, has established that for every $5 million (approximately) removed from society through misallocation of resources, there will be one premature death likely to have been induced. Thus, expenditure of say $100 billion on such a venture as a nuclear waste disposal facility is likely to result in about 20 000 needless deaths. On the other hand, as the development of such a facility would not reduce the already small risks in any significant way, and would not save any lives, as none are threatened, so the actual cost would far exceed any expected benefit now, or in the future.

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Word Count: 12 000