1

Classifications and Origins of Radioactive Waste

1.1. Introduction

Compared to other categories of waste, the quantity of radioactive waste is relatively small. In France, nuclear waste represents 2 kg per year per inhabitant [AND 17a], compared to 580 kg of household waste, 900 kg of non-construction waste and 3.4 tons of industrial waste [ADE 20]. But these residues represent an immense problem because some of them are extremely radioactive and remain harmful over excessively long time scales, for some hundreds of thousands or millions of years, that humanity cannot control.

What can we do with this radioactive waste? In the past, the ocean has served as a dumping ground for nuclear powers, which have immersed tens of thousands of radioactive drums. This time is fortunately over. Some eccentric people have suggested dropping them into space. Fortunately, the idea was not pursued. The solution now being considered for the most dangerous waste is to bury it in deep layers of clay, granite, salt or tuff, hoping that nature and geology will compensate for the weaknesses of human technology [AMI 13]. Sweden was the first nation to choose an underground storage site. All other countries, faced with the concerns of their populations and the vagaries of political changes, have postponed their decisions. On the contrary, in the United States, the suspension of the Yucca Mountain storage project in Nevada, which was ready to open, is a sign of the American administration's desire to listen to the public. However, the State must find a new solution.

Since no alternative solution is yet mature, we must take our time in making a decision that will commit humanity for a long time. France, like Canada, Switzerland and Japan, has made the principle of reversibility central to its doctrine. On the contrary, Sweden and Finland do not require it, and the United Kingdom is still considering it. It is not only a question of being able to recover radioactive packages, but of leaving the decision-making process open and giving it back to the political institutions. Parliament has once again become the master of nuclear waste management and future generations have the guarantee that nothing will be decided inescapably. The approach is virtuous. Let us hope that it is not an admission of powerlessness in the face of an insoluble puzzle [AMI 13]. It should also be emphasized that this postponement amounts in practice to leaving to future generations the care to manage and pay for the waste produced by the present generation.

Those responsible for the civilian and especially the military use of nuclear energy have in the past been very unaware of the seriousness with which the problem of nuclear waste is treated today. For example, the Hanford site in the United States was heavily polluted by unauthorized dumping during intensive plutonium production after World War II. Recently, six underground tanks leaked. In the former Soviet Union (USSR), waste in the form of highly active liquid solutions was injected directly into deep storage [MAC 96]. The United Kingdom in particular, but also other countries, and even France, have thrown drums of waste into international waters, a practice that is now prohibited [CAS 02].

Nuclear energy has been questioned almost since its inception and one of the main problems concerning its social acceptability in the world is the management of nuclear waste [ROD 17]. It is therefore imperative that nuclear nations manage radioactive waste in an exemplary way.

1.2. What is radioactive waste?

A few definitions should be kept in mind. Radioactive waste is radioactive material for which no further use is planned or envisaged. Ultimately radioactive waste is radioactive waste that can no longer be treated under current technical and economic conditions, in particular by extracting its recoverable part or by reducing its polluting or dangerous nature (French Environmental Code, article L 542.1-1). Conversely, if a radioactive material also contains radionuclides, it has a potential future use. This is the case for depleted uranium or spent nuclear fuel that can eventually be reused.

A radioactive substance is a substance that contains radionuclides, natural or artificial, whose activity or concentration justifies radiation protection control. The radionuclides contained in radioactive waste can be of artificial origin, such as cesium-137, or natural origin, such as radium-226.

Radioactive waste has three main characteristics, the type of radionuclide, the activity and the half-life. The type of radionuclide contained is related to the radiation emitted (alpha, beta, gamma). The activity is the number of atomic nuclei that spontaneously disintegrate per unit of time; it is expressed in becquerels (Bq). The half-life is the time required for the activity of a radionuclide in a sample to decrease by half [IRS 13a, IRS 13b].

1.3. Classifications of nuclear waste

Waste classification is not unique. Indeed, while the IAEA has provided broad guidelines for defining and classifying radioactive waste, each state is free to use its own nomenclature.

1.3.1. *General information on the classification of radioactive waste*

As regards the classification of radioactive waste, there are two main approaches: one by a waste management channel and the other by a waste production channel. The latter approach is partly inherited from the historical concept of radiation protection.

The management pathway approach often combines the activity and lifetime parameters of the radionuclides constituting the waste. This classification was recommended by the IAEA in the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. This classification is used in France, Belgium and Spain. Sometimes this approach is based only on activity. In Canada, for example, there are only three main categories of radioactive waste (ILW, HLW and spent fuel), except for the specific management of waste from mines. In the Netherlands, the classification has a larger number of categories, but no distinction is made between short- and long-lived waste and consequently there are no plans for surface disposal. In Germany, the classification is based mainly on the exothermic character of the waste.

The production chain approach leads to a more complex classification, with specific chains for certain types of waste, and combining activity and lifespan. This is the approach of the United States, Japan and Sweden (in fact in Sweden, the two types of approach coexist). In Finland, a category is sometimes added for waste from hospitals, universities, etc.

There are also national specificities, as in Belgium, which treats 50% of the radium sources used in the world (the result of uranium mining in the Congo, which is historically Belgian), or in Canada, which has large uranium mines. Similarly, in France, it should be noted that there is no release threshold for waste containing, or likely to contain, only very small quantities of radioactive elements [AMI 13].

1.3.2. *The IAEA's recommendations*

The IAEA proposes dividing radioactive waste into five categories, in addition to the category of waste considered as released (EW, Exempt Waste), according to two criteria, the amount of activity and the half-life of the radionuclide (Figure 1.1). These categories are very short-lived waste (VSLW), very low-level waste (VLLW), low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW) [IAE 09a].

In certain circumstances, such as acceptance into a radioactive waste disposal facility, Waste Acceptance Criteria (WACs) may be established for certain radionuclides. WACs are quantitative or qualitative criteria that may include, for example, restrictions on the activity concentration or total activity of particular radionuclides (or types of radionuclides) in the waste, or requirements regarding the form or packaging of the waste.

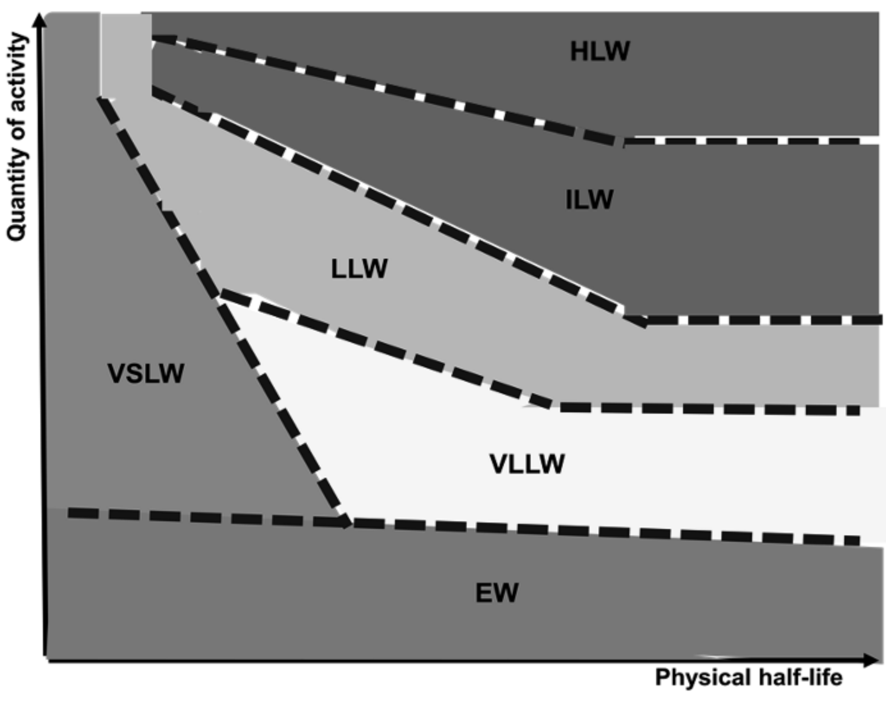

Figure 1.1. *Proposed IAEA classification of radioactive waste (source: [IAE 09a]). EW: exempt waste; HLW: high-level waste; ILW: intermediate-level waste; LLW: low-level waste; VLLW: very low-level waste; VSLW: very short-lived waste. For a color version of this figure, see www.iste.co.uk/amiard/radioactive.zip*

1.3.3. *The French classification of radioactive waste*

The details of the French classification are as follows. Radioactive waste is classified according to two criteria: mass activity and physical half-life. The "mass activity" criterion divides waste into four groups: *déchets de très faible activité*, called TFA or very low-level waste (VLLW), *déchets de faible activité*, FA or low-level waste (LLW), *déchets de moyenne activité*, MA or intermediate-level waste (ILW) and *déchets de haute activité*, high-level waste (HLW). The "life" criterion is divided into three classes to distinguish between *déchets à vie courte*, short-lived waste (SLW), *déchets à vie moyenne*, medium-lived waste (MLL) and *déchets à vie longue*, long-lived waste (LLW). The combination of the two criteria makes it possible to classify the waste into 12 categories (Table 1.1) [PNG 10].

	Very short life (VSL) <100 days	**Short life (SL) ≤31 years old**	**Long life (LL) More than 31 years old**
Very low activity (VLL) <100 Bq.g^{-1}	VLL-SL Morvilliers	VLL-SL Aube Center	VLL-LL Aube Center
Low activity (LLW) Thousands of Bq.g^{-1}	LLW-VSL Beaumont-Hague, Soulaines	LLW-SL Aube Center	LLW-LL (call for applications)
Average activity (AA) Millions of Bq.g^{-1}	AA-VSL Beaumont-Hague, Soulaines	AA-SL Aube Center	AA-LL Bure?
High activity (HLW) Billions of Bq.g^{-1}	HLW-VSL Not applicable	HLW-SL Bure?	HLW-LL Bure?

Table 1.1. *French classification of radioactive waste and storage sites in operation in France (source: modified from [PNG 10, MTE 18]). For a color version of this table, see www.iste.co.uk/amiard/radioactive.zip*

Radioactive waste management simplifies these subdivisions by grouping certain categories to manage them together. In the end, in France, by combining the four levels of activity with the three ranges of radioactive periods, six categories of waste are distinguished, defined by an order of April 4, 2014. In addition, this decree defines the nature of the information that nuclear activity managers and companies are required to establish, maintain and periodically transmit to ANDRA.

At present, only two categories have well-defined channels: VLA-SL at Morvilliers and LA-SL and AA-SL at Soulaines in the Aube region (and previously in the commune of La Hague, at the *Centre de stockage de la Manche-CSM*, 1969–1994). The other channels are still being studied, as are certain specific wastes such as tritiated waste, mining waste, sealed sources and graphite waste (see Chapter 5).

1.3.3.1. *Activity levels used in France*

Based on their activity levels, nuclear waste can be classified into the following six categories:

– Very short-lived waste (VSL) is managed by allowing it to decay on site and then it is disposed of in conventional channels. It is therefore not sent to a storage facility dedicated to radioactive waste.

– Very low-level waste (VLLW) comes from the operation of nuclear power plants and research centers, from fuel cycle facilities and research centers. The activity level of this waste is generally less than 100 $Bq.g^{-1}$. However, the management of this waste justifies radiation protection monitoring.

– Low-level and intermediate-level short-lived waste (LL/IL-SLW) come from the operation and dismantling of nuclear power plants and research centers and, for a small part, from biomedical research activities. The activity of this waste is between a few hundred $Bq.g^{-1}$ and 1 million $Bq.g^{-1}$.

– Long-lived low-level waste (LL-LLW) consists mainly of graphite waste and radium-bearing waste. Graphite waste has an activity of between 10,000 and 100,000 $Bq.g^{-1}$, essentially long-lived beta emitting radionuclides. It comes from the dismantling of first-generation nuclear power plants (UNGG). Radium-bearing waste, mostly from non-nuclear industrial activities, is mainly composed of long-lived alpha-emitting radionuclides and has an activity of between a few tens of $Bq.g^{-1}$ and a few thousand $Bq.g^{-1}$.

– Long-lived intermediate-level waste (LL-ILW) comes mainly from spent fuel reprocessing activities. It is technological waste (used tools, equipment, etc.), waste from the treatment of effluents such as bituminous sludge and structural waste, the shells and end caps that make up the nuclear fuel cladding, packaged in cemented or compacted waste packages. The activity of this waste is of the order of 1 million to 1 billion $Bq.g^{-1}$.

– High-level waste (HLW) also consists mainly of vitrified waste packages from the reprocessing of spent fuel. These waste packages concentrate the great majority of radionuclides, whether fission products or minor actinides. The activity level of this waste is of the order of several billion $Bq.g^{-1}$ [JOR 14].

1.3.3.2. *French radioactive waste systems*

As Table 1.1 indicates, not all categories of waste have their storage site yet closed in France. We will detail this aspect later (Chapter 5).

Two important aspects condition the classification of radioactive waste. The first aspect is that there is no single classification criterion for determining a waste class. It is indeed necessary to study the activity of the different radionuclides present in the waste to position it in the classification. However, in the absence of a single criterion, the wastes in each category generally fall within a range of mass activity indicated below.

The second aspect is that a particular type of waste may fall into a defined category but not be accepted in the corresponding management channel because of other characteristics (e.g. its chemical composition or physical nature, such as radium-bearing waste that emits a radioactive gas, radon-222). Consequently, the waste category is not necessarily assimilated to its management channel [AMI 13].

1.3.3.3. *Hospital radioactive waste*

With respect to hospital radioactive effluents, French legislation is very strict and requires the intervention of official institutions, in particular ANDRA, for the conditioning, elimination, transport and storage of this waste [FRE 01, ACR 12]. This statement must be moderated, however, in view of the increase in practices involving radionuclides. The next radionuclides to be used will be beta and especially alpha emitters, which have a limited range in living matter. Recently, research is therefore exploring a number of products under development using isotopes such as lutetium-177, promethium-149, bismuth-212, bismuth-213, astatine-211, radium-223 and polonium-210.

1.3.3.4. *Harmfulness of radioactive waste*

For France, the IRSN [IRS 18b] proposes a methodology and possible criteria for assessing the harmfulness of radioactive materials and waste. In order to make the indicators understandable to a wide audience, the situations are defined to respect a minimum degree of realism. Their choice also aims to cover the main exposure routes and a diversity of contexts.

Four situations are considered, the first two of which involve the presence of an individual in a room containing a package of radioactive waste or radioactive material, whether intact or damaged. The last two situations concern the dispersion of the package in the environment and the impact on an entire local human population or the impact on an aquatic ecosystem.

The report also provides an example of the application of the method for three families of waste (vitrified HA, bituminous MAVL and FAVL ^{14}C). The annual impacts after 100 or 1,000 years are provided and proposals are made for broader deployment, making it possible in the long-term to have an indication of the harmfulness of each of the families defined in the national inventory of radioactive materials and waste [IRS 18b].

1.3.4. *American classification*

The American classification of radioactive waste has three classes (A, B and C) based on the maximum activity of a given radionuclide (Table 1.2).

Radionuclide	Class A	Class B	Class C
^{3}H	40	MC	MC
^{14}C	0.8	–	8
^{60}Co	700	MC	MC
^{90}Sr	0.04	150	7,000
^{99}Tc	0.3	–	3
^{129}I	0.008	–	0.08
^{137}Cs	1	44	4,600
All radionuclides with half-life <5 years	700	MC	MC
α emitters with a half-life >5 years	10		100
^{241}Pu	350		3,500
^{242}Cm	2,000		20,000

Table 1.2. *Excerpt from the US NRC classification of radioactive waste based on maximum concentrations of radionuclides and expressed in Ci.m^{-3} (source: [BLA 01]). MC: maximum concentration (no limit for this class)*

1.3.5. *British classification*

The British classification of radioactive waste adopts the IAEA classification into five categories by defining its own criteria for activity levels (Table 1.3).

Waste classes	Characteristics of this class
VLLW, small volume	Waste of 0.1 m^3 that can be disposed of with regular garbage if it contains less than 400 kBq of activity, as well as hospital and university waste. For waste containing carbon-14 and tritium, the activity limit is 4,000 kBq
VLLW, large volume	Radioactive waste with an upper limit of 4 MBq per ton (not including tritium) is disposed of in specified landfills. For waste containing tritium, the upper limit is 40 MBq per ton
LLW	Containing radioactive material other than that suitable for disposal with ordinary waste, but not exceeding 4 GBq per ton of waste or 12 GBq per ton of β and γ activity
ILW	Waste with radioactivity levels above the upper limits for LLW, but which does not generate heat
HLW	Wastes in which the temperature can increase significantly due to their radioactivity, so this factor must be taken into account in the design of storage or disposal facilities

Table 1.3. *The British nuclear waste classification system (source: [OJO 14, RAH 15])*

1.3.6. *Russian classification*

The Russian classification of radioactive waste is based on a division into three classes according to the specific activity of various categories of radionuclides (Table 1.4). The limits of the categories are high.

Category	Specific activity ($Bq.g^{-1}$)			
	Tritium	Beta (except ^3H)	Alpha (except transuranium elements)	Transuranium elements
Low activity	10^6–10^7	$<10^3$	$<10^2$	<10
Average activity	10^7–10^{11}	10^3–10^7	10^2–10^6	10–10^5
High activity	$>10^{11}$	$>10^7$	$>10^6$	$>10^5$

Table 1.4. *Practical classification of radioactive waste in Russia (source: [OJO 14])*

1.3.7. *Comparisons of the various classifications*

Various comparisons can be made between the classifications of radioactive waste used by different countries.

1.3.7.1. *American classification and IAEA recommendation*

The classification recommended by the IAEA and that applied by the United States have no overlap (Table 1.5).

<table>
<tr><td>NRC</td><td colspan="2">Class A</td><td colspan="2">Class B</td><td>Class C</td><td colspan="2">Excess C or GTCC</td></tr>
<tr><td>IAEA</td><td>VLLW</td><td colspan="2">LLW</td><td colspan="3">ILW</td><td>HLW</td></tr>
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Table 1.5. *Comparison of IAEA ([IAE 09a], GSG-1) and NRC ([NRC 15]) classifications (source: [NEA 16a])*

1.3.7.2. *Comparison between the Belgian, French and Canadian radioactive waste classifications*

In Belgium, class A waste has a specific destination and class B and C waste are managed together. In France, the VLLW and LLW-SL categories are managed together, the AA-LL and HALL categories are managed together, while the FA-VL category is managed independently. For the three states, a distinction is made between current waste and historical waste [PAR 18].

	Belgium	**France**	**Canada**
Number of categories	3	5	4
Classification by lifespan and activity level	A (LLW) B (ILW) C (HLW)	TFA (VSLW) FMA-VC (LLW) FA-VL (VLLW) MA-VL (ILW) HA-VL (HLW)	LLW (LLW) ILW (ILW) HLW (HLW + spent fuel) Mining waste
Other more vague categories	NORM, T-NORM Radifer Waste from future sanitation Spent fuel Spent MOX fuel	Waste without a channel Fuel and MOX	

Table 1.6. *Comparison of radioactive waste classifications in Belgium, France and Canada (source: [PAR 18]). In brackets, the equivalences with the IAEA classification from 2009 [IAE 09a]*

1.3.8. *Classification of sealed sources*

For sealed sources, the IAEA [IAE 09a] recommends the classifications reported in Table 1.7.

Type	Half-life	Activity	Volume	Examples
VSLW	<100 days	100 MBq	Small	^{90}Y, ^{198}Au (brachytherapy)
VSLW	<100 days	5 TBq	Small	^{192}Ir (brachytherapy)
LLW	<15 years	<10 MBq	Small	^{3}H, ^{60}Co, ^{85}Kr
ILW	<15 years	<100 TBq	Small	^{60}Co (irradiators)
LLW	<30 years	<1 MBq	Small	^{137}Cs (brachytherapy)
ILW	<30 years	<1 PBq	Small	^{90}Sr (thickness gauges, thermoelectric generators), ^{137}Cs (irradiators)
ILW	>30 years	<40 MBq	Small but with a large number of sources	Pu, Am, Ra (static eliminators)
ILW	>30 years	<10 GBq		^{226}Ra, ^{241}Am (gauges)

Table 1.7. *Examples of the use of the IAEA classification for disused sealed radioactive sources (source: [IAE 09a])*

1.4. Origins of nuclear waste

Radioactive waste has multiple origins, which can be subdivided into three main sources: waste from the fuel cycle contributing to nuclear electricity (NFC, Nuclear Fuel Cycle), waste from other very varied origins (medicine, research, etc.) and waste resulting from a nuclear accident. Fuel cycle waste differs according to whether it comes from upstream or downstream plants or from nuclear power reactors in operation (Figure 1.2).

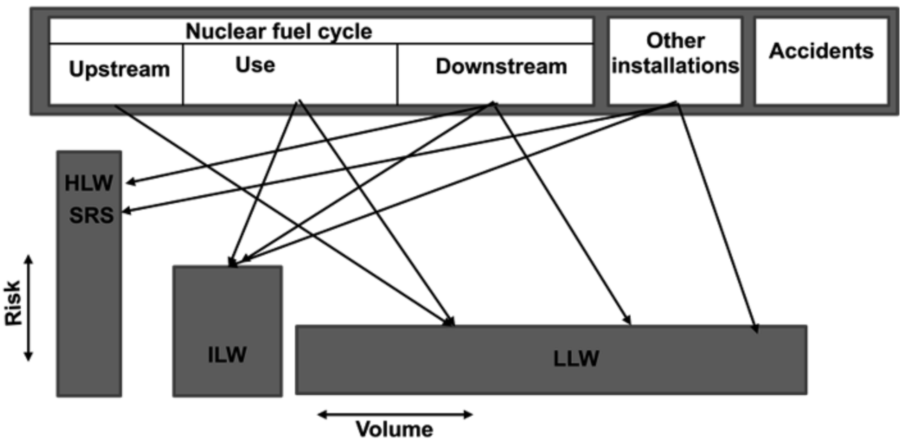

Figure 1.2. *Diagram of the origins of radioactive waste (source: [OJO 14]). HLW: high-level waste; ILW: intermediate-level waste; LLW: low-level waste; NFC: nuclear fuel cycle; SRS: sealed radioactive sources. For a color version of this figure, see www.iste.co.uk/amiard/radioactive.zip*

1.4.1. *The main radionuclides in radioactive waste*

The principal radionuclides in radioactive waste are very varied and can be classified into four categories. These are fission products (H, Se, Br, Kr, Rb, Sr, Y, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb and Dy), activation products (C, Cr, Mn, Fe, Co, and Ni) and heavy nuclei (U, Nb and Zr), those that are both fission and activation products (Zr and Nb), heavy nuclei (U, Np, Pu, Am and Cm) and some elements with long-lived radioactive isotopes (C, Zr, Tc, Pd, Sn, I, Cs and Sm) to which are added the five heavy nuclei elements.

1.4.2. *Wastes related to the nuclear fuel cycle*

A distinction should be made between two fuel cycles, the so-called open NFC and the closed NFC, the latter reprocessing spent nuclear fuel in order to reuse the extracted by-products (uranium and plutonium) in other reactors, whereas in the case of the open NFC, the spent fuel is considered as radioactive waste and therefore disposed of. A representation of the two types of fuel cycle is shown in Figure 1.3.

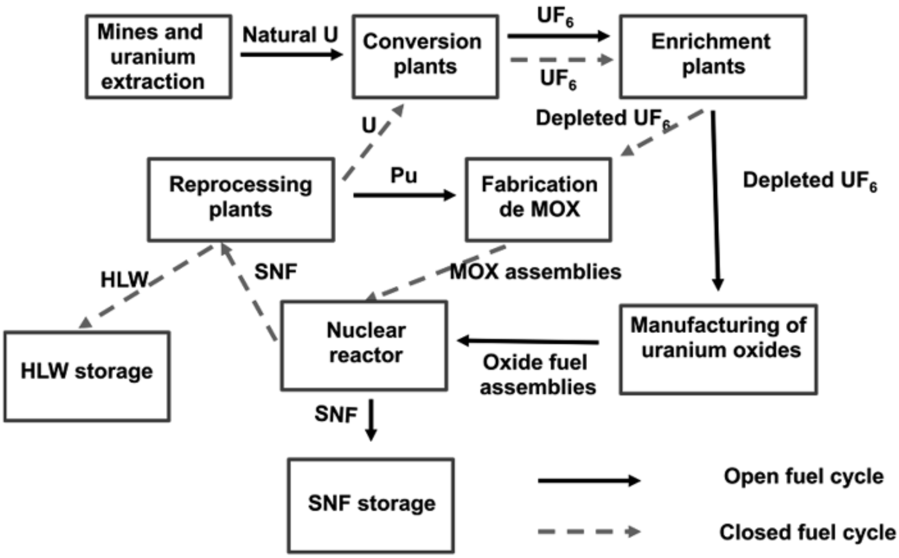

Figure 1.3. *The various stages of the nuclear fuel cycles in open and closed versions (source: [OJO 14]). HLW: high-level waste; MOX: mixed oxide; NFC: nuclear fuel cycle; Pu: plutonium; SNF: spent nuclear fuel; U: uranium; UF6: uranium hexafluoride. For a color version of this figure, see www.iste.co.uk/amiard/radioactive.zip*

The number of states reprocessing civilian spent fuel in 2013 was still six (China, France, India, Japan, the United Kingdom and Russia) with a theoretical annual reprocessing capacity of 5,900 tons to be increased to 6,700 tons [OJO 14]. In 2020, the United Kingdom gave up reprocessing and Japan has had its plants shut down for many years.

The chemical and radioactive composition of HLW varies greatly from state to state. Thus, for transuranium elements, the quantities present in HLW, expressed in $g.L^{-1}$, are 2.0 for the British Magnox reactors, 5.1 for the waste from the La Hague reprocessing plant in France, 7.6 for the WIP (Waste Immobilization Plant) in India, 12.6 for the waste from the Tokai reprocessing plant in Japan and <0.1 for American Hanford waste. Similarly for fission products, the quantities expressed in $g.L^{-1}$ are 87.0 at La Hague, 1.1 at the Indian WIP, 49.0 for the Japanese Tokai plant and <2.5 for the Hanford waste. This can be explained by the characteristics of the reactors and nuclear fuels used, as well as by the cooling methods used and the reprocessing technologies [OJO 14].

1.4.3. *Nuclear waste from electricity production*

About 90% of radioactive waste comes from electricity generation. This waste is of three types. The first category includes waste of various origins (also called type A waste); these are chemical products, work clothes, tools, etc., generally of low radioactivity (18,000 $t.yr^{-1}$ in France). The second group contains technological waste related to the atomic fission process (also called type B waste); this is fairly highly radioactive waste, consisting in particular of metal structures and zircaloy "shells" (an alloy of zirconium and tin, about 1,800 $t.yr^{-1}$ in France). The last group includes waste resulting directly from the fission process of the atom itself (also called type C waste); these are fission products and actinides (approximately 63 $t.yr^{-1}$ and 1.9 $t.yr^{-1}$, respectively, in France), i.e. volumes of 100–240 $m^3.yr^{-1}$. Still for France, each year the nuclear industry produces more than 1,000 tons of spent fuel that is sent to the Orano (previously Areva) plant at La Hague. A portion is processed each year to extract the plutonium (1%) and uranium (95%) and to condition the residue (4%). This is the stage that produces by far the most radioactive waste [AMI 13]. The plutonium is reused in the manufacturing of new fuels (MOX), which are composed of a mixture of plutonium and uranium oxides. There are currently 2,140 tons of irradiated MOX fuel, while 424 tons are loaded into 900 MW reactors [AND 20c].

The quantities of low- and intermediate-level radioactive waste and the tonnage of spent nuclear fuel generated vary widely among the nuclear technologies (Table 1.8.).

	LWR	BWR	PWR	WWER	RBMK	CANDU	Magnox	AGR
LLW and ILW	100	260	130	320	850	80	1,740	400
Spent fuel	25	22	20	28	42	145	240	29

Table 1.8. *Quantities of radioactive waste ($m^3.GW^{-1}$) and spent fuel ($t.GW^{-1}.yr^{-1}$) generated by the various types of nuclear reactors in operation (source: [OJO 14]). LWR: light-water reactor; BWR: boiling water reactor; PWR: pressurized water reactor; WWER: water-water energy reactor; RBMK: Reaktor Bolshoy Moshchnosti Kanalnyi, CANDU: Canadian dioxide uranium; Magnox: magnesium non-oxidizing; AGR: advanced gas-cooled reactor*

1.4.4. *Nuclear waste related to military activities*

Nuclear defense facilities, many of which are currently being dismantled, have generated waste in the past that has not been treated. This old waste, stored in the facilities of the time, will have to be taken back and conditioned. The current maintenance of nuclear weapons also generates waste in small quantities. This waste is managed in the same way as waste from the civilian industry.

The radioactive waste, Soviet and then Russian, dumped in the Kara Sea in 1993–1994 is relatively large (Table 1.9) [NYF 03].

Waste category	Material	Number of objects	Total activity (TBq)
High activity	Reactors with fuel or containers	7	4,700
Intermediate activity	Fuel-less reactors	10	20
Low or intermediate activity	Containers	6,508	580
	Large objects	154	
	Vessels	15	

Table 1.9. *Radioactive waste dumped in the Kara Sea in the Arctic Ocean in 1993-1994 (source: [NYF 03])*

1.4.5. *Wastes related to medical and industrial uses*

Radionuclides have many uses in medicine and biological research. There are about 23 radionuclides that are used as radioactive tracers for various diagnostic purposes. Other radionuclides are present in sealed sources and serve as sources of ionizing radiation for medical, industrial and research applications [AMI 13]. The types of sealed sources are very varied and there are about 52 types of irradiators [IAE 19a].

Various medical and industrial, civilian and military accidents have occurred with abandoned irradiators [AMI 18, AMI 19].

Some industrial activities, such as chemical treatment related to the production of rare earths or the manufacture of phosphate fertilizers, lead to the concentration of natural radioactivity in a residue that becomes radioactive waste. This is particularly the case for the Rhodia plant in La Rochelle (Charente Maritime).

Many radioactive sources in sealed form are used in medicine to treat cancer (brachytherapy). They are used in industry to radiograph welds to test their integrity, to measure the water content of soil and for many other applications. They are also used in research or medicine to establish diagnoses (scintigraphy) or to treat certain cancers (thyroid) as radioactive tracers, in liquid form. The quantity of waste generated is small, but there are more than a thousand users scattered over the French territory [AMI 13].

1.4.6. *Nuclear waste related to the dismantling of nuclear installations*

The CEA monograph [CEA 17] details the various processes for treating materials resulting from dismantling. During the clean-up and dismantling of a nuclear installation, the various treatments generate a wide variety of wastes, organic wastes, graphite wastes, magnesian wastes and very special wastes such as mercury wastes. High-level waste in sludge or powder form and tritiated waste are also produced.

The volumes of solid radioactive waste generated during the decommissioning of the various nuclear fuel cycle facilities are very variable, with a clear preponderance from the deconstruction of nuclear power reactors (Table 1.10).

Step	Type of waste	Quantity ($m^3.GW^{-1}.yr^{-1}$)
UF_6 conversion	Solid	0.5–1
UF_6 enrichment	Solid	5
UO_2 manufacturing	Solid	1–2
Reactor	Solid	375
Reprocessing	Solid	5

Table 1.10. *Quantities of radioactive waste generated during the decommissioning of various nuclear fuel cycle facilities (source: [OJO 14])*

Ojovan and Lee [OJO 14] quantify these various categories of waste from the dismantling of a nuclear power reactor (Table 1.11).

Step	Type of waste	Quantity ($m^3.GW^{-1}.yr^{-1}$)
Miscellaneous (scrap metal)	Solid	15
Sludge	Solid	0.02
Effluents with tritium	Liquids	70
HLW	Liquids	28
ILW	Liquids	25
LLW	Liquids	15
LLW	Solid	65

Table 1.11. *Typical waste during reactor shutdown (source: [OJO 14])*

1.4.7. *Waste from nuclear accidents*

The NEA Expert Group on Fukushima Waste Management and Decommissioning Research and Development (EGFWMD) was established in 2014 to advise Japanese authorities on the management of large quantities of on-site waste with complex properties and to share their experiences with the international community [NEA 16a].

1.5. The global radioactive waste balance

Radioactive waste inventory data are an important element in the development of a national radioactive waste management program because they affect the design and selection of final disposal methods.

The inventory data are generally presented as quantities of radioactive waste in different waste classes, according to the waste classification system developed and adopted by the country or national program in question.

The diversity of classification systems among countries has limited the comparability of waste inventories and made it difficult to interpret waste management practices, both nationally and internationally. To help improve this situation, the Nuclear Energy Agency has developed a methodology that ensures consistency in national radioactive waste and spent fuel inventory data when submitted. This report is a follow-up to the 2016 report [NEA 16b] that presented the methodology and layout for spent fuel submission. It now extends this methodology and layout to all types of radioactive waste and the corresponding management strategies [NEA 17d].

National radioactive waste management programs require very large amounts of data and information across multiple and disparate disciplines. These programs tend to span a period of several decades, resulting in a serious risk of data and information loss, which in turn can threaten the production and maintenance of robust safety records. The NEA has taken the lead in creating a Radioactive Waste Repository Metadata Management (RepMet) project [NEA 18a].

In 2011, Ojovan and Lee [OJO 14] estimated 68.10^6 m^3 of waste stored and $76,10^6$ m^3 of waste disposed (Table 1.12).

At the end of 2013, the quantities of spent fuel discharged from nuclear reactors amounted to 367,600 metric tons, of which about half was stored in wet form, one-third needed to be reprocessed, and the rest was stored in dry form [IAE 18a] (Table 1.13).

Waste category	Stored waste (m^3)	Disposed waste (m^3)
VLLW	153.10^3	113.10^3
LLW	$56{,}663.10^3$	$64{,}792.10^3$
ILW	$8{,}723.10^3$	$10{,}587.10^3$
HLW	$2{,}743.10^3$	72.10^3
Total volume	**$\sim 68.10^6$**	**$\sim 76.10^6$**

Table 1.12. *Global estimate of the global radioactive waste inventory in 2011 (source: [OJO 14])*

Geographical area	Wet storage	Dry storage	Reprocessing	Total
Africa	850	50	NP	900
Eastern Europe	28,600	7,700	3,200	40,000
Western Europe	37,000	4,600	108,000	154,100
Far East	32,100	5,700	8,600	46,400
North America	79,300	41,900	NP	131,200
Latin America	3,000	2,000	NP	5,000
Grand total	180,800	56,900	120,300	367,600

Table 1.13. *Quantities of discharged spent fuel (in ton) at the end of 2013 (source: [IAEA 18a]). NP: not provided*

The storage of spent fuel is carried out for 81% near the producing reactor (59% under water and 22% dry) and for 15% far from this reactor (13% under water and 2% dry), and for the remaining 4% the storage is not known [IAE 18a].

Figure 1.4 highlights the significant quantities of solid radioactive waste worldwide. The less hazardous categories of waste (VLLW and LLW) are larger than the more hazardous ones (ILW and HLW). However, it should be noted that the final solutions are more effective for the former categories compared to the solutions not found for the more hazardous ones.

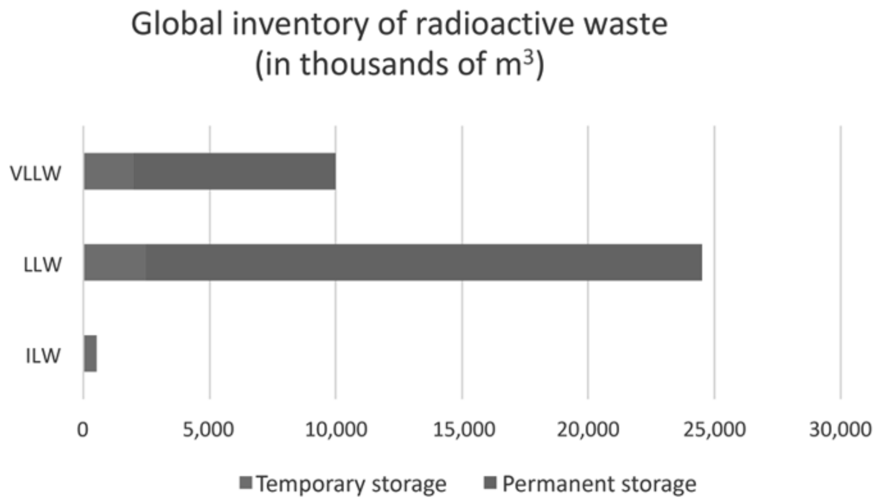

Figure 1.4. *Summary of global inventories of solid radioactive waste in storage and disposal (source: [IAE 18a]). For a color version of this figure, see www.iste.co.uk/amiard/radioactive.zip*

The distribution of solid waste at the end of 2013 by major waste categories and by geographical area is presented in Table 1.14.

Geographical area	VLLW	LLW	ILW	HLW
Africa	7,000	20,000	1,000	0
Eastern Europe	15,000	2,479,000	101,000	7,000
Western Europe	224,000	355,000	269,000	6,000
Far East	5,000	331,000	4,000	0
North America	2,105,000	248,000	84,000	8,000
Latin America	0	37,000	0	0
Middle East and South Asia	0	3,000	0	0
East Asia and Pacific	0	5,000	1,000	0
Grand total	2,356,600	3,479,000	460,000	22,000

Table 1.14. *Quantities of solid waste (in m^3) at the end of 2013 (source: [IAE 18a])*

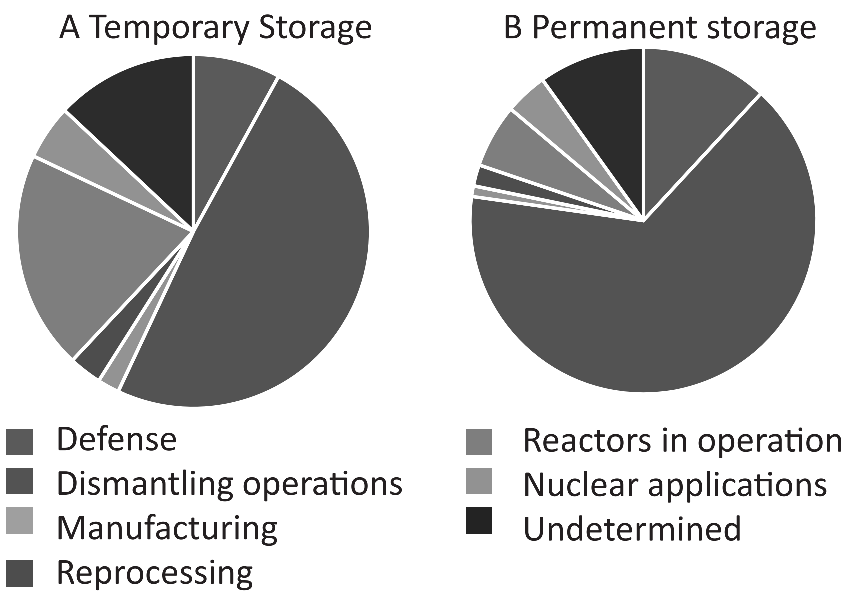

Figure 1.5. *Global origins of radioactive waste in 2013 for A) storage and B) final disposal (source: [IAE 18a]). For a color version of this figure, see www.iste.co.uk/amiard/radioactive.zip*

Worldwide, the majority of radioactive waste comes from dismantling operations (49% and 66%, respectively, depending on whether the storage is interim or final) (Figure 1.5).

Globally, the volumes of radioactive waste at the end of 2013, both solid and liquid, in interim and final storage, for the various categories are shown in Tables 1.15 and 1.16. LLW is the largest category.

Category	Solid	Liquid	Total
VLLW	2,356,000		2,356,000
LLW	3,479,000	53,332,000	56,811,000
ILW	460,000	6,253,000	6,713,000
HLW	22,000	2,786,000	2,808,000

Table 1.15. *Radioactive waste in temporary storage globally at the end of 2013 (in m^3) (source: [IAE 18a])*

The global waste volumes that are permanently stored are 69% for LLW, 29% for VLLW and only 1.63% for ILW and 0.06% for HLW.

The distribution of total activity is 95% for HLW, 3% for ILW, 1.5% for LLW and 0.5% for VLLW [IAE 18a].

Category	Solid	Liquid	Total
VLLW	7,906,000		7,906,000
LLW	20,451,000	39,584,000	60,035,000
ILW	107,000	8,628,000	8,735,000
HLW	0	68,000	68,000

Table 1.16. *Radioactive waste in final storage globally at the end of 2013 (in m^3) (source: [IAE 18a])*

1.6. Conclusions

Radioactive waste is a radioactive substance for which no further use is planned or envisaged. This definition has many implications and divides states into two groups depending on whether their nuclear fuel cycle is open or closed. In the first case, all spent fuel is considered as waste; in the second case, it is radioactive material that can still be used.

The IAEA proposes a classification of radioactive waste based on two criteria: the level of mass activity of the waste and the physical period or half-life of the radionuclide present in the waste. Each state has adopted its own classification, which has a strong influence on the management of radioactive waste.

The origin of radioactive waste is multiple. All activities, whether military or civilian, generate radioactive waste. However, it is the decommissioning and dismantling of nuclear installations that generate the largest volumes. The reprocessing of spent fuel, carried out by a small number of states that have adopted the closure of the nuclear fuel cycle, generates larger volumes of waste, all categories combined, but less high-level waste than the open cycle. Indeed, in the case of an open fuel cycle, the volume of spent fuel is large and this waste is hazardous and difficult to store.

A number of historical nuclear wastes, such as military wastes, mining residues and others, pose difficult conditioning and management problems.