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Research article

Management of radioactive waste from application of radioactive materials and small reactors in non-nuclear industries in Canada and the implications for their new application in the future

George Sikun Xu[1,]* and Nicholas Chan[2]

[1] Environment & Waste Technologies Branch, Canadian Nuclear Laboratories, 286 Plant Road, Chalk River, ON K0J 1J0, Canada
[2] Waste Management Function Branch, Canadian Nuclear Laboratories, 286 Plant Road, Chalk River, ON K0J 1J0, Canada

* **Correspondence:** george.xu@cnl.ca; Tel: +16135843311x43888; Fax: +16135849182.

Abstract: A large number of artificial-origin radionuclides from irradiation in small reactors and/or nuclear reactions in accelerators are currently used in non-nuclear industries such as education, oil and gas, consumer merchandise, research, and medicine. Radioactive wastes from the use of these radionuclides in non-nuclear industries include expired sealed radioactive sources, biological materials, radionuclide-containing chemicals, contaminated equipment, and very small quantities of used nuclear fuel. Although being less challenging and complex than nuclear energy production and research waste streams, these wastes are subject to the common nuclear regulations by the Canadian Nuclear Safety Commission, and are managed following domestic and international standards and guidelines made by the Canadian Standards Association, International Atomic Energy Agency, and International Organization for Standardization. Management practices used in the nuclear industry in Canada are commonly applied to the non-nuclear industry radioactive waste streams, such as waste handling, treatment, packaging, storage, transportation, clearance and exemptions, and disposal. The half-lives of radionuclides in non-nuclear applications range from hours to thousands of years, and their activities in non-nuclear industrial applications can be as low as their clearance level or as high as the upper limits for intermediate level radioactive waste. Waste containing only short half-life radionuclides is placed in temporary storage to allow decay, and then is cleared and disposed of through non-radioactive waste routes. Non-clearable waste materials are treated, consolidated, and managed along with radioactive waste generated from the nuclear industries at designated radioactive waste management sites.

Key words: radioactive waste; radionuclides; small reactors; non-nuclear industries;regulations; industrial standards; radioactive waste clearance

1. Introduction

Applications of radioactive materials and small reactors in non-nuclear industries are recognized to benefit the general public in many ways. These applications include many radioactive isotopes for medical diagnosis, imaging, brachytherapy, radiation therapy; biological research; radiation food processing; sealed sources in consumer products; oil and gas, petroleum sealed sources; and academic research and industrial radioactive tracers. These radionuclides are mostly of artificial origins, and are produced from small reactors and, to a lesser extent, from accelerators. The medical and biological research applications account for the majority of radioactive isotopes in the non-nuclear industries. While radioactive waste management in the nuclear industry attracts great attention, management of waste radioactive materials that are closer to the public life appears to be less visible and concerning to the public, largely because of the tiny quantities involved in bulk materials. Nonetheless, non-nuclear industry radioactive waste management has been subject to the same standards as the nuclear industry worldwide [1,2]. Higher-than-background levels of radioactive iodine isotopes were previously found in municipal sewage [3]. Examples such as this lead to more rigorous strategies taken to address the concerns of radioactive materials in non-nuclear industries, and to understand their health effects. Examples of these radioactive materials include medical isotopes, e.g., iodine-131 from thyroid cancer treatment facilities [4,5], sealed sources used in the non-nuclear industries [2,6], and reactor waste from university-based research reactors [7]. In Canada, the waste is generally managed together with the waste of the same classification from the nuclear industry. In particular, Atomic Energy of Canada Limited (AECL), a federal crown corporation, takes ownership of the non-nuclear industry radioactive waste, and is responsible for the storage and final disposal of the waste on a commercial contract basis.

Currently, various radionuclides are being investigated for cancer radiation therapy, such as Ac-225 and Pb-212 Targeted Alpha Therapy, and small modular reactors are under development for off-grid energy production and other applications in Canada and many other countries. In anticipation of potential deployment of small modular reactors and radiation therapy for applications in non-nuclear industries, a review of current radioactive waste management practices in the non-nuclear industries will be useful in addressing public concerns on the waste issues from these future applications. This paper summarizes the regulations and practices of radioactive waste management for non-nuclear industries in Canada.

2. Radioactive waste management of regulations and oversight in Canada

2.1. Regulatory oversight and standards

The protection of public health and the environment is paramount in the activities that involve radiation and radioactive materials. These activities are regulated according to the laws and regulations by a national regulatory body in a country. In Canada, the Canadian Nuclear Safety Commission (CNSC) regulates all activities that involve radioactive materials and devices, including the radioactive waste produced from applications of nuclear materials, radiation devices, and small reactors in the non-nuclear industries. Except for a few circumstances under which naturally occurring radioactive materials (NORM) are regulated by the CNSC, NORM falls under the responsibility of provincial jurisdictions [8,9]. In addition to provincial NORM regulations, Management of Naturally Occurring Radioactive Materials guidelines have been developed to harmonize standards throughout Canada [10].

The CNSC states that "The oversight and management of Canada's radioactive waste consists of policy and legislative framework, CNSC regulatory oversight and framework, radioactive waste facilities and inventory in Canada, radioactive waste inventory, waste hierarchy, and responsibilities for long-term management, transport of radioactive waste, international responsibilities" [11], which is illustrated in Figure 1. The policies and legislations cover both nuclear and non-nuclear industries. Specifically, the regulatory framework, e.g., on radioactive waste management, includes the Nuclear Safety and Control Act (NSCA) [12], its associated regulations, licences and licence conditions handbooks and, finally, the CNSC's regulatory documents. The regulatory documents are prepared to help the users understand the expectations from CNSC's regulatory actions. Waste generators are required to consult the regulations, the regulatory documents, and policies made by the overseeing governmental agencies and departments. A few important radioactive waste management regulatory documents are listed below:

- REGDOC-2.11.1, Waste Management, Volume I: Management of Radioactive Waste [13].
- REGDOC-2.11.1, Waste Management, Volume III: Safety Case for Disposal of Radioactive Waste [14].
- REGDOC-2.11.2, Decommissioning [15].
- The regulatory documents are complemented with Canadian Standards Association (CSA) standards.

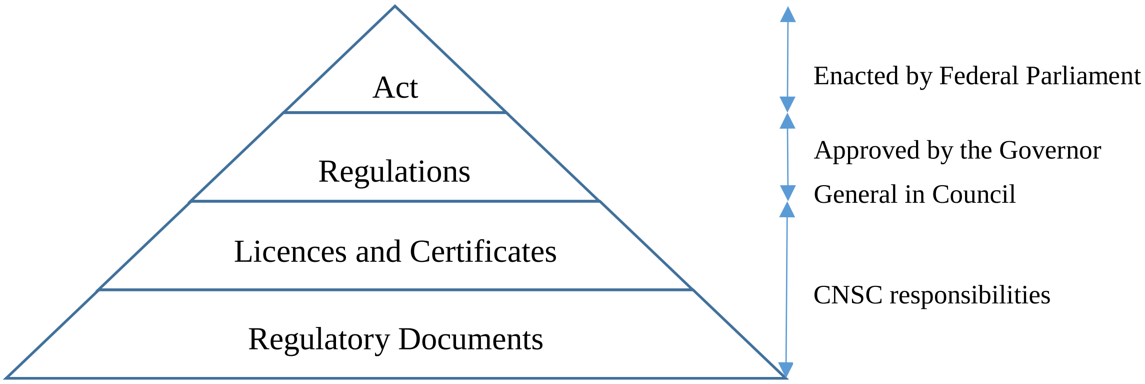

Figure 1. CNSC's regulatory framework [16].

The International Atomic Energy Agency (IAEA) publishes safety guides for classification, monitoring and surveillance, processing and handling, storage, and disposal of radioactive waste. The safety guides that may be referenced in the waste management practices of non-nuclear industries are shown below:

- SSG-45, Predisposal Management of Radioactive Waste from the Use of Radioactive Material in Medicine, Industry, Agriculture, Research and Education [17].
- No. RS-G-1.10, Safety of Radiation Generators and Sealed Radioactive Sources [18].

The IAEA safety guides, if applicable, may be considered as sources of information in preparing policies, regulations, and operational requirements and procedures.

The CSA nuclear-series standards on waste management complement the CNSC’s regulatory documents. General radioactive waste management practices follow the CSA nuclear-series standards. The International Organization for Standardization (ISO) standards, in the event of the absence of a Canadian standard, may be used in Canada. The ISO standards complement the IAEA safety guides. All standards are intended to provide information to facilitate radioactive waste management practices by waste generators. A few important CSA and ISO standards that are often used are listed below:

- N292.0:19, General principles for the management of radioactive waste and irradiated fuel [19].
- N292.1-16, Wet storage of irradiated fuel and other radioactive materials [20].
- N292.5-11, Guideline for the exemption or clearance from regulatory control of materials that contain, or potentially contain, nuclear substances [21].
- N292.6-18, Long-term management of radioactive waste and irradiated fuel [22].
- CSA Z317.10:21, Handling of health care waste materials (including radioactive waste materials) [23].
- ISO 11932:1996, Activity measurements of solid materials considered for recycling, re-use or disposal as non-radioactive waste [24].
- ISO 12807:2018, Safe transport of radioactive materials - Leakage testing on packages [25].
- ISO 16640:2021, Monitoring radioactive gases in effluents from facilities producing positron emitting radionuclides and radiopharmaceuticals [26].

2.2. Radioactive waste classifications in Canada

The radioactive waste classifications in Canada follow the CSA Standard N292.0:19 [19]. The standard is developed from IAEA GSG-1 [27] and LLW Repository Ltd. NWP-REP-134 [28]. Four classes of radioactive waste are recognized for radioactive waste management in Canada [19]:

a) “Low-level radioactive waste (LLW), a limit of 400 Bq/g on the average (and up to 4,000 Bq/g for individual waste packages) for long-lived alpha emitting radionuclides can be considered in the classification process. For long-lived beta and/or gamma emitting radionuclides, such as C-14, Cl-36, Ni-63, Zr-93, Nb-94, Tc-99 and I-129, the allowable average activity concentrations can be considerably higher (up to tens of kBq/g) and can be specific to the site and disposal facility”. This class also includes very-short-lived low-level radioactive waste and very-low-level radioactive waste.

b) “Intermediate-level radioactive waste (ILW), a precise boundary between LLW and ILW cannot be provided, as limits on the acceptable level of activity concentration will differ between individual radionuclides or groups of radionuclides.”

c) “High-level radioactive waste (HLW) is used (i.e., irradiated) nuclear fuel that has been declared as radioactive waste and/or is waste that generates significant heat (typically more than 2 kW/m^3) via radioactive decay. HLW typically has levels of activity concentration in the range of 10^4 to 10^6 TBq/m^3.”

d) “Uranium mine and mill tailings are a specific type of radioactive waste generated during the mining and milling of uranium ore and the production of uranium concentrate.”

CSA Standard N292.0:19 [19] also provides guidance on waste exemption, and clearance and storage decay.

2.3. Clearance quantities

Since many radionuclides are used with very low activity concentrations in non-nuclear industries, they may be exempted from regulatory oversight or waste radioactive materials may be cleared for disposal through non-radioactive waste routes. Regulatory limits have been established for exemption, exclusion, and clearance of radioactive materials in Canada [29]. These limits are set by taking into consideration the data from the International Atomic Energy Agency (IAEA) Safety Guides and international practices.

IAEA Basic Safety Standards (BSS) Series 115 [30] and the IAEA-RS-G-1.7 safety guide [31] have established the concepts of exemption, exclusion and clearance, taking into consideration international nuclear practices. The guidance in the IAEA BSS and IAEA-RS-G-1.7 is based upon the concept of trivial dose. IAEA-SS-89 [32] indicates that the level of dose that is considered trivial, i.e., not warranting regulatory control, ranges from 10 µSv/a to 100 µSv/a. In setting a dose-based criterion for risk-based regulatory processes, the lower value of the range was selected in the IAEA BSS (10 µSv/a). IAEA BSS Series 115 schedule I addresses moderate quantities of clearance materials and IAEA RS-G-1.7 addresses bulk quantities of clearance materials. Many countries have adopted the IAEA guidance on the concepts with some modifications to suit their particular situations. In Canada, the Nuclear Substances and Radiation Devices Regulations (NSRDR) was amended with exemption and clearance concepts in 2008 [29]. The regulation sets the requirements for:

1) Unconditional (unrestricted or generic) clearance or release largely using IAEA RS G-1.7 guidelines, and
2) Conditional clearance using the IAEA BSS dose criterion.

The relation among the terms and definitions is illustrated in Figure 2.

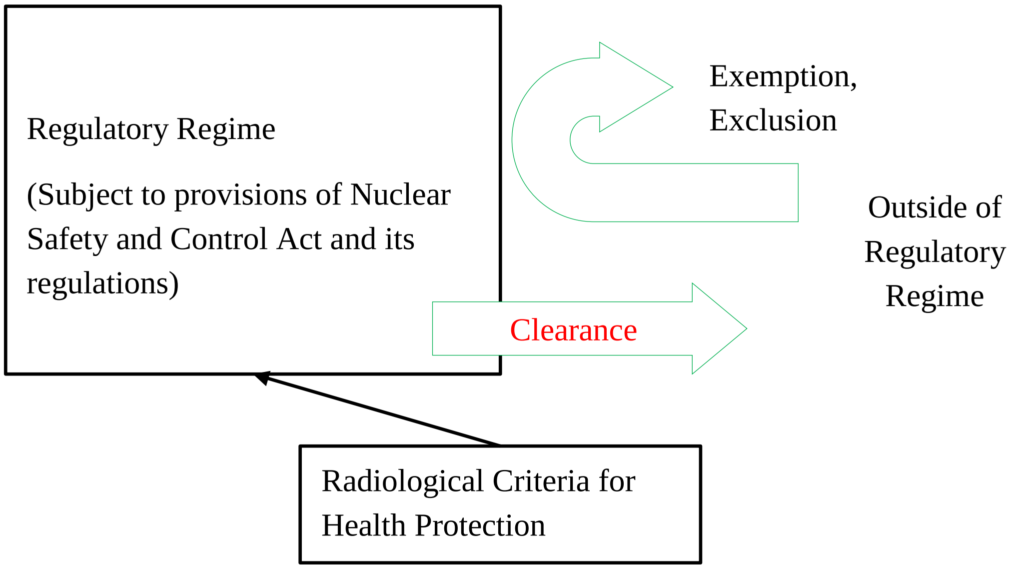

Figure 2. Concepts for clearance, exemption, and exclusion.

2.3.1 Unconditional clearance levels and methods

In most cases, radiation doses resulting from artificial-origin radionuclides, which are extensively used in non-nuclear industries, are the main concern for waste material clearance. The activity concentrations (mass specific activity) and area specific activity of selected artificial isotopes are compared in Tables 1 [29,31,33,34] and 2 [29,35–38]. Most clearance limits are the same among different jurisdictions, and only a few are different. Those specific activities represent unconditional clearance levels without the need for defining the destination of clearance materials.

For material containing a mixture of radionuclides, the following formula, also known as sum of fractions or the unity rule, is used for clearance criteria:

$$\sum_{i=1}^{n} \frac{C_i}{(Clearance\ level)_i} \leq 1 \tag{1}$$

C_i – the mass specific or surface specific concentration (Bq/g or Bq/cm^2) of radionuclide i in the material.

$(Clearance\ level)_i$ – the value of clearance level for radionuclide i in the material.

n – the number for radionuclides present in the material.

By manipulating Eq 5, an alternate gross activity can also be used as clearance criteria for material containing a mixture of radionuclides:

$$gross\ clearance\ activity\ level = \frac{1}{\sum_{i=1}^{n} \frac{f_i}{(Clearance\ level)_i}} \tag{2}$$

f_i – the relative fraction of the total radioactivity contributed by radionuclide i in the material.

$(Clearance\ level)_i$ and n – defined above.

The volumetric clearance of materials is realized through non-destructive gamma radiation measurements or destructive radiochemical sample analyses. These measurement techniques are dependent on the radionuclides present in the waste materials. The clearance level activity measurements are not discussed here.

Table 1. Samples of regulatory activity concentrations for unconditional clearance of typical radionuclides (unit: Bq/g).

Reference Isotope	[31] IAEA RS-G-1.7	[33] EC RP-122	[34] Japan	[29] Canada
H-3	100	100	100	100
C-14	1	10	1	1
Fe-55	1000	100	1000	1000
Co-60	0.1	0.1	0.1	0.1
Sr-90	1	1	1	1
Cs-137	0.1	1	0.1	0.1
Eu-154	0.1	0.1	0.1	0.1
U-234		1	1	1
Pu-241	10	1	10	10
Am-241	0.1	0.1	0.1	0.1
Cf-252	1	0.1		1

Table 2. Surface contamination levels for regulatory unconditional clearance.

Country	Surface Contamination Criteria (area specific activity)					
European Commission [39]	Unconditional Clearance Levels for Large Structures, Bq/cm^2					
	H-3	3800	Sr-90	34	Pu-241	11
	C-14	2800	Cs-137	15	Am-241	0.34
	Fe-55	10000	Eu-154	0.69		
	Co-60	0.36				
Canada	The CNSC considers that it is the responsibility of licensees to demonstrate their clearance limits to meet the definitions of clearance levels in the NSRDR [29], or, as specified in CNSC Radiation Protection REGDOC-2.7.1 [35], to consult the limits in ANSI/HPS N13.12-2013 "Surface and Volume Radioactivity Standards for Clearance" [36]. The clearance values from the UK guidelines issued in 2005 [37] are used by waste generators in Canada: 40 Bq/cm^2 for low toxicity beta emitters, 4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, or 0.4 Bq/cm^2 for all other alpha emitters. The IAEA Safety Standards No. SSR-6 [38] is also used as a guideline. The clearance limits for some specific radionuclides established on the lower dose limit of 10 μSv/a in ANSI/HPS N13.12-2013 may be lower than the generic values in the UK guidelines. CSA Standard N292.5-11 (R2021) [21] provides guidelines for the exemption or clearance from regulatory control of materials that contain, or potentially contain, nuclear substances.					

The IAEA has included surface-area specific criteria in an early TECDOC-855 report [40], and there are surface contamination criteria from European Commission and from the US DOE 10 CFR 835 [41]. For conditional clearance approved on a case-by-case basis in Canada, many licensees use the values from the 2005 UK guidelines [37]. These are also commonly applied to non-nuclear industries.

2.3.2 Surface contamination and clearance

Typically, surface contamination (excluding tritium), expressed as Bq/cm^2, does not penetrate more than a few millimetres on hard surfaces, e.g., equipment used for handling radionuclide chemicals in medical and research tracer applications. Therefore, the most efficient way to limit the radioactivity spread is to carry out the clearance measurements on the surfaces, if practical. A distinction between removable, fixed and total surface activity is only meaningful on undamaged coatings and surfaces. Any surface specific clearance levels should therefore apply to the total (sum of removable and fixed) activity. This clearance approach has the advantage of making the measurements where the activity is located, which increases the chances of finding and removing contamination for clearance. The same is true for volumetric contamination. Regardless how the surface clearance measurements are carried out, the radioactive inventory in the cleared material must be minimized, which reduces radiation exposure to the environment and public.

3. Waste radionuclides and materials from non-nuclear industries

3.1. Radionuclides and prediction of decay clearance

Apart from the nuclear energy sector, radioactive materials and chemicals are used extensively in the areas of medicine, consumer products, industrial devices, agriculture, research and education. These radioactive materials involve a large number of radionuclides, primarily of artificial origin, e.g., from reactor irradiation, heavy metal fission, and/or accelerators. For waste management with low radioactivity materials, an ideal scenario is that radionuclides decay to stable isotopes, their radioactivity is reduced to below their unconditional clearance levels in a reasonable time frame, and the waste materials that contain these radionuclides can be cleared for disposal through non-radioactive conventional waste routes. To distinguish the waste radionuclides with a short half-life that can be cleared after decay from the long half-life radionuclides that must be managed as radioactive waste, the radionuclides used in non-nuclear industries are generally categorized into two groups: radionuclides with a half-life of greater than 100 d (Table 3) and radionuclides with a half-life of shorter than 100 d (Table 4) [42–46]. The tables list the majority of radionuclides available in the literature. Canada may not currently use every radionuclide listed in the tables. However, those radionuclides that are not used in Canadian non-nuclear industries may find their use in Canada in the future.

The approach of declassification or clearance by decay is particularly useful for non-nuclear industrial waste generators, as their waste may contain a single radionuclide with a short half-life.

A_t – the activity of the radionuclide at time t.

A_0 – the activity of the radionuclide at time $t = 0$.

$t_{1/2}$ – the half-life of a radionuclide.

Most radionuclide users will have limited waste storage facilities, and a storage period of 2–3 years is commonly assumed to be long enough to allow radioactive decay. After a 2 or 3 year decay, a radionuclide with a half-life of less than 100 d will have decayed to below 0.6% or 0.05% of its starting activity, respectively. Because of their initial low concentrations and quantities in the applications, these short half-life radionuclides in the waste, after a 2 or 3 year decay time, can reach levels below their clearance levels, and be cleared from regulatory oversight. For the radionuclides with a half-life of greater than 100 d, wastes containing these radionuclides generally have to be shipped to a radioactive waste management site and managed together with nuclear industry waste if their activities are not exempted or clearable at the time of waste generation.

The above cases are only applicable if the radionuclides decay to stable isotopes, where radioactivity is expected to decrease with time. However, the decay events of radionuclides can be more complex than the above simple cases, particularly for those alpha-emitting heavy metal elements used in Targeted Alpha Therapy (TAT) applications. For example, a radionuclide may decay:

- By emitting two types of particles each having different energy to two different daughter radionuclides,
- To intermediate daughter radionuclide(s) with a shorter half-life, or
- To intermediate daughter radionuclide(s) with a longer half-life.

The radionuclides with the above decay events are summarized in Table 5, which are extracted from Tables 3 and 4.

The activity decay of a radionuclide is expressed by:

$$\frac{A_t}{A_0} = exp\left(-\frac{\ln(2)}{t_{1/2}} * t\right) \tag{3}$$

Table 3. Use of radionuclides with a half-life of greater than 100 days in non-nuclear industries.

Isotope	Decay Product	Half-life (d)	Specific Activity Bq/g	Application	Method of Production
H-3	He-3	4.49E+03	3.58E+14	Consumer products - lighting. Radioisotopic thermoelectric generators. Radioimmunoassay. Biomedical research.	Reactor irradiation, accelerator.
C-14	N-14	2.08E+06	1.66E+11	Radioimmunoassay. Physical measurement gauges. Biomedical research.	Reactor irradiation, accelerator.
Na-22	Ne-22	9.50E+02	2.31E+14	Materials research – Mossbauer.	Accelerator.
Al-26	Mg-26	2.62E+08	7.10E+08	Mg-26 Generator.	High energy accelerator.
Si-32	(P-32) S-32	5.59E+04	2.70E+12	Tracer.	High energy accelerator.
Mn-54	Cr-54	3.12E+02	2.87E+14	Tracer.	Reactor irradiation, accelerator.
Fe-55	Mn-55	1.00E+03	8.79E+13	Laboratory or portable systems.	Reactor irradiation, accelerator.
Co-57	Fe-57	2.72E+02	3.12E+14	Positron imaging. Radioimmunoassay. Research - Mossbauer. Tracer/radiolabelling. Physical measurement gauges.	Accelerator.
Co-60	Ni-60	1.93E+03	4.18E+13	Radiotherapy with sealed sources. Radiation processing. Physical measurement gauges. Non-destructive testing.	Reactor irradiation.
Ni-63	Cu-63	3.66E+04	2.10E+12	Physical measurement gauges.	Reactor irradiation, accelerator.
Zn-65	Cu-65	2.44E+02	3.05E+14	Tracer.	Reactor irradiation, accelerator.
Ge-68	Ga-68	2.71E+02	2.62E+14	Positron imaging.	Reactor irradiation, accelerator.
Se-75	As-75	1.20E+02	5.38E+14	Non-destructive testing.	Accelerator.
Sr-90	Y-90	1.06E+04	5.09E+12	Endovascular radiotherapy. Physical measurement gauges. Radioisotopic thermoelectric generators. Y-90 generator.	Heavy metal fission product.
Ru-106	Pd-106	3.72E+02	1.23E+14	Radiotherapy with sealed sources – Brachytherapy.	Heavy metal fission product.
Cd-109	Ag-109	4.62E+02	9.60E+13	Laboratory or portable systems.	Heavy metal fission product.
Ag-110m	Ag-110	2.50E+02	1.76E+14	Tracer.	Heavy metal fission product.
Sn-119m	Sn-119	2.93E+02	1.39E+14	Materials research – Mossbauer.	Heavy metal fission product.
Ba-133	Cs-133	3.84E+03	9.45E+12	Positron imaging calibration source.	Heavy metal fission product.
Cs-134	Ba-134	7.54E+02	4.78E+13	Tracer.	Heavy metal fission product.
Cs-137	(Ba-137m) Ba-137	1.10E+04	3.21E+12	Positron imaging calibration source. Radiotherapy - brachytherapy. Physical measurement gauges.	Heavy metal fission product.

Continued on next page

Isotope	Decay Product	Half-life (d)	Specific Activity Bq/g	Application	Method of Production
Pm-147	Sm-147	9.58E+02	3.43E+13	Physical measurement gauges.	Reactor irradiation.
Gd-148	(Sm-144, 148) (Nd-144) Ce-140	2.59E+04	1.26E+12	Imaging. Neutron absorber.	High energy accelerator.
Eu-152	Sm-152 72.1%, Gd-152 29.1%	4.94E+03	6.43E+12	Brachytherapy.	Fission product.
Gd-153	Eu-153	2.40E+02	1.31E+14	Bone density measurement. Imaging.	Reactor irradiation.
Hf-172	(Lu-172) Yb-172	6.83E+02	4.11E+13	Tracer/imaging/radiotherapy.	High energy accelerator.
Ta-182	W-182	1.14E+02	2.32E+14	Brachytherapy – obsolete.	Reactor irradiation.
Tl-204	Hg-204 97.1%, Pb-204 2.9%	1.38E+03	1.72E+13	Physical measurement gauges.	Reactor irradiation.
Po-210	Pb-206	1.38E+02	1.66E+14	Static electricity discharge.	Reactor irradiation.
Ra-226	(Pb-212) (Bi-212) Pb-208	5.79E+05	3.69E+10	Targeted Alpha Therapy (TAT), radiopharmaceuticals.	Reactor irradiation.
Th-228	(Pb-212) (Bi-212) Pb-208	6.98E+02	3.03E+13	TAT, radiopharmaceuticals.	Reactor irradiation.
Th-229	(Bi-213) Tl-205	2.88E+06	7.33E+09	TAT, radiopharmaceuticals.	Reactor irradiation.
U-232	(Th-228) (Hg-200) (Bi-212) Pb-208	2.51E+04	8.29E+11	Th-228 generator.	Reactor irradiation.
U-233	(Th-229) (Ra-225) (Ac-225) (Bi-213) Tl-205	5.81E+07	3.57E+08	Heavy isotope generator.	Reactor irradiation.
U-235	(Th-231) Pa-231	2.57E+12		Heavy isotope generator.	Natural resource.
U-236	Th-232	8.55E+09	2.39E+06	Heavy isotope generator.	Reactor irradiation.
U-238	Th-234	1.63E+12	1.24E+04	Heavy isotope generator.	Natural resource.
Pu-238	U-234	3.21E+04	6.33E+11	Radioisotopic thermoelectric generators.	Reactor irradiation.
Pu-239	U-235	8.81E+06	2.30E+09	Heavy isotope generator.	Reactor irradiation.
Pu-240	U-236	2.40E+06	8.40E+09	Heavy isotope generator.	Reactor irradiation.
Am-241	Np-237	1.58E+05	1.27E+11	Bone density. Imaging. Physical measurement gauges. Smoke detectors.	Reactor irradiation.
Pu-241	Am-241	5.22E+03	3.84E+12	Consumer products.	Reactor irradiation.
Am-243	Np-239	2.70E+06	7.37E+09	Smoke detectors. Physical measurement gauges	Reactor irradiation.
Cm-244	Pu-240	6.61E+03	2.99E+12	Radioisotopic thermoelectric generators.	Reactor irradiation.
Bk-249	Cf-249	3.30E+02	5.88E+13	TAT, radiopharmaceuticals.	Reactor irradiation.
Cf-252	Cm-248	9.66E+02	1.98E+13	Physical measurement gauges, neutron sources.	Reactor irradiation.

Table 4. Use of radionuclides with a half-life of shorter than 100 days in non-nuclear industries.

Isotope	Decay Product	Half-life (d)	Specific Activity Bq/g	Application	Methods of Production
C-11	B-11	1.41E−02	3.11E+19	Positron imaging.	Accelerator.
N-13	C-13	6.92E−03	5.37E+19	Positron imaging.	Accelerator.
O-15	N-15	1.41E−03	2.28E+20	Positron imaging.	Accelerator.
F-18	O-18	7.62E−02	3.52E+18	Positron imaging.	Accelerator.
Na-24	Mg-24	6.25E−01	3.22E+17	Electrolytes tracer.	Accelerator.
Mg-28	(Al-28) Si28	8.71E−01	1.98E+17	Tracer.	High energy accelerator.
P-32	S-32	1.43E+01	1.06E+16	Radiotherapy with sealed sources - Endovascular radiotherapy.	Accelerator.
P-33	S-33	2.53E+01	5.78E+15	Tracer/radiolabelling.	Reactor irradiation.
S-35	Cl-35	8.75E+01	1.58E+15	Tracer.	Reactor irradiation.
K-42	Ca-42	5.13E−01	2.24E+17	Coronary blood flow tracer.	Accelerator.
Sc-46	Ti-46	8.38E+01	1.25E+15	Tracer.	Reactor irradiation, accelerator.
Cr-51	V-51	2.77E+01	3.42E+15	Tracer/radiolabelling.	Reactor.
Fe-59	Co-59	4.45E+01	1.84E+15	Radioimmunoassay.	Reactor irradiation, accelerator.
Cu-64	Ni-64 61%, Zn-64 39%	5.29E−01	1.43E+17	Tracer - imaging. Radiotherapy.	Accelerator.
Ga-67	Zn-67	3.26E+00	2.21E+16	Radiopharmaceutical imaging.	Accelerator.
Cu-67	Zn-67	2.58E+00	2.80E+16	Imaging and radiotherapy.	Accelerator.
Ga-68	Zn-68	4.70E−02	1.51E+18	Positron imaging, daughter of Ge-68.	Accelerator.
Rb-81	(Kr-81m, Kr-81) Br-81	1.90E−01	3.13E+17	PET agent in myocardial perfusion imaging.	Accelerator.
Sr-82	(Rb-82) Kr-82	2.56E+01	2.31E+15	Generator to produce Rb-82 for positron emission.	Accelerator.
Kr-85	Rb-85	2.56E+01	2.22E+15	Physical measurement gauges.	Fission product and decay.
Sr-89	Y-89	5.05E+01	1.07E+15	Radiotherapy and radiopharmaceuticals.	Reactor irradiation, decay.
Y-90	Zr-90	2.66E+00	2.02E+16	Radiotherapy and radiopharmaceuticals.	Fission product and decay.
Mo-99	(Tc-99m) Tc-99	2.75E+00	1.78E+16	Tracer/radiolabelling.	Fission product and decay.
Pd-103	Rh-103	1.70E+01	2.76E+15	Radiotherapy with sealed sources – Brachytherapy.	Accelerator.
In-111	Cd-111	2.80E+00	1.55E+16	Tracer/radiolabelling.	Accelerator.
Sn-117m	Sn-117	1.36E+01	3.04E+15	Radiotherapy and radiopharmaceuticals.	Accelerator.
I-123	123Te	5.51E−01	7.13E+16	Tracer/imaging.	Accelerator.
Sb-124	Te-124	6.02E+01	6.47E+14	Tracer.	Reactor irradiation.
I-125	Te-125	5.94E+01	6.51E+14	Radioimmunoassay. Radiotherapy with sealed sources - Brachytherapy. Biomedical research.	Fission product and decay.

Continued on next page

Isotope	Decay Product	Half-life (d)	Specific Activity Bq/g	Application	Methods of Production
Te-125m	Te-125	5.74E+01	6.73E+14	Materials research – Mossbauer.	Fission product and decay.
Cs-131	Xe-131	9.69E+00	3.81E+15	Brachytherapy.	Reactor irradiation, accelerator.
I-131	Xe-131	8.03E+00	4.60E+15	Radiotherapy and radiopharmaceuticals.	Fission product and decay.
Xe-133	Cs-133	5.24E+00	6.93E+15	Lung imaging.	Reactor irradiation.
Sm-151	Eu-151	1.93E+00	1.66E+16	Materials research – Mossbauer.	Reactor irradiation, accelerator.
Sm-153	Eu-153	1.93E+00	1.64E+16	Radiotherapy and radiopharmaceuticals.	Reactor irradiation, accelerator.
Gd-159	Tb-159	7.70E−01	3.95E+16	Tracer/imaging.	Reactor irradiation, accelerator.
Dy-165	Ho-165	9.72E−02	3.01E+17	Synovectomy treatment of arthritis.	Reactor irradiation, accelerator.
Ho-166	Er-166	1.12E+00	2.60E+16	Radiotherapy and radiopharmaceuticals.	Accelerator.
Yb-169		3.20E+01	8.93E+14	Non-destructive testing.	Accelerator.
Er-169	Tm-169	9.38E+00	3.05E+15	Radiotherapy and radiopharmaceuticals.	Accelerator.
Lu-177	Hf-177	6.65E+00	4.11E+15	Radiotherapy/imaging.	Reactor irradiation, accelerator.
Re-186	Os-186 (92.5%), W-186 (7.5%)	3.72E+00	6.99E+15	Radiotherapy and radiopharmaceuticals.	Reactor irradiation, accelerator.
W-188	(Re-188) Os-188	6.98E+01	3.68E+14	Radiotherapy with sealed sources - Endovascular radiotherapy.	Reactor irradiation, accelerator.
Re-188	Os-188	7.08E−01	3.63E+16	Radiotherapy and radiopharmaceuticals.	Reactor irradiation.
Ir-192	Pt-192 (95.1%), Os-192 (4.9%)	7.38E+01	3.41E+14	Radiotherapy with sealed sources - Brachytherapy, endovascular radiotherapy. Non-destructive testing.	Reactor irradiation, accelerator.
Au-198	Hg-198	2.70E+00	9.05E+15	Radiotherapy with sealed sources – Brachytherapy.	Reactor irradiation, accelerator.
Pb-200	(Tl-200) Hg-200	8.96E−01	2.70E+16	Tracer/analysis.	High energy accelerator.
Tl-201	Hg-201	3.04E+00		Diagnosis of coronary artery disease, replacement of Tc-99m.	Accelerator.
At-211	Bi-207 41.8%, Pb-207 58.2%	3.01E−01	7.6177E+16	TAT, radiotherapy and radiopharmaceuticals.	Accelerator.
Pb-212	(B-212) (Po-212) (Tl-208) Pb-208	4.43E−01	5.14E+16	TAT, radiotherapy and radiopharmaceuticals.	Reactor irradiation/decay.
Bi-212	Pb-208	4.20E−02	5.42E+17	TAT, radiotherapy and radiopharmaceuticals.	Reactor irradiation/decay.
Bi-213	(Pb-209) Bi-209	3.17E−02	7.17E+17	TAT radiotherapy and radiopharmaceuticals.	Reactor irradiation/decay.
Ra-223	Bi-209, Pb-207	1.14E+01	1.90E+15	TAT, brachytherapy.	Reactor irradiation/decay.
Ac-225	Bi-209, P-207	9.95E+00	2.16E+15	TAT, especially prostate cancers.	Separation of trans-uranium elements and alpha emitters.

Table 5. Radionuclides with very long half-life decay products.

Isotope	Half-life (d)	Decay Product	Decay Product Half-life (d)
Isotope with half-life < 100 d and decay product with a half-life > 100 d			
At-211	3.01E−01	Bi-207 41.8%	1.20E+04
		Pb-207 58.2%	Stable
Bi-213	3.17E−02	(Pb-209) Bi-209	6.94E+21
Ac-225	9.95E+00	(Fr-211) (At-217) (Bi-213) (Po-213) (Pb-209) Bi-209	6.94E+21
Isotope with half-life > 100 d and decay product with a half-life > 100 d			
Tl-204	1.38E+03	Pb-204 2.9%	5.11E+19
U-235	2.57E+12	(Th-231) Pa-231	1.20E+07
U-236	8.55E+09	Th-232	5.11E+12
U-238	1.63E+12	(Th-234) (Pa-234) U-234	8.97E+07
Pu-238	3.21E+04	U-234	8.97E+07
Pu-239	8.81E+06	U-235	2.57E+11
Pu-240	2.40E+06	U-236	8.55E+09
Am-241	1.58E+05	Np-237	7.83E+08
Pu-241	5.22E+03	Am-241	1.58E+05
Am-243	2.70E+06	(Np-239) Pu-239	8.81E+06
Cm-244	6.61E+03	Pu-240	2.40E+06
Bk-249	3.30E+02	Cf-249	1.28E+05
Cf-252	9.66E+02	Cm-248	1.27E+08

For a simple case of a parent-daughter decay chain, the activities of the parent, daughter (decay product), and a combination of the two, can be expressed as:

$$A_p(t) = A_p^0 e^{-\lambda_p t} \tag{4}$$

$$A_{dp}(t) = \frac{\lambda_p A_p^0}{\lambda_{dp} - \lambda_p}\left(e^{-\lambda_p t} - e^{-\lambda_{dp} t}\right) \tag{5}$$

$$A_{total}(t) = A_p(t) + A_{dp}(t) \tag{6}$$

$A_p(t)$ – the activity of the parent radionuclide.

A_p^0 – the activity of the parent radionuclide at time $t = 0$.

λ_p – the decay constant of the parent radionuclide, $\lambda_p = \ln(2)/(t_{p,1/2})$; $t_{p,1/2}$ – the half-life of the parent radionuclide.

$A_{dp}(t)$ – the activity of the decay product at time t.

λ_{dp} – the decay constant of the decay product, $\lambda_{dp} = \ln(2)/(t_{dp,1/2})$; $t_{dp,1/2}$ – the half-life of the decay product.

$A_{total}(t)$ – the total activity of the parent and daughter radionuclides.

The evolution of activities of the parent and daughter radionuclides, and their total activity with time, include two scenarios illustrated in Figure 3:

- $t_{p,1/2} > t_{dp,1/2}$, the total activity $A_{total}(t)$ will be dominated by the parent radionuclide's activity $A_p(t)$ after secular equilibrium, where $A_p(t) = A_{dp}(t)$, is reached between the parent and decay product in a simple parent-daughter decay chain. The total activity decreases with time, but can be greater than the initial activity of the parent radionuclide before the total radioactivity decreases to below the initial activity. The time that the secular equilibrium is reached is expressed as:

$$t = \frac{ln\left(\frac{\lambda_{dp}}{\lambda_p}\right)}{\left(\lambda_{dp} - \lambda_p\right)} \tag{7}$$

- $t_{p,1/2} < t_{dp,1/2}$, the total activity $A_{total}(t)$ will be dominated by the decay product's activity $A_{dp}(t)$ after a certain time. The total activity decreases with time, and will always be lower than the initial activity. The time that the decay product in the total activity $A_{total}(t)$ will become dominant, e.g., when $A_{dp}(t) = 1000 * A_p(t)$, can be expressed as:

$$t = \frac{ln\left(1 + \left(1000 * \frac{-\lambda_{dp} + \lambda_p}{\lambda_{dp}}\right)\right)}{-\lambda_{dp} + \lambda_p} \tag{8}$$

The calculations of more complex decay events than a simple parent-daughter chain are done by decay physics models and databases, and can be found in references, e.g., [47]. The time for the isotopes in Table 5 to decay to their clearance levels is very long, and storage for decay and clearance is not practical. The wastes containing these radionuclides will be managed with nuclear industry waste if their activities are deemed to be above the exemption and clearance limits at the time of waste generation.

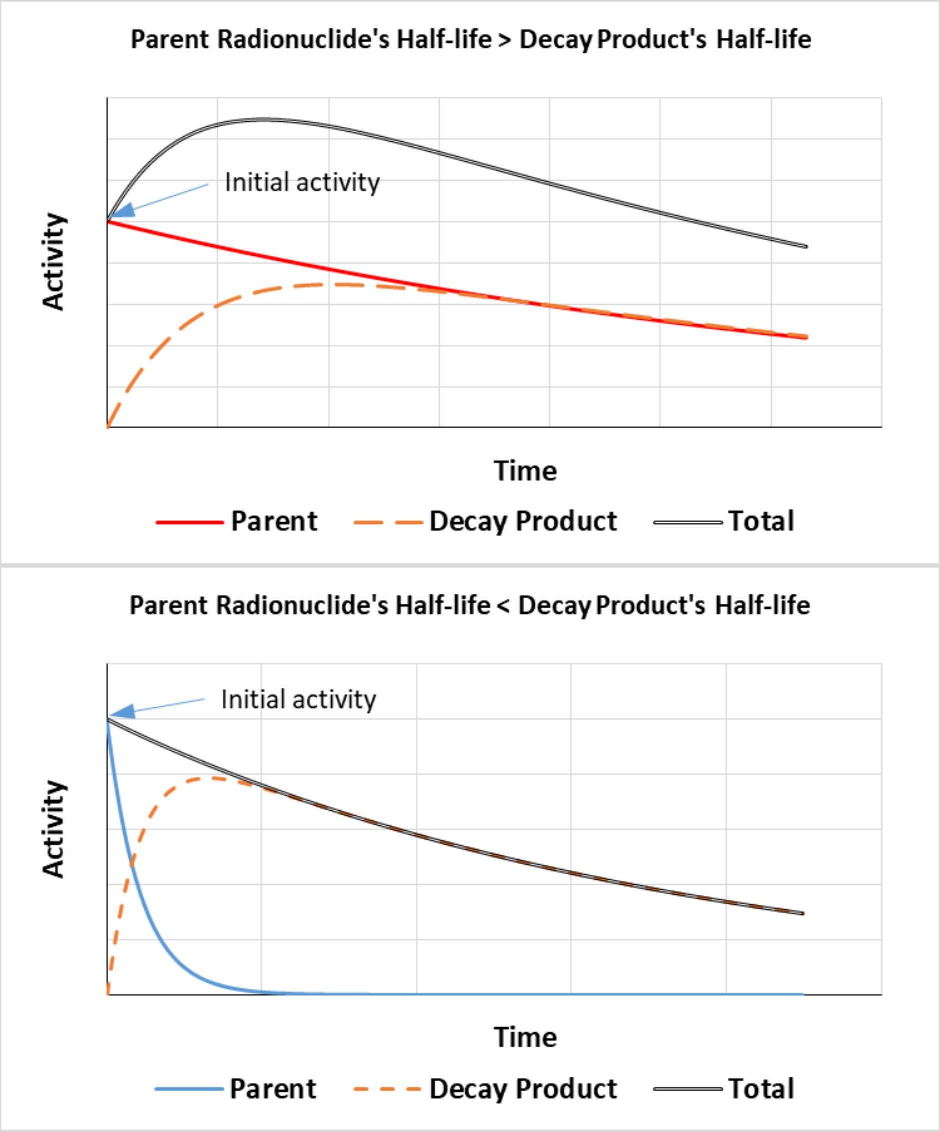

Figure 3. Activity evolution of a simple chain of parent and daughter radionuclides with time.

3.2. Waste matrix materials

The waste that cannot be exempted or cleared from regulatory oversight will be managed together with radioactive waste from the general nuclear industry. Waste mostly contains non-radioactive matrix materials and a very small portion of radionuclide materials. The waste matrix materials from the use of radionuclides vary significantly in the state of phase and characteristics.

The majority of wastes generated from the industry are solid wastes, with some liquids and gases, depending on their processes. Examples are those from waste processors, such as return of ash from incineration, and producers of medical isotopes, which may include waste equipment and personal protective equipment and clothing (PPE&C).

Waste from hospitals, research reactors and accelerators, e.g., SLOWPOKE small reactors and TRIUMF (The Tri-University Meson Facility), are generally solid in the form of PPE&C. In more limited quantities, there are disused equipment, disused sealed sources, and occasionally irradiated fuel. In addition, radioactive biowaste has been generated from research institutions. However, normally material of this type would be either treated at the point of generation or processed through a service provider, resulting in a radioactive inorganic solid material, which is considered more stable for long-term storage and disposal. The non-radioactive components in the radioactive waste are largely non-toxic, and there will be no additional management requirements for the non-radioactive constituents. However, if the waste contains both chemical toxicants and radioactive nuclides, it will have to be managed as mixed waste.

The above materials are per normal operations from the non-nuclear industry waste generators. However, the variety of waste types changes as facilities undergo repairs and decommissioning. This waste stream also includes a limited amount of depleted uranium (DU). As per the CNSC [48], approximately 1,500 metric tonnes of DU as oxides and metals are stored at Cameco's Port Hope Conversion Facility, which results from nuclear fuel fabrication activities for the nuclear industry. In addition, there are some limited quantities of DU elsewhere in Canada, as DU metal is commonly used as shielding in medical radiation therapy and industrial radiography equipment, and as counterweights in aircrafts. Some countries use DU metal to produce ammunition, but this does not occur in Canada. Depleted uranium, like other uranium in Canada, is subject to the NSCA and its regulations.

4. Current management practices

4.1. Waste characterization

Characterization of radioactive wastes is an area receiving increasing scrutiny as proposed radioactive disposal facilities progress. This development includes a new CSA standard N292.8 on Waste Characterization [49]. In general, characterization information must be available to ensure that the waste materials meet the requirements of a storage and/or disposal facility Waste Acceptance Criteria (WAC).

Once that information has been provided, additional verification of the characterization may be performed by the receiving facility. This may include visual inspection, non-destructive analysis (e.g., gamma spectroscopy), and destructive analysis of waste materials.

4.2. Exempted from radioactive waste

Waste materials containing nuclear materials can vary in the types of radionuclides and their quantities. Common household and commercial products are generally exempted as an individual product, but are no longer exempted in larger quantities, as per NSRDR [29]. Examples of this type of waste include smoke alarms and emergency exit lighting. Although the examples provided are in solid form, the emergency lighting radionuclide content is in the tritium-containing gas. Tritium-containing gaseous contents are generally not required to be extracted for conversion into a solid form as long as they can be safely stored.

In many cases, manufacturers are required to accept the return of their disused/spent products containing radioactivity. As a result, those manufacturers may have a quantity of materials that no longer meet exemption and must therefore be handled as radioactive waste.

Separately, in agreement with the regulator, materials can be cleared from regulator control. This can be accomplished using CSA N292.5 [21] and the values as listed in the NSRDR [29], or alternatively through allowable surface contamination values by using the following references as guides:

- Clearance and Exemption Principles, Processes and Practices for Use by the Nuclear Industry, Nuclear Industry Safety Directors Forum, 2005 [37].
- Specific Safety Requirements No SSR-6, Regulations for the Safe Transport of Radioactive Material, International Atomic Energy Agency, 2018 [38].

In order to be able to clear materials from regulator control, some waste generators will also perform delay (or storage) and decay. If the waste materials are primarily very short-lived radionuclides (e.g., less than 100 days), waste generators may choose to store their waste on-site for a predetermined period (e.g., ten half-lives) in order to decay radioisotopes to less than unconditional clearance levels, at which point the materials could be handled as conventional waste.

4.3. Waste volumes and characteristics from non-nuclear industries

Chalk River Laboratories (CRL) manages radioactive waste from non-nuclear industrial users on behalf of AECL and in turn, the Government of Canada. In 2020, CRL received 87.6 m^3 of radioactive waste from external organizations for storage and eventual disposal [50], with > 90% of the material as LLW and the remainder being ILW. The recent annual volumes received at the CRL site are shown in Table 6 [50]. Although HLW (or irradiated fuel of small reactors) may be received from external organizations, it is generally very infrequent and normally as a result of either refurbishment or decommissioning of a small research reactor.

Table 6. Annual commercial waste volumes received at Chalk River Laboratories for storage.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
Vol (m^3)	92.9	89.6	82.8	69.1	37.4	55.9	35.7	55.1	87.6

An example of some of the modeled characteristics of a small research reactor are presented in Table 7. A further breakdown of radionuclides measured by sampling and analysis for an example research reactor is provided in Table 8. Modeling, sampling and analysis are the primary tools for waste characterization of decommissioned small research reactors from the university and institutes. The modeling is relatively inexpensive as compared to the sampling and analysis. The reliability of modelling results is verified by analysis of samples from selected reactor components.

Table 7. Modelled activities (Bq) of significant radionuclides in example SLOWPOKE research reactor sections at one year after shutdown.

	Activity (Bq/g) after 33 Years of Irradiation Operation			
Component	Co-60	Zn-65	Sc-46	Sb-124
Reactor Vessel Lower Section	6.94E+02	5.20E+03	3.28E+00	6.86E−01
Reactor Vessel Upper Section	1.33E−02	1.56E−01	9.86E−05	2.06E−05
Core Support Platform	3.46E+02	2.60E+03	1.64E+00	3.44E−01
Support Structure	4.44E−03	5.18E−02	3.28E−05	6.86E−06
Beryllium Shim Tray	3.46E+02	2.60E+03	1.64E+00	3.44E−01
Irradiation Tubes	1.73E+03	1.30E+04	8.22E+00	1.72E+00
Control Rod	8.66E+02	6.48E+03	4.10E+00	8.58E−01
Detectors and Guide Tubes	1.73E+01	1.30E+02	8.22E−02	1.72E−02

Table 8. Simplified fission products and actinides in an example SLOWPOKE research reactor at one year after shutdown for decommissioning.

Nuclide	Half-life (a)	Activity (Bq/g)	Nuclide	Half-life (a)	Activity (Bq/g)
H-3	12.3	2.19E+03	Eu-152	13.5	3.06E+04
C-14	5670	1.84E−03	Eu-154	8.6	1.21E+03
Se-79	1.10E+06	1.09E+01	Eu-155	4.8	3.94E+02
Rb-87	4.75E+10	4.33E−04	Actinide	Half-life (a)	Activity (Bq/g)
Sr-90	28.79	2.68E-05	Ac-227	21.8	1.07E−02
Zr-93	1.53E+06	2.25E+01	Th-228	1.9	4.03E−02
Nb-93m	16.1	1.36E+01	Th-230	7.54E+04	3.71E+01
Nb-94	2E+04	6.73E−04	Pa-231	3.3E+04	1.28E−02
Tc-99	2.14E+05	2.38E+02	U-232	69.8	4.14E−02
Rh-102	2.9	2.21E−02	U-233	1.6E+05	1.09E−06
Ru-106	1.0	2.19E+04	U-234	2.5E+05	8.49E−05
Pd-107	6.5E6	1.76E−01	U-235	7E+08	3.71E+01
Cd-113m	14.1	5.44E+01	U-236	2.4E+07	6.56E+00
Sn-121m	55	9.43E+00	U-238	4.5E+09	4.51E−01
Sb-125	2.7	2.58E+03	Np-237	2.1E+06	1.28E−02
Sb-126	2.3E+05	3.55E+00	Pu-238	87.7	9.02E−01
I-129	1.6E+07	3.90E−01	Pu-239	2.4E+04	1.26E+01
Cs-134	2.1	8.55E+02	Pu-240	6.6E+03	8.67E−01
Cs-137	30	2.16E+01	Pu-241	14.3	1.39E+00
Ce-142	5E+16	1.02E+06	Pu-242	3.7E+05	7.08E−07
Pm-147	2.6	4.57E−04	Am-241	432.8	4.64E−02
Sm-151	90	1.94E+05	Am-242m	141	1.50E−04

4.4. Gaps and improvements

Generally, the current radioactive wastes being generated from the non-nuclear waste generators have disposition pathways available. Due to the nature of the non-nuclear sectors, discovery of items without an existing waste disposition pathway are exceedingly rare to non-existent. However, materials of that nature are likely to be available and the nuclear sector has to determine an appropriate pathway for them, e.g., ILW Polychlorinated Biphenyl (PCB) waste.

In some cases, storage space available for delay and decay of radioactive materials may not be feasible (e.g., longer storage periods, controls). This challenge may present an opportunity where segregation of these types of materials could result in minimization of long-term legacy waste.

However, there are future wastes for which there may be gaps. With the development of small modular reactors (SMRs), which may be used by various industries as energy sources and for other purposes, the proposed fuel types present in some of these systems are significantly different from the systems currently deployed in Canada. As a result, the waste characteristics are still currently unknown and may present challenges when trying to navigate a disposition route. For instance, to adhere to the open fuel cycle adopted for the heavy water reactors (HWRs) in Canada, SMR designs may also assume an open fuel cycle to the exclusion of reprocessing of spent fuel, indicating direct disposal of SMR spent fuels; yet incorporating SMR spent fuels into the direct disposal plan designed for the HWR spent fuel will be challenging. With more stringent regulations and public scrutiny, it becomes a common requirement that the waste generated from potentially new applications of nuclear materials must have a clear management strategy and disposal pathway before the applications can be deployed.

5. Summary

A systematic approach, including regulations and industry standards, has been used in the management of radioactive waste generated from the nuclear industry. This system is extended to the wastes generated from non-nuclear industrial applications. Domestic waste management organizations that are used by the nuclear industry, which non-nuclear industrial users can also rely on, provide integrated strategies on managing waste streams from diverse sources and waste generators. This integration allows for best practices applied in environmental protection and for waste management cost reduction for the non-nuclear industry waste generators. The current waste streams from non-nuclear industry waste generators account for a very small amount of the total radioactive inventory in Canada and are well managed within the current waste management regulatory framework. Potential waste streams from any new applications of radionuclides and small reactors should have well-defined waste management plans before the applications are deployed for use.

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Conflict of interest

The authors declare no conflicts of interest.

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