RADIOACTIVE WASTES, ORIGINS, CLASSIFICATION AND MANAGEMENT

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Contents

Summary

This chapter 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 lowest 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 societies.
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 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 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 ore body 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 radio nuclides as indicated in Table 1 and are therefore, without exception, naturally radioactive to some degree as shown in Table 2.

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**	1.39E10 y
Thorium-234	24.1 d	Thorium-231	25.6 h	Radium-228	6.7 y
Protactinium-	1.18 m	**Protactinium-231**	3.43E4 y	Actinium-228	6.13 h
234	6.7 h	Actinium-227	21.6 y	Thorium-228	1.910 y
Protactinium-	2.50E5 y	Thorium-227	18.17 d	Radium-224	3.64 d
234	8.0E4 y	Francium-223	22 m	Radon-220	51.5 s
Uranium-234	1620 y	Radium-223	11.68 d	Polonium-216	0.16 s
Thorium-230	3.82 d	Astatine-219	0.9 m	Lead-212	10.6 h
Radium-226	3.05 m	Radon-219	3.92 s	Astatine-216	3E-04 s
Radon-222	26.8 m	Bismuth-215	8m	Bismuth-212	60.5 m
Polonium-218	2.0 s	Polonium-215	1.83E-03 s	Polonium-212	3E-07 s
Lead-214	19.7 m	Lead-211	36.1 m	Thallium-208	3.10 m
Astatine-218	1.64E-04 s	Astatine-215	1E-04 s	**Lead-208**	Stable
Bismuth-214	1.32 m	Bismuth-211	2.15 m		
Polonium-214	19.4 y	Polonium-211	0.52 s		
Thallium-210	5.0 d	Thallium-207	4.79 m		
Lead-210	138.3 d	**Lead-207**	Stable		
Bismuth-210	4.2 m				
Polonium-210	Stable				
Thallium-206					
Lead-206					
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 the radon gas daughter does not escape from the U-238 series. Secular equilibrium is reached relatively quickly (about 50 years) in the thorium series.					

Table 1: The Naturally Occurring Terrestrial Radionuclides, Most of Which are Present in all Life Forms.

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 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.A., and the predicted social turmoil, served as a lesson for other local governments to leave such matters in the hands of the experts.

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. Data are from the IAEA and other sources.	

Table 2: Typical Very Approximate Activity or Activity Ranges in Selected Industrial Wastes and Other Materials in Society

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.

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, 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.

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.	

Table 3: Major Sources of Radioactive and Mostly-Controlled Wastes

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.

Reactor Produced Isotopes	**Use**	**Half-life**	**Cyclotron Produced Isotopes**	**Use**	**Half-life**
Mo-99 (Tc-99m)	Skeletal and	2.75 d,	Ga-67	Tumor studies	78 h
	Heart imaging	6 h	Tl-201	Myocardial studies	73 h
Cr-51	Labels red	27.7 d	I-123	Thyroid studies	13 h

	blood cells		Kr-81m	Lung studies	13 s
Co-60	Radiation	5.27 y	In-111	Brain studies	67 h
I-131	therapy	8.02 d	C-11	Brain imaging, PET	20 m
	Thyroid			scans, Cardiology	
	diagnosis		N-13	Cardiology	10 m
			O-15	Oxygen utilization	2 m
			F-18	studies	110 m
				Epilepsy	

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

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

Table 5: Some Common Radio-nuclides used in Industry and Biological Research

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, is as highly radioactive as many medical therapy devices.

1.1.1. 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 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.

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

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

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, poultry and other 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.

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Bibliography

Eisenbud, M. (1987) Environmental Radioactivity from Natural, Industrial and Military Sources. Academic Press Inc. [This text is one of the best introductions to the subject of radiation, providing data for the beginning student as well as the advanced specialist].

International Atomic Energy Agency (IAEA). Web site address: www.iaea.org [This United Nations site is a comprehensive source of detailed international nuclear and radiation related information of high quality. Details of radioactive waste management throughout the world are provided in their many publications].

Lamarsh, John R. and Baralta, A. J. (2001). Introduction to Nuclear Engineering. Prentice Hall. [This book is a basic comprehensive text for university engineering students. It provides high quality and fairly detailed information on nuclear physics principles, radiation, and nuclear reactors].

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.]

Biographical Sketch

John K. Sutherland obtained a First Class Honors degree and PhD in Geology at Manchester University in England. He accepted a position in a research laboratory in Canada in which he was responsible for chemical and instrumental analyses of rocks, ores and minerals, including the development and use of X-ray diffraction, X-ray Fluorescence and Electron Microprobe analyses. In 1980, he joined the Health Physics Department of the local utility. He was responsible for the Environmental Radiation Monitoring Program, and for external beta-gamma dosimetry for the 600 nuclear facility employees over almost 20 years. He developed analytical techniques for the analysis of strontium-90, and for rapid analysis of vanadium in fly ash, and wrote the complete chemical analytical procedure for analyzing coal and fluidized bed combustion products in a coal burning facility. He was responsible for revising the Derived Emission Limits for the nuclear facility and for contributing to Shift Supervisor training and Radiation Protection training for plant employees, and contributed to Emergency Response Co-ordination and training. He conducted a radiation monitoring program of the nuclear waste and storage facilities over many years and was also engaged in monitoring spent fuel transfers to the storage facilities. During plant maintenance and other outages, he participated in Radiation Protection activities during maintenance work, including Fuel Channel replacement. He became an adjunct professor at the University of New Brunswick, where he taught Nuclear Safety and Reliability to graduate engineers. Since retiring, he has engaged in consulting work, including developing nuclear and radiation training for plant employees, emergency responders, and at other facilities where radioactive materials are used. He teaches and writes extensively on all radiation related issues.