RADIOACTIVE WASTES, ORIGINS, CLASSIFICATION AND MANAGEMENT

John K. Sutherland.
Fredericton, New Brunswick, Canada

Keywords

Radioactive Wastes, High Level Wastes, Transuranic Wastes, Low Level Wastes, Spent Fuel, Waste Management, Licensing, Waste Disposal Options, Deep Geological Disposal, Transmutation.

Contents

Glossary

ADS	Accelerator Driven System for power production and transuranic waste destruction
Bq	Becquerel. Unit of Radioactivity. One disintegration per second
CANDU	CANadian Deuterium (natural) Uranium
DU	Depleted Uranium
GW	Gigawatt, one billion watts
HEPA	High Efficiency Particulate filter
HLW	High Level Waste
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate Level Waste
LILW	Low/Intermediate Level Waste
LILW-LL	Low/Intermediate Level Waste, Long Lived
LILW-SL	Low/Intermediate Level Waste - Short Lived
LLW	Low Level Waste
MW	Megawatt, one million watts
NIMBY	Not In My Backyard - opposition to a process
NNPT	Nuclear Non Proliferation Treaty
NORMS	Naturally Occurring Radioactive Materials
PWR	Pressurized Water Reactor
TENORMS	Technologically Enhanced NORMS
TW	Terawatt, 1E12 Watts
TU	Transuranic - transuranium - above uranium in atomic number
WIPP	Waste Isolation Pilot Project

Summary

This article discusses the various sources of radioactive wastes throughout society and provides some indication of the activity present in many items throughout society that may or may not be classified as radioactive wastes. A comparison of radiation doses throughout society from all major sources of radiation shows that natural and medical radiation are the largest public sources of dose, while industrial and nuclear sources and wastes provide the smallest doses. It also examines some of the radiation accidents that are likely to directly affect workers and the general public through improper use or careless disposal of such materials. It provides a very brief overview of licensing, regulation, and various work-related practices that generally ensure full control and adequate management of both sources and their wastes to ensure that both the workers and public are safeguarded from encountering or being injured by exposure to such materials.

A description of the broadly accepted and approximate categories of radioactive wastes including Low Level, Intermediate Level, High Level and Transuranic Wastes is presented, with brief descriptions of each of the major waste types, their origins and how they are controlled and managed. Some detail is provided on spent fuel and the major options for dealing with it in the short, intermediate and long term. The long term disposal options for dealing with radioactive wastes, including deep geological disposal are briefly examined, including several that have been suggested in the past, but which do not generally meet the requirements for safe or adequate long term disposal.

1. RADIOACTIVITY AND RADIOACTIVE WASTES

Summary Points about Radiation and Radioactive Wastes

1. Radiation and radioactivity were discovered more than 100 years ago, and were widely used around the world in medical treatments within weeks of their discovery.
2. Radiation is now widely applied in thousands of uses throughout developed society.
3. The major sources of dose to the public are natural and medical sources of radiation.
4. The least radiation doses arise from industry and nuclear operations and all of their wastes.
5. Any source of industrial radiation, as with most hospital radiation sources, can be entirely shielded to protect workers and the public
6. Radiation and its uses - especially in medicine - are associated with thousands of times more beneficial effects than with harm.
7. All uses of radiation and some industrial processes produce radioactive wastes.
8. Radioactive wastes contain radiation sources which are not cost-effectively recyclable.
9. Radioactive wastes are securely and safely managed.
10. Radioactivity is a continuously decreasing quantity which is a function of the half-life (lives) of the responsible radionuclides.
11. Even near-surface natural uranium orebodies are difficult to find by sensitive techniques, despite the radiation from their numerous, intimately associated progeny (Table 1).
12. Deeply emplaced radioactive wastes, which fairly rapidly decay away totally (fission wastes), or become pure uranium-plutonium orebodies (decayed spent fuel), present no significant radiological risk of harm to any future society.
13. The risks associated with deep disposal are conventional industrial risks to those workers who construct and operate a facility, and risk of road accidents to those who transport the waste shipments. These risks significantly outweigh those minuscule risks from radiation, which exist from either disposing of the waste geologically, or leaving the relatively small volumes of HLW in secure, safe and managed surface-storage which the public does not encounter.
14. The value in spent fuel suggests that it should be surface-stored, as at present, and ultimately reprocessed rather than discarded as wastes that will likely be retrieved in the future from the relatively pure and low radioactivity uranium-plutonium orebody that it forms after a few decades.

1.1 Sources of Radioactive Waste

All industrial, agricultural, medical, household and human products, living spaces and wastes throughout society contain naturally occurring radionuclides as indicated in Table 1 and in graphs in the appendix, and are therefore, without exception, naturally radioactive to some degree as shown in Table 2.

Table 1. The Naturally Occurring Decay Series of Terrestrial Radionuclides, Most of Which are Present Throughout the Biosphere and in all Life Forms.

The Uranium Series		The Actinium Series		The Thorium Series	
Nuclide	**Half-life**	**Nuclide**	**Half-life**	**Nuclide**	**Half-life**
Uranium-238	4.50E9 y	**Uranium-235**	7.10E8 y	**Thorium-232**	1.4E10 y
Thorium-234	24.1 d	Thorium-231	25.6 h	Radium-228	6.7 y
Protactinium-234m	1.18 m	**Protactinium-231**	3.43E4 y	Actinium-228	6.13 h
Protactinium-234	6.7 h	Actinium-227	21.6 y	Thorium-228	1.910 y
Uranium-234	2.50E5 y	Thorium-227	18.17 d	Radium-224	3.64 d
Thorium-230	8.0E4 y	Francium-223	22 m	Radon-220	51.5 s
Radium-226	1620 y	Radium-223	11.68 d	Polonium-216	0.16 s
Radon-222	3.82 d	Astatine-219	0.9 m	Lead-212	10.6 h
Polonium-218	3.05 m	Radon-219	3.92 s	Bismuth-212	60.5 m
Astatine-218	2.0 s	Bismuth-215	8m	Polonium-212	3E-07 s
Lead-214	26.8 m	Polonium-215	1.83E-03 s	Thallium-208	3.10 m
Bismuth-214	19.7 m	Astatine-215	1E-04 s	**Lead-208**	Stable
Polonium-214	1.64E-04 s	Lead-211	36.1 m		
Thallium-210	1.32 m	Bismuth-211	2.15 m		
Lead-210	19.4 y	Polonium-211	0.52 s		
Bismuth-210	5.0 d	Thallium-207	4.79 m		
Polonium-210	138.3 d	**Lead-207**	Stable		
Mercury-206	8 m				
Thallium-206	4.2 m				
Lead-206	Stable				

The bold formatted long half-life progeny between uranium and stable lead ensure that secular equilibrium is not reached between refined uranium-238 and uranium-235 and all of their progeny for many thousands of years. This also assumes that radon gas does not escape from any of the series. Secular equilibrium is reached relatively quickly (about 50 years) in the thorium series.

The basic definition of what constitutes a controllable radioactive material varies from one country to another. Depending upon how radioactive waste is defined, many commonplace and naturally radioactive things around us could and in some extreme cases, have become unjustifiably classified as radioactive wastes.

If the definition is sufficiently restrictive, it could include discarded food wastes, building materials, concrete, soil, wood, water supplies, beer, milk, blood, fish, sewage, animal manure and even human beings themselves, to identify just a few.

This occasional desire to legislate an extreme degree of safety, has led to some states (Oregon), municipalities, and local government deciding to adopt a zero tolerance attitude to anything radioactive. Obviously, such legislators had not realized that everything is radioactive, and attempted to pass laws concerning radiation tolerance, radiation use and radiation disposal, with predictable results. The few examples of this, in parts of the U.S., and the predicted social turmoil, served as a lesson for other local governments to leave such matters in the hands of the experts.

Table 2. Typical Very Approximate Activity or Activity Ranges in Selected Industrial Wastes and Other Materials in Society	
Industrial Radioactive 'Waste'	**Activity (Bq kg^{-1} or as indicated)**
Metal Mining Wastes	Background to 400 000
Coal Ash	200 to 25 000
Scale in oil/gas pipes	Background to 15 000 000
Oil/Gas sludges	Background to 40 000
Oil/Gas produced water	10 000 to 40 000
Water Treatment solids	600 to 1 300 000
Phosphate processing solids	5 000 to 25 000
Geothermal solids	Background to 400 000
Nuclear 'Wastes'	
Depleted Uranium, DU (no progeny)	12 000 000
Spent Fuel (40 000 MWdays/tonne), after 6 years	2E13
LILW	100 000 to 1E9
Other Radioactive Materials	
Pitchblende or Uraninite	120E6
Granite	1000 to 5000
Wood ash	Background to 1000
Tritium EXIT sign	7E10 per sign
Radiography inspection device	1E12 per device
Radiation Therapy Co-60 source	4E13 per device
Hospital diagnostic radionuclides	1E6 to 1E10 per source
Household smoke detector	50 000 per device
Typical granulated fertilizer	5000
Typical adult human	7000
Human 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	10 000 Bq m^{-3} to >1 000 000 Bq m^{-3}
The industrial radioactive waste is known as 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.	

When the inevitable immediate difficulties and embarrassments likely to result were pointed out, the proposed legislation was rapidly revised, allowed to die, or quietly swept from the books totally. It continues to raise its head from time to time as politicians are replaced.

The 'difficulties' would be with transporting cadavers to graveyards or to a crematorium or burying them; transporting fertilizer or milk from farms or to stores; collecting blood donations; even letting some patients out of hospital; disposing of hospital wastes and using medical supplies; disposing of sewage; supplying drinking water; providing medical diagnostic procedures, as well as creating difficulties for most food transportation and use, as everything is radioactive to some degree.

The lesson was soon learned, but occasionally forgotten, that if the regulations governing radioactive wastes are defined too stringently, most activities in society come to a halt, international commerce stops and everything in nature becomes subject to impossible controls.

Properly defined and controlled 'radioactive' wastes usually contain elevated levels of radiation above 'normal' background (which can itself be much more radioactive than many people might feel comfortable with), as shown in Table 2, mostly because of certain changes which occur in processing or because of some other use of naturally occurring radioactive materials.

Major sources of controlled and some relatively uncontrolled waste (mostly mine tailings wastes) are shown in Table 3.

Table 3. Major Sources of Radioactive and Mostly-Controlled Wastes	
High Activity/Low-Volume Controlled Wastes	**Low Activity/High-Volume Controlled and Uncontrolled Wastes**
• Nuclear Reactor Spent Fuel. * • Fission Radionuclides from Re-Processed Spent Fuel. • Retired Medical Radiotherapy, And Industrial Irradiation Devices. • Military Reprocessing Wastes.	• Uranium Mine Tailings. • Thorium Mine Tailings. • Some Base-Metal Mine Tailings (Uncontrolled). • Maintenance Wastes From Nuclear Reactor Operations. • Depleted Uranium Stockpiles. *
* 'Wastes', only if not recycled.	

Other, less important and mostly uncontrolled sources arise from processing phosphates into fertilizer (U), burning coal (U and Th), and extracting water, oil or gas from underground reservoirs (Ra and Rn daughters). These are all examples of technological processes that may enhance the concentration of naturally occurring radionuclides (TE-NORMS).

The use of medical and industrial radionuclides, as shown in Tables 4 and 5, also produces radioactive wastes.

Table 4. Some Commonly-used Medical Diagnosis and Therapy Radionuclides Produced in Medical Reactors and Cyclotrons (Most Data are from the IAEA)

Reactor Produced Isotopes	**Use**	**Half-life**	**Cyclotron Produced Isotopes**	**Use**	**Half-life**
Mo-99 (Tc-99m)	Skeletal and Heart imaging	2.75 d, 6 h	Ga-67	Tumor studies	78 h
			Tl-201	Myocardial studies	73 h
Cr-51	Labels red blood cells	27.7 d	I-123	Thyroid studies	13 h
			Kr-81m	Lung studies	13 s
Co-60	Radiation therapy	5.27 y	In-111	Brain studies	67 h
I-131	Thyroid diagnosis	8.02 d	C-11	Brain imaging, PET scans, Cardiology	20 m
			N-13	Cardiology	10 m
			O-15	Oxygen utilization studies	2 m
			F-18	Epilepsy	110 m

Table 5. Some Common Radio-nuclides used in Industry and Biological Research			
Isotope	**Half-life**	**Isotope**	**Half-life**
Am-241	433 y	I-131	8.02 d
Cd-109	462 d	Ir-192	73.8 d
Ca-47	4.54 d	Fe-55	2.73 y
Cf-252	2.65 y	Kr-85	10.76 y
C-14	5715 y	Ni-63	100 y
Cs-137	30.07 y	P-32	14.28 d
Cr-51	27.7 d	Pu-238	87.7 y
Co-57	271.8 d	Pm-147	2.62 y
Co-60	5.27 y	Se-75	119.8 d
Cu-67	2.58 d	Na-24	14.95 h
Cm-244	18.1 y	Sr-85	64.84 d
I-123	13.2 h	Sr-90	28.78 y
I-129	1.57 y	Tc-99m	6.01 h

The nuclear reactor cycle produces significant radioactive waste volumes as shown in Figure 3, most of which are of low radioactivity, but some one percent of which, such as spent fuel, after a few weeks, is no more radioactive than many medical therapy devices.

Medical and Industrial Radionuclides and Wastes.

The production of radionuclides in small reactors usually dedicated to the production of medical and research radionuclides, eventually leads to the creation of radioactive wastes in hospitals, research laboratories and ultimately in the locations where they are used and discarded or managed; most often in hospitals. Canada is the world's major supplier of reactor-produced medical radionuclides, especially cobalt-60. Such cobalt-60 treatments of cancer is credited with benefiting and prolonging an estimated 500 000 lives in the world each year.

Over 40 000 medical procedures using about 30 different radio-isotopes - most of short half-life - are performed each day in North America alone (more than 10 million per year) and about 95 percent of all new medical drugs are tested using procedures involving radiation. All, produce radioactive wastes.

There are about 18 million shipments of radionuclides in the world each year. Most are medical radionuclides destined for hospital use. Their half-lives may be so short that new shipments are required each week. For example, molybdenum-99 has a half-life of 2.7 days. It produces a radioactive daughter technetium-99m with a half-life of 6 hours, which is 'milked' from the Mo-99 and which is used extensively in internal scans (diagnoses). The retired Mo-99, is stored in the hospital as radioactive waste for a few weeks until it is entirely decayed, and is then discarded into the controlled hospital wastes. Fortunately the relationship between half-life and mass of material, indicated in Table 6, means that such relatively short half-life nuclides are of very low mass and are easily shielded and securely packaged for shipment anywhere in the world, usually by air. Unfortunately, it also means that even a very small mass of a short half-life material can be extremely highly radioactive during the time that it is being transported and used effectively.

Rarely, a hospital may lose control of one or more of such sources and they prematurely appear in wastes destined for a municipal garbage dump. Only recently have the instruments for detection of such accidental disposal been available to municipal workers to identify a radiation problem that these may create in large cities.

Table 6. Relationship between half-life and mass for 1E9 becquerels (Bq) of radioactivity.

Radionuclide	Half-life	Mass (grams)
Nitrogen-16	7.1 seconds	2.7E-13
Iodine-131	8 days	2.2E-07
Iridium-192	73.8 days	3.0E-06
Cobalt-60	5.27 years	2.4E-05
Strontium-90	28.78 years	2.0E-04
Cesium-137	30.07 years	3.1E-04
Radium-226	1600 years	0.03
Uranium-235	7.04E8 years	12 500
Uranium-238	4.47E9 years	80 400
Thorium-232	1.4E10 years	247 000

Industrial radionuclides (such as iridium-192 with a half-life of 73.8 days, and used for weld inspections; or cesium-137 with a half-life of 30 years and widely used in level gauges) are usually of much longer half-life (though still of small mass even for relatively high activity devices), and are thus transported much less frequently, and when retired, are required to be stored for a much longer period.

Radioactive shipments are generally not associated with commercial nuclear power facilities. Exceptions to this are when about 20 to 100 tonnes of low radioactivity new fuel - required about once each year for PWR and CANDU reactors respectively - are transported to the reactor site; when highly radioactive and shielded spent fuel is transported to a reprocessing facility; and when irradiated cobalt-60 rods are removed from the reactor core and are transported in shielded flasks from certain CANDU reactors to a medical isotope fabrication facility. This commercially produced cobalt-60 is manufactured into medical therapy devices and is used in materials research and in other commercial irradiation devices for product sterilization and, increasingly, to kill life-threatening bacteria in meat, fish, poultry and other raw foods.

Solid and shielded radiation devices like cobalt-60 therapy units or irradiators eventually lose their effectiveness through radioactive decay (half-life 5.27 years). The device gradually loses its effectiveness and is at some stage recovered by the manufacturer and is either re-processed or managed as high-level radioactive waste until it has significantly decayed after about 100 years.

Reactor Wastes

The world use of uranium in energy production power reactors creates relatively small amounts of spent fuel each year (about 15 000 tonnes), and moderately large volumes of relatively low level wastes (about 45 000 m^3).

The 15 000 tonnes of spent fuel contain highly radioactive fission nuclides (about 450 tonnes) which are the main source of radioactivity in the spent fuel.

Most of the unconsumed low radioactivity uranium and transuranium nuclides like plutonium, which together make up about 95 percent of the spent fuel, could be recycled and used in further reactor cycles, though this is done in relatively few reactors at this time. As a result, most spent fuel is, at least temporarily, managed as waste.

After ten to fifteen half-lives - about 300 to 500 years for the longer-lived fission nuclides like strontium-90 and cesium-137 - all of the significant fission nuclides have decayed away, leaving the spent fuel only a little more radioactive than the uranium it started as. After that time and from the radiation point of view it is of relatively low radioactivity, but contains significant amounts of plutonium which, with the major quantities of pure uranium remaining in the then-decayed and low radioactivity spent fuel, could be returned to the reactor to produce energy.

Management of spent fuel after this time is with the main purpose of securing the small quantities of plutonium and not because of radioactivity.

Where spent fuel is reprocessed, as in France, the U.K, Germany, Japan and others, the uranium and transuranium nuclides are returned to the reactor cycle, and the small volume of highly radioactive fission wastes is further processed by drying and being fused into glass logs to be managed as high level radioactive waste, and eventually disposed in a deep geological repository.

Table 7. Summary of Fission Product Nuclides

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.**

Most of the more than 600 fission nuclides have half-lives less than 24 hours, with only 12 of them having half-lives longer than 10 years, as detailed in Table 7.

The half-life of the two significant and relatively long half-life fission nuclides (cesium-137 and strontium-90), in either spent fuel or the vitrified fission waste, is about 30 years.

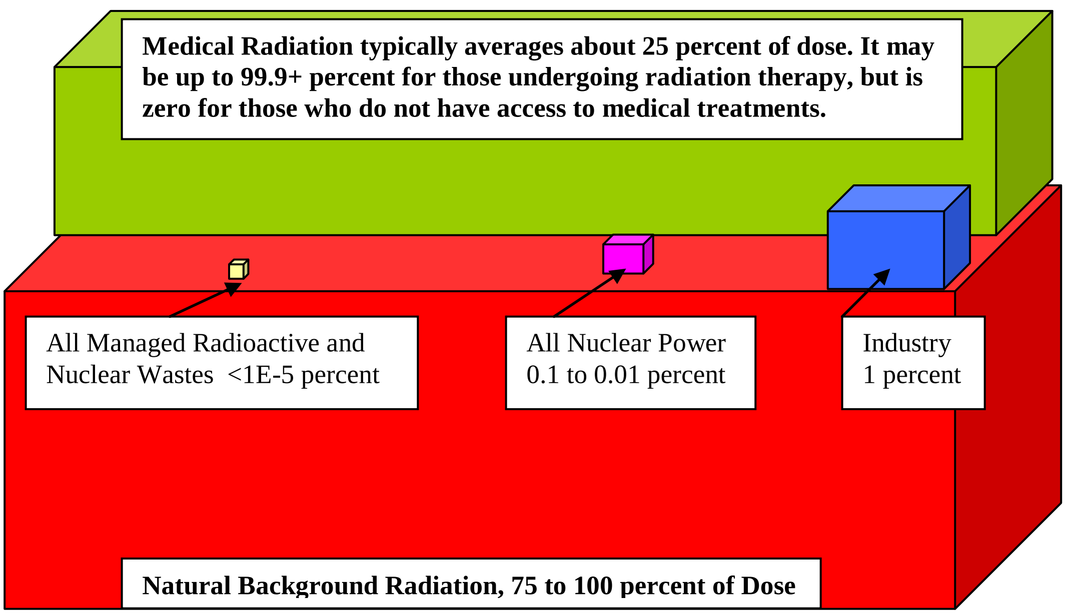
The public does not encounter either spent fuel or separated fission wastes as they are both rigorously controlled by regulation, and securely managed.

Spent fuel is typically contained at its point of origin for several decades, unless it is to be reprocessed in order to recover and recycle the uranium, plutonium and other Transuranic nuclides. The initial stage of spent fuel management is in water-filled spent-fuel bays which provide both cooling water and radiation shielding for the first few weeks. If fuel reprocessing is to take place the fuel is transferred after about 150 days, into shielded, crash resistant transportation flasks that exceed transportation safety requirements, and conveyed to a reprocessing facility.

If reprocessing is not required then the spent fuel remains in the cooling bay for at least seven years, where it cools and loses sufficient of its radioactivity that it can be transferred, in shielded flasks, to a controlled - usually adjacent - dry storage facility consisting of concrete bunkers or silos with about 1 meter thick walls. Heat output at this stage is usually less than about 1 kW Mg^{-1}. The concrete (and steel) shielding is designed to reduce the dose rate immediately outside of the filled container to no more than about 25 microsieverts per hour, in order to protect those workers who may spend most of their working year at this location. Actual measurements taken on a regular basis in contact with these filled containers indicate that the dose rate is typically much less than this and rarely exceeds about 2 microsieverts per hour. As the spent fuel in the container ages, the designed shield becomes increasingly effective in reducing the radiation field, as the fission nuclides decay away. After about 50 years or so in this facility, the spent fuel is of much lower radioactivity and heat output, and can be removed to a deep geological disposal facility, or placement in other storage, unless reprocessing at this later stage is considered.

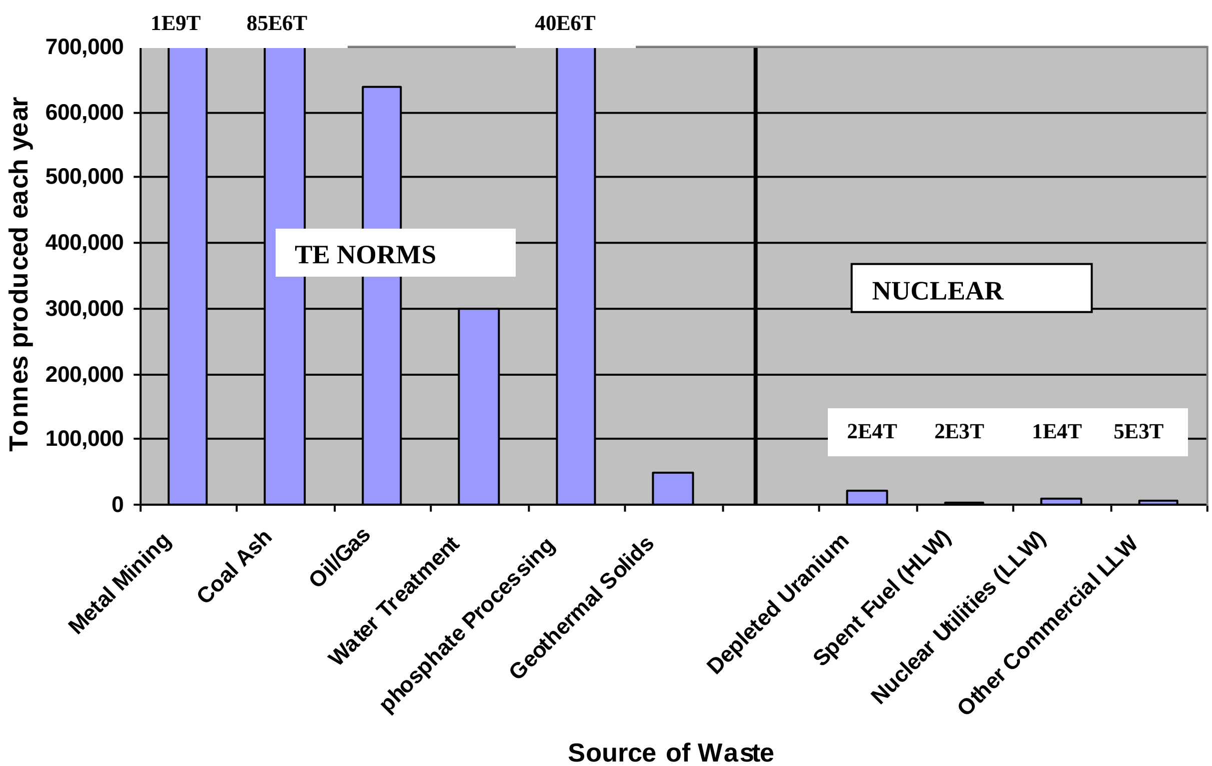
Some indication of the relative radiation impact upon the public, of various sources of radiation including the dominant natural and medical radiation and the highly publicized radioactive wastes, is shown in Figure 1.

Figure 1. Approximate Relative Magnitudes and Ranges of Public Annual Radiation Doses from All Potential Sources of Radiation throughout Developed Society. Major Variation is likely in Natural and Medical Radiation Percentages.



Data on sources of radiation, and radiation exposures throughout society over the last 100 years - the last 60 including nuclear reactor development - have shown that though the various reactor cycle wastes constitute about 95 percent of all man-made radioactive wastes in the world, they contribute the least to personal and public doses, whereas medical radioactive materials which constitute only about 1 percent of all man-made radiation sources and associated wastes, produce the largest personal and public doses. An indication of the relative annual production tonnages of TE-NORM wastes and nuclear power facility wastes in the U.S. is shown in Figure 2.

Figure 2. Estimated Annual Quantities of TE NORM Radioactive Wastes, and Nuclear 'Wastes' Produced in the U.S. (Most data from the IAEA).



Public fears of minor exposures to any poorly understood environmental agent in the U.S., have created a crisis in environmental policy. For example, for many years, no radioactive waste repository for medical wastes could be established, resulting in a buildup of radioactive wastes in medical institutions. This threatened to shut down the entire use of medical radioisotopes across the country. The public risk which would have been incurred by such a closure of a medical facility, would have been millions of times more harmful to society by denial of treatment, than the actual risk from what were truly minuscule public risks from such radiation.

In a similar vein, the US Department of Energy embarked on a program of radiation cleanup at DOE facilities which could eventually cost more than 200 billion dollars. Various studies show that after this effort, radiation exposures to the public would be reduced only by trivial amounts, as they were trivial to start with from this source, and human health would not benefit. The same has been true of the US 'superfund' cleanup effort over the last few decades.

Economic studies have shown that when about $5 000 000 dollars is wasted in society rather than being used in some constructive way such as preventive medicine, constructive employment, or education, it is equivalent to the premature loss of a single human life. Thus the waste of a trillion dollars can be said to result in the premature loss of 200 000 lives by being spent on the wrong risk in society.

1.2 Radiation Accidents and Exposures to Workers and the General Public

Neither the general public, nor radiation workers are significantly exposed to radiation or radioactive wastes in society. Although the issue of radioactive wastes is often highly publicized in negative ways, its actual harm to society or to any individual is so low as to be practically un-measurable, and it is among the least of the many thousands of common risks throughout all of society.

As nothing is, or can be made absolutely safe - not even food, or medical drugs - a risk of premature death of 1 in a million is a general target for most industries and social efforts, and is regarded as acceptable. However, even a risk target of 1E-6 from a widespread activity, implies that in the world, 6000 deaths will be expected. Of course it does nothing of the kind, but if the data are misused in this way, as they often are, then emotions take over, as no one wishes to be accused of calmly tolerating 6000 deaths. If emotions then insist that the risk should be reduced to 1E-7 or better, then costs will escalate significantly such that more people will be hypothetically at risk from the loss of monetary resource, than were at risk from the original 1E-6 target. Such cost-benefit comparisons are rarely made in society, though they should be, and should govern all governmental policy actions and decisions as they are supposed to.

Radiation workers are potentially most at risk from radiation accidents and radiation exposures as they work directly with radiation sources and wastes. However, the workplace procedures which govern such work and which limit and continuously monitor radiation dose, ensure that such workers are rarely, if ever, significantly exposed during employment. Rare, and usually slight over-exposures sometimes do occur in the reactor environment, but the most serious radiation over-exposures and injuries usually occur to industrial radiographers (below). Conventional accidents: falls, gravity injuries, punctures, burns, electrocution, etc., are much more of a serious source of actual injury and harm to any worker in any industry, than is radiation. The workplace is also generally much safer than home, where most serious accidents happen.

The general public is continuously exposed to natural radiation, but (outside of hospitals) is rarely exposed to radioactive devices or radioactive wastes other than through transportation accidents - mostly of hospital sources, loss of control of medical and industrial devices, the breakdown of regulation of such devices, or theft; typically of medical or radiographic devices.

Because of the onerous levels of control which apply to all significantly radioactive materials, there are typically less than about two or three serious injuries or fatalities in the world each year to radiation workers from such events. Most of these injuries are incurred by those very few workers who, despite having direct training, qualification and responsibility for the device and its operation, circumvent safety protocols and barriers, or become careless in other ways and become exposed to a temporarily unshielded device. The general public is not exposed in this circumstance, as these workers are usually the only ones injured, and at their place of work.

Radiation injuries and fatalities to patients undergoing therapy treatments in hospitals occur from time to time as at Zaragoza in Spain and other locations, but are not often recognized or reported. The ones that are recognized and acknowledged, arise when a therapy device malfunctions, is improperly programmed, or is improperly used. Patients undergoing such treatments are not subject to the same regulatory controls or dose limits as radiation workers, as their treatment doses may be several thousands of times above such limits, approach fatal radiation doses anyway, and are a necessary part of the treatment.

The most likely high (but non life-threatening) exposures to the general public, outside of hospitals, are also unlikely to be monitored or even recognized, and occur during industrial radiography work which takes place at most heavy industrial facilities, especially during construction and commissioning. Radiographic sources are used by licensed radiographers to inspect welds, but if carelessly used can significantly expose anyone within a few hundred feet of the work location. Few industrial facilities, other than nuclear power plants, have radiation detection devices to monitor and avoid these occurrences, and there are thousands of such licensed devices and millions of such radiography uses each year in North America alone. Not surprisingly, radiographers themselves are the ones most likely to be injured - severely burned by radiation, occasionally fatally - through carelessness in securing their own, extremely high activity devices, and by deviating from accepted work practices.

Theft of medical therapy devices for their valuable lead shielding, but without recognizing that they may still contain radionuclides, can lead to severe injury and death. Over the last 20 years such accidents, which have directly affected the public rather than radiation workers and caused several deaths and numerous injuries, have occurred in Brazil and Thailand. Such accidents may only become obvious when medical doctors suspect that illness and related injuries in scrapyard employees may be radiation related. Fortunately, such accidents are increasingly countered by better control and accountability for licensed radiation devices, and by the massively increasing use of radiation detectors throughout society and especially on highways and at border crossings.

The increasing use of highly sensitive radiation detectors at international border crossings and on major highways has allowed several shipments of radioactively contaminated materials from scrap yards and steel mills, to be tracked and intercepted before they could be used in public areas. Such materials generally do not pose a significant hazard to anyone, as they are of sufficiently low or dispersed radioactivity by the time they are shipped for use and discovered.

All of these industries and uses in the nuclear industry, universities, research laboratories, industrial facilities, hospitals, medical clinics, veterinary laboratories, factories, mines, and those many individuals who use radiation as part of their work and who produce radioactive wastes, are controlled by regulations, dose limits, dosimetry, and licensing.

Failures in the process are rare and, outside of medical radiation problems and injuries, are widely publicized.

1.3 Protection of Workers and the Public

A broad outline of many of the protective measures to deal with radioactive devices and their retirement, and with all defined radioactive wastes, are shown in Table 9.

Table 9. Some Regulatory Protective Measures for Public and Worker Safety from Radiation Devices and Radioactivity in Wastes

Control of Radioactive Devices and Radiation Work	Control of Radioactive Wastes, Waste Facilities and Waste Handling and Disposal
Personnel and public dose limits* Management responsibilities Defined radiation hazards Operator radiation training Continuing training Operator qualification and accountability Licensing of devices and operators License-to-license transfers of materials Procedures for safe use Procedures for malfunction Procedure for controlled disposal Radiation meters and device monitoring Shielded devices Personnel radiation dosimetry Personnel dose records Transport placarding Emergency contacts and response License inspections and renewal Legal responsibility and penalties for non-compliance.	Personnel and public dose limits* Management responsibilities Facility location, safety, design and design-life Environmental assessment of all operating stages Defined radiation fields and hazards Facility licensing Facility monitoring, safety and security Classification of radioactive wastes Segregation and shielding of wastes Handling and transportation procedures Upset procedures Individual training, qualifications and accountability Facility environmental monitoring Monitoring results and documentation Individual dose monitoring and facility monitoring Dose records Emergency planning and procedures License conditions Legal responsibility and penalties for non-compliance Future long-term considerations

* The rigid enforcement of dose limits for both radiation workers and the General Public, and active monitoring of radioactive wastes and waste sites, ensure that radiation injuries are unlikely to occur. Current worker dose limits (ICRP recommendation) are for no more than 100 mSv (milli-sieverts) of dose over five years, with no more than 50 mSv in any one year of the five. Worker average doses are about 2 mSv a^{-1} Public dose limits are for no more than 1 mSv each year from any industrial radiation or nuclear activity. Public average dose from industry is much less than 1 microsievert in a year, which is one thousand times less than the regulatory limit.

All of these many processes and controls ensure that neither the public, nor radiation workers are likely to encounter significant exposures to radiation outside of nature or medicine and, outside of their work, are unlikely to ever encounter or be injured by radioactive wastes.

2. CATEGORIES OF RADIOACTIVE WASTES.

Different jurisdictions classify radioactive wastes differently and control them in different ways. However, most adhere to similar standards and regulations, and most abide by the general guidelines and recommendations of the IAEA.

To accurately characterize all known radioactive wastes and to ensure that they are clearly defined and differentiated for purposes of management, transportation and disposal or storage, they are generally subdivided into Exempt Wastes; Low (and Intermediate) Level Wastes (LILW) as either one or separate categories; High Level Wastes (HLW); and transuranic or alpha wastes as shown in Table 10.

Different member states of the IAEA may adopt some minor variation of these classes and define them differently.

Table 10. Broad Classification of Radioactive Wastes, Management Time Frame and 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**	**Half-lives <30y**	**Half-lives >30y**	**Half-lives <30y**	**Half-lives >30y**
Material	Uranium mine and other tailings. Some coal ash. Some wood ash. Phosphate 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.
Disposal Options	No radiological restrictions, disposal as for other mine wastes.	Enclosed surface, or near-surface facility.	Near surface facility or intermediate geological facility.	Geological disposal facility.	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.					

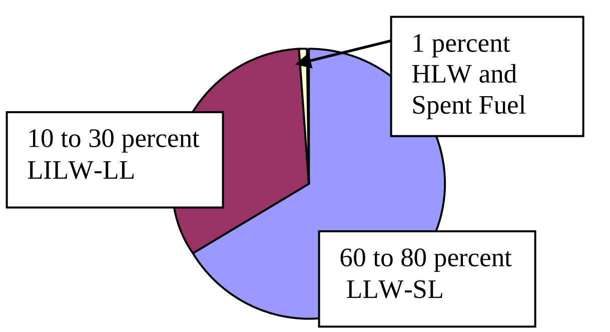
Uranium mine tailings wastes, though radioactive with traces of uranium and residual radium and radioactive daughters, are generally not regarded even as Low Level Wastes and thus do not require specific disposal actions, though how they are disposed of in the environment at the mine site, and protected, does have to meet stringent environmental protection criteria to guard mostly against weather erosion and acid-mine-drainage in most jurisdictions.

A very approximate indication of the relative volumes of the major classes of waste from the commercial nuclear cycle is shown in Figure 3. Only the High Level fraction of these wastes may require consideration for very long-term management.

High level fission wastes separated from spent fuel require management for no longer than a few hundred years at most, until they have significantly decayed.

Un-reprocessed spent fuel is managed as high-level waste. Continuing long-term management of spent fuel after the fission nuclides have decayed, is to securely manage the associated strategic plutonium because of proliferation concerns, rather than because of any radiation hazard, which is low at that time.

Figure 3. Relative Volumes of Radioactive Waste Types Produced In The Commercial Nuclear Electricity Cycle



2.1 Low (and Intermediate) Level Wastes (LILW)

These wastes contain generally short-lived (SL) radioactive materials in sufficient concentrations to require protection of those workers and the public who may encounter them. They come from various nuclear and industrial activities including medical and industrial uses of isotopes and from research activities using radiation.

They consist of radioactively contaminated materials such as disposable protective clothing, gloves, rags, glassware, packaging and cleaning materials, as well as process filters and ion exchange resins. If possible, they are usually compacted into as low a volume as possible, as disposal costs of these wastes are mostly influenced by volume.

They may be subdivided, based upon the half-lives of the radionuclides of concern into 'short-lived' (SL - less than 30 years) to 'long-lived' (LL - greater than 30 years), and thus are defined based upon the length of time that shielding and longer-term management may be required. The short-lived wastes, mostly containing short-lived fission nuclides such as Zr-95, may require management for as little as about 30 years. These may be discarded into normal waste streams after a short period of storage time sufficient to allow 'complete' radioactive decay. Longer-term storage beyond a few decades, where required, is often into controlled shallow-burial sites and enclosed concrete vaults, or even into deep geological disposal locations, depending upon specific requirements imposed by national regulations.

2.2 Intermediate Level Wastes (ILW)

These are not always specifically distinguished from Low Level Wastes. Where they are differentiated, it is because they consist of different types and activities of wastes, usually from the reactor cycle: - HEPA filters from exhaust ducts, process filters, ion exchange resins, chemical sludges, and materials with generally greater radioactive contamination and associated dose rates. They also may include used industrial and medical devices and related isotopes.

They usually require different management conditions than lower level wastes, including protection of fluids from escaping by leakage, greater shielding, and a longer management time frame that may extend to a hundred or so years. Some may not be readily compactable and may need to be packaged in steel drums. Where possible such wastes are compacted and packaged for storage in surface concrete vaults.

Dispersed wastes which are not easily contained or packaged, can be stored in steel drums - perhaps filled with high density shielding and stabilizing materials such as sand, concrete or bitumen - before being placed into surface storage facilities for management and monitoring, or into shallow or deep burial sites.

2.3 High Level Wastes (HLW)

These may contain short-lived and long-lived radionuclides. They consist of those materials that contain sufficient radioactivity and heat, that they require significant shielding, isolation and specific management controls to limit radiation exposures and heating effects over some defined interval of time depending upon half-lives and security.

They are made up mostly of spent nuclear fuel and/or separated fission wastes and retired medical and industrial devices. Initially, in the case of spent fuel, they may require water-cooling for up to about 10 years to remove radioactive decay heat. Because these highly radioactive materials constitute such a low volume compared with their large energy production, the relatively few tons produced each year at each large reactor (from about 20 to 150 tonnes, depending upon the reactor type and capacity factor - burn-up rate) are managed almost entirely at the reactor sites or facilities where they are produced.

If the reactor spent-fuel is unlikely to be reprocessed, then the entire volume of spent fuel will be managed as High Level Waste, and according to national or international regulatory requirements.

If the spent fuel is reprocessed, then the approximately 95 percent by volume of separated uranium and plutonium (both of low radioactivity) are returned along with the other transuranic nuclides to the reactor cycle in fabricated fuel, and the approximately 3 to 5 percent by volume of separated high level fission products is managed as high level waste.

2.4 Transuranic (TU) or Alpha Wastes

These consist of those wastes contaminated with minor quantities of plutonium (a strategic nuclide) and other alpha emitting nuclides above uranium in atomic number. They are typically of low radioactivity and can be shielded and managed as for long-lived Low Level Waste. They arise mostly from nuclear weapons production programs or from spent fuel reprocessing where those wastes are not returned to the reactor cycle for destruction. Transuranic wastes from nuclear-weapons programs are usually managed by the military at specific, controlled sites.

In 1999 in the U.S. a deep geological disposal facility - WIPP: Waste Isolation Pilot Plant - was commissioned in New Mexico (after about 11 years of litigatory delay) and began to receive military TU wastes from Los Alamos. The facility is contained in a geologically old salt formation, at a depth of 2150 feet below the surface. Most of this waste is of relatively low radioactivity and, in the U.S. at least, and for the present, is managed separately from the HLW wastes from commercial fission reactors.

In the U.S., such TU wastes and TU-contaminated soils amount to a total of about 1 000 000 cubic meters (by about 2002).

Most military radioactive wastes are similar to those from civilian operations and can be classified and dealt with accordingly. Generally, military operations lie outside of the control of those regulatory authorities which oversee civilian operations, or are administered by a different process.

3. RADIOACTIVE WASTE MANAGEMENT AND DISPOSAL OPTIONS.

3.1 Hospital and Reactor Wastes

There are two major radioactive waste streams in the world. The one prevalent throughout the public domain, and which the public unknowingly encounters from time to time and generally ignores, is that from medical and other social uses of radiation. The other, which it rarely sees or encounters, but is highly conscious of because of the extensive and detailed adverse publicity given to it, is that from nuclear reactors.

Further important distinctions are in the differences in the character, control, management and accountability of the wastes from the two.

Hospital wastes are typically low-volume, relatively low activity (with some exceptions) wastes usually containing single nuclides of short half-life. They typically require management in a secure shielded environment within the hospital for days to weeks before becoming 'inactive', at which time they may be disposed into normal waste channels. The more persistent and longer lived nuclides and contaminated hospital wastes may be shipped to special licensed disposal facilities for longer-term management. The expense associated with such disposal occasionally sees some of these short-lived wastes in the larger centers being 'accidentally' (possibly deliberately, illegally and clandestinely) discarded into regular landfills where, up until the present time at least, there has been little ability to monitor for radiation. The exceptions are retired medical therapy devices which are of very high radioactivity, relatively long half-life, and are usually, but not always, recovered by the manufacturer to be reprocessed or managed as high level wastes.

Nuclear wastes consist of much larger volume and higher activity wastes, all of which is typically managed at each reactor site where it is produced. The bulk of these wastes is relatively short half-life maintenance and process wastes contaminated with fission nuclides, though the overall half-life is much longer than that of typical hospital wastes. There are also relatively small volume, very high level wastes and spent fuel, of much longer half-life. The approximate volume relationships are shown in Figure 3.

Uranium, when enriched or formed into fuel bundles becomes a 'prescribed' substance and is subject to stringent regulatory and international controls including being accounted for from manufacture to final disposal. Such new fuel, and the produced spent fuel (containing strategic radionuclides such as plutonium-239 as well as remaining uranium-235 and newly formed uranium-236) from all reactors in those countries which are signatories to the international Nuclear Non Proliferation Treaty (NNPT), is independently inventoried by the international inspectors of the IAEA, and traced from manufacture to reprocessing (if done) and to ultimate disposal.

3.2 Transportation Regulations and Radiation Licenses

Radioactive materials or wastes may be transported only according to the regulations governing such materials and must be packaged, labeled, shielded or transported according to legal guidelines and by approved methods and carriers.

All legal transfers of radioactive materials take place only from a currently licensed supplier to a currently licensed user of demonstrated competence to safely handle and safeguard such materials. The supplier will typically request a copy of the user's license before shipping any materials. The licenses granted to applicants to manufacture, possess and use or store radioactive materials, specify the nuclides, activity limits, device design, and configuration. They also indicate the specific responsibilities associated with license possession, and identify some of the penalties for deviation from license specifications. These can include fines, jail terms and permanent loss of license.

Careful and documented accounting for all radionuclides and sources in a licensee's possession, descriptions of their use and eventual disposal or retirement, is typically a condition for granting a license.

Retired solid or enclosed devices are either securely stored under the conditions spelled out in the license, are shipped under license to a licensed disposal facility, or are returned to the licensed supplier after permission and the exact conditions for shipment have been determined and approved.

3.3 Radioactive Waste Management

The required management process governing any radioactive waste is a function of activity, half-life and volume. These also determine the costs, complexity, and time frame over which the material must be managed. In the case of reactor wastes, the following main processes are defined, with only the first three having been followed to any extent at this time, with the fourth being prepared for extensive use by about 2010 and later, or as required.

1. Initial and short-term waste management
2. Surface storage of wastes
3. Shallow burial of selected wastes
4. Deep Geological disposal of HLW and Transuranic wastes

The discussion below is concerned very generally with the management and disposal of reactor wastes. A summary of the classes of wastes and how they are currently managed in many jurisdictions, along with future Deep Disposal is presented in Table 11.

Table 11. Summary of Radioactive Nuclear Waste Categories and Disposal

High Level Wastes (HLW, initially, very intensely radioactive)

These consist of the small tonnage of spent fuel discharged from the reactor. They contain all of the fission products (about 3 percent of the wastes) and un-fissioned actinides (about 97 percent). The spent fuel 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 fission radionuclides from spent fuel reprocessing in those countries where spent fuel is re-cycled.
The long-lived HLW including spent fuel, fission and TU wastes are generally to be stored in Deep Geological Formations, which are required to generally maintain their integrity for several thousands of years.

Intermediate Level Wastes (ILW)

These consist of bulky radioactive wastes 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 in this category. 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 in Deep Geological Repositories along with HLW, but much of it can be placed in relatively shallow burial.

Low Level Wastes (LLW)

These 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 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.

3.3.1 Initial and Short-Term Waste Management

Disposal methods currently in use or planned for Low, Intermediate and High Level wastes are generally comparable from one country to another within the IAEA Member States, with only minor variations. The main processes include:

1. Surface storage and management. Packaged and compacted LLW and usually uncompacted ILW are immediately placed into concrete-shielded surface storage structures in a secure and managed area, where they remain for about 30 years. After that time, most of the short-lived radioactivity has gone, and they may be revisited for re-classification, disposal or recycling of recoverable tools or equipment.

   With the passage of even a short space of time, short-lived LLW becomes non-active, and even some originally short-lived HLW (such as certain medical devices), can be reclassified as LLW or even as inactive. Spent fuel is stored in water-filled spent fuel bays for about 150 days prior to transportation for reprocessing or, where not reprocessed, remains there for the first few years to cool before being moved to surface storage silos for up to about 50 years, or until a deep repository is licensed and operational.

2. Longer lived LILW may be transferred for storage at surface; in near surface storage, or in deeply emplaced facilities according to what is available and in operation. Near-surface storage comprises about 80 percent of all repositories.

3. Eventual removal of HLW from surface storage locations and disposal into deep geologic repositories. These may also contain conditioned and vitrified fission wastes, transuranium wastes, and non-reprocessed spent fuel in the case of those countries where reprocessing is uneconomic (spent natural uranium fuel) or does not take place. Whether or not spent fuel will actually be emplaced in such a facility is constantly open to political review, as it represents a resource (certainly in the case of spent enriched fuel) that is not cost-effectively reprocessed with the low current price of uranium, but may be more extensively recycled by the time such disposal facilities are likely to be brought into operation.

The first waste disposal operation was at Oak Ridge, in the U.S. in 1944, and was part of the weapons program. At this time, worldwide, about 100 near surface disposal facilities have been commissioned since about 1960, and an additional 40 facilities are expected to be in operation by about 2015. Such facilities are politically sensitive; require some degree of governmental and regulator approval, and are always strictly licensed and controlled.

3.3.2 Deep Geological Disposal

Deep geological 'waste disposal', of which there have been many pilot projects and decades of experience, uses technically simple engineering principles. That no significant permanent disposal of HLW has yet taken place is due to several issues:

1. Political indecision and political opposition based upon NIMBY;
2. Activist opposition, misinformation and legal challenges;
3. Lack of immediate need - because of the extremely low volumes of HLW; and
4. Uncertainty (again influenced by politics) over the possible reversal of any premature decision that might involve discarding, rather than recycling an extremely valuable material - spent fuel. There is no comparable uncertainty over what will eventually be done with true waste - the waste which cannot be re-cycled and must be secured for as long as it is significantly radioactive.

The term 'nuclear waste' is loosely used to include spent fuel in those jurisdictions where re-processing is not practiced, or where the advanced fuel cycles are not yet considered as options. In reality, spent fuel is not waste. It still contains between 95 and 99 percent of unused energy. When discharged from the reactor, it contains about 95 percent of the starting uranium-238; about 1 percent of unfissioned uranium-235 (in the case of spent enriched fuel); about 1 percent of fissionable transuranium nuclides and uranium 236; and about 3 percent of fission wastes. Only the latter is true waste at the present time.

Spent fuel should not be considered for permanent non-retrievable disposal as it represents a valuable source of unused energy that will be required at some time in the future. Recognition of this possibility is why most deep disposal projects specifically address the possibility of authorized future retrieval.

The estimated costs (in US$) of spent fuel disposed in geological repositories, as far as can be determined prior to actual commissioning of a disposal site for HLW, range from about 0.4M$ TWh^{-1} (A terawatt hour, is 1 billion kilowatt hours) in the U.S., to about 1.8M$ TWh^{-1} in Finland. These costs fall, as the starting nuclear fuel is increasingly enriched, allowing greater burnup on the same mass of fuel and thus less spent fuel requiring disposal. The costs also decrease notably with time, as any delay in placement allows for significant decay, and results in less overall heating from the waste that may then be more closely packed.

If spent fuel is re-processed, then the costs of the much smaller volume of disposed fission wastes range from about 0.25M$ TWh^{-1} in the U.K. to about 1.65M$ TWh^{-1} in Switzerland. The approximate value of a TWh of electricity (assuming a value of the cost of generation at about US$50 MWh^{-1}) is about US$50 000 000. Thus, the costs of disposal are a small fraction of the production cost of electricity.

Although the broad consensus on IAEA member states is that deep geological disposal is the preferred option to deal with HL wastes, each member state adapts the basic process to its own political climate, time frame, requirements and available facilities, and may or may not closely follow the suggested process. For example, some countries already have deep mine sites or even open pit mines that appear to be acceptable as geological repositories as they meet, or can be made to meet, the overall requirements. Others do not produce sufficient wastes to justify the costs of such disposal and may need to contract their waste disposal to another jurisdiction.

3.4 Alternative Disposal Processes

Alternative processes are still open to consideration. Some of those that had been originally publicized, or even used, have either been abandoned or are still being researched. These include:

5. Deep-sea disposal.
6. Transmutation.
7. Deep space or solar or lunar disposal, and others.
8. Private and international repositories.

The first of these options (not to be confused with the illegal and unethical dumping of liquid or improperly contained wastes in the open ocean) might have been rationally considered for only small volumes of re-processed wastes or - briefly - for discarded weapons materials. If done properly, it represents non-retrievable disposal.

3.4.1 Deep Sea Disposal

This was and still is the most rational, safe and economic process for permanent, secure, non-retrievable disposal, provided the disposed wastes are vitrified or otherwise solidified to ensure stability and a slow rate of solubility (zero solubility is not achievable even for granite). One process - when properly applied - requires that the contained and solid wastes be encased in weighted cylinders to ensure deep penetration into the unconsolidated sediments directly above known subduction zones in the deepest ocean areas. Another requires placement in specifically drilled seabed locations. However, deep-sea disposal is not generally considered at this time following the London (Ocean Dumping) Convention, and because of adverse and emotionally misleading publicity, political sensitivity, and poorly controlled sea dumping in the past.

3.4.2 Transmutation

Transmutation is the process of changing one element to another - to transform specific nuclear wastes into less hazardous materials - it has been proposed by Carlo Rubbia in Italy, and by others. Transmutation is the process - as it is applied to reactor wastes - of transforming transuranium radionuclides - particularly americium, curium neptunium and plutonium - and some long lived fission nuclides (e.g., technetium-99, iodine-129 and cesium-135) to others which may be more fissionable, are of usually shorter half-life, or which are generally less hazardous.

This suggested process - known as an accelerator-driven system, or ADS - is well-defined scientifically from a theoretical standpoint, but from a practical technological point of view is still under research. It uses a combination of proton accelerator, molten-lead moderation (producing hard neutrons by spallation from lead) and sub-critical fission reactor technologies in a fast neutron system that is capable of producing electrical energy; or of transmuting long-lived radioactive wastes (contained in a blanket assembly); or some combination of the two. If the transmuting reactor is based upon thorium-232, then transuranium wastes produced in the reactor cycle itself are negligible, as activation of thorium-232 is at least five neutron-absorbing steps removed from transuranium nuclides, of which the most obvious are the plutonium nuclides.

In the Fast Breeder Reactor cycle - researched since the 1940s - the transuranium elements are mostly destroyed by the fast fission and transmutation process within the reactor core. By re-introducing into the new fuel load, spent fuel elements or assemblies of those transuranium elements that remain upon reprocessing, they continue to be consumed in succeeding cycles. With this FBR cycle, there is no requirement for any alternative removal process. If the FBR is unlikely to be brought into use, and there is some political urgency to deal with these materials outside of the reactor cycle other than discarding them into a waste disposal facility, then such transmutation may be considered.

It is the presence of the transuranium nuclides (especially plutonium) in the proposed disposal facilities that prolongs the waste management and security time frame, and raises concerns about future site integrity and future weapons proliferation possibilities from the uranium/plutonium ore body that is created.

3.4.3 Other methods

Other methods for dealing with nuclear wastes have been publicized from time to time, such as the suggestion to propel such wastes in rockets into the sun; using a lunar site; injecting them into abandoned oil fields; or burying them beneath 'permanent' ice caps. They are generally not sufficiently rational; do not stand up to scientific evaluation; are too costly and ineffective; are not adequately safe; or cannot meet the long-term human security requirements.

Deep borehole disposition of properly packaged, low volume HLW, is being examined as an alternative means of disposing of certain retired, small-volume, medical and industrial radioactive devices. The injection of liquid radioactive nuclear processing wastes by way of boreholes drilled into deep geological strata on land, was practiced for some time in the U.S., but encountered significant problems and was abandoned when it was discovered that these pressure-injected fluids were lubricating slip-fault zones, and triggering detectable seismic dislocations.

3.4.4 Private and International Repositories.

Most recently there has been a gradual recognition in some regions that there are short term and long term social economic, energy, and political benefits to be gained by offering very long term, secure, controlled waste disposal facilities and services, as a private industrial economic enterprise. Alternatively, there could be consensus upon the establishment of an international controlled facility. This would avoid the politically sensitive action of having a controversial disposal site being thrust upon many unwilling and resisting participants and regions.

Some native bands in the U.S. are considering the social and financial benefits of allowing some geologically suitable areas of native reserve lands to be used for certain, approved waste disposal purposes. Whether or not these may progress, often depends upon the factual or emotional quality, and depth of information presented to the bands by opposing interests.

A Russian proposal (May 2001) was to accept the world's spent nuclear fuel; charging up to $1600 per kilogram for disposal. The proposal astutely reserved the option to reprocess and re-sell the recovered fuel if the economics became favorable. Kazakhstan is also proposing a similar venture.

Whatever option is chosen, the general consensus among developed nations is that the preferred long-term solution to dealing with High Level Wastes is for medium-term surface storage with all required safeguards, followed by permanent geological disposal. At the present time, no country has yet placed any commercial reactor HLW in deep geological disposal, and the first such 'permanent' repositories are not likely to become operational until about 2010 or later.

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U.S. DOE. Web site address: www.eia.doe.gov (this very large site provides comprehensive data on energy use throughout the U.S. with links to numerous sites for specific energy and U.S. radioactive waste information.

U.S. Health Physics Society. www.hps.org. (The related web site in the University of Michigan from which current factual radiation and radiation protection information is most readily and comprehensively obtained is www.umich.edu and by following 'radinfo' links).

World Nuclear Association. Web site address: www.world-nuclear.org. This site provides recent comprehensive and factual general information on almost everything nuclear in the world.

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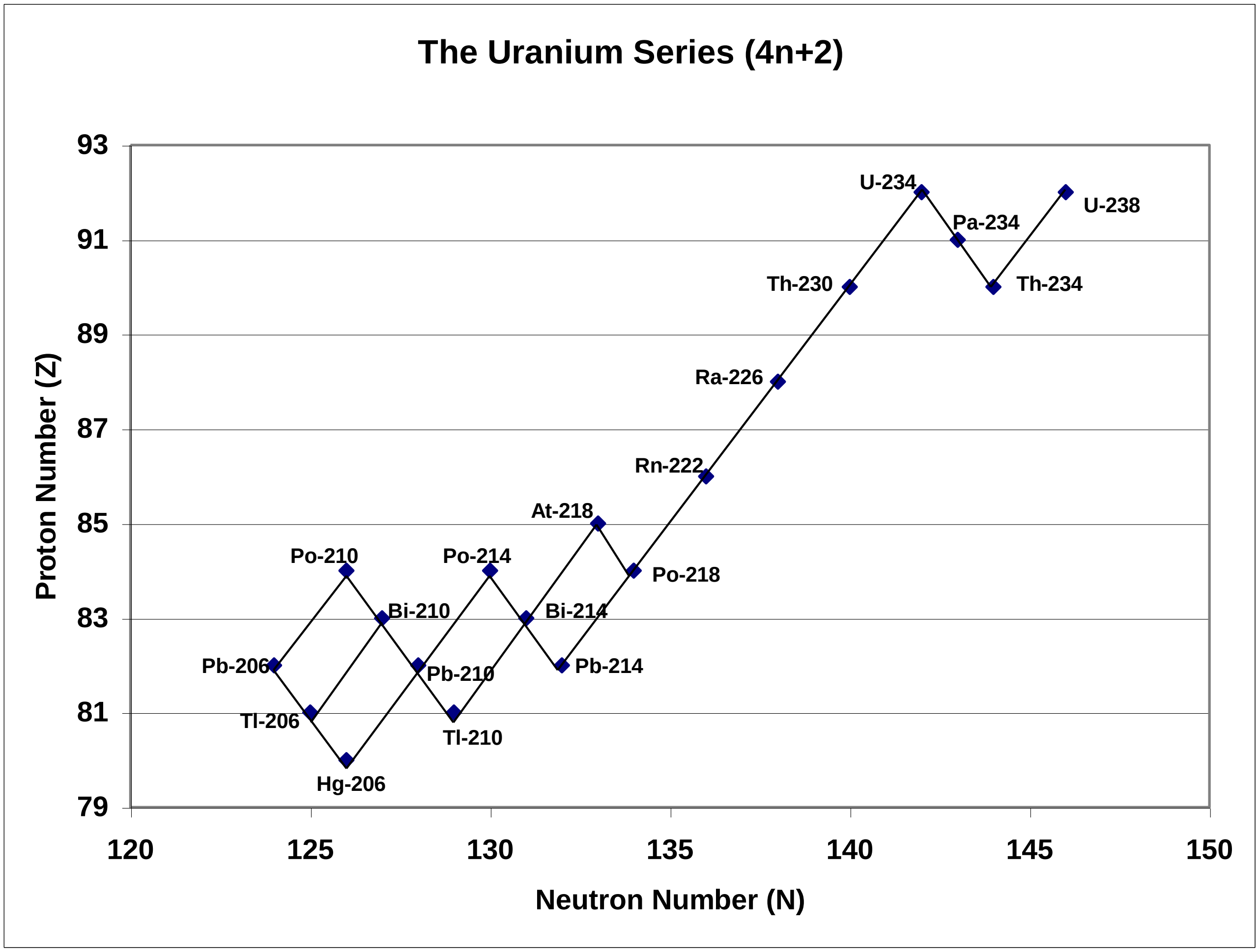
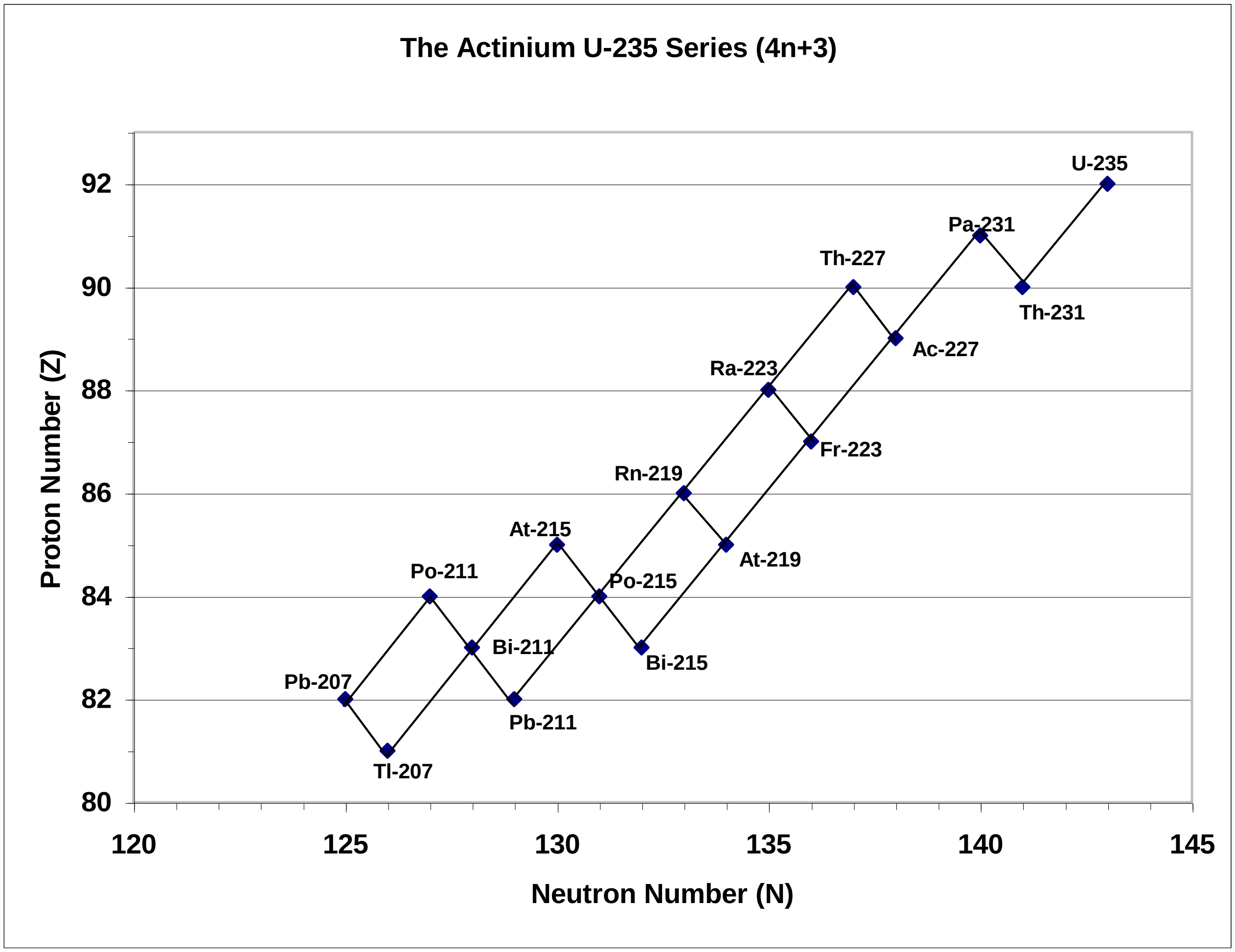
Appendix.

Radioactive decay sequences in the naturally occurring uranium species and thorium are shown in the following diagrams. The parent nuclide is at the top right in each sequence, with the final and stable (non-radioactive) lead product in each case at the lower left. Diagonal progression downwards from right to left, with decreasing proton number and decreasing neutron number, is indicative of alpha decay (usually accompanied by gamma emission). Diagonal progression upwards from right to left, maintaining the same isotope number, but increasing atomic (proton) number indicates beta decay (usually accompanied by gamma emissions).

The Uranium-238 Decay Series.



The Uranium-235 Decay Sequence.



The Thorium-232 Decay Series